AUSTRALASIAN SLAG ASSOCIATION ASA INC 1990

vicroads

RTA

A Guide to the Use of Iron Blast Furnace Slag in Cement and Concrete

FOREWORD

As evidence of the RTA's commitment to the increased use of recycled materials, in June 1993 the RTA in conjunction with the Australasian Slag Association, released “A Guide to the Use of Slag in Roads”. VicRoads shares the same commitment to the use of recycled materials and supported the publication of that original document.

This Guide to the Use of Iron Blast Furnace Slag in Cement and Concrete produced by the Australasian Slag Association offers an expansion of the technical data contained in the original Guide and is supplementary to it.

The RTA and VicRoads are pleased to co-operate with the Slag Association in the production of this Guide to facilitate the appropriate use of recycled products.

DAVID THOMSON
DIRECTOR RTA TECHNOLOGY
April 1997

KERRY BURKE
DIRECTOR PRODCTION SERVICES
April 1997

CONTENTS

1 INTRODUCTION

Throughout the world there is an increasing focus on the need to recycle and to more fully utilise by-products of manufacturing processes in an attempt to conserve our finite natural resources. Technical evaluation supported by field experience has shown that a by-product such as iron blast furnace slag has, in many applications, properties suitable to replace or supplement and improve traditional materials.

This booklet which is supplementary to the Association's *Guide to the Use of Slag in Roads,* reviews in some detail the properties of slag in cement and concrete. As there are many types of slag, it should be particularly noted that the term slag used throughout this booklet refers specifically to metallurgical slag produced in modern iron blast furnaces, ie; iron blast furnace slag and not basic oxygen steel slag or electric arc furnace slag which are steel furnace slags.

It cannot be over emphasised that blast furnace slag's potential to improve concrete quality, particularly with slag blended cements, will not be realised unless standard good practice is observed with the handling and placement of the concrete. Correct cover, compaction and curing are all essential to ensure that the resultant hardened concrete will achieve the required design properties such as strength and durability. The same criteria of course apply equally to concrete containing ordinary Portland cement.

Although the term recycling is referred to when slag is used in any of its applications, strictly speaking slag is not a recycled material. As a by-product in the manufacture of iron, blast furnace slag is a renewable virgin material, i.e. slag has not been previously used but has been formed as part of the iron making process. As slag leaves the blast furnace in a molten form at 1500°C it is a homogeneous material free from foreign matter.

TYPES OF BLAST FURNACE SLAG

Blast Furnace slag in Australia is produced in three forms:

1.1 BLAST FURNACE ROCK SLAG

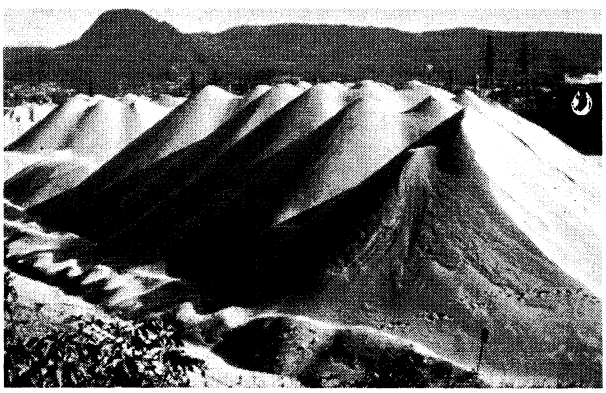
Molten slag on leaving the furnace is allowed to flow into ground bays where it air cools to form a rock like material.

1.2 GRANULATED BLAST FURNACE SLAG (GBFS)

Molten slag on leaving the furnace is allowed to flow into' a trough or granulator containing high pressure, high volume water sprays. The heat energy extracted from the molten slag causes it to change instantly into a coarse sand sized material.

1.3 GROUND GRANULATED BLAST FURNACE SLAG (GGBFS)

Granulated Blast Furnace Slag when ground to cement fineness and in the presence of a suitable activator becomes a cementitious binder.



GRANULATED BLAST FURNACE SLAG READY FOR DELIVERY.

2. IRON BLAST FURNACE SLAG CONCRETE AGGREGATES

Rock slag can be crushed and screened to a full range of aggregate sizes. It is important that slag aggregate should not be simply substituted for another aggregate in an existing concrete mix without considering differences in particle density, grading etc. As for any aggregate, a mix should be specifically designed to suit the characteristics of the aggregate. Therefore the slightly lower particle density and higher absorption of slag should be taken into account in the mix design.

2.1 WATER ABSORPTION

As a result of its manufacturing process, slag is vesicular. This means that the individual pieces of slag aggregate contain voids which tend to be unconnected to each other occurring throughout the slag and appearing as blind holes on the surface.

Water absorption of slag is normally in the range of 3 to 6% by mass. Some natural aggregates may have an absorption in the order of 4%. The value of 2.5% set as a maximum water absorption in some specifications appears to be a derivation from Note 2 to clause 8.3 of AS 2578.1 (1) which reads:

> *"The average absorption of aggregate, other than lightweight, is about 2 per cent".*

However, there does not seem to be any intent in AS 2758.1 (1) to nominate a maximum value for water absorption for any aggregate including slag. Notes to Australian Standards are for general information and are not mandatory.

The following effects should also be noted as influencing the measurement of the absorption of slag aggregate, viz.:

- Greater surface area of the slag particles;
- Lower particle density of the slag.
- Sometimes when drying to a saturated surface dry (SSD) condition, all of the water held in the shallow surface pits of slag aggregate is not removed by the standard test method of surface drying.

Because of the vesicular structure of air cooled blast furnace slag, provision is made in AS 2578.1 (1) for the different water absorption of slag aggregate viz.,

> *"The water absorption of lightweight or vesicular aggregates can vary considerably without affecting many of the properties of concrete made using such aggregates". (Note 4 to clause 8.3, AS 2758.1)*

There is no doubt that the moisture content of slag aggregates for concrete is important. To avoid potential difficulties with the batching and placing of concrete, slag is supplied in a pre-wetted condition. It is important that this moisture content, around SSD condition, be maintained whilst slag is in storage ready for batching. Dust control water sprays fitted to delivery bins at most modern concrete plants may be all that is necessary to maintain the desired moisture content.

2.2 PARTICLE SHAPE

A characteristic of slag's structure is that it crushes to a desirable cubical shape.

AS 2758.1 (1) specifies that the proportion of misshapen particles shall not exceed 10%. Quality assurance testing of 20mm slag aggregate since 1991 has shown that the proportion of misshapen particles when tested to AS 1141.14 (2) at a 3:1 ratio is no more than 3%.

2.3 WET STRENGTH

In AS 2758.1 (1), one of three methods of specifying aggregate durability is by wet strength and wet/dry strength variation. There is some question from a technological viewpoint as to whether the Wet/Dry Strength Variation test is a true guide to the durability of slag aggregate.

The Wet/Dry Strength Variation Test was devised many years ago to identify natural gravels which appeared suitable for use in road pavement construction when dry, but failed in service under wet conditions. It was subsequently found that some natural gravels which satisfied the maximum Wet/Dry strength variation, failed in service because they had low Wet or Dry Strength. So with the introduction of AS 2758.1 (1) minimum Wet Strength as well as a minimum Wet/Dry Variation was introduced.

The tests themselves require skill and care for accurate, repeatable results. A brief description of the test follows. A given mass of aggregate is placed in a cylinder and a compressive force applied to a plate on top of the aggregate. The load that would create approximately 7.5 to 10% of fines from the sample is applied. The load is recorded together with the actual mass of fines produced. The test is repeated with another load that would create fines from the sample in the range 10 to 12.5%. The load and actual mass of fines is again recorded. The load value representing 10% loss is interpolated graphically.

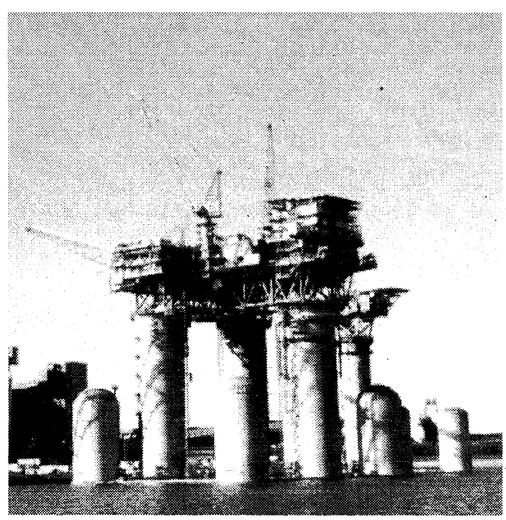
The test is applied to a dry sample and to a sample which has been soaked in water for at least 24 hours to become a wet sample. From the two tests, the Dry Strength, the Wet Strength and Wet/Dry Strength Variation are determined.

AS 2758.1 (1) permits values other than those laid down in Table 1 for Wet Strength and Wet/Dry Strength Variation when vesicular aggregate is considered. Note to Table 4 in AS 2758.1 (1) reads as follows:

> *"For some aggregate other* (wet strength) *values could be substituted in Table 4 based on satisfactory local experience of materials and performance, eg. vesicular aggregate".*

In the USA it has also been recognised that a test of this type is not applicable to aggregates such as air cooled blast furnace slag. Hence, the American Society for Testing and Materials, ASTM, excludes the crushing test from the procedures used to assess the suitability of a material for use as an aggregate in concrete.

Whilst the test procedure is valuable in assessing natural gravels and aggregates for use in road pavements, it is less significant with vesicular aggregates such as slag. The vesicular nature of slag causes the corners and edges to readily break off when contact occurs between single size particles in the laboratory loading test. This type of point contact does not occur when the slag is set in hardened concrete. The apparent lack of strength of the slag aggregate does not prevent its satisfactory use in high strength concrete. This is illustrated by compressive strengths in excess of 100 MPa being obtained from concrete test specimens in which air cooled blast furnace slag was used as the coarse aggregate. Refer to Table 1.



ESSO - WEST TUNA - BREAM B OIL PLATFORMS.
SLAG CEMENT

TABLE 1 - **COMPRESSIVE STRENGTH OF SLAG AGGREGATE CONCRETE** MIXES

Concrete Grade	Nominal Max Size (mm)	Water Absorption (%) ÷	Wet Strength (kN) ÷	Compressive Strength (MPa) for Various Mixes □				
				7 days		28 days		91 days
50	10 & 20	4 - 5	75 - 95	39.5	39.0	60.5*	59.0**	
				42.5	35.0	64.5*	59.5**	NOT
				35.0	47.5	53.5*	67.0-t	CAST
				38.0	40.0	58.0*	60.0**	
60	10 & 20	4 - 5	75 - 95	57.0	56.0	74.0*	73 .0+	
				57.5	52.0	72.5*	66.5+	NOT
				52.0	47.0	75.0*	63 .0+	CAST
				54.0	48.0	72.5-t	67.5+	
High Strength	7	3 - 4	80 - 100	102.5		117.5+		119.0
	10	4 - 5	75 - 95	86.0		114.5+		117.0
				86.5		104.0+		107.5
				84.0		101.0+		107.0
Test Method		AS 1141.5&6 (3)	RTA-T2 15 (4)	AS 1012.9 (5)				

Note:

1. ÷ Values for "Water Absorption" and "Wet Strength" are from tests carried out in the NATA laboratory of Australian Steel Mill Services in the period 1991 - 1994.

2. * Trial mixing and testing carried out at Pioneer Concrete NATA Laboratory (6)
   ** Trial mixing and testing carried out at Testrite NATA Laboratory (7)
   Trial mixing carried out at ASMS Laboratory (8)

3. □ The proportions for the mixes shown are detailed in Appendix A.

2.4 LOS ANGELES VALUE

The Los Angeles test consists of placing a given mass of sized aggregate into a revolving drum containing steel balls. After a prescribed number of revolutions the aggregate is removed and screened. The fine material abraded from the aggregate is weighed and expressed as a percentage loss from the original sample. The test is a very severe impact test and usually reflects the toughness of the aggregate particle. AS 1141.23 (9).

As for the Wet Strength Test, the Los Angeles test is not reflective of the performance of slag in concrete in the field.

Again this is due to the vesicular nature of slag which allows corners of the slag particle to be readily abraded giving a misleading Los Angeles value which is not an accurate indication of the performance of slag concrete.

AS 2758.1 (1) provides for values other than those laid down in Table 5 for natural aggregates, with the inclusion of a category for 'Artificial Aggregates (including slags)', viz. Note 4 to Table 5 in AS 2758.1 (1) reads as follows: -

> *"The maximum acceptable Los Angeles value for each source should be nominated in the works specification. The value to be adopted should be based on the performance history of the particular aggregate",*

2.5 SODIUM SULPHATE SOUNDNESS

Sulphate solutions such as sea water and certain ground waters can degrade some absorptive aggregate by expansive crystallisation within the particles. The minerals and sulphate solutions form crystals, the growth of which ultimately cause particle disintegration. Slag aggregate exhibits a high degree of resistance to sodium sulphate attack. Quality assurance testing of blast furnace slag aggregate since 1991 has shown that sodium sulphate loss to be less than 1% when tested to AS 1141.24 (10)

AS 2758.1 (1) specifies maximum sodium sulphate soundness losses for particular concrete exposures as shown in Table 2.

TABLE 2 - SODIUM SULPHATE SOUNDNESS

Concrete Exposure Classification	Maximum Weighted Average Loss Percent
Severe	6
Moderate	9
Protected	12

2.6 CHLORIDE CONTENT

After processing, slag aggregate has a chloride level comparable to natural aggregates.

The chloride ion content of blast furnace slag aggregate tested in accordance with AS 1012.20 (11) generally lies in the range 20-460 ppm (0.002-0.046%).

The corresponding values for natural coarse aggregates are 10 - 330 ppm (0.001-0.033%).

2.7 SULPHATE CONTENT

The sulphate ion content tested in accordance with AS 1012.20 (11) generally lies in the range 680 to 1600ppm (0.068,0.160%).

The corresponding values for natural coarse aggregates are lo-1450 ppm (O.OOl-0.145%).

2.8 BULK DENSITY

Slag has the following Bulk Density. (Single size 20mm aggregate)

Loose - 1200-1300 kg/m'. RTA Test Method T211 (12).

Compacted - 1300-1400 kg/m'. RTA Test Method T212 (13).

These values are lower than those typically obtained for natural aggregate.

2.9 ALKALI AGGREGATE REACTION

Alkali-aggregate reaction in concrete results from alkalis in the cement reacting with certain types of silica or carbonate compounds contained in some aggregates.

Over the past few decades the problems of alkali aggregate reaction in concrete from particular natural aggregates have become better known and understood. This reaction can be very harmful as it leads to expansion and cracking of the concrete. In the case of some aggregates which have a slow reaction, damage to the concrete may take up to 20 years to become evident. For this reason an appraisal of aggregates with this tendency is important for critical structures.

The Australian Standard for testing of aggregates for concrete, AS 1141, lists Method 39 (14) as a means of recognising aggregate that may be alkali reactive.

Regular quality assurance testing of slag aggregate to AS 1141.39 (14), since 1991 has shown slag aggregate to be classified as "innocuous" as far as alkali aggregate activity is concerned in accordance with this standard.

An examination of the mineralogy of Australian blast furnace slag from Port Kembla shows that slag does not contain reactive forms of minerals which can cause alkali aggregate reaction.

2.10 FALLING OR DUSTING UNSOUNDNESS

When some blast furnace slags cool from the molten state at about 1500°C to around 490°C an inversion of beta dicalcium silicate in the slag to the gamma form may result in disruption of the slag mass. This disruption leads to a condition of the slag known as falling or dusting unsoundness.

AS 2758.1 (1) notes that *no evidence has been found, either in Australia or overseas, of delayed inversion of β dicalcium silicate in iron blast furnace slag, or of deterioration of concrete due to the presence of β dicalcium silicate.*

2.11 IRON UNSOUNDNESS

Iron unsoundness, which occurs as disintegration of the slag when immersed in water, is highly likely when the slag contains more than 3% ferrous oxide and at least 1% of sulphur. AS 2758.1 (1) notes that iron unsoundness has not been recorded for Australian blast furnace slag.

Quality control testing of slag aggregate to AS 1141.37 (15) Test Method for Iron Unsoundness since 1991 has found no evidence of iron unsoundness.

Chemical analysis of slags from Port Kembla, Newcastle and Whyalla show that their ferrous oxide and sulphur contents are significantly below the maximum values noted in AS 1466.74 (16). [Replaced by AS 2758.11

2.12 SUMMARY OF SLAG AGGREGATE'S PROPERTIES

Property	Rating
Water absorption	Medium to high
Particle shape	Cubical
Wet strength	+ Low
Los Angeles abrasion value	* High
Sodium Sulphate soundness	Sound
Chloride content	Low
Sulphate content	Low to medium
Alkali/aggregate reactivity	Innocuous
Drying shrinkage	Low
Flexural strength potential	Adequate
Suitability for pumping (mix and pump dependent)	Adequate

+ Refer Section 2.3
* Refer Section 2.4

3. SLAG AGGREGATE IN CONCRETE

3.1 COMPARISON WITH NATURAL AGGREGATE

The most detailed analysis in recent years of slag as a concrete aggregate compared to natural aggregate was undertaken and subsequently reported by Gomes & Morris. This occured when designs for the Sydney Harbour Tunnel immersed tube concrete segments were being prepared.

This work was undertaken by the Connell Wagner Group Pty Ltd in partnership with Freeman Fox (Hong Kong) and was reported in detail in a paper presented at "Concrete for the Nineties", Leura 1990, by Lewis Gomes and Martin Morris (17).

Despite better performance of slag aggregate concrete as regards to drying shrinkage and flexural strength, *"it was reluctantly decided not to pursue the use of slag aggregate':* This was because slag aggregate concrete would have been 3% lighter than basalt aggregate concrete and therefore a greater volume of concrete would be required to achieve the design mass.

Figures 1, 2 and 3 show test results for Compressive Strength, Flexural Strength and Drying Shrinkage reported by Haber (18). The conclusion section of that paper is quoted below.

These little published results, for slag aggregate, achieved in Sydney Harbour Tunnel Immersed Tube concrete testing program might help focus fresh attention upon the potential benefit; beckoning the user of slag aggregate concrete. The two main benefits emerging are seen as follows.

Drying- Shrinkage

Significant benefits are likely to accrue from the use of air-cooled slag as the coarse aggregate in the concrete. This is not altogether surprising in view of the vesicular nature of the aggregate. For the same reason, care must be exercised in ensuring that the slag aggregate is pre-soaked in stockpiles.
(Ed. Referring to Figure 3, the drying shrinkage at the age of 91 days for the slag aggregate mixes was less than the corresponding basalt mixes by 50 to 180 microstrain for the range of binder combinations tested)

Flexural Strength

More surprising to many is the apparently significant advantage in terms of flexural strength and associated tensile strain capacity accruing from the use of slag aggregate in combination with particular binders. It has long been recognised that enhanced tensile/flexural strength of concrete derives from the mortar/aggregate bond, which, in this instance, is again assisted by the vesicular nature of the slag aggregate. (Ed. Referring to Figure 2, the flexural strength at 28 days for the slag aggregate mixes was higher than the corresponding basalt mixes by 0.3 to 0.9 MPa for the range of binder combinations tested)

It is also of interest to designers that the compressive strength of the slag aggregate concrete doesn't appear to suffer by comparison with concrete containing basalt aggregate, the lower particle wet strength of the slag aggregate notwithstanding.

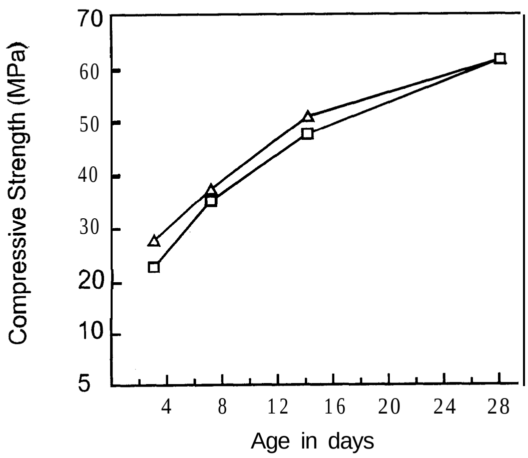
*In addition to this the results of compressive strength testing were as follows.**

For the four binder combinations tested, the compressive strength of the concrete made using the slag aggregate was higher than when basalt was used at all ages of test except for Type "C" (now, TYPE LH LOW HEAT) cement at 28 days. In this case, the compressive strengths were equal for the two aggregates.

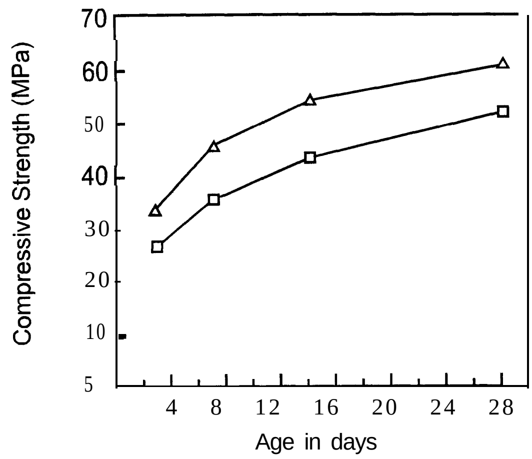
FIGURE 1 - COMPRESSIVE STRENGTH

Key: □ Dunmore basalt
A Port Kembla slag
(ED. Type "C" cement = low heat cement
ACSE = type SL, shrinkage limited cement
pfa = fly ash)

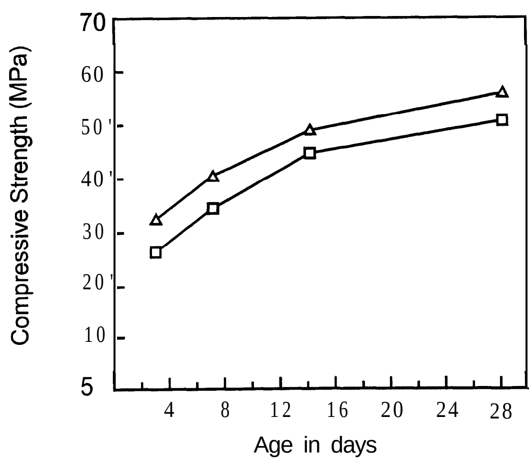
Type "C" Cement



50% ACSE/50% Slag Cement



50% ACSE/35% Slag/l 5% pfa Cement



75% ACSE/25% pfa Cement

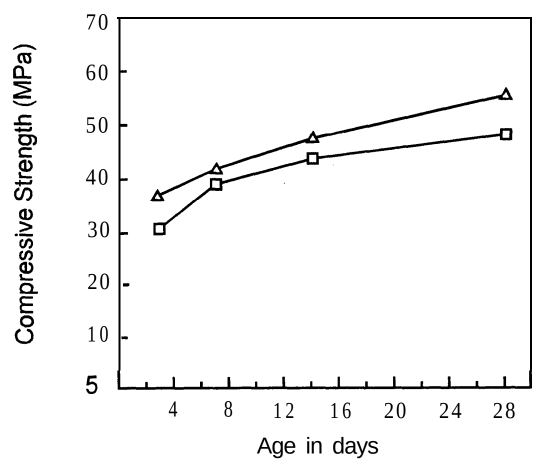


FIGURE 2 - FLEXURAL STRENGTH

Key

- □ Dunmore basalt
- A Port Kembla slag

(ED. Type "C" cement = low heat cement
ACSE = type SL, shrinkage limited cement
pfa = fly ash)

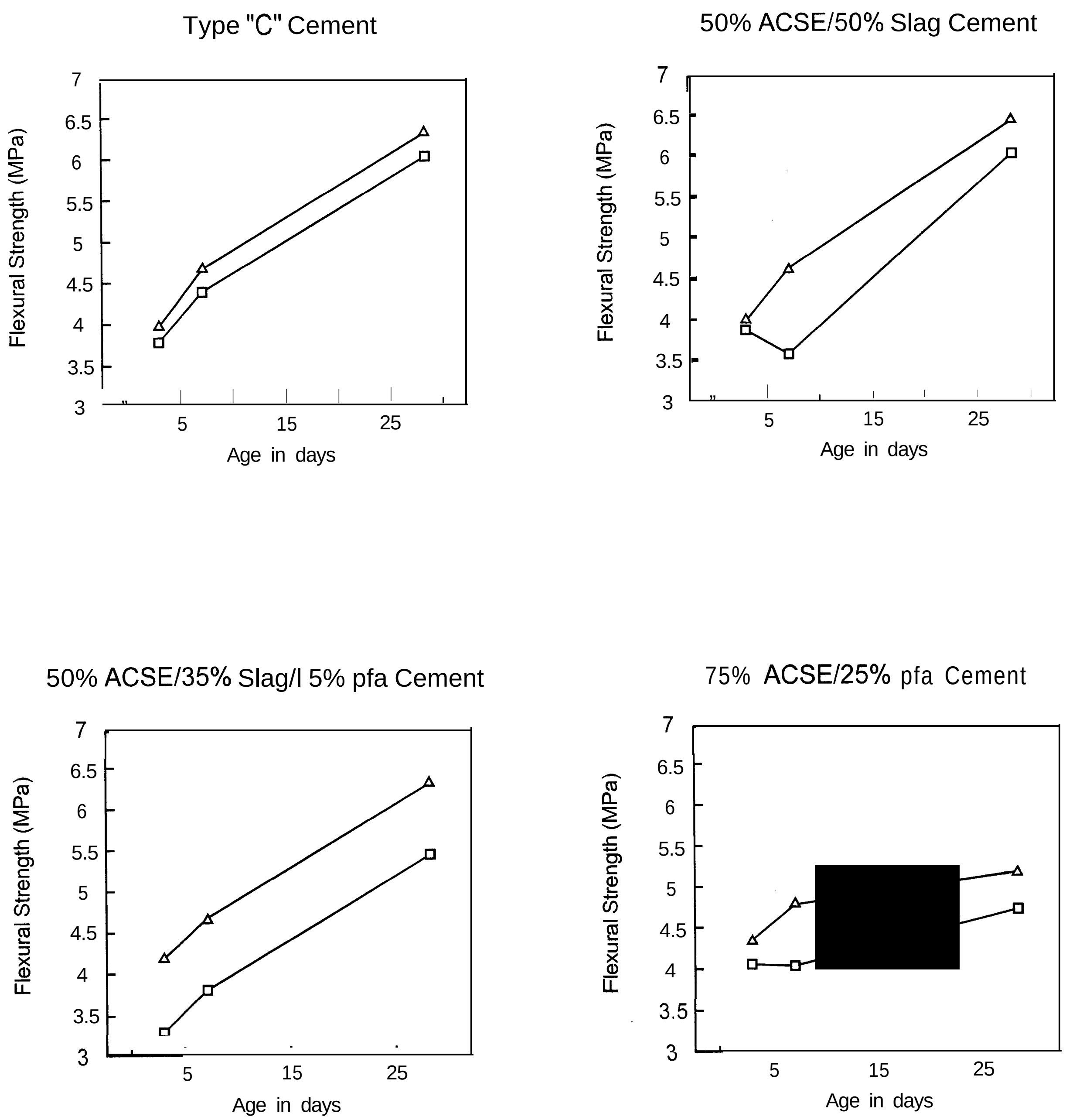


FIGURE 3 - DRYING SHRINKAGE

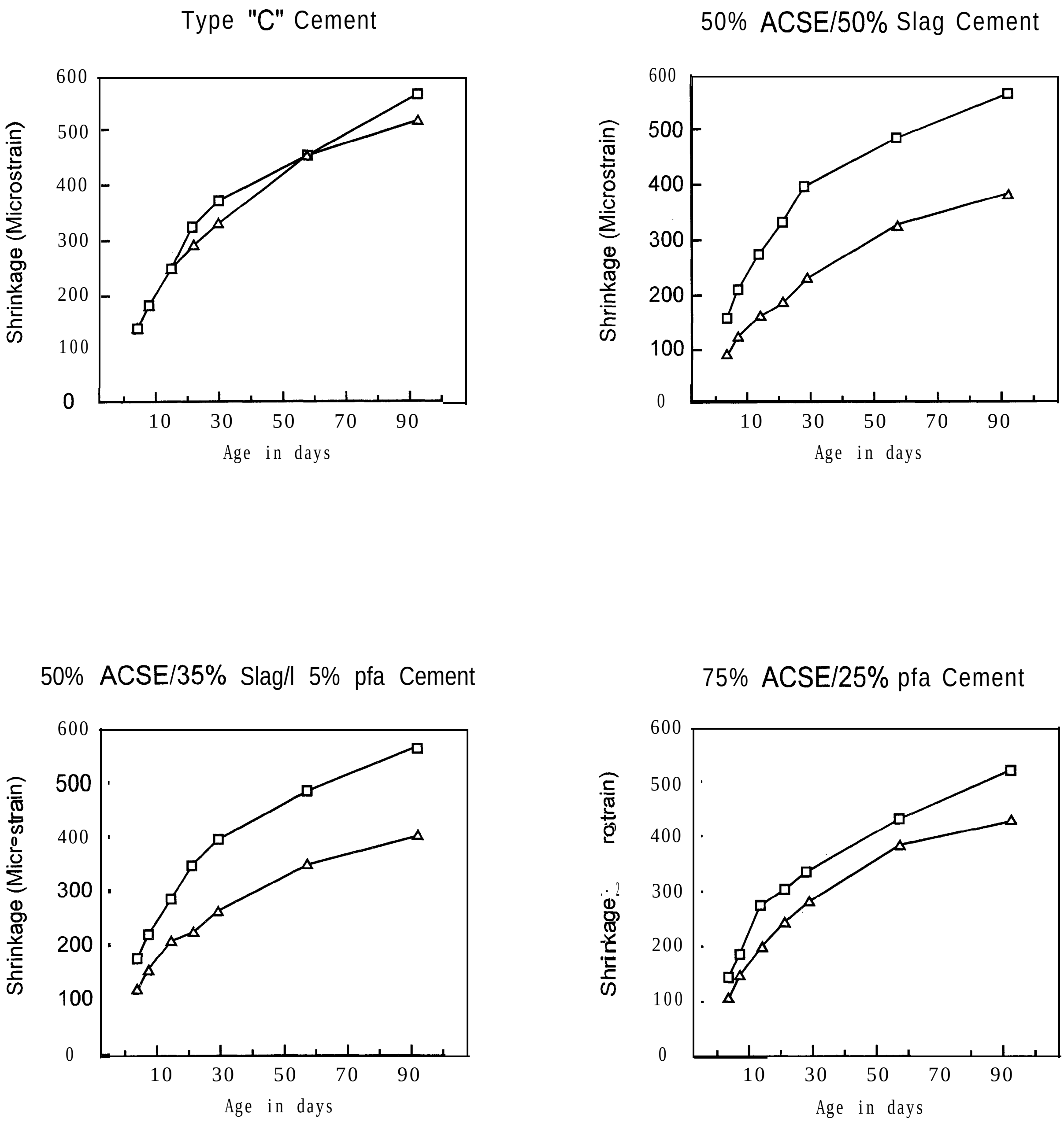
Key: □ Dunmore basalt

A Port Kembla slag

(ED. Type "C" cement = low heat cement

ACSE = type SL, shrinkage limited cement

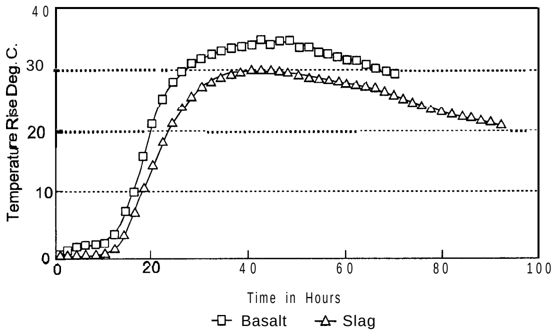
pfa = fly ash)



One fascinating feature to emerge from the Sydney Harbour Tunnel investigation not previously published is the benefit to be gained in terms of reduced heat of hydration from the use of slag aggregate in combination with a slag/y ash blended cement. Figure 4 depicts the adiabatic temperature profile obtained from the use of such a cement blend in combination with slag aggregate compared with Dunmore basalt aggregate. (Ed. Commonly referred to as Illawarra basalt)

FIGURE 4 -TEMPERATURE RISE IN CONCRETE
EFFECT OF AGGREGATE TYPE

35% Slag/l 5% Fly Ash/SO% ACSE



3.2 CEMENT PASTE AND AGGREGATE INTERACTION

Vaysburd (19) reported that lightweight aggregate in concrete developed a contact zone between the cement paste matrix and the lightweight aggregate particles which was different to the zone that formed between the cement matrix and dense aggregate.

- The zone around the lightweight aggregate was shown to be low in porosity and free from micro-cracks and porous pockets.

- The zone around the dense aggregate was weak and porous due to water being trapped at the underside of the aggregate particle and insufficient packing of the cement paste around the aggregate.

Vaysburd (19) illustrated the crack free and low porosity zone around lightweight aggregate by a scanning electron microscope. This clearly showed uninterrupted adherence of the cementitious matrix to the aggregate particle in structural grade concrete.

Zhang and Gjorv (20) illustrated the penetration of cement paste into the pores of lightweight aggregate using backscattered electron images.

While air-cooled slag is not a true lightweight aggregate, its relatively higher absorption and surface characteristics tend to make the contact zone around the slag particles less porous than for dense aggregate.

Presence of a porous and micro-cracked transition zone between a natural aggregate, Indiana limestone, and the cement paste and cement mortar matrix has been illustrated by Aquino et al **(21)** using scanning electron microscopes. A water to cement ratio of 0.35 was used in all mixes for this study.

In work commissioned by James (22) it was shown that in concrete containing Port Kembla blast furnace slag, the vesicles in the surface of the slag particles are filled by the cementitious mortar resulting in a dense zone of material immediately surrounding the slag particle. This was clearly illustrated in a micrograph of a section taken through the concrete (normal structural grade strength).

The test data in Table 1 demonstrate that the higher water absorption of slag aggregate is not a sign of weakness of the aggregate.

3.3 PUMPING

Concrete made with vesicular coarse aggregate, such as slag aggregate, can be successfully pumped. However as with any other aggregate, attention to detail is required to ensure trouble-free pumping and some basic information is listed below.

As for any other aggregate, the mix design for slag aggregate must satisfy certain requirements viz.:

3.3.1 Adequate Cement Content

Concrete with a cement content below 280 kg/m^3 will generally prove difficult to pump because of lack of lubrication. However cement contents in excess of 450 kg/m^3 can produce stickiness and reduce pumpability.

3.3.2 Adequate Ultra-Fines Content

An adequate amount of ultra-fine material should be incorporated in the mix, i.e. material finer than 150 microns. This is generally contributed from part of the cement, flyash, ground granulated blast furnace slag, sand, and all of the silica fume. The total weight of cement and ultra-fines should be between 300 and 450 kg/m" for concrete containing 20mm maximum size aggregate.

3.3.3 Water to Cementitious Material Ratio

This ratio should lie generally between 0.4 and 0.65 to provide a pumpable mix.

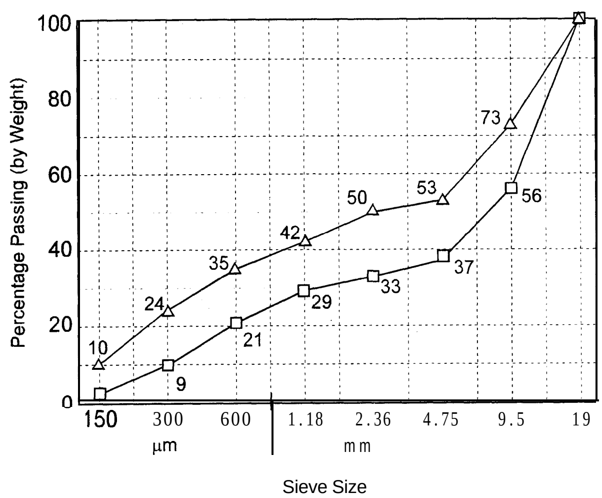
3.3.4 Slump

The slump of the concrete should be within the range 80 to 100mm. Slumps in excess of 100mm can be pumped as long as steps are taken to prevent segregation of the mix ingredients. Any concrete below 80mm slump may be more difficult to pump than higher slump concrete.

3.3.5 Aggregate Proportions

The coarse and fine aggregate generally should be proportioned to produce a continuous grading although gap graded concrete can be pumped as long as the gap is not too pronounced. For small diameter lines, 75 and 100mm, the grading envelope presented by Egan (23) in Figure 5 may be used as a guide for proportioning the aggregates for a 20mm nominal mix.

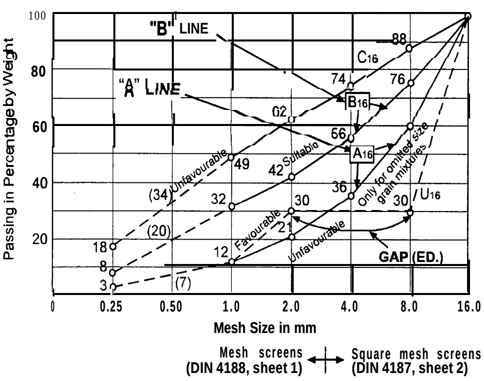
FIGURE 5 - COMBINED AGGREGATE GRADING ENVELOPE FOR PUMPING CONCRETE THROUGH 75 AND 100mm DIAMETER LINES .



Gap graded concrete may be pumped provided the gap does not extend over more than two sieve sizes as shown on a typical graph in Figure 6.

Absence of material between consecutive sieves requires an increase in material both finer and coarser than the omitted fraction. (Refs. 24 and 25). The actual amount of adjustment of the finer and coarser material will depend on the gradings of the aggregate used.

FIGURE 6 - RECOMMENDED COMBINED GRADING ENVELOPE FOR PUMPING CONCRETE (16mm Aggregate - Schwing)



Schwing recommends grading design between lines A & B

Figure 6 illustrates the gap in the grading curve between the 2.0 and 8.0mm mesh sizes. This has been taken from the German publication "Pumping Concrete and Concrete Pumps" from Schwing (24) which uses the standard German sizes for sieves and aggregates.

It should be noted that the graphs in Figures 5 and 6 apply to any aggregate and not just slag.

Concrete, in which the aggregate grading has a gap or lack of particles of more than one size within the grading, is more likely to be moisture sensitive and segregate at high slumps and may have poor workability. Hence when considering the workability of concrete, the overall grading of the combined coarse and fine aggregate, and not just the coarse aggregate, must be taken into account. In fact, it is thought that the grading of the fine aggregate is more important for workability and reduced bleeding than that of the coarse aggregate.

Mixes made using slag aggregate may require a slightly higher sand content to provide pumpability. Australian experience has shown that this increase is of the order of 2%.

Another approach to proportioning the coarse and fine aggregate in a concrete mix designed for pumping is to use an optimum volume of coarse aggregate per cubic metre of concrete.

For a slag with a known particle density, this can be translated into a particular mass of coarse aggregate per cubic metre of concrete.

As a guide, for a slag with a particle density of the order of 2540kg/cubic metre, the quantities of coarse slag aggregate shown in Table 3 provide a base line for proportioning the coarse and fine aggregate.

TABLE 3 - QUANTITY OF COARSE SLAG AGGREGATE PER CUBIC METRE OF CONCRETE FOR PUMPABLE CONCRETE

MAXIMUM SIZE OF COARSE AGGREGATE (mm)	Mass of Coarse Aggregate (Saturated surface dry condition) kilograms per cubic metre of concrete. A value towards the lower end of the range should be used where pumping factors are expected to be less favourable due to conditions such as low cement and/or ultra-fines content of the concrete.
20	900 - 1050
10	650 - 850

Difficulties encountered in pumping concrete containing 20mm slag aggregate in conditions adverse to pumping, ie through lines of less than 100mm diameter, with abrupt reducers or excessive lengths of rubber hose, can be eliminated by replacing 25 to 50% of the slag aggregate in the mix with an equal volume of well graded, good shaped 20mm natural aggregate.

3.3.6 Moisture Condition of the Aggregate

To enable concrete containing slag aggregate to be pumped, the slag must be at or near the Saturated Surface Dry condition at the time of batching.

3.3.7 Chemical Admixtures

Chemical admixtures that are suitable for use in concrete containing aggregate other than slag are normally suitable for use with slag aggregate concrete.

3.3.8 Some reasons for concrete (irrespective of aggregate type) not being able to be pumped include -

a) too little water;

b) too much water;

c) poor shape of the aggregate;

d) oversize pieces of aggregate;

e) inadequate pre-wetting of porous or vesicular aggregates;

f) use of inappropriate admixtures or incorrect dosage;

g) foreign objects in the concrete;

h) inadequate priming of the pump and pump line;

i) poor condition of the pump or line;

j) pump line configuration too severe;

k) inadequate line diameter and the number of bends, reductions, etc.;

1) hardening or bleeding of the concrete in the pump or line;

3.4 CORROSION

Slag aggregate does not have any adverse effect on reinforcing steel in concrete. As with natural aggregates the concrete should be of adequate quality and well compacted with sufficient cover given to the reinforcing steel.

Slag aggregate is alkaline in the presence of moisture, having a pH in the range of 10.5 to 11.5. The presence of slag aggregate in concrete does not reduce the alkalinity of concrete and therefore does not increase the likelihood of corrosion of steel reinforcement.

An extract from a previous Australian Standard 1466 - 1974 Metallurgical Furnace Slag Aggregate (16) reads as follows:

> *"The suggestion has often been made that iron blast furnace slag aggregate in concrete may contribute to corrosion of steel reinforcement. It has, however been found from numerous tests and extensive practical experience that the use of such slag complying with existing standards does not introduce any cause of corrosion not present with other aggregates. Provided that the same precautions are taken to obtain a properly consolidated concrete and adequate cover to the reinforcement as are necessary with dense natural aggregates, there is no additional risk of corrosion."*

Research carried out by the CSIRO (26) shows that use of slag cement is not likely to increase the corrosion rate of steel reinforcement compared to ordinary Portland cement.

CORE SAMPLE FROM 60MPA SLAG CEMENT & SLAG AGGREGATE CONCRETE.

4. SLAG CEMENT

4.1 GENERAL

Slag cements currently available in Australia contain 20-40% slag for general construction and 60-70% slag for applications which require reduced heat of hydration, increased resistance to the ingress of chloride ions, improved sulphate resistance and to inhibit alkali-aggregate reaction. Cement with a high proportion of slag is particularly useful for concrete in a marine environment.

Slag cements of other binder proportions may be produced by cement manufacturers if required in commercial quantities.

AS 3582.2 (27) sets out the requirements for ground granulated blast furnace slag as a supplementary cementitious material in cement and mortar.

Ground granulated blast furnace slag (GGBFS) may perform differently with various brands and types of Portland cement with which it is blended or interground. In some cases this may lead to better strength development and shorter setting times. For special applications trial mixes are recommended to determine the optimum slag blend.

When specifying slag cement, the particular requirements of the concrete and the conditions to which the concrete will be exposed should be advised. Table 4 gives some indicators of desirable slag contents.

Note:

For the purpose of this document, the long established term Ordinary Portland Cement (OPC) has been used rather than General Purpose Cement (GP). This is consistent with the terminology used in an earlier guide to the use of slag in roads.

TABLE 4 - RECOMMENDED SLAG CONTENT IN CEMENT FOR VARIOUS APPLICATIONS OF CONCRETE

Application	Slag Proportion As Percentage Of Total Slag And Portland Cement Content (Note 3)
General construction	20 - 40
Where it is desirable to reduce heat of hydration (Note 1)	50 - 80
Structures exposed to chloride attack (Note 2)	50 - 80
Structures exposed to sulphate attack (Note 2)	50 - 80
Marine structures	60 - 80
Where the cement and aggregate to be used in the concrete has the potential for alkali-aggregate reaction	50 - 70

Note 1: Depends on degree of reduction required. Portland cement content is also important.

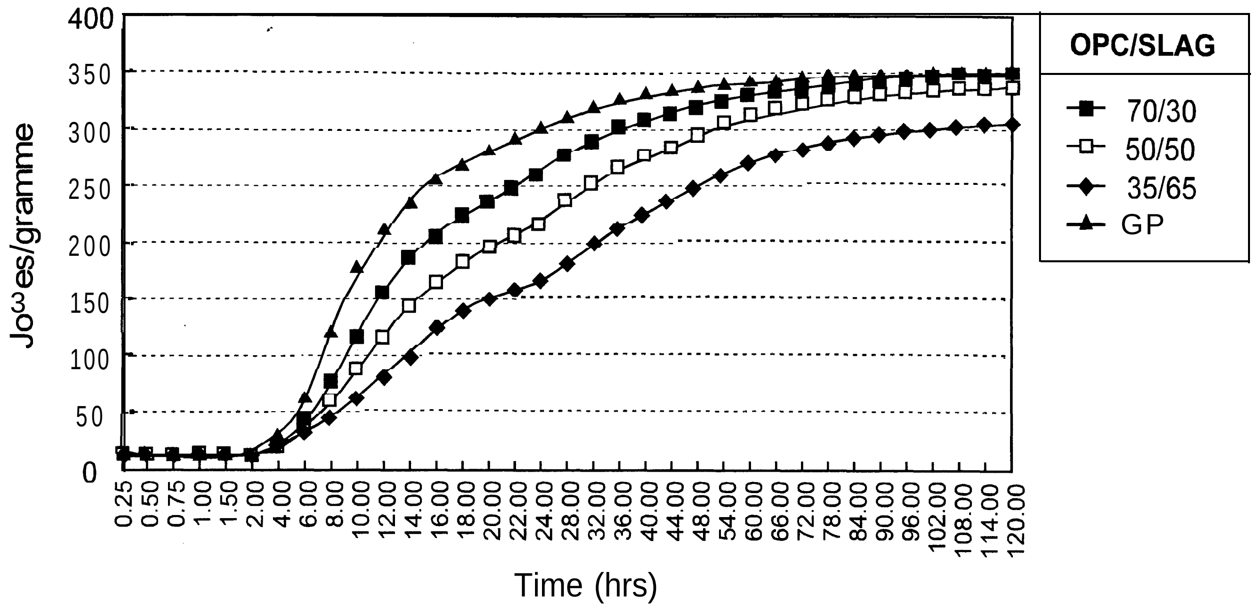
Note 2: Degree of severity of expected exposure also requires consideration.

Note 3: Higher slag contents may be considered subject to trial mixes.

4.2 HEAT OF HYDRATION AND TEMPERATURE RISE

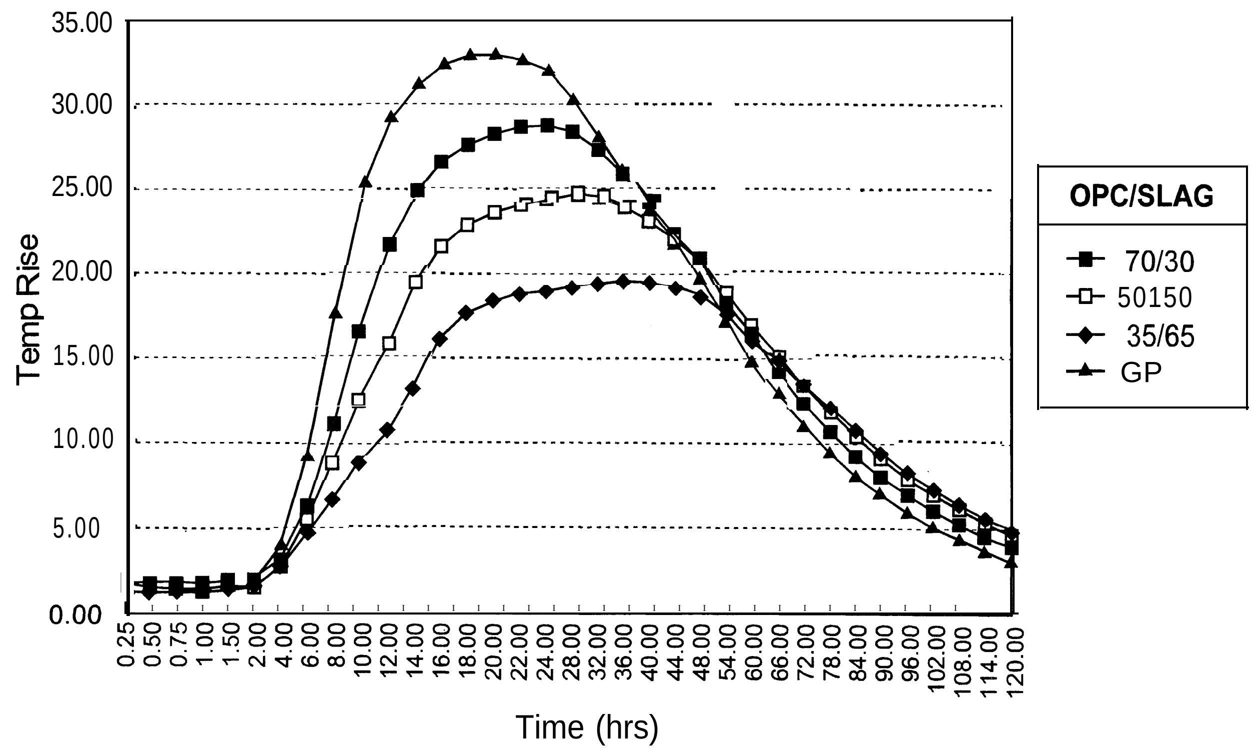
The use of slag cement will reduce the rate of heat generation in concrete and the extent of temperature rise. The actual level of reduction will depend on the nature and relative quantity of cement and slag being used. In concrete, factors such as cement content, fineness of the slag, ambient temperature, the size and shape of the element will influence the rate and extent of temperature rise. Typical heat of hydration and changes in temperature for cement blends tested in a Langavant calorimeter are shown in Figures 7 and 8.

FIGURE 7 -ADIABATIC HEAT OF HYDRATION



Note: Langavant Method

FIGURE 8 - TEMPERATURE DIFFERENCE DEGREES (ADIABATIC)



Note: Langavant Method

4.3 SETTING TIME

Under normal conditions an increase in concrete setting time can be expected when slag cement is used. The level of set retardation is dependent on the initial curing temperature of the concrete, the water to cement ratio, the OPC content and the percentage of slag in the cement. The characteristics of the OPC and any admixture used are also important. If setting time is critical, trial mixes are recommended to establish what increase in setting time will occur.

In summer time and other times when the ambient temperature would normally cause the concrete to set more quickly and so reduce the available finishing time, this increase in setting time can be advantageous.

Setting time tests were carried out with four different brands of Australian OPC. These cements were tested both before and after blending with slag in the proportions of 70% OPC, 30% slag both with and without three locally available similar type chemical admixtures.

The range of initial set results for these cements is shown in Table 5. As can be seen some slag cements will set more rapidly than some Portland cements both with and without admixtures.

TABLE 5 - INITIAL SET OF VARIOUS CEMENTS AND ADMIXTURE COMBINATIONS*

Cement	Without Admixture	With Admixture
Ordinary Portland Cement (OPC)	4.80 to 6.00 hours	5.25 to 6.75 hours
Slag Cement (70% OPC, 30% slag)	5.50 to 7.25 hours	6.08 to 9.16 hours

* Initial set tested in accordance with AS 1012.18 (28)

4.4 WORKABILITY

Workability is generally improved in concretes containing slag cement compared to concretes with OPC. There are a number of theories to explain the phenomenon. It appears the improved workability is due to the increased paste volume and higher fluidity of the paste and mortar.

The improved workability of concretes containing slag cement is reflected in water demand which is reduced compared to OPC concrete of similar slump. The water/cementitious ratio can be reduced to obtain the same slump for an OPC concrete. When the water to cement ratio is considered to be particularly critical, it may be necessary to carry out a trial mix to determine the effect of the use of the slag cement on this ratio. A reduced water demand usually results in greater density and strength.

4.5 CUBING

Curing is extremely important for all concrete to develop its potential strength and durability. When a sufficiently moist atmosphere is not maintained at the concrete surfaces in the initial stages of hardening and strength development, early drying will occur and the potential properties of the concrete will not be achieved.

From the time of placement all concrete should be protected, from the excessive evaporation due to high winds, high temperature and low relative humidity. Once concrete has sufficiently hardened, all of its exposed surfaces should be protected from drying out by using an appropriate procedure eg. ponding with water, covering with polythene sheeting, wet hessian, or spraying completely with an effective curing compound.

Concrete made with slag cement hydrates more slowly than OPC concrete which can be quite beneficial. However, slag cement concrete does require greater attention to curing.

In the absence of any requirements of particular specifications, such as RTA BSO (29), the data shown in Table 6 is a guide to recommended wet curing times for slag cement concrete.

TABLE 6

Number of Wet Curing Days			
Average Ambient Daily Temp	**20 - 40% Slag**	**40 - 55% Slag**	**55 - 70% Slag**
Above 20°C	5	7	7
12 - 20°C	7	9	9
5 - 12°C	9	12	12

Placing of any concrete at low temperatures (below 5°C) will interfere with the hydration process, resulting in delayed development of strength, and if below 0°C, possible frost damage. It is advisable to maintain the concrete temperature above 10°C by providing insulation or supplying heat to the concrete.

When it is proposed to use elevated temperature curing for products such as pre-cast or pre-stressed concrete units, it is important to establish the most suitable curing cycle for that concrete mix irrespective of whether it contains slag or not.

4.6 COMPRESSIVE STRENGTH

Concrete containing slag cement generally develops strength more slowly than concrete made from OPC. [Hinczak (30), Butler & Ashby (3 1)]. However, slag cement concrete continues to gain strength at a higher rate at later ages than OPC concrete. Slag cements are capable of being used to produce concrete with high strengths at 28 days and later ages.

Slag cement containing higher slag contents, ie. 50% slag and above, is normally specified for purposes other than strength eg. heat of hydration. Strengths are sometimes specified in these cases at ages later than 28 days. Strength at 56 days is frequently nominated.

4.7 FLEXURAL STRENGTH

The design requirements for flexural strength can be readily achieved using slag blended cement.

Hinczak (30) reported that at ages beyond 7 days concrete made using slag cement generally gave higher modulus of rupture values than concrete containing only OPC at the same binder level.

Flexural strength in excess of 4 MPa at 3 days and 6.5 MPa at 28 days for concrete containing 50/50 slag cement was reported by Haber (18) Figure 2.

4.8 DRYING SHRINKAGE AND CREEP

The drying shrinkage of concrete is affected by many factors such as the nature and amount of cement paste and the type and quantity of aggregate.

It has been indicated that the long term drying shrinkage of concrete containing ground slag is similar to OPC concrete but may be higher at early ages. (Hinczak, 30)

Work at the Western Australian Institute of Technology indicates that for concrete with a cementitious content of 420 kg/m", drying shrinkages for 100% OPC concrete and 65% slag 35% OPC concrete were similar for up to 3 weeks drying but from 3 to 12 weeks drying the 100% OPC concrete shrank at an increasingly greater rate than the 65% slag 35% OPC concrete (32).

Drying shrinkage testing of the 50 and 60 grade mixes of Table 1 made using slag cement with 65% slag content illustrates the low shrinkage of this cement type with shrinkage values for these mixes after 56 days drying all below 350 microstrain (6).

The inclusion of ground slag in concrete can reduce its creep compared to concrete containing only OPC as the binder. This effect is enhanced as the slag content is increased.

4.9 COLOUR

Depending on the fineness and the chemical composition of the slag, the colour of exposed concrete surfaces containing slag blended cement is usually lighter than concrete containing only OPC as the binder. The colour is influenced to a large extent by the colour of the OPC used.

In some instances a bluish tinge appears in the concrete when slag cement is used. This is caused by the presence of trace quantities of calcium sulphides. These oxidise rapidly and the bluish tinge dissipates when the concrete is exposed to the atmosphere. The phenomenon is normal and does not affect the quality of the concrete.

4.10 SORPTIVITY

Sorptivity, or the rate of ingress of water into concrete, has received a lot of attention by researchers in recent years. This interest has arisen because of the increased awareness of the need to improve the durability of reinforced concrete structures.

Work reported by Ho (33) showed that the response of concrete to the rate of water absorption and to interrupted curing can be improved by the incorporation of ground slag. The rate of water absorption in concrete by capillary action was significantly reduced when 35 percent ground slag was used and a water reducing admixture was incorporated. At the lower range of strengths, the sorptivity of concrete containing slag cement was not as adversely affected by interrupted curing as concrete with OPC as the binder.

Tests for water sorptivity were conducted in developing a concrete specification for the Esso offshore concrete gravity oil drilling platform (34). The results are shown in Table 7.

TABLE 7 - WATER SORPTIVITY

Cementitious Binder	Test Results ($mm/min^{0.5}$)
OPC + SF	0.08
	0.08
OPC + GGBFS + SF	0.07
	0.05
OPC + GGBFS	0.07
	0.08

This test measures the uptake of water into the concrete

OPC = Ordinary Portland Cement or General Purpose cement.
SF = Silica fume
GGBFS = Ground granulated blast furnace slag.

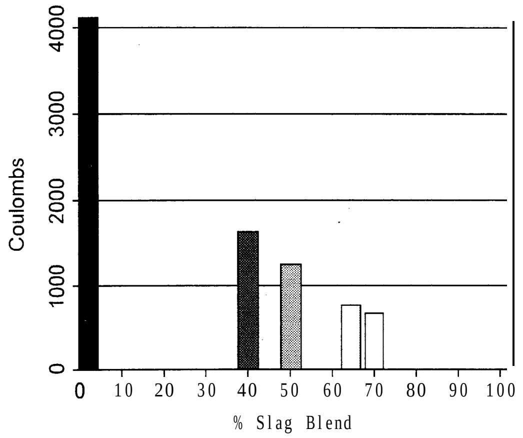
The results are all below the value of 0.12 $mm/min^{0.5}$ which is an acceptable value for good quality concrete. The triple blend mix is a slightly better performer although all mixes exhibit minimal capillary uptake of water.

4.11 CHLORIDE ION RESISTANCE

The resistance to the penetration of chlorides into concrete is dependent mainly on the pore structure of the cement paste and the nature of the products of the binder/water reactions.

For blends of ground slag and OPC, the resistance to chloride penetration increases with increasing slag proportion. Concrete made using cement containing 60% or more of slag is considered to be highly impermeable to chloride ions (35). Refer to Figure 9.

FIGURE 9 - RESISTANCE TO CHLORIDE ION PENETRATION (BINDER CONTENT 300Kg/m^3)



ASTM C1202-91, "Standard Test Method for Electrical Indication of Concrete's Abilitv to Resist Chloride Ion Penetration".

In this test, the higher the charge passed, the lower the resistance to chloride ion penetration.

4.12 SULPHATE RESISTANCE

Concrete can be exposed to attack from sulphates from various sources including ground waters, industrial effluent and its by-products, decay of organic matter, sewage, and sea water.

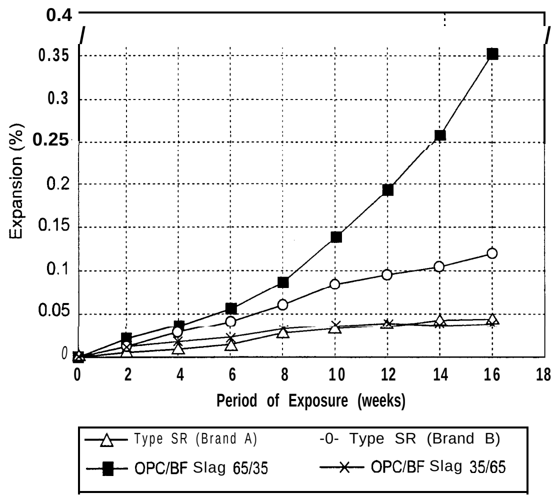
Slag cements improve the resistance of concrete to sulphate attack by reducing the permeability of the cement paste matrix and reacting with the calcium hydroxide in the hardened cement paste thus reducing the availability of one of the compounds that are highly susceptible to sulphate attack (37).

Work by CSIRO, using a test method developed by the Cement and Concrete Association of Australia (36), has shown that slag cement containing 40 .to 80% slag has higher sulphate resistance than OPC and some sulphate resisting cements complying with AS 3972 (38).

Frearson concludes in his paper 'Sulfate Resistance of Combinations of Portland Cement and Ground Granulated Blast Furnace Slag' (39) *"Even at the lowest* (30%) *replacement levels tested, the OPC - Slag mortars were more resistant to sulfate attack than OPC alone although they were generally less resistant than SRPC mortars"* (Sulphate Resistant Portland Cement).

The use of cement with higher slag contents showed greater resistance to sulphate attack than the lower slag contents (40). Figure 10 illustrates the improved sulphate resistance provided by slag cements.

FIGURE 10 - EXPANSION OF MORTAR BARS EXPOSED TO SULPHATE SOLUTION



Test Method, Australian Standard AS 2350.14 (37)

4.13 ALKALI-AGGREGATE REACTION (ALKALI-SILICA REACTION)

The alkali-aggregate reaction refers to the reactions that can occur between the alkali of cement and certain siliceous compounds found in some aggregates.

These reactions can cause expansion and cracking in concrete.

It has been shown that slag cement is effective in reducing the expansion of aggregates that have been found to be alkali-silica reactive.

s obtained using varying proportions of irom 10 to 50% of the total cementitious ıer indicated that of the proportions used, ; minimum percentage of slag to obtain less xpansion than the 100% OPC mixture was 20% (41). With high cement content mixes it was concluded that it was necessary to replace more than 40% of the cement by slag to prevent damage from occurring due to alkali silica reaction (41).

4.14 GROUND SLAG BLENDED WITH OTHER SUPPLEMENTARY CEMENTITIOUS MATERIALS

The use of fly ash and or silica fume together with ground granulated slag and OPC provide blended cements which have been in common use in particular applications for many years.

The use of ground slag and fly ash together with OPC was pioneered in Australia by Visek (42). Further reports were made on using ground slag and fly ash in OPC concrete by Heaton (43), Brantz (44) and Hinczak (45).

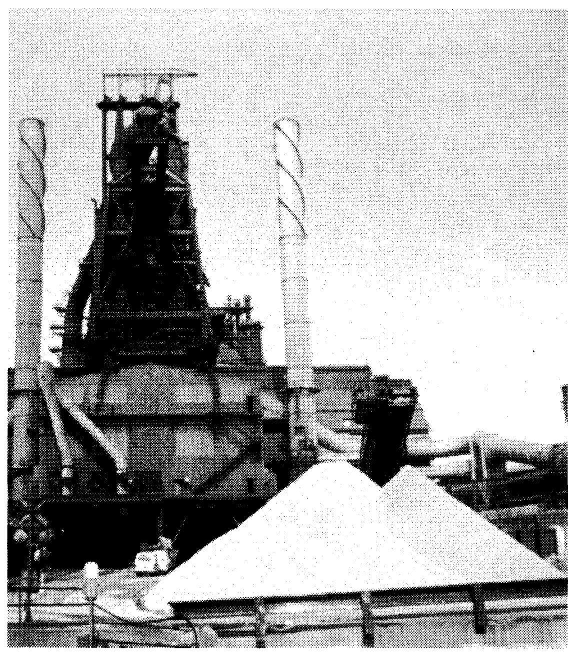
Malhotra (46) reported on concrete mixes made using OPC together with the three materials, ground slag, fly ash and silica fume all in the same mixes. All of these concrete mixes gave 28 day compressive strengths in excess of 85 MPa.

The use of combinations of these three supplementary cementitious materials with OPC in concrete, is technically and practically valid. It has been shown that these materials ıre very compatible and complementary when ıed together in concrete.

nbinations of these materials are therefore as ways to achieve improved performance ncrete such as enhanced durability and th. The combination to be used will on the design requirements of the ır project and the economics and ty of each supplementary ous material.

4.15 SUMMARY OF SLAG CEMENT CONCRETE PROPERTIES

Property	Rating
Heat of hydration	Low
Setting time	Extended
Workability	Improved
Curing time	Increased
Compressive strength	Adequate
Flexural strength	Adequate
Drying shrinkage	Normal
Creep	Reduced
Sorptivity	Reduced
Chloride ion resistivity	Improved
Sulphate resistance	Improved
Alkalli/aggregate reactivity	Improved



GRANULATED SLAG BEING PRODUCED AT NO.5 BLAST FURNACE. BHP PT. KEMBLA.

7. PROJECTS WHICH HAVE USED SLAG PRODUCTS

1. Sydney Harbour Tunnel

   The cement for the immersed tube segments comprised 40% ACSE (Shrinkage limited) cement with 60% BF granulated slag interground with optimised gypsum content. Approx. 36,000 tonnes of cement were used for these units.

2. 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.

3. 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.

4. 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.

5. 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.

6. 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.

7. Calder Freeway Upgrade (Bridges)

   60% OPC, 40% slag.

8. New Crown Casino Piles

   Aggressive ground water conditions adjacent to the Yarra Piver required piles to have a high durability. 30,000m^3 of concrete using high slag and fly ash was used.

9. New Melbourne Exhibition Centre

   This 84m x 360m post tensioned floor used 30-50% slag cement to give 30,000m^2 of pillarless uninterrupted space. (Largest open area exhibition space in the Southern Hemisphere).

10. Post tensioned floor system for Major Warehouse / Distribution Centre for the Murray Goulburn Company.

Slag cement 70% OPC, 30% slag. 17,000m^2 of floor space.

11. Ballarat Road Bridge. Melbourne

35% slag, 65% OPC. 5,000m^3 of concrete.

12. Rockmans Regency Hotel, Melbourne

35% slag, 65% OPC. 16,000m^3 of concrete.

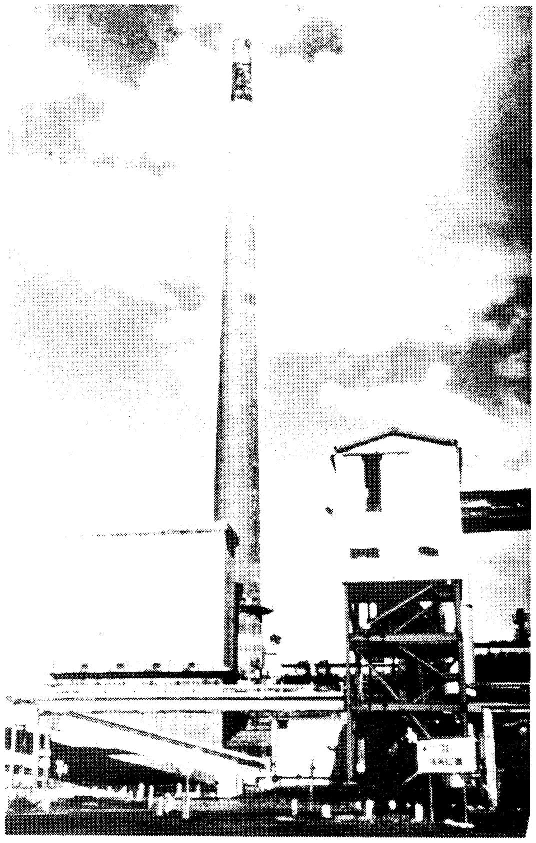
13. Womens Prison - Deer Park, Victoria

35% slag, 65% OPC. 4,000m^3 of concrete.

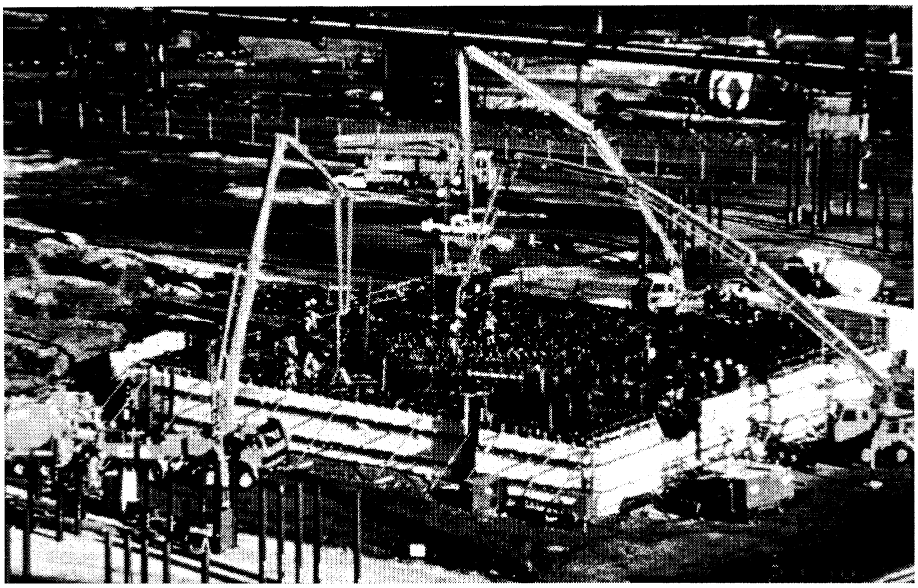
14. Textile Factory, Melbourne
35% slag, 65% OPC. 15,000m^3 of concrete paving.

15. Offshore Oil Storage Platform, Wandoo. Western Australia.
65% slag cement. Structure weight 8 1,000 tonnes.

16. Concrete Stack, BHP Port Kembla
140m tall stack used slag aggregate 35 & 40Mpa concrete.



SLAG AGGREGATE CONCRETE STACK
140M TALL. PORT KEMBLA.



FOUNDATION BLOCK NO 6 BLAST FURNACE PT KEMBLA. SLAG CEMENT & SLAG AGGREGATE.

6. CONCLUSION

Today more than ever before , environmental awareness and recycling are receiving increased attention. The slag products described in this publication are all suitable for the purposes outlined, and as such are competent construction materials suitable for use in their own right and not just as an alternative to dumping.

The use of slag in cement represents a substantial reduction in the generation of greenhouse gases. A reduction of one half a tonne of CO, discharged into the atmosphere is achieved for every tonne of slag substituted for OPC 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.

This Guide, together with supplementary booklets, is intended to provide an overview of available research data together with references to enable Engineers to evaluate the cost-effectiveness of slag as an important civil engineering and constuction material.

7. APPENDICES

APPENDIX A

Refers to Table 1 on Page 5

1. **Mix Proportions (SSD) kg/cu.m**
   Concrete Grade 50

Material	Mix Designation							
	c 5	C6	c 9	Cl4	Cl5	Cl8	C20	c22
Slag cement 1	450	450	400	420	-	410	440	400
Slag cement 2					420	-	-	-
Ultra fine fly ash	-	-	40					
Silica fume								20
20mm slag	640	650	620	675	675	690	660	670
10mm slag	280	280	270	295	295	300	290	290
Medium river sand	-	790	-	820	820	830	826	811
Slag crusher fines	440	-	550	-	-	-	-	-
Dune sand	410	-	330	-	-	-	-	-
Water reducer	✓	✓	✓	✓	✓	✓	✓	✓
A.E.A.							✓	
Superplasticiser	✓	✓	✓	✓	✓	✓	✓	✓
Water (litres)	170	160	160	150	160	140	144.5	155

Slag cement 1 - Portland cement brand 1 with high proportion of slag

Slag cement 2 - Portland cement brand 2 with high proportion of slag

Appendix A (Continued)

2. **Mix Proportions (SSD) kg/cu.m**
Concrete Grade 60

Material	Mix Designation							
	S1	S2	S3	MS1	MS2	MS3	MS4	MS5
Slag Cement 3				450	450	430	450	430
Slag Cement 4			450	-	-	-	-	--
ACSE cement	400	400	-	-	-	-	-	-
Fly ash			100	-				
Silica fume	25	25	10	30	**30**	30	**30**	40
20mm slag	710	680	640	670	670	675	660	660
10mm slag	310	300	280	300	300	300	295	295
Medium river sand	-	790	-	760	760	770	750	750
Slag crusher fines	280	-	454	-				
Dune sand	500	-	270	-				
Water reducer	✓	✓	✓	-	✓			
A.E.A.		-	-	-				
Superplasticiser	✓	✓	✓	✓	✓	✓	✓	✓
Water (litres)	160	160	174	150	150	150	160	160

Slag cement 3 - Portland cement brand 3 with high proportion of slag.
Slag cement 4 - Portland cement brand 4 with lower proportion of slag.

3. **High Strength Mixes**
Mix Proportions (SSD) kg/cu.m

Material	Mix Designation			
	1	2	3	4
Ordinary Portland cement	543		543	
Slag Cement (65% OPC 35% Slag)	-	570	-	572
Silica fume	97	68	97	68
10mm slag	719	717	711	711
7mm slag	83	83	83	83
-6mm slag			342	342
Medium river sand	793	790	472	472
Superplasticiser	✓	✓	✓	✓
Water (litres)	116.5	115.6	123.6	123.6

APPENDIX B

Refers to Section 3.1 including Figures 1, 2 & 3

"Two sets of four mixes were produced, each set being identical except for the use of natural (Dunmore basalt) or slag aggregate,. However it was necessary to use a slightly increased water/cement ratio for the natural aggregate mixes'!

Mix Components (Stage 1 Test)

Binder	Ratio%
Type C	100
ACSE/GGBFS	50/50
ACSE/GGBFS/PFA	50/35/15
ACSE/PFA	75/25

MARIBYRONG RIVER BRIDE - MELBOURNE - SLAG CEMENT

CONCRETE ARTERIAL ROAD. KEILOR PARK - MELBOURNE - SLAG CEMENT

8. REFERENCES

1. AS 2758.1 -Aggregates and rock for engineering purposes - Part 1 - Concrete aggregates, Standards Association of Australia, 1985.

2. AS 114 1.14 - Methods of sampling and testing aggregates - particle shape by proportional calliper, Standards Association of Australia, 1974.

3. AS 114 1.5 & 6 - Methods of sampling and testing aggregates - Bulk density and water absorption of fine & coarse aggregate, Standards Association of Australia, 1974.

4. RTA T2 15 - NSW Roads and Traffic Authority Test Method "Washington Degradation Test".

5. AS 10 12.9 - Methods of testing concrete: Method for the determination of the compressive strength of concrete specimens, Standards Association of Australia, 1986.

6. Pioneer Concrete Laboratory Report Numbers 5602815603 1, 56029/56032, 56030/56033, 56014156025, 56015156026, 56016156027.

7. Testrite Laboratory Report Numbers C9 176, C9177, C9185, C9233.

8. ASMS Internal Memo dated 21/4/94, 19/5/94.

9. AS I 14 1.23 - Methods of sampling and testing aggregates - Los Angeles Value, Standards Association of Australia, 1980.

10. AS 114 1.24 - Methods of sampling and testing aggregates: Soundness (by use of sodium' sulphate), Standards Association of Australia, 1974.

11. Australian Standard AS 1012-20: Methods of testing concrete. Determination of chloride and sulfate in hardened concrete and concrete aggregates - Standards Australia, 1992.

12. RTA T211 - NSW Roads and Traffic Authority Test Method "Loose Unit Mass of Aggregate".

13. RTA T2 12 - NSW Roads and Traffic Authority Test Method "Compacted Unit Mass of Aggregate".

14. AS 1141.39 - Methods of sampling and testing aggregates - Potential Reactivity of Aggregates (Chemical Method), Standards Association of Australia, 1974.

15. AS 1141.37 - Methods for sampling and testing aggregates - iron unsoundness.

16. AS 1466 - Australian Standard for Metallurgical Furnace Slag Aggregate, Standards Association of Australia, 1974. (Withdrawn)

17. Gomes L. & Morris M.W., 1990 - "The Design and Performance of a Slag/Cement Concrete for the Sydney Harbour Tunnel Immersed Tube Units". Cements for the Nineties, Leura NSW.

18. Haber E, 1994 - "Physical Characteristics of Concrete Containing Port Kembla Iron Blast Furnace Slag Aggregates" - Concrete in Australia; Vol. 20, No. 2, June 1994, pp 14-16. Concrete Institute of Australia, North Sydney, Australia.

19. Vaysburd A.M. - "Durability of lightweight concrete and its connections with the composition of concrete, design and construction methods", American Concrete Institute SP 136-7. 1992 Detroit USA.

20. Zhang, M.H. and Gjorv, O.E. "Penetration of cement paste into lightweight aggregate", Cement and Concrete Research, Vol. 22, pp 47-55, 1992 Pergamon Press, USA.

21. Aquino, M.J., Zongjin, L. and Shah, S.P., "Mechanical Properties of the aggregate and cement interface". Advanced Cement Based Materials, 1995, 2, pp 211-223, Elsevier Science Inc NY, USA.

22. James, W., Examination using a high powered microscope of the interface between blast furnace slag aggregate and the cementitious mortar, ASMS Internal Report, 1993.

23. Egan D.E. - "Concrete Pumping for Multi-Storey Buildings" - Construction Review, May 1985, pp 1-8.

24. Eckardstein K.E. Van - "Pumping Concrete and Concrete Pumps - A concrete placing manual" (Schwing) Germany, 1983.

25. Putzmeister Ltd - "Concrete for Pumping". Derbyshire S419QB, United Kingdom (BP 192-1 UK).

26. Cao H.T., MacPhee D.E., Bucea L. and Sirivnatnanon V. - "Corrosion Characteristics of Steel in Blast Furnace Slag - Portland Cement Blends" - 9th International Congress on the chemistry of cement, New Delhi, India 1992.

27. AS 3582.2 - Supplementary Cementitious Materials for use with Portland Cement. Slag-ground Granulated Iron Blast Furnace, Standards Australia, 1991.

28. AS 1012.18 - Methods of Testing Concrete - Method for Determination of Setting Time of Fresh Concrete, Mortar and Grout by Penetration Resistance (metric units). Standards Association of Australia, 1975.

29. NSW Roads and Traffic Authority - QA Specification B80, Concrete Work for Bridges, Edition 3, 1994.

30. Hinczak 1. - "Properties of Slag Concretes - an Australian Experience" International workshop on the use of fly ash, slag, silica fume and other siliceous materials in concrete. Concrete '88 Workshop - Sydney, Australia July 4-6, 1988 pp 199-229.

31. Butler B. & Ashby J. - "A further report on the influence of curing environment upon the properties of concrete made using a variety of Portland cement supplements" - Transactions of Institution of Engineers, Australia, Civil Engineering, Paper C/609 pp 45-55, 1986.

32. Anderson L., Report on testing of slag cement concrete for Swan Cement, CSR Readymix Concrete and BHP Engineering; Western Australian Institute of Technology, Perth, Western Australia, 1982.

33. Ho D.W. S., Hinczak I., Conroy J. J. and Lewis R.K. - "Influence of slag cement on the water sorbtivity of concrete" Second International Conference on use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Vol. 2, Madrid, Spain, 1986.

34. Taywood Engineering report, 19 November 1994, "Shaft Mixes for Esso Project, Section 2.4.1 Water Sorptivity".

35. Baweja D., Sirivnatnanon V. & Koerstz P.- "Rapid Chloride Ion Permeability of Concrete Samples" - CSIRO Report BIW 0492, November 92.

36. Mak S.L., Ho D.W.S., Ritchie D. CSIRO document 92/63(m) - "Sulphate Resistance of Portland Cement Slag Binders", May 1992.

37. AS 2350.14 - Methods of Testing Portland and Blended Cements Length Change of Portland and Blended Cement Mortars Exposed to a Sulfate Solution, Standards Association of Australia, 1996.

38. AS 3972 - Portland and Blended Cements - Standards Australia, 199 1.

39. Frearson J.P.H. - "Sulfate Resistance of Combinations of Portland Cement and Ground Granulated Blast Furnace Slag" - Proceedings, Second International Conference on use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Vol. 2, Madrid, Spain, 1986.

40. Mak S.L., Ho D.W.S. & Ritchie D. "Sulphate Resistance of Portland Cement Binders" - CSIRO document DBCE Doc. 92/63(M) May 1992.

41. Higgins D.D. and Connell M.D. - "Effectiveness of granulated blast furnace slag in preventing alkali silica reaction" - Proceedings of 5th International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Milwaukee, Wisconsin USA, June 1995.

42. Visek J.C. - "The Development and Use of Blast Furnace Pozzolan and Fly Ash together with Ordinary Portland Cement as Cementitious Material in Concrete", Internal report, Specified Concrete Pty Limited, Wollongong, NS W Australia, 1969, p 17.

43. Heaton B.S. - "Characteristics of Concrete with Partial Cement Replacement by Fly Ash and Ground Granulated Slag: Symposium on Concrete, Cases and Concepts" Institution of Engineers, Australia, Canberra, 1979.

44. Brantz H.L. and Beal D.L. "Development of Suitable Mixes for Portland Cement Concrete Containing both Fly Ash and Granulated Blast Furnace Slag", Concrete for the Nineties, Leura, Australia., Concrete Institute of Australia and CSIRO Division of Building, Construction and Engineering, 1990.

45. Hinczak 1. and Roper H. - "Ternary Cements", Concrete for the Nineties, Leura, Australia, Concrete Institute of Australia and CSIRO Division of Building, Construction and Engineering, 1990.

46. Malhotra V.M. - "Ternary Cementitious Systems for Producing High-Strength Concrete", Concrete for the Nineties, Leura, Australia, International conference on the use of fly ash, slag, silica fume, and other siliceous materials in concrete, 1990.

47. Andrews-Phaedonos F., 1993 - "Use of Supplementary Cementitious Materials in Concrete, Ground Granulated Blast Furnace Slag, Fly Ash, Silica Fume".

48. Haber E, 1994 - "Slag Blended Cements in Concrete", Melbourne.

49. Hinczak 1, 1993 - "Granulated Iron Blast Furnace Slag as a Cementitious Constituent in Concrete"

50. Anderson J.R. & Wellings P.W., 1991 "Construction of the Foundations for the Towers of the New Cable-Stayed Glebe Island Bridge", Concrete Institute of Australia Conference, May 1991.

51. Bakker R.F.M., 1991 - "Use & Performance of Blast Furnace Cement Concrete", Supplementary Cementitious Materials in Concrete Seminars, C&CA, September 199 1.

52. Baweja D. Munn R.L., Roper H. & Sirivnatnanon V., 1992 - "In Situ Assessments *of* Long Term Performance of Plain & Blended Cement Structures", Institution of Engineers, Australian Civil Engineering Transactions, June 1992.

53. Burgman J. Morrehead D.R. & Boyd R.E., 1991 - "Shielding Concrete for the National Medical Cyclotron", Department of Nuclear Medicine, Royal Prince Edward Hospital, Sydney. CIA Concrete '9 1, Sydney 199 1.

54. Hinczak I., 1991 - CIA Current Practice Note No. 26. Ground Granulated Iron Blast Furnace Slag & Its Use in Concrete.

55. Munn R.L. Baweja D., Roper H. & Sirivnatnanon v., 1991 - "Field Performance of Pavement and Wharf Structures having Blast Furnace Slag and Fly Ash Blended Cements", Concrete Institute of Australia'9 1.

56. Sirivnatnanon V. Cao H.T. & Baweja D., 1991 "Durability Performance of Blast Furnace Slag Blend Concrete Structures, CSIRO, Australasian Slag Association Seminar, Port Kembla, July 199 1.

57. Snowden R., 1992 - "The Specification & Use of Slag in South Africa", Supplementary Cementitious Materials in Concrete Seminars, C&CA, September 1992.

SYDNEY HARBOUR TUNNEL SUBMERGED TUBE SECTION - SLAG CEMENT

9. ACKNOWLEDGEMENTS

The Guide is the product of extensive cooperation between the NSW Roads and Traffic Authority, Vicroads and the Australasian Slag Association to better understand and develop the utilisation of industrial slag products.

The invaluable contribution to this Guide of the experience and expertise of the following is gratefully acknowledged:

Len Anderson	Consultant
Fred Andrews-Phaedonos	Vicroads
John Ashby	Australian Steel Mill Services
Robert Barber	Ability Building Chemicals
Barry Butler	CemConSult International
Val Brizga	Roads & Traffic Authority of NSW
David Dash	Roads & Traffic Authority of NSW
Gordon Dobson	Steel Cement Ltd
Alan Dow	Steel Cement Ltd
Chris Francis	Roads & Traffic Authority of NSW
Ed Haber	Taywood Engineering
Brian Heaton	University of Newcastle
lhor Hinczak	Blue Circle Southern Cement
Wayne James	Australian Steel Mill Services
David Jones	BHP Flat Products Division
Andrew Kemeny	Heggies Bulkhaul
Lance Midgley	Vicroads
John Pattison	Pioneer Concrete
Doug Prosser	Australasian Slag Association
Paul Ratcliff	Australian Steel Mill Services
Andrew Robertson	Cockburn Cement
Martin Venour	BHP Long Products Division
Mike Veysey	Roads & Traffic Authority of NSW
Tom Wauer	Steel Cement Ltd
Geoff Youdale	Consultant

Particular recognition is made'to the efforts of the Editorial Committee comprising John Ashby, Wayne James and Doug Prosser.

NOTES