Multi-Sustainability Benefits of Low Carbon Concrete

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Abstract: Low carbon concretes (LCC) with General Purpose (GP) cement and high supplementary cementitious material (SCM) have been developed and being specified in New South Wales Government specifications for both building and infrastructure works. The sustainability objectives of specifying LCCs are three-fold: the reduction of embodied carbon (EC); the achievement of the design life; and the full utilisation of both high quality and marginal aggregates from existing quarries. SCMs have much lower EC than GP cement and they can be effectively used in formulating concrete with significant reduction in EC and improved durability performance at equivalent mechanical and volume stability properties to GP cement concrete. SCMs are proven effective in mitigating deleterious alkali-silica reaction (ASR) as well as the prevention of possible deleterious delayed ettringite formation (DEF) in heat-cured precast concrete production. In this paper, the choice of the use of either fly ash or blast furnace slag or their combinations in the production of LCC are given to overcome the supply chain limitation of some SCMs in certain remote locations. LCCs can be developed to meet either the existing performance-based specifications or both prescriptive and performance-based specifications. In addition, new performance-based requirements to prevent carbonation-induced corrosion are developed to update the deem-to-comply concrete cover requirements in the two Australian Standards AS 3600 – Concrete Structures and AS 5100.5 – Bridge Design: Part 5.

Keywords: embodied carbon, fly ash, ground granulated blast furnace slag, low carbon concrete, supplementary cementitious materials.

1. INTRODUCTION

In Australia, there are joint government and private sector efforts to improve the sustainability of the concrete construction industry. Two areas that are technically achievable in the short to medium term are in the greater use of low carbon concrete and greater or full usage of our natural aggregate resources. The availability of supplementary cementitious materials (SCM) such as fly ash and ground granulated blast furnace slag are important resources for the production of low carbon concrete (LCC). According to a QTMR report (1), a large number of hard rock quarries in Queensland have aggregates which are susceptible to alkali-silica reaction (ASR) when used in concrete. This restricts the greater use of concrete aggregates produced from these existing quarries.

Low carbon concretes (LCC) with GP cement and high amount of SCM have been developed for both building and infrastructure works. The sustainability objectives of specifying LCCs are three folds: the reduction of embodied carbon (EC); the achievement of the design life; and the full utilisation of both high quality and marginal aggregates from existing quarries thus reducing the demand for new quarries. SCMs have much lower EC than GP cement and they can be effectively used in formulating concrete with significant reduction in EC and improved durability performance at equivalent mechanical and volume stability properties to GP cement concrete (2, 3). SCMs have been proven effective in mitigating deleterious ASR (4) as well as the prevention of possible deleterious delayed ettringite formation (DEF) in heat-cured precast concrete production (5).

In this paper, the choice of the use of either fly ash (FA) or ground granulated blast furnace slag (SL) or their combinations in the production of LCC are explored. This enable the flexibility in the use of LCC according to the availability of SCMs in the supply chain. LCCs are developed to meet either the existing performance-based specifications or both the prescriptive and performance-based specifications. In addition, new performance-based requirements to prevent carbonation-induced corrosion are developed.

2. SUSTAINABLE CONCRETE STRUCTURES

Low carbon concrete (LCC) is defined as concrete which meets all performance requirements at the lowest embodied carbon (EC). There are generally 3 performance requirements namely (i) good workability and constructability, (ii) adequate mechanical and volume stability properties, and (iii) durability with respect to the design life for the in-service exposure conditions.

The embodied carbon of common concreting materials is shown in Table 1. There are two types of LCC:

1. SCM blended cement concrete produced from an AS3972 cement and one or more SCMs complying with the relevant part of AS3582.
2. Alkali-activated binder (geopolymer) concrete produced from one or more SCMs as precursor and activated by alkalis. See SA TS199 (2024).

Low carbon concrete can be achieved by the reducing the use of high embodied-carbon cement in the binder or completely replacing cement with a small amount of embodied-carbon alkali activator(s) in the binder. In this paper, the development of concrete with high SCM content to lower the EC will be presented.

Table 1 Intensity factors (Life cycle stages A1-A3) taken from Infrastructure Sustainability Materials Calculator (6)

Name	LCI Source	Global Warming Potential (kg CO2e/tonne)
Alkali activator (Sodium silicate)	AusLCI Shadow database	1099.1
Ordinary Portland Cement, Australian average	AusLCI	966.9
General Purpose Cement, Australian average	AusLCI	917.8
Coarse Aggregates (Gravel, crushed)	AusLCI Shadow database	10.5
Fine Aggregates (Sand)	AusLCI Shadow database	4.2
Fly ash	AusLCI	19.8
GGBF slag	AusLCI	192.2
Mains water	AusLCI Shadow database	0.4
Manufactured sand (Gravel, crushed)	AusLCI	10.5
Recycled Aggregates	AusLCI	5.1

2.1 Low carbon concrete with SCM

Concrete mix designs were developed with a range of binder systems at 5 water to binder ratios. The binder materials used are listed below and details are shown in Figure 1.

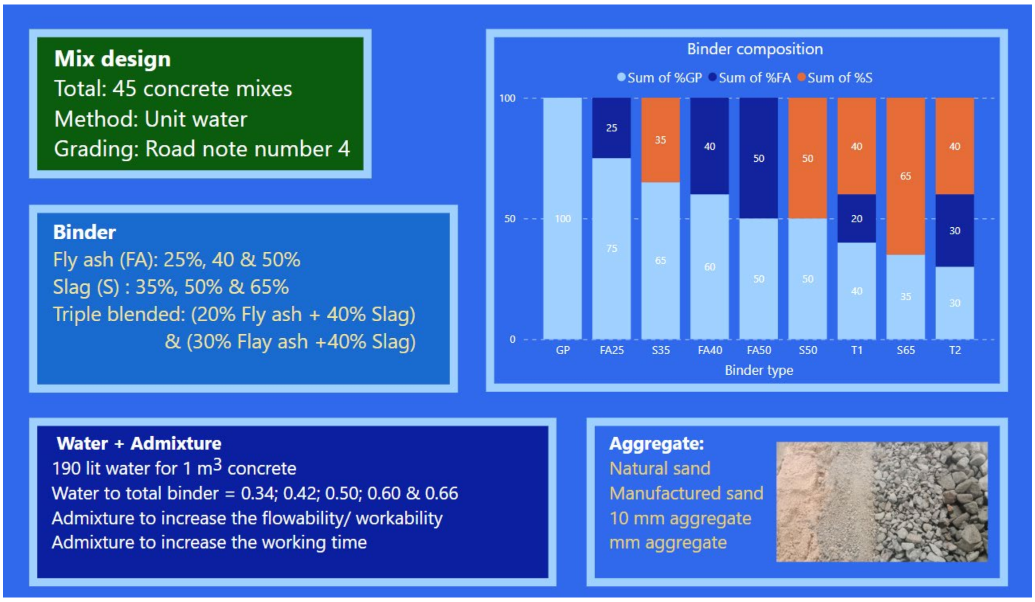


Figure 1. Details of concrete mix designs, binder, water and chemical admixtures

The following concreting materials were used.

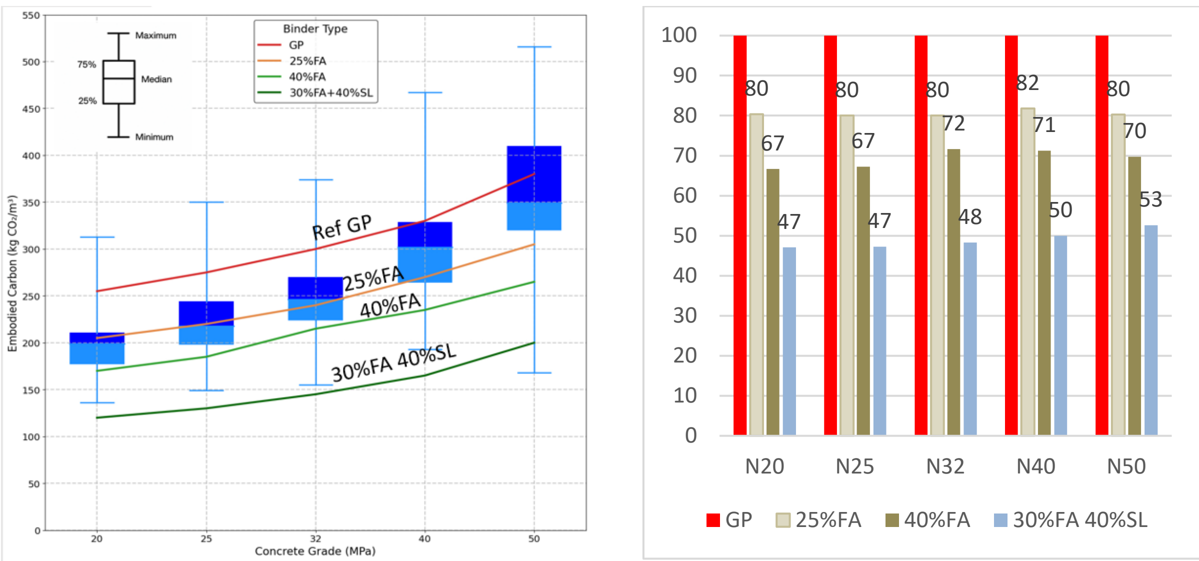
AS3972 General Purpose Cement (AS3972 Type GP) containing up to 7.5% limestone
AS3582.1 Fly ash complying to AS3582.1
AS3582.2 Ground granulated blast furnace slag complying to AS3582.2

A range of properties such as slump, air content, plastic density, compressive strength development, heat-cured 1-day compressive strength, drying shrinkage, resistance to chloride penetration (ASTM C1202, Nord test N443 and N492), resistance to sulfate attack (7) and AVPV were tested but not all are reported in this paper.

2.2 Influence of type and dosage of SCM

AS1379 Normal class concretes with a slump of 100±20 mm have been designed for concrete grade 20, 25, 32, 40 and 50 with the corresponding 28-day characteristic strengths. These concretes meet AS1379 characteristic 28-day compressive strength 95% compliance requirement. With an assumed production standard deviation of 3.5 MPa, a strength margin of 6 MPa is required for 28-day mean compressive strength. Concrete with high SCM have been found to have higher carbonation rate (3). The durability with respect to carbonation-induced corrosion has therefore been re-examined and concrete cover requirements revised in the revised Australian Standard AS3600 to be published in the latter part of 2025. AS3600 is a deem-to-comply standard for concrete structure with a 40 to 60 years design life.

The embodied carbon of various grades of concrete can be reduced with the various type and dosage of fly ash (Fig 2), slag (Fig 3) and combined fly ash and slag (Figs 2 and 3). In Fig 2(a), the level of EC for each grade can be compared to the current EC percentile of Australian concrete suppliers' EPD reported by MECLA (8). Concrete with 25% and 40% FA has EC around the median and 25% percentile of Australian EPD data. Triple blend of 30%FA/40%SL gave the lowest EC around the minimum Australian EPD. The influence of increasing dosage of SCM such as fly ash can be clearly seen in Fig 2(b). Concrete with 25-40% FA can provide around 20-30% EC reduction compared to GP cement concrete. The triple blend mixes can result in around 50% EC reduction.

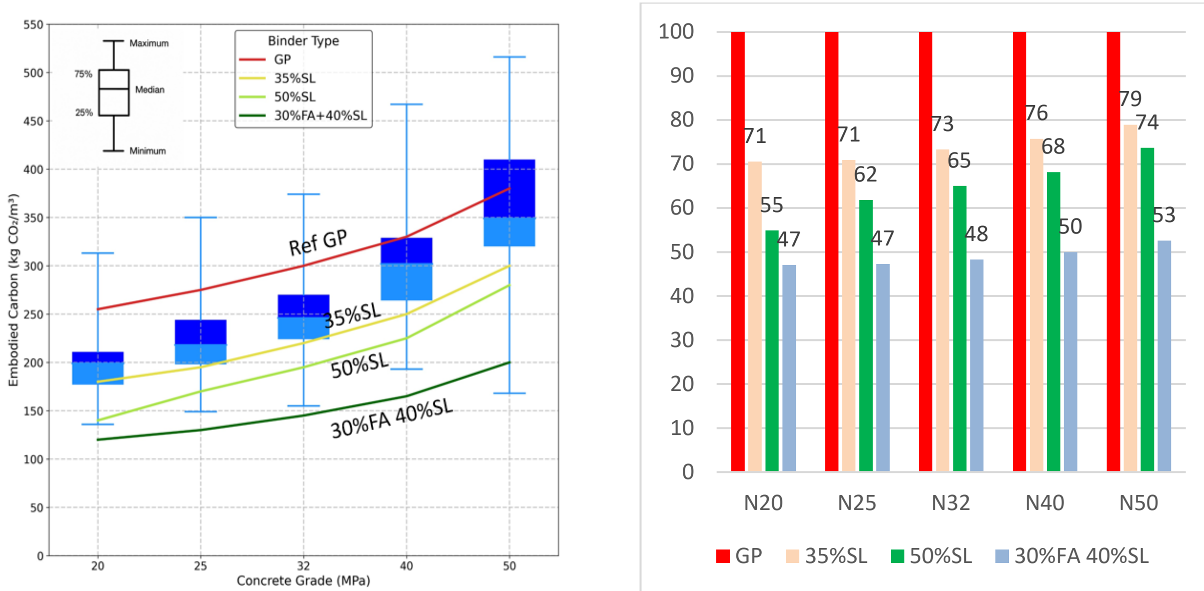


a) Comparison to Australian EPD data (8)

b) Percentage EC of mixes compared to GP

Figure 2. Embodied carbon of concrete with FA and triple blend of FA and SL (slag)

The use of ground granulated blast furnace slag (SL) can also effectively reduce the EC of the Normal class concrete of various grades. The effectiveness of slag can be seen in Figure 3. Concrete with 35%SL can reduce the EC of GP cement concrete by 21-29 % as shown in Fig 3(b). These reductions are around the 25% percentile of Australian EPD data as shown in Fig 3(a). Significantly further reduction in EC can be achieved with the use of 50%SL.



a) Comparison to Australian EPD data (8)   b) Percentage EC of mixes compared to GP

Figure 3. Embodied carbon of concrete with slag and triple blend of FA and SL (slag)

AS1379 Special class concrete are required for infrastructure work. Special class concrete has additional performance requirements such as higher slump or slump flow, low drying shrinkage, high resistance to chloride penetration and acid sulfate attack. Concrete with high SCM and specific aggregates can be designed to achieve these performances. The EC of special class concrete will be increased slightly compared to normal class concrete. This is mainly due to the increase of chemical admixtures. In Australia, the design life of infrastructure is at least 100 years with durability requirements specified in Australian Standard AS5100.5.

Transport authorities usually specify concrete with both prescriptive and performance-based requirements. Prescriptive requirements such as minimum cement content and maximum water to binder ratio will control the EC of concrete. It is therefore important to develop and drive the acceptance of performance-based specifications that enable innovative design of LCC (9).

2.3 Sustainable concrete structures

In order to achieve sustainable concrete structures, design engineers will have to optimise their design by combining structural efficiency, constructability and the appropriate choice of LCC. An efficient structural system may demand the use LCC with slightly higher EC but achieve a more sustainable structure with lower quantity of LCC. Faddoul and Sirivivatnanon (2024) has demonstrated an example of such design (10). The use of precast concrete elements in modern structures will generally requires LCC with higher EC but may benefit from greater speed and reduced site footprint. It is therefore necessary to develop LCCs that are suitable for various usage both for in-situ and precast construction. In addition, season dependent LCC may be required for specific applications such as for post tensioned slab construction.

3. SUSTAINABILITY OF HARD ROCK QUARRIES

To support the sustainability of Australian limited quarry resources, it is important that alkali-silica reactive aggregates can be used by limiting the deterioration of concrete due to alkali silica reaction (ASR). Standards Australia's Handbook 79 - Guidelines on minimising the risk of damage to concrete structures in Australia (11) has been used successfully for this purpose.

3.1 Recommended properties and dosage of SCM

HB79 (11) recommends the use of SCMs as a means to mitigate ASR. The two important factors to be considered when using SCMs to mitigate ASR are the quality and quantity of the SCM used in the concrete mix. HB79 Table 3.2, reproduced below, shows the recommended SCM content when no specific test is carried out to test the effectiveness of SCM to mitigate ASR of specific aggregates used.

TABLE 3.2

SUMMARY OF PROPERTIES OF SCMS USED FOR THE SUPPRESSION OF ASR (% BY MASS)

SCM	Recommended SCM content in binder for ASR mitigation[a]	Maximum SCM alkali level (Na2O equiv) as total alkali[b]	Alkali available from SCM contributing to ASR[c]	Maximum recommended calcium oxide[d]
Fly ash	~25[e]	3	20	8
Silica fume[f]	~10	1	100	—
Slag (GGBFS)	~65[g]	1	50	—
Metakaolin[h]	≤15	—	100	—

3.2 Accelerated testing methods

The reliability of AMBT (AS1141.60.1) and CPT (AS1141.60.2) in testing the effectiveness of SCM in mitigate alkali-silica reaction of field concrete has been studied and reported (12).

Eight reactive aggregates were tested by 3 commercial laboratories with different dosage of fly ash or slag from various sources to measure AMBT and CPT expansion. The results are summarised in Table 2. The result clearly demonstrated the efficacy of SCM in mitigating ASR.

The results of such laboratory tests and their correlation with long-term performance, up to 20 years, of large concrete blocks and structural elements at CANMET's and Ontario Hydro's outdoor exposure sites in Ottawa and Kingston in Canada, and the 18-year exposure site data from the BRE site in the UK were examined. It was found that Standard AMBT and CPT have proven to consistently correlate well with the long-term performance of field concrete with SCM up to an exposure period of 20 years for cement with low-alkali cement and alkali content of up to 0.90% Na_2Oe. This is particular the case when the Australian CPT expansion limit of 0.03% at 2 years is used instead of the 0.04% expansion limit used in the ASTM and Canadian standards (12). A 2024 visit by the first author to CANMET exposure site enabled the visual confirmation of effective mitigation up to 32 years of outdoor exposure.

3.3 Mitigation of ASR of LCC with SCM

The use of fly ash, slag and a combination of fly ash and slag have been shown to enable effectively reduction the EC in concrete. Concrete mixes with 25% fly ash or 50% slag have been found to effectively mitigate ASR (Table 2). SCM has also been found to mitigate ASR in binder systems with higher alkali contents (4).

3.4 Prevention of DEF

Minimisation of the risk of DEF in precast concrete is achieved by specifying the temperature limits within the concrete during curing and by applying compositional limits in sulfate and alkali content (Na_2O_e) which, in Australia, are typically 70 to 80°C, 0.6% Na_2O_e and 3.0-3.5% SO_4^{2-}, but vary by jurisdiction. A unified approach to specification across the jurisdictions of Australia requires investigation of the role of these factors in the risk of DEF. These have been investigated and reported for expansion tests by UTS which demonstrated that, if the sulfate and alkali content is maintained below 3% SO_3 and 1% Na_2O_e, elevated temperatures up to 90°C could be applied to the curing without risk of deleterious expansion. SCM such as fly ash has been found to effectively mitigating the potential DEF in concrete (14).

4. CONCLUSIONS

The sustainable benefits of low carbon concrete with supplementary cementitious materials are in both the reduction of embodied carbon and mitigation of potential deleterious alkali-silica reaction and delayed ettringite formation. The benefits of SCM to mitigate ASR greatly support the sustainability of existing hard rock quarries and reduces the need to open new quarries. The use of LCC with SCM is therefore an important technology supporting the drive toward Net Zero.

Table 2 Summary of AMBT and CPT expansion results (13)

Aggregate	Type	%	AMBT Expansion (%)			Classification		CPT Expansion (%)		Classification	
			10 d	14d	21 d	ASTM C1567	AS1141 60.1	1 Y	2 Y	CSA A23.2-28A	AS1141 60.2
Dacite	Eraring Flyash	0.0	0.35	0.47	0.64	R	R	0.233	-	R	R
		10.0	0.11	0.18	0.29	R	R	0.080	0.148	R	R
		15.0	0.03	0.06	0.11	N	SR	0.008	0.022	N	N
		25.0	0.01	0.01	0.02	N	N	-0.002	0.001	N	N
Rhyolite	Eraring Flyash	0.0	0.24	0.35	0.47	R	R	0.142	-	R	R
		10.0	0.04	0.07	0.12	N	SR	0.001	0.005	N	N
		15.0	0.02	0.03	0.04	N	N	-0.005	-0.003	N	N
		25.0	0.01	0.01	0.02	N	N	-0.006	0.001	N	N
Meta Greywacks	Central Qld Flyash	0.0	0.23	0.34	0.49	R	R	0.158	-	R	R
		10.0	0.10	0.19	0.30	R	R	0.058	0.115	R	R
		15.0	0.04	0.08	0.15	N	SR	0.021	0.046	R	R
		25.0	0.01	0.02	0.04	N	N	0.005	0.011	N	N
Quartz	Central Qld Flyash	0.0	0.09	0.15	0.27	R	R	0.003	-	N	N
		10.0	0.03	0.06	0.13	N	SR	-0.003	0.007	N	N
		15.0	0.01	0.03	0.05	N	N	-0.004	-0.003	N	N
		25.0	0.00	0.01	0.01	N	N	-0.008	-0.007	N	N
Hornfels	ICL Slag	0	0.17	0.27	0.40	R	R	0.070	0.155	R	R
		30.0	0.10	0.17	0.27	R	R	-0.006	0.013	N	N
		40.0	0.04	0.07	0.13	N	SR	-0.023	-0.011	N	N
		50.0	0.02	0.03	0.04	N	N	-0.011	-0.003	N	N
Rhyodacite	Mt Piper Flyash	0.0	0.23	0.32	0.43	R	R	0.059	0.087	R	R
		15.0	0.06	0.09	0.15	N	SR	0.002	0.010	N	N
		22.5	0.02	0.03	0.04	N	N	-0.006	-0.003	N	N
		30.0	0.02	0.02	0.02	N	N	-0.006	-0.001	N	N
Meta Greywacke	Sunstate Flyash	0	0.23	0.30	0.39	R	R	0.053	0.122	R	R
		15.0	0.03	0.04	0.07	N	N	-0.017	-0.009	N	N
		20.0	0.02	0.03	0.03	N	N	-0.006	-0.001	N	N
		25.0	0.01	0.02	0.02	N	N	-0.007	-0.009	N	N
Basalt	Eraring Flyash	0	0.52	0.73	1.05	R	R	0.007	0.024	N	N
		15.0	0.05	0.08	0.21	R	SR	-0.009	-0.007	N	N
		22.5	0.02	0.02	0.05	N	N	-0.010	-0.005	N	N
		30.0	0.01	0.02	0.02	N	N	-0.014	-0.009	N	N

AS1141.60.1 & 60.2 Classification: N - non reactive, SR – slowly reactive, R – reactive.
ASTM C1567 & CSA A23.2-28A Classification: N – non reactive, R – reactive.

Figure 4 A 2014 visit to CANMET exposure site in Ottawa

5. ACKNOWLEDGEMENT

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