

## Final Project Report

# R1P29-Development of low-carbon concrete products using industrial by products



### Administration

Lead researcher	Prof Patrick Tang
Contact details	Email: <a href="mailto:Patrick.tang@newcastle.edu.au">Patrick.tang@newcastle.edu.au</a> ; Phone: 02 49217246
University	The University of Newcastle (UON)
Date of submission	March 2026

## Table of Contents

<b>Acknowledgements and Project Team</b> .....	3
1.1 Specific Problems Addressed.....	7
1.2 Barriers to Current Solutions .....	7
1.3 Affected Stakeholders and Costs.....	8
1.4 Impact of Research Outcomes.....	8
<b>2. Project Objectives, Hypotheses and Impact Pathways</b> .....	9
2.1 Industry Challenges Addressed by the Project.....	9
2.2 Key hypotheses, underlying assumptions, and success looks .....	10
2.3 Impact Pathways .....	12
<b>3. Project Methodology and Key Activities</b> .....	13
3.1 Research Strategy and Experimental Design .....	13
3.2 Materials, facilities and equipment applied.....	14
3.3 Prior Work and Background IP Leveraged.....	15
3.4 Uniqueness/novelty and competing approaches.....	15
3.5 Validation approach, standards basis, and success metrics .....	16
3.6 Industry Engagement During Delivery .....	17
<b>4. Analysis of Key Results, Deliverables, Description of Outputs and Project IP</b> 18	
4.1 Key results discussion .....	18
4.1.1 FBA as fine aggregate in concrete and mortar.....	18
4.1.2 FBA as fine aggregate and cement replacement in concrete. ....	20
4.1.3 Life cycle assessment .....	26
4.1.4 Field applications.....	27
4.2 Highlights from the Key Results .....	29
4.3 Implications for project success .....	31
4.4 Addressing the Industry Challenges.....	33
4.5 Deliverables analysis: contracted versus achieved/actual.....	34
4.6 Description of Outputs and IP.....	36
<b>5. Next Steps – Commercialisation &amp; Impact Plan</b> .....	36
5.1 Awareness, adoption and application plan.....	36
5.2 Ongoing Activities and Asset Requirements .....	37
5.3 Commercialisation and impact table.....	37
<b>6. Education and Training</b> .....	39
6.1 New Technologies and Processes .....	39
6.2 Training Providers and Target Trainees .....	40

6.3	Training requirements.....	40
6.4	Research capacity building and academic dissemination.....	40
<b>7.</b>	<b>Conclusions, Implications and Recommendations.....</b>	<b>41</b>
7.1	Challenges Overcome and Remaining .....	41
7.2	Project highlights .....	41
7.3	Learnings for future research.....	42
<b>8.</b>	<b>Publication List .....</b>	<b>43</b>
<b>9.</b>	<b>Acronyms and Abbreviations.....</b>	<b>44</b>
<b>10.</b>	<b>References.....</b>	<b>45</b>
<b>11.</b>	<b>Appendices and Attachments.....</b>	<b>47</b>
11.1	Appendix A: deliverables submitted to SmartCrete CRC.....	47
11.2	Appendix B: Mortar mix proportions (kg/1 m <sup>3</sup> ).....	48
11.3	Appendix C: Concrete mix proportions (kg/1 m <sup>3</sup> ).....	49
11.4	Appendix E: Mix Designs for Trial concrete mixes.....	50

## Acknowledgements and Project Team

The project team would like to express our sincere gratitude to the **SmartCrete Cooperative Research Centre (CRC)** for funding and supporting this vital research.

We extend our deep appreciation to our industry partners, particularly **Delta Electricity** and their Business Development Manager, **Anthony Callen**, for supplying the Furnace Bottom Ash (FBA) and coordinating the trial concrete applications from the **Vales Point Power Station**. We also thank **Daracon (Daracrete)** and their Director of Business Development, **Adam Kelly**, for their instrumental contributions in providing materials, offering technical expertise, conducting full-scale industrial trials, and supplying Ground Granulated Blast Furnace Slag (GGBFS).

We would also like to thank **Transport for NSW (TfNSW)** and their Director Technical – Maritime, **Harish Srivastava**, for their strong support and invaluable technical guidance throughout the project. Their expertise has been essential in shaping the direction and practical relevance of this work.

Further acknowledgement is extended to **Molycop, Concrush Pty Ltd, Pacific Blue Metal Pty Ltd, Walter P & Gisela M Duber**, the **Ash Development Association of Australia (ADAA)**, and our academic collaborators at the **Royal Melbourne Institute of Technology (RMIT)** for their expertise in Life Cycle Assessment.

We also wish to acknowledge the project team led by **Professor Patrick Tang**, including **Dr Yanju Liu, Associate Professor Willy Sher, Dr Chethana, Dr Umer Sajjad**, and PhD candidate **Ali Onaizi**, whose dedication, technical contributions, and collaborative effort were vital to the success of this research. Finally, we extend our sincere thanks to **the University of Newcastle** for providing state-of-the-art facilities and professional support throughout the project.

## Executive Summary / Abstract

### The Problem

Australia generates 13 million tonnes of coal ash annually, yet furnace bottom ash (FBA), a coarse by-product from coal-fired power stations, remains underutilised. In New South Wales, more than 200 million tonnes of coal ash are stored in largely unlined ash dams across several power stations, representing potential environmental legacy issues and on-going management liabilities. Although only a fraction of this total is FBA, it still accounts for a sizeable and largely untapped resource that is currently stockpiled rather than beneficially reused. For power station operators, these ash repositories present escalating costs associated with storage, monitoring, and remediation. For the concrete industry, which contributes around 8% of global CO<sub>2</sub> emissions, there is an urgent need for viable alternatives to cement and natural aggregates. Unlocking the potential of FBA as a construction material could simultaneously reduce waste, cut carbon emissions, and improve resource efficiency.

### Project Objectives

The project sought to:

1. Characterise the physical and chemical properties of FBA from NSW power stations to establish its suitability for concrete applications.
2. Develop cost-effective processing methods to enhance FBA reactivity.
3. Validate concrete performance through laboratory testing and an industrial-scale field trial.
4. Identify compliance pathways with Australian Standards and environmental regulations to facilitate market adoption.
5. Quantify environmental and economic benefits.

### Key Findings

The project successfully delivered all milestones and demonstrated that FBA can be reliably processed and incorporated into commercial-grade concrete mixes.

**Standards and Regulatory Alignment:** Comprehensive testing confirmed that treated FBA meets the chemical requirements for Class F fly ash and Grade 1 and Grade 2 materials under both ASTM C618 and AS/NZS 3582.1. For aggregate applications, FBA particle size distribution complies with AS 2758.1 specifications. The elemental concentration analysis of solid materials using ICP-MS / ICP-OES demonstrated that heavy metal concentrations are below NSW EPA and US EPA waste reuse thresholds, therefore supporting pathways for end-of-waste classification under NSW Resource Recovery Orders and Exemptions.

**Processing Technology:** A laboratory-based processing protocol was developed and validated with reproducible outcomes, demonstrating that drying, sieving, and short-duration

ball milling (15-30 minutes) can transform raw FBA into a consistent construction material. Co-grinding with other supplementary cementitious materials (SCMs) such as Ground Granulated Blast Furnace Slag (GGBFS) was shown to enhance pozzolanic reactivity without additional binder activation steps.

**Mortar and Concrete Performance:** Concrete and mortar trials confirmed that 25% FBA as a fine aggregate replacement combined with 10-20% ground FBA (GFBA) as a cement replacement delivered superior compressive and flexural strength while reducing water absorption compared with conventional cement-based mixes. Building on these results, eight concrete formulations were systematically evaluated, establishing optimal replacement levels of 25% FBA for sand and 10-20% GFBA for cement. The optimal FBA concrete mix achieved a 28-day compressive strength 11% higher than conventional concrete, demonstrating that processed FBA can not only match but exceed the performance of traditional materials. The research produced validated mix designs suitable for different strength grades, providing industry with immediately adoptable formulations.

**Industrial Validation:** An industrial-scale footpath constructed at Vales Point Power Station in February 2025 successfully demonstrated that FBA concrete can be produced using standard batching plant equipment, transported, placed, and finished using conventional techniques, complying with AS 1379 requirements for concrete supply, TfNSW R53 for general works requirements for supply and placement, and TfNSW R54 for footpath construction and general concrete paving requirements.

**Life Cycle Assessment (LCA):** LCA confirmed that using FBA in concrete mixes achieves a 20–36% reduction in embodied carbon through combined cement and sand replacement (with 10–30% GFBA as cement replacement and 25% FBA as sand replacement) compared with a standard M20 mix. Cost analysis demonstrated savings of \$71–111 per cubic metre when using optimised FBA mixes with up to 30% cement replacement. For a medium-sized concrete supplier producing 70,000 m<sup>3</sup> annually, this represents potential savings of \$5.0–7.8 million per year.

**Guidelines for Industry Application:** A comprehensive set of guidelines (DEL-111) for incorporating FBA into concrete as a sustainable construction material has been developed based on the project results. These guidelines provide evidence-based recommendations for using FBA both as a partial fine-aggregate (sand) replacement and as a supplementary cementitious material (SCM) through the use of GFBA. The guidelines translate laboratory findings into clear, practical directions covering sourcing, processing, proportioning, and performance validation, enabling safe, reliable, and commercially viable adoption of FBA in concrete production.

### Next Steps

- **Standards Development:** A key future development includes a review of relevant Australian standards for similar pozzolanic materials (e.g., fly ash and slag) to define a

pathway to either include FBA under clear acceptance criteria in existing standards or develop a dedicated FBA guideline/standard to support uptake.

- **Processing Infrastructure:** Investigate and commercially evaluate grinding facilities at power stations to optimise logistics costs.
- **Industry Training:** Use DEL-111 checklists and procedures to run practical training; build on the workshops/events already delivered in 2025 (DEL-108) to engage key stakeholders.
- **Regulatory Engagement:** Use the project datasets to support end-of-waste / EPA-aligned classification pathways and de-risk approvals for reuse.

### Conclusion

This project has demonstrated that FBA, currently a liability, can be transformed into a valuable resource for low-carbon concrete. With demonstrated compliance with existing standards, proven performance exceeding conventional concrete, clear regulatory pathways, and substantial cost savings validated by Life Cycle Assessment, widespread adoption could reduce landfill, cut CO<sub>2</sub> emissions by up to 36%, and create significant new value for power station operators and the construction industry.

## Industry Problem, Needs and Relevance

### 1.1 Specific Problems Addressed

This project addressed two critical, intersecting problems: the massive accumulation of industrial waste from coal-fired power stations and the high environmental impact of traditional concrete production. Australia produced approximately 10.3 Mt of ash annually in 2022–23, representing about 13.6% of the nation's total headline waste stream (DCCEEW, 2024). Furnace Bottom Ash (FBA) constitutes about 10% of this output. In New South Wales (NSW) alone, coal-fired power stations generate about 4.8 million tonnes of coal ash per year (Winn, 2020), with around 3.8 million tonnes per year being disposed of to ash dams, emplacement areas, or mine voids. These disposal practices have resulted in an estimated ~160 million tonnes of coal ash accumulated at operating sites, and approximately ~216 million tonnes when broader legacy stockpiles are considered (Winn, 2020, p. 23). Furnace Bottom Ash (FBA) is typically around 10% of coal ash, indicating a substantial bottom-ash stream within this potential resource. At the same time, the concrete industry is heavily reliant on the extraction of natural sand and the energy-intensive production of Portland cement, which is a major contributor to global greenhouse gas emissions.

The specific challenge is that while fly ash (FA) is widely utilised in the construction industry as an SCM, FBA remains largely underutilised. Globally, coal ash utilisation remains incomplete; published reviews report 25–30% reuse for fly ash, while bottom ash (including FBA) remains predominantly stored/landfilled (>85%) and, where reused, is typically used in lower-value civil applications such as fill and road base/sub-base (Guan et al., 2023; Mathapati et al., 2021; ARRB, 2022). A significant portion is still managed through storage in ash dams as landfill sites. Although disposal of CCPs to ash dams or landfill is often treated as the lowest immediate-cost management option, this approach can be economically inefficient over the longer term because it converts a potentially valuable material into an ongoing cost item through handling, transport, storage, monitoring, and long-term management, rather than a value-adding input to construction supply chains.

### 1.2 Barriers to Current Solutions

Several constraints have prevented industry from overcoming these challenges:

**Technical Barriers:** Unlike fly ash, which consists of fine, spherical particles with high pozzolanic reactivity, raw FBA is characterised by coarse, irregular, and highly porous particles. This high porosity leads to excessive water absorption when used in concrete, which negatively impacts workability and can compromise the final strength of the concrete if not properly managed. Furthermore, raw FBA exhibits low inherent pozzolanic reactivity, meaning it does not readily react with calcium hydroxide to form strength-contributing compounds unless it undergoes significant pre-treatment. The variability in the chemical and physical properties of FBA, depending on the coal source and combustion conditions, further complicates its use as a consistent construction material.

**Economic Barriers:** The pre-treatment required to make FBA suitable for concrete, specifically drying, sieving, and grinding, incurs additional processing costs. Historically, these costs have deterred concrete manufacturers from adopting FBA, especially when natural sand and traditional SCMs like fly ash or slag have been readily available and relatively inexpensive.

**Regulatory and Knowledge Barriers:** There is a significant lack of specific Australian Standards and end-of-waste guidelines tailored to the use of FBA in structural concrete. This regulatory vacuum creates uncertainty and risk for concrete producers and specifiers. Furthermore, there is widespread industry skepticism regarding the quality and long-term durability of concrete products incorporating FBA, stemming from a lack of comprehensive, localised research and full-scale industrial demonstrations.

For details, please refer to [DEL-109](#) and [DEL-111](#).

### 1.3 Affected Stakeholders and Costs

The challenges associated with FBA disposal and the environmental impact of concrete production affect multiple stakeholders across the supply chain.

**Coal Power Plant Operators:** Coal-fired power station operators bear financial liabilities associated with the construction, maintenance, and long-term environmental monitoring of ash dams. Operational costs include transportation, capping, on-going monitoring and compliance reporting, water management, and rehabilitation activities. In addition, these operators face increasing scrutiny and expectations from regulators and the community regarding responsible ash management, resourcing circular-economy solutions, and demonstrating progress toward reducing long-term liabilities.

**Concrete Industry (Suppliers and Manufacturers):** The concrete industry faces escalating costs for natural aggregates due to resource depletion, stricter environmental regulations on quarrying, and increasing transportation distances. Additionally, the industry is under mounting pressure to reduce its carbon footprint, facing potential carbon taxes and shifting market demands towards sustainable construction materials. The reliance on traditional Portland cement, a highly carbon-intensive material, exposes the industry to significant economic and regulatory risks.

**Government and Community:** The community at large is impacted by the greenhouse gas emissions associated with traditional concrete production, which contribute to climate change.

### 1.4 Impact of Research Outcomes

The impact of the research outcomes is by outlining how the project evidence and guidelines translate into increased awareness, improved adoption readiness, real-world application confidence, and established dissemination pathways across the concrete industry, as follows:

#### 1) Awareness

The research outcomes have generated strong awareness value by providing a consolidated, industry-ready evidence base (detailed in **DEL-111 as guidelines**) that demonstrates how FBA can be processed and used in concrete. This includes clear technical data on pre-

treatment and co-grinding benefits, supported by practical and full-scale experiments, which together reduce uncertainty for concrete producers and end users.

## 2) Adoption

The outcomes enable adoption by translating research into practical implementation guidance. **DEL-111** consolidates material sourcing and QA requirements, processing steps, batching and handling controls (including moisture and slump management), and acceptance testing aligned with Australian Standards and TfNSW specifications. This converts the project results into a form that can be incorporated into operational procedures and procurement documentation.

## 3) Application

The outcomes support immediate application by establishing a validated performance window for FBA use in concrete and documenting practical lessons from field implementation. Together, these provide confidence that FBA concrete can be manufactured, transported, placed, and finished using standard industry practices, while maintaining performance suitable for near-term infrastructure applications.

## 4) Dissemination channels already established

The project has already established effective dissemination pathways through workshops/conferences channels (see **DEL-108**), including industry events, briefings, and stakeholder engagement. These channels strengthen the impact of the research outcomes by increasing visibility across the supply chain and supporting ongoing uptake by specifiers and procurement decision-makers, with ADAA and TfNSW providing important pathways for broader industry acceptance.

# 2. Project Objectives, Hypotheses and Impact Pathways

## 2.1 Industry Challenges Addressed by the Project

This project responded to the practical barriers that have kept FBA underutilised in concrete in Australia, despite the scale of the resource available and growing decarbonisation pressure on the supply and utilisation of construction materials.

### Challenge 1: Waste liability and constrained reuse pathways

Coal combustion products are a major waste issue in Australia, with FBA typically stored in ash dams or used in limited, lower-value applications (e.g., road sub-base). The project promoted the conversion of FBA from a legacy liability into a value-adding input for concrete production (see Project Agreement and DEL-102 for more details).

### Challenge 2: Technical limitations of raw FBA for structural concrete

Raw FBA is highly variable, and porous, and typically has a coarse particle size and wide particle size distribution with low reactivity, which can reduce workability and compromise mechanical performance if used without treatment in concrete mixes (see DEL-109).

### Challenge 3: Lack of practical, scalable processing procedures

Industry needs implementable pre-treatment and processing methods (drying, sieving, grinding/co-grinding) that can be scaled beyond the laboratory and embedded into existing supply chains (see DEL-109).

#### **Challenge 4: Standards/specification and confidence barriers**

FBA adoption is constrained by the lack of FBA-specific guidance within Australian Standards and specifications, plus limited full-scale demonstration evidence to build confidence with specifiers and asset owners (see DEL-111- Regulatory Framework section and DEL-109).

### **2.2 Key hypotheses, underlying assumptions, and success looks**

This subsection summarises the hypotheses investigated and the measurable definitions of success used to evaluate them through laboratory studies, mix optimisation, and a field trial demonstration.

#### **Hypothesis 1: Mechanical Activation**

A practical mechanical processing pathway, specifically co-grinding FBA with SCMs such as GGBFS, can modify particle size distribution and microstructure sufficiently to enhance reactivity and enable FBA to function as both a supplementary cementitious material and partial fine aggregate replacement.

#### **Underlying Assumptions Tested:**

The enhanced performance of the processed material is attributed to synergistic interactions between GGBFS and GFBA, arising from four interconnected mechanisms (see Figure 1), as reported in DEL-111 and summarised as follows:

##### **1. Particle Refinement and Surface Area Enhancement:**

Co-grinding increases the fineness and specific surface area of both materials, improving reactivity and ensuring homogeneous particle distribution through centrifugal and impact forces during milling.

##### **2. Alkalinity-Driven Activation:**

During hydration, CaO-rich GGBFS dissolves, increasing pore solution alkalinity. The elevated pH environment promotes dissolution of amorphous aluminosilicate phases within GFBA.

##### **3. Secondary Hydration Product Formation:**

Released  $\text{Ca}^{2+}$  ions react with dissolved silicate and aluminate species, accelerating pozzolanic reactions and forming additional strength-contributing hydration products, primarily C-S-H and C-A-S-H gels.

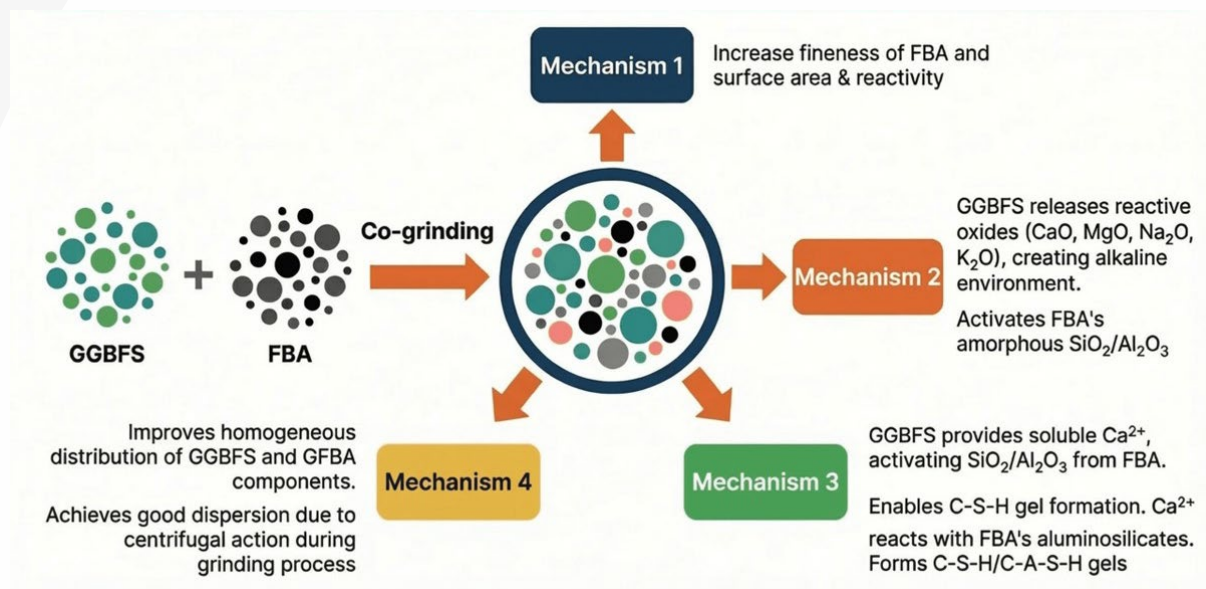
##### **4. Mechanical Disruption of Less Reactive Phases:**

Mechanical activation partially disrupts crystalline or less reactive phases within FBA, increasing the proportion of reactive surfaces available for hydration reactions.

Collectively, these mechanisms demonstrated an improvement in early and later-age strength development and durability performance of FBA-based concrete mixes.

### Definition of Success:

- FBA-based concrete performance demonstrated an improvement relative to conventional concrete systems (DEL-104 procedures and DEL-111 performance assessment).



**Figure 1: Mechanisms of Co-grinding GGBFS and FBA in Cementitious Systems.**

### Hypothesis 2: Performance equivalence to conventional concrete at practical replacement levels

- Hypothesis:** With appropriate processing, FBA can replace up to 50% of fine aggregate and support 10–30% cement replacement (via GFBA, with slag co-processing) without compromising performance for intended applications.
- Underlying assumptions tested:** The underlying assumptions were evaluated by investigating different FBA replacement levels (25%, 50%, 75%, and 100%) and their effects on mortar performance. After identifying 25% FBA as the optimal fine aggregate replacement, three combinations of GGBFS and GFBA (GGBFS–GFBA) were examined at ratios of 25:10, 25:20, and 25:30, corresponding to total cement replacement levels of 35%, 45%, and 55%, respectively.
- Success definition:** The results showed that a 25% replacement level performed comparably to, and in some cases surpassed, conventional concrete performance (DEL-105 and DEL-111). Concrete incorporating 25% FBA as a fine aggregate replacement with a 25:10 GGBFS–GFBA ratio outperformed conventional concrete at all testing ages. Meanwhile, mixes with 25:20 and 25:30 ratios exhibited performance comparable to conventional concrete at early ages and surpassed it at later ages (DEL-105 and DEL-111). The industrial footpath trial met TfNSW footpath specifications with ~31 MPa at 28 days compared with the ~33 MPa control (see DEL-107 and DEL-111).

### **Hypothesis 3: Economic feasibility (net benefit to suppliers and generators)**

1. **Hypothesis:** The benefits of material substitution, including reduced use of cement and natural sand, outweigh the processing costs, resulting in net savings and strengthening the business case for industry partners.
2. **Underlying assumptions tested:** Processing and logistics can be incorporated into a workable cost structure; value can be created for both concrete producers and power station operators (DEL-103a stakeholder framing; DEL-111 economic discussion).
3. **Success definition:** Demonstrated cost reductions per m<sup>3</sup> for optimised mixes and credible annualised savings for realistic production volumes. Based on the project's validated mix-cost dataset, optimised mixes show saving of \$71–111/m<sup>3</sup>, equating to \$5.0–7.8 million per year for production of 70,000 m<sup>3</sup>/year (see DEL-110).

### **Hypothesis 4: Environmental benefit (embodied carbon reduction)**

1. **Hypothesis:** Replacing cement (and partially replacing sand) with treated FBA reduces embodied CO<sub>2</sub> per m<sup>3</sup> compared with conventional concrete.
2. **Underlying assumptions tested:** Cement replacement drives the majority of carbon savings; sand replacement alone provides limited carbon benefit.
3. **Success definition:** Quantified reduction in embodied CO<sub>2</sub> per m<sup>3</sup> relative to control concrete. The results showed reductions in CO<sub>2</sub> emissions of up to 36% across the investigated mix range, consistent with the trend that higher cement replacement levels deliver greater savings (see DEL-110).

## **2.3 Impact Pathways**

### **Short-term pathway: prove and specify**

- Use the industrial-scale footpath demonstration as an evidence anchor for specifiers and local councils, supported by deliverables and technical guidance (DEL-107; DEL-111).
- Package the processing workflow (drying/sieving/grinding/co-grinding) into operational guidance for producers (DEL-104).
- Disseminate outcomes through SmartCrete CRC channels in line with the Communications & Engagement process, including staged approvals, partner communication contacts, and planned publication and outcome profiling (Communication plan).

### **Medium-term pathway: scale processing and formalise acceptance**

- Establish commercial pre-processing capability (preferably co-located at or near generation sites or ash sources), including drying, sieving and grinding/co-grinding, to deliver consistent product streams (DEL-104 scaling intent; DEL-111 logistics/processing challenges).
- Work toward incorporation into guidance and formal standards pathways (DEL-111 regulatory and standards chapter outlining the need for FBA-specific standardisation).

### Long-term go-to-market plan: commoditise and expand applications

- Transition from demonstration and niche applications (laboratory-scales trials and footpaths/pavements) to broader infrastructure and, where justified by data and standards acceptance, more structural applications.
- Establish supply chain norms: QA specifications, acceptance testing protocols, stable pricing mechanisms, and procurement inclusion.
- Create a manufacturing model that can be applied across multiple power stations and concrete suppliers, leveraging SmartCrete CRC dissemination channels.

## 3. Project Methodology and Key Activities

### 3.1 Research Strategy and Experimental Design

The project employed a comprehensive, multi-phased methodology to rigorously test the hypotheses, moving from fundamental material characterisation to laboratory optimisation, and culminating in a full-scale industrial trial.

#### Phase 1: Material Characterisation and Pre-treatment Development (DEL-102 to DEL-104)

The research began with a thorough literature review and data compilation regarding the availability and properties of FBA in NSW. FBA samples were sourced from the Vales Point and Eraring power stations. These samples underwent rigorous physical and chemical characterisation using X-ray Fluorescence (XRF) and Scanning Electron Microscopy (SEM). The XRF analysis confirmed that the chemical composition of the FBA (high proportions of silica and alumina) met the standards for Class F fly ash, indicating its potential as an SCM.

To address the inherent limitations of raw FBA (high porosity large particle size), a laboratory-based refinery procedure was developed. This involved:

- 1 **Drying:** Raw FBA was oven-dried at  $105^{\circ}\text{C} \pm 10^{\circ}\text{C}$  for 24 hours to remove excess moisture, allowing for accurate water calculation in the concrete mix design.
- 2 **Sieving:** The dried FBA was sieved to separate particles, with a gradation range from 4.75 mm to 75  $\mu\text{m}$ , to achieve a particle size distribution similar to fine sand, in accordance with AS 2758.1.
- 3 **Grinding:** To enhance pozzolanic reactivity for use as an SCM, the FBA was ground using a planetary ball mill (Across International PQ Series) with steel balls. A milling time of 15 to 30 minutes at 450 rpm was identified as optimal.
- 4 **Co-grinding:** A novel technique of co-grinding FBA with GGBFS was investigated to further activate the material mechanochemically.

#### Phase 2: Laboratory Testing of Mortar and Concrete Mixes (DEL-105 to DEL-106b)

Extensive laboratory testing was conducted to determine the optimal mix proportions for mortar and concrete applications.

- **Mortar mixes:** Initial tests evaluated FBA as a sand replacement (25%, 50%, 75% and 100%) and as a cement replacement (10%, 20% and 30%). Tests measured flowability, density, compressive strength, flexural strength and water absorption.
- **Concrete mixes:** Based on the mortar results, eight different concrete mix designs were formulated. These included a control mix of conventional concrete, a mix with 25% FBA as a sand replacement, and various mixes utilising separately ground and co-GFBA and GGBFS as SCMs. The mixes were tested for fresh properties (initial slump, slump retention, density and air content) and hardened properties (compressive strength at 7, 28, and 56 days, flexural strength, split tensile strength and modulus of elasticity). Durability performance was also rigorously evaluated, including water absorption, abrasion resistance, sulphate and acid attack resistance, drying shrinkage and carbonation resistance.

### **Phase 3: Industrial Trial and Life Cycle Assessment (DEL-107 and DEL-110)**

The optimised laboratory mix was scaled up for an industrial-scale trial. On 20 February 2025, Daracon manufactured the FBA concrete at their Cameron Park batching plant and transported it 45 km to construct a 10x1,2x0.2 m pedestrian footpath near the Vales Point Power Station. The performance of the FBA concrete was evaluated against a control mix and Transportation for NSW (TfNSW) R83 specifications. Concurrently, a comprehensive LCA was conducted using SimaPro software and supporting mathematical calculations to quantify the environmental and economic benefits of the concrete mixes.

### **3.2 Materials, facilities and equipment applied**

This project deliberately combined university laboratory capability with industry production capability to ensure that outcomes were both scientifically defensible and operationally realistic.

#### **• Materials**

- Furnace Bottom Ash (FBA): Supplied by Delta Electricity from Vales Point and Eraring Power Stations (NSW), representative of operational coal combustion processes.
- Ground Granulated Blast Furnace Slag (GGBFS): Supplied by Daracon for co-grinding trials.
- Portland Cement and Aggregates: Commercially sourced through Daracrete/Daracon batching operations for both laboratory validation and industrial field trials.
- Admixtures: To improve the workability of mixes, a high-range water-reducing admixture (MasterGlenium SKY 8100), complying with AS 1478.1 was used.

#### **• Facilities and Equipment**

- University of Newcastle (UON) Materials Laboratories – supporting material characterisation, process development, and performance validation:
  - Across International PQ Series Planetary Ball Mill for controlled grinding and co-grinding trials (including optimisation speed and duration) (DEL-104).
  - Sieving and oven-drying facilities for raw FBA preparation and processing.

- Laser particle size analyser (e.g., Mastersizer), XRF, and SEM for particle size distribution, chemical composition, and microstructural characterisation.
- Concrete and mortar testing facilities for evaluation of fresh properties, mechanical performance, and durability.
- SimaPro LCA software (licensed) for cradle-to-gate CO<sub>2</sub> footprint, energy consumption, and environmental impact assessment of designed concrete mixes.
- Industry Infrastructure (Piloting Capability):
  - Access to commercial concrete batching and delivery systems (Daracon Group) to enable scale-up validation and practical implementation trials.

### 3.3 Prior Work and Background IP Leveraged

- Prior Work Leveraged

The project built upon established international and Australian research on coal combustion products (CCPs) and supplementary cementitious material (SCM) systems, with particular emphasis on overcoming the historic under-utilisation of FBA due to its physical and processing limitations.

- Background IP and Capability Contributions

University of Newcastle contribution (background capability/IP): expertise in concrete materials science, advanced characterisation (chemical, physical, and microstructural), and the development of controlled grinding/co-grinding processing methodologies.

- Industry contributions (background capability/IP):
  - Facilitation of access to FBA feedstock streams and provision of operational insight (Delta Electricity).
  - Supply of slag for concrete production and trial mix production (Daracon).
  - Standards development and CCP industry knowledge networks (ADAA).
  - Batching, scale-up, and piloting capability using the Daracon mix design framework for Grade 40 eco-efficient concrete (Daracrete/Daracon).

- Life Cycle Assessment (LCA):

The project primarily leveraged UON team know-how, operational capability, and applied processing and product lifecycle assessment. Its differentiator lies in integrating these capabilities into a validated, repeatable workflow for low-carbon Grade 40 concrete production.

### 3.4 Uniqueness/novelty and competing approaches

- Uniqueness and novelty
  - A co-grinding pathway (FBA + GGBFS) implemented as a practical refinery-style processing procedure (DEL-104), rather than a purely academic activation concept.

- A dual-function utilisation model: FBA is treated as both a partial fine-aggregate replacement stream and a cementitious contribution pathway (GFBA + GGBFS system), rather than a single-use application.
- End-to-end validation from laboratory testing to industrial trials, followed by LCA and cost modelling within an Australian procurement and transport context (DEL-111).
- This project's key advantage is that it targets a currently underutilised by-product (FBA) and demonstrates a pathway compatible with existing concrete batching infrastructure and specification-based adoption, while quantifying both CO<sub>2</sub> and cost impacts for the same mix family.
- Competing solutions/technologies
  - Conventional SCM substitution routes (fly ash, slag, silica fume), geopolymer systems, and commercially available low-carbon blended cements are the main competing approaches to lowering embodied carbon in concrete.

### 3.5 Validation approach, standards basis, and success metrics

Validation was designed as a series of progressive “gates” linked to hypotheses, moving from material suitability to mix performance, followed by constructability, and finally life-cycle and economic feasibility.

- **Performance and compliance metrics**

- **Fresh properties:** slump/workability and production consistency in both lab and industrial contexts (DEL-106 and DEL-111).
- **Mechanical performance:** compressive strength development relative to control mixes and suitability for the nominated footpath application (DEL-106 and DEL-111).
- **Durability screening:** water absorption, abrasion resistance, shrinkage, carbonation and chemical resistance (DEL-111).
- **Life Cycle Assessment:** modelled using ReCiPe 2016 and supplementary manual calculations; results reported per m<sup>3</sup> and per MPa, with sensitivity analysis (DEL-110 and DEL-111).

- **Definition of Successful Delivery**

Outputs were deemed successfully delivered when the following criteria were met:

- A repeatable and documented processing protocol for FBA preparation and co-grinding was established and experimentally validated (DEL-104).
- Optimised concrete mixes achieved required structural performance and constructability benchmarks, including validation under industrial trial conditions (DEL-111).
- Environmental and economic feasibility was rigorously quantified using recognised LCA and cost modelling methodologies, demonstrating measurable value relative to control concretes (DEL-111; DEL-103a for early-stage feasibility).

- Successful delivery was formally reviewed and agreed upon by all project entities and consortium members in accordance with the Project Agreement governance framework.

### 3.6 Industry Engagement During Delivery

Industry engagement was systematically planned and actively implemented through formal workshops, technical forums, partner collaboration, and live demonstration activities, ensuring ongoing technical relevance, industry feedback, and adoption readiness throughout project delivery.

- **Continuous Partner Engagement (Project Agreement Framework)**

Industry partners were actively involved across the program lifecycle, contributing feedstock supply (FBA and slag), batching capability, operational expertise, specification requirements, and end-user perspectives. Collaboration between the University of Newcastle, Delta Electricity, Daracon/Daracrete, and other consortium members ensured alignment between laboratory development and real-world implementation.

- **Structured Workshops, Seminars, and Conferences**

Industry communication and knowledge transfer were delivered through formal seminars, industry forums, and national/international conferences, as documented in DEL-108, including:

- SmartCrete Community of Practice – Sustainable Concrete (20 May 2025), with more than 40 industry participants.
- Concrete Institute of Australia Forum – Implementing Circular Economy Practices in Concrete: Challenges and Solutions (3 April 2025), with more than 30 professionals.
- SmartCrete CRC Sustainability in Concrete Workshop (September 2025), with more than 50 attendees.
- Concrete 2025 – 32nd Biennial Conference of the Concrete Institute of Australia (7–10 September 2025, Adelaide Convention Centre), supporting national dissemination of low-carbon concrete research outcomes.
- The 2023 International Conference on Green Building (ICoGB 2023), contributing to international knowledge exchange on sustainable construction materials.

These events targeted engineers, sustainability practitioners, government stakeholders, CCP producers, and cement and concrete manufacturers. Presentations covered laboratory results, LCA findings, regulatory considerations, and scale-up pathways, with structured Q&A sessions addressing performance concerns and industrial grading and specification feasibility. These structured engagements ensured technical dissemination across academia, industry, regulators, and end-users, thereby strengthening adoption pathways for FBA-based low-carbon concrete systems.

- **Demonstration-Based Engagement**

Feedback from the workshops and industry forums demonstrated strong interest in rigorous LCA validation, clearer regulatory and standards pathways, and progression towards pilot-

and commercial-scale implementation. Engagement activities materially strengthened academia–industry collaboration, de-risked technology adoption through technical dialogue and demonstration, and supported the transition from laboratory optimisation to specification-ready eco-friendly concrete aligned with circular-economy and decarbonisation objectives.

## 4. Analysis of Key Results, Deliverables, Description of Outputs and Project IP

### 4.1 Key results discussion

#### 4.1.1 FBA as fine aggregate in concrete and mortar

- **FBA as fine aggregate replacement in mortar**

The mortar results presented in Table 1 show that increasing the FBA replacement level generally reduced workability and density. Flowability decreased from 169.5 mm for the control mix to 152.5 mm at 100 % FBA replacement, indicating that higher FBA contents made the mixes less workable. This is likely due to the angular shape and higher water absorption of FBA compared with natural fine aggregate. The 28-day density also decreased as the FBA content increased, from 2341.1 kg/m<sup>3</sup> for the control mix to 1781.0 kg/m<sup>3</sup> at 100 % replacement, which is consistent with the lower density of FBA.

In terms of performance, the mix containing 25 % FBA gave the best overall result. It achieved the highest 28-day compressive strength of 43.9 MPa and the lowest water absorption of 6.2 %, compared with 37.9 MPa and 7.2 % for the control mix. At replacement levels above 25 %, compressive strength decreased and water absorption increased. The 100 % FBA mix gave the lowest strength and highest absorption. Based on these results, a 25 % volumetric replacement of fine aggregate with FBA appears to be the most suitable option for further consideration.

**Table 1. Effect of FBA as a fine aggregate replacement on flowability, density, compressive strength and water absorption. See Appendix B for mix design proportions**

FBA as Fine Aggregate Replacement (%)	Flowability of Mixes (mm)	Density at 28 Days (kg/m <sup>3</sup> )	Compressive Strength at 28 Days (MPa)	Water Absorption (%)
0	169.5	2341	37.9	7.2
25	163.5	2187	43.9	6.2
50	161	2076	31.9	7
75	157.5	1905	31	8.5
100	152.5	1781	29.3	10.6

- **FBA as fine aggregate and cement replacement in mortar**

Table 2 shows that when FBA was used as both fine aggregate and cement replacement, flowability decreased further as the GFBA replacement level increased, reaching 175 mm at 30 % GFBA. The 28-day density of all mortars containing FBA was lower than that of the control mortar, which is consistent with the lower density of FBA-based materials.

In terms of strength, the best result was achieved when 25 % FBA as fine aggregate replacement was combined with 10–20 % GFBA as cement replacement, achieving 40.5 MPa. At 30 % GFBA, compressive strength decreased to 35.9 MPa, indicating that the higher replacement level was less favourable. For 28-day flexural strength, the mortar containing 25 % FBA as fine aggregate replacement and 10 % GFBA as cement replacement gave the best result among the modified mortars, while the 30 % GFBA mix gave the lowest value.

The 28-day water-absorption results show that the lowest water absorption was recorded at 10–20 % GFBA, which also corresponded with the highest compressive strength result. This indicates that 20 % GFBA as cement replacement, together with 25 % FBA as fine aggregate replacement, provided the most balanced performance in terms of workability, strength and absorption.

**Table 2. Summary of mortar properties for mixes containing 25 % FBA as a fine-aggregate replacement and GFBA as a cement replacement. See Appendix B for mix design proportions**

FBA as fine aggregate replacement (%)	GFBA as cement replacement (%)	Flow table value (mm)	Density at 28 days (tonnes/m <sup>3</sup> )	Compressive strength at 28 days (MPa)	Flexural strength at 28 days (MPa)	Water absorption at 28 days (%)
0	0	185	2.341	34.9	4.5	4.61
25	0	182	2.187	37.4	3.9	4.99
25	10	182	2.201	38.1	4.4	4.7
25	20	178	2.197	40.5	4.1	4.49
25	30	175	2.165	35.9	3.7	4.77

- **FBA as fine aggregate replacement in concrete**

Table 3 shows that replacing natural fine aggregate with FBA affected both the fresh and hardened properties of the concrete. The slump dropped from 220 mm for the control mix to 180 mm at 25 % FBA when the same superplasticiser dosage was used, confirming that FBA reduced workability. At higher FBA replacement levels, additional superplasticiser was required to recover or increase slump. This means that the higher slump values at 75 % and 100 % FBA should not be interpreted as improved natural workability, but rather as the result of higher chemical admixture dosage. The 28-day density decreased steadily from 2342 kg/m<sup>3</sup> for the control mix to 2161 kg/m<sup>3</sup> at 100 % FBA, which is consistent with the lower density of FBA compared with natural sand.

As shown in Table 3, the strength results indicate that moderate FBA replacement can be used without loss of mechanical performance. The 28-day compressive strength increased slightly at 25 % FBA and reached the highest value at 50 % FBA, at 46.96 MPa, compared with 42.47 MPa for the control mix. However, performance dropped noticeably at 75 % and 100 % replacement, where the 28-day strength fell to 34.43 MPa and 31.01 MPa, respectively. Water absorption at 28 days remained similar to or slightly lower than the control mix at 25 % and 50 % FBA, but increased at 75 % FBA. The 100 % FBA mix did not show the highest absorption, which suggests that water absorption was influenced not only by FBA content but also by the higher superplasticiser dosage and overall mix behaviour. Overall, the concrete results suggest that FBA can be used effectively as a partial fine-aggregate replacement with 25–50 % replacement appearing to be the most suitable range for further consideration.

**Table 3. Effect of FBA as a fine aggregate replacement on concrete slump, density, compressive strength and water absorption of concrete.**

FBA as Fine Aggregate Replacement (%)	Achieved Slump (mm)	Density at 28 Days ( $\text{kg/m}^3$ )	Compressive Strength at 28 Days (MPa)	Water Absorption at 28 Days (%)
0	220	2342	42.47	4.4
25	180	2262	45.4	4.1
50	210	2238	46.96	4.1
75	220	2199	34.43	5.8
100	240	2161	31.01	4.5

Based on the results, the optimum FBA content is 25 % for mortar and 25–50 % for concrete. On balance, 25 % FBA is the preferred option because it provides the most balanced performance across workability, strength, and water absorption, while 50 % FBA also performed well in terms of concrete strength.

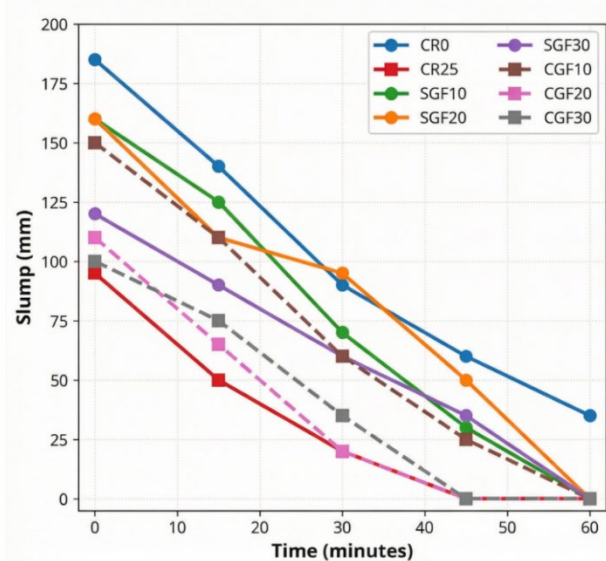
#### 4.1.2 FBA as fine aggregate and cement replacement in concrete.

- **Fresh properties (See Appendix C for mix design proportions)**

Figure 2 shows the slump and slump-retention results for the concrete mixes. The control concrete, with no FBA as fine-aggregate replacement and no cement replacement, achieved the highest initial slump of 185 mm using  $1.7 \text{ L/m}^3$  of superplasticiser. When 25 % of the fine aggregate was replaced with FBA, the initial slump dropped to 95 mm, and workability was lost after 45 minutes. This indicates that FBA reduced workability and increased the rate of slump loss.

Concrete mixes containing 25 % FBA as fine-aggregate replacement together with GGBFS–GFBA binder replacement required a higher superplasticiser dosage of  $2.7 \text{ L/m}^3$ .

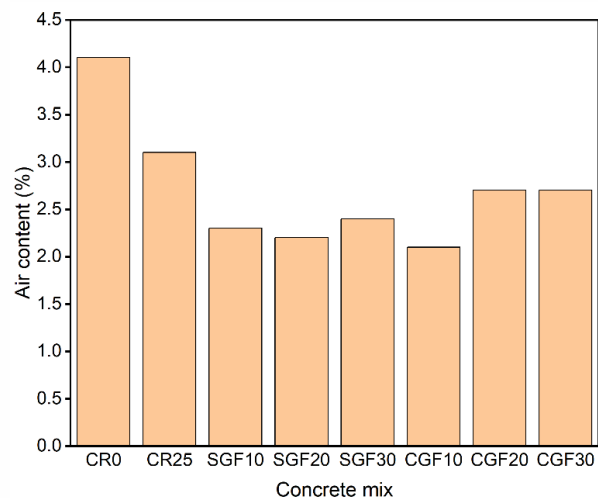
These mixes performed better than the concrete containing 25 % FBA only, but still showed lower slump retention than the control concrete. In general, slump retention reduced as the GFBA replacement level increased from 10 % to 30 %. The mixes produced using separately ground GGBFS–GFBA binder performed better than those produced using co-ground binder. Accordingly, lower GFBA replacement levels and separate grinding gave better workability retention, while higher replacement levels and co-grinding increased water demand and reduced slump retention.



**Figure 2: Slump retention of concrete mixes**

Figure 3 shows that the use of FBA generally reduced the air content of the concrete mixes. The control concrete recorded the highest air content at 4.1 %, while the concrete containing 25 % FBA as fine-aggregate replacement showed a reduction to 3.1 %. When 25 % FBA as fine-aggregate replacement was used together with GGBFS–GFBA binder replacement, the air content was generally below 3.0 %.

The results also show only minor differences between the two grinding methods. The separately ground mixes were in the range of approximately 2.2–2.4 %, while the co-ground mixes were in the range of approximately 2.1–2.7 %. On balance, the modified mixes showed lower air content than the control concrete, indicating that the inclusion of FBA and blended binder materials altered the air-void behaviour of the fresh concrete.

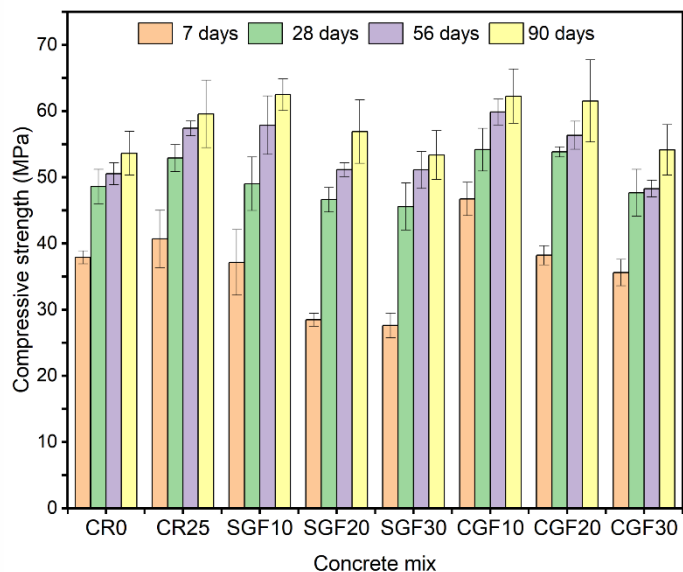


**Figure 3: Air content of Concrete Mixes**

### • Mechanical Performance

Figure 4 shows that the use of FBA as a partial replacement for fine aggregate generally enhanced concrete strength compared with the control mix. The concrete containing 25 % FBA as fine-aggregate replacement performed better than the control concrete at all test ages, indicating that this replacement level is suitable and beneficial for strength development.

The results also show that combining 25 % FBA as fine-aggregate replacement with GGBFS–GFBA binder replacement can further enhance compressive strength, particularly at lower GFBA replacement levels. In general, the mixes prepared using the co-grinding method showed better early-age strength, while both grinding methods gave comparable later-age strength. Higher GFBA replacement levels showed lower early strength, but strength increased with curing time.



**Figure 4: Compressive strength of Concrete Mixes**

Table 4 shows that using 25 % FBA as fine-aggregate replacement on its own resulted in only a small reduction in density and mechanical properties compared with the control concrete. The density reduced from 2334.49 kg/m<sup>3</sup> for the control mix to 2295.23 kg/m<sup>3</sup>, while split tensile strength, flexural strength and modulus of elasticity also showed only minor reductions. This

indicates that 25 % FBA can be used in concrete without a major loss in overall structural performance.

Table 4 also shows that improved results were achieved when 25 % FBA as fine-aggregate replacement was combined with GGBFS–GFBA cement replacement. The strongest overall performance was obtained with 25 % GGBFS + 10 % GFBA using the co-grinding method. This mix achieved the highest split tensile strength (4.82 MPa), the highest flexural strength at 28 days (6.50 MPa), and the highest modulus of elasticity at 28 days (34.27 GPa). Its density (2316.11 kg/m<sup>3</sup>) also remained close to that of the control concrete. This result suggests that the combination of moderate replacement levels and co-grinding produced a more effective binder system and improved overall concrete performance.

As the GFBA cement-replacement level increased, density and mechanical performance generally decreased for both grinding methods. This trend was more pronounced at higher replacement levels, particularly for flexural strength and modulus of elasticity. In general, the co-ground mixes performed better than the separately ground mixes at the same replacement level, especially at lower GFBA contents. On balance, the results indicate that 25 % FBA as fine-aggregate replacement is suitable for concrete, and that the most favourable results were achieved when it was combined with lower GFBA cement-replacement levels, particularly when using the co-grinding method.

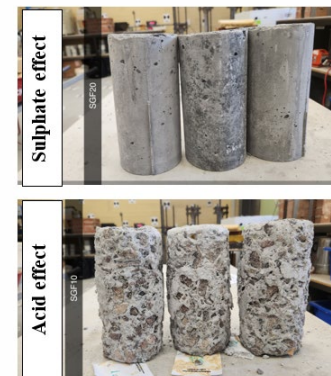
**Table 4. Summary of concrete density, water absorption, and mechanical properties for mixes containing FBA as a fine-aggregate replacement and GGBFS–GFBA as a cement replacement.**

FBA as fine aggregate replacement (%)	Cement replacement	Grinding method	Split tensile strength (MPa)	Density (kg/m <sup>3</sup> )	Flexural strength (MPa)	Modulus of elasticity (GPa)
0	None	Not applicable	4.72	2334	6.33	33.53
25	None	Not applicable	4.3	2295	5.72	33.06
25	25% GGBFS + 10% GFBA	Separate grinding	4.34	2294	5.67	32.79
25	25% GGBFS + 20% GFBA	Separate grinding	3.69	2278	4.87	29.18
25	25% GGBFS + 30% GFBA	Separate grinding	4.47	2247	4.44	28.43
25	25% GGBFS + 10% GFBA	Co-grinding	4.82	2316	6.5	34.27
25	25% GGBFS + 20% GFBA	Co-grinding	4.21	2291	5.71	32.67
25	25% GGBFS + 30% GFBA	Co-grinding	3.76	2249	5.28	29.69

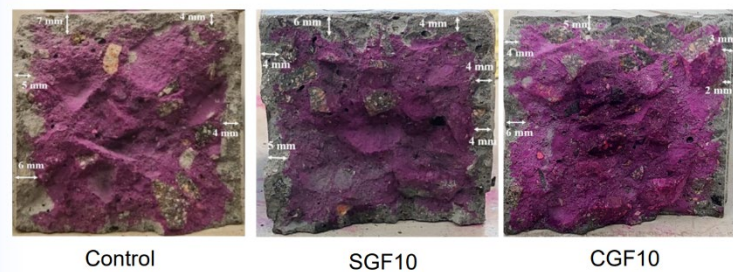
- **Durability**

Table 5 shows that using 25% FBA as fine-aggregate replacement alone resulted in a small improvement in some durability results compared with the control concrete. Mass loss in sulphuric acid, and compressive-strength loss in both sulphuric acid and magnesium sulphate, were lower than those of the control mix, while water absorption remained similar. However, carbonation depth increased, indicating that the use of FBA as a fine aggregate on its own did not improve all durability properties.

Figure 5 shows the visual condition of the concrete specimens after exposure to magnesium sulphate and sulphuric acid solutions. The specimens exposed to magnesium sulphate showed only minor surface changes, with limited discolouration and no major loss of section. In contrast, the specimens exposed to sulphuric acid showed severe surface deterioration, including paste loss, roughened surfaces, and clear exposure of coarse aggregate. Better overall durability was achieved when 25% FBA as fine-aggregate replacement was combined with 25:10 and 25:20



**Figure 5: Visual observation of immersed specimens**



**Figure 6: Visual observation of carbon penetration depth**

GGBFS:GFBA ratios as cement replacement. In general, these mixes showed lower mass loss and lower strength loss than both the control concrete and the concrete containing 25% FBA only. The best overall performance was obtained at the lower GFBA replacement levels, particularly when the binder was prepared using the co-grinding method. This combination resulted in the lowest sulphuric-acid mass loss, the lowest sulphuric-acid strength loss, low magnesium-sulphate strength loss, and a low carbonation depth. Water absorption was also lower than that of the control concrete, indicating a denser and less permeable concrete matrix.

As the GFBA cement-replacement level increased, durability performance generally declined. This trend was observed under sulphuric acid exposure, magnesium sulphate exposure, water absorption, and carbonation depth. Figure 6 shows the visual appearance of the three concrete specimens with the highest carbonation resistance after the accelerated carbonation test. The increase in carbonation depth was more noticeable at higher GFBA replacement levels for both grinding methods.

It can be concluded that 25% FBA as fine-aggregate replacement can be used successfully in concrete; however, the most favourable durability performance was achieved when it was combined with lower GFBA cement-replacement levels, particularly when using the co-grinding metho.

**Table 5. Summary of durability properties for concrete containing FBA as a fine-aggregate replacement and GGBFS–GFBA as a cement replacement. See Appendix C for mix design proportions**

FBA as fine aggregate replacement (%)	Cement replacement	Grinding method	Mass loss after sulphuric acid exposure (%)	Mass loss after magnesium sulphate exposure (%)	Compressive strength loss after sulphuric acid exposure (%)	Compressive strength loss after magnesium sulphate exposure (%)	Water absorption at 28 days (%)	Carbonation depth after 56 days in 4% CO <sub>2</sub> (mm)
0	None	Not applicable	16.06	0.88	51.15	15.52	3.98	4.33
25	None	Not applicable	14.43	0.9	47.61	13.31	3.87	5.67
25	25% GGBFS + 10% GFBA	Separate grinding	8.22	0.65	46.31	9.62	3.31	4.58
25	25% GGBFS + 20% GFBA	Separate grinding	8.56	0.61	47.45	9.72	3.58	8.08
25	25% GGBFS + 30% GFBA	Separate grinding	10.99	0.81	49.53	13.02	3.74	8.58
25	25% GGBFS + 10% GFBA	Co-grinding	7.15	0.63	41.28	9.47	3.26	4.17
25	25% GGBFS + 20% GFBA	Co-grinding	10.28	0.59	43.85	10.07	3.17	6
25	25% GGBFS + 30% GFBA	Co-grinding	11.26	0.78	48.72	11.75	4.08	7.58

Figure 7 shows the drying shrinkage for the concrete mixes. The results show that using 25 % FBA as fine-aggregate replacement alone increased drying shrinkage compared with the control concrete. However, when GFBA was also used as part of the cement replacement, shrinkage was reduced. In general, the mixes containing 25 % FBA as fine-aggregate replacement together with GGBFS–GFBA binder replacement gave lower shrinkage than the mix containing 25 % FBA only. This indicates that the binder replacement helped offset the higher shrinkage associated with FBA used as fine aggregate. On balance, the shrinkage results remained within acceptable limits for practical application.

The abrasion results, as depicted in Figure 8, show that surface durability improved with curing time. At 28 days, the concrete containing 25 % FBA as fine-aggregate replacement alone showed only limited improvement compared with the control concrete. Better abrasion performance was achieved when 25 % FBA as fine-aggregate replacement was combined with GGBFS–GFBA binder replacement, particularly for the mixes prepared using the co-grinding method. At 56 days, all mixes showed lower mass loss than at 28 days, confirming improved abrasion resistance with continued curing. Overall, the results indicate that abrasion resistance was influenced by curing age, grinding method and GFBA replacement level, with the most favourable performance generally achieved using the co-grinding method and lower GFBA replacement levels.

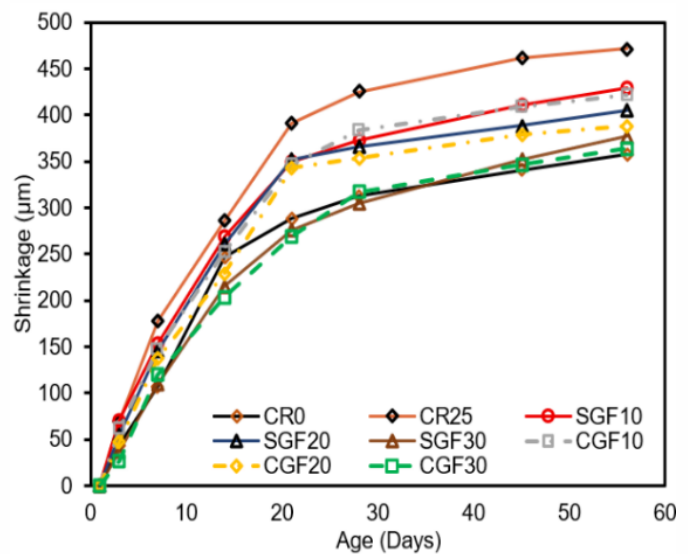


Figure 7: Drying Shrinkage of Concrete Mixes

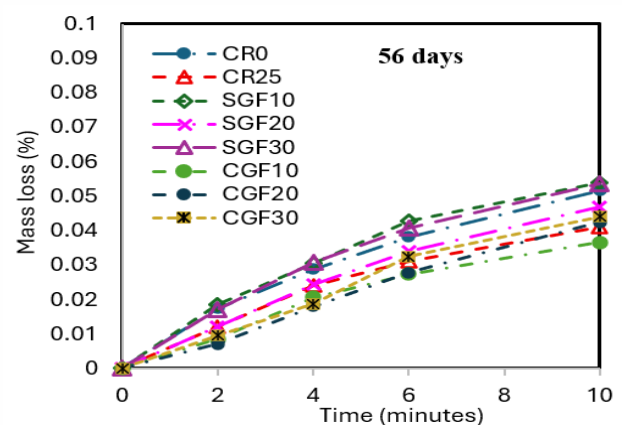
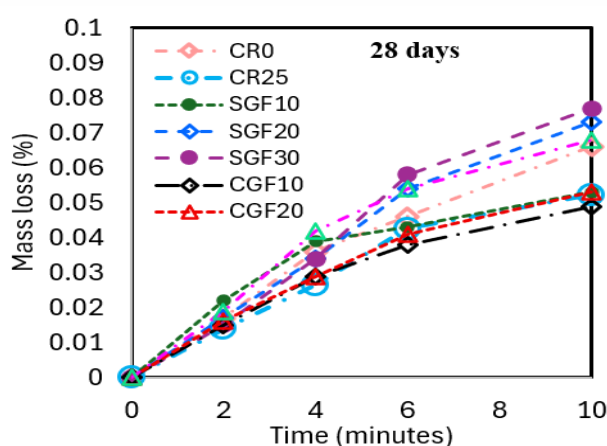


Figure 8: Abrasion resistance: mass loss percentages at 28 and 56 days.

### 4.1.3 Life cycle assessment

Figure 9, Figure 10 and Figure 11 show that using 25% FBA as fine-aggregate replacement had only a limited effect on the overall environmental and cost indicators. Compared with the control concrete, the total embodied energy and total CO<sub>2</sub> emissions were slightly higher due to the drying and sieving treatment of FBA, while the mix cost was slightly lower. However, the performance-based indicators, expressed per unit strength, showed a small improvement. This indicates that replacing fine aggregate with FBA alone did not deliver a major reduction in embodied impacts, but did slightly improve efficiency when strength is considered.

Clearer benefits were achieved when 25% FBA as fine-aggregate replacement was combined with GGBFS–GFBA binder replacement. In general, these mixes showed lower embodied energy, lower CO<sub>2</sub> emissions and lower material cost than both the control concrete and the concrete containing 25% FBA only. The same trend was also observed for the binder-only values. As the GFBA replacement level increased, the total energy, total CO<sub>2</sub> and total cost generally decreased.

Results confirmed that using FBA in concrete mixes can achieve a 20–36% reduction in embodied carbon through combined cement and sand replacement (with 10–30% GFBA as cement replacement and 25% FBA as sand replacement) compared with a standard normal concrete mix. The lowest overall values were recorded for the mixes with the highest GFBA replacement levels, particularly for the mix prepared using the separate grinding method. This mix also achieved the lowest energy, carbon emissions and cost values when expressed on a per-unit-strength basis. Cost analysis

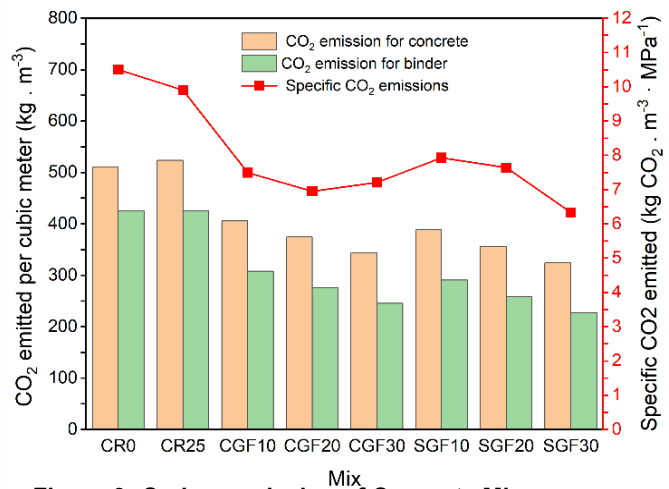


Figure 9: Carbon emission of Concrete Mixes.

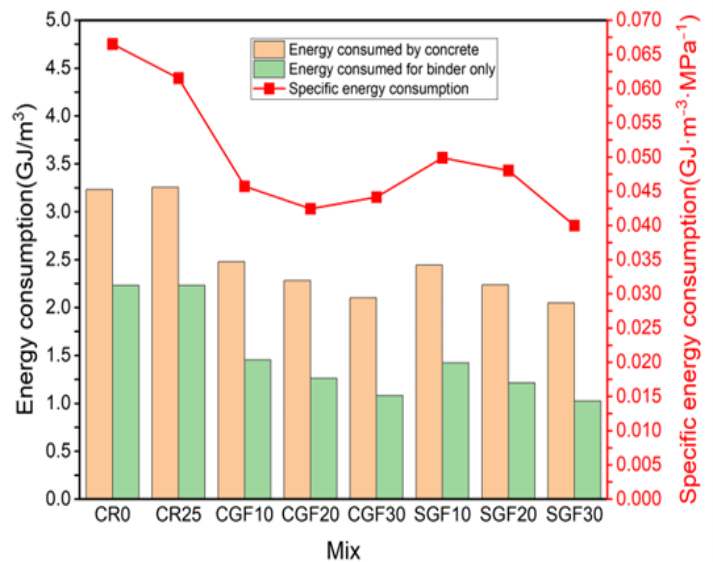


Figure 10: Energy consumption of Concrete Mixes

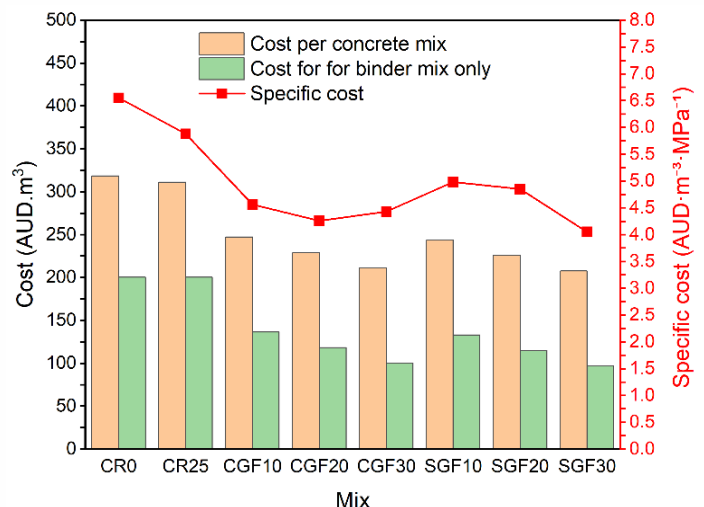


Figure 11: Production cost of Concrete Mixes

demonstrated savings of AUD \$71–111 per m<sup>3</sup> when using optimised FBA mixes with 30 % cement replacement. For a medium-sized concrete supplier producing 70,000 m<sup>3</sup> annually, this represents potential savings of AUD \$5.0–7.8 million per year.

Ultimately, the results indicate that the main environmental and cost benefits came from reducing cement content through the use of GGBFS–GFBA binder replacement, rather than from using FBA as fine-aggregate replacement on its own. From a practical point of view, the results show that higher binder-replacement levels provided the greatest reduction in embodied impacts and cost, although the final mix selection should also consider strength, durability, and workability requirements.



Figure 12: The trial footpaths location

#### 4.1.4 Field applications

- **Fresh and hardened properties (See Appendix E for mix design proportions)**

The trial footpaths were constructed at Tom Barney Oval, near Delta Electricity’s Vales Point Power Station at Mannering Park, as shown in Figure 12. Concrete was transported from the batching plant to site over a distance of approximately 45 km, with a travel time of approximately 40 minutes. The site was appropriately prepared before casting, including excavation, formwork and reinforcement (Figure 13). Both the control concrete and the FBA concrete were delivered, placed, compacted and finished successfully under normal site conditions (Figure 14).



Figure 13: The trial footpaths construction

In terms of mix performance, Table 6 shows that the FBA concrete achieved lower strength than the control concrete but still met the performance requirements for footpath applications. In the laboratory trial, the FBA concrete had a similar slump to the control concrete. Under industrial production conditions, the FBA concrete showed a lower slump and slightly higher air content; however, it remained sufficiently workable for placement.

The compressive strength of the FBA concrete was lower than that of the control concrete at 7, 28, and 56 days. The difference was greatest at early ages, while the gap reduced at later ages. The FBA concrete still achieved acceptable 28-day and 56-day strength for the intended application. Flexural strength was also

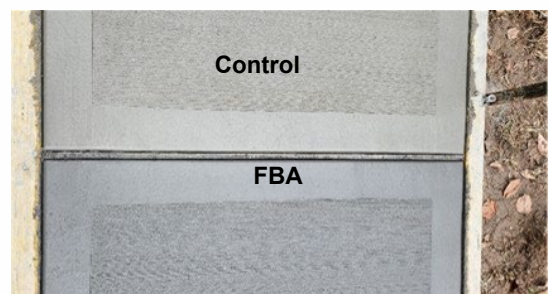


Figure 14: Colour differences of Two mixes

slightly lower than that of the control concrete. Density remained in a similar range for both mixes.

The FBA concrete showed higher drying shrinkage than the control concrete in both the laboratory trial and the industrial application results. This indicates that shrinkage control measures and appropriate curing practices remain important for the field use of FBA concrete.

The trial results indicate that the FBA concrete was suitable for footpath construction. The mix was practical to produce, transport and place at site, and it achieved satisfactory fresh and hardened performance for this application.

**Table 6: Summary of fresh and hardened concrete properties for laboratory trial and industrial-application concrete mixes. See Appendix E for mix design proportions.**

Description	Trial Mix (UON Lab)		Industry Application Mixes			
	Control Concrete	FBA concrete	At batching plant		(UON Lab)	
	Control Concrete	FBA concrete		Control Concrete	FBA concrete	
Slump (mm)	120	125	125	110	-	-
Air Content (%)	-	-	2.6	2.8	-	-
Compressive Strength (MPa)						
7 days	21.5	13.2	20.0	13.5	20.8	13.1
28 days	29.8	27.6	35.5	26.5	33.4	31.2
56 days	-	-	39.0	32.5	37.7	34.5
Flexural Strength (28 days) (MPa)	4.56	4.14	-	-	4.02	3.74
Density (kg/m <sup>3</sup> ) (7 Days)	2278.76	2244.11	2270	2150	2236.71	2244.82
Shrinkage (21 days)	235	291	-	-	397	418

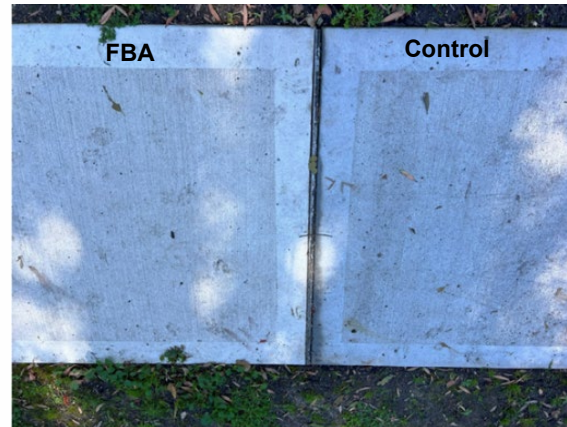
- **Post-cast observations**

A visual inspection of the footpaths was carried out approximately two months after casting. At that time, some surface dusting was observed on the footpath constructed with the FBA concrete mix, as shown in Figures 15 and 16. This was likely caused by rainfall after placement, which may have introduced excess moisture to the surface and weakened the surface layer during early-age curing. The risk of this type of surface issue may be higher in FBA concrete because FBA is more porous than conventional aggregates and can retain more water within the mix. This highlights the importance of appropriate curing practices and surface protection measures when using FBA concrete in field applications.



**Figure 15: Dusting on FBA concrete (after two months)**

A further inspection was conducted on approximately seven months after casting. The FBA concrete footpath showed satisfactory performance, with no significant surface wear, cracking, scaling, discolouration, spalling, delamination or joint deterioration, as shown in Figure 17. The surface condition remained sound under normal field exposure. These observations indicate that, despite the early dusting observed after two months, the longer-term performance of the FBA concrete footpath was satisfactory.



**Figure 16: Surface condition of trial mixes after two months**



**Figure 17: FBA concrete pavement: Surface appearance after two months**

## 4.2 Highlights from the Key Results

The key results demonstrate that the project achieved substantially more than a proof-of-concept. It established a validated and repeatable processing pathway, identified an optimal mix design and a wider range of viable alternatives, confirmed the advantages of co-grinding over separate grinding, demonstrated field-scale constructability, and quantified both environmental and commercial benefits. This provides a strong foundation for future standards development, scale-up, and broader industry implementation.

- A key result of the study was the identification of 25% FBA as the optimal fine aggregate replacement level. At this replacement level, the concrete consistently achieved the best overall balance of workability, strength, durability, and practical constructability. However, the results also showed that 50% FBA as fine aggregate replacement remained technically feasible, with performance broadly comparable to that of the conventional control mix. This is significant because it shows that the project outcomes are not confined to a single,

narrowly defined mix, but instead enable implementation across a wide range of performance requirements, processing capability, and economic conditions.

- For cementitious replacement, the most effective formulation was the co-ground blend containing 25% GGBFS and 10% GFBA, used in a concrete mix with 25% FBA as fine aggregate replacement. This mix delivered the most favourable overall performance and was therefore identified as the optimal mix configuration. It achieved compressive strengths of up to 54 MPa, with strength gains of approximately 23 % at 7 days and 11 % at 28 days relative to the conventional control concrete. The mix also recorded the highest split tensile strength, approximately 2% above the control, along with improved resistance to chemical attacks, carbonation, and abrasion, confirming that the benefits of the optimised blend extended beyond compressive strength alone.
- The broader strength results were equally important. The mix incorporating 25% GGBFS and 20% GFBA, together with 25% FBA as fine aggregate replacement, exhibited strength comparable to the control concrete at early ages and exceeded the control at later ages, while also demonstrated superior durability performance. Similarly, the mix containing 25% GGBFS and 30% GFBA showed slightly reduced early-age strength relative to the control concrete but achieved comparable or higher mechanical strength at later ages. These findings are important for industry application, as they demonstrate that higher levels of GFBA substitution remain technically viable, provided that slower early-age strength development can be accommodated within construction program requirements. In practical terms, the project therefore established not only a single optimal mix, but also a family of viable mix designs, offering flexibility to balance early-age performance, later-age strength development, reduction in carbon emissions, and cost outcomes.
- Another major finding was that co-ground mixes consistently outperformed their equivalent separately ground mixes, confirming the effectiveness of the co-grinding approach developed in this project. Co-grinding enhanced the interaction between GFBA and GGBFS, resulting in improved strength development, more favourable density characteristics, and superior durability-related performance. This result is strategically important because it demonstrates that the project's innovation lies not only in material substitution, but also in the processing methodology used to unlock the performance potential of FBA-based composites.
- The durability results further strengthened the case for adoption. Although the replacement of sand and cement with FBA generally reduced concrete density, the co-ground mixes achieved densities closer to that of the control concrete, indicating a more refined and cohesive matrix. The optimal co-ground mix recorded 18-20% lower water absorption and approximately 64% lower mass loss under abrasion testing compared with the control mix, and also demonstrated improved resistance to sulphate and acid attack. These outcomes indicate that the optimised FBA systems can deliver not only equivalent strength, but also measurable durability enhancement directly relevant to practical service-life performance.
- The industrial trial was one of the most important results of the project, as it demonstrated the successful translation of laboratory findings into a real construction field. The full-scale FBA-based concrete footpath achieved a 28-day compressive strength of 31.3 MPa, exceeding the 25 MPa design requirement and performing comparably to the control mix (33.4 MPa). This confirmed that the material could be reliably batched, transported, placed, finished, and cured under field conditions. At the same time, it identified a key

operational consideration: due to the absorptive nature of FBA, effective moisture management and slump-retention control are essential in commercial practice. This finding represents a valuable project outcome, as it clearly defines the practical handling and quality-control requirements necessary for successful implementation.

- The environmental and economic results further reinforced the significance of the technical outcomes. The LCA confirmed that the optimised FBA concrete systems can achieve substantial reductions in embodied carbon, in the order of 20-36%, depending on the extent of cement replacement, FBA processing, transportation distance and mix configuration. The greatest environmental benefit was associated with the cement replacement using GGBFS-GFBA, rather than sand replacement alone. From economic perspective, the results demonstrated that the optimised mixes have the potential to reduce concrete production costs, while simultaneously delivering additional value through reduced ash disposal requirements and improved utilisation of by-product materials. Taken together, these findings demonstrate that the project not only established technical feasibility, but also delivered a credible and integrated business and sustainability case for industry adoption.

### 4.3 Implications for project success

This project generated an integrated set of technical, environmental, economic, and industry-engagement outcomes that collectively demonstrate the practical viability of using FBA in concrete. Evidence from the laboratory program, field trial, LCA, and industry engagement shows that the project went beyond concept validation and established a credible, implementable pathway for transitioning FBA from legacy waste liability to a functional and value-adding construction material.

- **Processing and activation viability**

The project confirmed that raw FBA can be upgraded through a defined refinery-style processing pathway comprising drying, sieving, grinding, and co-grinding with GGBFS. The processing work reported in DEL-104 and carried forward into DEL-105, DEL-106 and DEL-111 showed that untreated FBA is variable and porous for direct high-value use; however, controlled pre-treatment produces a more consistent and reactive material suitable for concrete production. The co-grinding approach was particularly significant, as it enhanced fineness and reactivity and enabled FBA to function as part of a blended SCM system, rather than being limited to use as a low-value fine aggregate sand.

- **Implication for project success:**

This result directly validates the project's first core proposition: that FBA requires processing, and that such processing is technically achievable and can be formalised into a repeatable, scalable procedure suitable for future implementation.

- **Performance equivalence and concrete optimisation**

The laboratory program identified a well-defined family of viable mix designs, with the best performance achieved by mixes incorporating 25 % FBA as fine aggregate replacement together with 25% GGBFS and 10–20% GFBA as cement replacement. The strongest laboratory outcome was the obtained for the mix containing 25 % FBA as fine

aggregate and 10 % FBA co-ground with 25% GGBFS as cement replacement, which achieved approximately 54 MPa at 28 days, outperforming the control concrete. This mix also exhibited improved split tensile strength and favourable durability indicators. Across the broader program, the results consistently demonstrated that properly processed FBA-based systems can achieve satisfactory workability, mechanical performance, abrasion resistance, and resistance to aggressive exposure conditions.

- **Implication for project success:**

This result directly challenges the assumption that FBA is suitable only for low-grade or non-structural applications. It demonstrates that, when appropriately processed, FBA can be incorporated into technically robust concrete systems that deliver performance comparable to, or exceeding, conventional mixes for selected applications.

- **Industrial trial validation**

The project progressed beyond laboratory validation by demonstrating practical constructability through a full-scale footpath trial reported in DEL-107 and DEL-111. The industrial application, constructed near Vales Point Power Station for a 25 MPa-Grade concrete footpath, used an FBA-based mix under real batching, transport, placement, and curing conditions. The field trial achieved a 28-day compressive strength of approximately 31.3 MPa, compared with 33.4 MPa for the control mix, and exceeded the nominal TfNSW footpath strength requirement of approximately 25 MPa. The trial also highlighted an important operational consideration: due to the absorptive nature of FBA, effective moisture management and slump-retention control are essential for successful commercial implementation.

- **Implication for project success:**

The successful field trial was one of the project's most significant achievements, as it translated laboratory research into practical implementation evidence and materially strengthened the case for adoption by specifiers, local councils, and concrete producers.

- **Environmental and economic outcomes**

The LCA analyses reported in DEL-110 and DEL-111 confirmed that the most significant reductions in embodied carbon are achieved through cement replacement, rather than fine aggregate replacement alone. Across the evaluated mix group, the project demonstrated embodied carbon reductions of approximately 20–36 %, depending on the level of cementitious replacement and the processing pathway adopted. This is a significant outcome, as it positions FBA-based concrete as a genuine decarbonisation strategy, rather than solely a waste-reuse solution.

The economic case also strengthened over the life of the project. An initial scenario-based cost and environmental assessment was presented in DEL-103a, while subsequent project outputs and final mix-cost analysis demonstrated that the optimised mixes could deliver material cost reductions and establish a viable economic pathway for both concrete manufacturers and power-station operators. It can be concluded that the project demonstrated clear commercial promise, with cost benefits increasing at higher SCM replacement levels and additional indirect value arising from landfill avoidance and reduced ash-dam management burdens.

- **Implication for project success:**

The project demonstrated that FBA concrete can simultaneously address cost reduction, embodied carbon mitigation, and waste-management challenges, while delivering environmental performance, mechanical properties, and durability that match or exceed those of conventional concrete – a combination that is critical for industry adoption.

#### 4.4 Addressing the Industry Challenges

Table 7 summarises the key industry challenges associated with the use of FBA in concrete and demonstrates how the project outcomes addressed each of these barriers. Overall, the project systematically responded to technical, environmental, regulatory, and commercial constraints by establish a refining pathway for raw FBA, validating concrete performance at both laboratory and industrial scales, quantifying lifecycle carbon benefits, and identifying clear pathways for standards development and industry uptake. Collectively, these outcomes demonstrate that FBA can be repositioned from a legacy waste liability to a value-adding construction material resource.

**Table 7: shows how the Addressing the Industry Challenges**

Industry challenge	How project outcomes addressed the challenge
<b>FBA is treated as a legacy liability rather than a resource</b>	The project established a technically validated and implementable pathway for incorporating FBA into concrete as both a fine aggregate replacement and a component of blended SCM system, thereby transforming an ash-dam liability into a potential valuable product stream.
<b>Raw FBA has poor particle size grading, high porosity, and low reactivity</b>	DEL-104 and DEL-111 collectively detailed and validated a refinery-style processing protocol, comprising drying, sieving, grinding, and co-grinding with GGBFS, that effectively overcome these limitations.
<b>Industry lacks confidence in FBA concrete performance</b>	The project generated both laboratory-scale evidence and a full-scale footpath demonstration, showing that FBA concrete can achieve acceptable fresh properties, mechanical performance, and durability, and can be reliable batched, transported, placed and cured under practical site conditions.
<b>There is limited guidance for the use of FBA in concrete</b>	DEL-109 and DEL-111 reviewed relevant normative documents, analysed regulatory barriers, and established a technical foundation for the development of future FBA-specific standards, specifications, and quality-assurance pathways.
<b>Environmental benefits are often asserted but not quantified</b>	DEL-110 and DEL-111 quantified lifecycle carbon impacts using a combination of manual calculations and SimaPro-based LCA, demonstrating clear and measurable carbon

	reductions associated with the optimised SCM replacement pathway.
<b>Commercial value for industry partners has been unclear</b>	DEL-103a, DEL-110 and DEL-111 demonstrated that FBA use can support a viable business case through material substitution, landfill avoidance, and improved circular-economy utilisation of ash resource.

#### 4.5 Deliverables analysis: contracted versus achieved/actual

Table 8 compares the originally contracted project deliverables with those ultimately achieved. Overall, the project successfully delivered all major outputs, with several deliverables refined or expanded to more accurately reflect the depth and scope of the work undertaken. In some cases, deliverables were subdivided into more detailed components to improve clarity and practical usefulness, while the final national plan was delivered in the form of applied guidelines that fulfilled the same intended purpose. Although the full-scale trial was completed later than initially planned, it was delivered successfully. Taken together, these outcomes demonstrate that the project not only met its core objectives, but also added value through a broader, and more robust evidence base.

**Table 8. Summary of contracted deliverables and actual project achievements**

<b>Deliverable code</b>	<b>Contracted deliverable</b>	<b>Achieved outcome</b>
<b>DEL-101</b>	Recruitment of Research Assistant and enrolment of PhD candidate	<b>Achieved.</b>
<b>DEL-102</b>	Review of coal ash/CBA including quantities, location and geographic variation	<b>Achieved.</b> DEL-102 provides a comprehensive baseline assessment of FBA quantities, geographic distribution, and material composition across NSW, thereby and establishing the resource context for the project.
<b>DEL-103</b>	Cost-benefit impacts and normative documents	<b>Achieved in modified form.</b> The contracted deliverable was completed through <b>DEL-103a</b> , addressing cost and environmental benefits, and <b>DEL-103b</b> , providing a review of relevant normative documents).
<b>DEL-104</b>	Development of standard treatment/refinery procedures	<b>Achieved.</b> DEL-104 establishes the laboratory-based refinery procedures, including drying, sieving, grinding, and recommendations for scale-up.

<b>DEL-105</b>	Preliminary test results	<b>Achieved.</b> DEL-105 reports characterisation and preliminary mortar/concrete performance of refined FBA systems.
<b>DEL-106</b>	Final report on laboratory studies	<b>Achieved in expanded form.</b> The laboratory program was delivered as <b>DEL-106a</b> and <b>DEL-106b</b> , separating the main performance program from the later durability-focused investigations. This represents an expansion of scope and supporting evidence, rather than a shortfall against the contracted deliverable.
<b>DEL-107</b>	Full-scale trial	<b>Achieved, with timing later than originally anticipated.</b> The industrial footpath trial was completed in February 2025 and documented in DEL-107. The field trial occurred and produced usable validation evidence.
<b>DEL-108</b>	Training workshops	<b>Achieved.</b> DEL-108 documents three industry workshops/events and two conference engagements, including the <b>SmartCrete Community of Practice – Sustainable Concrete</b> (20 May 2025), the <b>Concrete Institute of Australia Forum</b> (3 April 2025), and the <b>SmartCrete CRC Sustainability in Concrete Workshop</b> (September 2025). In addition, project outcomes were disseminated at two further conferences: <b>Concrete 2025</b> conference (Adelaide) and the <b>International Conference on Green Building (ICoGB 2023)</b> .
<b>DEL-109</b>	National use – opportunities and challenges	<b>Achieved.</b> DEL-109 identifies the barriers and opportunities for national-scale adoption of FBA concrete products.
<b>DEL-110</b>	Life cycle assessment	<b>Achieved.</b> DEL-110 provides a detailed and dedicated LCA of FBA concrete using both manual calculations and SimaPro modelling.
<b>DEL-111</b>	Publication of National Plan for use of new product	<b>Achieved as "Guidelines".</b> DEL-111 is the final integrated guidelines document that fulfils the contractual intent of providing a practical roadmap for the use of FBA in concrete. It provides comprehensive guidance covering material characterisation, processing procedures, mix design, performance validation, industrial trial outcomes, environmental impacts

		assessment, economic considerations, and implementation pathways.
<b>DEL-116</b>	Intellectual property (IP) generation and final report	<b>Achieved:</b> The final report documents the project IP generated, including validated FBA processing procedures and concrete mix formulations, thereby fulfilling the intent of DEL-116 as the formal project close-out report.

The project achieved the substantive technical objectives of the contracted deliverables. Several deliverables were appropriately repackaged into sub-deliverables or expanded reports (e.g., DEL-103a/103b, DEL-106a/106b, and DEL-111) to better reflect the scope and depth of work undertaken. While the industrial trial was completed later than originally scheduled., it was delivered successfully. DEL-116 should be confirmed separately at project close-out.

#### 4.6 Description of Outputs and IP

The primary outputs of this project are a comprehensive suite of technical reports (DEL-102 to DEL-111) that systematically document the full project pathway, from fundamental material characterisation through to full-scale industrial application. Key outputs include:

- Established FBA pre-treatment protocols, including drying process, sieving gradations, and grinding/co-grinding duration and parameters.
- Optimised concrete mix design formulations validated through laboratory and industrial trials.
- Detailed life cycle assessment (LCA) datasets and cost-benefit models supporting environmental and economic evaluation.
- Practical site-based guidance and checklists for handling and placing FBA concrete.

**Project Intellectual Property (IP):** The Project IP generated consists of the proprietary knowledge, methodologies, and process known-how developed during the research. This includes the validated co-grinding parameters (GGBFS:FBA ratios, milling durations, and operating speeds) required to activate FBA for use as an SCM, as well as the high-performance concrete mix designs confirmed through the both laboratory testing and full-scale industrial trials.

## 5. Next Steps – Commercialisation & Impact Plan

### 5.1 Awareness, adoption and application plan

The plan for awareness and adoption is ground in full body of evidence generated by the project, including laboratory testing, durability assessment, life cycle carbon and cost analysis, and the full-scale footpath trial. All of this information is considered in DEL-111 (Guidelines), which is serves as the primary reference document for industry uptake. The key findings relevant to adoption are as follows:

- FBA can be made suitable for use in concrete through controlled drying, sieving, and grinding, with performance further enhanced when FBA is co-ground with GGBFS.
- A 25 % replacement of natural fine aggregate with FBA provides the most balanced overall performance; however, 50 % replacement also demonstrated performance broadly comparable to conventional concrete.
- For cement replacement, the optimal binder blend was 25 % GGBFS with 10 % GFBA. Mixes containing 20 % GFBA achieved performance comparable to the control at early ages and exceeded it at later ages, while 30% GFBA exhibited lower early-age strength but still reached target strengths by 28 days.
- Depending on the mix configuration, embodied carbon reductions of approximately 20–36 % were achieved. The field trial also highlighted important practical considerations, particularly the need active moisture management and slump-retention control during production and placement.

For industry adoption, DEL-111 serves as a practical implementation guide. It provides comprehensive guidance on material sourcing and characterisation, FBA processing requirements, concrete batching and handling practice, and the testing needed to demonstrate compliance with relevant Australian Standards and TfNSW specifications. Industry awareness and uptake can be further supported through the engagement channels documented in DEL-108, including targeted workshops, industrial forums, and direct engagement with specifiers and procurement teams.

## **5.2 Ongoing Activities and Asset Requirements**

To ensure that the research outcomes remain accessible and scalable, ongoing efforts should focus on supply-chain logistics and supporting infrastructure development. A primary requirement is the establishment of industrial-scale FBA pre-treatment facilities. As recommended in DEL-104, drying and sieving operations are best integrated directly at FBA generation sites to minimise transportation costs to major markets and increase the material's value at the point of origin. Grinding and co-grinding operations are most suitable integrated within existing cement manufacturing facilities or dedicated processing hubs, where appropriate capital assets (e.g. industrial ball mills) and operational expertise already exist. Achieving this will require targeted capital investment and strategic partnerships between power generators and cement manufacturers.

## **5.3 Commercialisation and impact table**

Table 9 summarises the post-project management and utilisation of project outputs and outlines a practical pathway for longer-term adoption. It clarifies arrangements for the handover and hosting of deliverables, management of project data and equipment, treatment of project IP, support for commercial uptake, ongoing dissemination activities, and identification of potential follow-on research opportunities.

**Table 9: Output handover, governance and long-term adoption pathway**

Consideration	At project close	Longer term
Handover of outputs	Comprehensive technical deliverables (DEL-102 to DEL-111) were produced, including validated FBA processing protocols (drying, sieving, grinding, and co-grinding), validated mix-performance outcomes (e.g., 25 % FBA as fine aggregate replacement combined with 25 % GGBFS and 10–30 % GFBA as cement replacement options), and LCA and cost datasets provided to SmartCrete CRC and participating industry partners, including Delta Electricity and Daracon/Daracrete.	Development of formal, standardised guidelines and plant-ready checklists for batching plants across Australia to support repeatable production and QA of FBA concrete.
Hosting of project outputs	Reports stored on the SmartCrete CRC repository and shared via secure partner-access platforms in accordance with project governance and the Communication Plan.	Key findings translated into publicly accessible technical publications, guidance notes, and presentations at major industry events (e.g., ADAA channels) to support broad accessibility.
Project data, materials and equipment	Laboratory equipment remains at UON. Remaining FBA samples stored for follow-up testing (e.g., longer-term durability checks) and to support future partner enquiries.	Datasets used to support standards development and end-of-waste/guideline pathways for FBA utilisation, including specification-ready performance and QA evidence.
IP management	SmartCrete CRC and industry partners manage project know-how relating to the FBA processing protocol and validated mix design approaches (including the co-grinding methodology and handling/QA controls), consistent with the Project Agreement.	Protection and commercial use of specific processing know-how and mix design guidance, where commercialised as proprietary low-carbon concrete products by industry partners.
Commercialisation	Industry partners assess integration of the validated FBA mix family into commercial offerings for near-term applications (e.g.,	Establishment of dedicated FBA processing capability (drying/sieving/grinding/co-grinding), ideally co-located at power stations or regional hubs, to supply consistent

	footpaths, shared paths, kerbs and similar low-to-moderate risk products), using DEL-111 as the implementation reference.	product at scale to the broader concrete market.
Dissemination	Project outcomes disseminated through industry workshops and briefings documented under DEL-108, supported by approved communication assets and partner networks.	Ongoing promotion through peak bodies and industry networks (e.g., Ash Development Association of Australia) and continued engagement with specifiers, councils, and transport authorities to normalise procurement and specification.
Follow-up research	Continued monitoring of demonstration works (where applicable) and targeted durability follow-up to build confidence in long-term field performance.	Expansion into additional applications (e.g., alkali-activated/geopolymer systems, advanced optimisation of mix designs) and broader validation across different FBA sources and operating conditions.

## 6. Education and Training

### 6.1 New Technologies and Processes

Integrating FBA into concrete production introduces new and modified practices across the supply chain. Targeted training is required to ensure these practices are implemented consistently, safely, and reliably, and to minimise performance variability arising from FBA's inherent porosity and moisture sensitivity.

- Pre-treatment and processing (QA-driven):** Personnel involved in material preparation require training in the full refinery-style processing pathway, including drying, sieving, grinding, and co-grinding with GGBFS. Training should emphasise the purpose of each step—such as grading control, fineness and reactivity development, and batch-to-batch consistency—and how these factors influence concrete performance. Instruction should also cover routine quality-assurance checks, including moisture content, particle grading, material variability, and appropriate handling and storage controls, to ensure repeatable and compliant feedstock quality.
- Concrete batching, mixing and handling:** Batch-plant operators and site crews require practical training on mix-specific handling controls for FBA concrete, with particular emphasis on moisture management and slump retention. The industrial trial demonstrated that the absorptive nature of FBA can increase water demand and contribute to slump loss between batching and placement if not proactively managed. Training should therefore address moisture correction, controlled water and admixture adjustments, and appropriate batching, transport, and site practices to ensure consistent workability and performance.
- Specification and acceptance testing:** Specifiers, asset owners, and quality-assurance teams require training to apply acceptance criteria and testing regimes aligned with relevant Australian Standards and TfNSW requirements. This includes appropriate interpretation of early-age and later-age strength development for different

SCM replacement combinations, recognising that some FBA–SCM blends exhibit slower early-age strength gain while achieving equivalent or superior later-age performance.

- **Work health and safety (WHS) requirements for material handling:** Training should also address WHS requirements associated with material handling, particularly where materials may contain crystalline silica (RCS) during processing, handling, and batching activities, in accordance with applicable WHS regulations and best-practice dust-control measures.

## 6.2 Training Providers and Target Trainees

Training on the use of FBA in concrete is recommended for relevant personnel involved in concrete production, power station material handling, transport, and processing. Key topics include material handling and characterisation, processing requirements, batching and mix control, quality assurance, and site practices for placing, finishing, and curing concrete. The intended audience includes batch plant operators, quality control personnel, civil contractors, and site trades involved in concrete production and construction.

## 6.3 Training requirements

Training may take the form of practical workshops, seminars, and standardised guidance materials. Existing practical tools, such as the Checklist for FBA Concrete at Site (DEL-111), provide a useful foundation for this purpose. Key topics include the practical differences between FBA concrete and conventional mixes, particularly in relation to water demand, workability adjustments, and curing appropriate practices.

## 6.4 Research capacity building and academic dissemination

The project also delivered strong education and workforce-development outcomes through both research staffing and higher-degree research contributions.

- **Research assistant contribution:** The project was supported by a dedicated Research assistant appointment (Dr Umer Sajjad), providing essential capability for laboratory coordination, materials testing support, documentation of procedures, and assisting the delivery of technical outputs and engagement activities.
- **PhD candidate contribution:** A PhD candidate (Ali Onaizi) contributed substantially to laboratory experimentation, analysis, and dissemination activities. This work underpinned key findings across the processing protocol development, mix optimisation, and durability validation program, and strengthened the evidence base required for industry adoption.
- **Conference participation and publications:** The PhD program and associated research outputs were disseminated through conference presentations and a growing publication record, including contributions to conferences and the following peer-reviewed or draft manuscripts aligned with project outcomes:
  1. *Integrated Use of Furnace Bottom Ash as Fine Aggregate and Cement Replacement for Sustainable Mortar Production* (Tang et al., 2024).

2. *Co-grinding treatment for developing integrated-properties SCMs from basic oxygen furnace slag and furnace bottom ash: A step toward synthesis advanced SCMs* (Onaizi, Tang, & Liu, 2024).
3. *Towards increased adoption of furnace bottom ash as sustainable building materials: Characterization, standardization, and applications* (Onaizi, Tang, Amran, et al., 2024).
4. *Comparative assessment of the effects of furnace bottom ash and fly ash on mortar performance* (Onaizi & Tang, 2024).

**Next Steps:** The PhD candidate is currently finalising his thesis submission and preparing several academic journal articles based on additional results generated through the project. This publication will contribute significantly to the academic dissemination of the research and the broader scientific understanding of FBA utilisation.

## 7. Conclusions, Implications and Recommendations

### 7.1 Challenges Overcome and Remaining

The project successfully overcame the primary technical challenges associated with FBA, including its high-water absorption, variable particle size, and low inherent reactivity. Through the development of a rigorous and scalable pre-treatment protocol involving drying, sieving, and co-grinding, the research team transformed a challenging coal-combustion by-product into a high-performance concrete ingredient. Furthermore, the successful execution of the full-scale industrial trial addressed and overcame industry scepticism regarding the practical application, workability, and constructability of FBA-based concrete.

However, challenges remain in relation to the commercial scale-up of these processes. Industry will require significant capital investment to establish dedicated drying, sieving, and grinding infrastructure at power stations and cement plants. Ensuring a consistent and reliable commercial-scale supply of refined FBA remains the primary barrier to widespread adoption. In addition, the formal development of FBA-specific Australian Standards is required to provide regulatory certainty for specifiers, designers, and engineers.

### 7.2 Project highlights

The project yielded several major highlights and significant achievements:

- **Exceptional material performance:** The development of the optimised mixes incorporating 25 % FBA as fine aggregate replacement together with 25% GGBFS and 10–20% GFBA as cement replacement, which achieved compressive strengths of up to 54 MPa and demonstrated a 64% improvement in abrasion resistance compared with conventional concrete.
- **Successful industrial validation:** The full-scale footpath trial at Vales Point demonstrated the practical feasibility of FBA concrete under field conditions. The FBA-based FBA trial mix achieved 31.3 MPa at 28 days, exceeding the 25 MPa compressive strength requirement for the footpath application in accordance with TfNSW specifications, and demonstrated that FBA trial mix concrete can be produced

and placed using standard equipment and practices. The trial mix concrete also highlighted important practical considerations related to curing and surface finishing.

- **Significant sustainability gains:** The product provided robust empirical evidence demonstrating that the optimised use of FBA can reduce the embodied carbon footprint of concrete by approximately 23 % - 29 %, with reduction up to 36 % achievable for optimal mix configuration. This sustainability gains were achieved alongside potential cost savings of up to 35 % for concrete suppliers, strengthening the combined environmental and commercial case for adoption.

### 7.3 Learnings for future research

The project generated several important learnings that will guide future research and commercial implementation. A key finding was that, while FBA can be used solely as a fine aggregate replacement, the most significant environmental and economic benefits are achieved when FBA is activated through co-grinding and utilised as a SCM.

Future research should focus on:

- **Long-term durability:** Ongoing monitoring of the Vales Point footpath trial site to assess long-term durability and performance under real-world environmental conditions.
- **Advanced applications:** Exploration of the use of FBA in geopolymer or alkali-activated concrete systems, which may offer even greater reduction in embodied carbon and more significant mechanical performance and durability.
- **Machine learning optimisation:** Application of machine learning algorithms to further optimise mix designs based on the variable chemical compositions of FBA sourced from different power stations across Australia, ensuring consistent performance regardless of the source material.

## 8. Publication List

1. Ali M Onaizi, Waiching Tang, Mugahed Amran, Yanju Liu, Umer Sajjad, Mohammad Alhassan. Towards increased adoption of furnace bottom ash as sustainable building materials: Characterization, standardization, and applications. *Journal of Building Engineering*. Volume 82, 1 April 2024, 108274. <https://doi.org/10.1016/j.jobe.2023.108274>
2. Ali M Onaizi, Waiching Tang, Yanju Liu. Co-grinding treatment for developing integrated-properties SCMs from basic oxygen furnace slag and furnace bottom ash: A step toward synthesis advanced SCMs. *Case Studies in Construction Materials*. Volume 20, July 2024, e03163. <https://doi.org/10.1016/j.cscm.2024.e03163>
3. Ali M Onaizi, Waiching Tang. Comparative assessment of the effects of furnace bottom ash and fly ash on mortar performance. *E3S Web of Conferences*. E3S Web of Conferences 546, 01010 (2024). <https://doi.org/10.1051/e3sconf/202454601010>
4. Waiching Tang, Ali M Onaizi, Sagheer A Onaizi, Umer Sajjad, Yanju Liu. Integrated Use of Furnace Bottom Ash as Fine Aggregate and Cement Replacement for Sustainable Mortar Production. *Materials* **2024**, 17(15), 3834. <https://doi.org/10.3390/ma17153834>
5. Ali M. Onaizi, Waiching Tang, Umer Sajjad. Eco-Friendly Concrete with Ternary Binders involving GGBFS and Furnace Bottom Ash for Sustainable Construction and Pavement Applications. 2025 Conference.
6. Ali M. Onaizi, Umer Sajjad, Amer Baras, Mugahed Amran, Mohammad Alhassan, Waiching Tang. Upcycling of furnace bottom ash as sustainable materials for low carbon concrete. Accepted and available online. *Cleaner Materials Journal*. <https://doi.org/10.1016/j.clema.2026.100400>
7. Durability and Life Cycle Assessment of Sustainable Concrete Incorporating Furnace Bottom Ash and Ground Granulated Blast Furnace Slag. Under Preparation.
8. Evaluation of Reactivity, Strength Development, and Hydration phase products of FBA–GGBFS Blends. Under Preparation.

## 9. Acronyms and Abbreviations

Acronym	Definition
ADAA	Ash Development Association of Australia
FBA	Furnace Bottom Ash
GFBA	Ground Furnace Bottom Ash
CCP	Coal Combustion Products
FA	Fly Ash
FBA	Furnace Bottom Ash
GGBFS	Ground Granulated Blast Furnace Slag
HCEC	Hunter Community Environment Centre
LCA	Life Cycle Assessment
NFA	Natural Fine Aggregates
SCM	Supplementary Cementitious Material
TfNSW	Transport for New South Wales
UON	University of Newcastle

## 10. References

1. ARRB. (2022). Bottom ash [Factsheet]. ARRB. [https://irfofficial.org/wp-content/uploads/2022/06/DAWE\\_Combined-Bottom-Ash-FA-REV2.pdf?utm\\_source=chatgpt.com](https://irfofficial.org/wp-content/uploads/2022/06/DAWE_Combined-Bottom-Ash-FA-REV2.pdf?utm_source=chatgpt.com)
2. Department of Climate Change, Energy, the Environment and Water. (2024, December 12). [https://www.dcceew.gov.au/environment/protection/waste/publications/national-waste-resource-recovery-reporting/resource-recovery-waste-material-analysis-2024?utm\\_source=chatgpt.com](https://www.dcceew.gov.au/environment/protection/waste/publications/national-waste-resource-recovery-reporting/resource-recovery-waste-material-analysis-2024?utm_source=chatgpt.com)
3. Guan, X., Wang, L., & Mo, L. (2023). Effects of ground coal bottom ash on the properties of cement-based materials under various curing temperatures. *Journal of Building Engineering*, 69, 106196. <https://doi.org/https://doi.org/10.1016/j.jobe.2023.106196>
4. Mathapati, M., Amate, K., Prasad, C. D., Jayavardhana, M. L., & Raju, T. H. (2021). A review on fly ash utilization. *Materials Today: Proceedings*, 50, 1535–1540. <https://doi.org/10.1016/j.matpr.2021.09.106>
5. Onaizi, A. M., & Tang, W. (2024). Comparative assessment of the effects of furnace bottom ash and fly ash on mortar performance. *E3S Web of Conferences*, 546, 1010.
6. Onaizi, A. M., Tang, W., Amran, M., Liu, Y., Sajjad, U., & Alhassan, M. (2024). Towards increased adoption of furnace bottom ash as sustainable building materials: Characterization, standardization, and applications. *Journal of Building Engineering*, 82, 108274. <https://doi.org/https://doi.org/10.1016/j.jobe.2023.108274>
7. Onaizi, A. M., Tang, W., & Liu, Y. (2024). Co-grinding treatment for developing integrated-properties SCMs from basic oxygen furnace slag and furnace bottom ash: A step toward synthesis advanced SCMs (Under review). *Case Studies in Construction Materials*, CSCM-D-23-.
8. Tang, W., Onaizi, A. M., Onaizi, S. A., Sajjad, U., & Liu, Y. (2024). Integrated Use of Furnace Bottom Ash as Fine Aggregate and Cement Replacement for Sustainable Mortar Production. *Materials*, 17(15), 3834.
9. SmartCrete CRC Project 21.R1.0042-P. (2022). *Project Agreement* (20 May 2022).
10. SmartCrete CRC Project 21.R1.0042-P. (2022). *Communication Plan* (21.R1.0042-P).
11. SmartCrete CRC Project 21.R1.0042-P. (2022). *Review of coal ash/CCP/FBA* (DEL-102).
12. SmartCrete CRC Project 21.R1.0042-P. (2023). *Cost and Environmental Benefits of Using Furnace Bottom Ash (FBA) as Fine Aggregates in Structural Concrete* (DEL-103a).
13. SmartCrete CRC Project 21.R1.0042-P. (2023). *Review of Normative Documents in Australia and Elsewhere on the Use of FBA in Concrete Structures* (DEL-103b).
14. SmartCrete CRC Project 21.R1.0042-P. (2023). *Development of a Laboratory-Based Refinery Procedures for FBA Use in Concrete* (DEL-104).
15. SmartCrete CRC Project 21.R1.0042-P. (2023). *Preliminary Test Results on the Characteristics of Refined FBA and Their Effects on Fundamental Properties of Cementitious Composites* (DEL-105).
16. SmartCrete CRC Project 21.R1.0042-P. (2024). *Final Report (Part 1) on Laboratory Studies of Using FBA to Produce Low-Carbon Concrete* (DEL-106a).
17. SmartCrete CRC Project 21.R1.0042-P. (2025). *Final Report (Part 2) on Laboratory Studies of Using FBA to Produce Low-Carbon Concrete* (DEL-106b).
18. SmartCrete CRC Project 21.R1.0042-P. (2025). *Full Scale Industrial Trial Application of FBA Concrete* (DEL-107).
19. SmartCrete CRC Project 21.R1.0042-P. (2025). *Workshops and Seminars: Communicating Project Outcomes* (DEL-108).
20. SmartCrete CRC Project 21.R1.0042-P. (2025). *National Use – Opportunities and Challenges* (DEL-109).
21. SmartCrete CRC Project 21.R1.0042-P. (2024). *LCA (Life Cycle Assessment) of FBA Concrete* (DEL-110).
22. SmartCrete CRC Project 21.R1.0042-P. (2025). *Technical Viability for the Production and Use of Furnace Bottom Ash in Concrete* (DEL-111).
23. Winn, P. (2020, October 14). Out of the Ashes II: NSW water pollution and our aging coal-fired power stations. Hunter Community Environment Centre.

24. University of Newcastle. (2022). *Research Assistant Position Description (HEW 5)* – SmartCrete CRC funded program support document.
25. University of Newcastle. (2022). *PhD Scholarship – Development of Eco-Friendly Concrete Using Industrial By-Products*.

## 11. Appendices and Attachments

### 11.1 Appendix A: deliverables submitted to SmartCrete CRC

Below is the list of deliverables submitted to SmartCrete CRC:

- DEL – 102 Review of coal combustion products / furnace bottom ash
- DEL – 103a Cost and Environmental Benefits of Using Furnace Bottom Ash (FBA) as Fine Aggregates in Structural Concrete
- DEL – 103b Review of Normative Documents in Australia and Elsewhere on the use of FBA in Concrete Structures
- DEL – 104 Development of a laboratory-based refinery procedures for FBA use in concrete
- DEL – 105 Preliminary test results on the characteristics of refined FBA and their effects on fundamental properties of cementitious composites
- DEL – 106 Final report (Part 1) on laboratory studies of using FBA to produce low carbon concrete
- DEL – 106 Final report (Part 2) on laboratory studies of using FBA to produce low carbon concrete
- DEL – 107 Full Scale Industrial Trail Application of FBA Concrete
- DEL – 108 Workshops and Seminars: Communicating Project Outcomes
- DEL – 109 National Use – Opportunities and Challenges
- DEL – 110 LCA (Life Cycle Assessment) of FBA concrete
- DEL – 111 Guidelines for Low-Carbon Concrete Using FBA

**11.2 Appendix B: Mortar mix proportions (kg/1 m<sup>3</sup>)**

<b>Mixture</b>	<b>Sand</b>	<b>FBA as Sand</b>	<b>GFBA as cement</b>	<b>Cement</b>	<b>w/c</b>
CR0	1537.5	0	0	467.5	0.6
FBA25	1153.2	234.4	0	467.5	0.6
FBA50	1041.7	604.2	0	467.5	0.6
FBA75	520.8	906.3	0	467.5	0.6
FBA100	0.0	1208.3	0	467.5	0.6
F10	1153.2	234.4	46.75	420.75	0.6
F20	1153.2	234.4	93.50	374.00	0.6
F30	1153.2	234.4	140.24	327.25	0.6

### 11.3 Appendix C: Concrete mix proportions (kg/1 m<sup>3</sup>)

Mix ID	Cement (kg/m <sup>3</sup> )	GGBS (kg/m <sup>3</sup> )	GFBA (kg/m <sup>3</sup> )	20 mm normal aggregate (kg/m <sup>3</sup> )	10 mm normal aggregate (kg/m <sup>3</sup> )	Natural fine sand (kg/m <sup>3</sup> )	Natural coarse sand (kg/m <sup>3</sup> )	Furnace bottom ash (kg/m <sup>3</sup> )	Water Quantity (kg/m <sup>3</sup> )	superplasticiser (L/m <sup>3</sup> )
<b>CR0</b>	435	0	0	690	280	380	380	0	174.0	1.7
<b>CR25</b>	435	0	0	690	280	285	285	190	196.8	2.7
<b>CGF10</b>	281.5	110	43.5	690	280	285	285	190	196.8	2.7
<b>CGF20</b>	238	110	87	690	280	285	285	190	196.8	2.7
<b>CGF30</b>	194.5	110	130.5	690	280	285	285	190	196.8	2.7
<b>SGF10</b>	281.5	110	43.5	690	280	285	285	190	196.8	2.7
<b>SGF20</b>	238	110	87	690	280	285	285	190	196.8	2.7
<b>SGF30</b>	194.5	110	130.5	690	280	285	285	190	196.8	2.7

## 11.4 Appendix E: Mix Designs for Trial concrete mixes

Materials	Units	Control Mix (25 MPa) (For 1 m <sup>3</sup> )	FBA Mix (For 1 m <sup>3</sup> )
Portland cement	kg	230	140
Fly ash	kg	90	0
Slag	kg	0	145
GFBA (as SCM)	kg	0	35
20mm	kg	660	620
10mm	kg	280	270
Coarse sand	kg	280	70
Fine Sand	kg	590	620
FBA (as Sand)	kg	0	190
Recycled water	kg	180	200
Admixture (WR) 8875	L	1.1	1.1