Influence of Ground Granulated Blast Furnace Slag Cement in concrete pavement mix designs

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ABSTRACT

Roads and Maritime Services (RMS) pavement specifications require the use of Grade 1 fly ash and Ground Granulated Blast Furnace slag cement (GGBFS) for R82 – lean mix concrete subbase [1], and also fly ash and/or GGBFS for R83 – Concrete Pavement Base [2], where reactive aggregates are used.

This investigation revisits the prior work done in this area by Whitaker [3] and further assesses the replacement of the fly ash in these applications with Ground Granulated Blast Furnace Slag (GGBFS).

In recent times fly ash supply has been less reliable, and the RMS specification 3211 – Cements, Binders and Fillers [4], allows for varying quantities of slag cement as a direct replacement.

Based on laboratory trials, including assessing the concrete properties for plastic cracking potential using ASTM method C1579-13, Standard Test Method for Evaluating Plastic Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert) [5], this paper assesses the two mixes with alternate supplementary cementitious materials and presents the findings of plastic and hardened properties.

The differences in the two specifications (R82 Lean Mix and R83 Base pavement), and application of the two supplementary cementitious materials, including QA specification 3211, are addressed and comparisons to the actual laboratory mix designs as trialled are investigated.

History/Background

Further to previous investigations in this area, Whitaker (2014) presented to the 10th November 2014 ASCP Forum theme of Concrete Pavements – A Focus on Materials, a topic covering Making Lean Mix Concrete with less Cementitious Content. This study on work performed for the Gateway Project, Perth, Western Australia was on the basis of a lack of availability and quality of fly ash, and a local preference for slag cement for concrete pavement.

The range of required cementitious materials in batched concrete according to the requirements of RMS R82 lean mix subbase specification at that time in 2014 and Main Roads W.A. specification for lean mix subbase (WA513) [6] are presented in Table 1 and 2 respectively.

Table 1: Required range of cementitious materials according to RMS R82 [1]

Minimum 250kg/m3 Total Binder		
Minimum 90kg/m3 Cement (OPC/GP/SL)		
SCM	**Minimum**	**Maximum (based on 250kg/m3)**
Fly Ash	40% - 100 kg	75% - 188 kg
GGBFS	10% - 25 kg	70% - 175 kg

Table 2: Required range of cementitious materials according to WA513[6]

SCM	**Fly Ash**	**GGBFS**	**Cement**	**Total Binder**
Fly Ash	100 kg min.		90 kg min.	220 kg min.
GGBFS		75 kg min.	75 kg min.	150 kg min.

Preliminary mixes were proven to exhibit excessive compressive strengths, compared to the WA513 specification, and subsequently the trialled and approved mix comprised 75kg GP cement and 75kg GGBFS.

In total 74 loads of lean mix concrete were supplied with a mean 7-day strength of 9.5MPa, and 28-day strength of 19.5MPa.

The conclusion drawn from the work/project was that RMS cementitious levels were resulting in excessive compressive strengths, and that lower levels of 75kg/m3 of both GP and GGBFS respectively are sufficient for strength purposes.

Specifications

(Cement 3211, Lean Mix Subbase R82 and Base Pavement Concrete R83)

As RMS NSW has not previously done significant project concrete supply of subbase and base course concrete containing GGBFS, as a direct replacement for fly ash, initially a review of conforming cementitious blends and minimum/maximum binder levels was performed under contemporary versions of the specifications.

It should be noted that this investigation comprises two stages, one for GGBFS at the start of 2018, and a repeat series in late 2018/early 2019 for both GGBFS, and an alternative alkali activated slag cement (utilising ZEP cement technology as manufactured by Boral Cement, and also referenced as Envisia® concrete). Both stages assessed the R82 LMC and R83 Base concrete under a similar testing regime.

QA Specification 3211 Cements, Binders and Fillers

In accordance with revision history, 3211 specification Edition 4/Revision 6 dated 22.11.2012, and Annexure D-D3 (iv) contained a requirement for the R83 Base concrete to have a minimum 40% of Ground Granulated Blast Furnace Slag cement for the 'Hot weather mix'.

This was subsequently removed in Edition 4/Revision 10 (1.11.2017).

Therefore for a non-reactive aggregate to any Alkali silica reactions, then less than 40% GGBFS may be used, but for conservatism of assessment a reactive aggregate was assumed and therefore 40% GGBFS adopted as per Table 3211/D.2.

Mix Designs

As previously mentioned, the mixes assessed for R82 Lean Mix Sub-base, were

1. a conventional fly ash mix in both Stages 1 and 2,
2. a GGBFS binary blend at 250kg/m3 cementitious in Stage 1, and 150kg/m3 in Stage 2, and finally
3. an activated GGBFS mix (Envisia®) at 150kg/m3 also, as per Table 3.

Table 3: R82 Lean Mix Subbase

	Stage 1		Stage 2A			Stage 2B		
Mix	R82 FA-Blend	R82 GGBFS -Blend	R82 FA-Blend	R82 GGBFS-Blend	R82 Activ. GGBFS	R82 FA-Blend	R82 GGBFS -Blend	R82 Activ. GGBFS
SL (Kg/m^3)	89	89	89	73	71	89	74	76
Fly ash (Kg/m^3)	158		159			159		
GGBFS (Kg/m^3)		158		73			74	
Activated GGBFS (Kg/m^3)					71			76
20mm aggregate (Kg/m^3)	802	801	805	792	763	803	797	817
10mm aggregate (Kg/m^3)	267	267	268	264	254	268	266	272
Manufactured sand (Kg/m^3)	673	682	676	704	678	674	708	726
Fine sand (Kg/m^3)	168	188	169	215	198	169	216	212
WR (ml/100kg)	396	395	397	391	377	396	393	403
Re (ml/100kg)	99	99	99	98	94	99	98	101
AEA (ml/m^3)	495	395	497	489	330	595	443	252
Water kg/m^3	146	165	156	151	151	155	152	143
Water/Cement ratio	0.59	0.67	0.63	1.03	1.07	0.63	1.03	0.95

The mixes assessed for the R83 Base concrete, were

1. a conventional fly ash mix in both Stages 1 and 2,
2. a GGBFS binary blend at 350kg/m3 cementitious in both Stages 1 and 2, and finally
3. an activated GGBFS mix (Envisia®) at 350kg/m3 also, as per Table 4.

Table 4: R83 Base Concrete Pavement

	Stage 1		Stage 2		
Mix	R83 FA Blend	R83 GGBFS Blend	R83 FA blend	R83 GGBFS Blend	R83 Activ. GGBFS
SL (Kg/m^3)	302	216	296	212	219
Fly ash (Kg/m^3)	58		57		
GGBFS (Kg/m^3)		147		145	
Activated GGBFS /ZEP (Kg/m^3)					150
20mm aggregate (Kg/m^3)	720	726	706	715	737
10mm aggregate (Kg/m^3)	331	334	325	328	339
Manufactured sand (Kg/m^3)	593	599	582	589	608
Fine sand (Kg/m^3)	165	157	162	155	150
WR (ml/100kg)	389	392	382	386	399
Re (ml/100kg)	97	98	95	97	100
AEA (ml/m^3)	340	343	334	314	399
Water kg/m3	157	175	168	169	174
Water/Cement ratio	0.44	0.48	0.48	0.47	0.47

Plastic Properties Assessment – Plastic cracking test method (ASTMC1579-13)

In changing from fly ash to GGBFS in both R82 Lean mix subbase and R83 Base concrete pavement, it was hypothesised that the increased fineness may result in less bleed water, and with the extended set time of the slag cement that plastic cracking potential may be worsened.

In order to assess the plastic cracking potential, the ASTM method C1579-13 ‘Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert)’, was performed.

The plastic cracking test method can be used to compare the plastic shrinkage behaviour of different concrete mixtures “containing fiber reinforcement”.
This project used a plain concrete, through the use of a modified test method containing no fibre reinforcement.

The test method is intended to evaluate the effects of

- evaporation,
- settlement, and
- early autogenous shrinkage

on the plastic shrinkage cracking performance of fiber reinforced concrete up to and for some hours beyond the time of final setting.

The measured values obtained from this test may be used to compare the performance of concretes with

- different mixture proportions,
- concrete with and without fibers,
- concretes containing various amounts of different types of fibers, and
- concrete containing various amounts and types of admixtures.

From Figure 1 to 5, in general, the method comprises casting duplicate panels into a stress inducing mould, containing three mechanisms for internal restraint. (See Figure 1) The concrete is then placed into an aggressive drying environment, with evaporation as high as 1.0kg/m^2/hr and exposed to this environment until at least final set time, as determined by concrete penetrometer testing of a sample within the environmental chamber. (See Figures 2(a) and (b)). The concrete is also subjected to elevated temperature to increase the evaporative nature of the test.

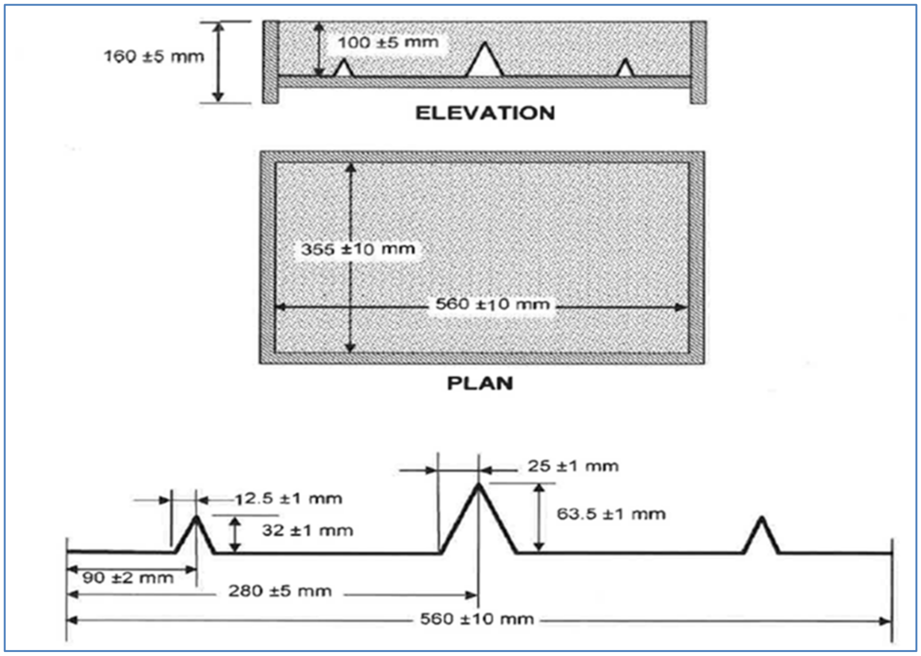


Figure 1 - Mould and Stress riser geometry

Figure 2(a) – ASTM environmental chamber

Figure 2 (b) – ASTM environmental chamber including set time sample and evaporation dish

Once the plastic concrete stage has completed, the samples are removed from the environmental chamber and are assessed by marking the cracks above the larger central crack inducer. Following identification of the cracking path, the width of crack is determined at 10mm intervals by optical microscope, to derive an average crack width across the transverse direction of the two panels. (See Figure 3 and 4)

The two panels are then assessed as a function of evaporation rate and average crack width. A check of evaporation rate from a dish in the chamber, and mass loss of the panel is performed to ensure the drying conditions are similar for the two sample panels to determine an average crack width.

At ~10mm intervals along the length of the crack

Figure 3 – Stage 1 Crack increment methodology – 10mm centres

Crack width measurement under an optical microscope

Figure 4 – Stage 1 Crack width methodology – optical microscope

This was carried out on Stage 1 (SL/FA and SL/GGBFS) as well as in Stage 2 (SL/FA, SL/GGBFS and SL/Activated GGBFS- Envisia®) where it was viewed the tensile strength development of the concrete may be improved by accelerating the ettringite formation and therefore the ability to resist tensile stresses of plastic cracking. See Figures 5(a) and (b) for Lean mix subbase, and Figure 6 for typical Base concrete cracking behaviour.

Figure 5 (a) – Stage 1 R82-LMC – SL/FA

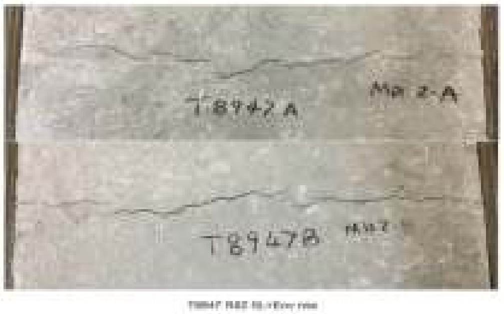


Figure 5 (b) – Stage 1 R82-LMC – SL/GGBFS

Figure 6 – Stage 1 R83-Base – SL/GGBFS

The specific crack widths and difference in characteristics are contained within Tables 5, 6, 7 and 8 for each of the specified concrete mixes being lean mix and base concrete, as well as at each stage of testing. The variance in crack width to the control mix (fly ash based mix design) is highlighted for each type of concrete. Generally the GGBFS mixes exhibited increased cracking potential, whilst the same quantity of activated GGBFS (Envisia®) had the same or even less plastic cracking for the same evaporative drying conditions.

Table 5 – Stage 1 R82 LMC Crack width/evaporation

Stage 1 – R82 Lean Mix Subbase				
ASTM C1579-13 Plastic shrinkage cracking	**Ave. cracking width panel 1**	**mm**	**SL/FA 0.60**	**GGBFS 0.65 (+8%)**
	Ave. cracking width panel 2	**mm**	**0.60**	**0.90 (+50%)**
	Temperature of 38°C room	°C	36~40	
	Relative Humidity of 38°C room	%	26~30	
	Avg wind velocity panel 1	m/sec	4.40	4.60
	Avg wind velocity panel 2	m/sec	4.40	4.50
	Avg evaporation rate panel 1	kg/m2.hr	0.79	0.76
	Avg evaporation rate panel 2	kg/m2.hr	0.74	0.81
	Moisture loss of concrete panel 1	kg/m2	3.32	3.17
	Moisture loss of concrete panel 2	kg/m2	3.12	3.02
	Moisture loss time interval	hr	5.20	4.90

Table 6– Stage 2 R82 LMC Crack width/evaporation

Stage 2 – R82 Lean Mix Subbase					
ASTM C1579-13 Plastic shrinkage cracking	**Ave. cracking width panel 1**	**mm**	**SL/FA 0.67**	**GGBFS 0.67 (0%)**	**Activated GGBFS 0.63 (-6%)**
	Ave. cracking width panel 2	**mm**	**0.65**	**0.68 (+5%)**	**0.59 (-9%)**
	Temperature of 38°C room	°C	36~40		
	Relative Humidity of 38°C room	%	26~30		
	Avg wind velocity panel 1	m/sec	4.40	4.80	4.70
	Avg wind velocity panel 2	m/sec	4.80	4.70	4.60
	Avg evaporation rate panel 1	kg/m2.hr	0.58	0.66	0.56
	Avg evaporation rate panel 2	kg/m2.hr	0.59	0.61	0.57
	Moisture loss of concrete panel 1	kg/m2	3.07	3.46	2.25
	Moisture loss of concrete panel 2	kg/m2	2.92	3.29	2.39
	Moisture loss time interval	hr	5.20	4.30	4.20

Table 7– Stage 1 R83 Base Crack width/evaporation

Stage 1 – R83 Base Concrete Pavement				
ASTM C1579-13 Plastic shrinkage cracking	**Ave. cracking width panel 1**	**mm**	**SL/FA** **0.70**	**GGBFS** **0.85 (+21%)**
	Ave. cracking width panel 2	**mm**	**0.50**	**1.00 (+100%)**
	Temperature of 38°C room	°C	36~40	
	Relative Humidity of 38°C room	%	26~30	
	Avg wind velocity panel 1	m/sec	4.50	4.60
	Avg wind velocity panel 2	m/sec	4.50	4.40
	Avg evaporation rate panel 1	kg/m2.hr	0.94	0.96
	Avg evaporation rate panel 2	kg/m2.hr	0.95	0.95
	Moisture loss of concrete panel 1	kg/m2	2.67	3.22
	Moisture loss of concrete panel 2	kg/m2	2.46	3.17
	Moisture loss time interval	hr	3.90	4.70

Table 8 – Stage 2 R83 Base Crack width/evaporation

Stage 2 – R83 Base Concrete Pavement					
ASTM C1579-13 Plastic shrinkage cracking	**Ave. cracking width panel 1**	**mm**	**SL/FA** **0.30**	**GGBFS** **0.53** **(+76% c.f. panel 1)**	**Activated GGBFS** **0.30** **(0% c.f. panel 1)**
	Ave. cracking width panel 2	**mm**	**0.13** **(Excluded)**	**0.47** **(+57% c.f. panel 1)**	**0.29** **(-3% c.f. panel 1)**
	Temperature of 38°C room	°C	36~40		
	Relative Humidity of 38°C room	%	31~35		
	Avg wind velocity panel 1	m/sec	4.40	4.80	4.70
	Avg wind velocity panel 2	m/sec	4.80	4.60	4.60
	Avg evaporation rate panel 1	kg/m2.hr	0.72	0.69	0.55
	Avg evaporation rate panel 2	kg/m2.hr	0.72	0.66	0.56
	Moisture loss of concrete panel 1	kg/m2	2.68	2.70	1.62
	Moisture loss of concrete panel 2	kg/m2	2.59	2.57	1.63
	Moisture loss time interval	hr	3.80	3.90	2.90

Analysis of results of Laboratory Trials

As has been demonstrated by Whitaker (2014) for the Gateway project in Western Australia, using lean mix concrete with a prescriptive cement blend, and minimum cementitious levels was again the case in Stage 1 work that concrete strengths were excessively high. At 90kg/m3 minimum OPC/SL cement and 160kg/m3 GGBFS to ensure the minimum cement level was achieved resulted in 28 day compressive strengths of approximately 33MPa, for 5MPa requirement as shown in Figure 6. The two stages of incumbent fly ash mix designs realised strengths of approximately 10MPa at 28 days as expected. The two stages of reduced binder content GGBFS and activated GGBFS/Envisia® mixes were in the range 14-19MPa. (See Figure 7)

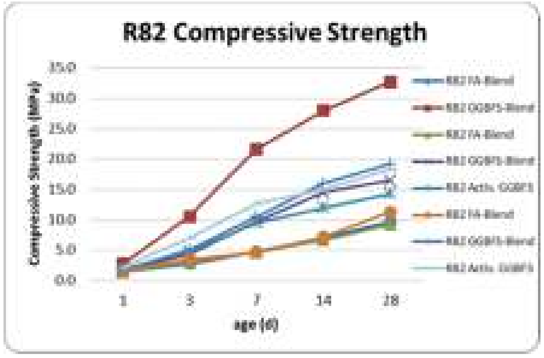


Figure 7 – LMC Compressive Strengths

Drying shrinkage for the two stages of R82/LMC trials shows the fly ash blends both having 21 day drying shrinkage results in the range 500-550 microstrain (µS), versus the specified limit of 550µS at 21 days. The two GGBFS mixes were 400-450µS for the neat milled slag and 300µS for the Activated GGBFS (Envisia®), representing a reduction in shrinkage of up to 20 and 40% respectively as demonstrated in Figure 8. Significant reduction in drying shrinkage of the Envisia® mix could be due to the increasing the amount of C-S-H gel hydrates, and accelerating ettringite formation in early age which consumes more free water, and thus reduces evaporation. This is in agreement with the findings of Li, Yao [8] and Atis [8]. This can also be deemed to be attributable to the lower total binder content of the slag cement blends, although it is evident the Envisia®/Activated GGBFS blend was a degree lower again at the same cement ratios and levels.

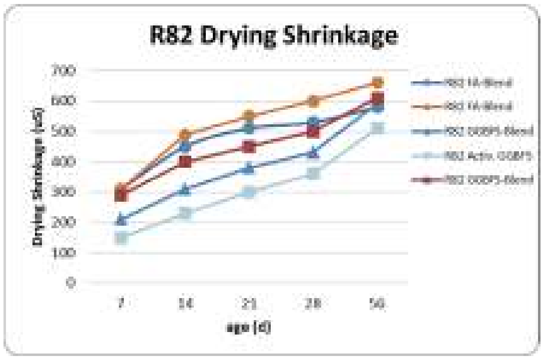


Figure 8 – LMC Drying Shrinkage

Bleeding of the concrete shows the fly ash to have a relatively late bleed profile, but the highest rate at 3% which provides some protection to plastic cracking, the GGBFS mix started bleeding late as well at 90 minutes and delivering 1% bleed before setting. The activated GGBFS/Envisia® mix also exhibited lower bleed at 1%, but delivered water to the surface earlier at 30 minutes before setting at 120 minutes. This provides early protection through to the early setting, to provide less risk of plastic cracking overall as shown in Figure 9. Khayat, Yahia [9] reported that replacing cement with SCM led to substantial enhancement in the resistance to bleeding.

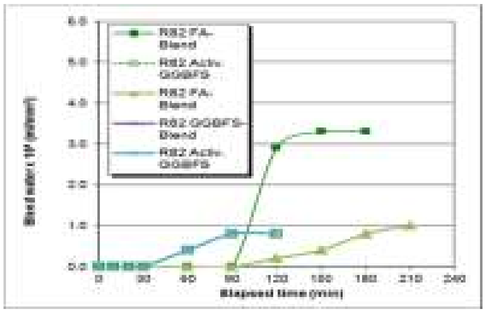
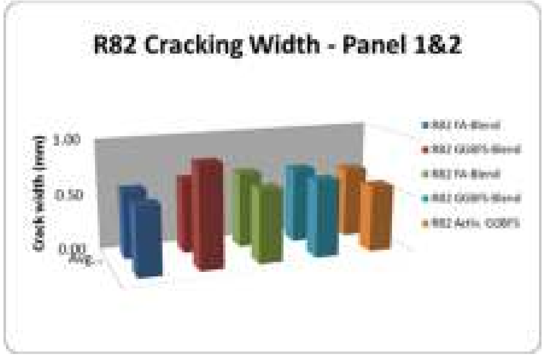


Figure 9 – LMC Bleed water profile graph

The lower bleed water in the GGBFS mixes is likely to have contributed to the higher cracking potential as determined by ASTM C179 when compared to the fly ash mixes. The GGBFS/Envisia® mix however did not have a higher cracking potential than the fly ash mixes despite having a similar bleed rate to the GGBFS mixes. The superior crack resistance of the GGBFS/Envisia® compared to the GGBFS mixes mix may be due to the earlier commencement of bleeding.

It was also observed that the evaporation rate for the first two SL/FA and SL/GGBFS mixes had a higher evaporation rate than the second stage of testing, but the cracking outcomes were repeatable. See Figures 10 (a) and (b)



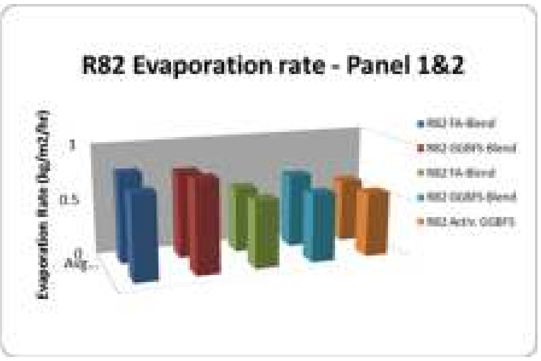


Figure 10 (a) – LMC Cracking width   Figure 10 (b) – LMC Evaporation rate

For the R83 series of trials, the compressive strength range of results was not as pronounced as for the lean mix concrete, except that the activated slag had the highest strengths at most ages, and GGBFS mixes typically achieving the higher results at 28 days. It is in agreement with the findings of Keyte, Lloyd [10]. Hogan, Meusel [11] also reported that partially replacing cement with GGBFS will slow reactivity and retard the hydration at early ages. However, Envisia® concrete increased the early age hydration significantly compared to the mixes containing fly ash or neat GGBFS as shown in Figure 11.

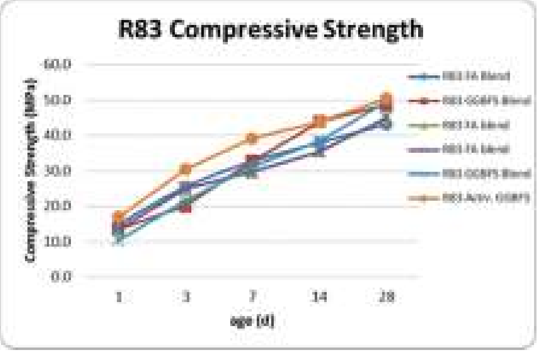


Figure 11 – Base Concrete Compressive Strengths

The drying shrinkage results mixes were relatively high for the fly ash and the GGBFS mixes which had been anticipated based on past experience with the aggregates. Typically the Stage 1 and 2 fly ash mixes were 490 to 520 microstrain (µS), versus 450µS maximum at 21 days, and further 630-640µS at 56 days versus 580µS specified. For the slag cement series of mixes, the neat milled slag trials were 640 and 530µS respectively at 21 days, versus 580µS specified, with 56 day results of 790 and 650µS respectively, versus 680µS specified.

The research also showed for the same underlying aggregate, that the GGBFS mix reduced to 320µS (580µS specified) at 21 days, and 460µS at 56 days (680µS specified), when activated as an Envisia® mix despite having the same w/b ratio. This is deemed to be a result of acceleration of the ettringite formation and consumption of free water at early age, and thus reduced volumetric change and reduction in water loss through drying shrinkage as shown in Figure 12. This is in agreement with the findings of Chandler, Hocking [12].Tanabe, Sakat [13] also reported evaporation of excess water of that required for hydration in early ages from the pore solution can cause shrinkage due to capillary forces.

Figure 12 – Base Concrete Drying Shrinkage

The bleed profiles of the three mixes in the two stages of research was inconclusive in that for the first series of two mixes the fly ash mix bled less and later than the GGBFS mix (2.0% versus 2.8% respectively). The second series resulted in all three cement blends realising nil bleed water in a similar internal environment at that time of year, with air-sealed bleed pots as demonstrated in Figure 13.

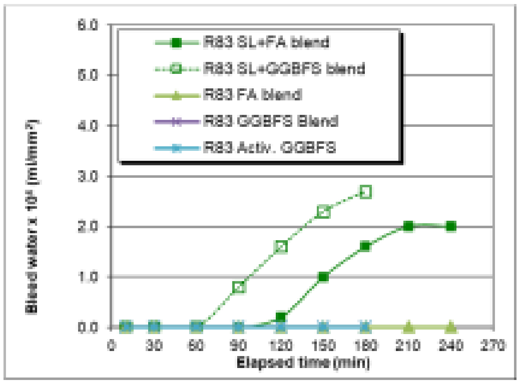


Figure 13 – Base Concrete bleed water profile

The flexural strengths achieved were typically 5.0-5.5 MPa for the fly ash conventional design mixes, whilst the GGBFS mixes were typically 6.5-7.0 MPa for essentially the same compressive strength. Of note however, there was improved interfacial bond between aggregate and paste, as well as consumption of free water into the ettringite formation. This then has the potential to reduce the bleed water being entrapped on the underside of coarse aggregate particles. It is concluded that this resulted in the activated GGBFS/Envisia® mix achieving flexural strengths of 7.5-8.0 MPa, which is approximately 47% above that of the conventional fly ash mix as shown in Figure 14. This is in agreement with the findings of Bornstein and Song [14].

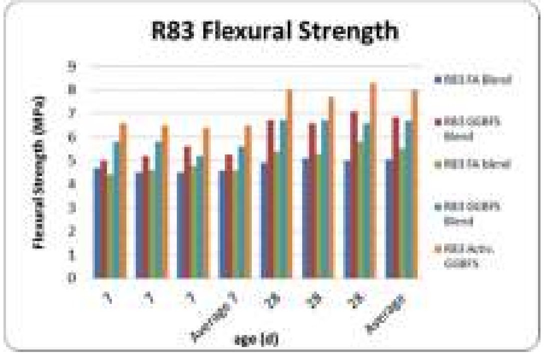


Figure 14 – Base Concrete Flexural Strength

In accordance with R83 specification, the coefficient of thermal expansion is a ‘report only’ requirement for the base course pavement, which is usually aggregate mineralogy/geology dependent. In this case the coarse and fine aggregate ratios were the same, and only the cement blends were varied.

From Figure 15, it can be seen that across the two stages of work, the fly ash mixes were approximately 7 microstrain/Degree C, whilst the GGBFS mixes were circa 8.5 microstrain/Deg C, and lastly the activated GGBFS/Envisia® mix had a COTE of approximately 9.0 microstrain/Deg C under test method AASHTO T236. This may be deemed to be from the increased glassy phase binder in moving from 60kg/m3 fly ash to

145kg/m3 to comply with the 40% minimum GGBFS under RMS 3211 for a reactive aggregate SL/GGBFS binary blend (Table 3211/D.2).

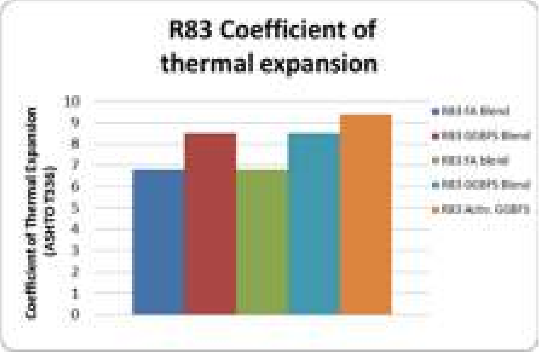


Figure 15 – Base Concrete Coefficient of Thermal Expansion

Of interest in the R83 crack potential testing, the crack width of the GGBFS mix was significantly higher at 20-76% above the fly ash mix, whilst the Activated GGBFS (Envisia®) was essentially the same crack width as the fly ash under slightly less drying conditions in the Stage 2 trials, as shown in Figure 16 (a) and (b).

Figure 16 (a) – Base Concrete Cracking width   Figure 16 (b) – Base Concrete Evaporation rate

Conclusion

For the R82 Lean mix concrete it is deemed the total minimum cementitious 250kg/m3 is too high for the GGBFS mix, as it achieved up to 32MPa at 28 days versus 15MPa maximum. This confirms the previous work by Whitaker (2014) and additional trials at 150kg/m3 (comprising 50% cement and 50% GGBFS), whilst still over-performing at up to 20MPa is more aligned to the lean mix required maximum strength of 15MPa.

Drying shrinkage of the higher cementitious GGBFS mix from Stage 1, was above the 550microstrain (at 21 days) whilst the same proportion of activated slag cement/Envisia® achieved the lowest drying shrinkage of all at 300microstrain, or 57% reduction on the baseline fly ash mix, and 22% lower than the equivalent GGBFS mix.
Increased fineness of GGBFS resulted in higher water demand (20l/m3) which in part offset the lower bleed water, and subsequent cracking potential.

The average crack width for the GGBFS mixes was up to 50% higher than the existing SL/FA mixes, when assessed by ASTM C1579-13. The Activated GGBFS/Envisia® mix was up to 9% reduction in crack width versus the SL/FA mix.

The R83 Base concrete typically had compressive strengths for all binder types in the range 40-50MPa as expected, since the total cementitious contents were similar and just the ratio of fly ash (16%) and GGBFS (40%) varied.

Drying shrinkage of the Base SL/FA concrete was nominally 500 microstrain at 21 days, whilst the GGBFS mix was in the range 520-620µS, yet the same proportion of activated GGBFS/Envisia® reduced to 300µS at 21 days. This demonstrates that for moderate/high drying shrinkage aggregate, that through management of water loss from the concrete paste, that drying and the resultant volumetric change potential can be minimised.

For this body of research, bleed water assessment of the R83 concretes was inconclusive between Stages 1 and 2, as the bleed water profile showed the GGBFS to bleed earlier and to a greater extent (2.8%) than the incumbent fly ash mix (2%) in Stage 1. Whilst in Stage 2 trials under similar batching conditions and an air tight sealed bleed test, there was no bleed water captured for any of the three cement blends.

Flexural strength of the R83 Base Concrete shows the fly ash mix to perform as expected at 5.0-5.5MPa. The flexural strength for the GGBFS mixes were higher, typically achieving 6.5-7.0MPa and the flexural strength of the GGBFS/Envisia® mixes were even higher achieving 8.0MPa at 28days. The improved performance is thought to be due to an improved paste to aggregate bond which has resulted in a superior flex/compressive strength ratio.

Coefficient of thermal expansion for the three mixes shows for the same underlying aggregate combinations, the fly ash mix was approximately 7 microstrain/Degree Celsius, whilst the GGBFS mixes were nominally 8.5 µS/Deg C, and activated GGBFS with the same slag content closer to 9.0-9.5µS/Deg C.

Lastly, cracking potential was assessed by ASTM 1579-13 Standard Test Method for Evaluating Plastic Shrinkage Cracking in both stages of R83 Base concrete. The GGBFS exhibited greater plastic cracking potential in both series of tests, than the fly ash mix to the extent of 20-75%. The Activated GGBFS/Envisia® mix showed similar cracking behaviour to the fly ash mix. It's improved performance compared to the GGBFs mix is deemed to be a result of accelerating the ettringite formation and ability to resist tensile stresses over the un-activated GGBFS mix.

In summary, whilst some areas of admixture and concrete technology may assist to overcome some aspects of utilising GGBFS cement in R82 Lean mix subbase and R83 Base concrete pavement, there is sufficient confidence to progress its use more widely as has been used in past Gateway (W.A.) and recent Northern Connector (S.A.) projects.

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