# Sustainable Concrete Pavement

**Tran Vu[1], Indira Vasikova[2],**

**Paul Thomas[3] and Vute Sirivivatnanon[4]**

[1] Postdoctoral Research Associate, BE (Civil Engineering Materials) & PhD (Concrete Tech), UTS

[2] PhD Candidate, Research Assistant, BE (Civil)& Master (Civil), UTS

[3] Senior Lecturer, University of Technology Sydney (UTS)

[4] Professor of Concrete Engineering, BE (Civil)& PhD (Concrete Tech), UTS

## ABSTRACT

The sustainability of the use of concrete pavement as a vital infrastructure requires a constant review on its performance namely mechanical and volume stability properties, durability with respect to service life, and embodied carbon (EC). Transport for New South Wales has collaborated with CCAA, UTS and SmartCrete CRC in examining the sustainability of concrete pavement complying with its R82 and R83 specifications. The research reveals that while the state-of-the-art R82 concrete is meeting its performance requirements at very low EC, R83 concrete can be further developed to meet all performance requirements at a significantly lower EC than the level achieved currently. The design life with respect to carbonation-induced corrosion was evaluated based on carbonation study of the concrete exposed to accelerate carbonation, indoor and outdoor exposure for a period of 12 months. This paper provides the details of the experimental program and results of the research justifying the use of low carbon R83 concrete which meet all performance requirements.

## KEY WORDS

Embodied carbon; carbonation-induced corrosion; concrete pavement; sustainability; performance requirements; alkali silica reactivity

## BACKGROUND

The sustainability of concrete pavements is increasingly evaluated through a multifaceted lens, encompassing not only mechanical and volumetric stability and long-term durability, but also the embodied carbon (EC). The collaborative research initiative led by Transport for New South Wales, in partnership with CCAA, UTS, and SmartCrete CRC [1], represents a critical step forward in aligning infrastructure performance with contemporary sustainability imperatives. This project indicates that state-of-the-art R82 concrete pavements (concrete subbase as shown in Figure 1) are currently achieving both mechanical properties, durability at notably low embodied carbon, illustrating that stringent performance requirements and environmental objectives can be met concurrently through optimized mix design and specification. Importantly, the research demonstrates that R83 concrete (concrete base) can be further developed to achieve substantial reductions in EC, while maintaining key performance criteria and meeting the required 40-year service life. This underscores significant potential for innovation within existing standards by leveraging supplementary cementitious materials (SCMs) and an appropriate concrete mix design method.

The project adopts a rigorous and comprehensive approach to evaluating the design life, particularly regarding carbonation-induced corrosion, because carbonation is considered a main issue for the durability of concrete pavement using a high percentage of SCMs. Given that the propagation phase of carbonation-induced corrosion typically lasts around 10-15 years, the carbonation depth should remain less than the minimum concrete cover to steel reinforcement within the first 40 years. This approach ensures the structure achieves a 40-year service life. In this project, the carbonation depths after 40 years are predicted through a comprehensive testing program that combines accelerated, indoor, and outdoor carbonation exposures conducted over twelve months. However, it is important to recognize the limitations of short-term studies when making predictions about performance over several decades. Long-term durability must ultimately be verified through ongoing field monitoring and detailed life-cycle assessments. Such continued validation will be critical to support updates in specifications and ensure the lasting resilience of concrete pavements.

This research sets a strong precedent for the development of sustainable concrete pavements in New South Wales and beyond. By showing that substantial reductions in embodied carbon can be achieved without compromising structural integrity or service life, the project encourages the wider adoption of performance-based specifications and innovative, low-carbon technologies throughout the transport sector.

Additionally, this project examines concrete pavements produced with quality, locally sourced materials, ensuring workability suitable for modern paving equipment and compliance with the mechanical and volumetric stability requirements set out in TfNSW R83 [2]. Durability considerations include resistance to carbonation and the effective management of alkali-silica reactivity. Finally, sustainability is assessed through the embodied carbon or global warming potential (GWP) associated with the concrete's life cycle stages A1–A3 [3].

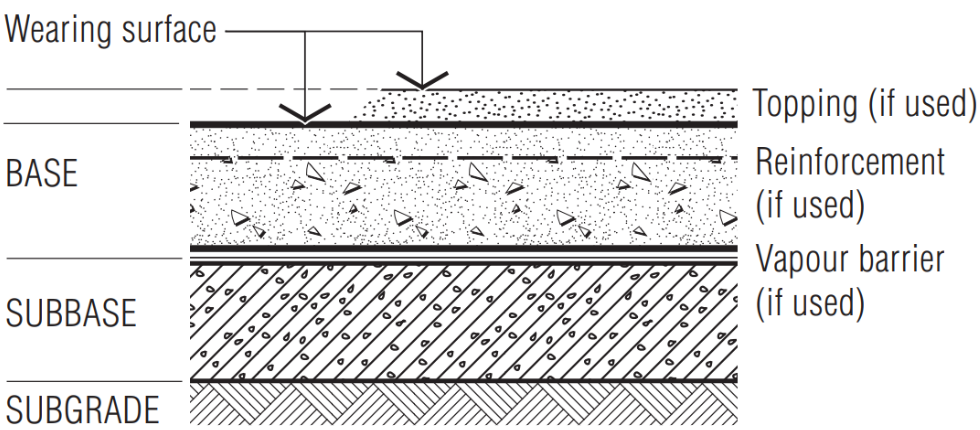


Figure 1. Elements of a typical concrete industrial floor/pavement [4]

# EXPERIMENTAL PROGRAM

### Concrete Mix Design Development

The chemical composition of Portland cement, fly ash, and slag used in this investigation is described in Table A in the Appendix. Four types of aggregates were carefully graded inside the limitation curves (the Tarantular curves) recommended by Cook et al. [5,6], shown in Figure 2. P1 consists of 100% by weight GP, while F25 contains 75% OPC and 25% FA, and similarly, F40 has 60% OPC and 40% FA. For slag-based mixes, S40 includes 60% OPC and 40% Slag, whereas S50 consists of 50% OPC and 50% Slag. The ternary blend T1 comprises 40% OPC, 40% Slag, and 20% FA. The number following the binder's name indicates the water-to-binder ratio (w/b). For example, P1-60 refers to a mix with P1 binder (100% GP) and a w/b of 0.60.

The concrete samples were produced according to the mix compositions in Table 1. All mixes were designed to comply with the requirements of R83, including:

(i) 28-day compressive strength is greater than 40 MPa and

(ii) 28-day flexural strength is from 4.6 to 5.4 MPa

(iii) Slump is from 40-50mm

(iv) Air content is 4.5±1.5%

(v) Dry shrinkage at 21 days is smaller than 580 (for mixes using slag) and 450 for mixes using other supplementary cementitious materials.

Apart from meeting all requirements mentioned, the concrete pavement investigated in this project must pass the box test [7], which assesses the concrete's response to vibration at energy levels similar to those used by a slip-form paving machine, as well as its ability to retain a stable edge after the formwork is removed. This test is important to concrete pavement because the conventional slump test is not sufficiently precise for evaluating the stiff workability required for slip-formed concrete [5,6].

Table 1. Concrete mix proportion investigated

| Concrete mix | P1-60 | S40-54 | S50-52 | F25-48 | F40-42 | T1-45 |
|---|---|---|---|---|---|---|
| Material Type | Design weight (kg/m³) | | | | | |
| Water | 181 | 168 | 168 | 153 | 150 | 159 |
| GP cement | 303 | 187 | 164 | 237 | 214 | 142 |
| Slag | 0 | 125 | 164 | 0 | 0 | 142 |
| Fly ash | 0 | 0 | 0 | 79 | 143 | 71 |
| 20 mm | 787 | 826 | 843 | 805 | 831 | 850 |
| 10 mm | 337 | 358 | 361 | 345 | 356 | 364 |
| man Sand | 736 | 691 | 698 | 666 | 633 | 648 |
| natural Sand | 184 | 173 | 174 | 167 | 158 | 162 |
| Admixture | ml/100kg binder | | | | | |
| AEA | 140 | 200 | 250 | 300 | 191 | 150 |
| MWR | 500 | 600 | 1265 | 1016 | 1219 | 962 |
| Retarder | 100 | 0 | 0 | 0 | 0 | 0 |
| w/b | 0.60 | 0.54 | 0.54 | 0.54 | 0.52 | 0.52 |

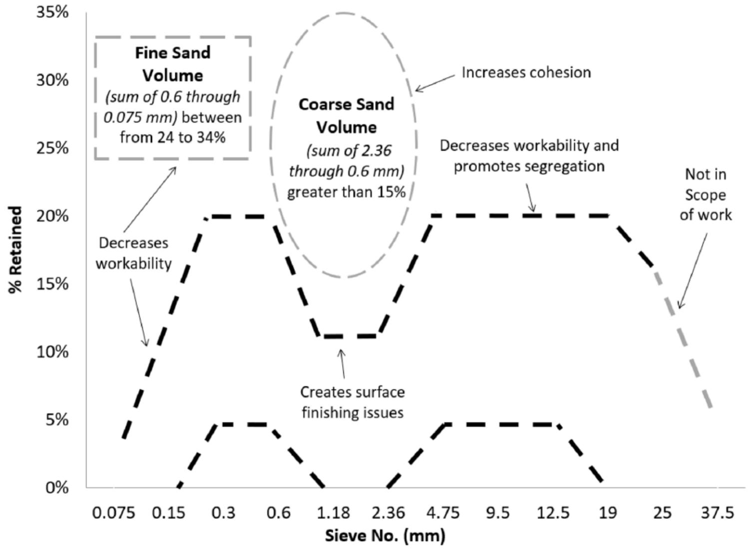


Figure 2. Summary limits for the combined gradation, fine sand volume, and coarse sand volume [5].

**Embodied carbon evaluation**

In the context of this project, embodied carbon (EC) or global warming potential, expressed in $kgCO_2/m^3$, denotes the carbon dioxide ($CO_2$) emissions linked with the cradle-to-gate stage according to BS EN 15804 [3], including the stages of raw material procurement A1, transportation A2, and manufacturing A3, as illustrated in Table 2.3. The embodied carbon of every concrete mix is calculated as per the formula (1) according to the method recommended by Transport for NSW.

$$\text{Embodied Carbon (EC)} = EC\_A1 + EC\_A2 + EC\_A3 \qquad (1)$$

**Carbonation study**

Concrete (75x75x375mm) prisms underwent accelerated and indoor carbonation, while slabs (50x240x320 mm) were exposed to natural outdoor conditions (see Figure 3) to evaluate surface finish effects (trowelled vs. off-formwork) and orientation of the specimen. All samples were demolded after one day, cured in lime-saturated water for six days, and then air-dried at 50% RH and 23°C until 42 days old.


Figure 3. Natural exposure site at UTS Ultimo campus

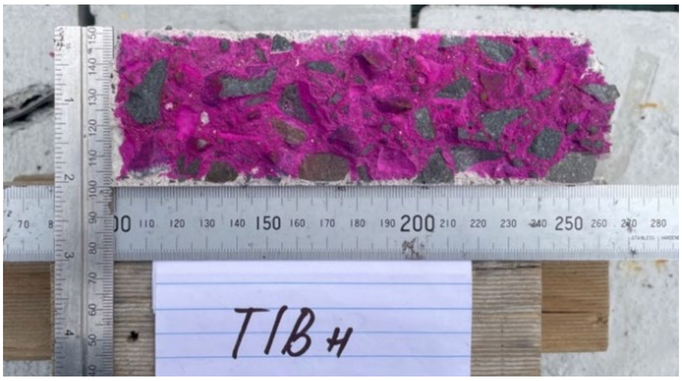

Figure 4. Measurement of carbonation depth

For accelerated and indoor conditions, humidity and temperature are controlled at 50% RH and 23°C, respectively. The primary distinction is in the carbon dioxide concentration, which is maintained at 2% in accelerated conditions, while indoors it is kept ambient at around 410 ppm [8]. The outdoor environment is ambient, where concrete samples are exposed to varying humidity, rain, wind, and sun, among other factors. To predict carbonation depth in real time, the relationship between accelerated carbonation results and indoor and outdoor carbonation [9] are used to estimate the carbonation depth in 40 years for the pavement following the first Fick's law of diffusion, and can be determined using the following equation [10]:

$$X_c(t) = k * \sqrt{t}, where$$

$X_c$ is the carbonation depth at time t= time of exposure, and k is the carbonation coefficient or carbonation rate obtained experimentally.

# RESULTS

**Workability, mechanical, and volume stability properties**

The results of all the tests and embodied carbon are given in Table 2. The results of the box test, as shown in Figure 5, are visually evaluated. So far, all the requirements for concrete pavement in R83 are satisfied.

Table 2. Results of Workability and mechanical tests

| Mix | P1-60 | S40-54 | S50-52 | F25-48 | F40-42 | T1-45 |
|---|---|---|---|---|---|---|
| EC, $kgCO_2/m^3$ | 323 | 241 | 228 | 263 | 243 | 204 |
| 28-day compressive strength, MPa | 40 | 40 | 42 | 6-Aug-25 | 6-Aug-25 | 6-Aug-25 |
| 28-day flexural strength, MPa | 5.0 | 6.2 | 6.0 | 6-Aug-25 | 6-Aug-25 | 6-Aug-25 |
| Slump, mm | 38 | 45 | 45 | 50 | 55 | 35 |
| AASHTO T 396 Box test | Void rating level 2 | Void rating level 1 | Void rating level 1 | Void rating level 1 | Void rating level 2 | Void rating level 1 |
| Air, % | 3.2 | 3.7 | 4.8 | 7.5 | 6.0 | 4.5 |
| 21-day Drying shrinkage, microstrain | 387 | 329 | 268 | 6-Aug-25 | 6-Aug-25 | 6-Aug-25 |

Figure 5. Level 1 – void rating in the box test, with 0 slump edge.

**Performance compared to TfNSW registered mixes**

Figure 6 clearly shows that the concrete mixes investigated in this study have lower embodied carbon than the registered mixes, with the exception of mix P1 containing 100% GP cement. The investigated mixes not only achieve a lower median value but also exhibit less variability, reflecting a more effective and controlled mix design. These findings underscore the potential for substantial reductions in embodied carbon for future sustainable pavement practices.

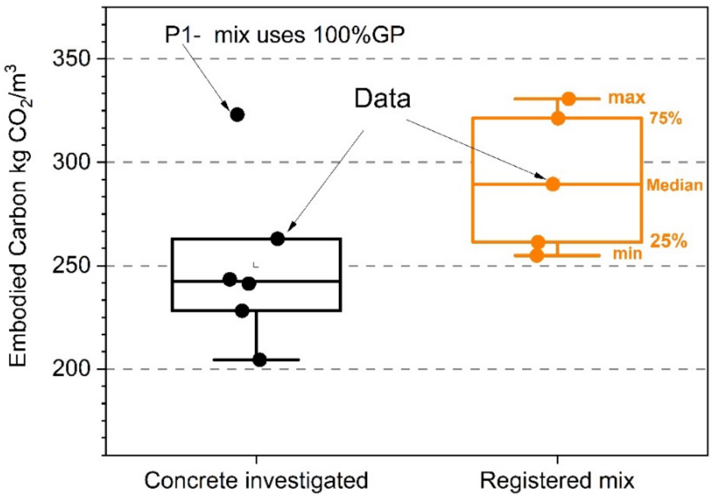


Figure 6. Comparison of embodied carbon of concrete investigated and registered mixes.

**Durability with respect to Carbonation**

The prescriptive requirements of R83 specify a minimum cement content of 300 kg/m³ for all pavements covered under this specification, except for the steel fibre reinforced concrete pavements, which require a minimum of 350 kg/m³. In addition, a minimum cement proportion must be satisfied based on the equation outlined in the 3211 QA specification [11]. However, to investigate the potential of higher SCM substitution and evaluate concrete performance in terms of carbonation resistance and 28-day compressive strength, this study considers an extended range of SCM contents and target strengths to understand the potential of decreasing embodied carbon.

Based on six months of collected carbonation data, it is possible to predict the carbonation depth for both indoor and outdoor environments about the performance-based strength requirements outlined in R83. The result for trowelled horizontal surfaces applicable to the surface of road pavement is shown in Figure 7.

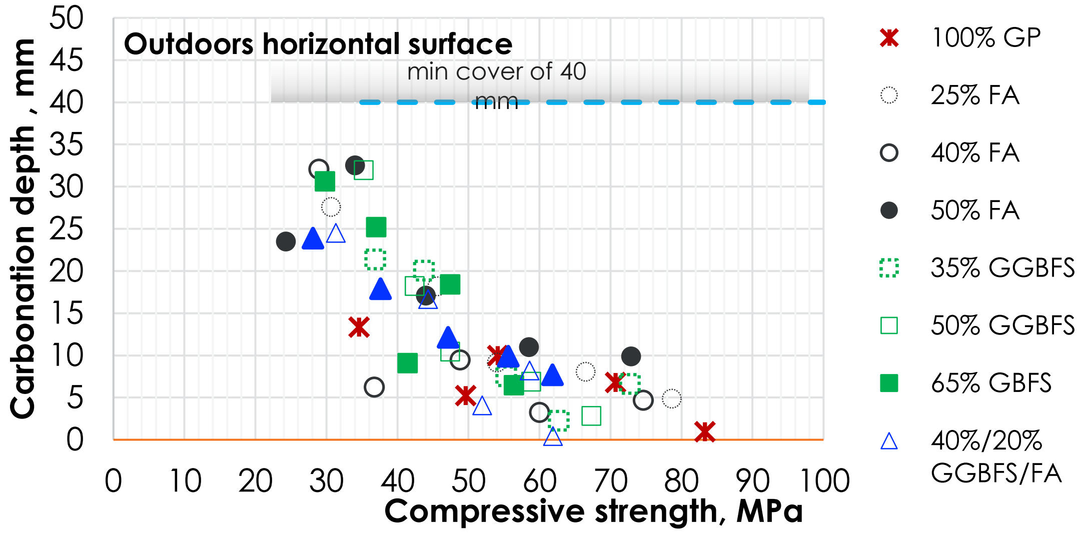


Figure 7. Prediction of carbonation depth in indoor and outdoor environment for the trowelled surface of concrete with various SCM contents.

According to the drawings from the TfNSW portal, the minimum cover for various pavements ranges from 40 mm to 110 mm, or potentially higher. For the purposes of estimating carbonation depth, a conservative minimum cover of 40 mm is assumed for all pavements, along with an initiation period of 40 years, in line with the design life of the pavement. Furthermore, the 28-day compressive strength requirements specify a minimum of 40 MPa for mixes containing supplementary cementitious materials (SCMs), and 46 MPa for mixes without SCMs [2].

All the concrete mixes investigated in this study have 28-day compressive strengths ranging from 40 to 50 MPa. Based on the data presented in Figure 7, the predicted carbonation depth after 40 years will be less than 25mm for outdoor exposure. These results indicate that the concrete using high percentage of SCMs (up to 60%), investigated in this study, can safely resist carbonation-induced corrosion after 40 years of initiation, thus can fully achieve the service life of more than 40 years.

# CONCLUSIONS

Sustainable concrete pavement can be developed by replacing Portland cement with suitable type and amount of supplementary cementitious materials. These concretes meet R83 workability, strengths and drying shrinkage requirements at significantly lower embodied carbon that the published registered mixes. These concretes are proven suitable for slip forming paving. Carbonation study shows carbonation depth after 40 years of outdoor exposure to be well within the minimum concrete cover of 40mm of various concrete pavements used by Transport for New South Wales. Hence the 40 years design life is met without the minimum Portland cement content. The 25% fly ash or 50% slag also meet HB79 SCM requirement to prevent deleterious ASR and the added advantage of utilising aggregates from most existing quarries.

# ACKNOWLEDGEMENT

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**References**

[1] https://smartcretecrc.com.au/projects/selecting-low-carbon-concrete-for-transport-infrastructures-now-and-future/, (n.d.).

[2] Transport for NSW, QA Specification R83-Concrete Pavement Base, 2021.

[3] European Standard, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products - EN-15804:2012 + A2:2019, n.d.

[4] Cement Concrete & Aggregates Australia, CCAA GUIDE T48- Guide to industrial floors and pavements, Cement Concrete & Aggregates Australia (CCAA), 2009.

[5] M.D. Cook, M.T. Ley, Impacts of Fine Aggregate Gradation on the Workability of Slip-Formed Concrete, Journal of Materials in Civil Engineering 35 (2023). https://doi.org/10.1061/jmcee7.mteng-15236.

[6] D. Cook, ; M Tyler Ley, A. Ghaeezadah, Effects of Aggregate Concepts on the Workability of Slip-Formed Concrete, 2016.

[7] AASHTO, Standard Method of Test for Evaluating the Workability of Slip Form Concrete Paving with the Box Test - AASHTO T 396, 2023.

[8] CSIRO, Greenhouse gases.https://www.csiro.au/en/research/environmental-impacts/climate-change/state-of-the-climate/greenhouse-gases, (n.d.).

[9] D.& R.K.L. Ho, The Compliance of Concrete with the Durability requirements of AS3600, in International conference on the use of Fly Ashm Silica Fume and other Silecious Materials in concrete, I.H. W.B. Butler, Editor. 1990, CSIRO: Leura (Blue Mountains), New South Wales, Australia., in: n.d.

[10] C.G.V. and N.F.M. Vagelis G. Papadakis, Fundamental Modeling and Experimental Investigation of Concrete Carbonation, ACI Mater J 88 (1991).

[11] Transport for NSW, IC-QA-3211 - Cementitious Materials, Binders and Fillers, 2020.

Appendix

Table A. Chemical composition of OPC, fly ash, and slag

| Oxide % | CaO | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | $SO_3$ | MgO | $Na_2O$ | $K_2O$ | SrO | $TiO_2$ | $P_2O_5$ | $Mn_2O_3$ | MnO | Total Alkali |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fly Ash | 4.8 | 54.9 | 25.7 | 8.7 | - | 0.2 | 1.3 | 0.31 | 0.88 | < 0.1 | 1.4 | 0.7 | 0.1 | - | 0.89 |
| OPC | 64.1 | 19.4 | 5 | 3.2 | - | 2.6 | 0.9 | 0.5 | - | - | - | - | - | - | - |
| Slag | 42.4 | 36.1 | 13.6 | - | 0.4 | < 0.5 | 5.8 | 0.23 | 0.34 | < 0.1 | 0.7 | < 0.1 | - | 0.4 | 0.45 |