INFORMING VOLUNTARY NSW GOVERNMENT SPECIFICATIONS FOR LOW CARBON CONCRETE

2025-26 Q2 Progress and Proposed Specifications

Tran Vu, Indira Vasikova, Yuxuan Yang, Bala Atpunthanathan,
Jaya Kandasamy, Yancheng Li & Vute Sirivivatnanon

Contents

Executive Summary 1
1. Objective 3
1.1 Scope of this report 3
1.2 Proposed definitions 3
1.3 Relevant Australian Standards 4
2. Testing Methodology and Assumptions 5
2.0 Background 5
2.1 Low Carbon Concrete Mix Design 5
2.2 Method of calculating Global Warming Potential or Embodied Carbon 6
3. Selecting Target GWP of LCC 9
3.0 AS 1379 production compliance 9
3.1 AS 1379 normal class concrete 9
3.2 AS 1379 special class concrete meeting AS 3600 construction requirements 11
3.3 AS 1379 special class concrete meeting AS 5100.5 prescriptive and construction requirements 13
3.4 One day heat cured compressive strength of AS 1379 normal class concrete 15
4. Carbon targets in NSW Government Specifications 16
4.1 LCC Specifications for AS 1379 Normal Class Concrete meeting AS 3600 16
4.2 LCC Specifications for AS 1379 Special Class Concrete meeting AS 3600 16
4.3 LCC Specifications for AS 1379 Special Class Concrete for AS 5100.5 17
4.4 One day heat cured compressive strength of AS 1379 normal class concrete 17
5. Proposed changes to concrete cover requirements 18
5.1 AS 3600 18
5.1.1 Comparison of cover requirement in BS 8500.1 19
5.2 AS 5100.5 20
6. Limitations of research 21
7. References 21
APPENDIX A: AS3600 Durability Requirements 22
APPENDIX B: AS5100.5 Amendment 2:2024 Durability Requirements 23
Appendix C. Service life modelling in AS 3600 25

Executive Summary

This report provides recommended specifications for low-carbon concrete (LCC) produced from Australian Standard cement, supplementary cementitious materials (SCM), aggregates and chemical admixtures. These types of concrete were jointly developed by CSIRO and industry in the early 1990s for specific applications in highly aggressive environments. They have been successfully used for almost half a century in Australia. Such concretes can be produced with less cement to provide better or similar durability properties to concrete with higher cement content. They are thus further developed as low-carbon concrete to reduce carbon emission and find use for problem waste fly ash and increase the amount of recycled content in NSW Government procurement.

Target global warming potential (GWP) of three groups of low-carbon concrete (LCC) produced at a slump of 100±20 mm for cast-in-place applications have been developed. They are:

1. AS 1379 Normal Class concretes meeting AS 1379 minimum 7-day strength construction and AS 3600 durability requirements and 56-day drying shrinkage of 1000 microstrain.

Type of Binder	Global Warming Potentials kg CO_2/m^3				
	Normal Class				
	N20	N25	N32	N40	N50
GP	275	295	320	355	405
Fly Ash	200	215	235	260	290
Slag	175	190	220	250	300
Fly Ash + Slag	140	150	170	190	225

2. AS 1379 Special Class concretes meeting AS 3600 minimum strength & curing requirements at 3 or 7-day depending on concrete grade. They also meet AS 3600 durability requirements and 56-day drying shrinkage of 800 macrostrain.

Type of Binder	Global Warming Potentials kg CO_2/m^3				
	Special Class meeting AS 3600 construction requirements				
	S20	S25	S32, SB32	S40, SB40	S50, SB50, SC50
GP	275	295	320	355	405
Fly Ash	210	215	235	260	290
Slag	245	245	220	250	300
Fly Ash + Slag	185	185	170	190	225

3. AS 1379 Special Class concretes meeting AS 5100.5 minimum strength & curing requirements at 3, 7 or 14-day depending on concrete grade. They also meet AS 5100.5 prescriptive and durability requirements and 56-day drying shrinkage of 800 microstrain.

Type of Binder	Global Warming Potentials kg CO_2/m^3			
	Special Class meeting AS 5100.5 construction requirements			
	S25	S32, SB32	S40, SB40	S50, SB50, SC50
GP	295	320	355	405
Fly Ash	225	235	260	290
Slag	260	235	260	300
Fly Ash + Slag	230	205	220	250

It should be noted that the main difference between normal and special class concrete is in the drying shrinkage which is highly dependent on the the type of aggregates and cement used. For infrastructure

works, AS 5100.5 required early strength at 3-day for grade S25 compared to early strength at 7-day for grade S32 & SB32. This resulted in an actual higher concrete grade for S25 and the corresponding higher GWP for mix with 50% slag and the 30% fly ash 30% slag triple blend.

The choice of LCC for prestressed and post-tensioned concrete may differ from LCC used in reinforced concrete due to different construction requirements. Design engineers and builders are in the best position to make the appropriate choice for their LCC. Concrete for post-tensioned slab will develop early strength differently depending on seasonal temperature variation. Local experience should dictate the choice of LCC for such application.

For precast concrete, there are different curing and early strength requirements for each precast concrete manufacturer. This report provides estimated one day heat cured strengths for various normal class concrete as a guidance for the choice of LCC used.

It is also necessary to point out that concrete for industrial and superflat floor slab demand specialized concreters who are highly experienced in using concrete with high SCM content. The use of LCC may be limited by the availability of such concreting crews.

This report reflects the feedbacks received from the well organised engagements with stakeholders from both the demand and supply side in October 2025.

1. Objective

The project aims to develop low-carbon concrete (LCC) suitable for NSW government specifications. The specific objectives are:

1. To develop a range of low-carbon concrete (LCC) which meets relevant Australian Standards AS 1379, AS 3600 and AS 5100.5 in both constructability and quality requirements.
2. To quantify the embodied carbon (EC) or global warming potentials (GWP) of the LCCs and propose how to specify target GWP of LCCs in NSW Government specifications.
3. To recommend any revision to existing durability requirements to ensure the successful use of LCC in various structures to meet the design life.

The report also address feedbacks in the 'Summary of Industry Feedback' received from industry consultation workshops, facilitated by Arup for NSW Department of Climate Change, Energy, the Environment and Water (NSW DCCEEW), NSW Environment Protection Agency (NSW EPA) and SmartCrete CRC.

1.1 Scope of this report

This report outlines the principle and methodology used in the development of LCC for cast-in-place onsite construction. These LCCs are suitable for both reinforced and prestressed concrete structures. Early-age strengths follow the constructability requirements in relevant standards. Consideration must be given to specific strength requirements for prestressing process. Target GWP of LCC meeting the relevant Australian Standards will be recommended.

The early strength and curing method for precast concrete can vary significantly between precast concrete manufacturer. Hence only the estimated one-day accelerated cured compressive strength of AS 1379 normal class concrete will be provided. Other specialised concrete such as concrete for post-tensioned slab with seasonal-dependent early strength requirements or concrete for industrial floor slab demanding specialized concreters are beyond the scope.

The method used to calculate the embodied carbon (EC) is based on NSW Embodied Carbon Databook.

1.2 Proposed definitions

The following definitions are adopted in this report.

Low-carbon concrete (LCC): concrete mix design that meets the performance requirements at the lowest possible embodied carbon. The primary performance requirements are (i) workability and constructability, (ii) mechanical and volume stability, and (iii) durability with respect to the design life.

Supplementary Cementitious Material (SCM): SCMs are fly ash (FA), ground granulated blast furnace slag (slag, SL) and amorphous silica (silica fume, SF) complying to AS 3582 part 1, 2 and 3 respectively.

Embodied Carbon (EC): CO_2 emitted from raw material extraction, either from fossil fuel inputs (directly related to embodied energy) or that released (e.g. converting limestone to cement) [1]. In this report, the upfront emission of LCC is calculated by the sum of production stage emission factors (A1-A3) of all concreting materials.

Embodied Energy (EE): the quantity of energy required to process, and supply to the construction site, the material under consideration [1].

Global Warming Potentials (GWP): A measure of how much heat a gas traps in the atmosphere relative to carbon dioxide over 100 years, where carbon dioxide = 1.0. The Global Warming Potentials GWP (kg CO_2/m^3) of concrete is calculated according to the methodology outlined in "Technical Guidance's Embodied Carbon Databook (v11)" by NSW Government Embodied Carbon Measurement for Infrastructure.

Target embodied carbon or Target GWP (TEC): is the embodied carbon of concrete that can be readily produced with GP cement and one or more type of SCM, depending on the availability of supply chain and batch plant capability.

Supplier embodied carbon or GWP (SEC): is the embodied carbon of concrete supplied by major concrete suppliers based on their environmental product declaration (EPD).

1.3 Relevant Australian Standards

AS 1379 - Specification and supply of concrete

AS 1478 – Chemical admixtures for concrete, mortar and grout

AS 2758 – Aggregates and rock for engineering purposes

AS 3972 - General purpose and blended cements

AS 3582.1 and AS 3582.2 - Supplementary cementitious materials

AS 3600 - Concrete structures

AS 5100.5 – Bridge design – Part 5. Concrete

2. Testing Methodology and Assumptions

Low-Carbon Concrete (LCC) is defined as a user-friendly concrete with good

1. Workability and constructability,
2. Mechanical and volume stability properties, and
3. Durability properties to provide the required design life to the structure

at the lowest embodied carbon (EC)

2.0 Background

High performance concretes (HPC) incorporating high SCM content were developed by CSIRO and the Australian concrete industry since the early 1990s for specific applications in highly aggressive environments. High slag blended cement concretes were first used in the construction of Sydney Harbour Tunnel (NSW) and the Wandoo oil platform (WA) in environments which are susceptible for chloride-induced corrosion of steel reinforcement. High volume fly ash concrete was developed and first used for the substructure of Crown casino (Victoria) exposed to aggressive acidic and sulfate soil conditions whereas silica fume concrete was used in precast concrete seawall of Sydney airport parallel runway in Port Botany [2]. These types of concrete have been successfully used for almost half a century in Australia.

The demand for LCCs to support our Net Zero target has broaden the applicability of concrete with high SCM to reduce GP cement content and thus the EC of concrete while maintaining or enhancing the performance of concrete. While the resistance to chloride-induced corrosion and acidic sulfate attack are well established, the lower resistance to carbonation-induced corrosion is recognised but quantitative performance data are limited. Therefore there is a strong need for comprehensive research in carbonation resistance of concrete with high SCM content.

2.1 Low Carbon Concrete Mix Design

LCC mix designs were developed based on an experimental program (Figure 1) covering 10 binder systems, with water/binder ratios ranging from 0.34 to 0.66. All concrete mixes were designed based on the Unit Water method incorporating two chemical admixtures.

A target slump of 100±20 mm was achieved with the use of a water reducer and a retarder. The retarder was used to ensure good slump retention. No acceleration was used in this program.

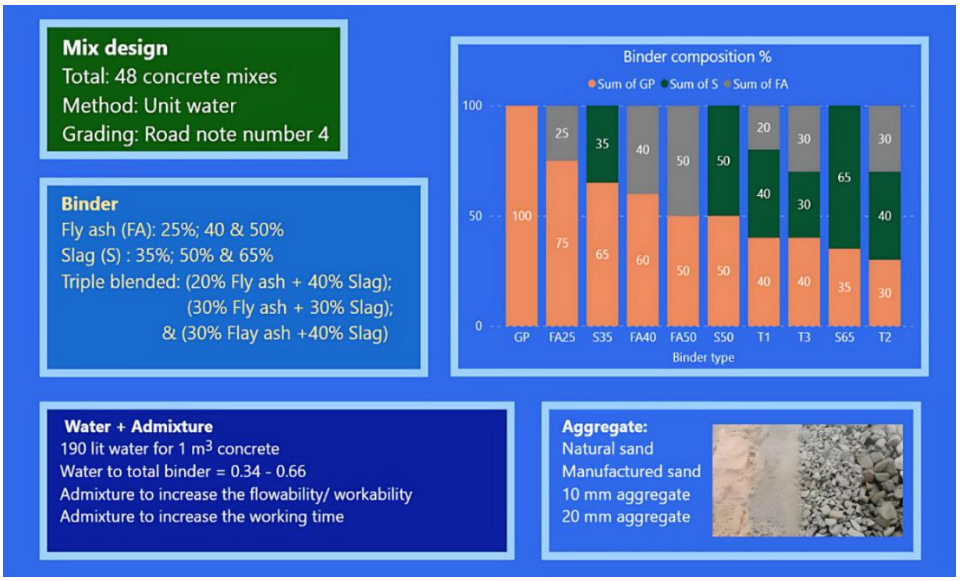


Figure 1. Experimental program

Aggregates were combined for total grading within various grading envelops in Road Note No. 4 [3] depending on the richness of the mix. Road Note No.4 gradings are similar to the Australian Readymix Concrete aggregate gradings. Good total combined aggregate gradings were used to deliver concrete with good workability including pumpability. Potential excessive bleeding is avoided by careful balancing of binder particles distribution and aggregate grading.

To comply with the prescriptive requirements of AS 5100.5, a third triple blend mix of 30%Fly Ash + 30% Slag was added to the initial experimental program. A range of concrete properties were determined including:

- compressive strength development,
- 1-day accelerate heat cured compressive strength,
- carbonation in 3 exposure conditions,
- resistance to chloride penetration,
- surface resistivity and AVPV,
- rapid sulphate penetration test, and
- drying shrinkage

Such comprehensive mix design and concrete properties data enable specific concrete mixes meeting AS 1379, AS 3600 and AS 5100.5 to be generated.

2.2 Method of calculating Global Warming Potential or Embodied Carbon

The upfront emission of LCC is calculated by the sum of production stage emission factors (A1-A3) of all concreting materials based on *Embodied Carbon Measurement for Infrastructure – Technical Guidance's Embodied Carbon Databook (v11) in NSW Government Embodied Carbon Databook.*

The embodied carbon (EC) or global warming potential, expressed in $kgCO_2/m^3$, is a measure of carbon dioxide (CO_2) emissions linked with the **cradle-to-gate stage** in according to BS EN 15804. This life cycle assessment includes the stages of raw material procurement **A1**, transportation **A2**, and manufacturing **A3**, as illustrated in Table 2.1. The embodied carbon of every concrete mix is calculated as per the updated formula (1) by Transport for NSW.

$$\textbf{Embodied Carbon (EC)= EC_A1 + EC_A2 + EC_A3} \qquad \textbf{(1)}$$

Where: EC_A1- Embodied carbon of the stage of raw material procurement A1;
EC_A2- Embodied carbon of the stage of transportation A2; and
EC_A3- Embodied carbon of the stage of manufacturing A3.

Embodied carbon of the stage of raw material procurement A1 is calculated according to Eq.2:

$$\textbf{EC_A1= Emission factor (Table 2.2, kg } CO_2\textbf{/kg) × Quantity of material used (kg/m}^3\textbf{)} \qquad \textbf{(2)}$$

Embodied carbon of the stage of transportation A2 is calculated according to Eq.3:

$$\textbf{EC_A2= Emission transport factor (Table 2.3, kg } CO_2\textbf{/km) × assumed distance to concrete plant (Table 2.3, km/kg) × the quantity of material used per cubic meter (kg/m}^3\textbf{) of concrete} \qquad \textbf{(3)}$$

Embodied carbon of the stage of manufacturing A3, abbreviated as **EC_A3**, is **6.9 kg CO_2** for 1 m^3 of concrete produced.

Table 2.1 Building Life Cycle Stages

Building Life Cycle Stages														
Product stage			Construction Process stage		Use stage							End-of-life stage			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
Raw material supply	Transport	Manufacturing	Transport	Construction/Installation	Use	Maintain	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/Demolitio	Transport	Waste processing	Disposal

Table 2.2 The emission factor from the Australian National Life Cycle Inventory Database (AusLCI).

Material	**Emission factor** (kg CO_2/kg)
Water	0.00045
GP Cement	0.91796
GGBF slag (SL)	0.19230
Fly ash (FA)	0.00
20 mm	0.01045
10 mm	0.01045
Man sand	0.00507
Natural sand	0.00419
Chemical Aadmixture	0.00167

Table 2.3 The transport emission factor from the Australian National Life Cycle Inventory Database (AusLCI) and assumed distance to the concrete plant.

Material Type	Assumed 28 t truck transport distance (km/kg)	Emission factor (kg CO_2/km)	Assumed sea freight transport distance (km/kg)	Emission factor (kg CO_2/km)
Water	0	0	0	0
GP	310	0.000102576	700	0.00001321
Slag	310	0.000102576	700	0.00001321
Fly ash	310	0.000102576	700	0.00001321
20 mm	40	0.000102576	0	0
10 mm	40	0.000102576	0	0
Man sand	40	0.000102576	0	0
Natural sand	40	0.000102576	0	0
Admixture	1000	0.000102576	8600	0.00001321

3. Selecting Target GWP of LCC

3.0 AS 1379 production compliance

AS 1379 is the Australian Standard for specification and supply of concrete. For each class of concrete, the production assessment demands concrete suppliers to produce concrete of various strengths and workability. In this report, compressive strength grades were designed to meet the target 28-day compressive strength with a margin of 6 MPa. This margin provides the characteristic strength with 95% of production compliance (statistical factor k=1.64) at an assumed standard deviation of 3.65 MPa, achievable by most reputable concrete producers. There are additional constructability requirements, such as curing, early-age strength or strength requirements for stripping of formwork for concrete meeting either AS 3600 or AS 5100.5.

3.1 AS 1379 normal class concrete

AS 1379 normal class concrete are specified for 28-day compressive strength grade as well as minimum 7-day compressive strength requirements. A full range of normal class low-carbon concretes were designed from different binders and their embodied carbon or GWP determined.

The GWP of various grades of concrete depends on the binder system are shown in Table 3.1.1. They compared favourably with MECLA's range of GWP compiled from EPD of various concrete suppliers [4].

Table 3.1.1 Target GWP of AS1379 normal class concrete of various binders

AS1379 Class		Normal Class				
Concrete Grade, MPa		20	25	32	40	50
Target Mean 28-day strength, MPa		26	31	38	46	56
Minimum mean 7-day strength, MPa		9	12	16	20	25
Target GWP of LCC	GP	275	295	320	355	405
	25%FA	225	240	265	290	330
	35%SL	200	215	240	275	325
	40%FA	200	215	235	260	290
	50%FA	185	195	215	235	260
	50%SL	175	190	220	250	300
	65%SL	160	175	205	245	305
	(20%FA 40%SL)[1]	150	165	185	215	255
	(30%FA 40%SL)[1]	140	150	170	190	225
	30%FA 30%SL	170	180	200	220	120
MECLA NSW EDP 15/9/25	Minimum	129	143	102	178	108
	25% percentile[2]	178	189	212	259	287
	50% percentile	198	222	250	297	337
	75% percentile	211	232	275	327	404
	Maximum	315	347	426	531	520

Note: [1] Non compliance to AS 5100.5 prescriptive requirements.
[2] MELCA's 25% percentile for NSW EPD in in the lower boundary of band D (Global ratings for low carbon and near zero concrete.

Increasing percentage of fly ash (FA) or slag (SL) or triple blends (FA+SL) resulted in increasing reduction of GWP as shown in Table 3.1.1. The benefit of each SCM or combined SCMS are clearly seen when their GWPs are shown as percentages of the GWP of GP cement concrete in Figures 3.1 and 3.2. A 25 to 40%FA resulted in around 20 to 30% reduction in GWP of GP cement concrete.

Similarly, a 35 to 50%SL resulted in around 20% to 35% reduction in GWP of GP cement concrete. The greatest reduction of around 50% GWP was derived from the 30%FA+40%SL triple blend mix.

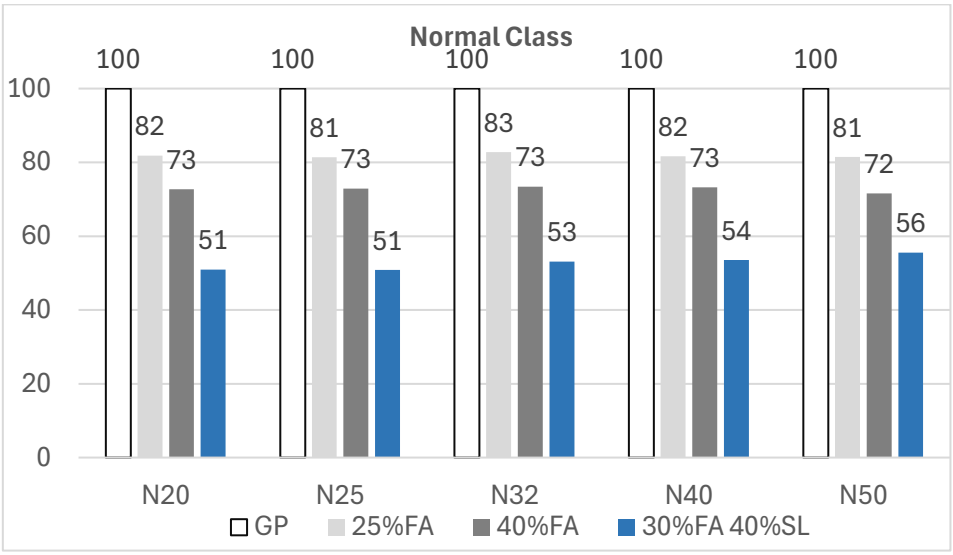


Figure 3.1 GWP of various LCC with different %SCM as percentage of GWP of GP cement concrete

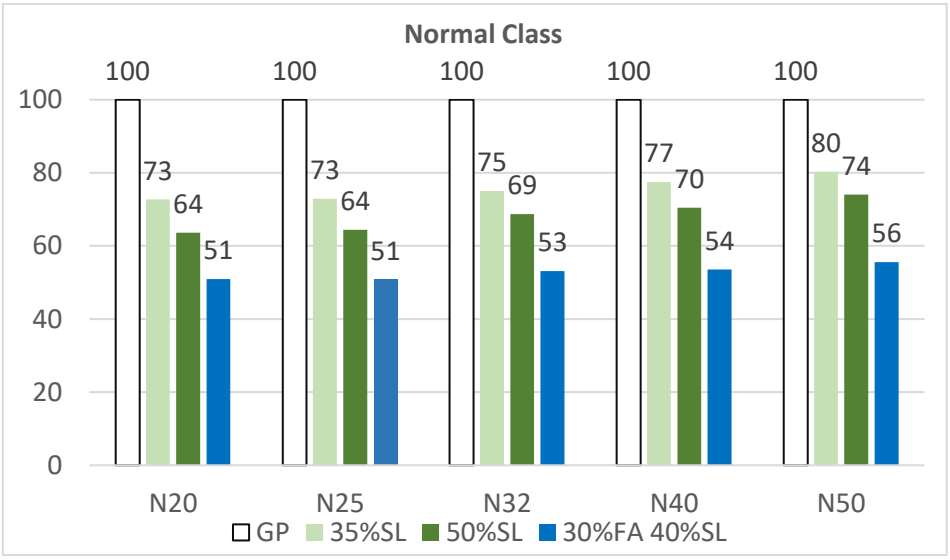


Figure 3.2 GWP of various LCC with different %SCM as percentage of GWP of GP cement concrete

The recommended target GWP shown in Table 3.1.2 are selected from either 40%FA, 50%SL or 30%FA/40%SL concrete depending on the availability of SCM. These are 100±20 mm slump LCCs which can be produced by most concrete suppliers and placed by most concreting crews. LCC with lower GWP can be achieved provided construction crews are highly experienced in working with concrete with very high SCM content.

Table 3.1.2 Target GWP of AS 1379 Normal Class LCC

Type of Binder	Global Warming Potentials kg CO_2/m^3				
	Normal Class				
	N20	N25	N32	N40	N50
GP	275	295	320	355	405
Fly Ash	200	215	235	260	290
Slag	175	190	220	250	300
Fly Ash + Slag	140	150	170	190	225

3.2 AS 1379 special class concrete meeting AS 3600 construction requirements

Concrete mixes were developed for various grades of AS 1379 special class concrete. These special class LCCs are designed in building works to meet AS 3600 50-year design life. They must also meet minimum initial curing and minimum average strength requirement at the time of stripping of forms or removal from moulds. (See Appendix A). These are LCCs with a 100±20 mm slump and low drying shrinkage of 800 microstrain.

The GWP of various grades of special class LCC are shown in Table 3.2.1. It is noted that the GWP are relatively higher than MECLA's range of GWP [4]. This was due to the additional AS 3600 construction requirements to meet the high early strength. The results are LCCs with much higher 28-day compressive strength than the target mean strength for the lower grade S20 and S25.

Table 3.2.1 Target GWP of AS1379 special class concrete meeting construction requirements in AS 3600

AS1379 Class		Special Class AS 3600 construction requirements				
Concrete Grade, MPa		20	25	32	40	50
Target minimum mean 28-day strength, MPa		26	31	38	46	56
Minimum 3-day or 7-day* strength, MPa		15	15	20*	25*	32*
Target GWP of LCC	GP	275	295	320	355	405
	25%FA	230	240	265	290	330
	35%SL	250	250	240	275	325
	40%FA	210	215	235	260	290
	50%FA	200	200	215	235	260
	50%SL	245	245	220	250	300
	65%SL	225	225	205	245	305
	(20%FA 40%SL)[1]	205	205	185	215	255
	(30%FA 40%SL)[1]	185	185	170	190	225
	30%FA 30%SL	210	210	200	220	250
MECLA	Maximum	313	350	374	467	516
	50% percentile	199	218	246	302	349
	Minimum	136	149	155	193	168

Note: [1]Non compliance to AS 5100.5 prescriptive requirements.

Increasing percentage of fly ash (FA) or slag (SL) or triple blends (FA+SL) resulted in increasing reduction of GWP as shown in Table 3.2.1. The benefit of each SCM or combined SCMS are clearly seen when their GWPs are shown as percentages of the GWP of GP cement concrete in Figures 3.2.1 and 3.2.2. A 25 to 40%FA resulted in around 20 to 30% reduction in GWP of GP cement concrete. Similarly, a 35 to 50%SL resulted in around 20% to 35% reduction in GWP of GP cement concrete. The greatest reduction of 45% GWP was derived from the 30%FA+40%SL triple blend mix.

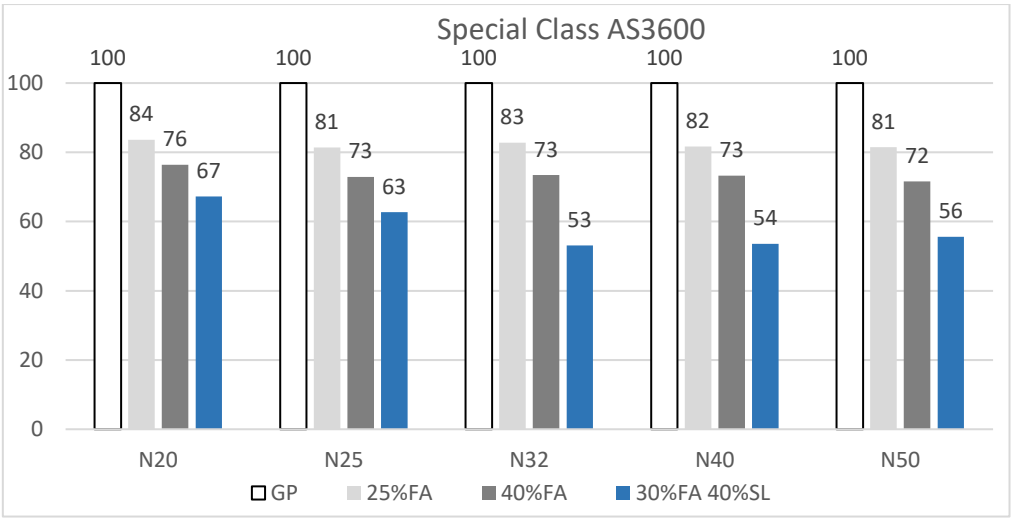


Figure 3.2.1 GWP of various LCC with different %SCM as percentage of GWP of GP cement concrete



Figure 3.2.2 GWP of various LCC with different %SCM as percentage of GWP of GP cement concrete

The recommended target GWP shown in Table 3.2.2 are selected from either 40%FA, 50%SL or 30%FA/40%SL concrete depending on the availability of SCM. They are 100±20 mm slump LCCs which can be produced by most concrete suppliers and placed by most concreting crews. LCC with lower GWP can be achieved provided construction crews are highly experienced in working with concrete with very high SCM content.

Table 3.2.2 Target GWP of AS 1379 Special Class LCC meeting AS 3600 construction requirements

Type of Binder	Global Warming Potentials kg CO_2/m^3				
	Special Class				
	S20	S25	S32	S40	S50
GP	275	295	320	355	405
Fly Ash	210	215	235	260	290
Slag	245	245	220	250	300
Fly Ash + Slag	185	185	170	190	225

3.3 AS 1379 special class concrete meeting AS 5100.5 prescriptive and construction requirements

Concrete mixes were also developed for various grades of AS 1379 special class concrete. These special class LCCs are designed for 100-year design life of infrastructure. They meet the AS 5100.5 prescriptive requirements in binary and ternary blends of cement materials, cement content and maximum water/cement ratio. There are also curing and minimum compressive strength requirements at completion of curing at various ages depending on the grade of concrete. (See Appendix B). These are LCCs with a 100±20 mm slump and low drying shrinkage of 800 microstrain.

The GWP of various grades of special class LCC are shown in Table 3.3.1. It is noted that the GWP are higher than MECLA's 50% percentile range of GWP [4]. This was due to the additional AS 5100.5 prescriptive and curing requirements to meet high early strength. The results are LCC with much higher 28-day compressive strength than the target mean strength of the concrete.

Table 3.3.1 Target GWP of AS1379 special class concrete meeting prescriptive and construction requirements in AS 5100.5

AS1379 Class		**Special Class, Min strength after 3 or 7 or 14 days curing**			
Concrete grade		**25**	**32**	**40**	**50**
Target minimum mean 28-day compressive strength, MPa		31	38	46	56
Minimum mean 3-day strength, MPa Minimum mean 7-day strength, MPa* Minimum mean 14-day strength, MPa**		17.5	22.4*	28*	35**
Target LCC	GP	295	320	355	405
	25%FA	250	265	290	330
	35%SL	270*	255	275	325
	40%FA	225	235	260	290
	50%FA	210	215	235	260
	50%SL	260*	235	260	300
	65%SL	250*	205	245	305
	20%FA 40%SL[1]	220*	205	220	255
	30%FA 40%SL[1]	200*	180	200	225
	30%FA 30%SL	230*	205	220	250
MECLA	Maximum	350	374	467	516
	50% percentile	218	246	302	349
	Minimum	149	155	193	168

Note: [1]Non compliance to AS 5100.5 prescriptive requirements.
GWP* of grade 25 concrete exceeding GWP of the higher grade 32 with the same binder.

The influence of increasing percentage of fly ash or slag on the GWP of concrete is evident in high grade LCCs from S32 to S50. 25%FA and 40%FA resulted in around 20% and 30% reduction in GWP respectively from the GWP of GP concrete. Increasing slag from 35% to 50% resulted in around 20% and 25% reduction in GWP respectively. The AS 5100.5-compliant 30%FA 30%SL triple blend resulted in around 35% reduction in GWP. These reductions can be clearly seen in Figures 3.3.1 and 3.3.2.

The recommended target GWP shown in Table 3.3.2 are selected from either 40%FA, 50%SL or 30%FA/30%SL concrete depending on the availability of SCM. They are 100±20 mm slump LCCs which can be produced by most concrete suppliers and placed by most concreting crews.

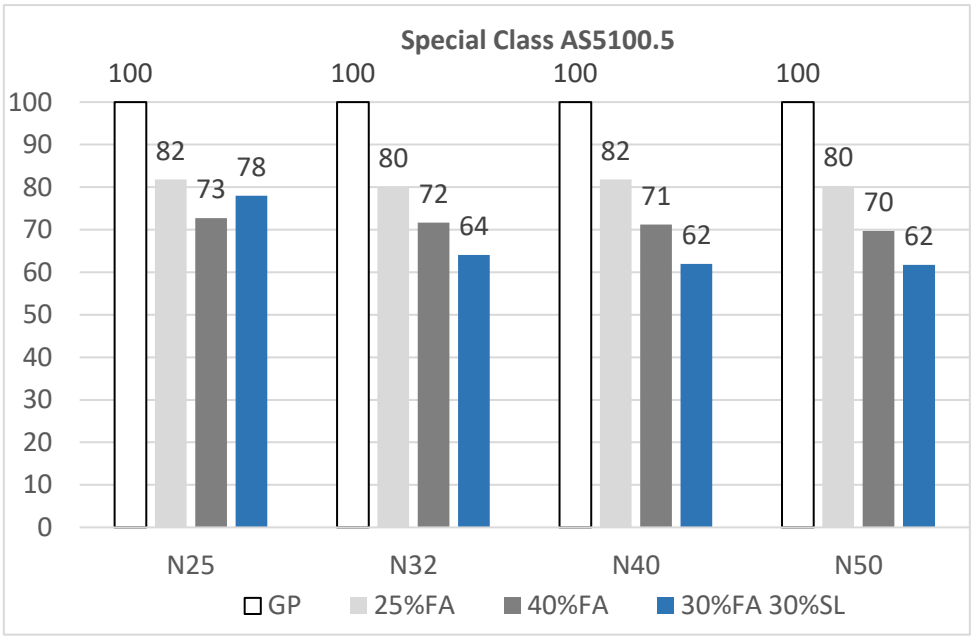


Figure 3.3.1 GWP of various LCC with different %SCM as percentage of GWP of GP cement concrete



Figure 3.3.1 GWP of various LCC with different %SCM as percentage of GWP of GP cement concrete

Table 3.3.2 Target GWP of AS 1379 Special Class LCC meeting AS 5100.5 construction requirements

Type of Binder	Global Warming Potentials kg CO_2/m^3			
	Special Class			
	S25	S32	S40	S50
GP	295	320	355	405
Fly Ash	225	235	260	290
Slag	260	235	260	300
Fly Ash + Slag	230	205	220	250

3.4 One day heat cured compressive strength of AS 1379 normal class concrete

Precast concrete are usually accelerately cured by heat or stream to attain early strength. There is no standard accelerated curing regime for building component. For infrastructure work, AS 5100.5 Table 4.4.1 (B) provides minimum concrete curing duration for accelerated curing as curing period ranging from 350 to 420 °C.hours. (See appendix B)

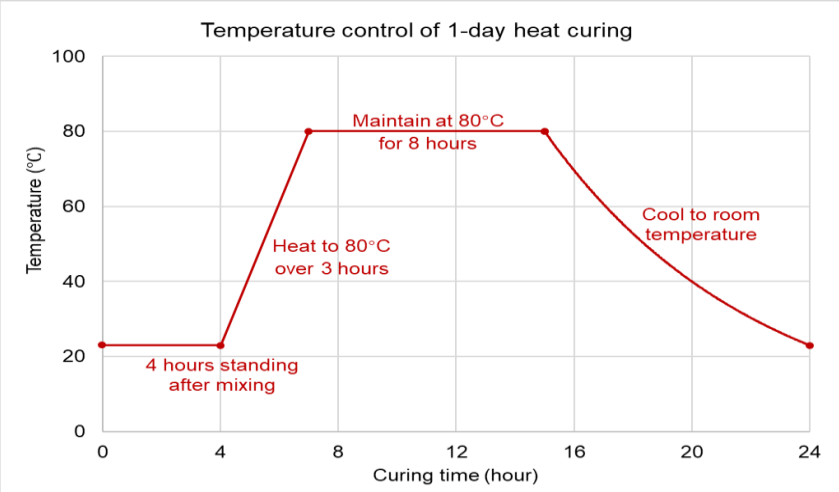


Figure 3.4.1 Temperature profile of 1-day heat curing

The estimated one-day accelerated cured normal class LCCs are provided in Table 3.4.1. This provides information for precast concrete manufacturers to examine the possible use of LCCs.

Table 3.4.1 One-day heat cured compressive strength of AS1379 normal class concrete – information for heat cured precast concrete

AS1379 Class		**Normal Class**									
Concrete Grade, MPa		**20**		**25**		**32**		**40**		**50**	
Target 28-day strength, MPa		26		31		38		46		56	
Minimum 7-day strength, MPa		9		12		16		20		25	
Target GWP and 1-day heat-cured strength of LCC	Type of Binder	GWP	Heat Cured (MPa)	GWP	Heat Cured (MPa)	GWP	Heat Cured (MPa)	GWP	Heat Cured (MPa)	GWP	Heat Cured (MPa)
	GP	275	17	295	22	320	28	355	35	405	44
	25%FA	225	14	240	19	265	24	290	32	330	40
	35%SL	200	8	215	13	240	18	275	26	325	36
	40%FA	200	19	215	21	235	27	260	32	290	40
	50%FA	185	15	195	19	215	24	235	30	260	38
	50%SL	175	10	190	12	220	18	250	25	300	36
	65%SL	160	11	175	14	205	20	245	27	305	36
	(20%FA 40%SL)[1]	150	7	165	12	185	18	215	26	255	34
	(30%FA 40%SL)[1]	140	12	150	15	170	20	190	25	225	33
	30%FA 30%SL	170	NA	180	NA	200	NA	220	NA	120	NA

NA = not available.

4. Carbon targets in NSW Government Specifications

NSW Government agencies are recommended to specify target GWP for various classes of concrete. Each class and grade of concrete can be used for various structural components in buildings or infrastructure. These concretes were designed to meet specific constructability, mechanical and volume stability, and durability properties to deliver the required design life aligned with other durability requirements in AS 3600 for building works or AS 5100.5 for infrastructure.

The capability of concrete suppliers to produce LCC depends on a number of factors such as number of cement or SCM silos, supply chains and relative cost of cement and SCM, and the experience of working with concrete with high SCM content. Most concrete producers are highly experienced in producing concrete with either 25% fly ash or 35% slag. It is therefore expected that most producers have the capability to supply LCC with at least one SCM.

The recommended LCCs are from either 40% fly ash or 50% slag or a triple blend of fly ash and slag. The lowest GWP are achieved from the triple blend mixes. The GWP of GP cement concrete is provided as a reference and for suppliers in remote regions of New South Wales.

4.1 LCC Specifications for AS 1379 Normal Class Concrete meeting AS 3600

AS 1379 Normal Class N20-N50 concrete with a slump of 100±20 mm meeting the following requirements:

1. Characteristic 28-day compressive strength for production compliance,
2. Required mean 7-day compressive strength, and drying shrinkage of 1000 microstrain,
3. 50 years design life when used with durability requirements in AS 3600.

The recommended target GWP is given in Table 4.1 . The table is designed for different type of SCM to cater to the specific supply chain and concrete batching plant capacities.

Table 4.1 Target GWP of AS 1379 Normal Class LCC (derived from Table 3.1.1)

Type of Binder	Global Warming Potentials kg CO_2/m^3				
	Normal Class				
	N20	N25	N32	N40	N50
GP	275	295	320	355	405
Fly Ash	200	215	235	260	290
Slag	175	190	220	250	300
Fly Ash + Slag	140	150	170	190	225

4.2 LCC Specifications for AS 1379 Special Class Concrete meeting AS 3600

The GWP of AS 1379 Special Class concrete with a slump of 100±20 mm, meeting the followings:

1. Characteristic 28-day compressive strength for production compliance,
2. Minimum strength and curing requirements at 3 or 7-day depending on concrete grades. (See table 4.4 in AS 3600 in Appendix A)
3. 56-day drying shrinkage of 800 microstrain, and
4. 50 years design life when used with durability requirements in AS 3600.

The prefix for special class concrete shall be S for exposure A1, A2 and B1, SB for exposure B1, SC for exposure C1 or C2, and SU for exposure U. See clause 1.5.4 in AS1379.
The target GWP for various grades and binders is given in Table 4.2. The table is designed for different type of SCM to cater for the supply chain and concrete batching plant capacity.

Table 4.2 Target GWP of AS 1379 Special Class LCC meeting AS 3600 construction requirements (derived from Table 3.2.1)

Type of Binder	Global Warming Potentials kg CO_2/m^3				
	Special Class meeting AS 3600 construction requirements				
	S20	S25	S32, SB32	S40, SB40	S50, SB50, SC50
GP	275	295	320	355	405
Fly Ash	210	215	235	260	290
Slag	245	245	220	250	300
Fly Ash + Slag	185	185	170	190	225

4.3 LCC Specifications for AS 1379 Special Class Concrete for AS 5100.5

For infrastructure work with 100 years design life, the target GWP of AS 1379 Special Class concrete with a slump of 100±20 mm meeting the characteristic 28-day compressive strength production compliance and the 56-day drying shrinkage of 800 microstrains. The concrete meets the durability requirements in AS 5100.5 as well as the minimum strength and curing requirements at 3, 7 and 14-day depending on concrete grades. See table 4.4.1 (B) of AS 5100.5 in Appendix B.

The prefix for special class concrete shall be S for exposure A1, A2 and B1, SB for exposure B1, SC for exposure C1 or C2, and SU for exposure U. See clause 1.5.4 in AS1379.
The target GWP for various grades and binders is given in Table 4.3. The table is designed for different type of SCM to cater for the supply chain and concrete batching plant capacity.

Table 4.3 Target GWP of AS 1379 Special Class LCC meeting AS 5100.5 construction requirements (derived from Table 3.3.1)

Type of Binder	Global Warming Potentials kg CO_2/m^3			
	Special Class meeting AS 5100.5 construction requirements			
	S25	S32, SB32	S40, SB40	S50, SB50, SC50
GP	295	320	355	405
Fly Ash	225	235	260	290
Slag	260	235	260	300
Fly Ash + Slag	230	205	220	250

4.4 One day heat cured compressive strength of AS 1379 normal class concrete

No recommended GWP can be provided for prestressed, post-tensioned nor precast concrete as they require specific early-age strength requirements.

In section 3.4, Table 3.4.1 provided the one-day heat cured (specific heat-cured temperature profile) compressive strength of AS1379 normal class concrete. This is an attempt to provide limited information for precast concrete manufacturers.

5. Proposed changes to concrete cover requirements

In Australia, concrete with high SCM content has been developed since the late 1980s for specific aggressive exposure conditions. These concretes have high resistance to chloride-induced corrosion [5] sulfate and acid-sulfate attack [6]. It was well understood that such concretes also had a higher carbonation rate [7] but were not developed for general applications. Significant research is required as the industry is moving to use LCC with high SCM content more broadly, as existing standards must be re-examined and, if necessary, revised. Both AS 3600 and AS 5100.5 are the focus as they are both deem-to-satisfied specifications. AS 3600 does not define cement nor SCM but concrete in AS 1379. Concrete cover requirements are therefore taken as applicable to concrete manufactured from cement with or without SCMs.

UTS has examined the impact of high SCM on the carbonation of a range of LCCs. Concrete specimens are exposed to 3 environmental conditions and their carbonation examined [8]. Using the service life model consists of initiation and propagation period making up the service life, the carbonation depth of various LCCs for an initiation period of 35 and 85 years are shown corresponding to their 28-day compressive strength in Figures 5.1 and 5.2 respectively. A propagation period of 15 years is expected to result in a crack width of 0.2-0.3 mm for a corrosion rate of 10 µm per year [9].

5.1 AS 3600

The most aggressive exposure class for carbonation-induced corrosion is class A2 outdoor exposure. The carbonation rate in A2 is lower than for indoor exposure A1, however the availability of moisture may result in corrosion of steel reinforcement if carbonation has reached and de-passivated the reinforcing steel. In Figure 5.1, it can be observed that some lower grade LCCs have been predicted to carbonate beyond the AS 3600 cover depths, thus making steel reinforcement more vulnerable to corrosion.

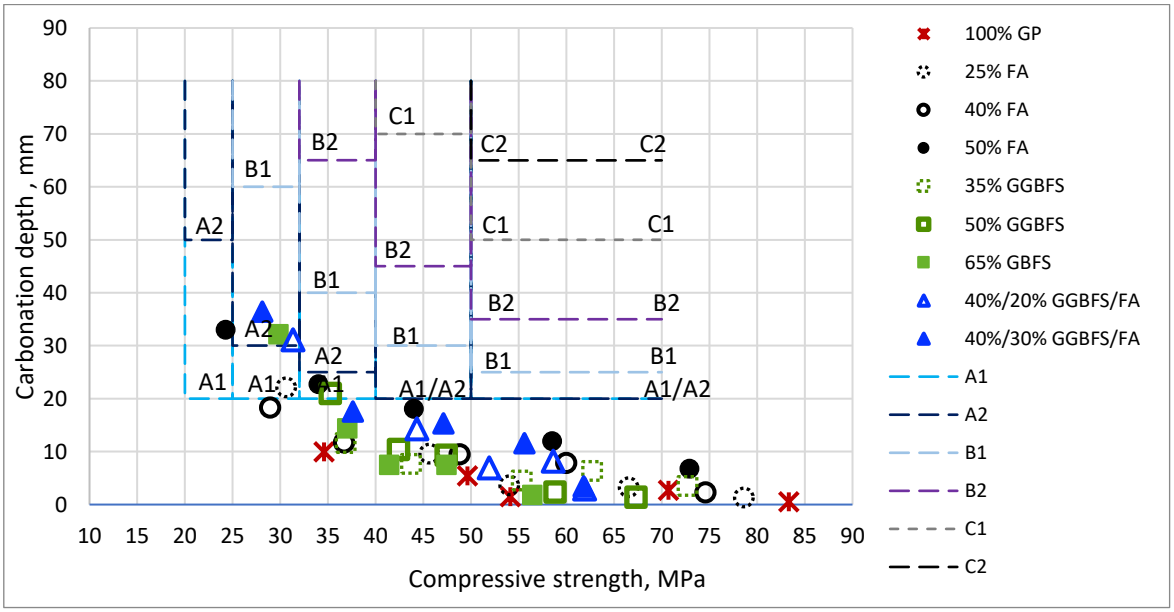


Figure 5.1 Prediction of carbonation depth in 35 years for LCC in outdoor environment

Recommendations have been made to Standard Australia BD-002 committee to increase the cover requirements for exposure A2 in AS 3600 Tables 4.10.3.2 and 4.10.3.3 as shown in red in Table 5.1. No concrete cover changes are required for indoor exposure A1 as no corrosion is expected without

source of moisture. Where there is potential source of moisture for indoor exposure condition, classification A2 should be specified.

Table 5.1 Recommended changes of concrete cover for exposure A2 in AS 3600
Tables 4.10.3.2 and 4.10.3.3

Exposure class	Required cover, mm				
	Characteristic strength, (f'_c)				
	20 MPa	25 MPa	32 MPa	40 MPa	≥ 50 MPa
A1	20	20	20	20	20
A2	**(~~50~~) (40)**	**~~30~~ 35**	**~~25~~ 30**	**~~20~~ 25**	**20**
B1		(60)	40	30	25
B2			(65)	45	35
C1				(70)	50
C2					65

Recommened cover for exposure XC3/4 in BS 8500-1 2023

Exposure	20 MPa	25 MPa	32 MPa	40 MPa	≥ 50 MPa
XC3/4		≥ 65 + Δc	45 + Δc	30 + Δc	20 + Δc

Note: Δc is an allowance in design for deviation e.g. to allow for workmanship.

5.1.1 Comparison of cover requirement in BS 8500.1

It should be noted that British Standard BS 8500-1 published in 2023, categorises various blended cements with equivalent performance (combined performance category - CPC) for concretes which are highly resistant to sulfate attack and chloride ingress. The standard highlights the well established durability to chloride and sulfate of blended cement concrete. However, CPC does not apply to carbonation.

BS EN206 defines exposure XC3/4 for concrete with an intended working life of at least 50 years for corrosion induced by carbonation (shown in Table 5.2). Exposure XC3/4 is similar to exposure A2 in AS 3600. It is interesting to note the recommended concrete covers in this recently revised BS8500 significantly exceed the recommended changes for exposure A2 in AS 3600. These cover requirements are tabulated below Table 5.1 for comparison.

Draft AS 3600- 2026 will be released for public comment in early 2026.

Table 5.2 BS EN206 Corrosion induced by carbonation (XC Classes)

XC1	**Dry or permanently wet**	**Reinforced and prestressed concrete surfaces inside enclosed structures except voided superstructures and areas of structures with high humidity** **Reinforced and prestressed concrete surfaces permanently submerged in non-aggressive water**
XC2	Wet, rarely dry	Reinforced and prestressed concrete surfaces permanently in contact with soil not containing chlorides
XC3 and XC4 (XC3/4)	Moderate humidity or cyclic wet and dry	External reinforced and prestressed concrete surfaces sheltered from or exposed to direct rain Reinforced and prestressed concrete surfaces subject to high humidity (e.g. poorly ventilated bathrooms, kitchens) Reinforced and prestressed concrete surfaces exposed to alternate wetting and drying Interior concrete surfaces of pedestrian subways are not subject to de-icing salts, voided superstructures, or cellular abutments Reinforced or prestressed concrete surfaces protected by waterproofing

5.2 AS 5100.5

Similar carbonation study is undertaken for exposure A in AS 5100.5. The predicted 85-year carbonation depths of various LCCs for outdoor exposure are shown in Figure 5.2. It can be observed that the lower grade LCC may carbonate beyond the AS 5100.5 specified covers for exposure A.

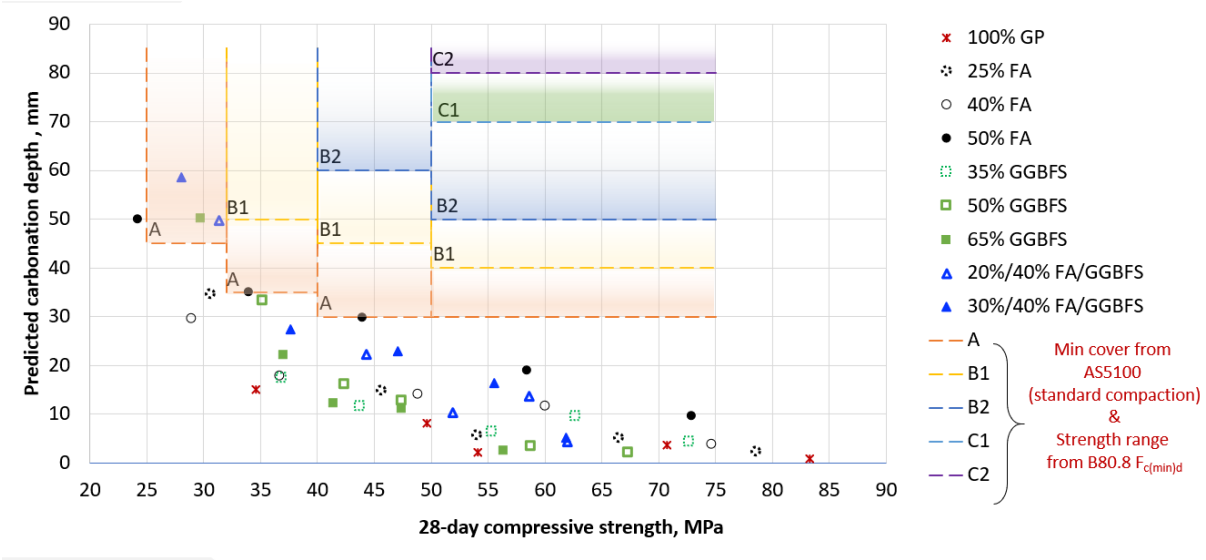


Figure 5.2 Prediction of carbonation depth in 85 years for LCC in outdoor environment

Further study is required on the sorptivity of carbonated LCC to evaluate their vulnerability to reinforcing steel corrosion. It may be necessary for recommendations to be made to Australian Standards BD-90 for cover adjustments similar to Table 5.3.

Table 5.3 Recommended changes of concrete cover for exposure A in AS 5100.5 Tables 4.14.3.2 and 4.14.3.3

Exposure class	Required cover, mm			
	Characteristic strength, (f'c)			
	25 MPa	32 MPa	40 MPa	≥50 MPa
A	~~45~~ 55	~~35~~ 40	~~30~~ 35	30
B1		50	45	40
B2			60	50
C1				70
C2				80

6. Limitations of research

The GWP of low carbon concrete has been developed as a target GWP for specifications by NSW Government and local councils. These are concretes that can be produced by most concrete suppliers. Concrete with even lower GWP could be readily supplied by all reputable suppliers.

In this research, LCC mixes were produced from a single batch of concreting materials. Within-batch variation is controlled by the production margin at a standard deviation that can be achieved by all reputable suppliers.

A limited number of LCC mixes have been produced from a second batch of concreting materials. They are being tested, and results will be compared with existing data to evaluate the batch-to-batch deviation. A follow-up recommend of an adjusted target GWP may then be proposed to account for variation in the properties of concreting materials.

7. References

1. Hammond & Jones, (2001) Inventory of Carbon & Energy (ICE) Version 2.0.
2. Sirivivatnanon, V., Tam, C.T. and Ho, D.W.S., 'Special Concrete and Application', Chapter 42, The Civil Engineering Handbook, Second Edition, edited by W.F. Chen and J.Y. Richard Liew, CRC Press LLC, September 2002.
3. Road Research, Design of concrete mixes, *D.S.I.R. Road Note No. 4* (London, H.M.S.O., 1954).
4. MECLA's Concrete and Cement Working Group, "A Guide to Low Carbon Concrete in Australia".
5. Sirivivatnanon, V., Xue, C. and Khatri, R., 'Service-Life Design of Low-Carbon Concrete Containing Fly Ash and Slag under Marine Tidal Conditions', ACI Materials Journal, November 2022.
6. Cement Concrete and Aggregates Australia, Technical Note TN68 Sulfate-Resisting Concrete, May 2011.
7. Sirivivatnanon, V., Cao, H.T., Khatri, R. and Bucea, L., 'Guidelines for the Use of High Volume Fly Ash Concretes, CSIRO Technical Report TR95/2, August 1995.
8. Vasikova, I., Kesarwani, A., Nairn, J., Thomas, P. and Sirivivatnanon, V., "Carbonation-induced corrosion service life design for low carbon concrete", Proceedings of Concrete 2025.
9. Andrade, C., Alonso, C. and Molina, F.J., 'Cover cracking as a function of bar corrosion: Part 1-Experimental test', Materials and Structures, 1993, 26, 453-464.

APPENDIX A: AS3600 Durability Requirements

Table 4.4 in AS 3600.

TABLE 4.4

MINIMUM STRENGTH AND CURING REQUIREMENTS FOR CONCRETE

Column 1	Column 2	Column 3	Column 4
Exposure classification	**Minimum f'_c (MPa)**	**Minimum initial curing requirement (see Clause 17.1.5.1)**	**Minimum average compressive strength at the time of stripping of forms or removal from moulds (MPa)**
A1	20	Cure continuously for at least 3 days	15
A2	25		
B1	32	Cure continuously for at least 7 days	20
B2	40		25
C1	50		32
C2	50		

Note: The minimum compressive strength at the time of stripping of prefabricated concrete from formwork in the factory and for delivery by transport or erection on site shall be determined by AS3850.

AS 3600 Table 4.10.3.2

TABLE 4.10.3.3

REQUIRED COVER WHERE REPETITIVE PROCEDURES AND INTENSE COMPACTION OR SELF-COMPACTING CONCRETE ARE USED IN RIGID FORMWORK

Exposure classification	Required cover, mm				
	Characteristic strength (f'_c)				
	20 MPa	25 MPa	32 MPa	40 MPa	≥ 50 MPa
A1	20	20	20	20	20
A2	(45)	30	20	20	20
B1	—	(45)	30	25	20
B2	—	—	(50)	35	25
C1	—	—	—	(60)	45
C2	—	—	—		60

NOTE: Bracketed figures are the covers when the concession given in Clause 4.3.2, relating to the strength grade permitted for a particular exposure classification, is applied.

APPENDIX B: AS5100.5 Amendment 2:2024 Durability Requirements

Prescriptive requirements in AS 5100.5 Amendment 2: 2024

Blends of cement materials shall include the following (percentages by weight of total cement material):

(A) Binary blends of—

(1) 60 % to 75 % GP cement, 25 % to 40 % fly ash; or

(2) 90 % to 96 % GP cement, 4 % to 10 % amorphous silica; or

(3) 30 % to 70 % GP cement, 30 % to 70 % ground granulated blast furnace slag; or

(B) Ternary blends of—

(1) 35 % to 55 % GP cement, 20 % to 35 % ground granulated blast furnace slag, and 25 % to 30 % fly ash; or

(2) 55 % to 71 % GP cement, 4 % to 10 % amorphous silica, and 25 % to 35 % fly ash; or

(3) 30 % to 46 % GP cement, 4 % to 10 % amorphous silica, and 50 % to 65 % ground granulated blast furnace slag.

Concrete using only GP cement may be used if approved by the relevant authority.

Alternative blends of cement materials outside the limits in (A) and (B) may be used if a project specific design and durability assessment is approved by the relevant authority.

TABLE 4.4.1(A)
MINIMUM STRENGTH AND CEMENT MATERIAL CONTENT, MAXIMUM WATER/CEMENT MATERIAL (W/C) RATIO

Column 1	Column 2	Column 3	Column 4
Exposure classification	Minimum specified f'_c MPa	Minimum cement material content kg/m³	Maximum water/cement material (W/C) ratio
A	25	280	—
B1	32	330	0.50
B2	40	400	0.45
C1	50	420	0.40
C2	50	420	0.36 [a]

TABLE 4.4.1(B)
CONCRETE CURING REQUIREMENTS

Specified f'_c [c] (MPa)	Minimum compressive strength at completion of curing (MPa) [a, b]	Minimum concrete curing duration [a]		
		Moist/wet curing or formwork retention days	Membrane curing days	Accelerated curing Curing period (°C.hours) [d]
25	17.5	3	3	Minimum necessary to achieve strength
32	22.4	7	7	350
40	28.0	7	7	350
≥ 50	35.0	14	14	420

[a] Clause 4.4.2.5 specifies requirements for when formwork is removed prior to the completion of the curing period, or when a partial accelerated curing process has been completed. If an accelerated curing process has been completed, no further curing is required.

[b] Minimum compressive strength at completion of curing is based on 0,7 × specified f'_c.

[c] For concrete characteristic strength (f'_c) greater than 50 MPa, curing requirements for durability are the same as those for 50 MPa concrete because there is no reduction in concrete cover. See Tables 4.14.3.2 and 4.14.3.3.

[d] Curing period for accelerated curing is the area under the time temperature curve where temperature is measured in the enclosure or under the covers. An alternative method is to measure the element surface temperature. See Clause 4.4.2.6.

TABLE 4.10
SUPPLEMENTARY CEMENTITIOUS MATERIAL LIMITS IN THE CONCRETE MIX TO MITIGATE ALKALI AGGREGATE REACTIVITY (AAR)

Supplementary cementitious material	Minimum percentage of supplementary cementitious material %
Fly ash	25
Slag	50
Amorphous silica	8

NOTE 1: The table is by percent of total combined weight of cement material (GP cement portion not shown).

NOTE 2: For additional requirements for blends of cement materials, see Clause 4.4.1 (improved durability) and Clause 4.11 (prevent effects of delayed ettringite formation).

4.11 DELAYED ETTRINGITE FORMATION (DEF)

To control the risk of DEF at later ages, the early-age maximum concrete temperature shall not exceed the following limits, unless analysis has been performed that justifies an alternative maximum temperature limit is sufficient to prevent the effects of DEF occurring:

(a) 70°C for concrete with cement type GP.

(b) 80°C for concrete with a minimum replacement of cement type GP with the following supplementary cementitious materials:

(i) 25 % fly ash; or

(ii) 40 % slag; or

(iii) 5 % amorphous silica in combination with 20 % fly ash or 5 % amorphous silica in combination with 30 % slag.

80°C for minimum 8 % to 10 % amorphous silica replacement not in combination with fly ash or slag may be considered only if—

(A) the other supplementary cementitious materials are not available; and

(B) suitable test results are available to prove the effects of DEF are not occurring.

TABLE 4.14.3.2
REQUIRED COVER WHERE STANDARD FORMWORK AND COMPACTION ARE USED

Exposure classification	Required cover, mm [a]			
	Characteristic strength (f'_c)			
	25 MPa	32 MPa	40 MPa	≥ 50 MPa
A	45	35	30	30
B1		50	45	40
B2			60	50
C1				70
C2				80

[a] In construction, the specified position of reinforcements and tendons shall not deviate from the required cover by more than the fixing tolerances specified in Clause 17.7.3.

NOTE: Cover requirements are based on effective, continuous and uninterrupted curing in accordance with Clause 4.4.2.1.

APPENDIX C: Service life modelling in AS 3600

In AS 3600, design life is described as a period for which a structure or a structural member is to remain fit for use for its designed purpose with maintenance. Service life modelling is based on a combined initiation and propagation period. For carbonation-induced corrosion, the initiation period covers time when carbonation has progressed to reach and depassivate the steel reinforcement. Corrosion may start with the availability of oxygen and moisture. One measure of a structure remain fit for use is by limiting the corrosion to cause concrete cover to crack within a reasonable crack width.

UTS has examined the impact of high SCM on the carbonation of a range of LCCs. Concrete specimens are exposed to 3 environmental conditions and their carbonation examined [8]. Using the service life model consists of initiation and propagation period making up the service life, the carbonation depth of various LCCs for an initiation period of 35 years plus 15 years propagation making up for a 50 years design life were examined against the specified concrete cover for outdoor exposure A2.

The propagation is reviewed in two ways. The first for a propagation period of 15 years is to allow a crack width of 0.2-0.3 mm for a corrosion rate of 10 µm per year. See Table 1 reproduced from [9] below. Such crack width has been found to be within acceptable limit. The second is to consider if concrete is succeptible to moisture ingress via water sorptivity. Outdoor vertical surface may be exposed to occasional wetting period. The sorptivity limits proposed by CSIRO [10] for moderate exposure A2 is reproduced in Table 3 below. The maximum allowable sorptivity for A2 was based on a 12 hours wetting period.

Sorptivity of carbonated LCCs is currently being measured and will be compared with the limits in Table 3 reproduced from [10].

Table 1 Expected time periods needed to crack a concrete cover

Corrosion rate per year	Time period (years)	
	Crack width of 0.05–0.1 mm (20 µm)[a]	Crack width 0.2–0.3 mm (100–150 µm)
1 µm	20	>100
10 µm	2	10–15
100 µm	0.2	1–2
1 mm	0.02	0.1–0.2

[a] Bar cross-section loss given in brackets.

Table 3. Recommendations on Maximum Allowable Values of Water Sorptivity (S^*) and Carbonation (C_a^*) from Accelerated Test for the Durability Design of Building Exteriors

Exposure classification	Cover (mm)	S^* ($mm/h^{0.5}$)	C_a^* ($mm/y^{0.5}$)
Very severe: B2	30	4.5	25
	40	6.0	40
	50	7.5	55
Severe: B1	30	6.0	40
	40	8.0	55
	50	10.0	70
Moderate: A2	30	9.0	60
	40	12.0	80
	50	15.0	100

References:

9. Andrade, C., Alonso, C. and Molina, F.J., 'Cover cracking as a function of bar corrosion: Part 1-Experimental test', Materials and Structures, 1993, 26, 453-464.

10. Ho, D.W.S. and Lewis, R.K., 'The specification of concrete for reinforcement protection – performance criteria and compliance by strength', Cement and Concrete Research, Vol. 18, 584-594, 1988.