SLAG BLENDED CEMENTS IN CONCRETE

Edwin W. Haber

'Ground Granulated Blast Furnace Slag
in Concrete and Stabilisation'
Seminar, St. Kilda, Melbourne, Australia,
24 October, 1994

SLAG BLENDED CEMENTS IN CONCRETE

(Presented to Seminar at St. Kilda, Melbourne, Australia, October 1994)

by EDWIN W. HABER
Principal Engineer - Concrete
Taywood Engineering

Preface

The following is a brief "snapshot" summation of issues presented at the Seminar on 'Ground Granulated Blast Furnace Slag in Concrete and Stabilisation', with particular reference to the use of slag blended cements in concrete.

1. Blended Slag Cements in Australia

Modern blending plants nowadays permit the blending of virtually any combination of cement and additive(s) including fly ash, silica fume, and ground granulated iron blast furnace slag (GGBFS), not to mention the addition of lime often required for stabilisation. However, for this presentation the focus is mainly upon GGBFS.

For use in concrete, the GGBFS is blended with General Purpose Portland Cement (GP)- otherwise referred to as Ordinary Portland Cement (OPC) or "Type A" or "Type ACSE", the latter being derived from the Association of Consulting Structural Engineers of New South Wales and currently being superseded by "Type SL" in compliance with the Australian Standard AS 3972.

In the case of the slag cements for use in concrete, the proportion of slag varies from around 35% slag referred to herein as "General Purpose" to around 65% (between 60 to 70%) referred to as "High Slag" or "Marine Grade" cement.

2. Coefficient of Thermal Expansion

While this presentation generally focuses upon the high end of the slag range, it is important to grasp the subtleties of the slag content upon the hardened concrete characteristics which is no better illustrated than in the context of the coefficient of thermal expansion (micron/^{o}C) after 28 days moist curing of the concrete -

with Ordinary Portland or GP Cement	9.9
with 35% GGBF Slag Cement	8.5
with 68% GGBF Slag Cement	11.0

(vide American Concrete Institute Materials Journal Technical Paper, "Deformations of Concretes made with Blast Furnace Slag Cement and Ordinary Portland Cement", by Chern & Chan, July/August 1989).

The potential role for the General Purpose Slag (35%) Blended Cement is in special purpose structures requiring the careful selection of mix ingredients to minimise the thermal expansion. One such outstanding example is for the use in concrete for road pavements where joint openings can be minimised as a result of the low thermal expansion of the concrete.

Another very different application is in cryogenic concrete (such as a concrete bund wall around a liquefied ammonia storage) where the impact of thermal shock is resisted by minimising the thermal expansion of the concrete; requiring the skilful selection of materials such as General Purpose Slag Blended Cement and, in particular, the use of aggregate such as limestone.

3. Summary of Benefits of High Slag ('Marine') Cement

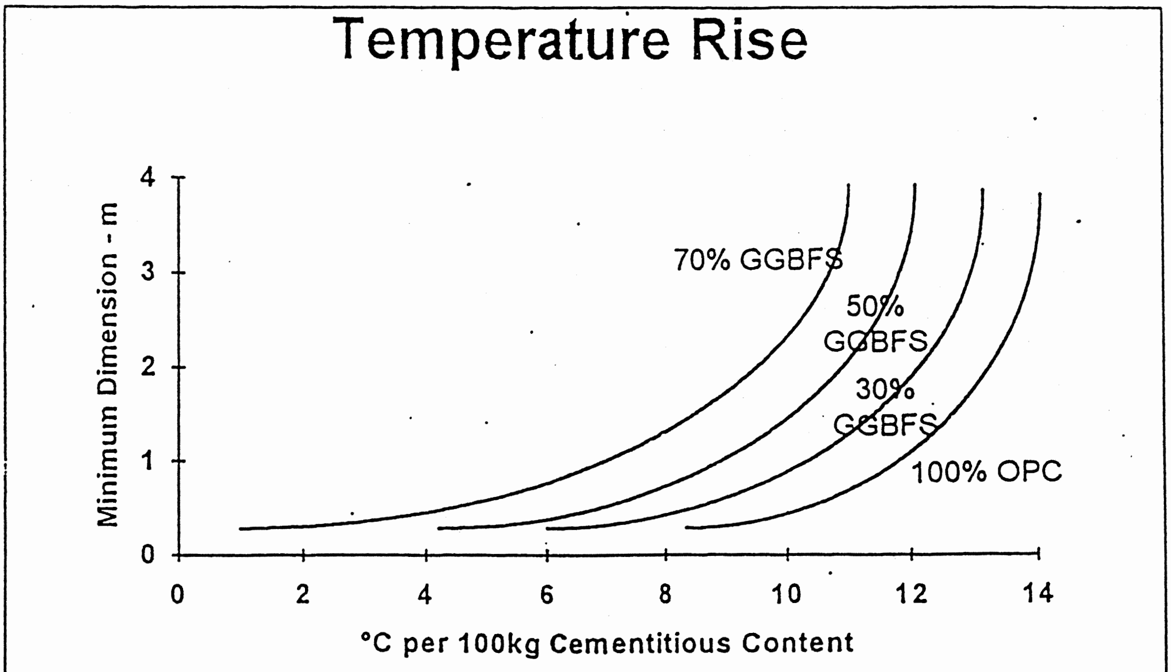
The benefits of High Slag ('Marine') Cement may be summarised as follows:

- mitigates heat of hydration
- improves workability (reduced slump loss)
- mitigates alkali-silica reactivity
- sulphate resistance
- chloride resistance
- reduced permeability
- enhanced durability

4. Heat of Hydration

Awareness of the role of increasing GGBF slag content of the cement to help mitigate the heat of hydration generated in mass concrete pours is not altogether new of novel. Figure 1 depicts a series of curves produced by Dr. P.B. Bamforth of Taywood Engineering in his article for the UK Concrete Society Digest No. 2, "Mass Concrete", 1984.

Figure 1



(P.B. Bamforth - Concrete Society Digest No.2, "Mass concrete", 1984)

Some of Bamforth's work was drawn on by the designers of the foundations for the towers of the cable-stayed Glebe Island Bridge currently under construction in Sydney Harbour (Anderson & Wellings - 15th CIA Conference, Sydney, 1991). The two foundation concrete pours, each around 2900 cubic metres of concrete containing high slag cement, were carried out in August and November 1990 - creating a new record for continuous mass concrete pours in Sydney.

While not quite as large, a more recent example of two similar mass concrete pours occured during the construction of the BHP No. 6 Blast Furnace at Port Kembla. The concrete for both pours comprised 400kg high slag cement plus 100kg fly ash, not to mention the use of air-cooled slag aggregate as well. The larger of the two pours - for the "oven block" - is of the order of 2100 cubic metres with instrumentation indicating that the desired outcome was achieved in terms of the suppression of temperature.

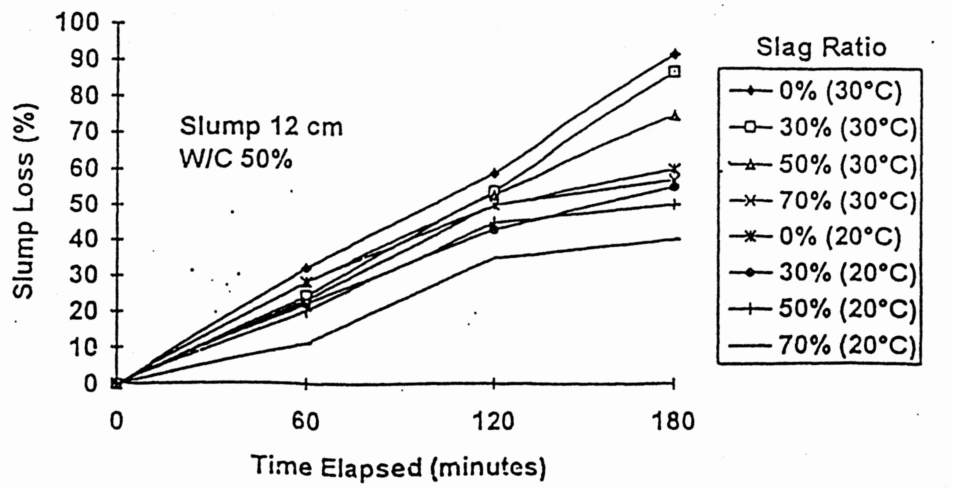
Also at Port Kembla at the nearby casting basin, work is currently proceeding on the construction of the ESSO-BHP West Tuna and Bream B concrete gravity structures, eventually to be floated to their respective oil and gas fields in the Bass Strait. A performance-based concrete specification has been adopted for this project for both the "caisson" and "shaft" concrete. While the latter requires a "chloride resistant" concrete yet to be submitted by the contractor; the caissons, which are currently being cast, require the heat of hydration generated by the concrete to fall within a predetermined adiabatic temperature profile. To meet this requirement, the contractor, Transfield, has chosen the use of High Slag cement - previously used by the same contractor in the concrete of the immersed tubes for the Sydney Harbour Tunnel (SHT).

Each of the eight SHT immersed tubes are 120m long x 26m wide x 7.5m high, detailed by Lewis Gomes & Martin Morris in "The Design and Performance of a Slag/Cement Concrete for the Sydney Harbour Tunnel Immersed Tube Units", presented to the 'Concrete for the Nineties' International Conference, held at Leura, NSW in September 1990.

5. <u>Workability</u> (Reduced Slump Loss)

It seems appropriate at this point to make brief reference to the temperature-related slump loss of fresh concrete. Before setting, the slump of placed concrete usually tends to decrease with time. However, as depicted in Figure 2 showing a series of graphical plots developed in Japan, the slump loss of GGBF slag cement concrete is less than that for Portland cement concrete.

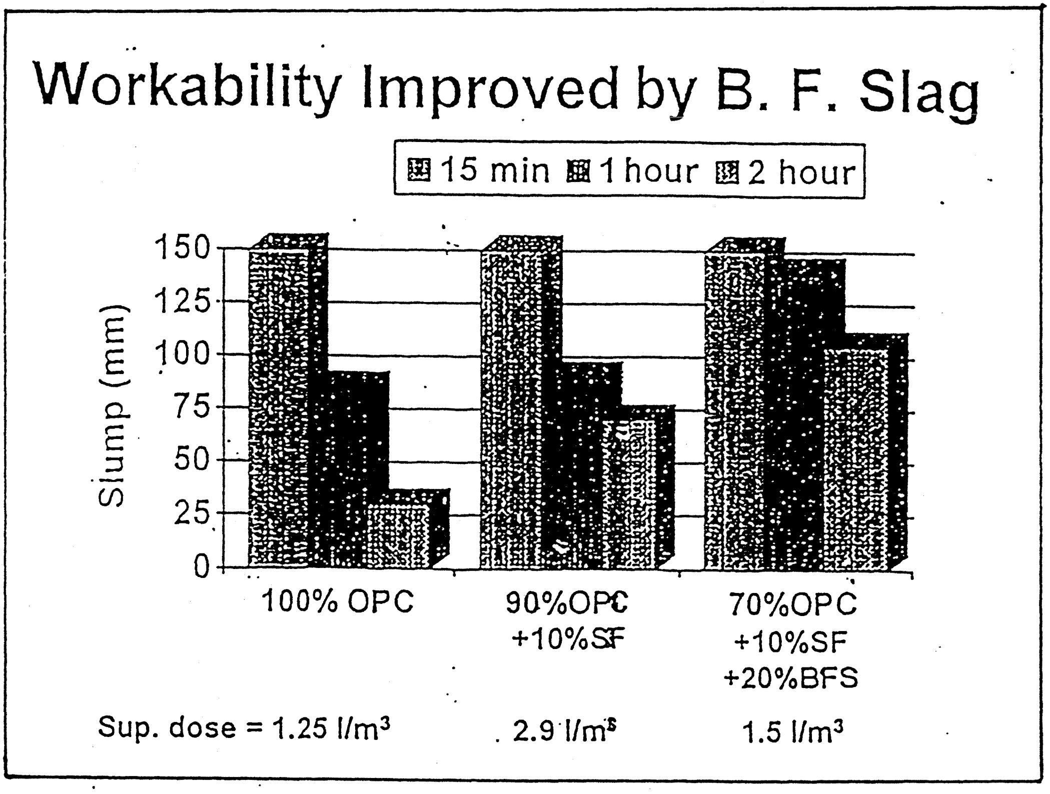
Figure 2 Slump Loss of Fresh Concrete: Trends



The easiest way to summarise the above seemingly complex series of plots is to equate the slump loss at 30°C of high slag (70%) cement concrete with that at 20°C of Portland cement concrete.

As a further example of the improved workability achieved by the addition of (ground granulated) blast furnace slag (BFS) is exhibited in Figure 3, prepared by the National Building Technology Centre (now incorporated into the CSIRO). It forms part of a study into the required dosage of superplasticiser and slump loss in high strength concrete mixes with and without the addition of GGBFS. The chart also refers to "SF" (silica fume), increasingly associated with high strength concrete. Yet modification of the Portland cement concrete mix with just 10% SF is insufficient in itself to ensure the desirable workability characteristics. The addition of a further 20% "BFS" significantly improves these properties.

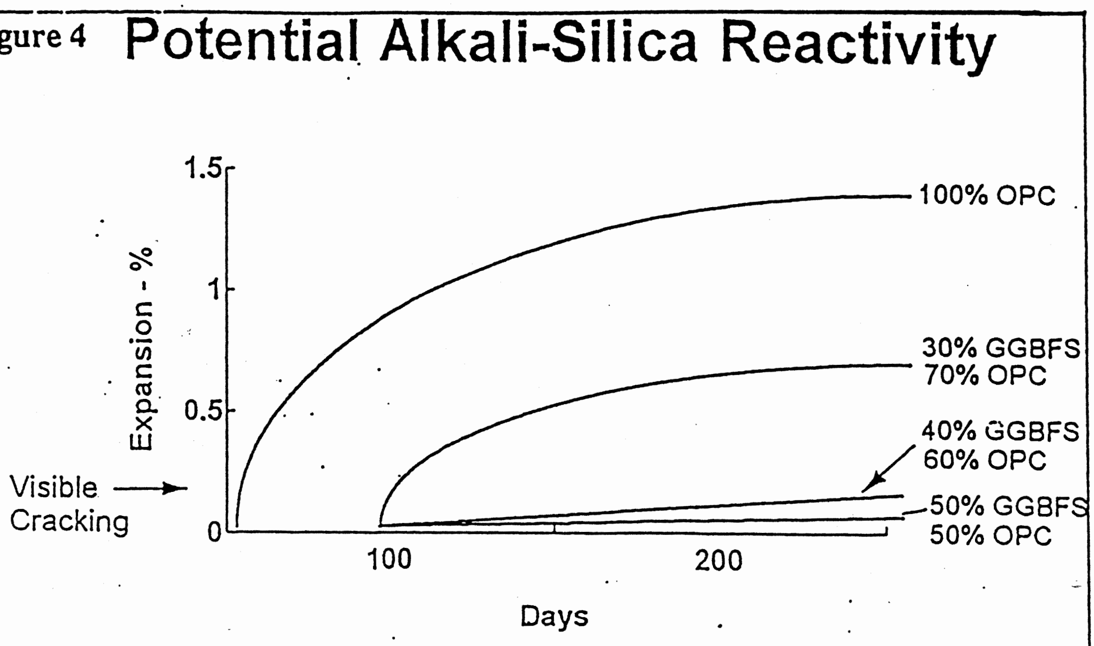
Figure 3



6. Potential Alkali-Silica Reactivity

The potential alkali-silica reactivity of aggregates is usually determined by various forms of mortar bar expansion tests in sodium hydroxide solution. Similar forms of accelerated tests are still being refined in South Africa, Canada and Australia (Ahmed Shyan, CSIRO Melbourne). However, the outcome of much earlier testing indicating the impact of GGBFS undertaken in the UK by D. W. Hobbs and published in the 'Magazine of Concrete Research' Vol.34, No.119 (1982), is shown in Figure 4. It is generally accepted that a GGBFS content of at least 50% cement is required to ensure against subsequent alkali-silica attack of the concrete.

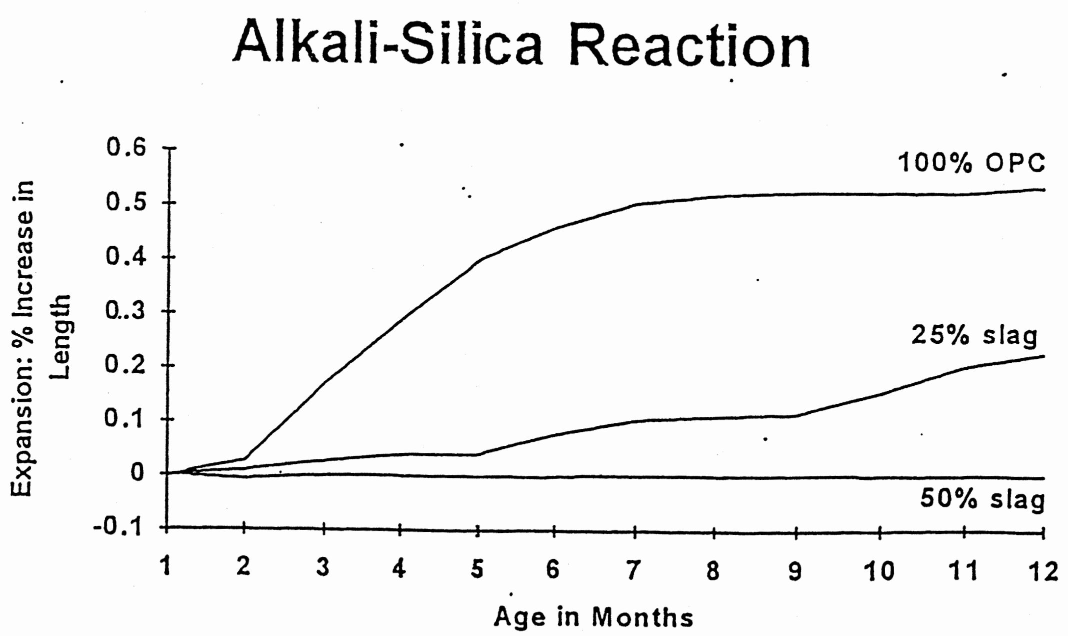
Figure 4



(D. W. Hobbs, Mag. of Conc. Res. Vol. 34. No 119, 1982; Mortar Prisms - Reactive Aggregate)

A similar "picture" emerges in Higgins and Uren review of 'The Effect of GGBFS on the Durability of Concrete' (published in 'Concrete', September/October 1991). Here the authors report the results of a separate independent concrete test program, co-ordinated by the British Concrete Society, verifying the previous findings relating to a minimum slag content of 50% to ensure against any alkali-silica reaction. The series of plots shown in Figure 5 clearly indicates the need for 50% slag, and not 25% slag, to guarantee against subsequent alkali-silica reaction. The authors state that the mitigating mechanism is not completely understood nor fully quantified but the low permeability of the GGBFS concrete to alkali ions is probably an important factor.

Figure 5

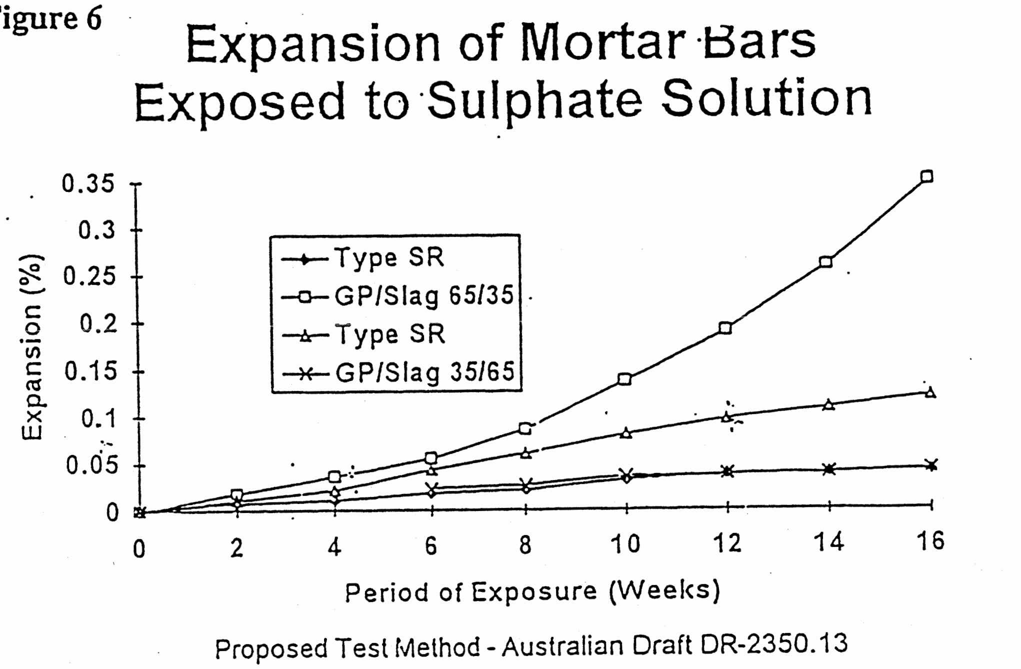


(Unpublished Results of Programme Co-ordinated by Concrete Society)

7. Sulphate Resistance

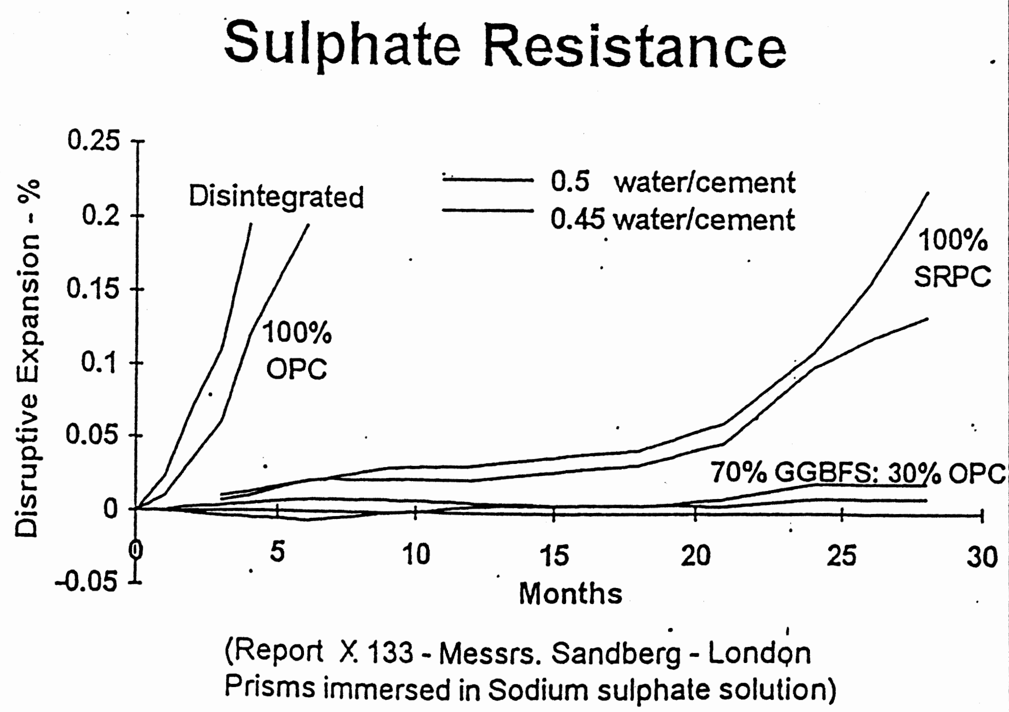
In a similar vein, a General Purpose (35%) Slag Cement is insufficient to ensure sulphate resistance of concrete which is best achieved by the use of High Slag cement. A study of the sulphate resistance of various Australian cements, co-ordinated by the Cement and Concrete Association of Australia as part of the development of a new Australian Standard test procedure for the sulphate resistance of cement mortars, revealed an inconsistent and fluctuating performance of current "sulphate-resisting" Portland cements compared with High Slag cement. Figure 6 depicts some early results.

Figure 6



A similar "picture" emerges from an earlier British study of the sulphate resistance of concrete. Figure 7 shows concrete containing sulphate-resisting Portland cement (SRPC) deficient in performance compared with concrete containing high slag (70%) blended cement.

Figure 7



Whereas sulphate resistance of Portland cement relies on a low tricalcium aluminate content, current literature points to higher levels of tricalcium aluminate and even alkalies (undesirable in potential alkali-aggregate reactivity situations) being necessary in Portland cement to limit chloride ion diffusion in the concrete. Herein lies the dilemma with the use of normal Portland cement in concrete subject to the combined forces of simultaneous chloride and sulphate attack - not altogether unusual and even experienced in and around Sydney Harbour, for example.

8. Chloride Resistance

The Concrete Institute of Australia Recommended Practice for Durable Concrete (February 1990) states

> " where the concrete is in a marine environment the effect of chloride ion diffusion, with the consequent increase in risk of reinforcement corrosion, is a major consideration. In these circumstances it is regarded as advantageous to use a cement with greater capabilities of binding chlorides and/or controlling the chloride ion mobility. Page et al measured the diffusivity of chloride ions in various cement pastes after two months of curing. the results are shown in Table 1. The results indicate the better performance of the blended cements, at least under the curing regime used in the test."

Table 1:Diffusion of chloride ions at 25^{o}C in cement pastes of W/C 0.5
(vide C. L. Page, et al, Cement and Concrete Research, Vol II, 1981)

Type of Cement	Diffusivity $10^{-9}cm^{2}/s$
SRPC	100.0
OPC	44.7
70% OPC/30% fly ash	14.7
35% OPC/65% GGBFS	4.1

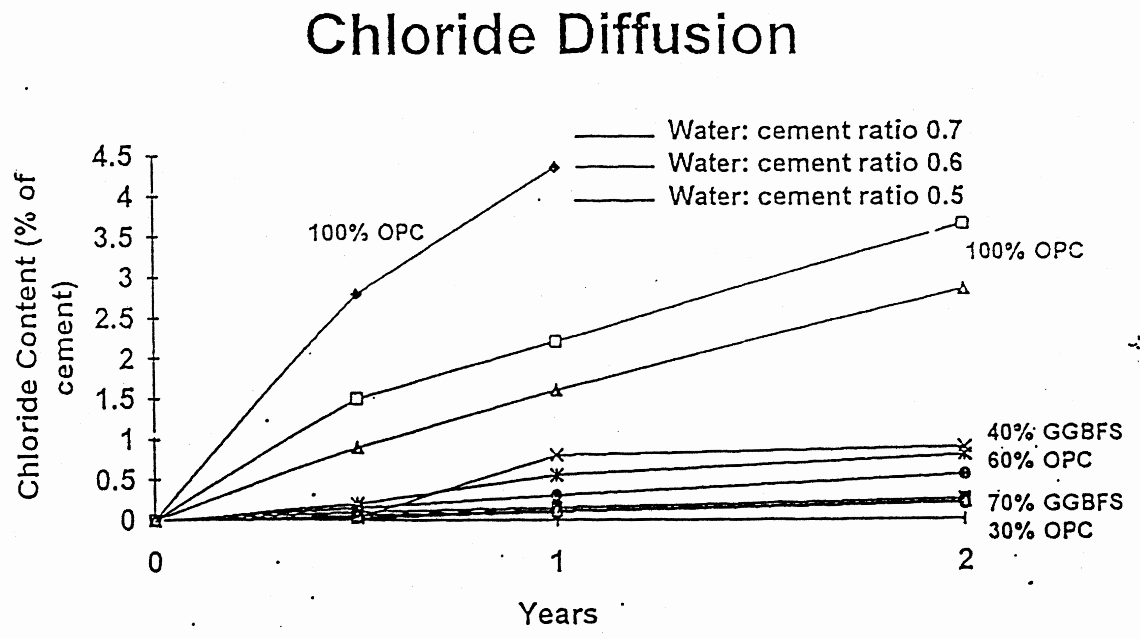
Table 2 shows figures for the coefficient of chloride diffusion on European mortars furnished by F.R.M. Bakker of the Netherlands on his visit to Australia in October 1991. These figures were extracted from Bakker's paper entitled "Permeability of Blended Cement Concretes", presented at the 'First International Conference on the Use of Fly Ash, Silica Fume, Slag and Other Mineral Byproducts in Concretes', held at Montebello, Quebec, Canada, 1983. The figures highlight the superiority of mortar containing 60% GGBFS blended cement over mortar with ordinary Portland cement.

Table 2. Chloride Ion Diffusion Testing of 28-day Mortars (vide Bakker)

W/C	Coefficient of Chloride Diffusion ($10^{-8}cm^2/sec$)	
Ratio	OPC	60% Slag
0.55	3.6	0.12
0.60	6.2	0.23
0.65	8.5	0.41

A similar pattern emerges from an earlier study of chloride diffusion by H. G. Smolczky presented in Paris during 1977. In this study concrete beams were stored in sodium chloride over two years and the actual chloride content determined as a percentage of cement and plotted as shown in Figure 8 for OPC, 40% slag blended cement, and 70% slag blended cement. While the chloride diffusion is significantly reduced by the inclusion of 40% slag, it is further reduced by the use of High Slag cement.

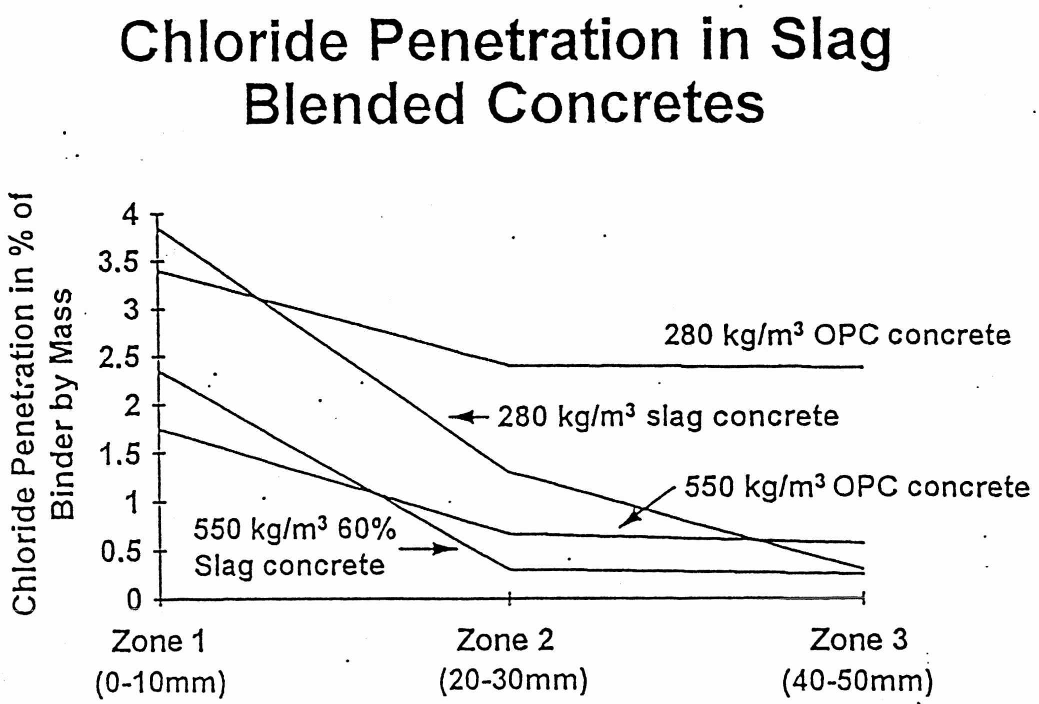
Figure 8



(H. G. Smolczyk - 6th Int. Steelmaking Day - Paris. 1977)
Concrete beams stored in sodium chloride solution

A more recent local study by the National Building Technology Centre (now CSIRO Division of Building, Construction, and Engineering) involved the drilling to various depths of concrete containing both High Slag cement and OPC with high (550kg per cubic metre) and low (280kg per cubic metre) cement contents and then analysing for chloride ion content. The results, depicted in graphical form in Figure 9, once again reveal the superior performance of High Slag cement, particularly beyond the surface layer of the concrete.

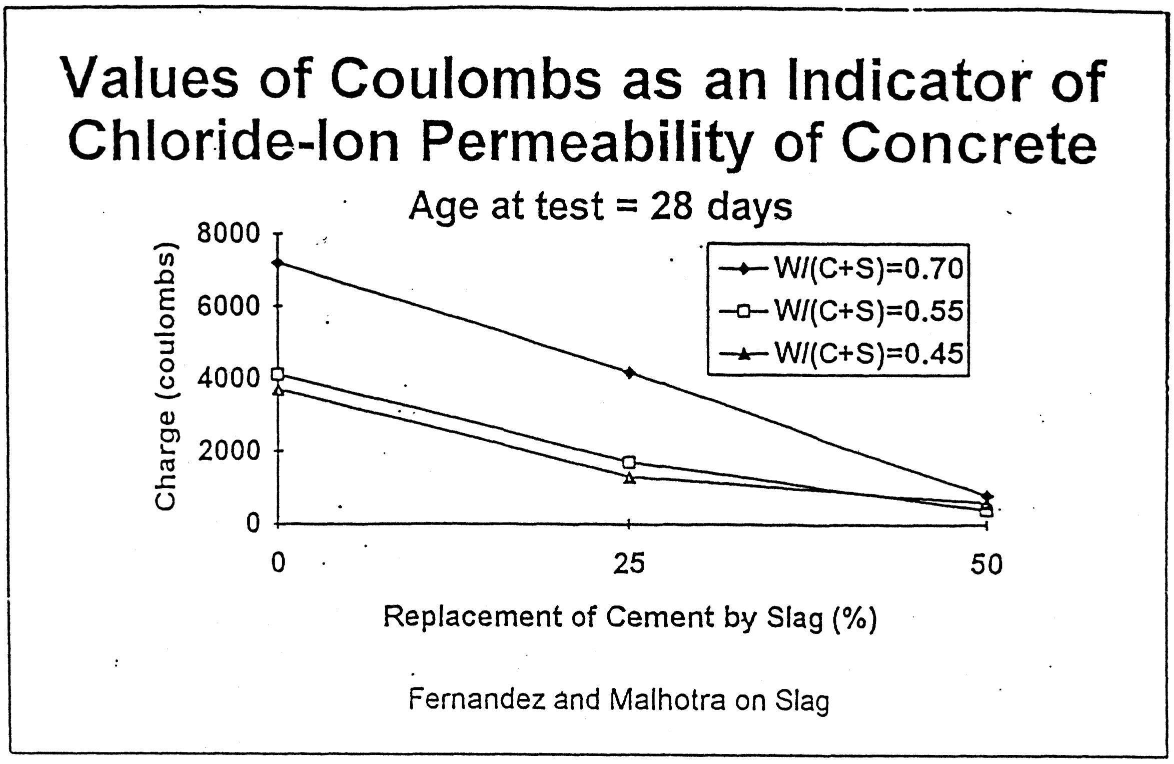
Figure 9



This finding is significant, particularly in terms of potential corrosion of the steel reinforcement which is not located in the surface (Zone 1) of the concrete; but at a depth more likely to be indicative of results shown in the vicinity of Zones 2 and 3.

A similar pattern to the foregoing emerges from a joint Brazilian/Canadian study of slag cements by Fernandez and Malhotra, using the ASTM (AASHTO) laboratory test procedure for determining chloride-ion permeability for concretes immersed in sodium chloride solution and an electrical potential applied to the system. The results shown in Figure 10 are expressed in terms of coulombs of electrical charge passing through the system and is only indicative of the chloride-ion permeability of the concrete. Nevertheless the results reflect the earlier findings for cement replacement by slag at levels of 0, 25 and 50 percent.

Figure 10



The foregoing studies undertaken in various parts of the world, adopting different techniques, prove conclusively the superiority of slag cements - particularly High Slag cement for marine applications.

9. Permeability

Table 3 details the findings of a study undertaken by Prof. Doug Hooten of the University of Toronto and reported during his Australian address to the Seminar on High Performance Concrete Beyond 2000 (CSIRO, Sydney, September 1992) entitled "Maximising Performance of Concrete".

Table 3 Permeability of Concrete with both Water and Air Curing

Cement		Permeability	
%OPC	%GGBFS	Water-cured	Air-cured
100	0	7.7×10^{-13}	1.9×10^{-11}
75	25	3.4×10^{-13}	2.3×10^{-11}
50	50	1.0×10^{-13}	5.0×10^{-11}

The tabulation not only demonstrates the potentially improved performance of fully-cured concrete with increasing slag content of the cement, but the reverse effect applicable to poorly-cured concrete. This serves to highlight that slag cements are more sensitive to poor curing and due account must be taken of this factor.

10. Curing

For the foregoing reasons and due to the slower hydration of GGBF slag and the tendency for early shrinkage, curing is vital in all circumstances.

Curing of the GGBFS concrete should commence immediately after finishing and should be continued so that the design requirements for strength, stripping and serviceability will be met.

The minimum period in days for effective moist curing of concrete containing slag cement is recommended as shown in Table 4.

Table 4 Recommended Curing Time (days)

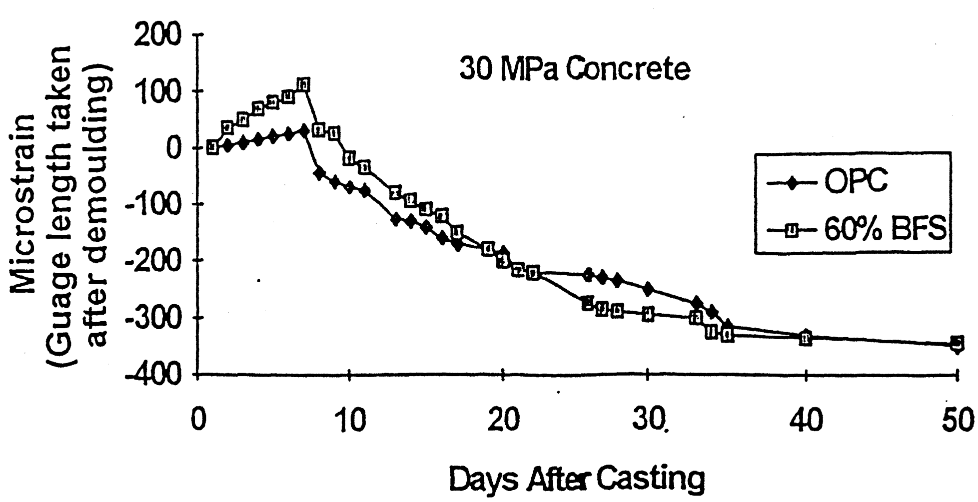
Average Atmospheric Temperature ^{0}C During Curing	Curing Time (days) corresponding to the GGBFS replacement ratio shown		
	30 -40	40 - 55	55 - 75
10 - 17	7	8	9
> 17	5	6	7

11. Drying Shrinkage

Any differences in drying shrinkage between Portland and slag cement are cancelled out by the adoption of a different "end point" or "zero measuring point", as demonstrated in a study by the National Building Technology Centre - the results of which are graphically depicted in Figure 11. In this study the initial measurement was made immediately after the demoulding of the specimen at age 1 day rather than after 7 days following 6 days moist curing before placing the specimens in a controlled environment. It is clear that the Australian Standard procedure for the drying shrinkage of concrete appears to discriminate against concrete with slag cement and requires redressing.

Figure 11 Variations in Length Changes Due to Drying of Slag Blended Cement Concrete

(1 Day in Mould + 6 Days Moist Cured)



12 Creep

A NSW Government study undertaken to compare the performance of 50 MPa concrete containing High Slag coment and Low Heat cement revealed that the relative creep recorded under standard laboratory conditions (23°C and 50% RH) shown in Figure 12 was apparently reversed under the possibly more realistic "atmospheric conditions" shown in Figure 13.

Figure 12

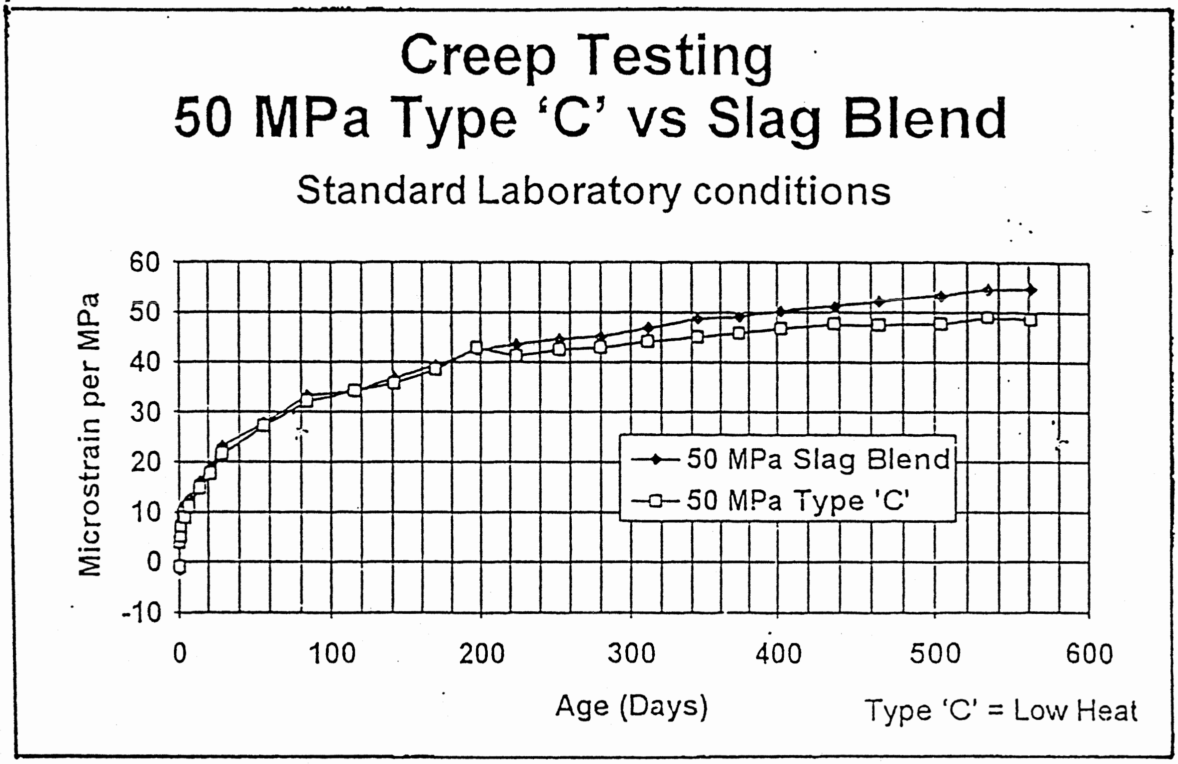
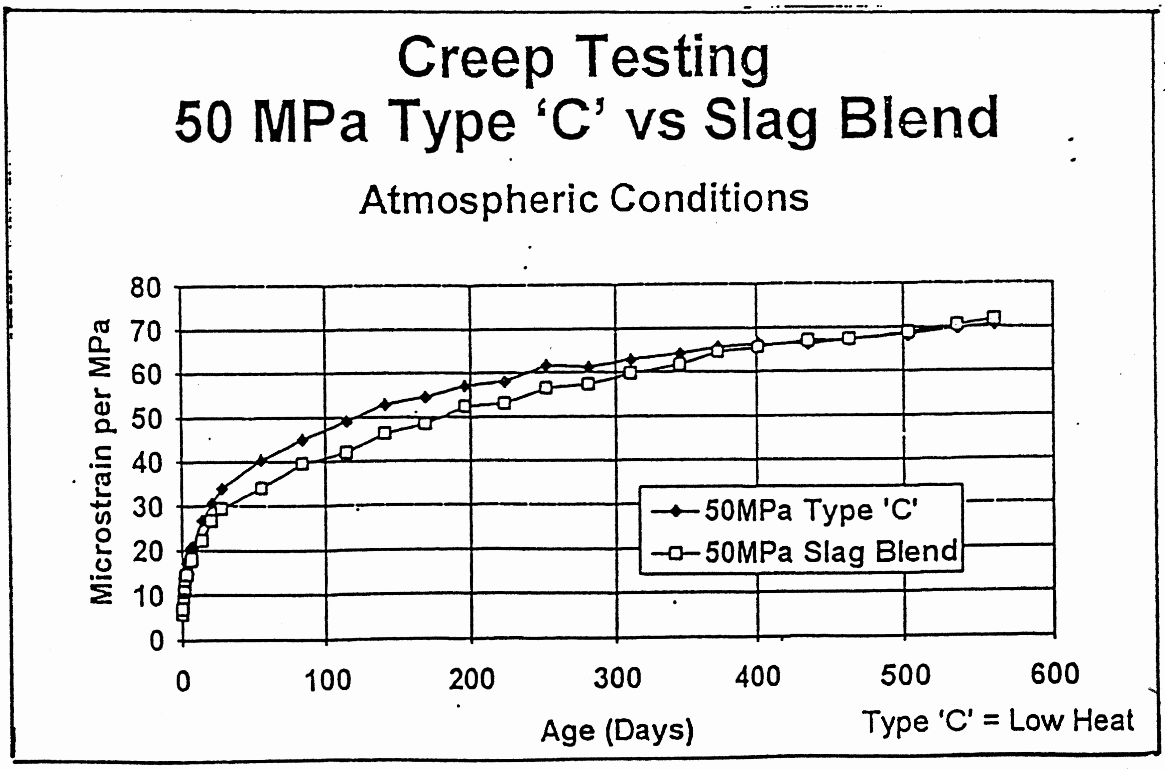


Figure 13



13. Australian Standard Specification for Cement (AS 3972)

The new Australian Standard is a first-ever attempt at the development of a performance-based cement specification rather than a "prescriptive" specification based upon chemical composition.

However the current edition of the new AS3972, Australian Standard for Portland and Blended Cements contains little reference to performance-based tests which are still in the final stages of development prior to the establishment of suitable specification limits applicable to the new procedures. The first such performance test applicable to shrinkage is virtually complete and ready for incorporation in AS3972 by way of amendment to be issued shortly. The testing program sponsored by the Cement and Concrete Association of Australia for the Langavant Heat of Hydration (superseding the current Heat of Solution applicable only to Portland cement) and, similarly, the Sulphate Resistance Mortar Bar Test are both well advanced. When incorporated into AS3972, these new performance-based tests will permit all blended cements to perform on their merits in the context of sulphate resistance and low heat of hydration.

As yet, Standards Australia has not developed a suitably reliable test for chloride resistant cement, though such a test would be welcome for the sake of completeness.

A comparison between the future performance-based AS3972 and the former prescriptive AS1315 is attached in summary form.

Australian Standard Cement Specifications

	AS3972 (Performance)	AS1315 (Prescriptive)	Remarks
Low Shrinkage	Type SL	-	Mortar bar test (max 750$\mu\varepsilon$)
Low Heat	Type LH (Langavant)	Type C (Heat of Solution -	Portland only not slag or flyash)
Sulphate Resisting	Type SR (Mortar bar test)	Type D (C_3A<5% -	Portland only not slag or flyash)
Chloride Resisting			No test or criteria yet developed

note - C_3A denotes Tricalcium Aluminate