Development of a high performance, low CO_2 concrete utilising a high proportion of supplementary cementitious material (SCM)

Bob Bornstein[1], and Tony Song[2]
[1]Manager Technical Services, Boral Construction Materials,
[2]Senior Development Engineer, Boral Construction Materials Technical Services,

Abstract: Over the last decade there has been an increasing need for low carbon footprint building materials. Concrete is a high contributor to CO_2 emissions due to the carbon intensive nature of Portland Cement production, so the use of SCMs has increased accordingly. These conventional "green" concretes replace high CO_2 intensive traditional Portland Cement with SCM (usually fly ash and/or ground granulated blast furnace slag GGBFS). Unfortunately there are performance trade-offs as these concretes typically exhibit lower early strength gain and higher drying shrinkage than the standard concretes.

This paper outlines the development of low carbon footprint concretes with less SL and more SCMs. The associated concretes have compressive strength gain similar to conventional concretes, but much lower drying shrinkage and improved durability properties. This high SCM binder was trademarked Zep® and the concrete products made from it are marketed as Envisia®.

1.0 INTRODUCTION

The demand for high sustainability structures has increased enormously since the beginning of the century. In Australia, the formation of the Green Building Council of Australia (GBCA) in 2002 and the development of its Greenstar rating scheme in 2003 was the catalyst for a "Green " change in the construction industry and has led to the development of a number of sustainable products. Early adopters, such as the "Council House 2" Project in Melbourne, focused on use of recycled materials generally, and for concrete the focus was on the use of relatively high levels of reclaimed aggregates and SCMs to replace high CO_2 intensive traditional Portland Cement.

SCMs used were typically fly ash and/or GGBFS, although others, such as ground glass, have been trialled also. One issue with the higher use of SCMs is that they can lead to concrete with lower early strength gain and higher shrinkage than standard concretes, potentially compromising construction cycle times and element design outcomes. With this as a background, Boral Cement commenced an R&D program in 2008 to develop a binder system with a low carbon footprint, but able to provide strength gain similar to conventional concretes and lower shrinkage.

2.0 NEW CONCRETES WITH HIGH SCM DEVELOPMENT

Following review of a number of options for new binder development, Boral Cement focused its R&D activities on an activated SCM binder which, when blended in a high proportion with normal Portland Cement, would exhibit similar early strength gain to a "standard" Portland cement based concrete. Initial work was promising and, following 5 years exhaustive laboratory testings and field trials, a new concrete, Envisia® was launched in 2013 using the new SCM binder, Zep®. The key criteria for Envisia®, when compared to "conventional" concretes were[1]:

- Compliance with existing relevant Australian Standards and Design Codes.
- Activator used is non-hazardous.

- Have the normal hydration products of Portland Cement (mainly mixed hydrates of calcium silicates, aluminates and ferrites) but improved etttringite formation and stabilisation (as a result, no compromise on early strength but improved shrinkage and durability).
- Exhibit similar compressive strength gains.
- Exhibit similar setting times and placing and finishing characteristics.
- Compatible with existing admixture technology.

3.0 EXPERIMENTAL PROGRAMS

It was acknowledged early in the research program that the quantity of activated SCM used in the new product can be varied to achieve a range of desired hardened state properties. But as one of the key criteria was to achieve a low carbon footprint concrete with similar strength gain and setting times to "conventional" concrete, a blend of 40% Portland cement and 60% Zep® was focussed on. Subsequent trial mixes were performed on different strength grades to assess the performance of the concrete in various applications. The laboratory trials were performed as per AS 1012.2 (lab trials), AS 1012.8 (curing), AS 1012.9 (compressive strength), AS 1012.11 (flexural strength), AS 1012.13 (drying shrinkage), AS 1012.16 (creep), AS 1012.18 (setting time), AS 1141.60.1 (alkali silica reaction), DIN 1048 (water permeability), ASTM C1585 (water absorption), Nordtest NT Build 443 and 492 (chloride diffusion/migration coefficient tests).

4.0 EXPERIMENTAL RESULTS

4.1 32 MPa concrete with 60% Portland cement reduction

Initial work[2] was done with a typical 32MPa concrete mix design, containing 330kg/m^3 cement (either SL or SL/Zep® blend), 750kg/m^3 20mm crushed river gravel, 300 kg/m^3 10mm crushed river gravel, 500kg/m^3 coarse river sand, and 300kg/m^3 fine sand. The cement mass is air dry mass while all aggregates are SSD mass. Water was added for a slump of 80±5mm.

The water demand, air content, setting time and drying shrinkage are presented in Table 1 while the compressive strength gain is showed in Figure 1.

Properties	Unit	Control Mix	Envisia®
SL Cement	Kg/m^3	331	133
ZEP Binder	Kg/m^3	-	199
Total Binder	Kg/m^3	331	332
% Portland Cement Reduction	%	-	60.0
Water - duplicate	L/m^3	192, 192	176, 176
Slump - duplicate	mm	80, 75	75, 75
Air Content - duplicate	%	1.4, 1.4	2.7, 2.9
Setting time (initial / final) - duplicate	min	(310, 295) / (405, 410)	(300, 300) / (405, 410)
56 days drying shrinkage - duplicate	με	530, 520	300, 280

Table 1. Water demand and air content of fresh concretes

It can be seen that the Envisia® concrete required about 16 litres/m^3 less water for the same amount of cement, 330kg/m^3, and for a similar 75-80mm slump. While the air content was 1.4% higher than the control concrete, the lower water/cement ratio made it possible for the Envisia®

concrete to develop equivalent strength as shown in Figure 1 (left graph). In addition, the setting time was similar to the control.

An unexpected property of the Envisia® concrete was a significant reduction in drying shrinkage. Figure 1 (right graph) clearly demonstrates that Envisia® concretes developed significantly lower free drying shrinkage, about 50% reduction at 28 days and 45% reduction at 56 days. This is comparable to results achieved by addition of 7 litres/m^3 shrinkage reducing admixtures[2].

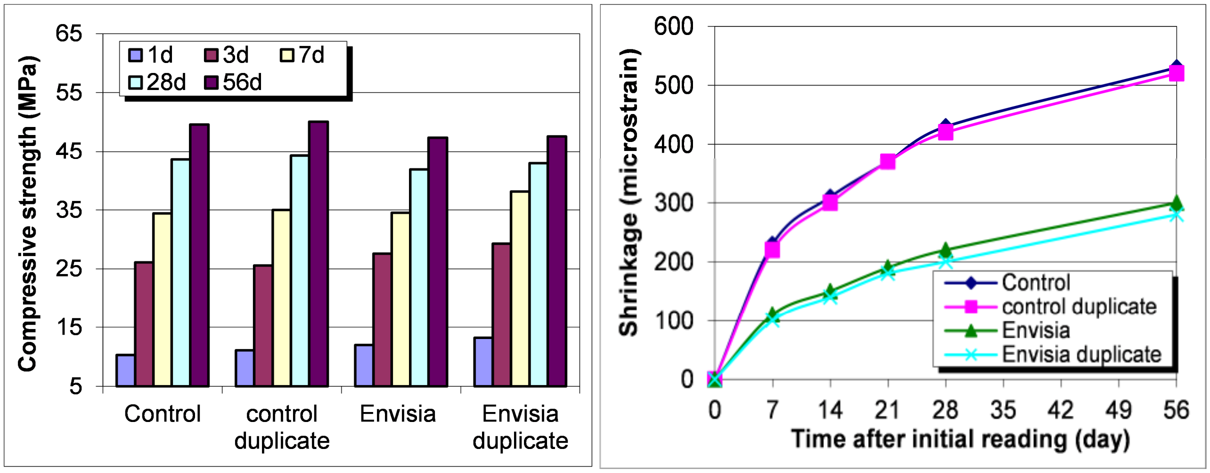

Figure 1. Compressive strength and drying shrinkage development of 32MPa concretes

4.2 40MPa post-tensioned concretes

High early strength is paramount for post-tensioned concretes. Figure 2 shows the comparison of typical 40MPa post-tensioned concretes, where Envisia® with 60% Portland Cement reduction was compared with the conventional 60% Portland Cement reduction (SL/GGBFS), revealing that the higher early strength of Envisia® is suited to post-tensioned concretes applications.

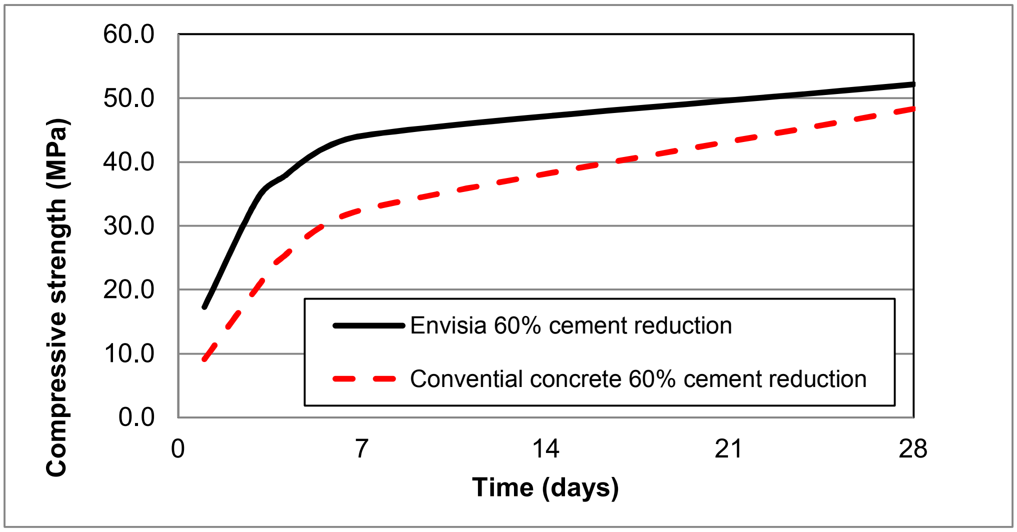

Figure 2. Early strength performance of post-tensioned concretes

4.3 40 MPa pavement concrete

With the low shrinkage exhibited by the Envisia® concrete, it was potentially suitable for warehouse floor applications. A "conventional" mix design suitable for this application was compared to an Envisia® mix with a 50% Portland cement reduction. The aim was to assess the relative flexural strengths of both concretes.

Strength results are summarised in table 2. While it was anticipated that the Envisia® concrete would perform well in flexural strength, the extent of its outperformance was surprising. It achieved a very high 7 day flexural result of 8.8 MPa, 91% higher than that of the "conventional" SL/Fly ash concrete. At 28 days the difference was also significant with the 9.7 MPa achieved being 51% higher.

Properties	Unit	SL/FA Control	Envisia®
3 days Compressive Strength	MPa	25.6	26.1
7 days Compressive Strength	MPa	28.1	35.5
28 days Compressive Strength	MPa	**42.3**	**43.3**
56 days Compressive Strength	MPa	**49.0**	**47.8**
7 days Flexural Strength	MPa	4.6	8.8
28 days Flexural Strength	MPa	**5.4**	**9.2**
56 days Flexural Strength	MPa	**6.4**	**9.7**

Table 2. Compressive strength and flexural testing results pavement concretes

4.4 60 MPa concrete durability tests

Durability tests were undertaken on 60 MPa concretes designed for high durability/low chloride permeability applications. Mixes compared contained binders composed of SL cement/Fly ash, a high SCM "marine" cement blend of SL and GGBFS in the proportions 35:65 and Envisia® containing SL cement and Zep® activated binder (40:60 proportion).

Properties	Unit	SL/FA Control	High SCM Mix	Envisia®
Total Binder content	Kg/m^3	520	520	520
% Portland Cement Reduction	%	25	65	60
3 days Compressive Strength	MPa	43.1	26.8	44.0
7 days Compressive Strength	MPa	55.1	41.8	55.9
28 days Compressive Strength	MPa	71.1	68.1	69.7
Nordtest NT Build 492 at 28 days	m^2/sec	1.04E-11	4.60E-12	1.47E-12
Nordtest NT Build 443 at 56 days	m^2/sec	2.92E-12	2.70E-12	1.21E-12
Din 1048 at 28 days	mm	5.8	3.6	3.1
ASTM C1585 at 28 days (initial)	m/sec$^{0.5}$	0.001893	0.000940	0.000626
ASTM C1585 at 28 days (secondary)	m/sec$^{0.5}$	0.000301	0.000196	0.000192

Table 3. High durability Testing Mix Details

The durability tests chosen include water permeability DIN 1048, water sorptivity ASTM C1585, and chloride migration/diffusion coefficient tests - Nordtest NT Build 492, NT Build 443, which now are extensively used to determine the chloride migration/diffusion coefficient of concrete and to estimate the service life of structures exposed to chloride rich environments. The NSW RMS also prescribes NT Build 492 and NT Build 443 chloride test coefficient limits as a durability requirement in its B80 Concrete Work for Bridges specification. Table 3 outlines the trial details.

It can be seen from Table 3 that, as expected, the NT Build 492 and NT Build 443 results of conventional marine concrete outperformed the conventional SL/FA control concrete. But this marine concrete only complies with B2 exposure limit. By contrast, the Envisia® concrete performed the best, meeting the requirements of Classification C limits.

Table 3 also demonstrates that the Envisia® concrete performed significantly better than the conventional concretes in both sorptivity and water permeability results. This indicates that the increased early strength facilitated by the Zep® activated binder impacted on the porosity of the Envisia® concrete.

4.5 Creep of high strength concretes

Creep performance was measured on 70 MPa concretes. The control contained SL cement and fly ash, having the 28d compressive strength of 84.8MPa, and the Envisia® concrete contained SL cement, Zep® and fly ash, with 28d compressive strength of 77.3MPa. The 12 month creep results are shown in Figure 3 below and indicate significantly lower creep performance by the Envisia® concrete.

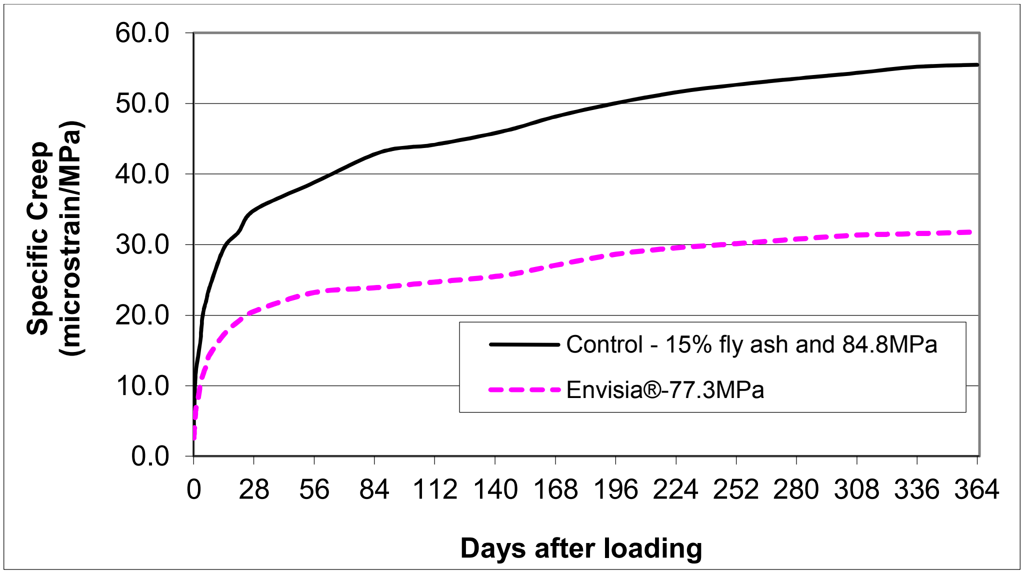

Figure 3. Creep of high strength concretes

4.6 Alkali Silica Reactivity (ASR)

A well-documented positive attribute of the inclusion of SCM's in concrete is their potential to mitigate alkali silica reactivity caused by reactive aggregates. Two mortars, one with SL cement and one with an SL/ Zep® blend, were tested by the Australian Standard accelerated mortar bar test (AMBT) method, AS1141.60.1. Three known reactive aggregates (reactive agg A, B, C) were used in the mixes.

The results are shown in Figure 4 and demonstrate, as expected, that the high proportion activated SCM binder has a significant mitigating effect on potential ASR expansion, reducing the expansion to well below the allowable limits (essentially < 0.10%).

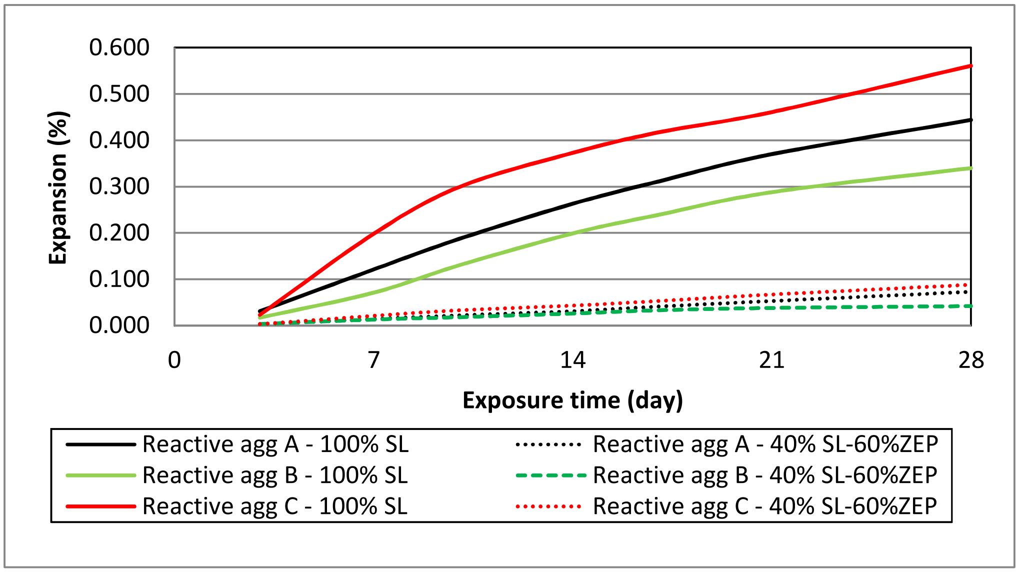

Figure 4. Mortar bar testing for alkali silica mitigation

5.0 CONCLUSIONS

5.1 A high proportion of activated SCM can be used to produce high performance concrete with lower carbon footprint due to reducing the Portland cement content.

5.2 The newly developed Envisia® concrete exhibits similar compressive strength gain characteristics to Portland cement concrete but higher early strength gain than conventional high SCM concretes. For the same compressive strength of conventional concretes, significantly higher flexural strength is achieved by Envisia® concrete.

5.3 Envisia® concrete exhibits significantly lower drying shrinkage and creep when tested in accordance with AS1012.13 and AS 1012.16, respectively. The lower drying shrinkage results are comparable to those achieved by about 7 litres shrinkage reducing admixtures.

5.4 Durability properties of Envisia® concrete in terms of water permeability, water sorptivity and chloride permeability are also significantly improved.

5.5 The high proportion of SCM in Envisia® concrete efficiently mitigates the alkali silica reaction impact of highly reactive aggregates.

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