



**R1 P29 Development of low-carbon concrete products using recycled concrete aggregate and furnace bottom ash.**

**Report submitted to**

**Smart Crete CRC**

**in fulfillment of Project Deliverable**

**DEL – 111**

**Technical viability for the production and use of furnace bottom ash in concrete**

----- 2025 -----

## Executive Summary

This report, prepared for SmartCrete CRC, explores the development of low-carbon concrete products using Furnace Bottom Ash (FBA)—a coal combustion by-product—as a sustainable alternative in concrete. The study addresses environmental, technical, and economic aspects of incorporating FBA as (a) partial replacement for fine aggregates and (b) supplementary cementitious material (SCM), aiming to reduce carbon emissions and promote circular economy practices.

### Background & Significance

- Australia generates ~13.1 Mt of coal ash annually; FBA accounts for 10%, with limited reuse (<30% globally).
- NSW alone produces ~0.99 Mt FBA annually, with 23–34 Mt stored in ash dams—representing a major resource opportunity.
- Using FBA in concrete reduces landfill, conserves natural aggregates, and lowers embodied carbon. Replacing 20% cement with FBA can cut CO<sub>2</sub> emissions by up to 33% and reduce costs by ~\$15/m<sup>3</sup>.

### Research Scope

- Physical and chemical characterization of FBA from Vales Point and Eraring power stations.
- Laboratory trials: Mortar mixes with 25–100% sand replacement; concrete mixes with FBA and GGBFS (slag) as SCM.
- Industrial trial: Footpath construction near Vales Point using FBA concrete.
- Life Cycle Assessment (LCA): Manual and SimaPro software analysis for carbon footprint, energy, and cost.

### Key Findings

- Optimal Mix: 25% FBA as sand replacement + 10–20% ground FBA as SCM delivers superior compressive strength (up to 54 MPa) and reduces carbon emissions by 23–29%.
- Durability: FBA concrete shows improved resistance to sulphate and acid attack, satisfactory shrinkage, and acceptable carbonation resistance.
- Industrial Trial: FBA concrete met TfNSW footpath specifications; 28-day strength ~31 MPa vs 33 MPa for control.
- Environmental Impact: SCM replacement drives major carbon savings; sand replacement alone offers minimal benefit.
- Economic Impact: Cost reductions up to 35% for mixes with higher SCM replacement; landfill avoidance adds indirect savings.

### Challenges

- Variability in FBA properties, high water absorption, and lack of specific standards.
- Pre-treatment (drying, grinding) and logistics require investment.

- Market acceptance and regulatory frameworks need strengthening.

### **Opportunities & Future Directions**

- Aligns with Australia's Net Zero 2050 goals and circular economy initiatives.
- Potential for advanced applications: geopolymer systems, lightweight aggregates, AI-driven mix design.
- Requires development of FBA-specific standards, stakeholder collaboration, and industrial-scale processing near power stations.

**Conclusion:** FBA offers a viable pathway to decarbonise concrete production, reduce costs, and transform coal waste into a valuable resource. With proper standards, processing, and industry adoption, FBA can play a critical role in sustainable infrastructure.

## Table of Contents

|  |    |
|--|----|
| <b>CHAPTER 1: INTRODUCTION TO FURNACE BOTTOM ASH (FBA)</b> .....                             | 6  |
| <b>1.1 Introduction</b> .....  | 6  |
| <b>1.2 Scope and purpose of the report</b> .....   | 6  |
| <b>1.3 Overview of FBA</b> .....   | 7  |
| <b>1.4 Environmental and economic significance</b> .....                                     | 9  |
| <b>1.5 Location and quantities of FBA in NSW</b> .....                                       | 10 |
| <b>1.5.1 Coal-fired Power Stations in NSW</b> .....  | 10 |
| <b>1.5.2 Annual Furnace Bottom Ash Production in Australia</b> .....                         | 11 |
| <b>1.5.3 Annual Furnace Bottom Ash Production in NSW</b> .....                               | 13 |
| <b>1.5.4 Estimated Quantities of CCPs in the Ash Dams of NSW Coal-fired Power Stations</b> . | 13 |
| <b>1.6 Summary</b> .....   | 15 |
| <b>CHAPTER 2: CHARACTERISTICS AND CLASSIFICATION OF FBA</b> .....                            | 16 |
| <b>2.1 Introduction</b> .....  | 16 |
| <b>2.2 Chemical and Physical properties of FBA</b> .....                                     | 16 |
| <b>2.3 Physical properties</b> .....   | 21 |
| <b>2.4 Comparison FBA properties with FA</b> .....   | 26 |
| <b>2.5 Environmental considerations</b> .....  | 28 |
| <b>2.6 Summary</b> .....   | 28 |
| <b>CHAPTER 3: PROCESSING AND HANDLING OF FBA FOR CONCRETE USE</b> .....                      | 29 |
| <b>3.1 Introduction</b> .....  | 29 |
| <b>3.2 FBA collection and initial treatment</b> .....  | 29 |
| <b>3.3 Pre-processing requirements</b> .....   | 29 |
| <b>3.4 Storage and handling practices</b> .....  | 33 |
| <b>3.5 Quality assurance and testing protocols</b> .....                                     | 34 |
| <b>3.6 Summary</b> .....   | 34 |
| <b>CHAPTER 4: FBA UTILIZATION IN MORTAR</b> .....  | 35 |
| <b>4.1 Introduction</b> .....  | 35 |
| <b>4.2 Mixes proportions</b> .....   | 35 |
| <b>4.3 Testing setup</b> .....   | 36 |
| <b>4.4 Results and discussion</b> .....  | 37 |
| <b>4.4.1 Mortar flowability</b> .....  | 37 |
| <b>4.4.2 Mortar densities</b> .....  | 38 |
| <b>4.4.3 Compressive strength</b> .....  | 39 |
| <b>4.4.4 Flexural strength</b> .....   | 41 |
| <b>4.4.5 Water absorption</b> .....  | 42 |
| <b>4.4.6 Environmental impact assessment</b> .....   | 43 |

|  |  |            |
|--|--|------------|
| 4.5  | Summary.....   | 46         |
| <b>CHAPTER 5: FBA UTILIZATION IN CONCRETE .....</b>                  |  | <b>48</b>  |
| 5.1  | Introduction.....  | 48         |
| 5.2  | Mix design considerations .....                                    | 48         |
| 5.3  | Fresh concrete properties with FBA.....                            | 53         |
| 5.4  | Hardened concrete properties with FBA .....                        | 57         |
| 5.5  | Durability Performance.....  | 64         |
| 5.6  | Summary.....   | 75         |
| <b>CHAPTER 6: TRIAL MIXES FOR FOOTPATH APPLICATION.....</b>          |  | <b>76</b>  |
| 6.1  | Introduction.....  | 76         |
| 6.2  | Trial Mixes (Laboratory).....                                      | 76         |
| 6.3  | Industrial trial application .....                                 | 81         |
| 6.4  | Summary.....   | 95         |
| <b>CHAPTER 7: LIFE CYCLE ASSESSMENT .....</b>                        |  | <b>96</b>  |
| 7.1  | Introduction.....  | 96         |
| 7.2  | Functional Unit .....  | 97         |
| 7.3  | Input Parameters .....   | 97         |
| 7.4  | Results and Interpretations.....                                   | 101        |
| 7.5  | Discussion and Recommendations.....                                | 112        |
| 7.6  | Summary.....   | 113        |
| <b>CHAPTER 8: CHALLENGES AND FUTURE TRENDS .....</b>                 |  | <b>114</b> |
| 8.1  | Introduction.....  | 114        |
| 8.2  | Opportunities and challenges.....                                  | 114        |
| 8.2.1  | <i>Opportunities</i> .....   | 114        |
| 8.2.2  | <i>Environmental Sustainability</i> .....                          | 114        |
| 8.2.3  | <i>Possibilities in Australia</i> .....                            | 116        |
| 8.2.4  | <i>Challenges</i> .....  | 118        |
| 8.3  | Summary.....   | 120        |
| <b>CHAPTER 9: REGULATORY FRAMEWORK AND APPLICABLE STANDARDS.....</b> |  | <b>122</b> |
| 9.1  | Introduction.....  | 122        |
| 9.2  | Applicable Standards for use as pozzolanic materials in concr..... | 122        |
| 9.2.1  | <i>Physical and mechanical criteria</i> .....                      | 123        |
| 9.3  | Applicable standards for use as aggregate in concrete .....        | 124        |
| 9.4  | Hazard assessments .....   | 125        |
| 9.5  | End-of-waste and Australian product standards .....                | 127        |
| 9.6  | Toward FBA-specific standardization.....                           | 128        |
| 9.7  | Sustainability assessment and carbon footprint implications .....  | 128        |

|   |  |            |
|---|--|------------|
| 9.7.1   | <i>Economic benefits</i> .....                                   | 129        |
| 9.7.2   | <i>Carbon footprint of cement and the case for FBA</i> .....     | 131        |
| 9.7.3   | <i>Life-cycle assessments and environmental trade-offs</i> ..... | 131        |
| 9.7.4   | <i>Resource conservation and circular economy benefits</i> ..... | 132        |
| 9.7.5   | <i>Environmental safety and potential impacts</i> .....          | 132        |
| 9.7.6   | <i>Socio-economic implications and policy alignment</i> .....    | 135        |
| 9.7.7   | <i>Balancing trade-offs and future directions</i> .....          | 136        |
| 9.8   | <b>Summary</b> .....   | <b>136</b> |
| <b>HAPTER 10: SUMMARY, RECOMMENDATIONS AND FUTURE STUDIES</b> ..... |  | <b>137</b> |
| 10.1  | <b>Introduction</b> .....  | <b>137</b> |
| 10.2  | <b>Conclusion</b> .....  | <b>137</b> |
| 10.2.1  | <i>Properties and characterization</i> .....                     | 137        |
| 10.2.2  | <i>Performance of FBA in Concrete Applications</i> .....         | 137        |
| 10.2.3  | <i>Environmental and Economic Benefits</i> .....                 | 138        |
| 10.2.4  | <i>Challenges and Limitations</i> .....                          | 138        |
| 10.3  | <b>Recommendations</b> .....                                     | <b>139</b> |
| 10.3.1  | <i>Recommendations for further Adoption</i> .....                | 139        |
| 10.4  | <b>Research trends and innovations in FBA concrete</b> .....     | <b>140</b> |
| 10.4.1  | <i>Enhanced processing and particle refinement</i> .....         | 140        |
| 10.4.2  | <i>Machine-learning-driven mix design</i> .....                  | 141        |
| 10.4.3  | <i>Integrated use of FBA as binder and aggregate</i> .....       | 141        |
| 10.4.4  | <i>Geopolymer and alkali-activated applications</i> .....        | 142        |
| 10.4.5  | <i>Lightweight aggregates and composite materials</i> .....      | 142        |
| 10.4.6  | <i>Future directions</i> .....                                   | 142        |
| 10.5  | <b>Concluding Remarks</b> .....                                  | <b>143</b> |
| <b>REFERENCES</b> .....   |  | <b>144</b> |
| <b>Appendix A: Checklist for Control Concrete at Site</b> .....     |  | <b>160</b> |
| <b>Appendix B: Checklist for FBA Concrete at Site</b> .....         |  | <b>161</b> |

# **CHAPTER 1: INTRODUCTION TO FURNACE BOTTOM ASH (FBA)**

## **1.1 Introduction**

The increasing global demand for sustainable construction materials has driven research into alternative and supplementary materials that can reduce the environmental impact of concrete production. One such material is Furnace Bottom Ash (FBA), a coal combustion by-product that is often underutilized compared to fly ash (FA) [1]. This chapter introduces the use of FBA in concrete, with a focus on its generation, particularly in the Australian context, and its potential role in sustainable construction practices.

This chapter outlines the scope and purpose of the report, provides an overview of FBA generation and its current handling, and discusses the environmental and economic benefits of incorporating FBA into concrete as part of a circular economy approach. In addition, the chapter highlights key differences between FBA and fly ash in terms of physical and chemical characteristics, performance in concrete, and typical applications. This foundational information sets the stage for the experimental investigation into the use of FBA as a sand replacement and supplementary cementitious material in concrete, which is explored in the following chapters.

## **1.2 Scope and purpose of the report**

The purpose of this report is to provide a comprehensive research output and guidelines for the use of FBA in concrete as a sustainable construction material. It explores the potential of FBA as both a partial replacement for fine aggregates (sand) and as a supplementary cementitious material (SCM) in concrete production.

The scope of the research includes the physical and chemical characterization of FBA, sourced from Vale Point Power Station and its properties compared with that of other FBA obtained from other sources, including Eraring Power Station. Then several mixes of eco-friendly mortars and concrete were designed, and fresh, mechanical, and durability properties of concrete/mortar containing FBA were evaluated. Particular emphasis is placed on assessing, slump performance, densities, air content, compressive strength, flexural strength, split tensile strength, modulus of elasticity, water absorption, shrinkage and long-term durability performance under aggressive environments, including sulphate resistance, acid resistance and carbonation resistance.

The suitability of FBA as a fine aggregate was evaluated by replacing fine sand in mortar with 25%, 50%, 75%, and 100% FBA by volume. The optimal replacement level was then selected for further use in concrete and mortar mixtures incorporating FBA as a cement substitute. An innovative co-grinding approach involving FBA and ground granulated blast furnace slag (GGBFS) is also examined to enhance the reactivity and pozzolanic performance of FBA when used as SCM. A total of eight concrete mix formulations were developed and tested under controlled laboratory conditions. A proposed mix design was implemented in the construction of a pedestrian footpath to evaluate the practical application of eco-friendly concrete for potential industrial use.

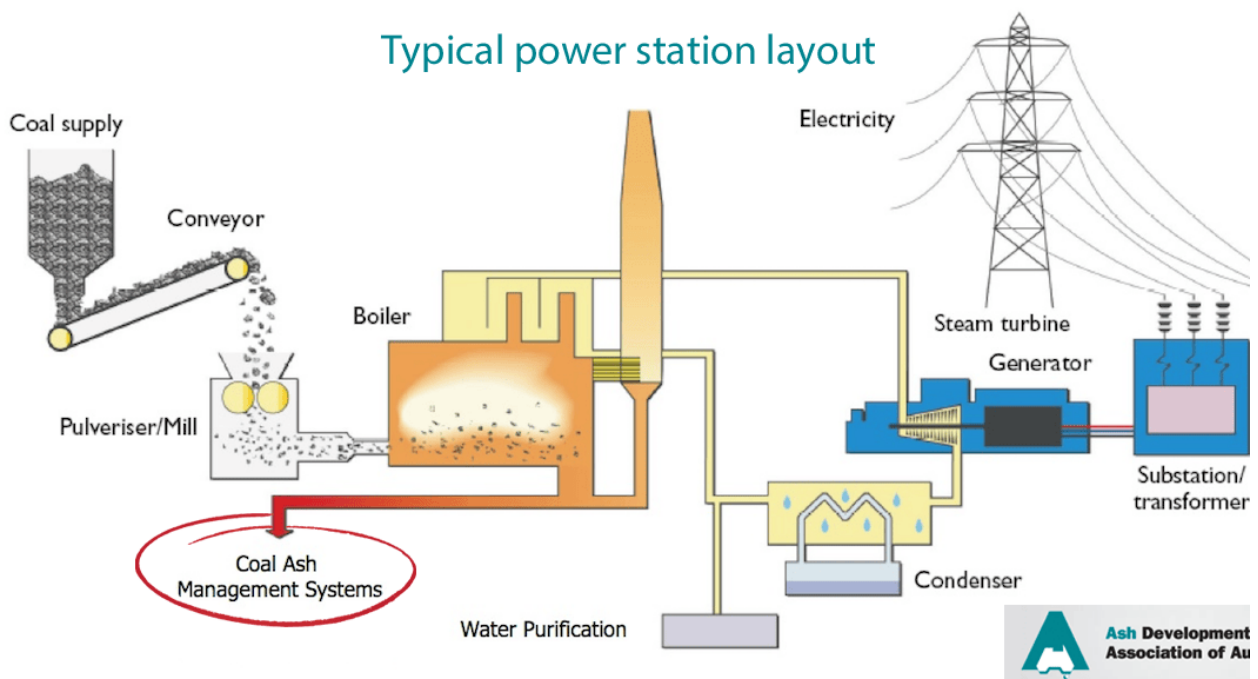
This report is intended to contribute to the growing body of knowledge on sustainable construction materials, providing practical insights for industry professionals, researchers, and policymakers. It supports the broader objective of promoting circular economy practices in construction by converting industrial waste into value-added products, ultimately aiming to reduce environmental impact and improve resource efficiency in the concrete industry.

### **1.3 Overview of FBA**

FBA is composed of the agglomerated particles of oxides that are left over after the pulverised coal combustion process, which impinge on the furnace walls or fall to the bottom of the boiler (Fig. 1.1), and has similar chemical characteristics to FA [2,3]. Numerous studies have proven the viability of using bottom ash in several construction and geotechnical applications, such as concrete production [4,5], ceramic production [6,7], road construction and maintenance [8], and soil remediation [9]. As with FA, FBA recycling fulfils sustainability requirements by reducing greenhouse gas (GHG) emissions, reducing pressure on the use of natural resources, and reducing waste production. However, it is interesting to note that the advancement of research on FBA is occurring at a slower speed, when compared to FA. Zhou et al. [10] have specified three reasons that push researchers to focus on FA over FBA: 1) The amount of FBA is lower compared to FA, constituting only about 10–20% of the total coal ash produced; 2) there is less leaching of toxic elements associated with FBA, compared to FA; and 3) the heterogeneous nature of FBA makes recycling it more difficult.

While millions of tonnes are generated annually, especially in coal-reliant countries like China, India, and the U.S., the global recycling rate for FBA remains low, typically under 30%. Australia generates approximately 13.1 million metric tonnes (Mt) of coal ash annually, with fly ash accounting for 80–90% and FBA comprising 10% of the total [11]. However, only about

6 million Mt of this by-product is currently being reused, and the utilization of FBA in the construction sector remains minimal. FBA is primarily produced in New South Wales (NSW) and Queensland, where coal remains a significant energy source. Despite its potential, the utilization of FBA in Australia remains limited. A significant portion of the material is stockpiled at power station sites. Nevertheless, there is growing interest in the beneficial reuse of FBA, particularly in the construction sector. Applications include its use as a partial replacement for natural aggregates in concrete, road base materials, and general fill in civil engineering projects.



**Fig.1.1:** A graphic diagram of the production of FBA [12].

Challenges to broader adoption include logistical constraints related to transportation from remote generation sites, variability in material properties, and the need for consistent quality standards. Addressing these issues through improved processing, regulatory support, and market development could enhance the sustainable use of FBA in Australia’s construction industry.

## 1.4 Environmental and economic significance

Recycling FBA holds significant environmental value when utilized in construction. Its reuse reduces the need for landfilling, conserves natural aggregates, and lowers the carbon footprint of concrete by partially replacing cement and virgin materials. This contributes to reduced greenhouse gas emissions and supports sustainable construction practices. Additionally, using FBA aligns with circular economy principles by transforming industrial waste into a valuable resource, and promoting material efficiency.

While there is some uncertainty regarding the environmental benefits of using furnace bottom ash (FBA) as a sand replacement in concrete, particularly due to varying outcomes based on mix design approaches, several studies indicate promising results. A study [13] reported mixed findings on the environmental impact, but Jeon et al. [14] demonstrated significant CO<sub>2</sub> emission reductions (up to 33.4%) when FBA replaced sand in soil-mixing and drainage layers. Life-cycle assessments (LCAs) showed FBA generally has lower environmental impacts than crushed rock, except in human toxicity potential (HTP) for cancer due to possible heavy metal leaching, particularly when FBA is used in unbound conditions. When FBA is incorporated into bound applications, this leaching risk is significantly reduced because the matrix immobilises contaminants. Nevertheless, FBA's HTP was found to be comparable to other virgin materials like limestone and siliceous gravel. Navaratnam et al. [15] further supported the environmental viability of FBA and fly ash, highlighting lower greenhouse gas emissions and resource depletion compared to natural aggregates. Overall, incorporating FBA in construction can reduce environmental burdens associated with coal waste and sand mining, although attention to potential leaching issues remains important when FBA is used in unbound applications.

The use of FBA as a cement replacement appears to offer clearer sustainability benefits compared to its use as an aggregate substitute. Studies consistently show significant reductions in CO<sub>2</sub> emissions, embodied energy, and production costs when FBA replaces a portion of cement. For instance, Bajare et al. [16] reported a 22.9 kg/ton CO<sub>2</sub> reduction with 20% FBA replacement, while Hanafi et al. [17] found that increasing FBA from 20% to 40% led to progressive decreases in embodied energy and CO<sub>2</sub> emissions across different cement percentages (7%, 10%, 13%). Emissions reductions doubled with higher FBA content.

Further, Bheel et al. [18] demonstrated that including 20% FBA reduced CO<sub>2</sub> emissions, and eco-strength efficiency improved, confirming that strength was maintained. Overall, the LCA findings strongly support the environmental and technical viability of using FBA as a

partial cement replacement, although its use as a fine or coarse aggregate replacement remains more uncertain.

Economically, FBA offers cost advantages by lowering material and waste management expenses. Its application in infrastructure projects can also enhance eligibility for green building certifications, adding market value. Furthermore, the development of FBA-based products can stimulate local economies, create jobs, and foster industrial symbiosis between energy producers and the construction sector. With appropriate quality control and regulatory support, FBA can play a vital role in advancing both environmental sustainability and economic resilience in Australia's transition to a low-carbon future.

For instance, substituting 20% of ordinary Portland cement (OPC) with ground FBA in concrete production can reduce the amount of OPC used by up to 250 kg per cubic metre. This substitution can lead to a cost saving of approximately \$15 AUD per cubic meter of concrete [19]. Additionally, concrete mixes that use 20% FBA in place of cement have shown similar strength performance compared to conventional concrete, while also cutting overall production costs by about 9.3%. Further, FBA, being a waste by-product, is cheaper than natural sand or cement, making it an attractive alternative from both environmental and financial perspectives. In terms of transportation costs, these were found to be similar to those incurred when delivering other raw materials like sand or cement to concrete plants, indicating that using FBA doesn't introduce significant additional costs for logistics [20].

These findings strongly support the economic and technical viability of using FBA in concrete, especially as a partial replacement for cement or natural sand, thereby contributing to sustainable and cost-effective construction practices.

## **1.5 Location and quantities of FBA in NSW**

### ***1.5.1 Coal-fired Power Stations in NSW***

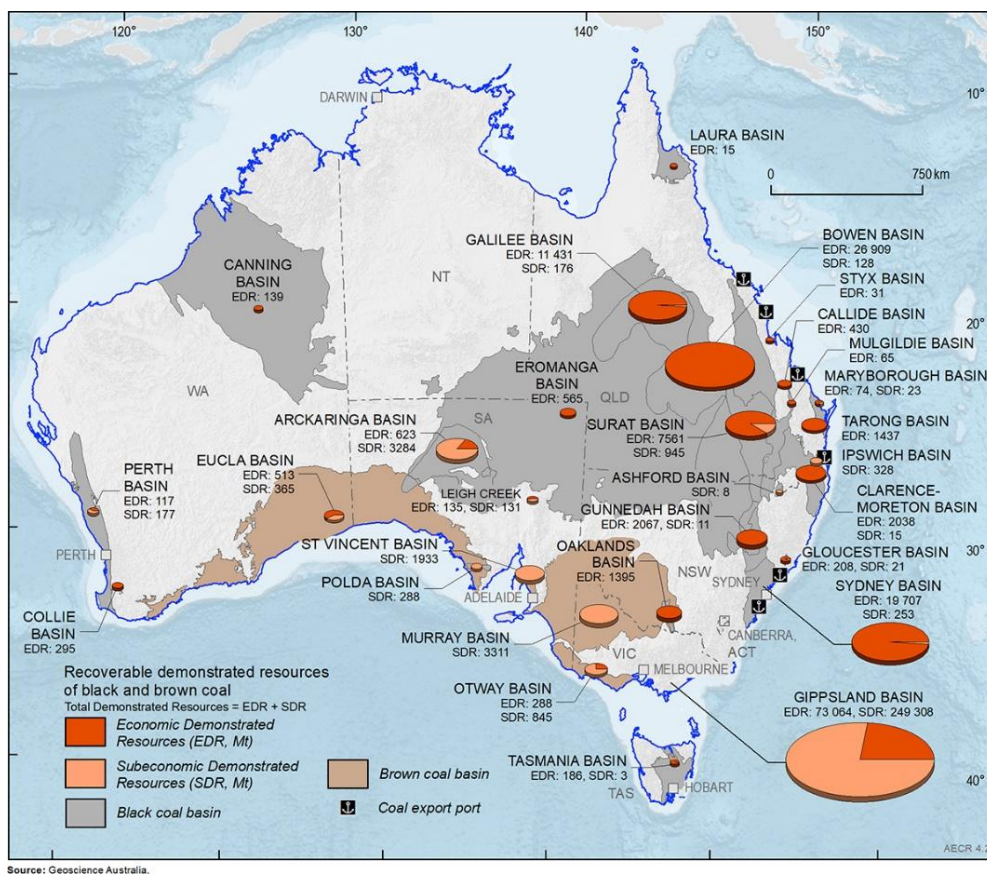
There are four active CFPS in NSW which are shown in Table 1.1 as well as details of the operators and scheduled year of closure. Two are located in the Hunter Valley, another two located in Lake Macquarie and the remaining plant located in the Central West region. A map of CFPS locations in NSW is shown in Fig. 1.2.

**Table 1.1:** Details of CFPS currently operating in NSW [21–23].

| Power Station | Max Capacity (MW) | Turbines | Operator          | Scheduled Closure |
|---------------|-------------------|----------|-------------------|-------------------|
| Bayswater     | 2,640             | 4        | AGL               | 2033              |
| Eraring       | 2,880             | 4        | Origin Energy     | 2025              |
| Mount Piper   | 1,390             | 2        | Energy Australia  | 2040              |
| Vales Point B | 1,320             | 2        | Delta Electricity | 2029              |

Approximate transport distances by road from the power stations to Lake Macquarie (Sydney CBD) are:

- Hunter Valley power stations (Bayswater & Liddell) – 103 kilometres.
- Eraring power station – 20 kilometres.
- Vales Point power station – 39 kilometres.
- Mount Piper power station – 266 kilometres.



**Fig. 1.2:** Map of coal basins in Australia [24].

### 1.5.2 Annual Furnace Bottom Ash Production in Australia

The Ash Development Association of Australia (ADAA) conducted an Annual Production and Utilisation Survey (January – December 2023). It estimated the total amount of coal combustion products produced in Australia was about 9.91 million tonnes as shown in Table 1.2. Of this estimate, the amount of furnace bottom ash produced was approximately 1.13 Mt or 11.4% of all coal combustion products produced in Australia. The survey did provide some information regarding the fate of FBA; it reported that out of the total estimated amount of FBA, approximately 0.84 Mt (approximately 74.0%) haven't been used and have been placed into storage, while only about 0.29 Mt (approximately 26.2%) have been reused for benefit (e.g., construction, civil and mine applications). There has been a dramatic decline in the amount of FBA reused when compared to previous years (e.g. 2020), wherein reuse rates were significantly higher. In addition, of the total amount of CCPs produced in 2023, an estimated 4,790,000 tonnes (approximately 48.0%) of all coal combustion products produced in 2023, will have been reused for beneficial purposes. This provides further evidence to support the finding that FBA is clearly one of the least reused streams of ash compared to fly ash(s). The annual processing capability for FBA in Australia is currently 1.13 million tonnes of which power stations in NSW produce 0.5 million tonnes compared with 0.56 million tonnes from Queensland power stations. Processing capability refers to the presently installed capacity to process CCPs for reuse into various end use markets. Processing can be capital intensive and market limitations can influence the quantity of CCP reused [22].

**Table 1.2:** Annual Australian CCP/FBA production & FBA processing capability [25].

| Parameter                         | Verified Value                   |
|-----------------------------------|----------------------------------|
| Total CCPs Produced               | 9,906,462 t ( $\approx$ 9.91 Mt) |
| Furnace Bottom Ash (FBA) Produced | 1,132,839 t ( $\approx$ 1.13 Mt) |
| FBA Not Used (Stored)             | 839,512 t ( $\approx$ 0.84 Mt)   |
| FBA Beneficially Used             | 293,327 t ( $\approx$ 0.29 Mt)   |
| FBA Utilisation Rate              | 25.9%                            |
| FBA Storage Rate                  | 74.1%                            |

However, trends in the data [22] for the quantities of CCPs produced since 2011 show a decline in totals as generation capacity from CFPS has reduced due to predicted retirements. Subsequently, retirement dates for CFPS have been brought forward and the earlier closures or further reduced generation capacity will likely affect future annual quantities of CCPs produced, but open possible pathways for harvesting of FBA from existing storage.

### ***1.5.3 Annual Furnace Bottom Ash Production in NSW***

In NSW, the proportion of FBA as a percentage of annual CCP products is higher than the national average and sits at 16 per cent. This is based on the reported annual CCP production in the state of 6.29 million tonnes of which bottom ash accounted for 0.99 million tonnes [25]. This higher percentage may be attributed to the CFPS in NSW burning bituminous or black coal. Bituminous coal has a higher average ash content of 24 per cent compared with sub-bituminous coal (8%) and lignite/brown coal (2%) [25]. It is assumed that Eraring and Bayswater Power Stations locations will produce higher quantities of CCPs, including FBA, as they have the largest power generation capacity.

### ***1.5.4 Estimated Quantities of CCPs in the Ash Dams of NSW Coal-fired Power Stations***

On a national level, ongoing monitoring of cumulative ash repositories by the ADAA estimates 650 million tonnes of CCPs are in storage across the country [25]. The ADAA also reports that there is approximately 0.84 Mt tonnes of FBA stored in ash dams [25] (see Table 1.2). The estimated range of stored FBA at a state level in NSW is 25.63 – 37.28 million tonnes (based on FBA accounting for 11-16 per cent of total CCP production). The large totals of stored CCPs including FBA presents an opportunity for harvesting which has already been recognised within government and industry sectors [26]. For example, FBA has been dredged from the ash dams at Liddell Power Station to recover useful materials and reduce the amount of waste held in storage. The ADAA advises that they have provided funding in support of a national supplementary cementing materials project to capture future predicted CCP volumes to 2040.

The ADAA has provided aggregate CCP production data at a state level for NSW [25]. This enables FBA as a percentage of total annual ash production to be determined (Table 1.3).

**Table 1.8:** Estimated total annual production of CCPs including FBA at NSW CFPS.

| <b>Power Station</b> | <b>Estimated Total Ash Produced (million tonnes per annum)</b> | <b>Estimated Production of FBA (million tonnes per annum) <sup>a</sup></b> | <b>FBA as a Proportion of total Ash Production</b> |
|----------------------|--|--|--|
| Bayswater            | 1.5  | 0.24   | 5%   |
| Eraring              | 1.2  | 0.19   | 3.96%  |
| Liddell              | 0.8  | 0.13   | 2.71%  |
| Mount Piper          | 0.6  | 0.09   | 1.9%   |
| Vales Point          | 0.7  | 0.11   | 2.3%   |
| <b>Totals</b>        | <b>4.8</b>   | <b>0.76</b>  | <b>-</b>   |

<sup>a</sup> - Based on bottom ash accounting for 16% of total CCP production in NSW.

FBA production as a percentage of total ash production for individual power stations can then be applied to the latest ADAA reported annual CCP figure for NSW of 6.29 million tonnes [25]. This calculation provides an updated annual estimate of potential bottom ash production for individual CFPS in NSW and is shown in Table 1.4. The total of 0.99 million tonnes aligns with the FBA figure reported by the ADAA [25].

**Table 1.4:** Updated estimate of annual FBA production for individual CFPS in NSW.

| <b>Power Station</b> | <b>FBA Proportion of Total Ash Production</b> | <b>Estimated Potential Annual Production of FBA (million tonnes)</b> |
|----------------------|---|--|
| Bayswater            | 5%  | 0.31   |
| Eraring              | 3.96%   | 0.25   |
| Liddell              | 2.71%   | 0.17   |
| Mount Piper          | 1.9%  | 0.12   |
| Vales Point          | 2.3%  | 0.14   |
| <b>Total</b>         | -   | <b>0.99</b>  |

As a reference guide and to provide an indication of potential FBA in storage at individual NSW CFPS, the total stored quantity of CCPs at NSW CFPS can be used to estimate a range of stored FBA (Table 1.5).

**Table 1.5:** Reported total CCPs in storage and estimated range of stored FBA.

| <b>Power Station</b>                                     | <b>CCPs Stored in Ash Dams (million tonnes)</b> | <b>Estimated Range of Bottom Ash in Ash Dams (million tonnes)<sup>c d</sup></b> |
|--|---|---|
| Bayswater  | 45  | 4.80 / 7.09   |
| Eraring (incl. decommissioned Wangi)                     | 40  | 4.26 / 6.30   |
| Liddell  | 39  | 4.16 / 6.15   |
| Mount Piper  | 15  | 1.60 / 2.36   |
| Vales Point (incl. decommissioned Munmorah) <sup>e</sup> | 61  | 6.50 / 9.61   |
| Wallerwang (decommissioned)                              | 13  | 1.39 / 2.05   |
| Tallawara (decommissioned) <sup>f</sup>                  | 3   | 0.32 / 0.47   |
| <b>Totals</b>  | <b>216</b>                                      | <b>23.03 / 34.03</b>  |

Note: <sup>c</sup> – Ranges based on bottom ash accounting for 11% of CCP production nationally / 16% in NSW.

<sup>d</sup> – FA and FBA are comingled in storage dams and would likely require some processing to reclaim.

<sup>e</sup> – Only Munmorah FA stored in Vales Point dam. FBA was stored at Munmorah.

<sup>f</sup> – CCPs not recoverable as site has been reclaimed and developed are light industrial estate.

## **1.6 Summary**

In this introductory chapter, the potential and feasibility of utilizing FBA in concrete applications are highlighted. FBA, a by-product generated from coal-fired thermal power plants, remains largely underutilized compared to other industrial residues like fly ash. Despite being produced in substantial quantities, its application in construction, particularly in concrete, has not yet gained widespread acceptance. However, FBA has considerable potential to serve as both a partial replacement for fine aggregates and as a SCM, when processed appropriately. Its incorporation into concrete can lead to significant environmental benefits by reducing reliance on natural resources, lowering carbon emissions, and diverting industrial waste from landfills. Economically, the reuse of FBA offers cost savings in material procurement and waste management. Overall, using FBA in concrete presents a promising pathway toward more sustainable and circular construction practices.

# CHAPTER 2: CHARACTERISTICS AND CLASSIFICATION OF FBA

## 2.1 Introduction

This chapter provides a detailed overview of the key physical and chemical characteristics of FBA, aiming to distinguish it from other construction materials, particularly SCMs. A classification framework for FBA has been developed based on particle size distribution, addressing its dual application as both a sand replacement and as SCM in concrete production. Understanding the intrinsic properties and composition of FBA is essential for identifying suitable processing methods and optimizing its use in concrete mixtures. Additionally, this chapter includes a comparative analysis between FBA and other widely used SCMs, such as fly ash, slag, and silica fume, to evaluate performance differences and guide its practical application. This foundational knowledge supports the development of eco-friendly concrete mixes that align with both environmental and structural performance goals.

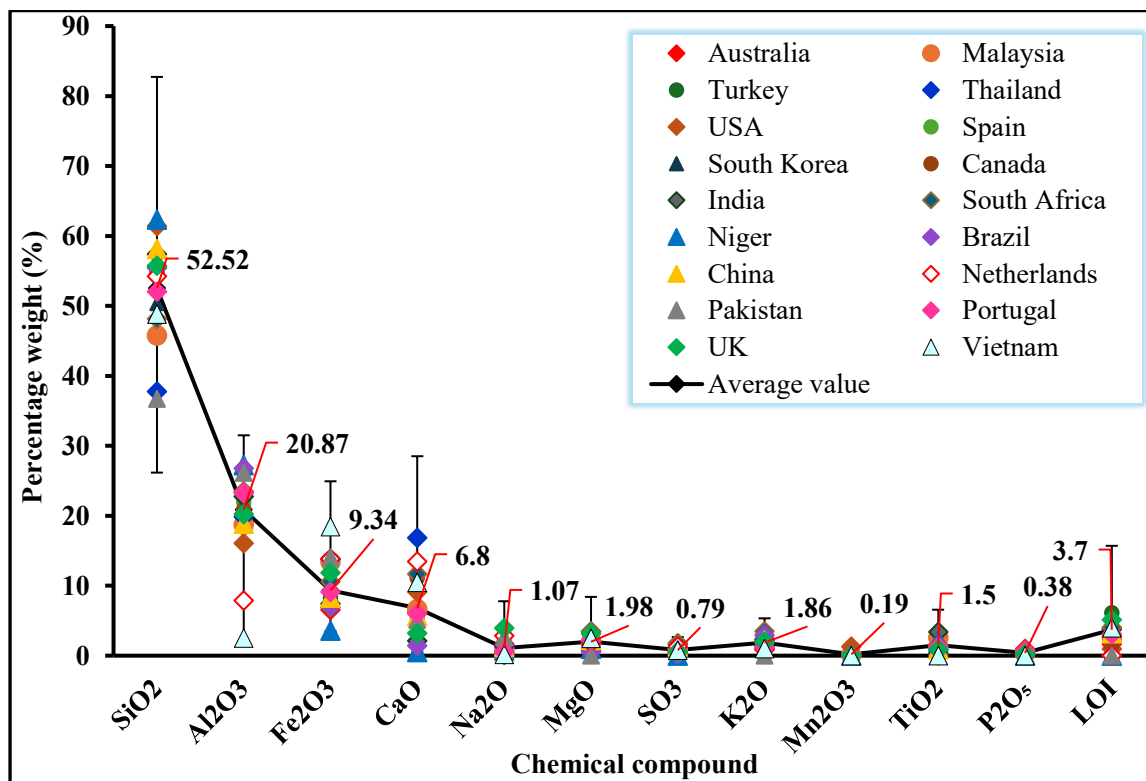
## 2.2 Chemical and Physical properties of FBA

The chemical properties of FBA change depending on the type of coal used, the combustion rate, and the efficiency of the thermal power plant [28]. For instance, the combustion of lignite coal yields FBA that is high in calcium and alkaline elements, whereas the combustion of anthracite coal yields FBA that is low in calcium and high in iron [6,28,29]. In contrast, the efficiency of the thermal plant and variation of the incineration rate may lead to fluctuations in the contents of carbon and organic impurities [29,30]. The primary crystalline forms typically present in FBA are mullite ( $\text{Al}_6\text{Si}_2\text{O}_{13}$ ), quartz ( $\text{SiO}_2$ ), and anorthite [ $\text{Ca}(\text{Al}_2\text{Si}_2\text{O}_8)$ ]. Iron is typically found in the form of magnetite ( $\text{Fe}_3\text{O}_4$ ) and hematite ( $\text{Fe}_2\text{O}_3$ ) [29].

Fig. 2.1 shows the average, maximum, and minimum values of the chemical composition of FBA reported in different countries. The average values of the chemical compound weight percentages vary by country, which may be attributed to the differences in coal type and thermal power efficiency. The main components of FBA are  $\text{SiO}_2$  (27–82%),  $\text{Al}_2\text{O}_3$  (2–32%), and  $\text{Fe}_2\text{O}_3$  (4–25%). Overall, pozzolanic oxides ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$ ) range between 50–97% of the total compounds in FBA by weight. The high proportion of

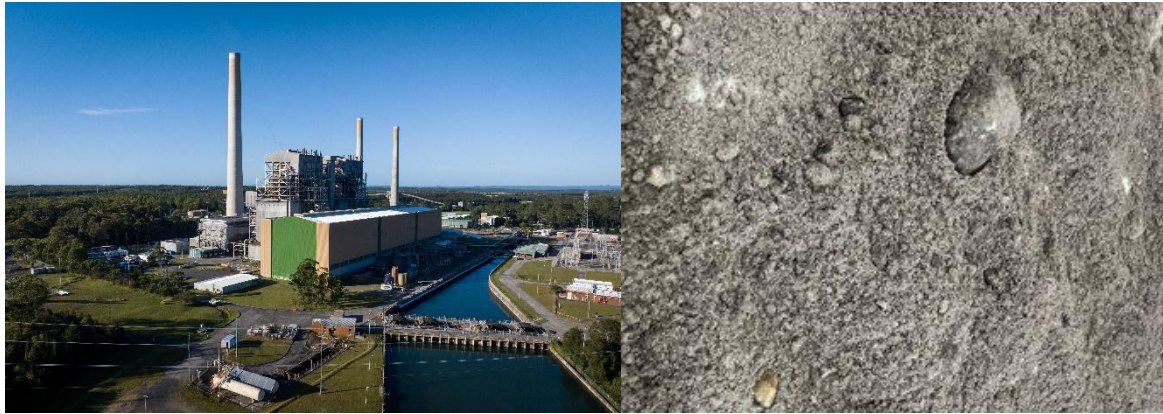
pozzolanic oxides provides FBA with relatively strong pozzolanic activity, enabling it to be utilized as a cementitious material in accordance with several standards, including AS/NZS 3582-2016 [56] and ASTM C618-15 [57]. On the other hand, its calcium content typically ranges between 0.5 and 17%, as indicated in Fig. 2.1, in some situations reaching roughly 28% (as reported by Hanjitsuwan et al. [58]). Furthermore, FBA presents relatively variable organic contents, with loss on ignition (LOI) ranging between 0.05 and 15.7%.

The total amount of  $\text{SO}_3$  ranges between 0.007–2.66%, presenting levels lower than the higher allowable limit in most of the building standards for FA ( $\leq 3\%$  and  $5\%$  according to AS/NZS 3582: 2016 [56] and ASTM C618 [57], respectively). Similarly, Fig. 2.1 indicates that the average values reported in previous studies for MgO are around 2%, lower than the upper limit prescribed in ASTM C618 [57]. FBA also contains various other oxides, such as  $\text{Na}_2\text{O}$  (0.05–7.78%),  $\text{K}_2\text{O}$  (0.34–5.34%),  $\text{Mn}_2\text{O}_3$  (0.06–1.27%),  $\text{TiO}_2$  (0.3–6.57), and  $\text{P}_2\text{O}_5$  (0.07–1.27%), as detailed in Fig. 2.1.



**Fig. 2.1:** Average values of chemical compounds in FBA based on the country and the average, maximum, and minimum values of the total data collected [11].

For this project, the FBA used was collected from Vales Point power station (Fig. 2.2).



**Fig. 2.2:** Vales Point Power Station and FBA sample collected.

The chemical characterisation was conducted using internal service (University of Newcastle, Australia) according to ISO/IEC 17025 [31], and an independent laboratory according to AS2350.2. This practice mitigated the chances of discrepancies in the characterisation of FBA. X-ray fluorescence (XRF) was used to identify the chemical composition of FBA. In addition, chloride contents and loss on ignition (LOI) values were also determined. Knowledge of the chloride content in concrete materials is important to monitor and to estimate the chances of steel corrosion in reinforced concrete. The LOI value is important as a recommendation of the material as SCM by following in place standards and specifications. The chemical compositions of FBA are presented in Table 2.1.

**Table 2.1:** Chemical Composition through XRF Analysis

| Oxide concentrations (%)                    | University Laboratory     |          | Independent Laboratory |          |                       | Average |
|---|---------------------------|----------|------------------------|----------|-----------------------|---------|
|   | Vales Point Power Station |          |                        |          | Eraring Power Station |         |
|   | FBA-2022                  | FBA-2023 | FBA-2022               | FBA-2023 | FBA-2023              |         |
| Silicon as SiO <sub>2</sub>                 | 55.9                      | 62.8     | 63.3                   | 61       | 62.4                  | 61.08   |
| Aluminium as Al <sub>2</sub> O <sub>3</sub> | 18.5                      | 14.7     | 14.8                   | 15.8     | 19.9                  | 16.74   |
| Iron as Fe <sub>2</sub> O <sub>3</sub>      | 10.2                      | 9.79     | 9.51                   | 8.6      | 8.93                  | 9.406   |
| Calcium as CaO                              | 3.05                      | 2.07     | 2.08                   | 1.76     | 2.4                   | 2.272   |
| Sodium as Na <sub>2</sub> O                 | 0.74                      | 0.9      | 0.84                   | 0.91     | 0.52                  | 0.782   |
| Chromium as Cr <sub>2</sub> O <sub>3</sub>  | 1.06                      | 0.93     | 0.84                   | 0.99     | 0.5                   | 0.864   |
| Magnesium as MgO                            | 0.9                       | 0.83     | 0.81                   | 0.84     | 1.1                   | 0.896   |
| Manganese as Mn <sub>3</sub> O <sub>4</sub> | 0.25                      | 0.25     | 0.25                   | 0.2      | 0.16                  | 0.222   |
| Nickel as NiO                               | 0.38                      | 0.33     | 0.3                    | 0.35     | 0.19                  | 0.31    |
| Phosphorus as P <sub>2</sub> O <sub>5</sub> | 0.08                      | 0.03     | 0.04                   | 0.04     | 0.11                  | 0.06    |
| Potassium as K <sub>2</sub> O               | 1.39                      | 1.45     | 1.49                   | 1.42     | 1.26                  | 1.402   |
| Sulfur as SO <sub>3</sub>                   | 0.11                      | 0.15     | 0.15                   | 0.21     | 0.03                  | 0.13    |
| Titanium as TiO <sub>2</sub>                | 0.71                      | 0.56     | 0.55                   | 0.62     | 0.82                  | 0.652   |
| Zirconium as ZrO <sub>2</sub>               | 0.05                      | 0.07     | 0.06                   | 0.06     | 0.09                  | 0.066   |
| Ignition Loss (LOI)                         | 6.21                      | 4.95     | 4.91                   | 6.96     | 0.98                  | 4.802   |

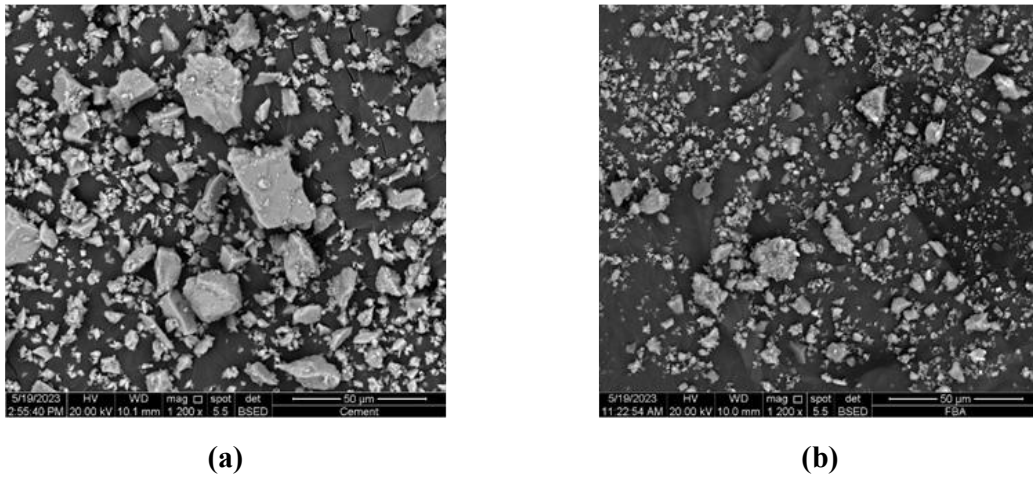
The tabulated data in Table 2.1 illustrates the oxide composition of FBA samples from different batches and power stations, specifically Vales Point Power Station across 2022 and 2023, and Eraring in 2022. A close examination of the concentrations of key oxides such as calcium oxide (CaO), silicon dioxide (SiO<sub>2</sub>), aluminum oxide (Al<sub>2</sub>O<sub>3</sub>), and iron oxide (Fe<sub>2</sub>O<sub>3</sub>) suggest a relative consistency in chemical composition, irrespective of the FBA source or the batch collection date. The concentration of SiO<sub>2</sub>, a crucial determinant of pozzolanic activity, remains relatively stable, showing minor fluctuations with values ranging from 55.9% in Vales Point 2022 to 63.3% in the same station in 2023. Al<sub>2</sub>O<sub>3</sub>, which contributes to the formation of aluminosilicate gel, important for strength gain, also exhibits consistency, with concentrations such as 18.5% in Vales Point 2022 and closely comparable 14.7% in Vales Point 2023. Similarly, Fe<sub>2</sub>O<sub>3</sub>, which can affect the color and thermal properties of the ash, shows no significant divergence, with values like 10.2% and 9.79% for consecutive years at Vales Point. Furthermore, the CaO content, which can greatly influence the fly ash's cementitious behavior, demonstrates minimal disparity across the batches, such as 3.05% in Vales Point 2022 compared to 2.07% in Vales Point 2023. Additionally, the sulfur trioxide (SO<sub>3</sub>) levels, important for assessing the ash impact on concrete durability, remain low and consistent, with a minor increase from 0.11% to 0.15% in Vales Point from 2022 to 2023. The LOI, indicative of organic content and affecting the pozzolanic reaction, also does not show a trend that would suggest a significant difference, with the values being fairly stable such as 6.21% in Vales Point 2022 and 4.95% in Vales Point 2023. Overall, the data indicates that there are not constitute substantial differences when comparing across the FBA source or collection dates. This indicates that although concerns about FBA quality are acknowledged, the findings somewhat contradict the claim by Gooi et al. [32] that FBA characteristics vary significantly according to the source or history of individual batches. In general, consistent coal quality results in consistent ash composition.

**Table 2.2:** Chemical requirements for Fly ash based on ASTM C618 [33] and AS 3582.1. [34]

| Description  | ASTM C618 Limits |          | AS/NZS 3582.2 Limits |           |               |
|--|------------------|----------|----------------------|-----------|---------------|
|  | Type F           | Type C   | Grade 1              | Grade 2   | Special Grade |
| <b>Fineness by mass passing 45 <math>\mu</math>m sieve (minimum %)</b>             |                  |          | 75                   | 55        | 85            |
| <b>SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub></b> | Min. 50%         |          | Min. 70%             | Min. 70%  | Min. 70%      |
| <b>CaO</b>   | Max. 18%         | Min. 18% | -                    | -         | -             |
| <b>SO<sub>3</sub></b>  | Max. 5%          | Max. 5%  | Max. 3%              | Max. 3%   | Max. 3%       |
| <b>Moisture Content</b>  | Max. 3%          | Max. 3%  | Max. 0.5%            | Max. 0.5% | Max. 0.5%     |
| <b>Chloride</b>  | -                | -        | Max. 0.1%            | Max. 0.1% | Max. 0.1%     |
| <b>LOI</b>   | Max. 6%*         | Max. 6%  | Max. 4%              | Max. 6%   | Max. 3%       |

\*Class F pozzolan containing up to 12% LOI may be approved by the user if either acceptable performance records or laboratory test results made available.

The standard limits for Class F fly ash in Australian standards and in ASTM are presented in Table 2.2. Due to the lack of availability of the standards for FBA, for indicative purpose the standards for fly ash had been used as both fly ash and FBA are the by-products from similar industrial procedures. Also, the use of FBA as SCM would be quite similar to fly ash. The major portion of chemical composition of ground FBA consist of silica and alumina [29]. For all samples of ground FBA (GFBA), the sum of silica, alumina and iron oxide was greater than 70% which is specified as the minimum limit in Australian standards for fly ash. The quantity of lime was well within limits prescribed in the standards. The LOI values are closer to the specified limits. This comparison of chemical compositions of ground FBA with available standards limits for Class F fly ash indicates that the ground FBA has the potential to be used as SCM. Both ASTM and AS/NZS 3582.1 limits were met. In our laboratory analysis, the percentage of total chloride was higher than the limit, but the external laboratory results showed that the percentage of chloride was within limits. For further characterisation of ground FBA, a scanning electron microscope (SEM) was used to highlight the particle shape of ground FBA. For comparison, SEM image of OPC is also presented in Fig. 2.2.



**Fig. 2.2:** SEM images (a) Cement and (b) ground FBA (UON Laboratory).

### 2.3 Physical properties

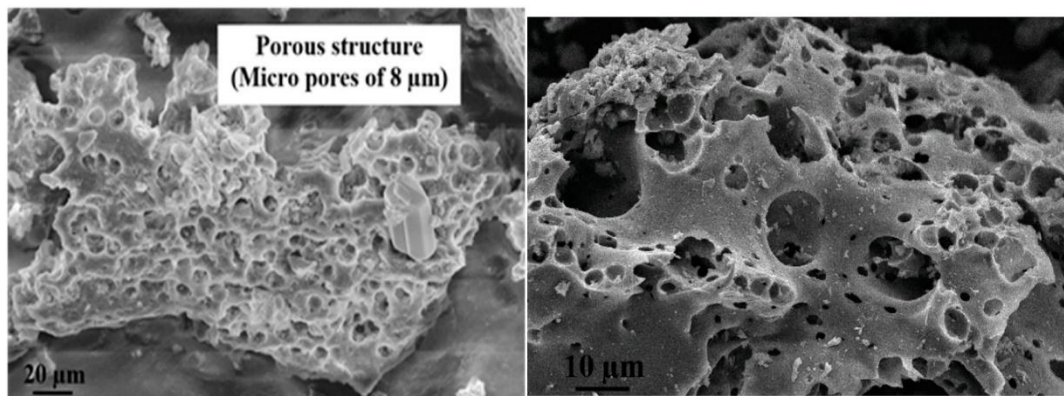
Raw FBA is a light and brittle material, the surface of its particles is almost rough, and its shape tends to be angular [35]. These particles vary in size, ranging from small gravel to fine sand (approximately 0.075–10 mm). In terms of appearance, it is notably darker than FA (see Fig. 2.3). The majority of relevant studies have agreed that FBA has an uneven and spongy texture, and its shape is angular and irregular [4,7,36,37]. The internal porous structure of FBA, as shown in Fig. 2.4, means that it is lightweight, making it an ideal candidate for the development of cellular or lightweight concrete [38].





**Fig. 2.3:** Appearance of FBA particles, a) obtained from [35], b) from the university of Newcastle (UON) laboratory.

Previous research on FBA used as a substituent for fine aggregate has primarily focused on its density, fineness modulus (FM), specific gravity (SG), moisture content (MC), and porosity. Conversely, research on FBA as a cement replacement has emphasized its specific surface area (SSA), SG, and MC. Previous studies indicate that the size distribution of FBA typically ranges between 90  $\mu\text{m}$  [39,40] and 4.75 mm [41,42] when used as a sand replacement, while it ranges between 2  $\mu\text{m}$  [43] to 300  $\mu\text{m}$  [44] when used as cement replacement. FBA used as a fine aggregate has a density range of 2190  $\text{kg}/\text{m}^3$  to 620  $\text{kg}/\text{m}^3$ , with an average value of 1378  $\text{kg}/\text{m}^3$ . However, there is a lack of recorded values for FBA density when it is used as a cement replacement. Similarly, only a few studies have reported on the SSA of FBA when used as fine aggregate. In contrast, when FBA was used as a cement replacement, SSA was more often considered; in this case, it ranged from 858.6  $\text{cm}^2/\text{g}$  to 8093  $\text{cm}^2/\text{g}$ , with an average value of 3940  $\text{cm}^2/\text{g}$ .



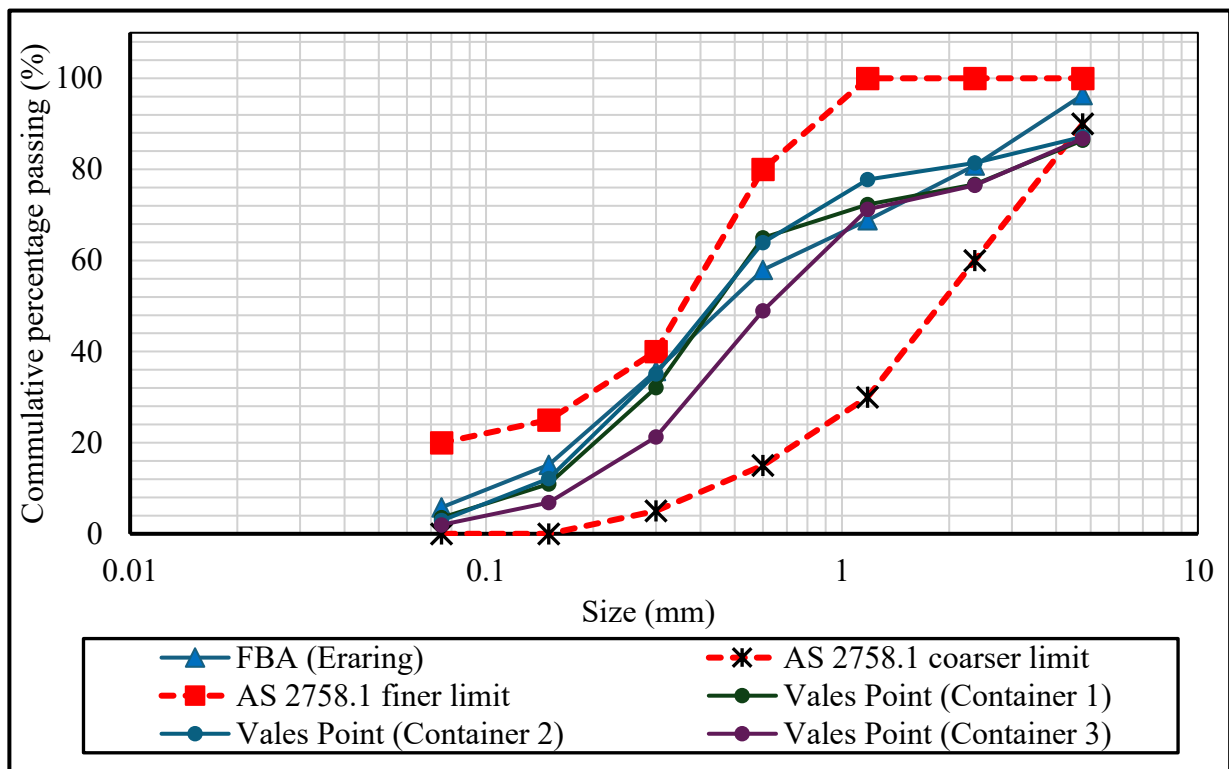
**Fig. 2.4:** Morphological structure of raw FBA [45].

The FM of FBA utilized as a fine aggregate fall within the range of 1.37 to 5.63, with an average value of 2.52. However, studies focused on the use of FBA as a cement replacement have reported FM less frequently, and the values ranged from 2.08 to 4, with an average value of 3.03. Additionally, while porosity values for FBA used as fine aggregate range from 10.19% to 50%, with an average value of 27.08%, no study has determined the porosity of FBA when used as a cement replacement. Nevertheless, it is worth noting that the determination of porosity has not been widely reported in previous studies, either for fine aggregate or cement replacement. In contrast, MC has been more widely studied when FBA is used as a fine aggregate, compared to when it is used as a cement replacement. Specifically, MC values for FBA used as fine aggregate fall within the range of 0.56% to 40%, with an average value of 13.12%, whereas those for FBA used as cement replacement range from 0.35% to 12.1%, with an average value of 4.3%. Several previous studies [16,46,47] have indicated that the processing and treatment of FBA (e.g., oven drying, pulverization, or grinding) significantly affect its physical properties; for example, variation of the grinding period led to a proportional change in the SG and SSA of the FBA [29].

For this project, the particle size distribution of FBA is presented (Fig. 2.5) showing FBA samples collected at different times from the same source (Vales Point power station) and from Eraring power station. Also, red dotted lines indicate the Australian Standard AS 2758.1 limits for fine aggregates. This shows that FBA lies within the specified limits for fine aggregates as per Australian standards and could be used as a replacement for fine aggregates. Also, Table 2.3 presents the particle size percentages and compares them with the ranges provided in Australian Standards.

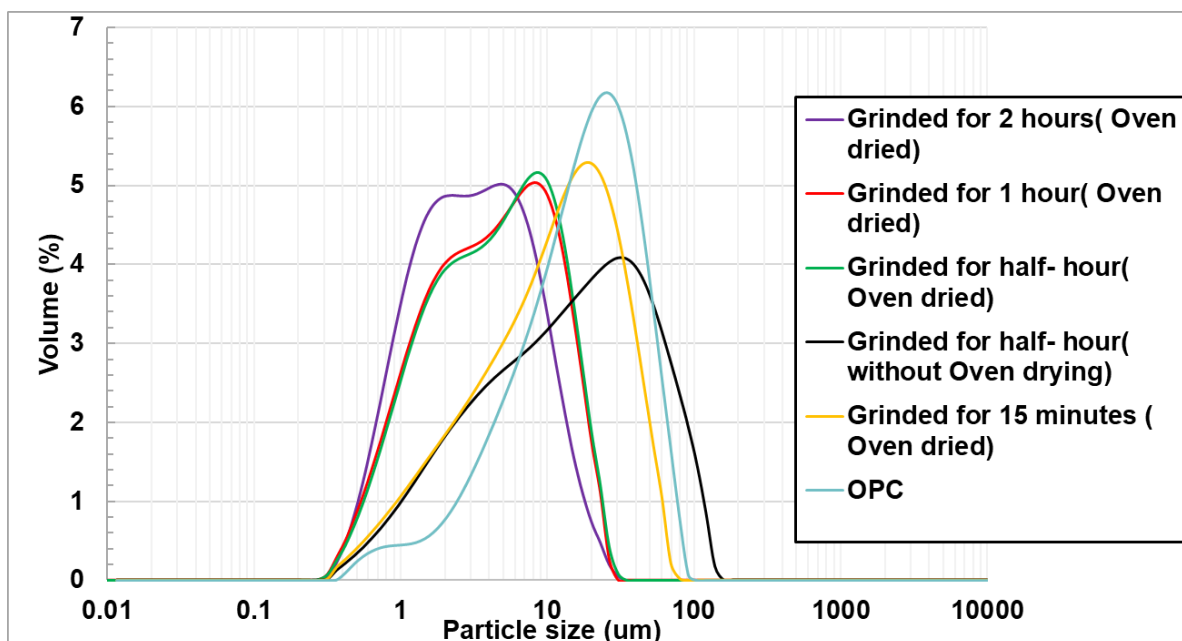
**Table 2.3:** Particle Size Ranges of FBA from different sources (UON Laboratory)

| Sieve Size | FBA (container 1)            | FBA (container 2) | FBA (container 3) | FBA (Eraring) | Ranges in AS 2758.1 |
|------------|------------------------------|-------------------|-------------------|---------------|---------------------|
|            | Percent of total passing (%) |                   |                   |               |                     |
| 4.75 mm    | 86.40                        | 87.16             | 86.79             | 96.36         | 90 – 100            |
| 2.36 mm    | 76.73                        | 81.42             | 76.53             | 80.84         | 60 – 100            |
| 1.18 mm    | 72.31                        | 77.76             | 71.27             | 68.85         | 30 – 100            |
| 600 µm     | 64.97                        | 63.92             | 48.92             | 57.93         | 15 – 80             |
| 300 µm     | 32.10                        | 35.14             | 21.24             | 35.75         | 5 – 40              |
| 150 µm     | 10.96                        | 12.13             | 6.83              | 15.15         | 0 – 25              |
| 75 µm      | 3.54                         | 2.89              | 1.97              | 5.81          | 0 – 20              |
| Pan        | 0.00                         | 0.00              | 0.00              | 0.00          | -                   |



**Fig. 2.5:** Particle Size Distribution of FBA (UON Laboratory).

The use of FBA as SCM requires enhancing the pozzolanic reactivity of FBA. One of the methods to do this is the grinding of FBA into fine particles. A Planetary Ball Mill was used to grind the samples. Different durations were implemented to acquire the optimum results. The particle size distribution of FBA after grinding is presented in Fig. 2.6 generated by conducting analysis on Master Sizer 2000. From Fig. 2.6, it can be concluded that grinding of oven dried FBA for 15 – 30 minutes provides the optimum particle size distribution.



**Fig. 2.6:** Particle Size Distribution of Ground FBA ((UON Laboratory).

Later, the properties of ground FBA were tabulated using Master Sizer analysis (presented in Table 2.4). This shows that the specific surface area of ground FBA with variable grinding durations is significantly different. It can be concluded from particle size distribution together with Master Sizer analysis that 30 minutes would be sufficient to grind the FBA.

**Table 2.4:** Results of Master Sizer Analysis (UON Laboratory)

| Materials  | Ground FBA           |                     |                        |                            |                         | OPC   |
|--|----------------------|---------------------|------------------------|----------------------------|-------------------------|-------|
|  | Grinding Duration    |                     |                        |                            |                         |       |
| Result transform type                            | 2 hours (Oven dried) | 1 hour (Oven dried) | Half-hour (Oven dried) | Half-hour (No Oven drying) | 15 minutes (Oven dried) |       |
| Volume weighted mean ( $\mu\text{m}$ )           | 4.27                 | 5.55                | 5.76                   | 22.95                      | 14.31                   | 20.37 |
| Uniformity                                       | 0.95                 | 0.94                | 0.92                   | 1.28                       | 0.91                    | 0.75  |
| Specific surface area ( $\text{cm}^2/\text{g}$ ) | 23933                | 20500               | 19733                  | 9857                       | 10967                   | 8650  |
| Surface weighted mean ( $\mu\text{m}$ )          | 1.93                 | 2.25                | 2.34                   | 4.68                       | 4.21                    | 6.94  |
| d (0.1), $\mu\text{m}$                           | 0.85                 | 0.93                | 0.97                   | 1.74                       | 1.64                    | 3.37  |
| d (0.5), $\mu\text{m}$                           | 2.90                 | 3.93                | 4.13                   | 13.76                      | 10.64                   | 16.48 |
| d (0.9), $\mu\text{m}$                           | 9.55                 | 12.69               | 13.06                  | 58.92                      | 32.83                   | 43.44 |

The physical properties of raw FBA were determined and are presented in Table 2.5. The moisture content of raw FBA was quite higher than the limits provided in Australian and

international standards (Table 2.2). The reason behind the higher moisture content is the collection process of FBA at the power plants where wet sluicing was usually implemented to avoid dust at the facility. This also complements the requirement of drying as a pre-treatment of FBA. The water absorption of raw FBA is quite high and needs to be considered in the mix design of concrete.

**Table 2.5:** Physical Properties of FBA.

| <b>Description</b>                            | <b>Raw FBA</b> | <b>Natural<br/>fine<br/>aggregate</b> | <b>Test Standard</b> |
|---|----------------|---------------------------------------|----------------------|
| Moisture Content (%)                          | 4 - 6          | 1.2                                   | AS 3583.2            |
| Uncompacted Bulk Density (kg/m <sup>3</sup> ) | 960            | 1400                                  | AS 1141.4            |
| Compacted Bulk Density (kg/m <sup>3</sup> )   | 1100           | 1650                                  | AS 1141.4            |
| Apparent Density (kg/m <sup>3</sup> )         | 1390           | 2490                                  | AS 1141.5            |
| Dry Density (kg/m <sup>3</sup> )              | 1220           | 2280                                  | AS 1141.5            |
| SSD Density (kg/m <sup>3</sup> )              | 1340           | 2360                                  | AS 1141.5            |
| Water Absorption (%)                          | 11.61          | 4.2                                   | AS 1141.5            |
| <b>Clay – fine silt content (%)</b>           | 2.8            | /                                     | AS 1141.33           |

## 2.4 Comparison FBA properties with FA

Table 2.6 compares oxide concentrations in FA from Eraring Power Station, Mt Piper Power Station, and an average for FBA. The similarities in chemical composition between FBA and FA from the two power stations are indeed noteworthy, with only minor differences observed. For Al<sub>2</sub>O<sub>3</sub>, the FBA average is 16.74%, which is closer to Mt Piper's 13.6% than to Eraring's 24.0%, suggesting a moderate variance but still within a similar range. In terms of CaO, the FBA's average of 2.272% is slightly higher than Mt Piper's 0.2% and Eraring's 1.59%. The Fe<sub>2</sub>O<sub>3</sub> content in FBA is 9.406%, which is significantly higher than Mt Piper's 2.8% and Eraring's 2.87%. When comparing SiO<sub>2</sub>, which is a major component in FA and affects its pozzolanic properties, the FBA average is 61.08%, aligning more closely with Mt Piper's 80.7% compared to Eraring's 65.9%. Although there is a difference, the SiO<sub>2</sub> content across all samples remains high, which is favorable for pozzolanic activity. Overall, the pozzolanic content (Fe<sub>2</sub>O<sub>3</sub> + Al<sub>2</sub>O<sub>3</sub> + SiO<sub>2</sub>) remains still fulfills the requirements of AS 3582.1 (higher

than 70%), with the FBA average reaching 87.23%, while the FA collected from Mt Piper Power Station is at 97.1%, and the FA from Eraring Power Station is at 92.77%.

**Table 2.6:** Comparing chemical composition FBA and FA from the same source.

| Oxides concentration (%)    | Al <sub>2</sub> O <sub>3</sub> | CaO  | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | MgO  | MnO  | Na <sub>2</sub> O | P <sub>2</sub> O <sub>5</sub> | SiO <sub>2</sub> | TiO <sub>2</sub> | SO <sub>3</sub> | LOI  |
|-----------------------------|--------------------------------|------|--------------------------------|------------------|------|------|-------------------|-------------------------------|------------------|------------------|-----------------|------|
| Eraring Power Station [48]  | 24.0                           | 1.59 | 2.87                           | 1.44             | 0.42 | 0.06 | 0.49              | 0.19                          | 65.9             | 0.915            | -               | 1.53 |
| Mt Piper Power Station [48] | 13.6                           | 0.2  | 2.8                            | 0.71             | 0.2  | 0.1  | 0.1               | 0.2                           | 80.7             | 0.5              | < 0.1           | 0.6  |
| FBA-Average from Table 2.1  | 16.74                          | 2.27 | 9.41                           | 1.40             | 0.90 | 0.22 | 0.78              | 0.06                          | 61.08            | 0.65             | 0.13            | 4.80 |

The minor constituents such as K<sub>2</sub>O, MgO, MnO, Na<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, TiO<sub>2</sub>, and SO<sub>3</sub> also show high degrees of similarity. For instance, the FBA has a K<sub>2</sub>O concentration of 1.402%, which is quite close to the 1.44% found in Eraring and 0.71% in Mt Piper. Similar small variances are seen in MgO, with FBA at 0.896% compared to 0.44% in Eraring and 0.2% in Mt Piper. The TiO<sub>2</sub> content is relatively similar across the board, with FBA averaging 0.652%, not far from Eraring's 0.915% and Mt Piper's 0.5%. SO<sub>3</sub> levels are very low in all samples, with FBA averaging 0.13%, which is again similar to Mt Piper's <0.1% and not significantly different from Eraring's absent value. Finally, the Loss on Ignition (LOI) values, which indicate the amount of unburnt carbon and volatiles, are 4.802% for FBA, higher than Mt Piper's 0.6% and Eraring's 1.53%.

In general, the comparison reveals that despite there being minor differences in the concentrations of various oxides between the average values for FBA and the FA values from Eraring and Mt Piper Power Stations, the similarities are substantial. It is also worth noting that the differences in the average oxides concentrations for FBA are not significantly far from the differences in oxides concentrations for the two types of FA, which suggests a strong possibility that these differences in chemical composition for FA could accommodate FBA as a comparable material.

## **2.5 Environmental considerations**

The presence of FBA in ash ponds could be risky as the presence of heavy could leach into the nearby water bodies which could cause water pollution. In Australia, however, ash ponds are highly regulated by a vigorous system of environmental regulation and engineered control to provide adequate containment, including but not limited to lined storage cells, leachate collection systems, groundwater monitoring bores and site specific environmental management. Notwithstanding the above controls, long-term responsibilities, storage capacity limitations and closure obligations support the diversion of FBA from ponds as being the preferred option of hierarchy. Utilising FBA to produce concrete will support a beneficial reuse option that not only minimises reliance on ash dams but also supports both a chemical and physical immobilisation of trace metals within the cement's matrix, e.g., C-S-H phases binding and encapsulating potential contaminants, which significantly reduces their leachability [49,50]. Therefore, the use of FBA in producing concrete represents a risk mitigation opportunity that supports sustainable materials management while protecting the environment..

## **2.6 Summary**

The physical and chemical properties of FBA have been discussed in this chapter. FBA has potential to be used as an ingredient in concrete and could enhance or at least retain the required properties of concrete for long term strength and durability. Careful consideration is required while selecting or using the FBA from various sources. Pre-quality or chemical composition determinations would help to plan the use of FBA in concrete effectively.

# CHAPTER 3: PROCESSING AND HANDLING OF FBA FOR CONCRETE USE

## 3.1 Introduction

FBA, in its raw form as collected from coal-fired thermal power plants or ash dams, is generally unsuitable for direct use in concrete applications—whether as a fine aggregate replacement or as a SCM. This is due to its inconsistent particle size, high porosity, potential contamination and low pozzolanic reactivity. To ensure its effective and safe integration into concrete, FBA must undergo a series of pre-treatment processes. These may include drying, sieving, grinding, and in some cases, chemical or thermal activation, depending on the intended application. This chapter outlines the essential pre-treatment steps required to enhance the physical and chemical characteristics of FBA, ensuring its compatibility with concrete mix designs and compliance with relevant engineering standards. These procedures play a critical role in unlocking the environmental and structural benefits of using FBA in sustainable construction practices.

## 3.2 FBA collection and initial treatment

FBA is normally collected from the bottom of the furnace and has coarser particles. To avoid dust in the facilities, FBA usually collects through water sluicing process and then stored in storage tanks or diverted to ash ponds for later reclamation. This collection and storage methods introduce various limitations to use raw FBA in concrete in its current form. The wet collection process results in excessive moisture in FBA and compaction or dumping cause agglomeration of raw FBA. Thus, the raw FBA requires to be dried, sieved and ground before using it into the concrete.

## 3.3 Pre-processing requirements

The pre-processing treatments required for the use of FBA either as fine aggregates or as SCM in concrete are drying, sieving and grinding. The details of each process are provided below:

### 3.3.1 *Drying*

The first step in using FBA in concrete, whether as a fine aggregate or as SCM, is drying the raw FBA prior to processing and incorporation. Because while collection of the FBA at power plants, mostly wet sluicing process has been adopted to avoid fugitive dust emissions at the facility. When FBA is collected or transferred to stockpiles, the water will remain in FBA.

The FBA is stored in bulk quantity and when extracted from stockpiles it is in wet condition. In a laboratory, FBA is being oven dried at  $105\text{ }^{\circ}\text{C} \pm 10\text{ }^{\circ}\text{C}$  to remove moisture from raw FBA, so that the water added to the concrete mix can be accurately determined based on the water absorption of FBA [51]. Otherwise, the excessive moisture present in FBA will affect the mix design, workability, and strength of the concrete.

### 3.3.2 Sieving

After oven drying, the next procedure required to utilize FBA in concrete is the sieving of the raw FBA according to AS 2758.1 [52]. The raw FBA might contain bigger particles although in smaller quantity but need to be separated to achieve the desired properties of concrete. The gradation of the FBA depends upon the combustion level at the power plants. To utilize FBA as fine aggregates, sieves used for gradation are from 4.75 mm to 75  $\mu\text{m}$  as shown in Fig. 3.1. The particle size distribution of FBA could be variable even from same source/power plant. Therefore, after sieving, by controlling the size proportions the required particle size distribution would be obtained to utilize the FBA in concrete. The sand/fine aggregates could be classified as shown in Table 3.1.

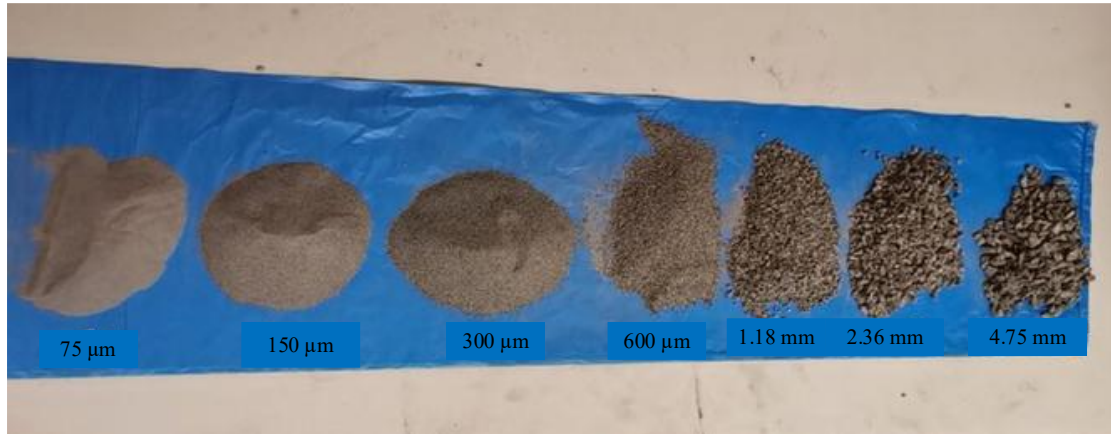


**Fig. 3.1:** Sieves (left) and raw FBA which has been oven dried (right).

**Table 3.1:** Particle Size Range [53].

| Texture     | Australian Standard Particle Size Range (mm) | United States Department of Agriculture Particle Size Range (mm) |
|-------------|--|--|
| Coarse Sand | 0.2-2  |  |
| Fine Sand   | 0.02-0.2                                     | 0.05-2   |
| Silt        | 0.002-0.02                                   | 0.05-0.002   |
| Clay        | < 0.002                                      | < 0.002  |

It would be decided based on the gradation curve what range of sizes are available and accordingly what type of fine aggregates would be replaced by FBA in concrete. In Fig. 3.2, the FBA after sieving has been presented. In this project, FBA was screened through 4.75 mm sieve, and it was found that particle size distribution of FBA was similar to fine sand. Therefore, FBA was blended with coarse sand to be used in this project.



**Fig. 3.2:** Different Sizes of FBA after Sieving from (right) 4.75 mm to 75  $\mu$ m(left).

### **3.3.3 Grinding**

The pozzolanic characteristics of FBA needs to be enhanced for use as SCM in concrete. In literature [54–56], the most attained method to increase the reactivity of FBA in cement concrete is grinding. The grinding of FBA in laboratory scale is done by using a ball mill. The duration of grinding and method depends on the type of available apparatus. In studies [57,58], the ball milling method has provided satisfactory performance. For this research project, ball milling conducted using Across International PQ series planetary ball mill (Fig. 3.3). The mode of ball milling adopted was unidirectional. Steel balls of 6 mm, 10 mm and 20 mm were used for the ball milling operation. Jars were filled with steel balls and FBA up to  $\frac{3}{4}$  of the total height of the jar as shown in Fig. 3.4. Then the jars were placed and tightened in the ball milling apparatus. Duration of the ball milling usually ranges between 1 hour up to 40 hours. In this project, the FBA samples were milled at the same speed (450 rpm) for various durations (15 mins, 30 mins, 1 hour and 2 hours). Preliminary results show that a milling time of 15 mins is sufficient to refine the FBA particle size. When FBA is ground to fine powder, it shows better strength than unground FBA as SCM in concrete.



**Fig. 3.3:** Planetary Ball mill with 4 Jars.



**Fig. 3.4:** Ball Milling Jars containing Steel Balls and FBA.

These methods need to be implemented to use FBA in concrete either as fine aggregates or SCM. Where FBA is used as fine aggregates replacement, drying and sieving processes are sufficient to obtain the desired properties of the concrete. In another case, using FBA as SCM in concrete, all three processes drying, sieving, and grinding should be done to achieve the required characteristics of concrete.

In this project, to further improve the pozzolanic reactivity of FBA in cement concrete, the effect of co-grinding has also been investigated. In co-grinding, FBA should be ground in a ball mill by adding other potential SCM's in concrete. The other potential SCM's might include slag from the steel industry or recycled aggregate fines. The slag could increase the calcium components which would benefit in hydration of cement [59]. The recycled aggregate fines had some un-hydrated cement which could enhance the pozzolanic characteristics of FBA. Co-grinding using a ball mill modifies the material through mechanical activation, promoting molecular rearrangement as well as partial amorphization and recrystallization of the crystal structure [60,61]. The resulting blend improved the strength and durability performance of concrete [62]. In this study, FBA was co-ground with GGBFS or steel slag in different proportions. The steel slag used was slightly coarser, and its inclusion increased the calcium content of the blended material. This enhanced the overall reactivity of FBA in the concrete mixture. The co-grinding process does not require significant additional processing effort, yet it can substantially improve the reactivity of FBA. Concrete incorporating FBA as a SCM typically exhibits low early-age strength. The formation of additional reactive phases through co-grinding contributes to improved early strength development. These findings demonstrate that co-grinding is a practical approach to enhancing the performance of FBA, supporting its more confident and reliable use at commercial scale.

### **3.4 Storage and handling practices**

The FBA, after undergoing the necessary pre-treatment processes, must be stored in a low-moisture environment, preferably in sealed, airtight containers or moisture-resistant silos, to prevent unwanted water absorption. Due to its high porosity and hygroscopic nature, FBA is particularly prone to absorbing moisture from the atmosphere. If not stored correctly, this absorbed moisture can significantly alter the moisture content of concrete mixes, leading to inaccuracies in water-to-cement ratios and inconsistencies in workability. This is especially critical when FBA is used as a replacement for fine aggregates or as a SCM, where moisture content must be carefully controlled. In the long term, such uncontrolled moisture variations

can adversely affect the mechanical properties, strength development, and durability of the concrete. Therefore, appropriate storage protocols are essential to maintain the integrity of FBA and ensure the reliable performance of concrete incorporating FBA.

### **3.5 Quality assurance and testing protocols**

Quality assurance and testing protocols are essential to ensure the suitability of FBA for use in concrete as a fine aggregate or as SCM. These protocols involve regular testing of physical properties such as particle size, bulk density, moisture content, and water absorption, as well as chemical composition to monitor levels of silica, alumina, calcium oxide, and potential contaminants. Pre-treatment processes like drying, sieving, and grinding must be verified to achieve consistent material quality. Trial mix designs help determine the optimal proportions for concrete performance, which is further validated through strength, durability, and workability tests. Durability assessments may include acid and sulphate resistance, carbonation depth, and chloride penetration. On-site quality control ensures consistency in batching and mixing, while compliance with relevant Australian standards is required for industrial application. These protocols collectively support the reliable and sustainable integration of FBA into concrete production.

### **3.6 Summary**

This chapter has outline the pre-processing of FBA to be used either as fine aggregates replacement or as SCM in concrete. Pre-processing is essential and must be as per requirements to avoid any deviation in the final product or alterations in the properties or performance of FBA concrete. This can be ensured by proper processing and proper handling or storage of pre-treated FBA. The pre-treatments required are drying, sieving and grinding before incorporating FBA in concrete. For handling the major constraint is to avoid any moisture from surroundings which could alter the moisture contents in FBA and will affect the properties of concrete. In addition, quality control and regular monitoring would be preferred to avoid any unwanted changes in the behaviour of FBA in concrete.

# CHAPTER 4: FBA UTILIZATION IN MORTAR

## 4.1 Introduction

Recycling fly ash and FBA helps reduce greenhouse gas emissions, conserving natural resources, and minimizing waste accumulation. However, research on recycling FBA is progressing slowly compared to FA. This chapter aims to explore the integration of the use of FBA as an alternative to sand and cement as SCM to reveal its impact on the mechanical properties of the produced mortar.

## 4.2 Mixes proportions

Table 4.1 delineates the mix proportions for designing mortar with FBA as a substitute for fine aggregate and cement replacement, following the M3 mortar type specifications for cement (GB/GP) as defined by AS3700 standards. Given the disparity in material densities, volume-based replacement for fine aggregate was preferred over mass to ensure accuracy in mix design. Four proportions of fine aggregate replacement by FBA are considered: 25%, 50%, 75%, and 100% by volume. After determining the optimal level of FBA as a fine aggregate replacement, the chosen proportion was used to proceed with mortar groups using FBA as a cement replacement. Three different mix formulations were developed (i.e., 25%) and 10%, 20% and 30% ground FBA (GFBA) as cement replacements. The water-to-binder (w/b) ratio was fixed at 0.6 for all mixtures. The water-to-cement (w/c) ratio was uniformly maintained at 0.60 for all batches. Notably, the intrinsic high water absorption characteristic of FBA, ranging between 10 and 15%, necessitates the careful adjustment of water content. To circumvent the excessive use of superplasticisers (SP), the water absorbed by FBA was meticulously calculated and integrated into each respective mix, or all materials were utilized in saturated surface dry (SSD) conditions. However, due to the difficulty of achieving SSD, the raw materials were used in oven-dry conditions, and the amount of water absorbed by the materials has been calculated and added to the mixing water. The additional water requisite (AWR) was quantified by the formula:  $AWR (\%) = (\text{water absorption } (\%) \text{ of FBA} - \text{moisture content } (\%) \text{ of FBA}) * \text{proportion of FBA in the mix}$ . This methodological approach is instrumental in research involving materials with pronounced absorption capacities, where achieving the desired workability is challenging without substantial superplasticizer application.

**Table 4.1:** Mortar mix proportions (kg/1 m<sup>3</sup>).

| Mixture | Sand   | FBA as Sand | GFBA as cement | Cement | w/c |
|---------|--------|-------------|----------------|--------|-----|
| 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 |

### 4.3 Testing setup

Table 4.2 outlines the specific tests administered on mortar formulated with FBA as a fine aggregate and cement replacement, along with the corresponding standards governing these procedures. The assessments include flowability to determine the mortar's ease of placement and consolidation according to AS 2701-200. compressive strength and density at ages of 7, 28 and 56 days, evaluated as per AS 1012.9:2014 and AS 1012.12 respectively. Flexural strength and water absorption for 28 days was measured following AS 1012.11-2000, and AS 1012.21-1999 respectively, to assess the mortar porosity and bonding characteristics.

**Table 4.2:** Tests performed on mortar designed with FBA and the standards of the applied procedures.

| Test                                    | Implementation Standards |
|---|--------------------------|
| Flowability                             | AS 2701-2001             |
| Compressive strength (7, 28 and 56days) | AS 1012.9:2014           |
| Density (7, 28, and 56 days)            | AS 1012.12               |
| Flexural strength (28)                  | AS 1012.11-2000          |
| Water absorption (28 days)              | AS 1012.21-1999          |

Emissions were evaluated in terms of carbon equivalent emissions according to the following equation:

$$\text{CO}^2\text{-e kg/m}^3 = \sum(m_i \times f_i)$$

Where  $m_i$  is the mortar material  $i$  in  $\text{kg/m}^3$ , and  $f_i$  is the global warming parameter equivalent to material  $i$  production. The  $f_i$  values were obtained from Dragon group database information on materials embodied emissions sourced from Infrastructure Sustainability Materials, as shown in Table 4.3.

**Table 4.3:** global warming parameter values.

| Material                             | Portland cement | GFBA for cement replacement | Fine aggregate | FBA as fine aggregate Rep. |
|--------------------------------------|-----------------|-----------------------------|----------------|----------------------------|
| kg CO <sub>2</sub> -e/m <sup>3</sup> | 0.982           | 0.121                       | 0.00789        | 0.00758                    |

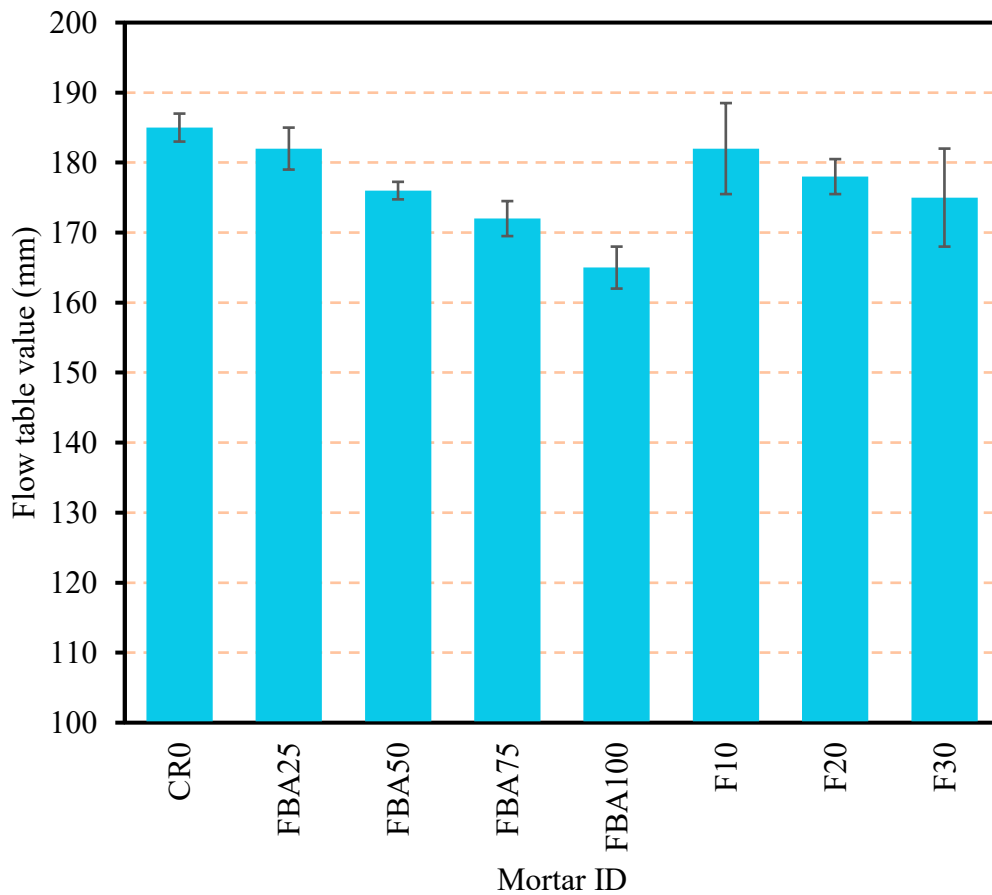
## 4.4 Results and discussion

### 4.4.1 Mortar flowability

Mortar flowability was determined through the flow table test according to AS 2701. Fig. 4.1 illustrates the results of a flow table test to evaluate the influence of FBA as a fine aggregate and partial cement replacement on the flowability of mortar. The results indicate that the mix with no replacement (CR0) exhibited the highest flowability, while when FBA was included as fine aggregate replacements, the mortar flowability decreased. The reduction of mortar flowability increased with increasing the replacement level, where the reduction percentages were 1.6%, 4.9%, 7.0% and 10.8%, corresponding to inclusion of 25%, 50%, 75% and 100% of FBA as fine aggregate replacement, respectively. These reductions are attributable to the high water absorption of FBA compared to natural fine aggregate as shown in Table 2.5. The irregular and rough shape of the FBA particles may have an effect on increasing intermolecular friction and reducing the kinetic energy of the mortar, thus, reducing its flowability [63,64].

The results are consistent with observations reported elsewhere [5,65], where the workability reduction tends to increase as the level of replacement increases. In the case of the inclusion of GFBA as partial cement replacement, the F10 mix showed a 4.9% decrease in flow value compared to CR0, identical to the FBA25 mix, whereas the F20 and F30 mixes experienced a 3.8% and 5.4% reduction compared to CR0, and 2.2% and 3.8% when compared to FBA25 mix, respectively. The decrease in flow diameter values compared to the control samples may be attributed to the rough and irregular surface of GFBA compared to cement particles. The rough and irregular shape of the GFBA particles may increase intermolecular friction, unlike the semi-smooth shape of cement particles, thus reducing mortar flowability. Furthermore, the high fineness of GFBA particles as shown in Table 2.4 make them tend to fill the inter area of the mixture particles, thus reducing the area available for particles dynamics, and therefore, an excessive amount of water is needed to lubricate the mixture to give it enough flowability [66]. These findings are consistent with several studies that report decreased flow values in mixes containing GFBA, such as the study by Abdulmatin et al. [19],

Abbas [45] and Aydin [67]. These researchers found that the reduction in mortar flowability gradually increases with increased GFBA content.

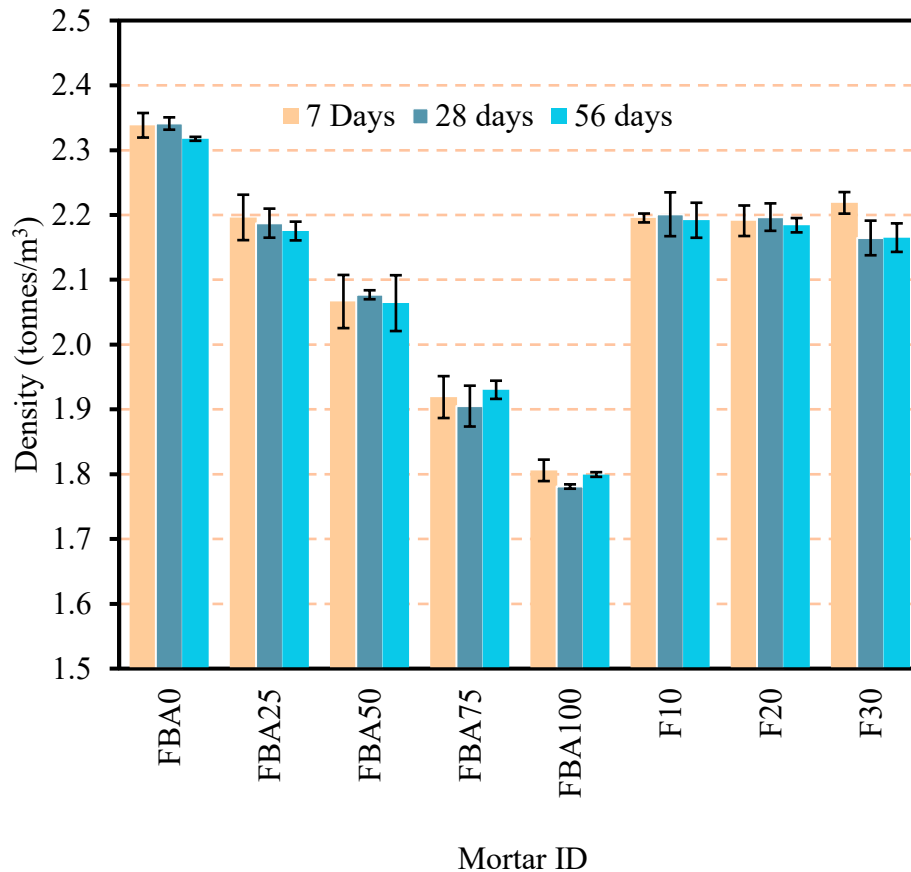


**Fig. 4.1:** Flow diameter of designed mortars.

#### 4.4.2 Mortar densities

Fig. 4.2 presents the densities of the mortar samples measured at 7, 28, and 56 days, with varying percentages of FBA as fine aggregate and cement replacements. From Fig. 4.2 the density decline is obvious in the case of using FBA as fine aggregate. For the FBA0 mix, which has no FBA replacement, the densities were 2.34, 2.34, and 2.32 kg/m<sup>3</sup> at 7, 28, and 56 days, respectively. The FBA25 mix had densities of 2.20, 2.19, and 2.17 kg/m<sup>3</sup> at the respective ages, showing a similar gradual decrease. This trend is consistent across the mixes with higher FBA contents; for instance, the FBA100 mix, in which the fine aggregate was fully replaced by FBA, recorded the lowest densities across all the ages 1.81, 1.78, and 1.80 kg/m<sup>3</sup>. The reduction in the mortar density with the increase of FBA content might be due to the lower density of FBA compared to the fine aggregate it replaces.

In the case of the inclusion of GFBA as partial cement replacement, no regular trend of densities was observed. For example, the F10 showed slightly higher density by 0.6% compared to FBA25 at 28 days. This could be attributed to the filling effect, leading to more compact matrix. The reduction of densities was lower than that when using FBA as a fine aggregate. However, the F20 mortar showed similar densities to those of FBA25, while F30 showed lower densities by around 1%.



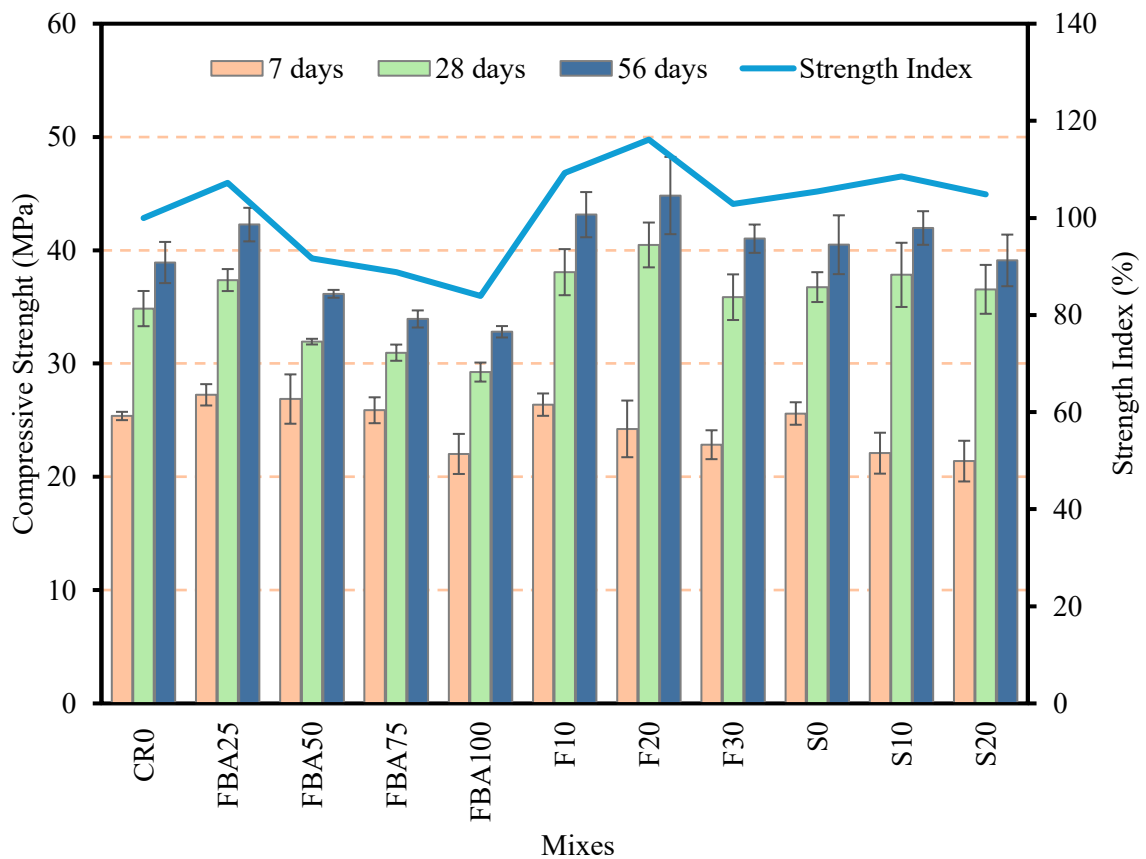
**Fig. 4.2:** Density of the designed mortars.

#### 4.4.3 Compressive strength

Compressive strengths were determined according to AS/NZS 2350.11. Fig. 4.3 depicts the compressive strength of the masonry mortar samples with various replacement levels of FBA over time, specifically at 7, 28, and 56 days. The FBA25 mix, with a 25% FBA replacement of fine aggregate, started with a higher initial strength of 27.2 MPa at 7 days, surpassing CR0 at 28 days by 7.2%, and achieved the highest compressive strength among all mixes at 56 days with 42.3 MPa. For the FBA50, FBA75 and FBA100 mixes, there was a slight decrease in strength at all ages compared to CR0, and the strength reduction increased with

increased fine aggregate replacement level. However, FBA50 achieved higher strength by 5.9% at 7 days compared to the control sample without FBA. This could be attributed to the partial pozzolanic reaction between the fine particles of FBA and with  $\text{Ca(OH)}_2$ , resulting in the enhancement of the early strength [30]. This potentially occurs with all mixes containing fine FBA as sand; however, at high replacement levels, the negative effect of FBA porosity and weak particles of FBA likely outweigh that improvement.

When 10% and 20% of GFBA was used as cement replacement with 25% of FBA as fine aggregate replacement, there was more enhancement of compressive strength. The compressive strength of both mixes, F10 and F20, surpassed those of CR0 and FBA25 at 28 and 56 days. This indicates the effectiveness of co-incorporation of GFBA as partial replacements for both cement and fine aggregate. This improvement might be correlated to improved microstructures which provides more compacted and stronger bonding possibility between the binder and the aggregate. Meanwhile, the finer particles and those used as a substitute for cement react with the  $\text{Ca(OH)}_2$  produced from the initial cement hydration, providing additional hydrates [68].

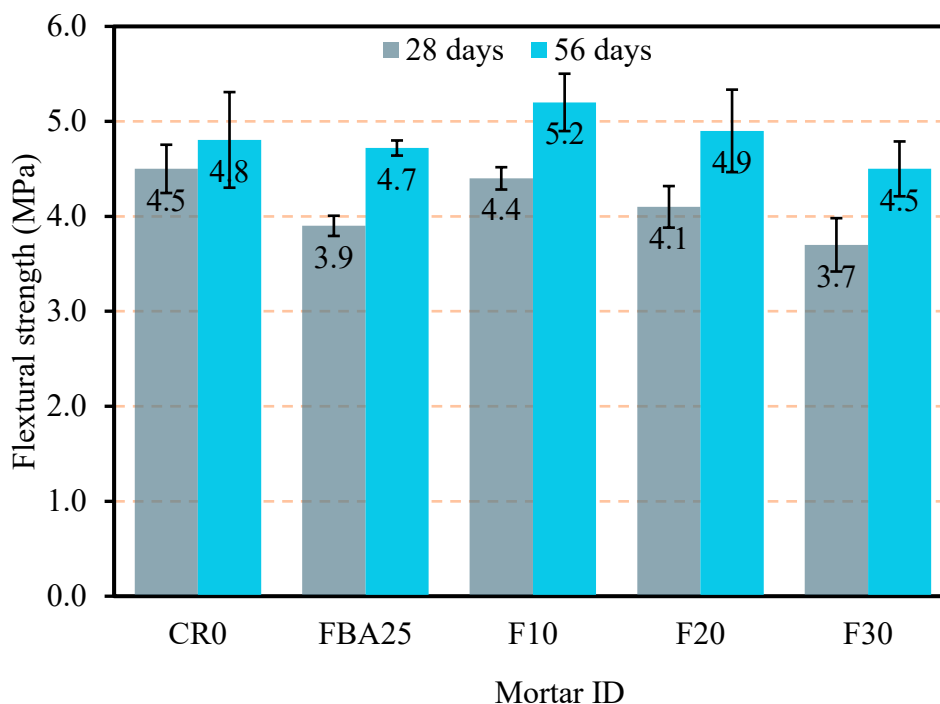


**Fig. 4.3:** Compressive strength performance of FBA-based mortars.

#### 4.4.4 Flexural strength

Flexural strength was determined according to AS 2350.12. Fig. 4.4 illustrates the flexural strength of the designed FBA-based mortar samples at 28 and 56 days. All samples containing FBA (25% of FBA as fine aggregate and, 10%, 20% and 30% as cement replacements) demonstrated lower strength compared to CR0 at 28 days. For example, FBA25 demonstrated a 13.3% reduction in strength compared to CR0 at 28 days, and similar flexural strength to that of CR0 at 56 days. The FBA25 sample exhibited a substantial improvement of 20.51%, with flexural strength increasing from 3.9 MPa to 4.7 MPa over the same period. At 28 days, F10 closely matched the control sample CR0, indicating comparable early strength, while F20 and F30 showed slightly lower flexural strength.

After 56 days, both F10 and F20 showed significant strength increases, with F10 (5.2 MPa) being stronger than both CR0 (8.3%) and FBA25 (10.6%), proving that co-incorporating GFBA as a partial replacement for fine aggregate and cement was beneficial. These findings are consistent with those reported in other studies [69–71], which demonstrated that the optimal GFBA replacements are lower than 25% and the enhancement in flexural strength usually appears after 56 days.

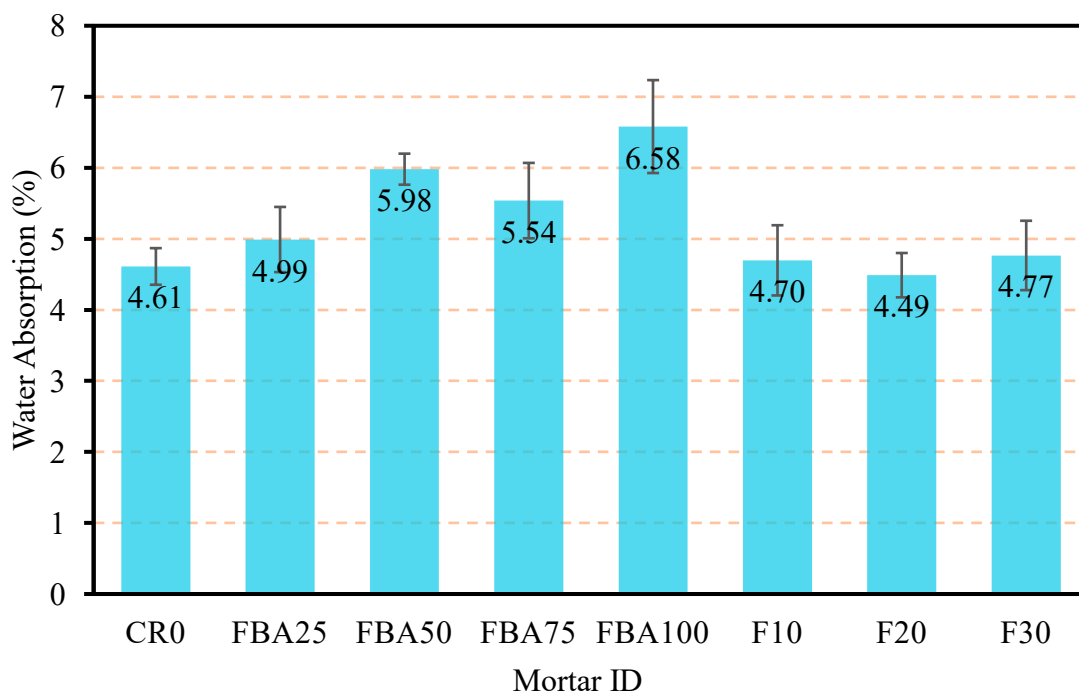


**Fig. 4.4:** Flexural strength of the designed FBA-based mortars.

#### 4.4.5 Water absorption

Fig. 4.5 shows absorbed water percentages for mortar samples with FBA as partial alternatives of fine aggregate and cement at 28 days. The water absorption rate of CR0 was 4.61%. When FBA is used as fine aggregate replacement, the percentages of absorbed water increased, and the increment was boosted by increasing the replacement level. Starting with FBA25, the increment was 8.2% compared to that of CR0. This trend reversed slightly with FBA75, where water absorption decreased from 5.98 for FBA50 to 5.54 % for FBA75. The higher water absorption rate was observed for the mortar sample with 100% replacement of the fine aggregate with FBA; for this sample the water absorption was 6.58%, which is higher than that of CR0 by 42.7%. The increase in water absorptions with increased FBA content could be attributed to the intrinsic properties of FBA, particularly its porosity, which might contribute to a greater overall porosity of mortar and thus higher water absorption.

However, with the co-incorporation of FBA, 25% as fine aggregate replacement and 10%, 20% and 30% GFBA as partial cement replacements, the water absorption rates were slightly lower than the FBA25 sample. This improved water absorption resistance can be attributed to both the pozzolanic reaction and the filling action by the fine particles. It can be claimed that the high fineness boosted the pozzolanic reactivity of GFBA particles due to the availability of higher surface area per volume, which resulted in the C-S-H gel filling the pores, hence, reducing water absorption [43]

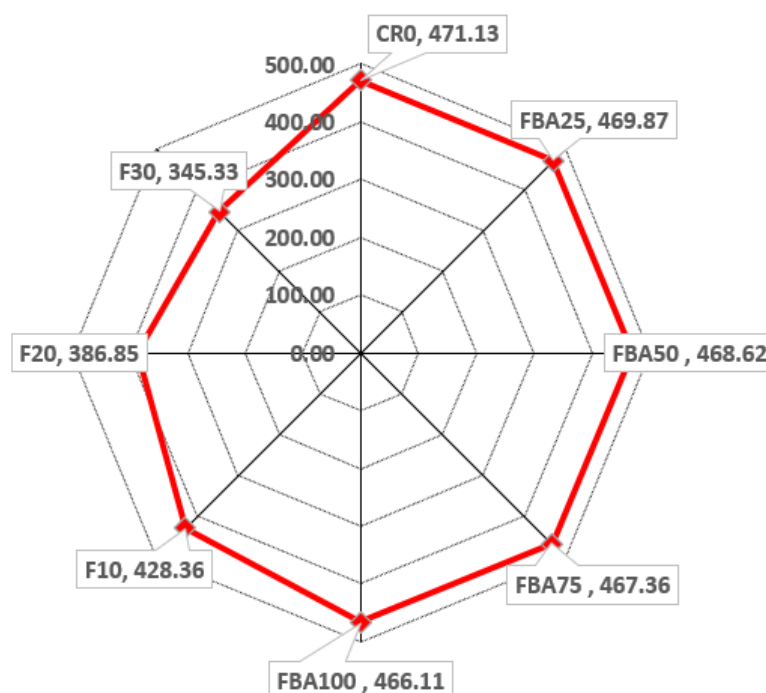


**Fig. 4.5:** Water absorption of the designed FBA-based mortars at 28 days.

## 4.4.6 Environmental impact assessment

### 4.4.6.1 Analysing emissions

Fig. 4.6 illustrates the equivalent carbon emissions for each mortar mix. It was observed that replacing fine aggregate with FBA did not result in a significant change in the amount of embodied carbon for the FBA25, FBA50, FBA75, and FBA100 mixes compared to the control sample CR0. This is attributed to global warming parameter values of natural fine aggregate (0.00789) and FBA aggregate (0.00758). The reduction rates were 0.26%, 0.53%, 0.80%, and 1.1% when 25%, 50%, 75%, and 100% of the fine aggregate was replaced with FBA, respectively. When the replacement rate of fine aggregate with FBA was fixed at 25%, and cement was replaced with 10%, 20%, and 30% GFBA, the equivalent carbon dioxide decreased from 469.87 kg/m<sup>3</sup> to 428.36, 386.85, and 345.33 kg/m<sup>3</sup>, respectively. This corresponds to reduction extents of approximately 9.1%, 17.9%, and 26.7%, respectively, compared to CR0. This is consistent with the conclusions of previous studies, which indicated that CO<sub>2</sub> emission decreased linearly with increasing FBA content as cement replacement [194,276].



**Fig. 4.6:** Embodied emissions (in kg/m<sup>3</sup>) from each mix.

#### 4.4.6.2 Leachability

Table 4.3 provides a comparative analysis of the leachability of trace elements from GFBA, OPC, and FA. Samples were analysed in duplicate using ICP-OES and ICP-MS following calibration with a standard curve ( $R^2 = 0.9999$ ), with CCV verification, certified reference soil and recovery checks (93.6–100.7%) for QA/QC, and method reporting limits of 0.1 ppb (ICP-MS) and 0.1 ppm (ICP-OES). The results indicate that nickel was detected in FBA but was absent in both FA and OPC, with its concentration exceeding the upper limits specified by regulations, including those of the EPA NSW, as depicted in Fig. 4.7.

Additionally, GFBA exhibited measurable concentrations of Mn, Zn, Cr, Fe, Co, Cu, Mo, Ag, Sn, and Ba, with some elements having lower concentrations than those found in FA or OPC, or both, as shown in Table 4.3.

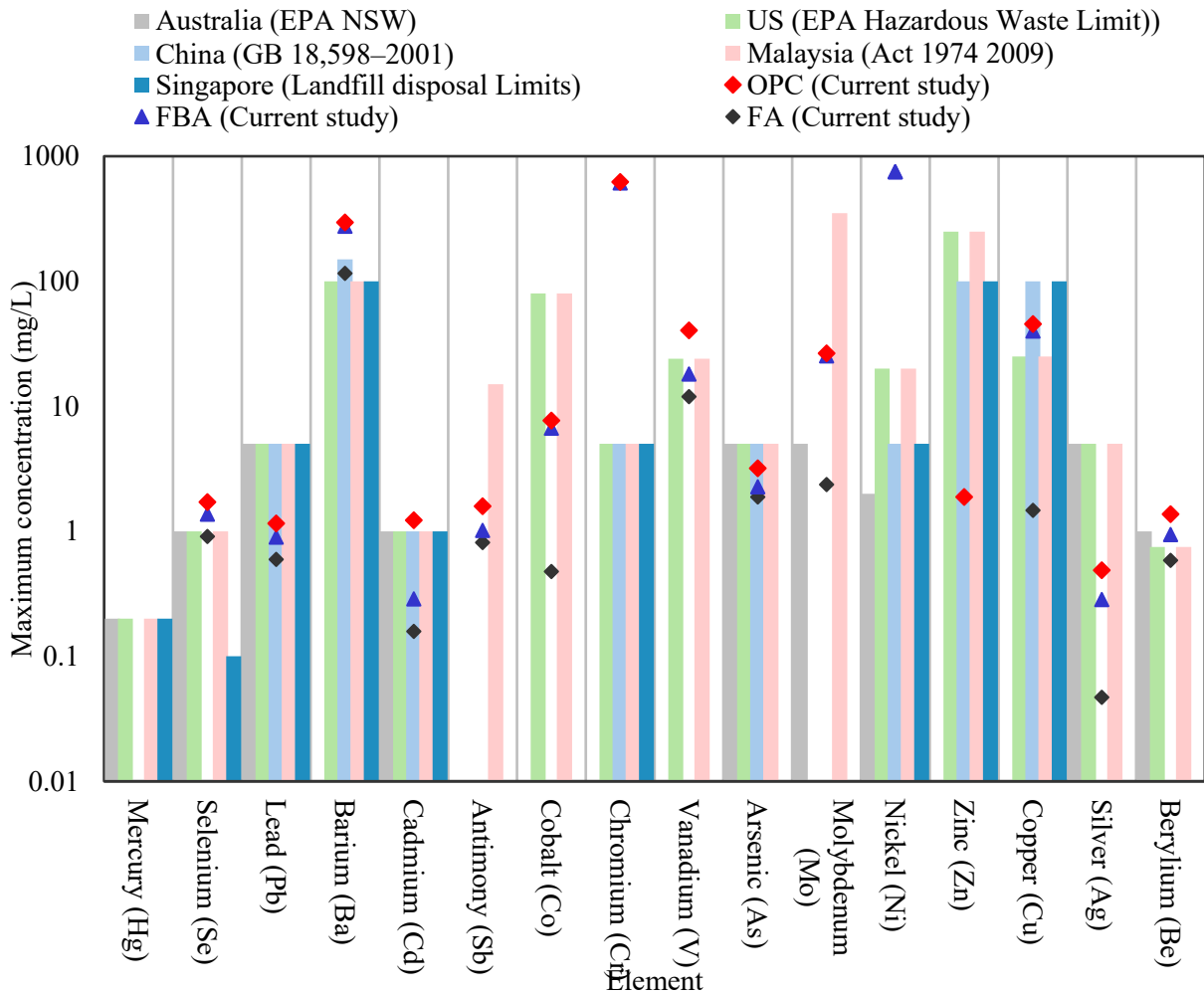
When compared with the regulatory upper limits for trace elements (Fig. 4.7), GFBA exceeded the allowable limits for Ba, Se, Cr, and Ni. However, similar exceedances were also observed in FA and OPC. For example, OPC recorded concentrations of Si, Ba, Cr, and V above the relevant criteria set by the NSW Environment Protection Authority. These findings indicate that exceedances of certain trace elements are not unique to GFBA but are common across cementitious materials currently used in practice. In NSW, the beneficial use of waste-derived materials such as FBA is regulated through a Resource Recovery Order and Exemption framework, which provides clear pathways for compliance. Where contaminant thresholds are exceeded, established measures such as blending, controlled application, encapsulation within concrete matrices, or project-specific risk assessments can be applied to ensure environmental safety. Accordingly, the results do not preclude the use of GFBA; rather, they highlight the importance of appropriate material management and compliance processes. With proper handling and regulatory alignment, GFBA remains a viable and sustainable supplementary cementitious material for large-scale application.

Previous studies have shown that although FBA and FA exhibit higher concentrations of some trace elements compared to relevant standards, including them in concrete bodies can immobilize their leachability. For example, Sutcu et al. [72] and Eliche-Quesada et al. [73] investigated the leaching concentrations from FBA-based fired bricks and discovered that the brick body effectively immobilized heavy metals. Similarly, Rafieizonooz et al. [74] noted that the leaching of heavy metals from concrete containing up to 100% FBA as a sand replacement was lower than the original FBA concentration and within the US EPA's SW-846 standard limits. This indicates that the concrete body immobilized the heavy metals sufficiently,

rendering them negligible. From the above, it can be concluded that the inclusion of FBA in concrete composites, similar to FA, significantly reduced the concentration of leached heavy metals compared to using FBA or FA alone.

**Table 4.3:** Concentrations (in mg/kg) of detected elements in FA, OPC, and FBA.

| Element | FA    | GFBA   | OPC   |
|---------|-------|--------|-------|
| Be      | 0.59  | 0.35   | 0.43  |
| V       | 11.9  | 6.2    | 22.4  |
| Cr      | NA    | 610    | 11.8  |
| Mn      | 56    | 251    | 216   |
| Fe      | 6273  | 44152  | 32292 |
| Co      | 0.48  | 6.21   | 1     |
| Ni      | NA    | 750.86 | NA    |
| Cu      | 1.47  | 38.5   | 5.52  |
| Zn      | NA    | NA     | 1.88  |
| As      | 1.88  | 0.39   | 0.93  |
| Se      | 0.91  | 0.46   | 0.34  |
| Sr      | 43.2  | 34.1   | 68.6  |
| Mo      | 2.36  | 23     | 1.08  |
| Ag      | 0.05  | 0.24   | 0.2   |
| Cd 111  | 0.06  | 0.04   | 0.48  |
| Cd 114  | 0.1   | 0.09   | 0.46  |
| Sn      | 2.89  | 4.71   | 3.21  |
| Sb      | 0.81  | 0.2    | 0.58  |
| Ba      | 1158  | 1599   | 205   |
| Pb      | 0.6   | 0.3    | 0     |
| Al      | 5428  | 9519   | 14029 |
| K       | 2239  | 2630   | 3237  |
| Ca      | 17962 | 16357  | 15144 |
| Mg      | 978   | 2388   | 3870  |
| Na      | 594   | 2085   | 3594  |



**Fig. 4.7:** Trace element concentrations from FBA leachate and the maximum limits allowed in the relevant standards/regulations to classify solid waste as non-hazardous waste. The maximum allowable limits for Australia [75], US [76,77], China [78], Malaysia [79] and Singapore [80,81] are shown in the figure.

## 4.5 Summary

In this chapter, the impact of co-incorporating FBA as a replacement for fine aggregate and cement on mortar performance was examined, focusing on flowability, compressive strength, flexural strength, water absorption, and microstructural characteristics. The combined incorporation of 25% FBA as a fine aggregate replacement and 10% GFBA and 20% as a cement replacement significantly improved the compressive strength of the mortar after 28 and 56 days of curing, surpassing the control samples and sample with 25% of FBA as fine aggregate replacement, though no significant variation was observed at 7 days. When the

replacement level of fine aggregate exceeded 50%, notable decreases in compressive strength were observed.

The flexural strength of mixtures with 25% FBA as a fine aggregate replacement alone and 25% FBA combined with 30% GFBA as cement replacement was similar to conventional mortar at 56 days, with a slight decrease at 28 days. However, samples with 25% FBA as fine aggregate and 10% and 20% GFBA as cement replacement showed flexural strength similar to traditional mortar after 28 days and improved strength after 56 days. Water absorption rates increased significantly with the inclusion of FBA as a fine aggregate replacement, while there was no noticeable difference in water absorption with 10%, 20%, and 30% GFBA as a cement replacement. There was a notable trend of increased compressive strength with decreasing water absorption rates.

In terms of environmental impact, replacing fine aggregate with FBA did not significantly change the amount of embodied carbon. However, fixing the fine aggregate replacement at 25% and replacing cement with 10%, 20%, and 30% GFBA resulted in reductions of approximately 9.1%, 17.9%, and 26.7%, respectively. GFBA exhibited lower concentrations of Mn, Zn, Cr, Fe, Co, Cu, Mo, Ag, Sn, and Ba compared to FA or OPC, but exceeded the permissible limits for Ba, Se, Cr, and Ni according to regulatory standards such as EPA NSW and US EPA for Hazardous Waste. However, based on relevant investigations conducted on concrete and bricks based on FBA, the leaching rates were lower and within permissible ranges. Further research is needed in this aspect.

# CHAPTER 5: FBA UTILIZATION IN CONCRETE

## 5.1 Introduction

The chapter provides the results of extensive experimental investigations performed to determine the optimum mix proportion for FBA concrete using FBA as sand replacement and as SCM simultaneously. A total of eight mix proportions were designed to make concrete samples. The mixes included and excluded FBA, as well as separate grinding and co-grinding utilizing different percentages of FBA. Several tests were conducted including slump, compressive strength, split tensile, modulus of elasticity, abrasion, water absorption, and density of concrete samples tests. The results were utilized to propose a mix proportion for the industrial trial testing of FBA concrete. The chapter also includes the experimental investigations and results flexural strength, modulus of elasticity, shrinkage, carbonation and microstructure of all the eight concrete mixes.

## 5.2 Mix design considerations

### 5.2.1 Mix Proportions

For this study, the mix proportions used were based on the recommendations of industrial partners for manufacturing concrete with a compressive strength of about 40 MPa. Later, the fine aggregates were partially replaced by FBA. To investigate the properties of concrete having FBA as SCM, different mix proportions were used based on the separate grinding or co-grinding of FBA and GGBFS. Also, some mix proportions were used based on the percentage of FBA as a cement replacement. Table 5.1 presents the mix proportions for the 40 MPa grade concrete. The 25% replacement of fine aggregate by FBA was determined based on findings from Chapter 3 and our study in [46].

Eight concrete mixes were developed, including a control mix of normal concrete, CR25 with 25% FBA as a fine aggregate replacement, and two groups incorporating GFBA and GGBFS. The first group (CGF) included mixes with 25% FBA as fine aggregate replacement and co-ground combinations of FBA and GGBFS, with the GGBFS ratio fixed at 25% for cement replacement. The GFBA content varied as follows: 10% (CGF10), 20% (CGF20), and 30% (CGF30) by weight of cement. The second group (SGF) followed a similar composition to the first group, but the GFBA and GGBFS were prepared using separate grinding processes instead of co-grinding, allowing for a comparison of the influence of

grinding methods on the performance of the mixes. The water-to-binder (w/b) ratio was maintained at 0.4 for all mixes. The superplasticizer content was adjusted based on preliminary slump tests for each mix. The concrete preparation and sampling were conducted following AS 1379 [82] and AS 1012.2 [83] specifications.

**Table 5.1: Mix Proportions.**

| 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                                  |

### **5.2.2 Mixing procedure**

The laboratory pan mixer was used to mix concrete. To avoid dust in the facility, 30% of the required water was added prior to mixing the dry ingredients. Firstly, coarse aggregates (< 19 mm) were added to the pan followed by less coarse aggregates (< 10 mm). Then fine aggregates were added, followed by coarser sand, fine sand and then FBA. Then cementitious materials including cement, GGBFA and ground FBA were then added to the mixer. Finally, the remaining water was added. The superplasticizer required for the mix was mixed with the required quantity of water prior to being added to the mix.

### **5.2.3 Testing**

Table 5.2 details the tests conducted on concrete and the relevant standards used. The air content and slump tests were conducted according to AS 1012.4.1[84] and AS 1012.3.1 [85], respectively. Slump retention was measured at 15-minute intervals, starting from the initial slump at time zero, followed by measurements at 15, 30, 45, and 60 minutes. The

strength performance was determined through tests for compressive strength, flexural strength, split tensile strength and modulus of elasticity, according to AS 1012.9 [86], AS 1012.11 [87], AS 1012.10 [88] and AS 1012.17 [89], respectively. To determine water absorption, AS 1012.21 [90] was followed, where the specimens were dried at  $100 \pm 5^\circ\text{C}$  for 24 hours and left to cool to  $23 \pm 2^\circ\text{C}$  and then weighed, and the process repeated until two successive weightings were almost identical ( $M_1$ ). Then the specimens were immersed in  $23 \pm 2^\circ\text{C}$  water until two successive weightings were almost identical. They were then surface-dried and weighed to obtain the saturated mass ( $M_2$ ), and then the water absorption was calculated as follows:

$$\text{Water absorption percentage (\%)} = \frac{M_2 - M_1}{M_1} \times 100$$

An abrasion test was performed according to ASTM C944 [91] for several interval periods of 2, 4, 6 and 10 minutes and then the percentages of mass loss were calculated. To prepare concrete samples for abrasion resistance, cylinders were cut to 50 mm thick discs and placed under a rotating wheel for 10 minutes. After completion the mass loss was determined. The test samples were prepared at the laboratory of The University of Newcastle as shown in Fig 5.1.

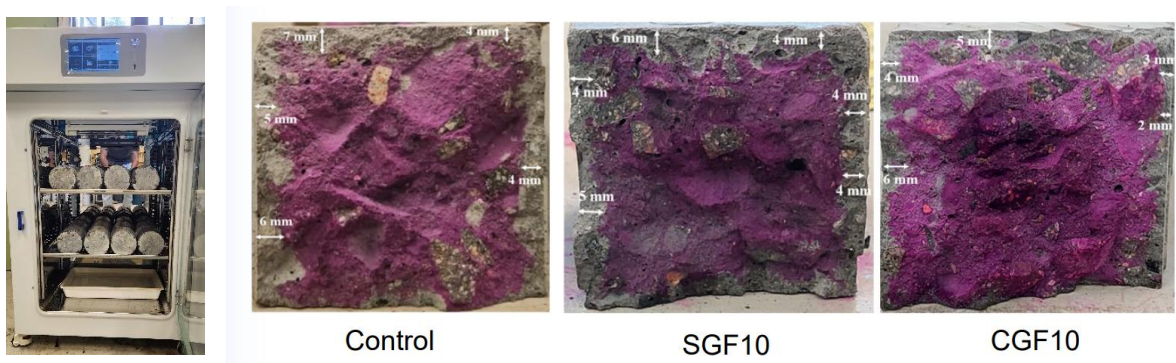


**Fig. 5.1:** Apparatus, test samples and setup of Abrasion Resistance Test.

**Table 5.2:** The tests performed on concrete designed with FBA and the standards of the applied procedures.

| Test performed            | Specifications        |
|---------------------------|-----------------------|
| Slump test                | AS 1012.3.1           |
| Air content               | AS 1012.4.1           |
| Density                   | AS 1012.12            |
| Compressive strength      | AS 1012.9:2014        |
| Flexural strength         | AS 1012.11-2000       |
| Split strength            | AS 1012.10            |
| Modulus of elasticity     | AS 1012.17            |
| Water Absorption          | AS 1012.21-1999       |
| Dry shrinkage             | ASTM C 157            |
| Abrasion resistance       | ASTM C418             |
| Accelerated Carbonation   | Spray Phenolphthalein |
| Acid and sulphate attacks | According to [92–95]  |

For the carbonation-resistance test, concrete prisms with dimensions 70 mm × 70 mm × 285 mm were cast and then placed in a carbonation chamber supplied by a CO<sub>2</sub> gas cylinder and equipped with temperature and humidity control. The chamber was set to 25 ± 2 °C, a relative humidity of 65%, and a CO<sub>2</sub> concentration of 4%. The specimens were kept in the chamber for 28 days and 56 days, after which they were removed and carefully split by adjusting the flexural test setup. The freshly exposed surfaces were then sprayed with a phenolphthalein solution, and carbonation depths were measured on multiple faces of each specimen. Four readings were taken from each selected face of the specimen. As opposing faces are expected to exhibit similar values, measurements were taken on one representative face per sample. For each mix, three samples were tested. The reported value therefore represents the average of four readings per sample, averaged across three sample, as shown in Fig. 5.2.



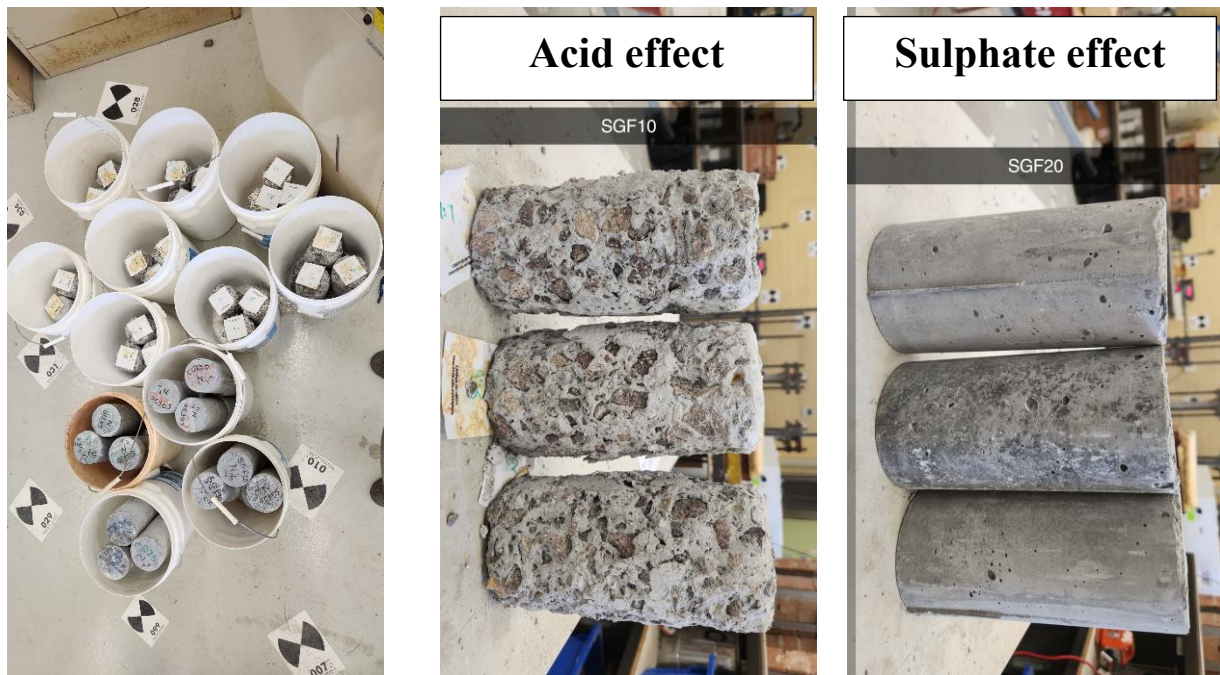
**Fig. 5.2** Samples showing carbonation depths.

A dry-shrinkage test for concrete prisms was conducted in accordance with ASTM C 157. After the initial curing period, concrete samples are transferred to a controlled drying environment,  $23 \pm 2$  °C and  $50 \pm 5\%$  relative humidity. Length measurements were taken using a length comparator at the start of drying and at specified intervals (Fig. 5.3). The difference between these measurements was used to determine the drying shrinkage of the concrete.



**Fig 5.3.** Shrinkage test setup.

The chemical attack resistance of concrete was tested by immersing specimens in different chemical solutions. A 5% sulphuric acid solution was used to evaluate acid resistance, and a 5% magnesium sulphate solution tested resistance to sulphate attack. The specimens were immersed for 90 days, and then weight and strength losses were evaluated to assess the concrete's durability against chemical degradation. Fig. 5.4 shows the visual affects of acid and sulphate on concrete samples after immersion period of 90 days.



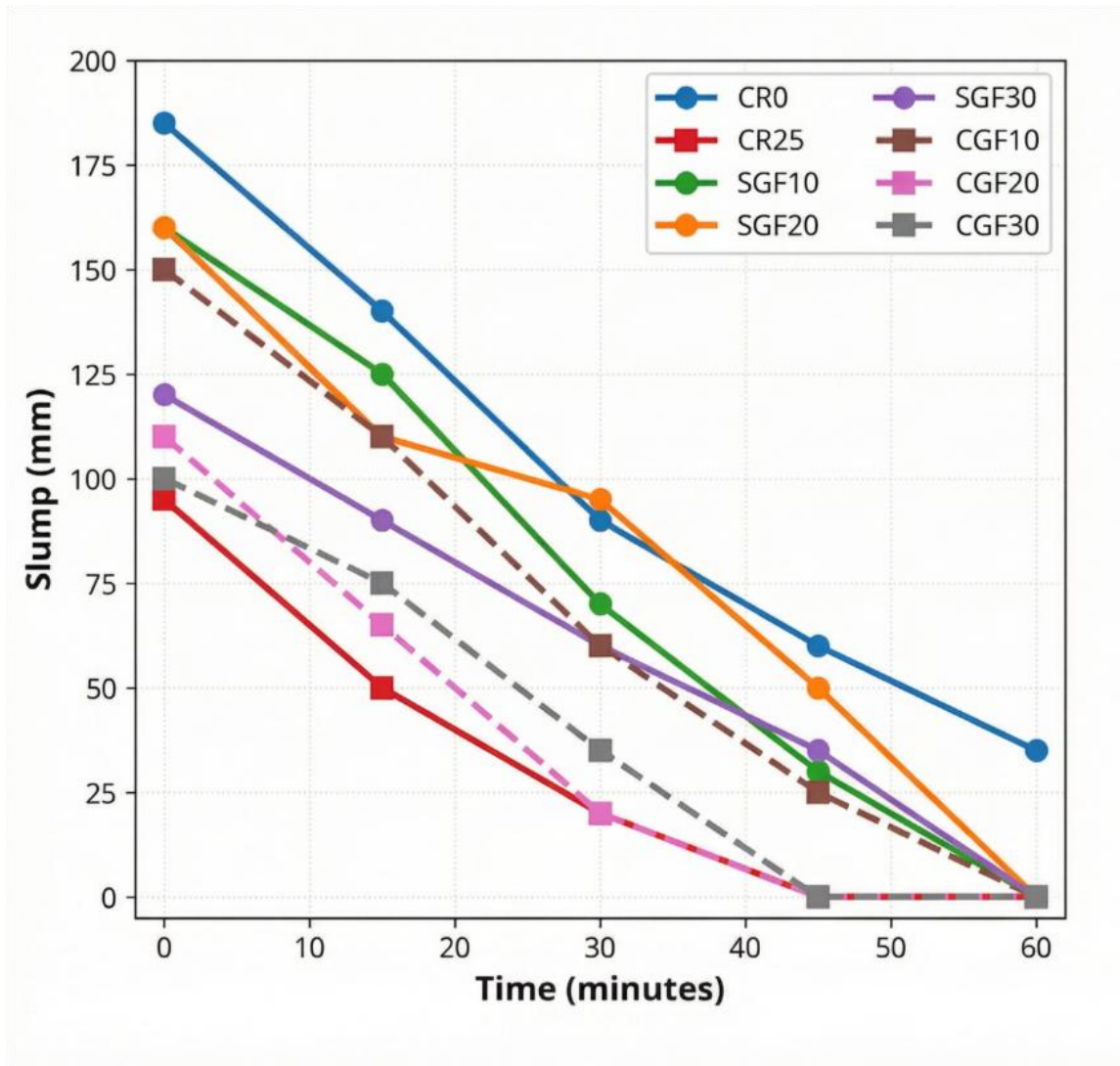
**Fig. 5.4:** The effects of acid and sulphates on concrete samples after a 90-day immersion period.

## 5.3 Fresh concrete properties with FBA

### 5.3.1 Slump and Slump retention

Fig. 5.5 presents the slump performance of the concrete mixes, where Fig. 5.5(a) presents the experimentally measured slump values, while Fig. 5.5(b) shows the corresponding RSM-based contour plot of predicted slump retention corresponding to grinding methods and GFBA replacement levels. As shown in Fig. 5.5(a), the control mix of normal concrete (CR0) exhibits the highest initial slump (185 mm) at a relatively low superplasticizer dosage (1.7 L/m<sup>3</sup>). In contrast, CR25, which replaces 25% of the fine aggregate with FBA, shows a markedly lower initial slump (95 mm) and loses workability faster, dropping to zero by 45 minutes. Comparing the two groups that incorporate both GFBA and GGBFS with CR0, a clear difference emerges between the initial slump and slump retention slump of mixtures. This difference, despite the fact that all SGF and CGF mixes used a higher superplasticizer dosage (2.7 L/m<sup>3</sup>), is higher than the control but showed lower slump retention where all mixtures of SGF and CGF groups reverted to zero at 60 minutes or earlier. However, both groups had a higher slump performance than that of CR25, due to increase SP dosages. These findings are consistent with several studies that report decreased workability mixes containing GFBA, as well as a gradual reduction of workability with increased GFBA content [19,45,67].

In terms of the combined influence of the grinding method and the GFBA replacement level on the slump retention behaviour of fresh concrete, all mixtures exhibit a systematic reduction in slump with increasing GFBA replacement from 10% to 30%, confirming that GFBA content is the primary governing factor for workability loss. This trend is consistent for both grinding methods and reflects the porous morphology and angular particle shape of GFBA, which increase water absorption and internal friction within the fresh matrix. A clear distinction between grinding methods was also observed. Separately ground mixes (SGF) consistently maintain higher initial slump values and superior workability retention compared to co-ground mixes (CGF). At 10% replacement, SGF10 and CGF10 show initial slumps of approximately 160 mm and 150 mm, respectively; however, the divergence becomes more pronounced at higher replacement levels. At 20% GFBA, SGF20 retains an initial slump of about 160 mm, whereas CGF20 decreases to approximately 110 mm, and at 30% GFBA, SGF30 maintains around 120 mm compared to roughly 100 mm for CGF30. The accelerated workability loss observed in co-ground mixtures can be attributed to the higher fineness and improved particle packing produced by co-grinding, which increase specific surface area, water demand, and mixture viscosity. The synergistic packing of finely ground GGBFS and GFBA particles reduces free water availability and restricts particle mobility, thereby increasing internal resistance to flow and accelerating slump loss. Similar mechanisms have been reported in previous studies, where enhanced fineness and optimized particle packing were shown to promote early stiffening and reduced workability retention in blended cementitious systems [63,66].

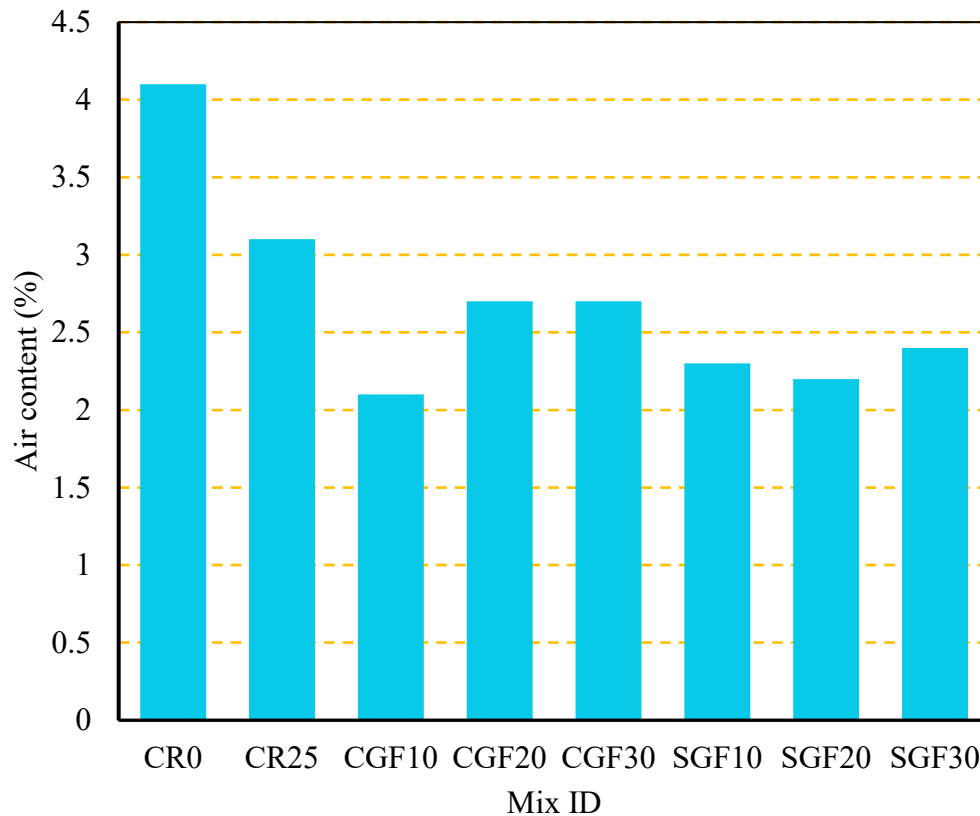


**Fig. 5.5:** The workability performance of designed concrete; a) initial slump and slump retention results, and b) actual photo of UON lab for CGF10 slump retention.

### 5.3.2 Air content

The air content results are presented in Fig. 5.6. As shown, the control mix CR0 has the highest air content at 4.1%. Unexpectedly CR25 showed lower air content at 3.1%, where it was expected to show higher air content compared to CR0 due to this high porosity of FBA compared to the natural fine aggregate. While the significantly lower initial slump (95 mm vs. 185 mm) typically correlates with higher viscosity and potentially higher air entrainment, FBA's adsorptive properties dominate, overriding this effect and causing a net decrease in air content. However, this reduction maybe due to unburned carbon residues in FBA and its irregular, angular particle morphology disrupts bubble formation and stability [96,97].

In cases of inclusion of GGBFS-GFBA combinations as cement alternatives, air contents generally drop below 3.0% for both SGF and CGF groups. This reduction may be attributed to the filling effect, where the fine particles reduce gaps that may be filled with entrapped air. Among the separate grinding mixes, values range from 2.2% to 2.4%, whereas the co-grinding mixes span from 2.1% to 2.7%. Notably, CGF20 and CGF30 show slightly higher air contents (both at 2.7%) compared to CGF10 (2.1%). Meanwhile, SGF20 records the lowest air content (2.2%) among the SGF group. Overall, introducing FBA and GGBFS either through co-grinding or separate grinding tends to reduce the air content compared to the control, with minor variations depending on the grinding method and the specific replacement levels. Zhang et al [98] note that GGBFS reduces air content due to improved packing effects and the forming of smaller bubbles within the matrix. Kostrzanowska-Siedlarz [99] also observes that the fine particles often have a greater particle surface area and viscosity, hindering air release, thereby explaining the reasons for showing higher air content in CGF mixes



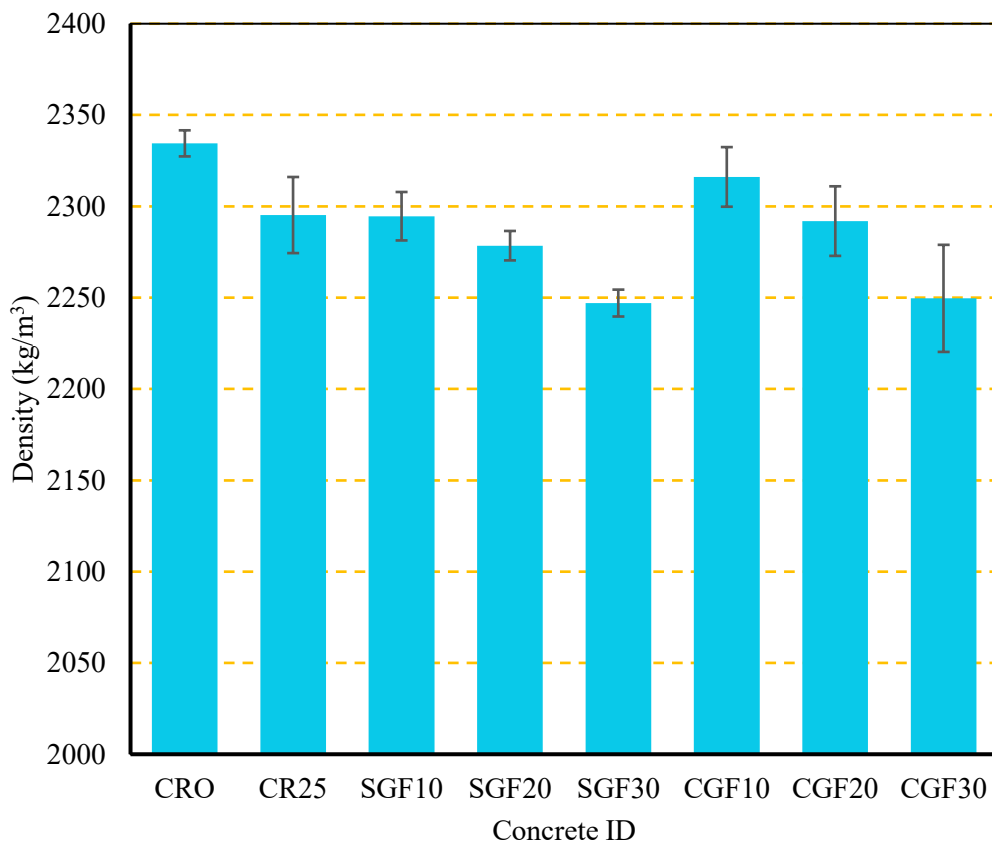
**Fig. 5.6:** Air content of eco-friendly concrete.

## 5.4 Hardened concrete properties with FBA

### 5.4.1 Density

The densities of all concrete mixes were measured in accordance with AS 1012.12.1-1998 [86] and the values recorded are presented in Fig. 5.7. The results indicate that the control mix (CR0) has the highest density of approximately 2334 kg/m<sup>3</sup>, while replacing 25% of fine aggregate with FBA in CR25 results in a slight density reduction to around 2295 kg/m<sup>3</sup>. This is due to FBA's lower specific gravity compared to that of river sand as stated by [100]. In the separate grinding group, densities decreased with higher GFBA content, ranging from 2294 kg/m<sup>3</sup> for SGF10 to 2247 kg/m<sup>3</sup> for SGF30. A similar trend was observed in the co-grinding group, where CGF10 has a relatively high density of about 2316 kg/m<sup>3</sup>, decreasing to approximately 2249 kg/m<sup>3</sup> for CGF30. Overall, the inclusion of FBA and GGBFS reduced concrete density compared to the control mix, especially at higher replacement levels. The reduction in density with FBA as fine aggregate or cement replacement is an expected result due to the low unit weight and high porosity of FBA compared to the fine aggregate and OPC.

Comparing separate grinding and co-grinding mixes at the same replacement levels (10%, 20%, and 30% GFBA), co-ground mixes consistently exhibited slightly higher densities. Specifically, CGF10 is about 0.95% denser than SGF10, CGF20 is 0.6% denser than SGF20, and CGF30 is 0.11% denser than SGF30. Although the density difference diminishes with increasing GFBA content from  $\sim 2316 \text{ kg/m}^3$  at CGF10 to  $\sim 2249 \text{ kg/m}^3$  at CGF30, co-grinding consistently produces slightly denser concrete. This higher density may be attributed to improved particle packing or an optimized particle-size distribution resulting from the combined grinding of FBA and GGBFS. In contrast, separate grinding may produce a less synergistic particle blend compared to that resulting from co-grinding, leading to marginally lower densities at equivalent replacement levels. It was found that improving the granular properties and fineness of the binder components offers significant potential for improving the mechanical, packing, and durability properties of low-clinker concrete [101]. Accordingly, the increased density of CGF samples compared to SGF samples can be attributed to improved packing properties.



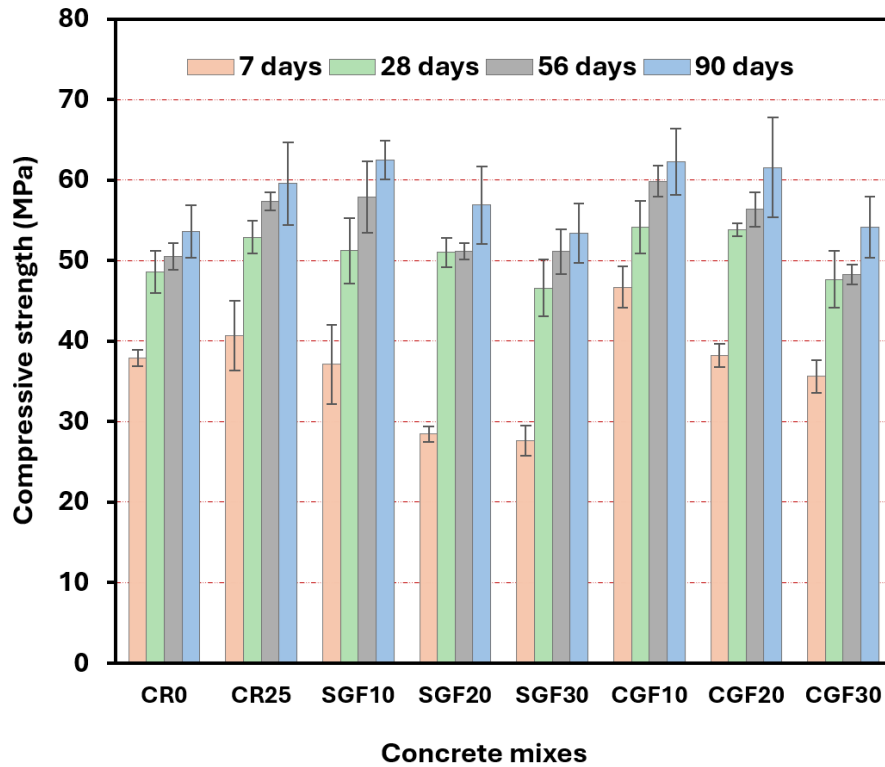
**Fig. 5.7:** Density of Concrete Mixes.

### ***5.4.2 Compressive Strength***

Compressive strength tests were performed at 7, 28, 56 and 90 days after casting in accordance with AS 1012.9:2014 [86]. Fig. 5.8 shows the compressive strengths for the concrete samples. Using FBA as fine aggregate, either alone or combined with GFBA and GGBFS replacing up to 55% of cement (separately or co-ground), enhances concrete compressive strength at both early and later ages. Lower GFBA contents of 10–20%, and 25% of GGBFS generally yield the most consistent and significant gains, particularly in the co-ground mixes, which often excel at early ages [11,102]. However, a higher GFBA usage of 30% still benefits from pozzolanic and filler effects over the long term but may initially lag in early strength compared to lower-replacement counterparts [11].

Overall, CR0 produced a compressive strength progression from 37.9 MPa at 7 days to 53.6 MPa at 90 days. Incorporating 25% FBA as fine aggregate replacement consistently increased compressive strength compared to CR0, achieving 40.7 MPa at 7 days versus 37.9 MPa for CR0 and maintained higher values throughout later ages, e.g., 52.9 MPa versus 48.6 MPa for CR0 at 28 days and 59.5 MPa versus 53.6 MPa for CR0 at 90 days. These enhancements can be ascribed to enhanced hydration or micro-filling effects, leading to improved strength development [1,30].

Among the separate-grinding mixes, early-age strength of 7 days varied more widely, with SGF10 at 37.1 MPa, close to that for control specimens, while SGF20 and SGF30 dropped to 28.4 MPa and 27.6 MPa, respectively. Over longer curing periods, however, each SGF mix surpassed or at least matched CR0. Notably, at 28 curing days, SGF10 and SGF20 reached 51.2 MPa and 51 MPa, respectively, while SGF30 was around 4% lower than the control sample. At 90 curing days, SGF10 reached 62.5 MPa, higher than the control sample by 17%, making it one of the best performers overall. SGF20 exceeded the control sample by 6%, while SGF30 has the same compressive strength as the control sample.



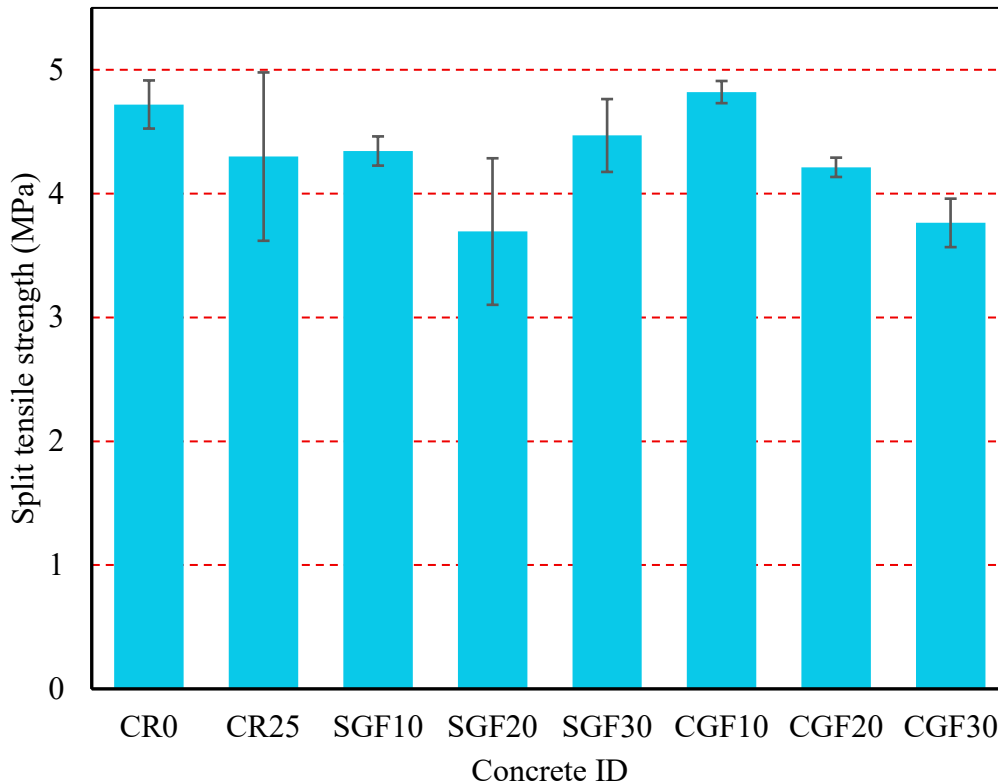
**Fig. 5.8:** Compressive Strength of Concrete Mixes.

In the case of the specimens prepared with co-grinded GGBFS and FBA, most specimens achieved the same compressive strength or surpassed it at early ages, particularly CGF10, which achieved 46.7 MPa, noticeably above both CR0 and all mixes prepared with separate grinding. This advantage continued through 28, 56, and 90 days, reaching 62.2 MPa by 90 days. CGF20 also showed strong performance, and achieved 38.2 MPa at 7 days, 53.8 MPa at 28 days and 61.5 MPa at 90 days. Conversely, CGF30 started at 35.6 MPa at 7 days and remained relatively subdued through 28 and 56 days but managed 54.1 MPa at 90 days, slightly above the control. These findings support the suggestion that the co-grinding process can yield excellent synergy [103,104], especially at GFBA levels of 35–45% of the total cement replacement percentages, boosting both early and later-age strengths.

### 5.4.3 Split Tensile Strength

The split tensile strength (also termed indirect tensile strength) of concrete was determined at 28 days in accordance with AS 1012.10:2014 [19]. The results, presented in Fig. 5.9, show that using FBA as 25% sand replacement reduced the split tensile strength of concrete by around 9% compared to control concrete without FBA. Similarly, for concrete mixes

prepared with separately ground FBA and GGBFS, the split tensile strengths were 5-22% lower than the split tensile strength of the control concrete. For concrete mixes with co-ground FBA and GGBFS, CGF10 showed 2% higher split tensile strength compared to the control concrete. Furthermore, the two mixes, CGF20 and CGF30, showed 11% and 20%, respectively, lower split tensile strength compared to the control mix.



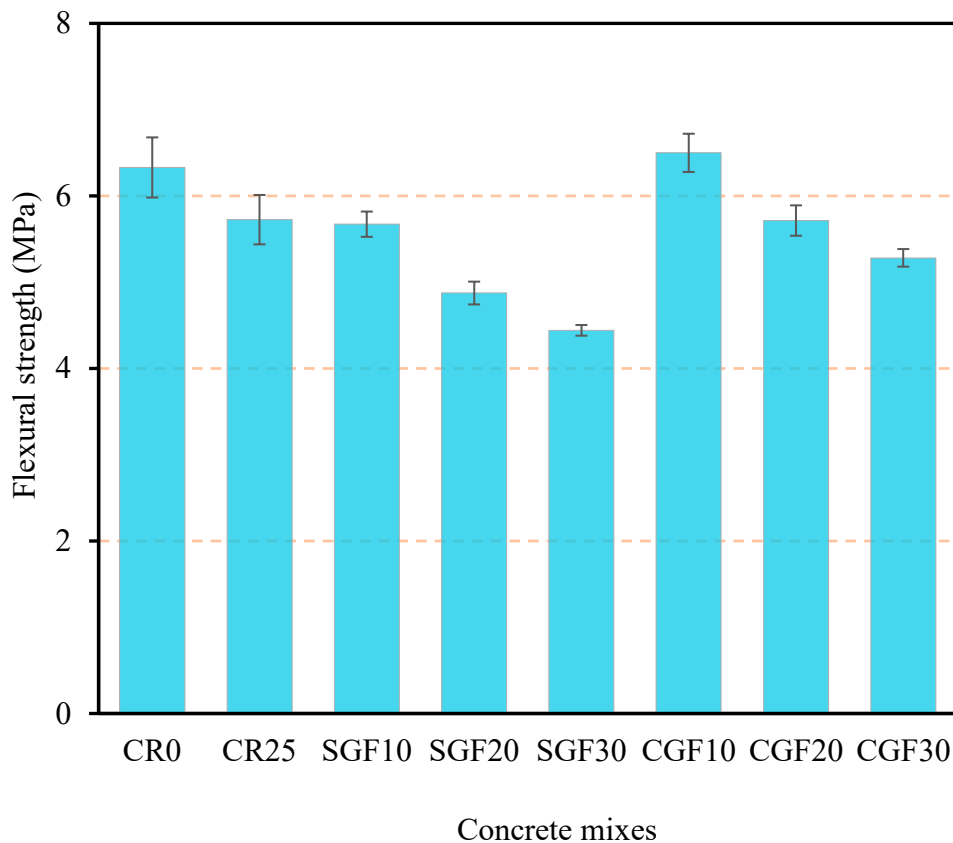
**Fig. 5.9:** Split tensile Strength of Concrete Mixes.

Like compressive strength, the highest split tensile strength was achieved by the CGF10 mix, which is a concrete mix with co-ground GGBFS and FBA and FBA as 25% sand replacement. Rafieizonooz et al. [105] also reported an increase in split tensile strength of concrete incorporating FBA as sand replacement. The split tensile strength improved because of the fine particle size of FBA and GGBFS. In addition, such particle sizes could enhance bonding among particles which improve the strength of concrete mixes [106].

#### **5.4.4 Flexural strength**

Fig. 5.10 shows the result of flexural strength for the designed concrete samples. The control mix CR0 exhibited a flexural strength of 6.33 MPa. In comparison, CR25, which incorporated 25% FBA as a fine aggregate replacement, achieves a flexural strength of 5.72

MPa, representing a 9.6% reduction compared to CR0. This decline aligns with the observed trend in split tensile strength, where CR25 also underperformed CR0, suggesting that the existence of porous FBA can leave weak Interfacial Transition Zone (ITZ), despite the compressive strength improvements noted earlier, where CR25 consistently outperformed CR0 at all ages. This divergence indicates that while FBA enhances compressive strength through micro-filling and hydration effects, it may slightly reduce flexural strength due to altered aggregate interlock or weaker ITZ [106].



**Fig. 5.10:** Flexural strength of designed concretes.

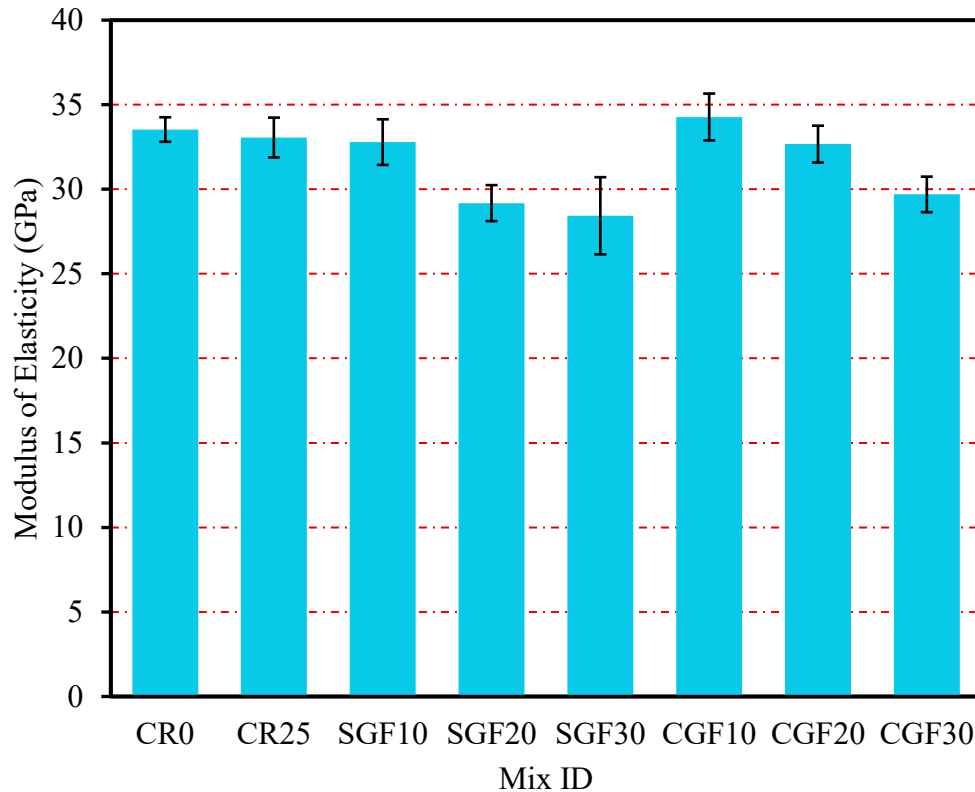
In terms of both grinding scenarios, the flexural strength results highlight CGF10 as the top performer at 6.50 MPa, exceeding both CR0 and CR25, with a notable 2.7% improvement over CR0 and 13.6% over CR25. In contrast, SGF20 (4.87 MPa) and SGF30 (4.44 MPa) exhibited the lowest flexural strengths, with reductions of 23.1% and 29.9% relative to CR0, respectively, indicating that higher replacement levels in the separate grinding series significantly compromise bending performance. This could be attributed to the higher pozzolanic content could leave unreacted or partially binder-reacted, weakening ITZ. Compared to CR0, most samples (CR25, SGF10, SGF20, SGF30, CGF20, CGF30) fell below

its flexural strength, with reductions ranging from 9.6% (CR25) to 29.9% (SGF30), except for CGF10, which slightly improved by 2.7%. Relative to CR25, SGF10 and CGF10 showed higher flexural strengths by 0.9% and 13.6%, respectively, while SGF20, SGF30, and CGF30 were lower than that of CR25.

#### **5.4.5 Modulus of Elasticity**

Fig. 5.11 shows the modulus of elasticity results, highlighting variations in stiffness across concrete mixes, with values ranging from 28.43 GPa to 34.27 GPa. The control mix (CR0) exhibited a baseline modulus of 33.53 GPa. CR25, with 25% FBA for fine aggregate replacement, showed minimal reduction at 33.06 GPa (-1.4%), indicating retained stiffness despite FBA incorporation. Separate-grinding mixes displayed progressive declines, where SGF10, with 10% GFBA and 35% of total cement replacement, was at 32.79 GPa (-2.2%), SGF20, with 20% GFBA and 45% of total cement replacement, was at 29.18 GPa (-13.0%), and SGF30, with 30% GFBA and 55% of total cement replacement, was at 28.43 GPa (-15.2%), suggesting increased porosity or weakened interfacial bonds at higher OPC replacements. Conversely, co-grinding mixes yielded mixed trends: CGF10, with 10% GFBA and 35% of total cement replacement, achieved the highest modulus (34.27 GPa, +2.2%), likely due to optimized particle packing, while CGF20, with 20% GFBA and 45% of total cement replacement, and CGF30, with 30% GFBA and 55% of total cement replacement, decreased to 32.67 GPa (-2.6%) and 29.69 GPa (-11.5%), respectively.

The stark reduction in SGF20–SGF30 and CGF30 underscores the detrimental impact of excessive GFBA replacement on stiffness, contrasting with CGF10's enhanced performance. The relevant research [5] highlights density as the primary determinant of modulus of elasticity (E), emphasizing porosity and matrix compactness as critical drivers of stiffness. In this study, higher-density mixes (e.g., CR0 at 2350 kg/m<sup>3</sup> with E=33.53 GPa) exhibited superior E values compared to lower-density variants (e.g., SGF30 at 2250 kg/m<sup>3</sup> with E=28.43 GPa), aligning with observations that reduced porosity enhances stress transmission and minimizes void-induced stress concentrations. While compressive strength ( $f_c'$ ) shows a moderate positive correlation with E (e.g., CGF10 with  $f_c' = 54.15$  MPa and E=34.27 GPa), exceptions such as SGF30 ( $f_c' = 46.59$  MPa, E=28.43 GPa) suggest that material-specific factors (e.g., aggregate type, interfacial transition zones) can override the  $f_c'$ –E relationship.



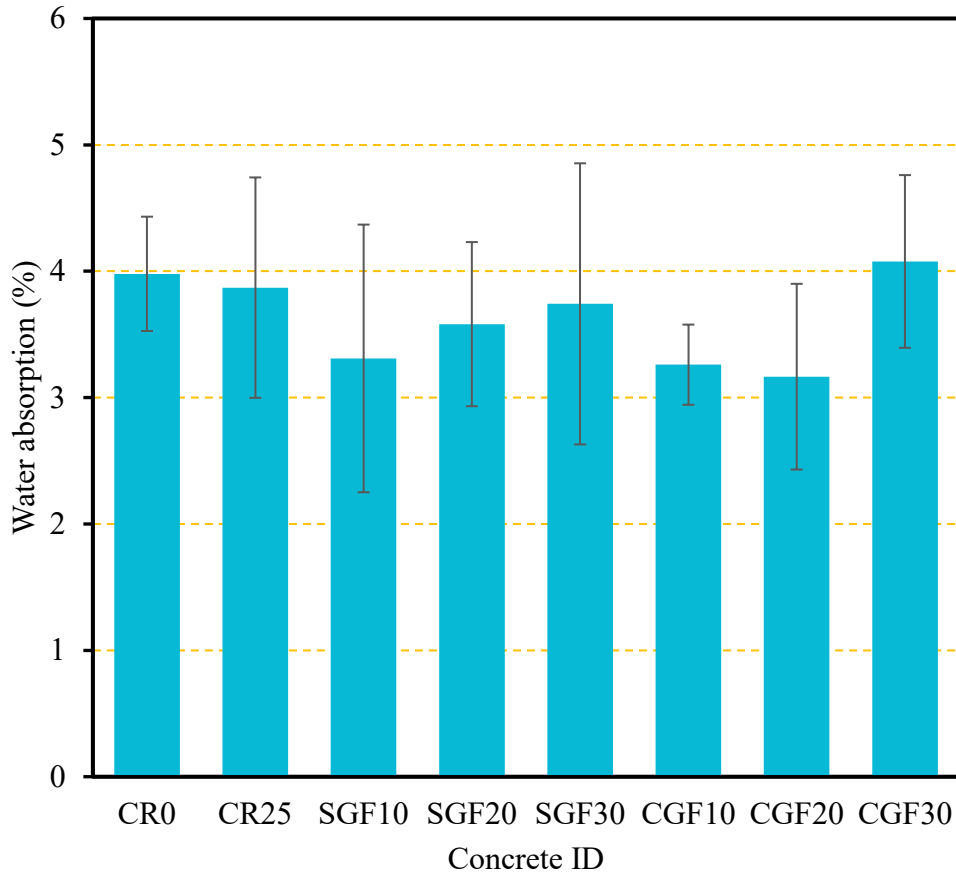
**Fig.5.11:** Modulus of elasticity of designed concrete.

## 5.5 Durability Performance

### 5.5.1 Water absorption

The water absorption of concrete was determined after 28 days in accordance with AS 1012.21-1999. The results are shown in Fig. 5.12. They indicate that CR0 exhibited a water absorption of 3.98%, while when 25% of the fine aggregate was replaced with FBA, water absorption decreased slightly by around 3% compared to CR0. Although FBA has a higher water absorption rate than fine aggregates, at optimal replacement rates, FBA acts as a filler, encouraging the development of more gels, improving pore structure and reducing absorption. This aligns with Rathee and Singh, [107] and Ashraf et al. [108], who found the concretes with replacement levels of 25% showed comparable water absorption with normal concretes. When OPC was replaced with GGBFS/GFBA, more pronounced effects on water absorption were observed. In the SGF group, water absorption ranged from 3.31% at SGF10 to 3.74% at SGF30, all values being below the control. SGF10 achieved the lowest absorption in this group, about 17% lower than CR0, while SGF20 and SGF30 showed reductions of approximately 10% and 6%, respectively. Although water absorption appeared to increase slightly with higher GFBA

content, the variability indicated by the error bars suggests this trend should be interpreted cautiously. Nonetheless, all mixes remained below the CR0 benchmark.



**Fig. 5.12:** Water Absorption of Concrete Mixes.

The co-grinding series generally achieved comparable or greater reductions in water absorption compared to separate grinding, particularly at 10% and 20% GFBA levels, but showed an adverse effect at 30%. Co-grinding results ranged from 3.17% for CGF20 to 4.08% for CGF30. Both CGF10 and CGF20 demonstrated significant reductions compared to the control, approximately 18% and 20%, respectively. This highlights that co-grinding improves the fineness and particle distribution of FBA and GGBFS, enhancing packing density and reducing pore connectivity [109] at lower GFBA levels. However, at 30% GFBA, the co-grinding approach led to a water absorption of 4.08%, exceeding CR0 by about 2.5%. This increase of water absorption at CGF30 is attributed to the potential of accruing agglomerations [110], due to a high level of finer particles in this mix. Comparing the separate grinding and co-grinding series, CGF10 and CGF20 exhibited lower water absorption than their separate grinding counterparts by approximately 2% and 12%, respectively. Conversely, CGF30 showed

a 9% higher water absorption than SGF30. Schack and Haist [101] found that water absorption is affected by particle fineness to a certain value, meaning that above a specific level, there is no impact on water absorption.

### 5.5.2 Abrasion Resistance

An abrasion resistance test was conducted based on ASTM C944. For this test, equipment was prepared in the laboratory of The University of Newcastle as shown in Fig. 5.13.



**Fig. 5.13:** Apparatus of Abrasion Resistance Test.

To measure abrasion resistance, cylinders were cut into 50 mm thick discs and were placed under the rotating wheel for 10 minutes. After completion, the mass loss was determined. The results of abrasion resistance of all concrete mixes are shown in Fig. 5.14.

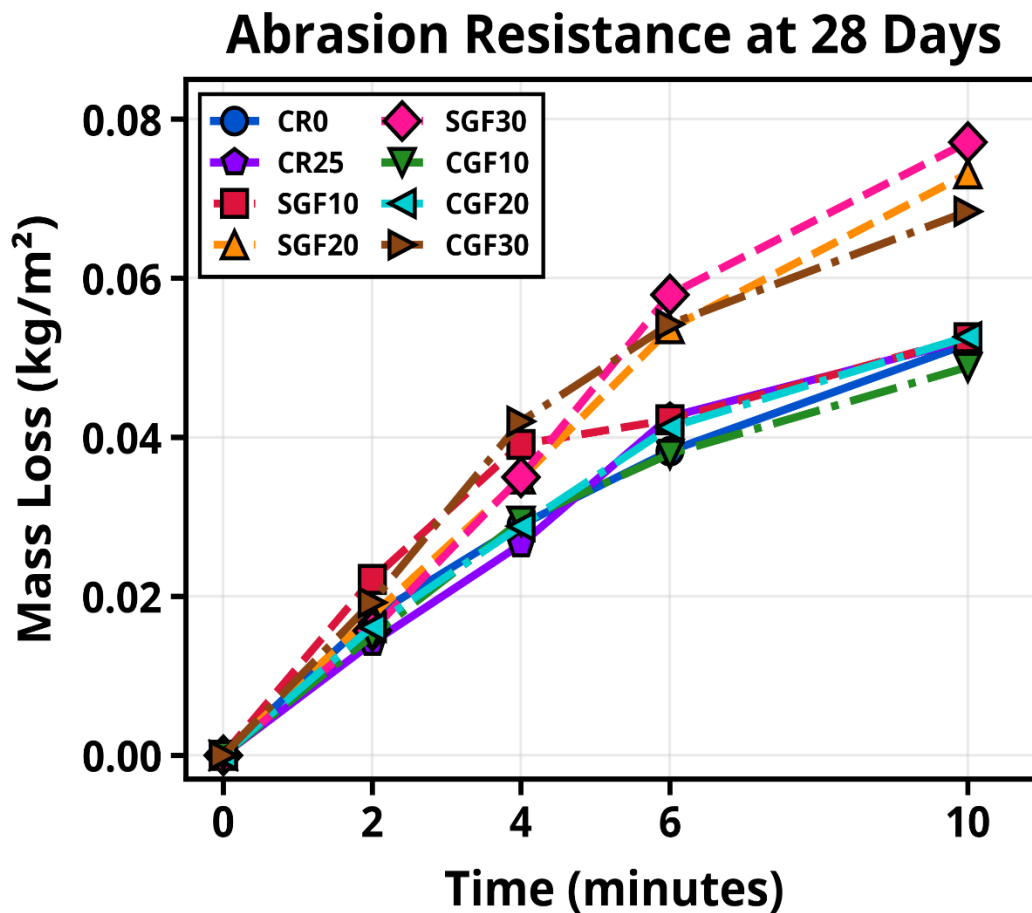


Fig. 5.14: Abrasion Resistance of Concrete Mixes.

The abrasion resistance of the concrete mixes, evaluated through mass loss percentages over increasing abrasion durations, revealed distinct trends influenced by replacement levels and grinding methods as shown in Fig. 5.14. The control mix (CR0) exhibited progressive mass loss from 0.017% at 2 minutes to 0.052% at 10 minutes, while CR25 with 25% FBA as a fine aggregate replacement demonstrated marginally better early resistance, with lower mass loss at 2 and 4 minutes with mass loss of 0.014% and 0.027%, respectively, but matched CR0's final mass loss at 10 minutes with mass loss of 0.052%. This suggests that FBA initially enhances abrasion resistance through micro-filling but aligns with conventional performance over prolonged exposure.

In the separate-grinding series (SGF), higher GFBA replacements correlated with reduced abrasion resistance. SGF10 showed moderate mass loss of 0.053% at 10 minutes, while SGF20 and SGF30 experienced significantly higher losses of 0.073% and 0.077%,

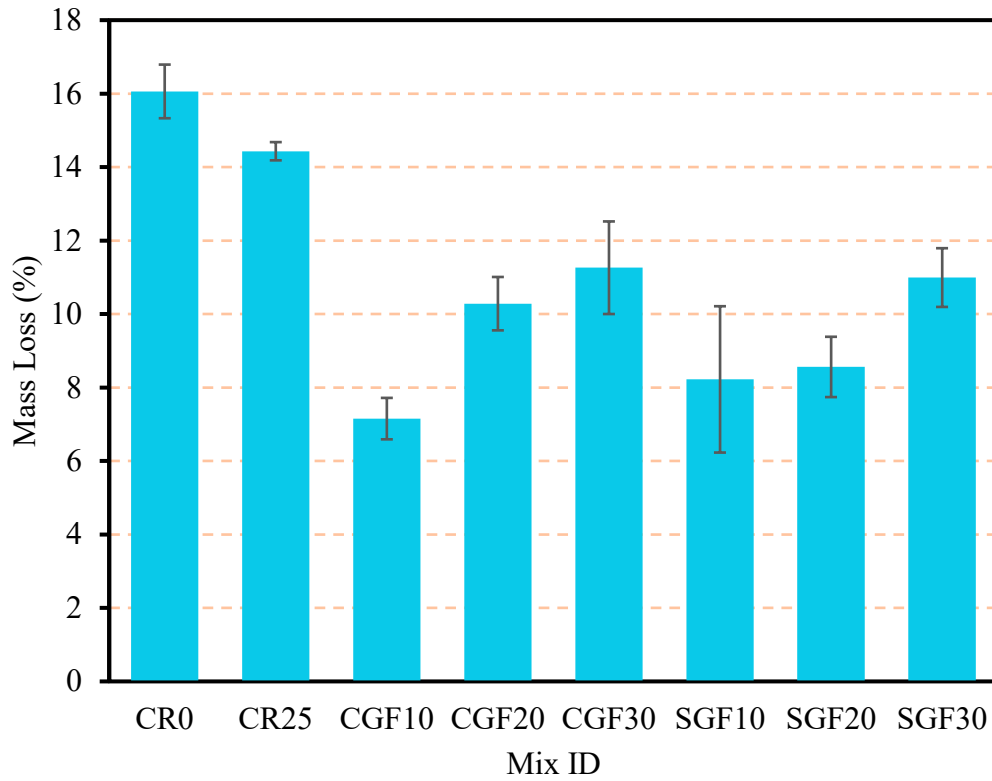
respectively. The increased porosity or weaker ITZ at higher GFBA levels likely accelerated surface degradation under abrasion. Conversely, co-grinding mixes (CGF) exhibited superior performance, particularly at lower replacements. CGF10 achieved the lowest final mass loss of 0.049% in 10 minutes, surpassing even CR0, indicating optimized particle packing and enhanced matrix cohesion from co-grinding.

However, higher replacements in this series (CGF20 and CGF30) led to progressive mass loss increases (0.053% and 0.068%, respectively). Singh and Siddiqui [5] indicate that low pozzolanic activity at higher levels of coal bottom ash content leads to reduced abrasion resistance. However, it is noteworthy that no studies to date have compared the abrasion resistance of concrete made with binary or ternary binders prepared via co-grinding versus separate grinding methods. In general, the improvement observed in the co-ground concrete series can be attributed to enhanced binder hydration and the effective filler effect.

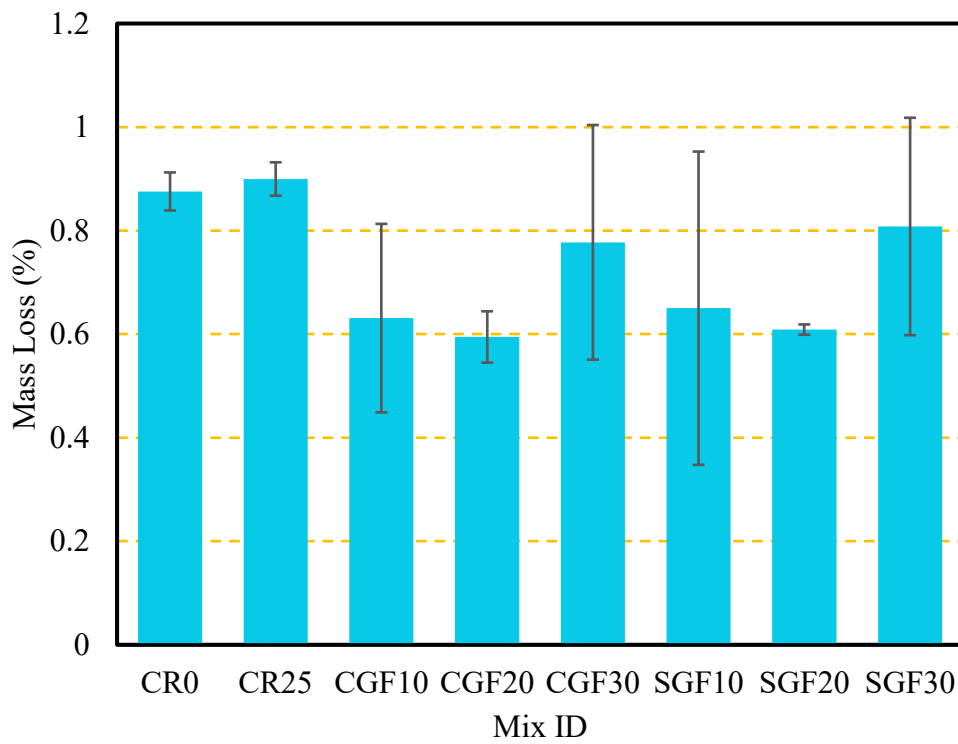
### **5.5.3 Chemical Resistance**

The chemical resistance of concrete mixes against sulphuric acid and magnesium sulphate was determined by noting the values of mass before and after immersion, and the results are presented in Fig. 5.15 & 5.16. The sulphuric acid solution significantly deteriorated the control concrete mix CR0 compared to FBA concrete mixes. CR0 tends to lose more weight in a sulphuric acid solution compared to FBA concrete due to its higher calcium hydroxide content, which reacts readily with acid to form expansive and soluble compounds like gypsum and ettringite, leading to surface damage and material loss. In contrast, FBA concrete benefits from pozzolanic reactions that consume calcium hydroxide and form additional C-S-H gel, resulting in a denser, less permeable matrix that resists acid attack more effectively. This improved chemical stability and reduced porosity in FBA concrete contribute to its lower weight loss and better durability in aggressive acidic environments [31].

Similarly, in case of immersion in magnesium sulphate solution, minimal mass loss was determined from all the concrete mixes ranging from 0.6-0.9 %, with the least mass loss observed for the concrete mix CGF20. Overall, the mass loss for FBA concrete mixes were lower compared to control concrete mixes. The FBA concrete mixes provided better chemical resistance primarily because of better microstructure and denser matrix. A study [32] reported similar results where the ash product improved the resistance against magnesium sulphate solution.



**Fig. 5.15:** Mass Loss of Concrete Specimens After immersion in Sulphuric Acid.

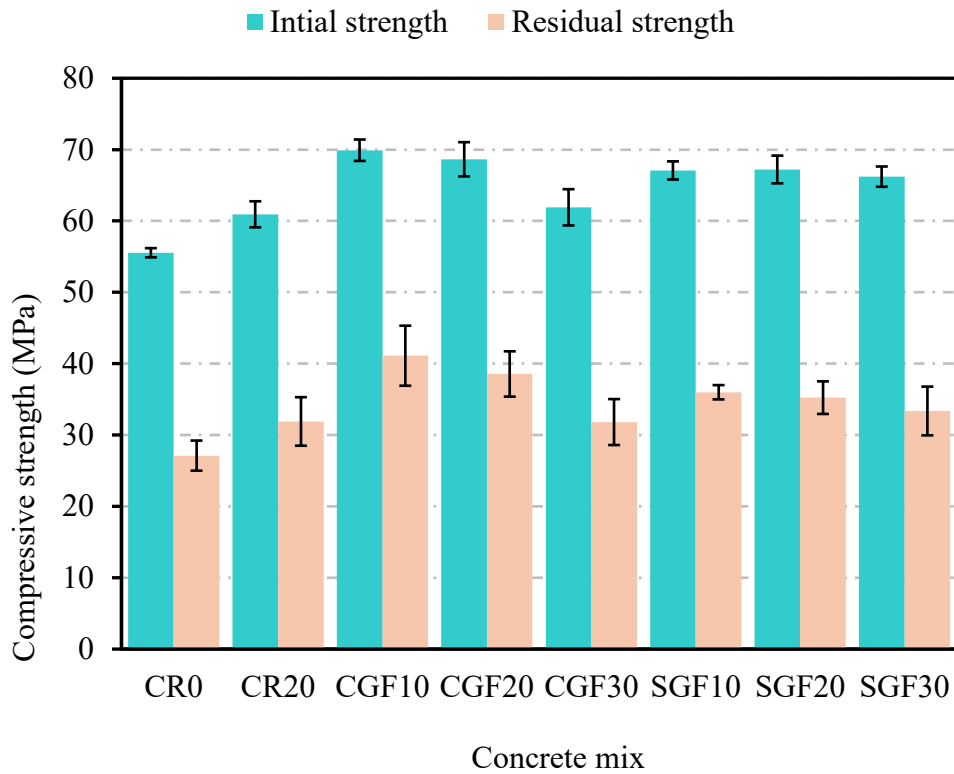


**Fig. 5.16:** Mass Loss of Concrete Specimens after Immersion in Magnesium Sulphate Solution.

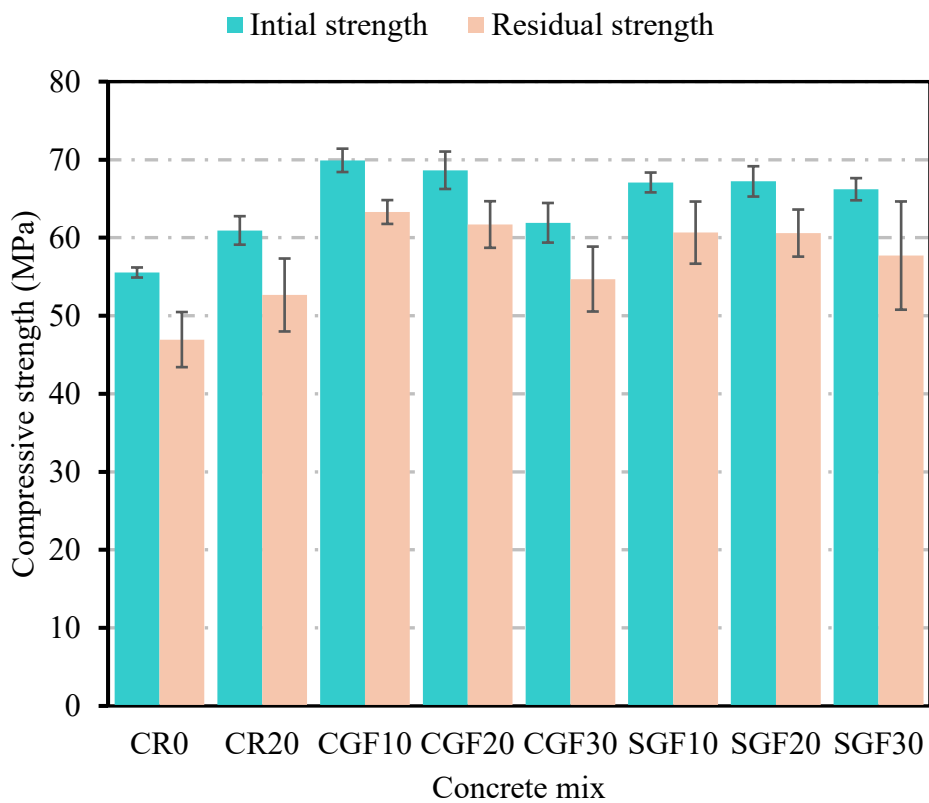
The samples were dried and then a compressive strength test was performed in accordance with AS1012.9:2014 [33] to determine the residual compressive strength of concrete mixes after prolonged immersion in sulphuric acid and magnesium sulphate solutions. The results are presented in Fig. 5.17 and 5.18.

The results showed that a significant strength loss was observed in case of immersion in acidic solution while a lower reduction was observed in the case of immersion in magnesium sulphate solution. The results were also compiled as compressive strength losses, expressed as percentages for easier comparison. The results are presented in Fig. 5.19 and 5.20 and show around 41-51 % strength loss in various mixes of concrete. The highest strength loss was observed for concrete mix CGF30, SGF30 and CR0, where they showed 48%, 49%, and 51%, respectively, while CGF10 showed the lowest loss (41%). Therefore, FBA concrete mixes showed sufficient durability against chemicals. When immersed in magnesium sulphate solution, the compressive strength loss ranged from 6-11%, where the highest loss was determined for the CR0 concrete mix and the lowest was for CGF20. The better packing of internal structure by utilizing FBA as sand and as SCM yielded promising results against chemicals attacks [13, 34].

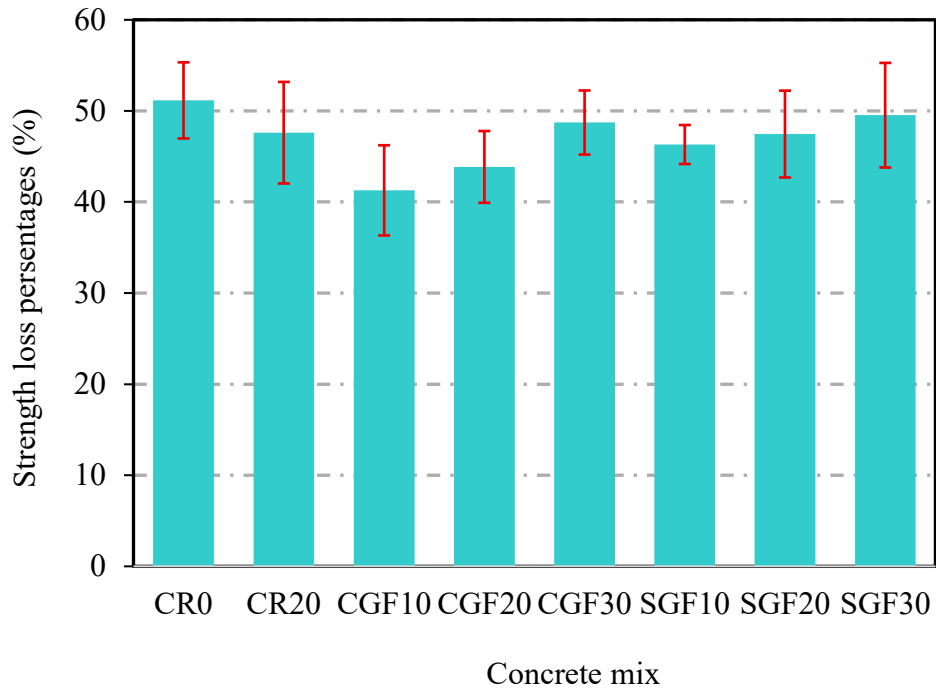
When comparing concrete mixes in the separate grinding group to that of the co-grinding group, no consistent trend related to the grinding scenario was observed. However, the CG10 mixture showed superior performance in durability relative to its strength and mass. It was also observed that the indices of strength and mass loss/retention after immersion tests in  $H_2SO_4$  and  $MgSO_4$  solutions exhibited behaviour similar to that of the specimens in terms of water absorption and compressive strength. This indicates that the governing factor is the interconnected porosity and the microstructural characteristics of the material.



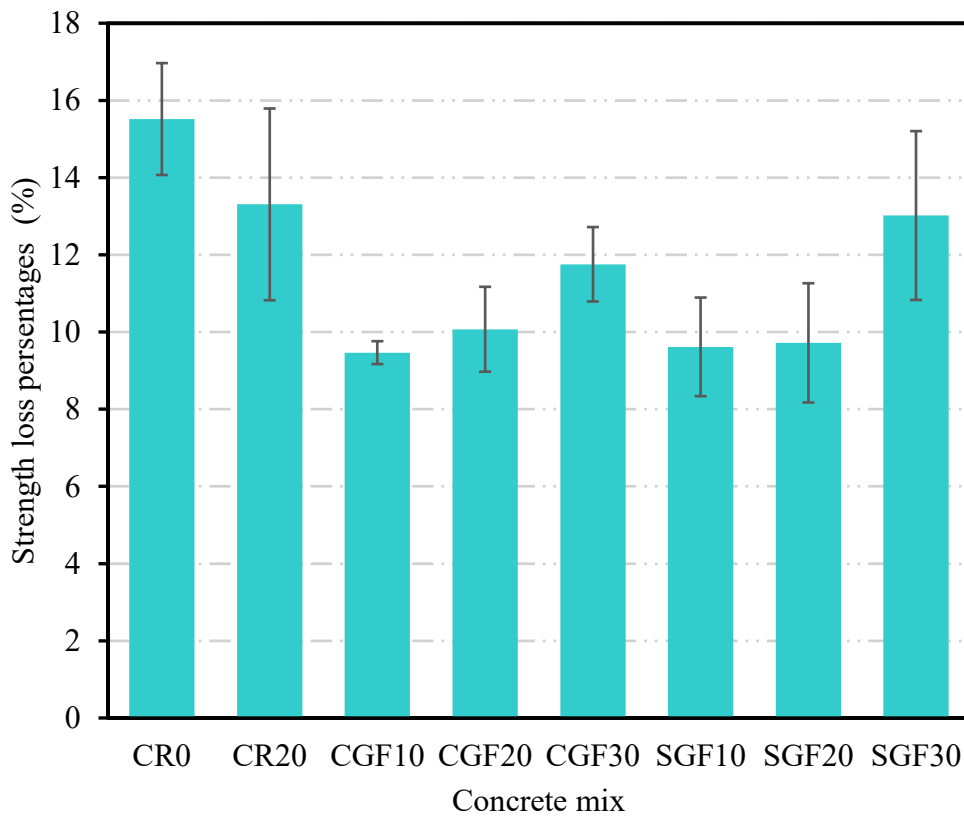
**Fig. 5.17:** Residual Compressive Strength after Immersion in Sulphuric Acid.



**Fig. 5.18:** Residual Compressive Strength after Immersion in Magnesium Sulphate Solution.



**Fig. 5.19:** Compressive Strength Loss (%) after immersion in Sulphuric Acid.

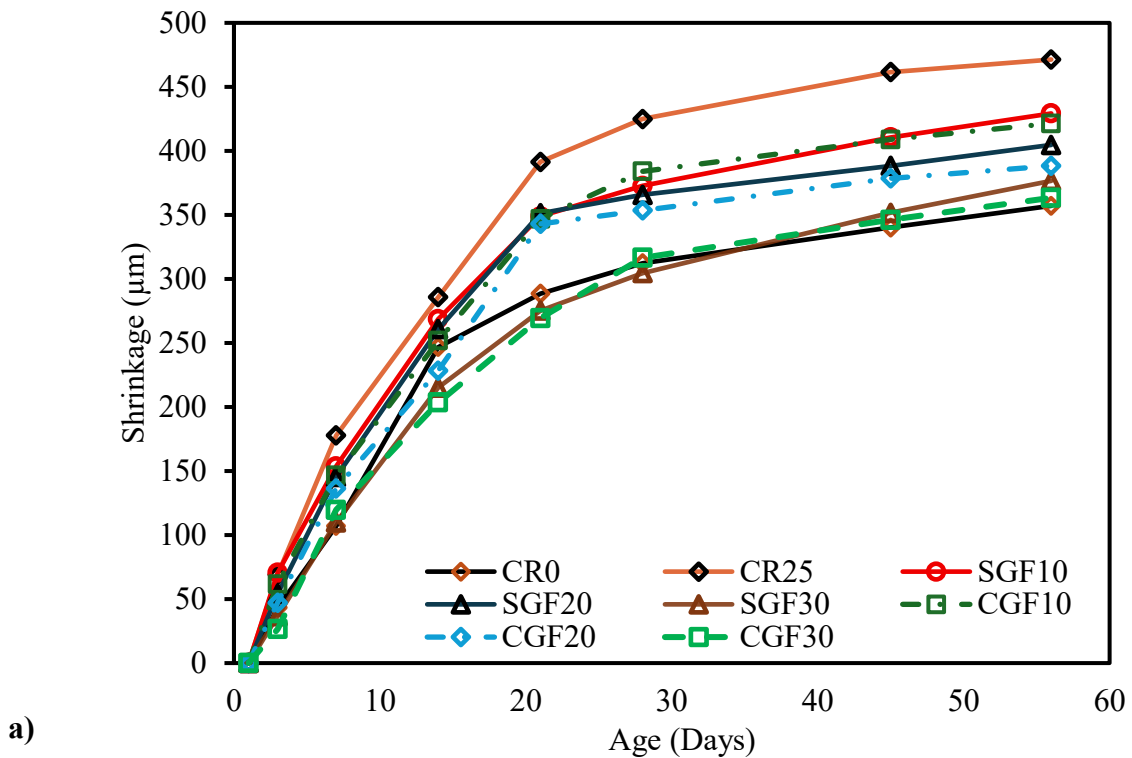


**Fig. 5.20:** Compressive Strength Loss (%) after immersion in Magnesium Sulphate.

#### **5.5.4 Drying Shrinkage**

The drying shrinkage of concrete samples prepared with eight concrete mixes were measured for up to 56 days and the results are presented in Fig. 5.21. The highest shrinkage (~471  $\mu\text{m}$ ) was observed for the control mix with 25% FBA as fine aggregate replacement while the lowest shrinkage (~357  $\mu\text{m}$ ) was observed for the control mix without FBA as sand or as SCM. For FBA concrete mixes the shrinkage values ranged from 363  $\mu\text{m}$  to 429  $\mu\text{m}$  with lowest shrinkage observed for the concrete mix CGF30. It is to be noted that increasing the amount of FBA as SCM reduced the drying shrinkage of concrete samples both for co-grinding and separate grinding mixes.

Overall, the shrinkage values were not much higher compared to the control mix and significantly lower than the values specified in TfNSW R83 specifications which concludes that the shrinkage of concrete mixes containing GGBFS should be lower than 580 at 21 days and for other concrete mixes the value specified is 450 at 21 days. Lei Wang et. al. [35] reported that the loss of water from concrete pores due to early-age evaporation can lead to the development of capillary stresses, which are a primary cause of the rapid increase in drying shrinkage during the initial stages of hydration. Based on this fact, it was expected that the concrete mix with 25% replacement of natural sand with FBA would have higher shrinkage as FBA is more porous and absorbed more water compared to natural sand. However, the use of ground FBA as SCM reduced the shrinkage by filling of pores and by providing more compact microstructure. Similar results were reported in relation to the use of fly ash where the use of fly ash as a partial replacement for cement has been shown to reduce drying shrinkage in concrete, primarily due to its ability to refine pore structure, lower heat of hydration, and improve long-term moisture retention within the matrix [36, 37].

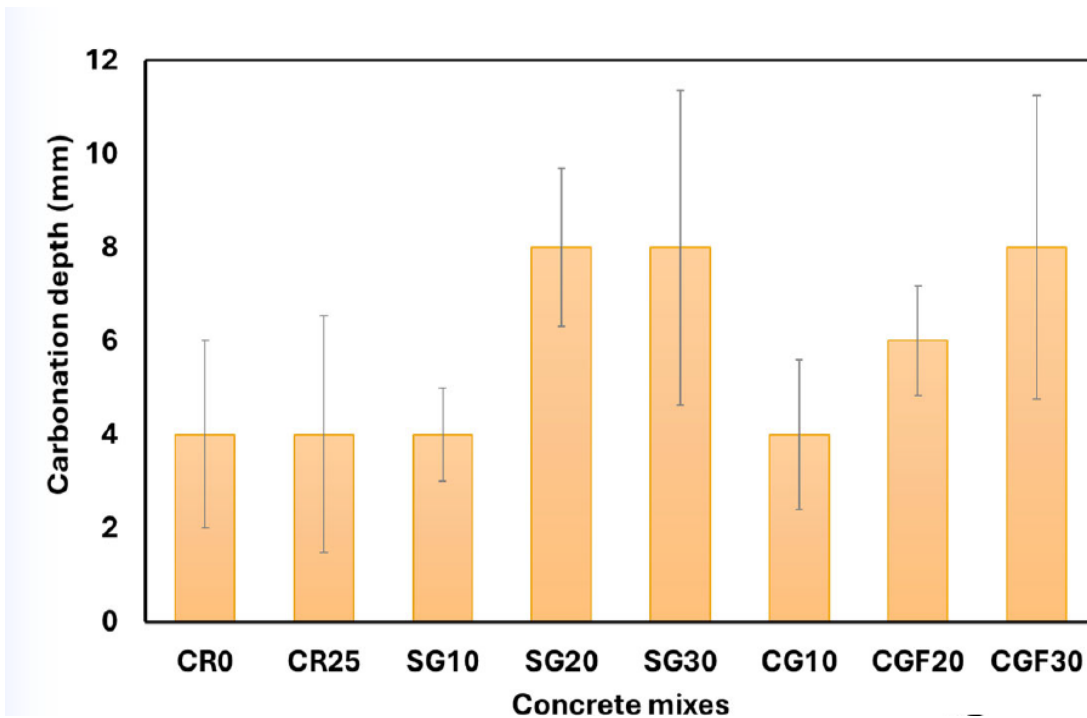


a)   
 b)   
 ?

**Fig. 5.21:** Drying Shrinkage of Concrete Mixes, a) shrinkage trend for mixes, b) show shrinkage performance on two curing age (28 and 56 days), showing error bars.

### 5.5.5 Carbonation Resistance

The carbonation resistance of eight concrete mixes was measured at 56 days via accelerated carbonation and the results are presented in Fig. 5.22. The carbonation depths show varying levels of resistance to carbonation. The control mixes, CR0 and CR25, both had a carbonation depth of 4 mm, indicating good resistance. Similarly, SG10 and CG10 also had a carbonation depth of 4 mm, showing no significant difference from the control mixes. However, as the cement replacement percentage increased, the carbonation depth increased. SG20, SG30, and CGF30 all had carbonation depths of 8 mm, which is twice as much as the control mixes, indicating reduced carbonation resistance with higher substitutions. The CGF20 mix had a carbonation depth of 6 mm, which is 50% higher than the control mixes but still lower than the higher-substitution mixes. Overall, the results suggest that carbonation resistance decreases with higher levels of substitution, with the highest carbonation depths observed in mixes with 20% or 30% substitutions.



**Fig. 5.22:** Carbonation of concrete mixes.

## 5.6 Summary

This chapter provides a comprehensive overview of the use of FBA as both a sand replacement and a SCM. An experimental program was conducted to evaluate the durability performance of FBA-based concrete compared to conventional control mixes. Eight different concrete mix designs were developed and tested to assess the use of FBA in replacing fine aggregate and contributing as an SCM. The FBA concrete mixes demonstrated superior chemical resistance and showed satisfactory performance in other key durability indicators, such as shrinkage. This study offers valuable insights into the behaviour of FBA concrete under various durability conditions, highlighting its potential for sustainable and long-lasting construction applications. Overall, the FBA mixes exhibited consistent and reliable performance, supporting their viability for broader use in eco-friendly low carbon concrete.

# CHAPTER 6: TRIAL MIXES FOR FOOTPATH APPLICATION

## 6.1 Introduction

This chapter presents the methodology, observations, and findings from the investigation of trial concrete mixes incorporating FBA as both a SCM and a sand replacement. Initially, this section outlines the development and testing of trial mixes cast at the University of Newcastle (UON) laboratory, focusing on determining their basic properties and performance. The process was then scaled up for an industrial application of a pedestrian footpath. The practical implementation of selected mixes is discussed here in detail.

## 6.2 Trial Mixes (Laboratory)

### 6.2.1 Materials

Two trial mixes were prepared to study the performance of both concrete mixes. One concrete mix was prepared as a control concrete mix which was without FBA and used fly ash as supplementary cementitious material (SCM). The second concrete mix utilized FBA as 25% sand replacement, and as 10% cement replacement. Also, in the second mix, ground granulated blast furnace slag was used as supplementary cementitious material (25%).

### 6.2.2 Mix Design

The details of the trial mix designs are presented in Table 6.1 below:

**Table 6.1:** Mix Designs for Trial concrete mixes (For 1 m<sup>3</sup>).

| Materials           | Units | Control Mix (25 MPa) | FBA Mix |
|---------------------|-------|----------------------|---------|
| 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     |

### 6.2.3 Test Matrix

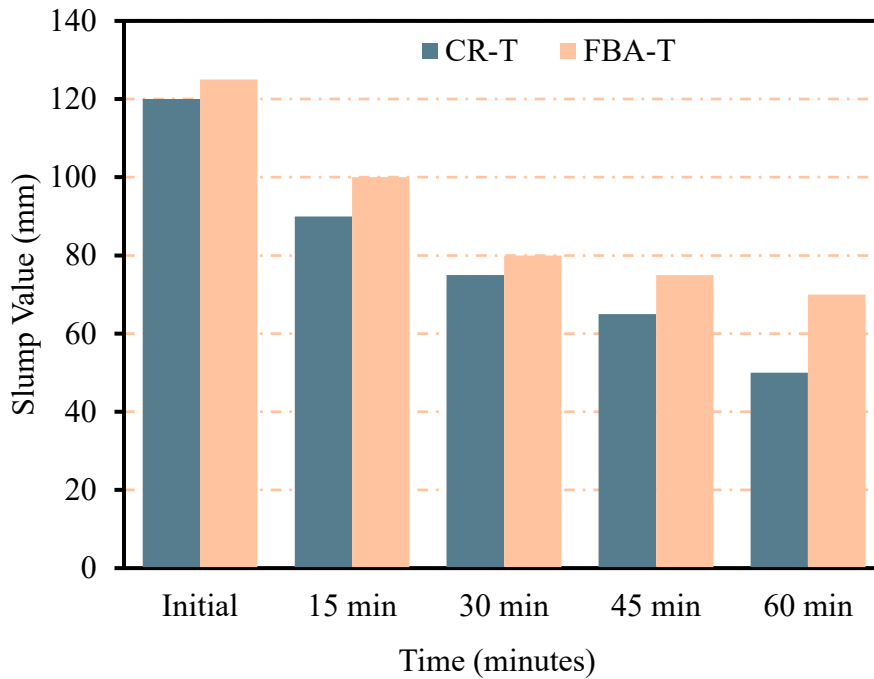
Table 6.2 details the tests performed on the concrete prepared with both trial mixes.

**Table 6.2:** Test Matrix for Trial concrete mixes.

| Tests                | Test Standard     | Specimen   | Volume (m <sup>3</sup> ) | No. of samples | Test age      |
|----------------------|-------------------|--|--------------------------|----------------|---------------|
| Slump                | AS 1012.3.1:2014  | 100 mm (top dia.)<br>200 mm (Bottom dia.)<br>300 mm height | 0.005                    | -              | Fresh         |
| Slump retention test |                   | 100 mm (top dia.)<br>200 mm (Bottom dia.)<br>300 mm height | 0.005                    | -              | Fresh         |
| Density              | AS 1012.12.1-1998 | 100 mm dia. and 200 mm height                              | -                        | -              | 28 days       |
| Compressive strength | AS 1012.9:2014    | 100 mm dia. and 200 mm height                              | 0.009                    | 6              | 7 and 28 days |
| Flexural strength    | AS 1012.11-2000   | 100 x 100 x 350 mm   | 0.021                    | 6              | 28 days       |
| Shrinkage test       | AS 1012.13:2015   | 75 x 75 x 285 mm   | 0.005                    | 3              | 3 - 56 days   |

### 6.2.4 Slump and Slump retention

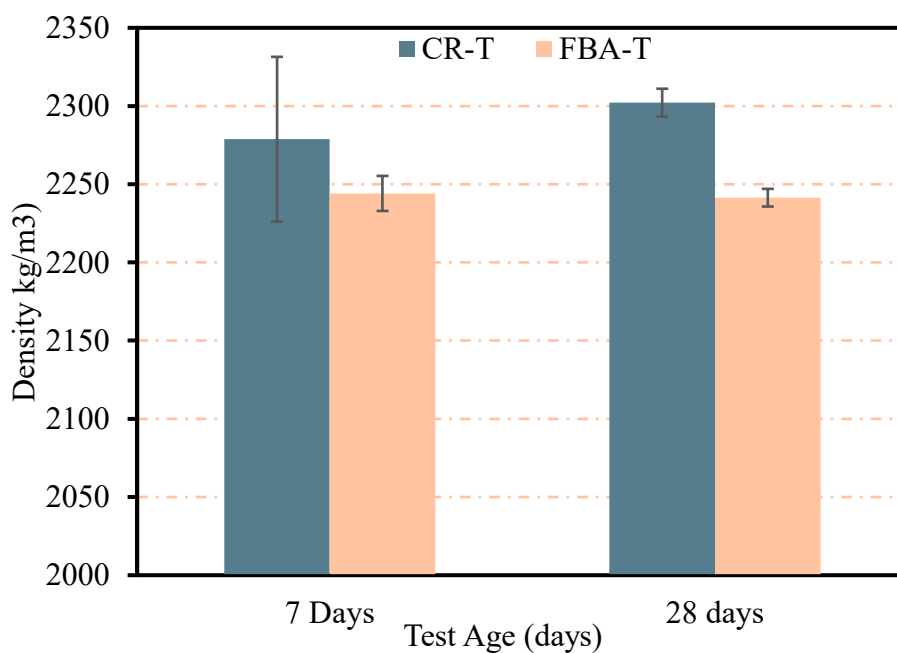
Slump and slump retention were measured for fresh concrete mixes and the results are presented in Fig.6.1. The guidelines followed were TfNSW QA Specification R53[111] which specifies a slump value of between 80 – 120 mm for the concrete used in footpaths (grade N32). The slump of both concrete mixes was close to 120 mm at the initial stage. The slump retention was measured to ensure there was enough time for the placement of concrete. The slump retention was measured for up to 60 minutes, and both concrete mixes provided satisfactory results.



**Fig. 6.1:** Slump and Slump retention.

### 6.2.5 Density

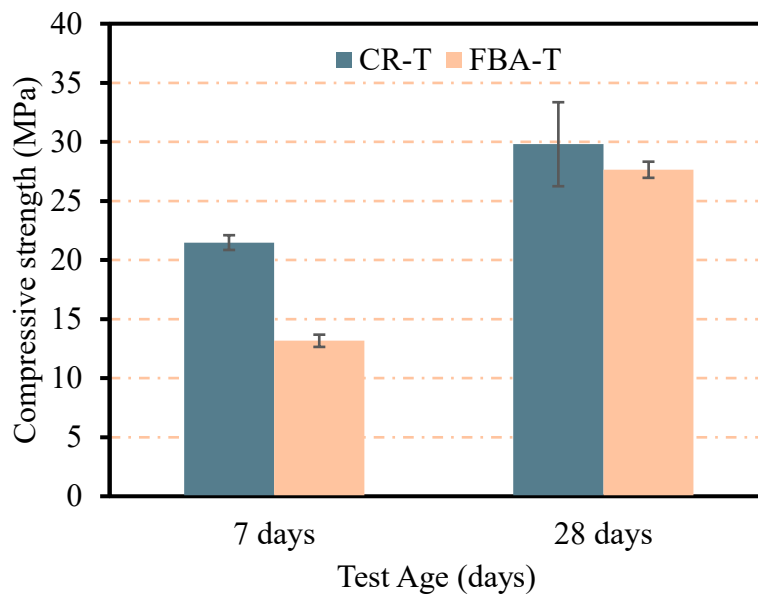
The densities of concrete mixes were measured at 7 and 28 days by measuring the mass and volume of the cylinders cast for the compressive strength. The results are presented in Fig. 6.2. The densities are within the range of normal concrete.



**Fig. 9.2:** Density of Concrete Mixes.

### 6.2.6 Compressive strength

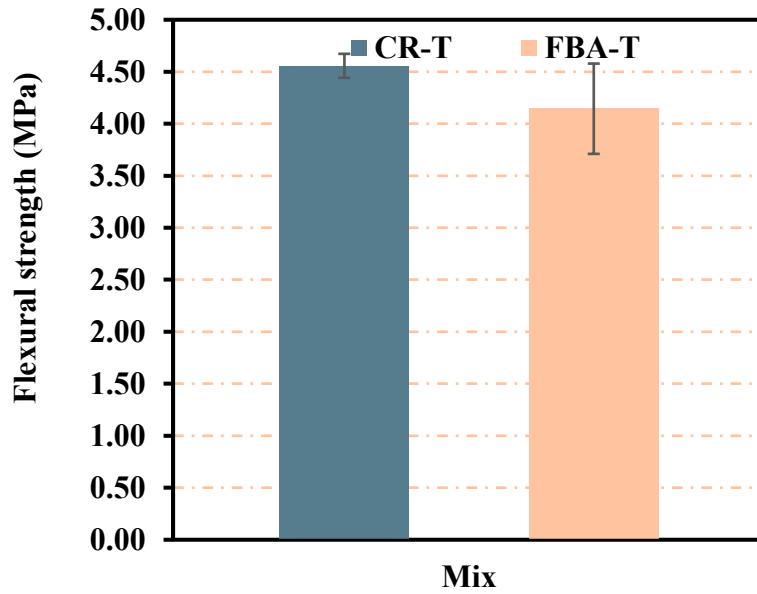
The compressive strengths of concrete mixes were measured at 7 and 28 days and results are presented in Fig. 6.3. Three cylinders were tested, and the average is reported here. The 7-day compressive strength of FBA concrete was significantly lower than the control concrete mix. However, the strength gain subsequently was satisfactory and higher than the 25 MPa mix, which was the design mix strength of both concrete mixes.



**Fig. 6.3:** Compressive strength of Concrete Mixes.

### 6.2.7 Flexural Strength

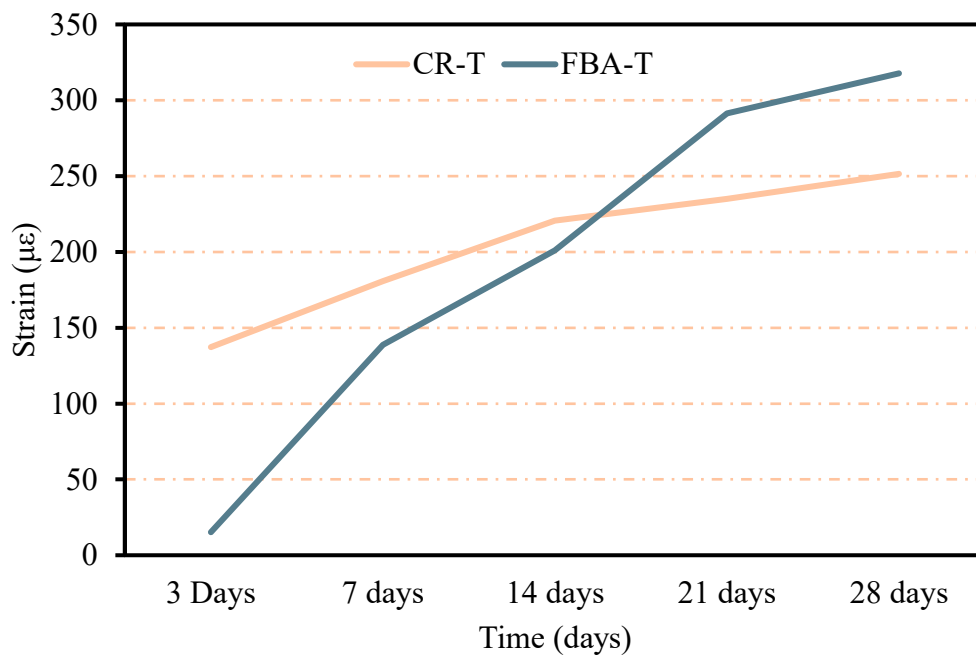
The flexural strengths of concrete mixes were measured at 28 days and presented in Fig. 6.4. The flexural strength of FBA concrete was slightly lower than the flexural strength of the control concrete mix but still satisfactory for the mix used for the footpath.



**Fig. 6.4:** Flexural Strength of Concrete Mixes.

### 6.2.8 Shrinkage

Shrinkage measurements were taken at regular time intervals and results are presented in Fig. 6.5. No specific requirements are specified for the footpath, but when compared to specifications for pavements, the shrinkage values of both concrete mixes are well within the specified limits.



**Fig. 6.5:** Shrinkage Tests result of Concrete Mixes.

## **6.3 Industrial trial application**

The industrial trial application of eco-friendly concrete made with FBA as sand and SCM was for a concrete footpath cast near Vales Point Power Station, Mannering Park. Details of what occurred are discussed here.

### **6.3.1 Materials**

The materials required to prepare concrete are listed below:

1. Ordinary Portland Cement
2. Fly ash
3. Slag
4. FBA
5. Coarse Aggregates
6. Fine Aggregates
7. Recycled water
8. Admixture (WR) 8875

Materials other than FBA were supplied by Daracon. The concrete was mixed at the Daracon concrete mixing plant (Cameron Park) and delivered to the Vales Point in transit mixers. Two transit mixers, each containing 3 cubic metres of concrete were supplied. The FBA used as sand replacement was provided by Delta Electricity and supplied directly to the Daracon concrete batching plant. For the FBA required as SCM, the raw FBA was supplied to University of Newcastle where the UON team oven dried and sieved the required amount of FBA. Then the required amount of FBA was delivered to AMML (an outsourced facility for grinding FBA) for grinding. The ground FBA (Volume weighted mean  $< 48 \mu\text{m}$ , specific surface area  $2926 \text{ cm}^2/\text{g}$ ) was then supplied to Daracon concrete batching plant for the industrial trial application. In addition to the eco-friendly concrete, another batch of control 25MPa concrete was supplied and used to cast a separate footpath for comparison.

### **6.3.2 Mix Design**

Table 6.3 details the mix designs for the concrete mixes without and with FBA as sand and as SCM. The coarse aggregates of 20 mm were replaced with coarse aggregates of 10 mm

size as per industry practices. The water added was also slightly higher compared to the laboratory trial mix to compensate for the travel time from the concrete batching plant to the construction site.

**Table 6.3:** Mix Designs for Industrial Applications.

| 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                              |
| 10mm                | kg    | 860  | 860                             |
| Coarse sand         | kg    | 260  | 70                              |
| Fine Sand           | kg    | 620  | 620                             |
| FBA (as Sand)       | kg    | 0  | 190                             |
| Recycled water      | kg    | 195  | 222                             |
| Admixture (WR) 8875 | L     | 1.1  | 1.1                             |

### 6.3.3 Scope of the Application

Two footpaths were cast based on two different concrete mixes. One control mix was manufactured without any FBA and the other was manufactured using FBA as 25% sand replacement and 10% cement replacement. The control footpath section measured 6 m in length, 100 mm in depth, and 1 m in width. In comparison, the FBA footpath section measured 10 m in length, 100 mm in depth, and 1 m in width. The footpaths are located in Tom Barney oval near Delta Electricity's Vales Point Power Station, Mannering Park (Fig. 6.6).



**Fig. 6.6:** Overhead View of the Site.

#### **6.3.4 Test Matrix/samples for laboratory testing**

The slump tests were conducted before the concrete was placed. Pouring concrete and preparation of samples were at the same time. A portable electric vibrator was used to compact the concrete samples. The next day the samples were transferred to the UON civil laboratory and demoulded. The samples were cured in curing room for the required duration. Table 6.4 shows the test matrix for concrete mixes from Industrial applications

**Table 6.4:** Test Matrix for Concrete mixes from Industrial applications.

| Tests   | Test Standard     | Specimen   | Volume (m <sup>3</sup> ) | No. of samples | Test age |
|---------|-------------------|--|--------------------------|----------------|----------|
| Slump   | AS 1012.3.1:2014  | 100 mm (top dia.)<br>200 mm (Bottom dia.)<br>300 mm height | 0.005                    | -              | Fresh    |
| Density | AS 1012.12.1-1998 | 100 mm dia. and 200 mm height                              | -                        | -              | 28 days  |

|                      |                 |                               |       |   |                   |
|----------------------|-----------------|-------------------------------|-------|---|-------------------|
| Compressive strength | AS 1012.9:2014  | 100 mm dia. and 200 mm height | 0.009 | 6 | 7, 28 and 56 days |
| Flexural strength    | AS 1012.11-2000 | 100 x 100 x 350 mm            | 0.021 | 6 | 28 days           |
| Shrinkage test       | AS 1012.13:2015 | 75 x 75 x 285 mm              | 0.005 | 3 | 3 - 56 days       |

### ***6.3.5 Observations on batching/placing***

The site was well-prepared for the trial application. Excavation was completed properly, and formwork was installed appropriately. Reinforcement was provided according to standards. The first mix was a control mix prepared with ordinary Portland cement at the concrete batching plant. The second mix was an FBA concrete mix, using 25% FBA as sand replacement, 10% FBA as SCM, and 25% slag as SCM. The distance travelled from plant to site was around 45 km which took around 40 minutes. Both mixes had good consistency and workability, and the workmanship was commendable. Joints were properly placed, and compaction was done using a portable electric vibrator. The contractor completed the work in a very professional manner. The observations during the placement/checklists of each concrete mix are provided in appendixes.

### ***6.3.6 Trial application images***

The following photographs (Fig. 6.7-6.12) were taken on the day of the trial mix application.



**Fig. 6.7:** Prepared site for footpath application.



**Fig. 6.8:** Slump of Control Concrete Mix.



**Fig. 6.9:** Slump of FBA Concrete Mix.



**Fig. 6.10:** Colour differences of Two mixes (FBA darker).



**Fig. 6.11:** Footpath after surface finish.



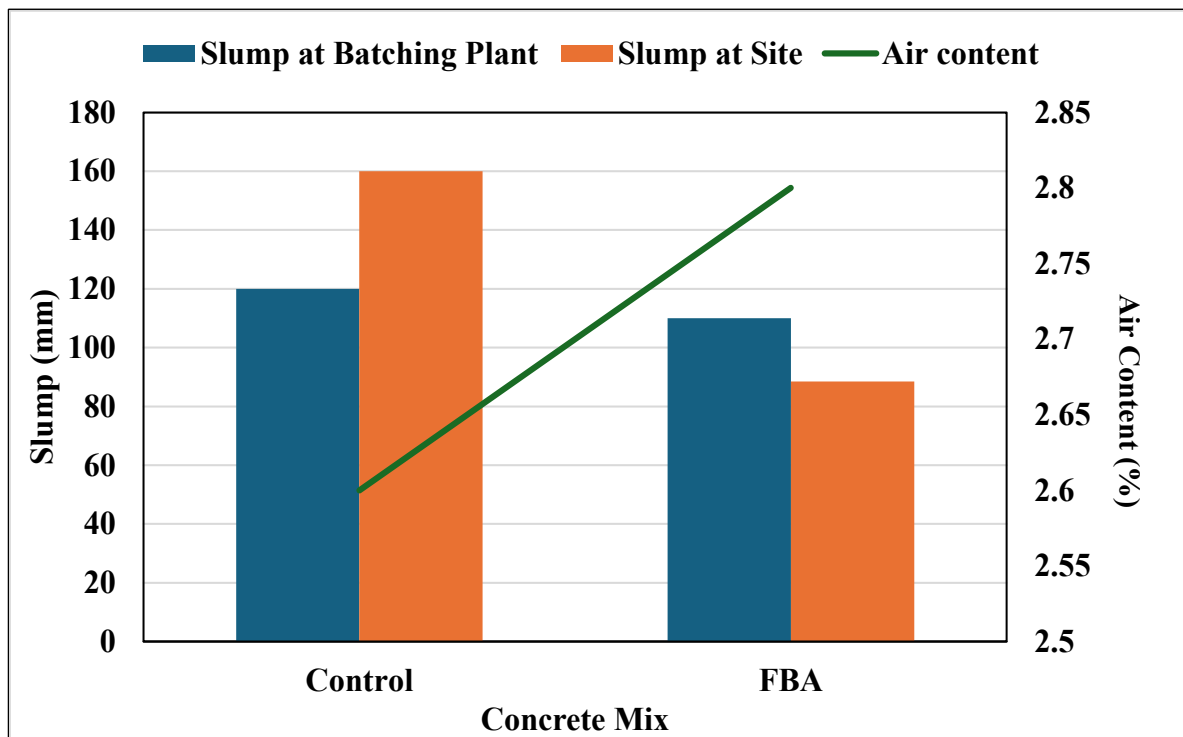
**Fig. 6.12:** Samples prepared for Lab testing.

### ***6.3.7 Test results***

The tests performed at the batching plant include slump and air content tests. An additional slump test was performed on site prior to the placing of concrete. For other tests like compressive, flexural and shrinkage the samples were prepared and tested at the required ages at Civil Lab of The University of Newcastle. The results are presented below:

#### ***6.3.7.1 Slump and void content***

The results are presented in Fig. 6.13. The slump for the control concrete at batching plant was 120 mm and at site slump for control concrete was 160 mm. The slump for FBA concrete at the batching plant was 110 mm and at site slump for FBA concrete was 88.5 mm. The slump for control concrete increased while for FBA concrete it decreased on site. The air content test was performed at the batching plant. The slump for FBA concrete decreased because of the water absorption tendency of FBA. The air content for the control concrete was 2.6 % and for FBA concrete the air content was 2.8 %. FBA has been reported to reduce concrete workability due to its porous structure, which absorbs free water from the mix. Additionally, its irregular shape, rough surface texture, and, when ground, ultra-fine particle size further contributes to decreased workability [5,29,65]. The air content for both concrete mixes is nearly similar showing that the replacement of sand and cement with FBA does not present any challenge in terms of air content in concrete.

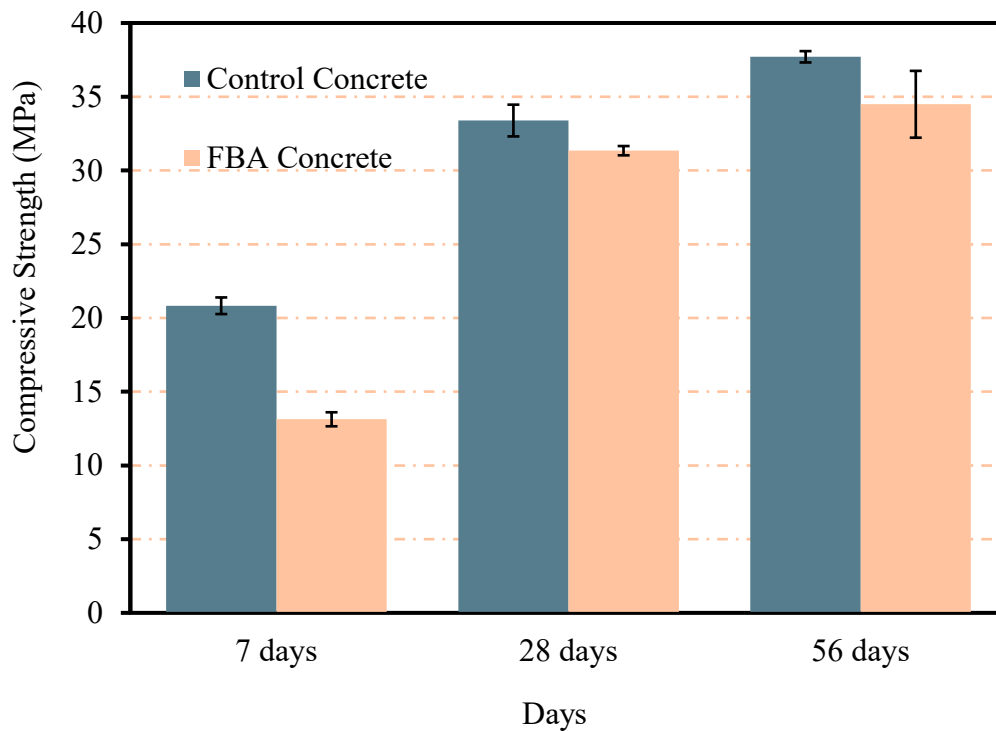


**Fig. 6.13:** Slump and Air Content.

#### 6.3.7.2 Compressive Strength

The compressive strength tests were performed on samples cast on site and the results are presented in Fig. 6.14. The 7- and 28-days compressive strength of control concrete was 20.8 MPa and 33.4 MPa, respectively. The 7- and 28-days compressive strength of FBA concrete was 13.1 MPa and 31.3 MPa, respectively. The early strength of FBA concrete was quite low, but this aligns with expectations as early age strength depends upon the pozzolanic

activity of the materials. The compressive strength of the concrete reduced slightly which could be attributed to the lower density and higher porosity of FBA compared to natural sand [112]. The strength gain for FBA concrete at 28 days was satisfactory. The requirement of compressive strength for footpath as per TfNSW specifications is around 25 MPa, so, both concrete mixes utilized here showed higher compressive strength than required. The 28-day compressive strength of FBA concrete was comparable to control concrete. This shows the potential of replacing sand and SCM in concrete to promote the circular economy. The 56-days compressive strengths were 37.7 MPa and 34.5 MPa for control concrete and FBA concrete, respectively. The major strength gain occurs by 28 days, and from then on, both concretes develop strength at a similar rate, with control concrete consistently showing slightly higher values.

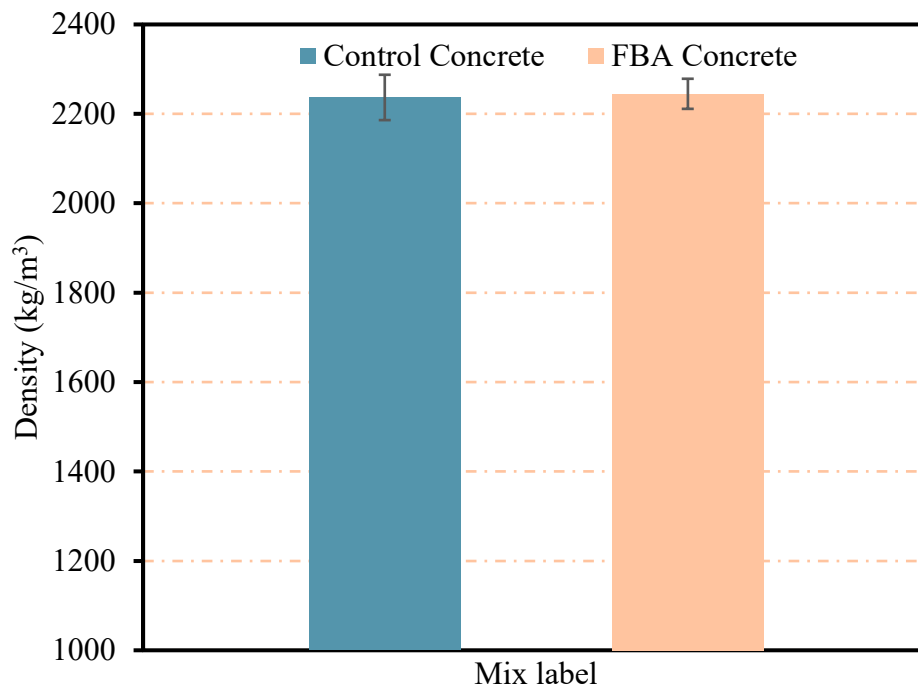


**Fig. 6.14:** Compressive Strength of concrete.

### 6.3.7.3 Density

The densities of both the control and FBA concrete at 28 days are presented in Fig. 6,15. The density of control concrete was around 2236 kg/m<sup>3</sup> while the FBA concrete showed a marginally higher density of around 2244 kg/m<sup>3</sup>. Both concrete mixes lie within the range of

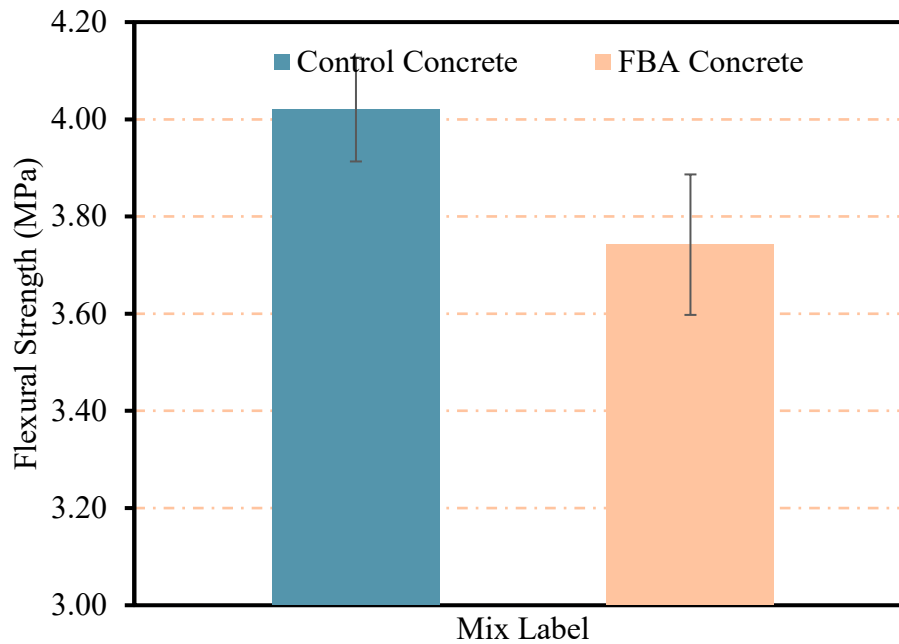
normal weight concrete. Replacing natural aggregates with FBA leads to a reduction in concrete density because the FBA has a lower density than the natural ones [113].



**Fig. 6.15:** Density of concrete.

#### 6.3.7.4 Flexural Strength

The flexural strengths of control and FBA concrete are presented in Fig. 6.16. The flexural strength of control concrete and FBA concrete were 4.02 MPa and 3.74 MPa, respectively. The FBA concrete yielded a slightly lower flexural strength compared to control concrete. The internal structure of FBA has pores which comprise of spherical particles. These weaken the cement paste, thus affecting the flexural strength of concrete [105]. There is no stringent requirement for flexural strength for footpaths in TfNSW specifications.

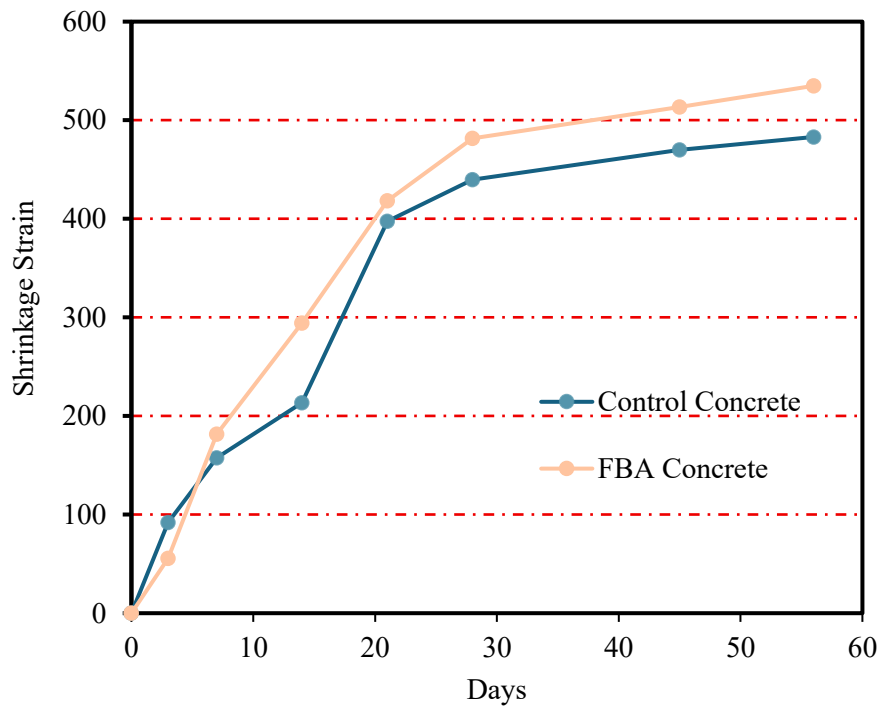


**Fig. 6.16:** Flexural Strength of concrete.

#### 6.3.7.5 Shrinkage

Shrinkage was measured at different time intervals for both control and FBA concrete and the results are presented in Fig. 6.17. At 3 days, the shrinkage of FBA concrete was lower than that of control concrete. This may be attributed to the higher water absorption capacity of FBA compared to normal sand. Later the FBA concrete showed higher shrinkage compared to control concrete but the difference of both concrete mixes is not significant.

At 21 days, the shrinkage values of control and FBA concrete are 397 and 418  $\mu\epsilon$ , respectively. The increased quantity of porous FBA particles in the concrete contributed to a gradual release of moisture during the drying process [1]. The values are significantly lower than those specified in TfNSW R83 which conclude that the shrinkage of mixes containing GGBFS should be lower than 580  $\mu\epsilon$  at 21 days and for other concrete mixes 450  $\mu\epsilon$  at 21 days. Therefore, both concrete mixes yield significantly lower shrinkage values compared to values mentioned in the specification. The shrinkage strain at 56-days was quite high compared to previous laboratory trial mixes. But this was expected as higher water/cement ratios were used for the trial. However, the values are still within the limits specified in TfNSW R83. The values for both concrete mixes, control and FBA, were slightly different.



**Fig. 6.17:** Shrinkage (um/m<sup>2</sup>) of concrete.

### **6.3.8 Post casting observations**

After two months a visual inspection of the footpaths was conducted (Fig. 6.18). Some dusting marks were observed on the footpath made with FBA concrete. This may be related to rainfall after the concrete was poured, which can introduce excess moisture to the surface. This extra water can weaken the bond between the surface layer and the rest of the concrete. As the concrete cures, the surface may become soft and powdery, leading to dusting. This is particularly true for concrete mixtures containing FBA due to its porous nature. FBA absorbs more water compared to traditional aggregates, which can result in excess water retention. This can weaken the surface layer, making it more prone to damage and dusting as it dries or cures improperly. Adequate curing is essential to prevent rapid drying and surface weakness in FBA concrete.



**Fig. 6.18:** Dusting on FBA concrete (after two months).

Fig. 6.19 and 6.20 showed another inspection conducted on 20 September after seven months. It showed positive results for the FBA concrete footpath, particularly in terms of overall durability and performance. The footpath made with FBA concrete showed no signs of significant surface wear, cracking, or scaling, indicating that the concrete is holding up well under typical environmental conditions. The absence of surface distress such as discolouration, spalling, delamination, or joint deterioration suggests that the concrete's structural integrity is intact. This is particularly noteworthy for FBA concrete, which often faces challenges related to moisture retention due to its porous nature.



**Fig. 6.19:** FBA concrete (Left) and Control concrete (Right).



**Fig. 6.20:** FBA concrete pavement.

### ***6.3.9 Comparison and Recommendations***

The results are summarized in Table 6.5. They include laboratory trial mixes prior to the test application, and results for the concrete mixes used in the industrial application. For each stage, two concrete mixes, control and FBA, were utilized for comparison. The parameters obtained showed satisfactory performance for the FBA concrete utilized for footpath construction. These results indicate the suitability of using FBA as sand and SCM replacements in concrete to be utilized for footpath applications. A slight variation between compressive strengths at the batching plant and in the laboratory was observed. These variations reduced the 56-days compressive strengths.

**Table 6.5: Comparison of Results.**

| 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 | Control Concrete | FBA concrete |
| Slump (mm)                            | 120                 | 125          | 125                        | 110          | -                | -            |
| Air Content (%)                       | -                   | -            | 2.6                        | 2.8          | -                | -            |
| <b>Compressive Strength (MPa)</b>     |                     |              |                            |              |                  |              |
| 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          |

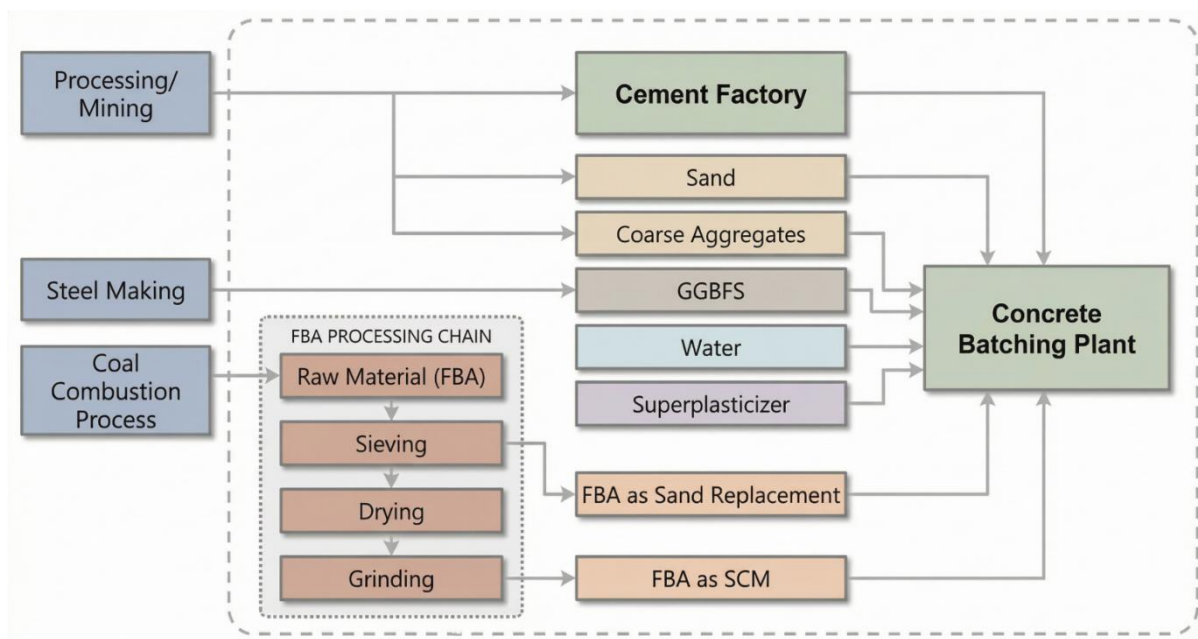
## 6.4 Summary

This chapter summarizes the use of FBA concrete used in a real industrial application. Initially, the FBA concrete was manufactured at the UON Laboratory utilizing the materials provided by Daracon. Two concrete mixes, control and FBA concrete were produced, and various tests were conducted to assess the performance of FBA concrete compared to control concrete. Later, similar concrete mixes were utilized to cast a footpath. Similar tests were performed on the concrete mixes and significantly similar results were obtained. The performance of FBA concrete was found to be satisfactory.

# CHAPTER 7: LIFE CYCLE ASSESSMENT

## 7.1 Introduction

The objective of this chapter is to evaluate and contrast the environmental impact of FBA concrete prepared using FBA as SCM and as sand replacement compared with conventional concrete using a cradle-to-gate LCA approach. The cradle-to-gate system boundary is presented in Fig. 7.1. The parameters considered simulate actual conditions. The life cycle after the manufacture of concrete has not been included as this would be similar for both control and FBA concrete. The preparation and transportation of materials to the concrete batching plant has been considered. The Eco invent database was used to produce the LCA using Sima Pro. The method used was ReCiPe 2016 Midpoint (H). For materials like cement, sand etc built in/available processes were implemented. For FBA, additional energy consumption required for sieving, drying and grinding were included.



**Fig. 7.1:** Cradle to gate system boundary (dotted lines).

## 7.2 Functional Unit

In Life Cycle Assessment (LCA), a functional unit is a quantified description of the performance of a product system, serving as the reference point for all impact calculations. It ensures that comparisons between different products or systems are based on equivalent functional performance. For this study, the manufacture of 1 m<sup>3</sup> of concrete was set as the functional unit. The materials required for the manufacture of 1 m<sup>3</sup> of concrete were used as input to the system. In addition, the processes required to prepare the required material like ground FBA were also considered. The required volume of concrete is the most adopted functional unit for the LCA of concrete.

## 7.3 Input Parameters

The mix proportions used in the LCA are presented in Table 7.1. CR0 is for concrete without FBA, CR25 is for concrete with 25% FBA as sand replacement, and other IDs refer to separate (Sep) or co-grinding (Co) of FBA with slag with replacement levels from 10-30% with interval of 10%.

**Table 7.1:** Mix Proportions for 1 m<sup>3</sup> of concrete (kg/m<sup>3</sup>).

| Mix ID   | Binder components |      |       | Coarse aggregates |       | Fine aggregate |             |     | Water | SP * |
|----------|-------------------|------|-------|-------------------|-------|----------------|-------------|-----|-------|------|
|          | Cement            | GGBS | GFBA  | 20 mm             | 10 mm | Fine sand      | Coarse sand | FBA |       |      |
| CR0      | 435               | 0    | 0     | 690               | 280   | 380            | 380         | 0   | 174.0 | 1.7  |
| CR25     | 435               | 0    | 0     | 690               | 280   | 285            | 285         | 190 | 196.8 | 2.7  |
| Sep-GF10 | 281.5             | 110  | 43.5  | 690               | 280   | 285            | 285         | 190 | 196.8 | 2.7  |
| Sep-GF20 | 238               | 110  | 87    | 690               | 280   | 285            | 285         | 190 | 196.8 | 2.7  |
| Sep-GF30 | 194.5             | 110  | 130.5 | 690               | 280   | 285            | 285         | 190 | 196.8 | 2.7  |
| Co-GF10  | 281.5             | 110  | 43.5  | 690               | 280   | 285            | 285         | 190 | 196.8 | 2.7  |
| Co-GF20  | 238               | 110  | 87    | 690               | 280   | 285            | 285         | 190 | 196.8 | 2.7  |
| Co-GF30  | 194.5             | 110  | 130.5 | 690               | 280   | 285            | 285         | 190 | 196.8 | 2.7  |

\* Superplasticizer quantity in (L/m<sup>3</sup>)

### 7.3.1 Parameters for manual calculations

For the manual calculations, the parameters used were decided based on literature. The equations used are as follows.

The following equation was adopted to determine the electricity energy ( $E_i$ ) consumed throughout the treatment process for FBA, slag and crushing aggregates

$$(E_i) = \sum_{k=i}^n m_i [(Pr \times t) + (MP_i \times t) + (Pc \times t)]$$

Where  $m_i$  = mass of component (kg per m<sup>3</sup>),

$Pr$  = Power rating of oven (kW/kg),

$Mp_i$  = Grinding machine Power (kW/kg),

$Pc$  = Power rating of crushing machine (kW/kg),

$t$  = time of process (h)

The direct energy consumption was evaluated using the following equation:

$$E_n = \sum_{k=i}^n m_i [(d_i \times D_i \times k_{1i} \times F_i) + (E_i \times k_{2i})]$$

Where  $m_i$  = mass of component (kg per m<sup>3</sup>),

$d_i$  = travelling distance (km),

$D_i$  = diesel consumption (litre/km),

$k_{1i}$  = Energy consumption for 1litre diesel (GJ),

$F_i$  = Volume fraction of delivered material per truck volume,

$E_i$  = total electricity consumption (GJ/kg),

$k_{2i}$  = Energy consumption for 1 litre diesel per 1 kg delivered material (GJ/l.km).

The total equivalent CO<sub>2</sub> emitted from the production, processing, and transportation of materials for producing 1 m<sup>3</sup> was calculated using the following equation:

$$\text{Total CO}_2 \text{ emission} = \sum_{k=i}^n m_i [(d_i \times D_i \times k_{3i} \times F_i) + (E_i \times k_{4i})]$$

Where  $m_i$  = mass of component (kg per m<sup>3</sup>),

$d_i$  = travelling distance (km),

$D_i$  = diesel consumption (litre/km),

$k_{3i}$  = CO<sub>2</sub> emission factor for 1litre diesel per 1 kg delivered material (kg/l.kg),

$F_i$  = Volume fraction of delivered material per truck volume,

$E_i$  = Electricity consumption for material production (Gj/kg),

$k_{4i}$  =CO<sub>2</sub> emission factor for 1 kwh electricity (kg/GJ).

The total estimated cost of the production, processing, and transportation of materials for producing 1 m<sup>3</sup> was calculated using the following equation:

$$\text{Total estimated Cost} = \sum_{k=i}^n m_i [(d_i \times D_{pi} \times F_i) + T_i + (E_i \times E_{Pi})]$$

$m_i$  = mass of material (kg per m<sup>3</sup>),

$d_i$  = travelling distance (km),

$D_{pi}$  = Transport charge (AUD/kg.Km),

$F_i$  = Volume fraction of delivered material per truck volume,

$T_i$  = purchasing price of material (AUD/kg),

$E_i$  = total electricity consumption of material production (Gj/kg)

$E_{Pi}$  = Electricity Cost for material production (AUD/kWh)

The required input values for manual calculations are listed in Table 7.2.

**Table 7.2:** Input parameters for manual calculations.

| Factor  | Symbol   | Unit               | Value          | Ref.       |
|---|----------|--------------------|----------------|------------|
| Grinding machine capacity   | $M_{ei}$ | kg                 | 2              | Laboratory |
| Grinding time   | t        | hour               | 0.5            | Laboratory |
| Grinding machine Power  | $M_{pi}$ | watt               | 750            | Laboratory |
| Power rating of oven  | $P_r$    | watt               | 2100           | Laboratory |
| Oven Capacity   | $C_p$    | m <sup>3</sup>     | 1.6            | Laboratory |
| Time of oven drying   | t        | hour               | 24             | Laboratory |
| Power consumption per m <sup>3</sup>                                      | $P_s$    | kWh/m <sup>3</sup> | 0.0142         | [114]      |
| Traveling distance  | $d_i$    | Km                 | 20             | /          |
| Diesel Consumption  | $D_i$    | L/km               | 0.09           | [114]      |
| Energy consumption for 1L diesel per 1 kg delivered material              | $k_1$    | Gj/L.km            | 0.0384         | [114]      |
| Energy consumption for Portland cement                                    | $E_p$    | GJ/ton             | 3.796 to 5.196 | [115][116] |
| Energy consumption for 1 kwh electricity                                  | $k_2$    | GJ                 | 0.0036         | [114]      |
| CO <sub>2</sub> emission factor for 1L diesel per 1 kg delivered material | $k_3$    | kg/L.kg            | 2.7            | [116]      |
| CO <sub>2</sub> emission factor for 1 kwh electricity                     | $k_4$    | kg/GJ              | 202            | [117]      |

|                                     |                    |                      |           |   |
|-------------------------------------|--------------------|----------------------|-----------|---|
| Truck volume                        | V                  | m <sup>3</sup>       | 50        | assumed   |
| Cement                              | $\rho_{OPC}$       | (kg/m <sup>3</sup> ) | 1450      | Laboratory  |
| FBA density                         | $\rho_{FBA}$       | (kg/m <sup>3</sup> ) | 1200      | Laboratory  |
| GGBFS density                       | $\rho_{GGBFS}$     | (kg/m <sup>3</sup> ) | 1450      | Laboratory  |
| Combination of GGBS and FBA density | $\rho_{Co}$        | (kg/m <sup>3</sup> ) | 1325      | Laboratory  |
| Coarse aggregate density            | $\rho_C$           | (kg/m <sup>3</sup> ) | 1600      | Laboratory  |
| Fine aggregate density              | $\rho_F$           | (kg/m <sup>3</sup> ) | 1600      | Laboratory  |
| Transport charge                    | D <sub>pi</sub>    | AUD/m <sup>3</sup>   | 1.31      | <a href="https://www.boral.com.au/concrete-service-fees">https://www.boral.com.au/concrete-service-fees</a> |
| Electricity Cost                    | E <sub>pi</sub>    | AUD/MWh              | 157       | [118]   |
| Cement                              | T <sub>OPC</sub>   | AUD/20 kg bag        | 9.25      | eBay  |
| Raw FBA price                       | T <sub>FBA</sub>   | AUD/ton              | /         | Waste   |
| GGBFS price                         | T <sub>GGBFS</sub> | AUD/ton              | /         | Waste   |
| Coarse aggregate price              | T <sub>C</sub>     | AUD/ton              | Around 65 | M.J. Rowles Building & Landscape Supplies website   |
| Fine aggregate price                | T <sub>F</sub>     | AUD/ton              | Around 75 | M.J. Rowles Building & Landscape Supplies website   |
| Superplasticizer                    | T <sub>sop</sub>   | AUD/L                | 2         | [119]   |

### 7.3.2 *Input parameters in software*

For the Sima Pro LCA, the baseline calculations used the same data as the manual calculations in Table 7.2. The data in Table 7.2 are based on the laboratory equipment available for the analysis. Additionally, a sensitivity analysis was conducted based on the different power and capacities of ball mills available at an industrial scale. The main variables include the specifications of the equipment used for grinding and the travel distance required for various materials. For the baseline scenario, the parameters of laboratory equipment were used, and the travel distance was considered as grinding of FBA at the university.

### 7.3.3 *Life cycle impact analysis*

The life cycle impact analysis in Sima Pro was performed using ReCiPe 2016 Midpoint (H) method. The impact categories discussed are presented in Table 7.3.

**Table 7.3:** Impact categories for LCA in Sima Pro.

| <b>Impact Categories</b>      | <b>Units</b>            |
|-------------------------------|-------------------------|
| Global warming                | kg CO <sub>2</sub> Eq   |
| Particulate Matter            | kg PM <sub>2.5</sub> Eq |
| Photochemical Ozone Formation | kg NO <sub>x</sub> Eq   |
| Water Consumption             | m <sup>3</sup>          |

## 7.4 Results and Interpretations

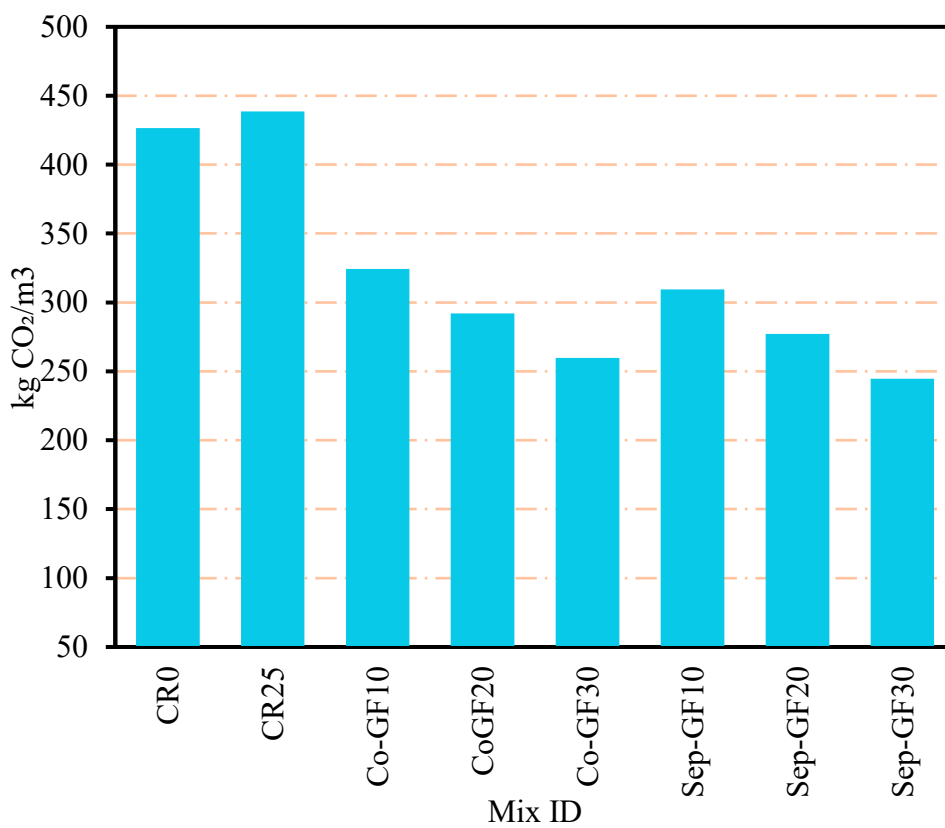
The results below are presented for both manual and software calculations.

### 7.4.1 Results from manual calculations

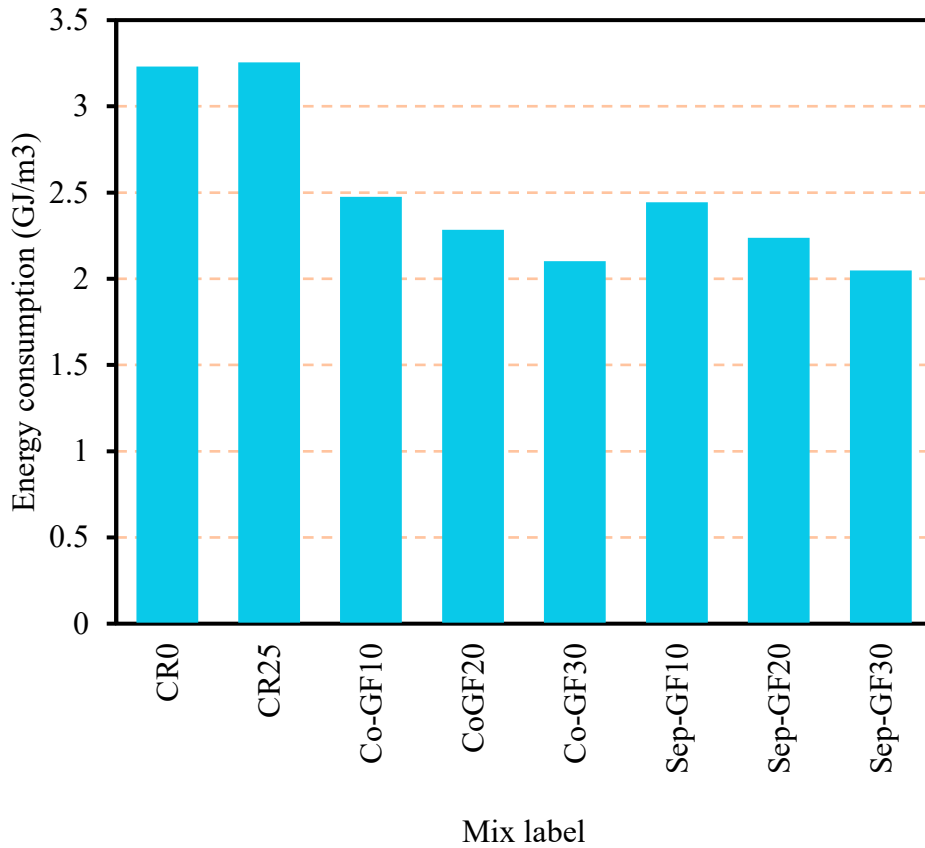
The results obtained from manual calculations for carbon emissions, energy consumption, and costs are presented in Fig. 7.2 to 7.4. These show that the use of FBA as sand replacement had no significant impact on the overall carbon emissions of 1 m<sup>3</sup> of concrete. The carbon emissions and energy consumption were higher for concrete having FBA as sand replacement only. On the other hand, the use of FBA as SCM significantly reduced the carbon emissions and energy consumption compared to the control concrete. This was expected as the major contributor to carbon emissions from concrete is cement and replacing it with FBA and slag lowered the carbon emissions. Unit travel distances were considered to simplify the calculations.

The concrete mixes prepared by separate grinding of FBA and slag showed slightly lower emissions and energy consumptions. The capacity of the ball mill meant that it had to run for more time

than for the co-ground material. This produced higher emissions and consumed more energy compared to separate grinding. Also, in the cost calculations, by-products like FBA and slag were considered free of charge. The use of FBA as 25% of sand replacement increased carbon emissions by around 3% compared to the control concrete. The carbon emissions from co-ground mixes was reduced by around 24%, 32% and 39% for Co-GF10, Co-GF20 and Co-GF30, respectively (Refer Fig. 7.2: Co-GF10, CoGF20 and CoGF30). Similarly, for separately ground mixes, the carbon emissions were reduced by around 27%, 35% and 43% for Sep-GF10, SepGF20 and SepGF30 (Refer Fig. 7.2: Sep-GF10, Sep-GF20 and Sep-GF30). In conclusion, the use of FBA as SCM could help to reduce carbon emissions.

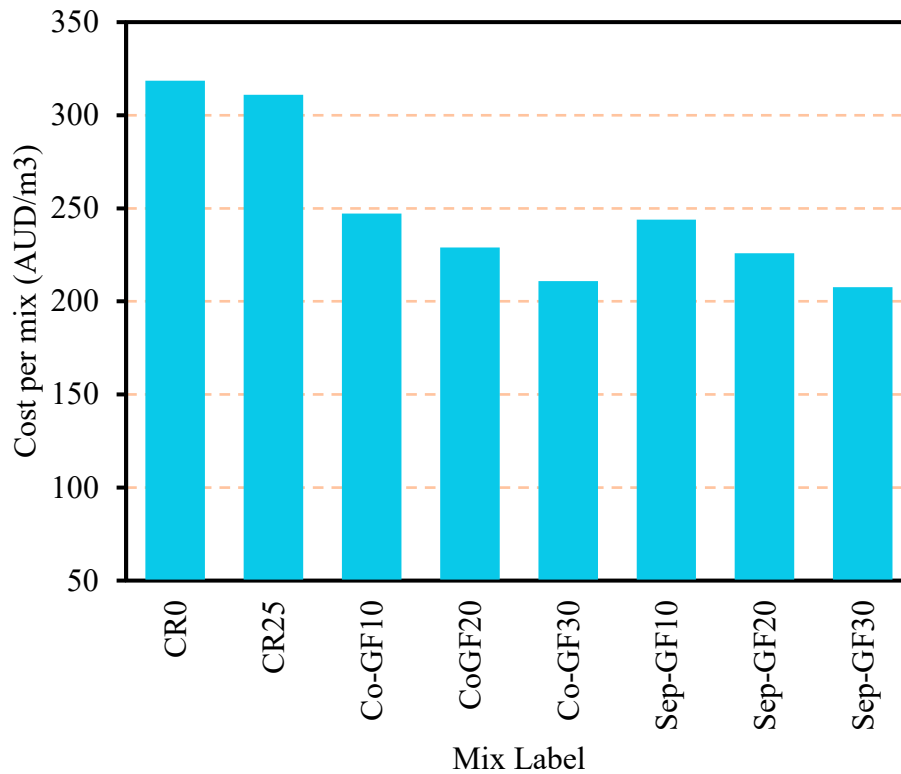


**Fig. 7.2:** Carbon emissions from manual calculations.



**Fig. 7.3:** Energy consumption from manual calculations.

Energy consumption was reduced when FBA was used as sand and as SCM (Fig. 7.3). This was around 2% for concrete having FBA as 25% sand replacement and around 26%, 33% and 39% for co-ground mixes with 10%, 20% and 30%, respectively FBA as SCM. The reduction in energy consumption was around 27%, 34% and 40% for separately ground mixes with 10%, 20% and 30%, respectively FBA as SCM.



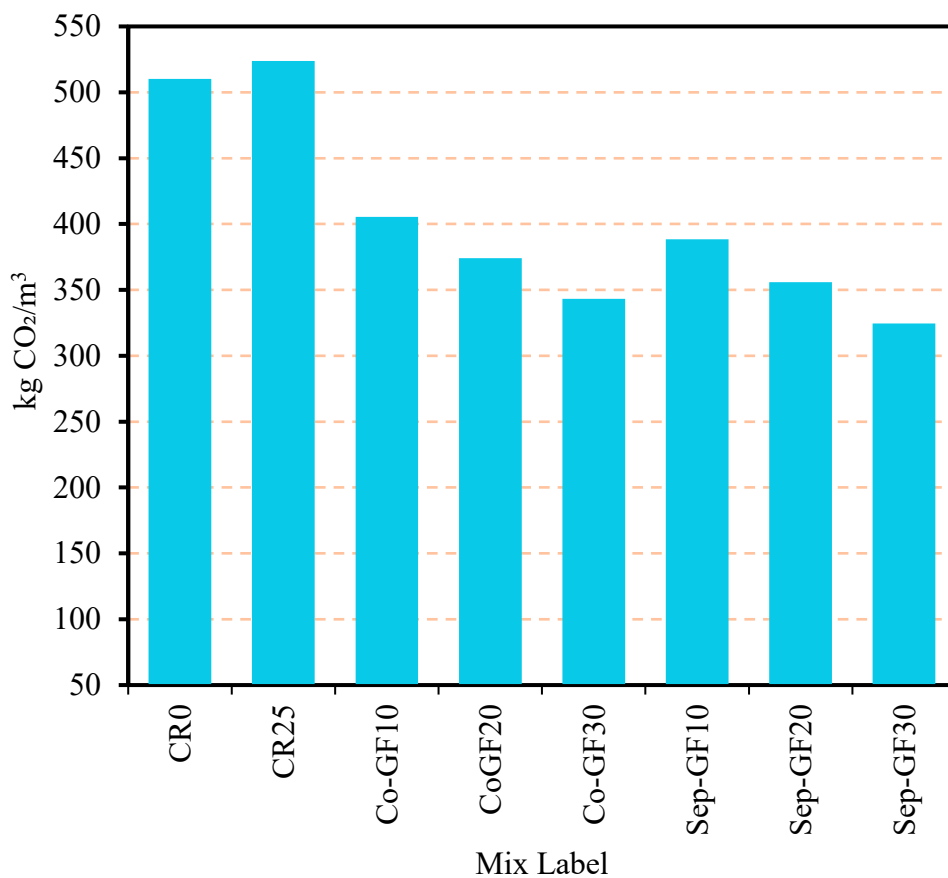
**Fig. 7.4:** Costs from manual calculations.

Fig. 7.4 shows the cost estimate for ecofriendly concrete with FBA. The cost reduction for concrete with FBA as 25% sand replacement is about 2% compared to the control mix. The cost reduction is around 22%, 28% and 34% for co-ground mixes with 10%, 20% and 30%, respectively, FBA as SCM. The cost reduction is around 23%, 29% and 35% for separately ground mixes with 10%, 20% and 30%, respectively, FBA as SCM.

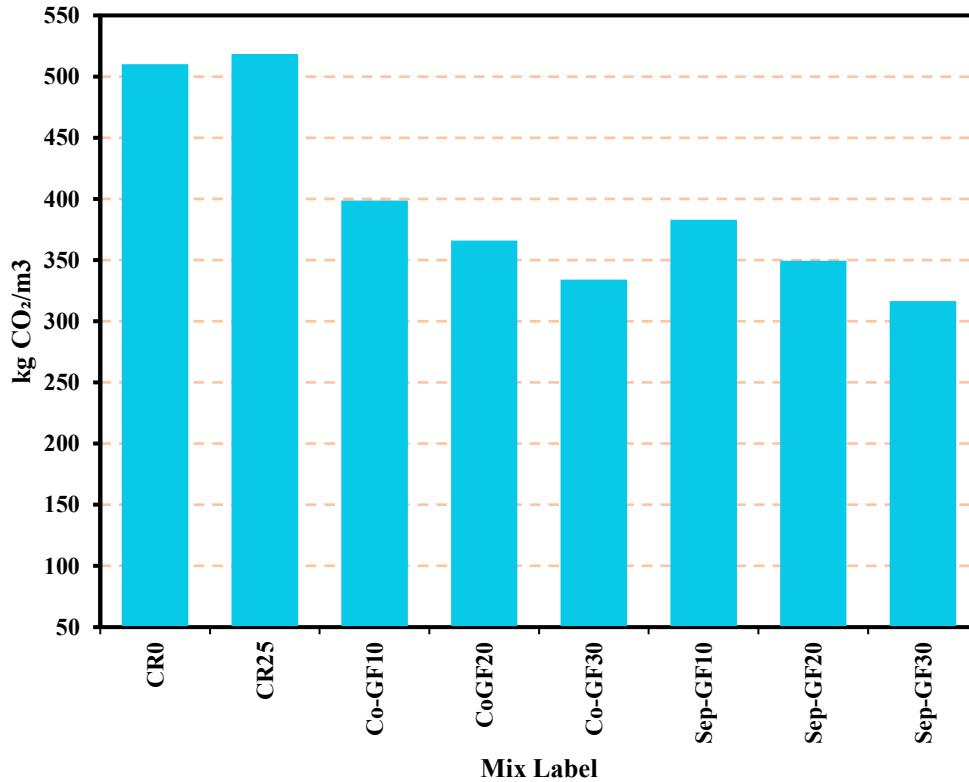
**Table 7.4:** Transportation Distances.

| Material                | Existing Transport Distance (km) | Matching Transportation Distance (km) |
|-------------------------|----------------------------------|---------------------------------------|
| Cement                  | 21                               | 21                                    |
| GFBA                    | 61                               | 21                                    |
| GGBFS                   | 24                               | 21                                    |
| Avg. (GFBA+GGBFS)       | 42.5                             | 21                                    |
| Coarse Aggregates       | 40                               | 40                                    |
| Crushed Fine Aggregates | 15                               | 15                                    |
| Fine Sand               | 15                               | 15                                    |
| Raw FBA                 | 50                               | 15                                    |
| Superplasticizer        | 9                                | 9                                     |

The manually calculated carbon emissions including for the transportation distances are presented in Fig. 7.5. The transportation distances are shown in Table 7.4. These distances significantly increased the carbon footprint of each concrete mix. Also, there were differences for FBA concrete based on travel distances from Vales Point power station to the University of Newcastle for processing of FBA and then from University to the concrete batching plant in Cameron Park. These significantly added to the carbon emissions for FBA concrete mixes. Another set of calculations was conducted to include transportation for ground FBA as cement, and transportation for raw FBA similar to fine aggregates (Table 7.4). The results (Fig. 7.6) for this case showed slight reduction in carbon emissions for FBA concrete mixes.



**Fig. 7.5:** Carbon emissions from manual calculations (including existing Transportation distances).



**Fig. 7.6:** Carbon emissions from manual calculations (including similar Transportation distances).

A sensitivity analysis was performed for the carbon emissions of ground FBA used for different concrete mixes produced considering variable transportation distances with respect to the amount. The results are presented in Table 7.5. These show that a slight increase in carbon emissions when the travel distance is increased. Overall carbon emissions are still lower than the control concrete mix.

**Table 7.5:** Sensitivity Analysis based on Transportation Distances for GFBA carbon emissions (kg CO<sub>2</sub>)

| Concrete Mix ID              | CR0 | CR25   | Co-GF10 | Co-GF20 | Co-GF30 | Sep-GF10 | Sep-GF20 | Sep-GF30 |         |
|------------------------------|-----|--------|---------|---------|---------|----------|----------|----------|---------|
| Required amount of GFBA (kg) | 0   | 0      | 43.5    | 87.5    | 130.5   | 43.5     | 87       | 130.5    |         |
| Transportation Distance (km) | 10  | 510.07 | 523.70  | 403.34  | 370.37  | 337.90   | 387.92   | 354.23   | 320.95  |
|                              | 20  | 510.07 | 523.70  | 403.77  | 371.08  | 338.96   | 388.00   | 354.53   | 321.64  |
|                              | 30  | 510.07 | 523.70  | 404.20  | 371.79  | 340.02   | 388.07   | 354.84   | 322.33  |
|                              | 40  | 510.07 | 523.70  | 404.63  | 372.50  | 341.08   | 388.15   | 355.15   | 323.02  |
|                              | 50  | 510.07 | 523.70  | 405.06  | 373.21  | 342.14   | 388.22   | 355.45   | 323.71  |
|                              | 60  | 510.07 | 523.70  | 405.50  | 373.92  | 343.20   | 388.30   | 355.76   | 324.40  |
|                              | 70  | 510.07 | 523.70  | 405.93  | 374.64  | 344.26   | 388.38   | 356.07   | 325.092 |

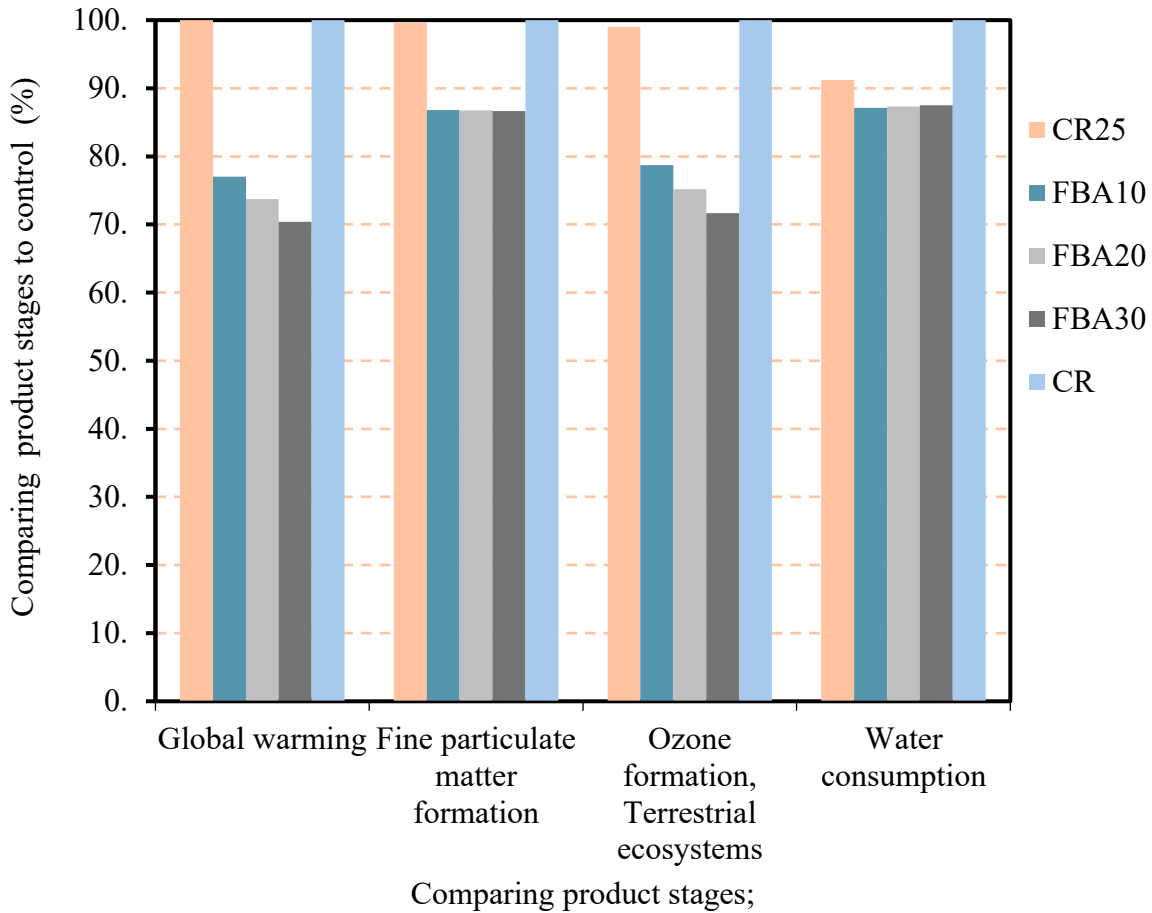
A comparison of carbon emissions of different compressive strengths of 1 m<sup>3</sup> concrete was made. The results are presented in Table 7.6. The carbon emissions per MPa for FBA concrete mixes are significantly lower than the per MPa carbon emissions for the control concrete mix.

**Table 7.6:** Carbon Emissions per MPa of concrete.

| Mix ID   | kg CO <sub>2</sub> /m <sup>3</sup> for each mix | kg CO <sub>2</sub> /m <sup>3</sup> . MPa |
|----------|---|--|
| CR0      | 510.07  | 10.50                                    |
| CR25     | 523.70  | 9.90                                     |
| Co-GF10  | 405.54  | 7.49                                     |
| CoGF20   | 373.99  | 6.95                                     |
| Co-GF30  | 343.31  | 7.21                                     |
| Sep-GF10 | 388.31  | 7.93                                     |
| Sep-GF20 | 355.79  | 7.64                                     |

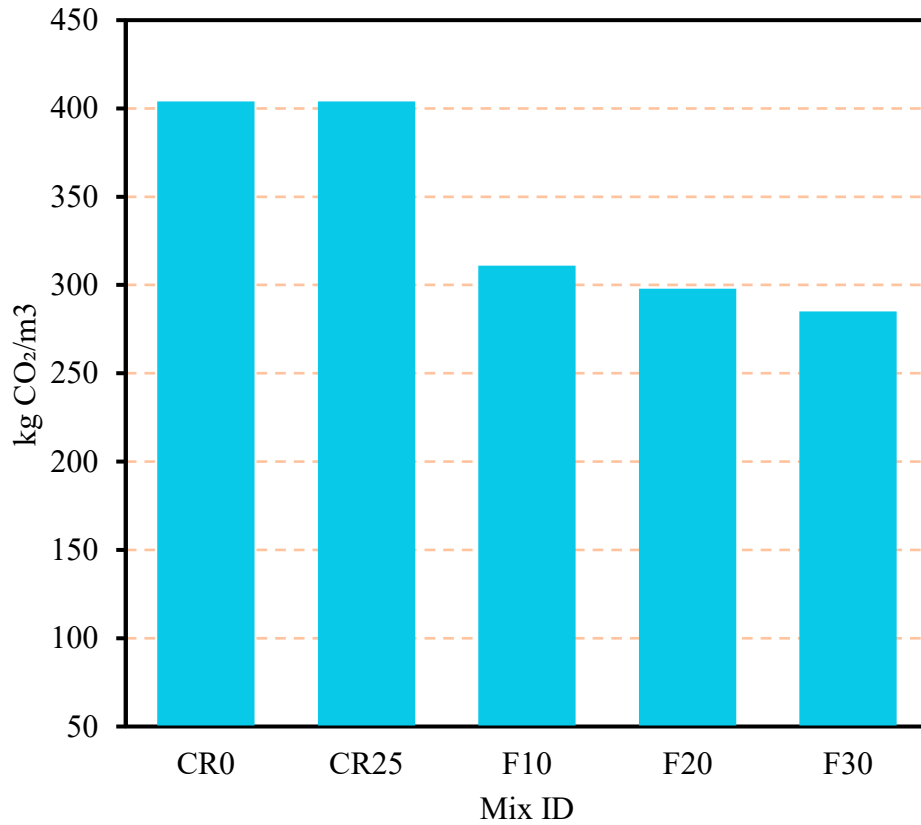
#### **7.4.2 Results from Sima Pro**

The ReCiPe method was used to quantify the carbon emissions for each mix. The primary results were obtained using input data similar to the manual calculations as a baseline. For software calculations, only control and separate grinding mixes were considered. The LCA results for major impact categories are presented in Fig. 7.7. It can be inferred that the use of FBA as SCM and as sand replacement reduced the potential global warming, fine particulate matter formation and ozone formation. However, freshwater and marine eutrophication increased due to electricity use. Water consumption was slightly lower than the control mixes but increased in line with the amount of FBA in the concrete mixes.

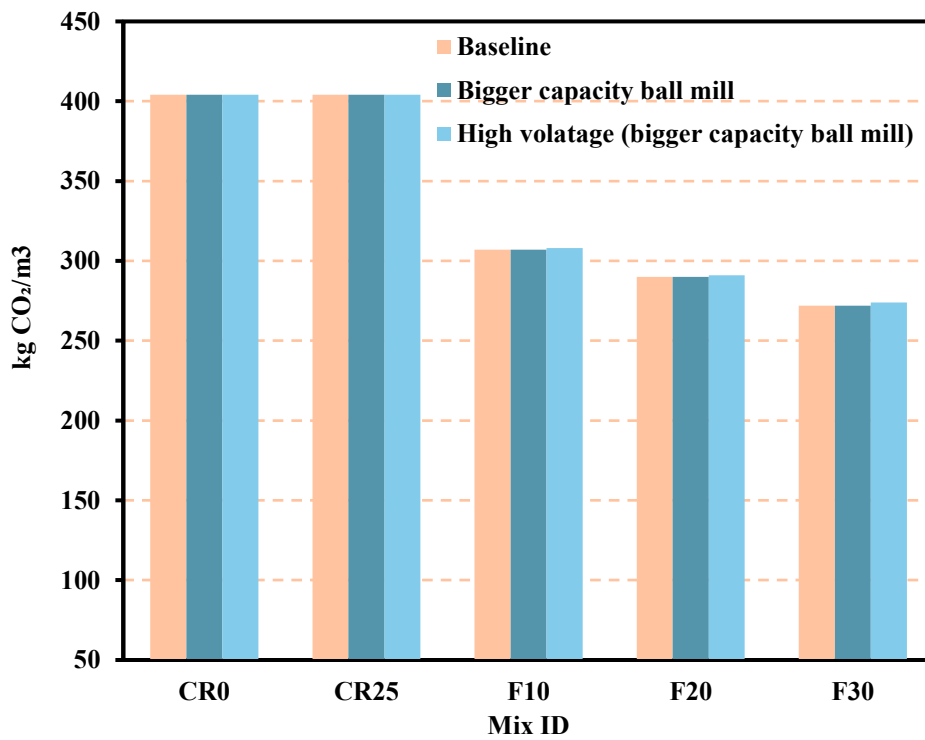


**Fig. 7.7:** LCA impact categories results for concrete mixes; Method: ReCiPe 2016 Midpoint (H) V1.09 / World (2010) H / Characterization.

Carbon emissions calculations obtained from Sima Pro for different scenarios warrant further discussion. The results for baseline cases are shown in Fig. 7.8. They trend in a similar manner to manual calculations, but the values are more realistic compared to manual calculations. Cement manufacturing emits 0.9 kg of CO<sub>2</sub> per 1.0 kg of cement production [120]. Therefore, mixes having 435 kg cement yielded around 404 kg CO<sub>2</sub>. It is to be noted that the use of FBA as sand replacement has not made any significant difference in reducing carbon emissions as the carbon emissions for sand were insignificant. However, the use of FBA as SCM results in a pronounced reduction in carbon emissions.



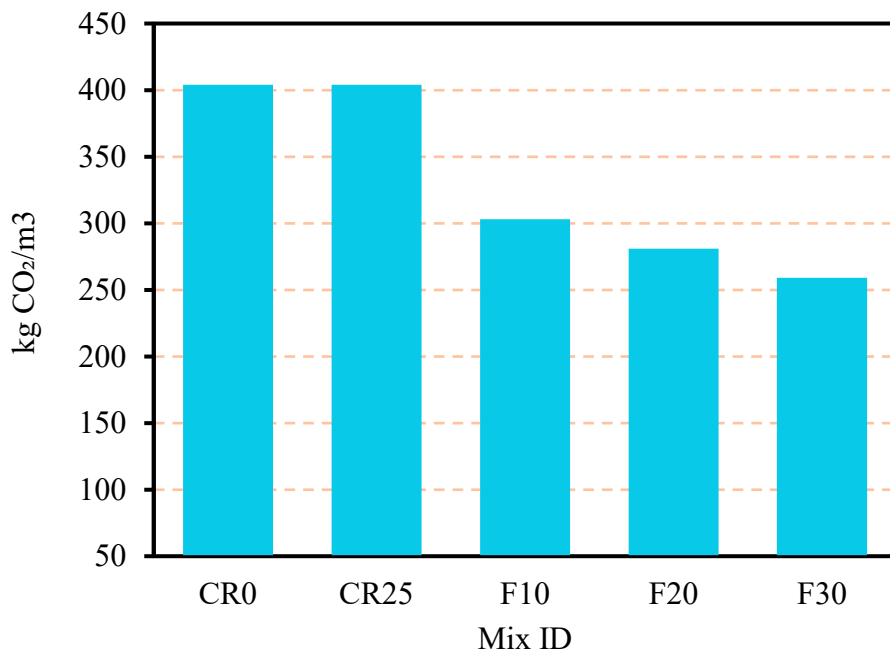
**Fig. 7.8:** Carbon emissions from Sima Pro (baseline case).



**Fig. 7.9:** Carbon emissions from Sima Pro (Variable parameters for Grinding).

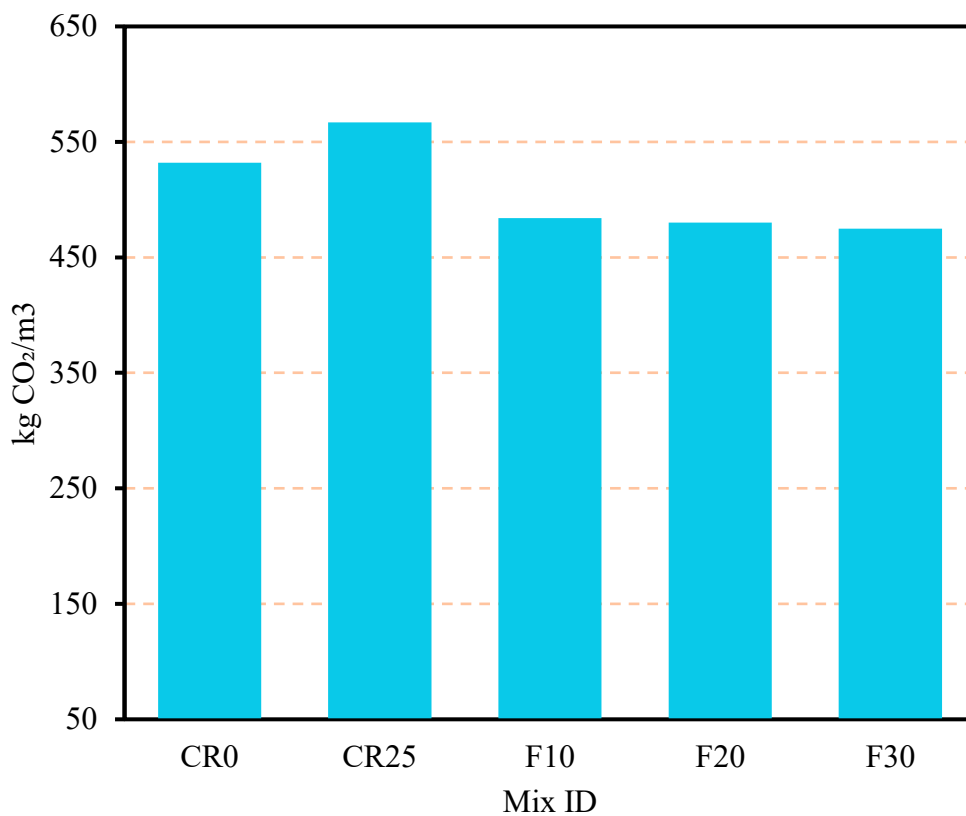
A comparison was established between different ball mills with variable capacities and the results of carbon emissions from software are presented in Fig. 7.9. In addition, the results were produced for use of high and low voltage electricity as per ball mill manufacturers specifications are shown. It can be seen that there is no significant difference between carbon emissions using these variables. The reason is that the power of high-capacity ball mills is significantly higher than lower capacity ball mills [121]. Also, high voltage electricity has higher efficiency (i-e lower losses) compared to low voltage electricity.

A grinding scenario was assumed based on the data available from a recognized mining equipment provider’s website (Metso). The specifications assumed are based on the lowest industrial model available with a capacity of over 200 kg, and power around 2.2 kW. The carbon emissions using this ball mill for 1 hour to obtain the required size of the ground FBA was considered. These emissions are presented in Fig. 7.10. It was observed that the use of an industrial ball mill further reduced the carbon emissions for the FBA concrete mixes. A high-capacity ball mill can produce higher amounts of ground FBA compared to laboratory ball mills. Conversely, the high-power slightly offsets the difference. Although the difference is minimal for 1 cubic metre of concrete, it could be pronounced when implemented at a larger scale.

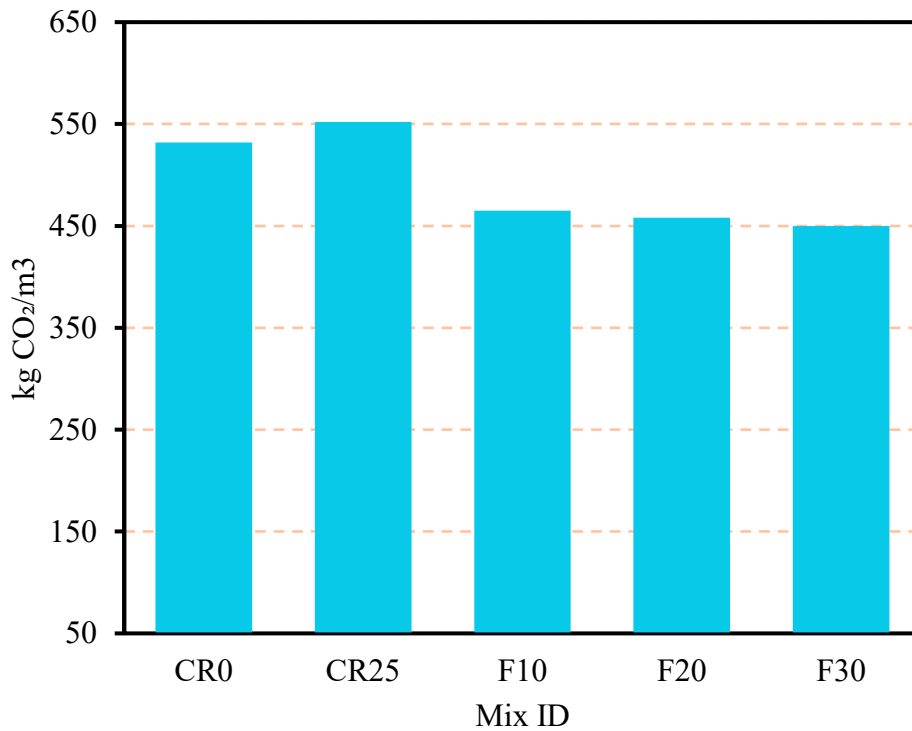


**Fig. 7.10:** Carbon emissions from Sima pro (using industrial scale grinding/ball mill parameters).

The transportation of raw materials from source to concrete batching plant is another significant factor for carbon emissions. The carbon emissions for transportation distances for each concrete mix are presented in Fig. 7.11. These show that the overall carbon emissions of concrete mixes with FBA are still lower than the control concrete, but distances increased the carbon emissions by around 60%, 71% and 83% for F10, F20 and F30 concrete mixes respectively. It is to be noted that existing transportation distances added 32% and 40% carbon emissions for CR0 and CR25 concrete mixes, respectively. Another hypothetical case study was conducted which includes similar distances for ground FBA as cement, and for raw FBA as fine sand. These results are presented in Fig. 7.12. The reduction in transportation distances (Table 7.4, Column 3) reduced 6% carbon emissions from FBA concrete mixes compared to the control concrete mix.



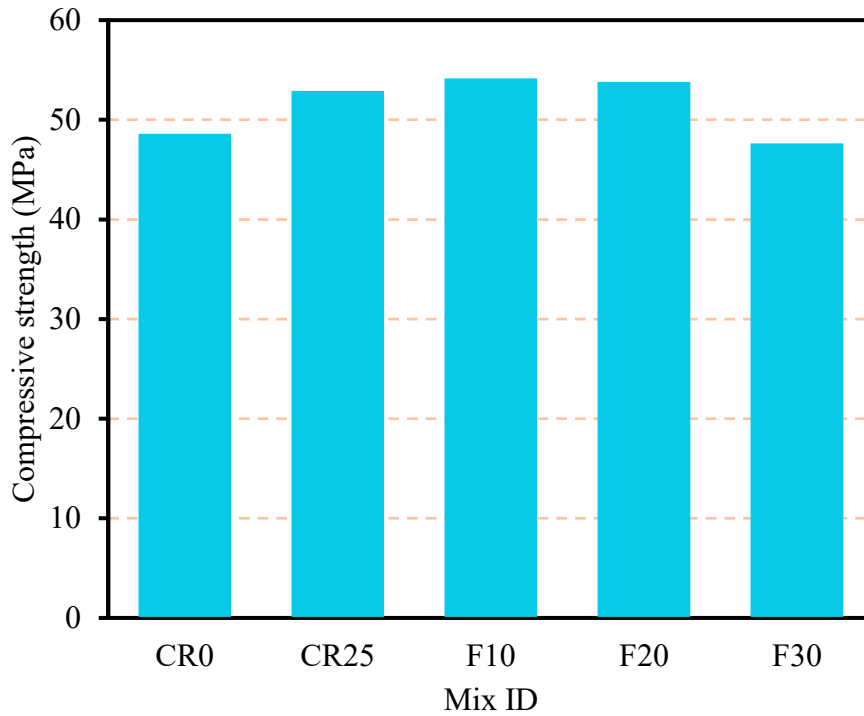
**Fig. 7.11:** Carbon emissions from Sima pro (using existing transportation distances).



**Fig. 7.12:** Carbon emissions from Sima pro (using similar transportation distances).

## 7.5 Discussion and Recommendations

The use of FBA as a supplementary cementitious material (SCM) and as a sand replacement reduced the carbon emissions, energy consumption, and cost of producing 1 cubic metre of concrete compared to control concrete. Carbon emissions were reduced by 23%, 26%, and 29% for concrete containing 10%, 20%, and 30% FBA, respectively. These reductions were consistent across both manual and software calculations. Using FBA as a 25% sand replacement did not affect carbon emissions according to software calculations but showed a 6% increase. This increase is likely due to the additional carbon emissions associated with the oven drying and sieving processes required for preparing FBA as a sand replacement. Similarly, although grinding FBA contributed noticeably to carbon emissions, these emissions were still lower than those from cement manufacturing. Moreover, using renewable energy sources such as wind or solar power for grinding could further reduce the carbon footprint of concrete containing FBA as an SCM.



**Fig. 7.13:** Compressive Strength of Concrete Mixes.

The compressive strengths of concrete mixes are presented in Fig. 7.13. The mix with 10% FBA as SCM and 25% FBA as sand replacement yielded the highest compressive strengths of around 54 MPa. This is 11% higher than the compressive strength of the control concrete. Thus, FBA concrete mixes with 10% FBA as SCM could yield higher compressive strengths and lower carbon emissions. In future, the processing of FBA at/near power stations or alternate FBA sources could further reduce carbon emissions especially for transport. The replacement of cement with industrial by-products always provides benefit in terms of carbon emissions and strength. Similar results were reported by Xing et al. [122] who noted that the replacement of cement imposed significant differences on the carbon footprint of concrete.

## 7.6 Summary

In this chapter, the LCAs of concrete without and with FBA have been presented. The scope of the LCA was to prepare raw materials to manufacture concrete at a batching plant. The functional unit for LCA was defined as 1 cubic metre of concrete. Two methods, manual and using specialist software, were adopted. The quantity of required materials was based on previous research within the scope of this project. The results showed that the replacement of cement with FBA significantly reduced carbon emissions and could be used for practical applications.

# CHAPTER 8: CHALLENGES AND FUTURE TRENDS

## 8.1 Introduction

This chapter explores the opportunities and challenges of using FBA as a sand or cement replacement in concrete. Utilizing FBA in concrete production offers significant financial and environmental benefits, such as reduced costs, lower carbon emissions, and better waste management. However, there are obstacles to its industrial-scale adoption, including the preparation of suitable FBA and the lack of standards and guidelines. This chapter discusses these opportunities and challenges in detail and outlines prospects for eco-friendly concrete manufacturing.

## 8.2 Opportunities and challenges

### 8.2.1 *Opportunities*

The use of FBA in concrete manufacturing holds significant potential to enhance sustainability and quality within the construction industry. The key benefits can be categorized into environmental, financial, and research innovation aspects, which are detailed below.

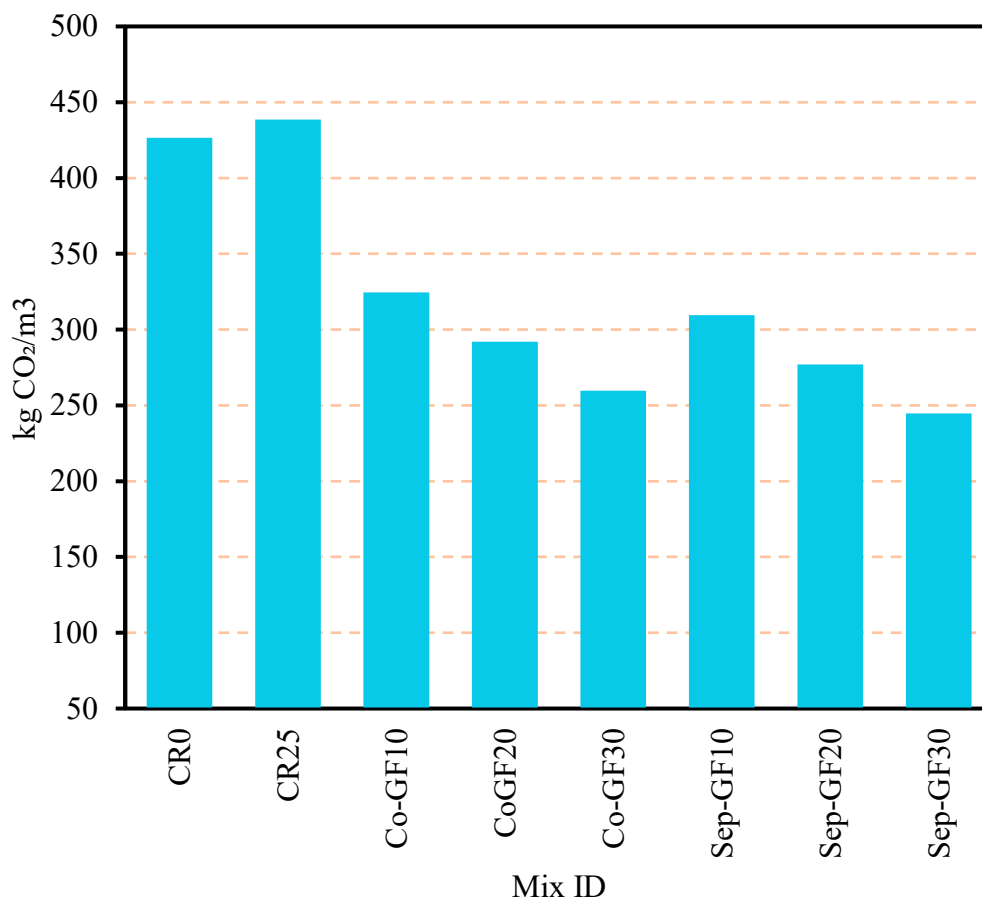
### 8.2.2 *Environmental Sustainability*

The use of FBA has significant potential to reduce the reliance on virgin resources and minimize landfill waste. Replacing natural sand with recycled materials, such as FBA, offers key environmental benefits, including the conservation of natural resources and more efficient landfill management. The impact of this substitution becomes even more pronounced when both aggregates and cement are replaced with FBA or other recycled products. According to Navaratnam et al. [15], FBA demonstrates superior environmental feasibility by mitigating the depletion of natural resources. Incorporating recycled industrial products like FBA into concrete production supports circular economy initiatives by transforming industrial waste into valuable materials [123]. This approach not only reduces resource consumption but also enhances the sustainability of the construction industry, ensuring a more resource-efficient economy in the long term.

#### 8.2.2.1 *Decarbonisation and Climate Goals*

The use of FBA could play a crucial role in decarbonizing the construction sector. Several studies [18,124–126] have reported that replacing 10-30% of cement with supplementary cementitious materials (SCM) could reduce 8-20 % embodied carbon for one

cubic metre of concrete. Similarly, replacing 25-50% natural sand with recycled aggregates could reduce 10-60% carbon emissions [127–129]. A few studies [16,17,130,131] have reported similar findings related to the use of FBA as SCM, stating that 20-40% replacement of cement with FBA could reduce up to 36% of carbon emissions. This could significantly reduce the carbon emissions from construction materials and for infrastructure projects. In this project, the FBA replaced 25% of natural sand and 10% of cement without compromising on the properties of concrete. This replacement reduced the embodied carbon emissions up to 30% compared to control concrete as calculated in DEL-110 [132] of this project, also presented in Fig. 8.1 below:



**Fig. 8.1:** Carbon emissions.

#### 8.2.2.2 Performance Advantage

The use of FBA as a SCM in a blend containing three materials enhance both the pozzolanic reactivity and the physical properties of concrete, resulting in improved overall performance [133]. Jaturapitakkul et al. [54] reported enhanced compressive strength at a later age using ground FBA as SCM. Fediuk et al. [134] replaced 45% of cement with FBA and

used basalt fibres to enhance the properties of concrete and reported significant improvements in mechanical properties. Bang et al.[135] prepared engineered cementitious composites using FBA as fine aggregate replacement and recorded relatively higher tensile strengths compared to control concrete. Singh et al.[29] summarized several research studies related to the use of FBA in cementitious composites and concluded that FBA has significant potential to be utilized in construction sector.

#### 8.2.2.3 *Economic Efficiency*

The use of FBA as sand and/or cement replacement could lower the cost of concrete compared to conventional concrete. Abdulmatin et al. [19] reported that the use of FBA as SCM could potentially reduce costs by 15 USD/m<sup>3</sup> for concrete production. Similarly, Chowdhury et al. [137] concluded there were significant reductions in cost when FBA was used as sand in concrete. The major reasons of cost reduction include avoiding the costs associated with landfill and land management of ash ponds. FBA concrete has better sustainability ratings as it aligns with United Nations sustainability goals especially 9, 12 and 13 [11]. This would further attract government funding opportunities to encourage the use of FBA in the manufacturing of eco-friendly concrete. The government's sustainability and climate change goals associated with the use of recycled materials would help to establish modern methods and technologies to incorporate the use of FBA in the construction sector [138]. Furthermore, the use of recycled materials like FBA would increase the demand for sustainable construction materials for residential, commercial, and infrastructure projects and would also provide better green star ratings of NABERS and / or other associated organizations [139]. This also has the potential to create jobs at national and international levels.

#### 8.2.2.4 *Resource Optimization*

The use of FBA in concrete production offers a practical solution to the challenge of coal ash disposal, while simultaneously promoting the conservation of natural resources. By replacing a portion of cement with FBA, this approach helps reduce the carbon dioxide emissions associated with cement production, contributing to a more sustainable and eco-friendly construction industry [131]. Additionally, it supports the recycling of industrial waste and reduces the requirement for the new extraction sites of construction materials.

### **8.2.3 Possibilities in Australia**

In Australia, significant amount of FBA exists and more will be generated prior to the closure of coal fired power plants. Various government and private organizations are working

to promote the circular economy and taking steps to inform the construction sector about various opportunities of using low carbon concrete. A few notable initiatives are listed below:

#### 8.2.3.1 *Environmentally Sustainable Procurement (ESP) Policy*

The Australian Government's ESP Policy leverages procurement practices to activate circular markets, reduce waste, and ensure materials remain in the economy longer. This policy encourages the use of recycled materials, including those in construction, to minimize environmental impact [140].

#### 8.2.3.2 *ReMade in Australia Scheme*

This initiative aims to increase the use and production of recycled materials within Australia. By certifying products with a recognizable logo, the scheme helps consumers identify products made with recycled content, promoting sustainable choices in the market [141].

#### 8.2.3.3 *Circular Economy Initiatives*

The Australian Government has introduced a Circular Economy Framework to boost the reuse, repair, and recycling of materials, thereby reducing waste and environmental impact. This framework supports the construction industry in adopting recycled materials, such as concrete aggregates, to promote sustainability.

#### 8.2.3.4 *Net Zero Emissions by 2050*

Australia's commitment to achieving net-zero emissions by 2050 includes strategies to decarbonize various sectors, including construction. Research into low-emission technologies, such as carbon capture, utilization, and storage (CCUS), is being explored to reduce emissions from cement and lime industries [142].

#### 8.2.3.5 *Industry Ambitions*

The Cement Concrete & Aggregates Australia (CCAA) has set an ambition to deliver net-zero carbon concrete by 2050. This initiative aligns with national climate goals and encourages the adoption of recycled materials and low-carbon technologies in concrete production [143].

These policies and initiatives collectively demonstrate the Australian government's intention to promoting sustainability and addressing climate change using recycled materials in concrete and other construction practices.

## 8.2.4 Challenges

The effective use of FBA faces several challenges for widespread adoption in the construction sector. Some major challenges have been highlighted in this report.

### 8.2.4.1 Technical

The physical and chemical properties of FBA vary depending on the type of coal used, burning temperature and collection methods. This variability could drastically affect the performance of concrete especially for long term durability. In addition, FBA reclaimed from ash dams may also differ in composition from to freshly produced FBA obtained directly from coal power stations. Anthracite coal has the highest carbon content (86-97%), followed by bituminous coal (40-80%). The specifications for coal grades are provided by ASTM. Differences in coal types result in variations in alumina, silica, loss on ignition, and ferric oxide levels in FBA [144]. The main components of FBA are SiO<sub>2</sub> (27–82 %), Al<sub>2</sub>O<sub>3</sub> (2–32 %), and Fe<sub>2</sub>O<sub>3</sub> (4–25 %). FBA also contains various other oxides, such as Na<sub>2</sub>O (0.05–7.78 %), SO<sub>3</sub> ≤3 %, MgO < 2%, K<sub>2</sub>O (0.34–5.34 %), Mn<sub>2</sub>O<sub>3</sub> (0.06–1.27 %), TiO<sub>2</sub> (0.3–6.57), and P<sub>2</sub>O<sub>5</sub> (0.07–1.27 %) [11]. The chemical compositions for FBA from different sources in Australia are presented in Table 8.1.

The chemical composition of coal used in different industries is influenced by their geological formations. In such circumstances, guidelines could be established based on the chemical compositions of FBA sourced from different batches. Another characteristic of FBA which could be problematic could be the higher water absorption tendency of FBA. Several research studies [67,144,145] have reported higher water absorption of raw FBA or concrete specimens made with FBA. This could be addressed by using additives, appropriate mix design considerations and choice of aggregates. Furthermore, many studies [146–148] have reported that the replacement of cement with FBA reduces compressive strength. This could be mitigated by blending FBA with other effective pozzolanic SCM's to overcome the reduction in compressive strength [1].

**Table 6.1:** Chemical Composition of FBA through XRF Analysis.

| <b>Composition</b>   | <b>Vales point (NSW) [149]</b> | <b>Eraring (NSW) [149]</b> | <b>Port Augusta (SA) [150]</b> | <b>Tarong (QLD) [150]</b> |
|--|--------------------------------|----------------------------|--------------------------------|---------------------------|
| Silica (SiO <sub>2</sub> )   | 62.37                          | 62.4                       | 54.0                           | 70.55                     |
| Alumina (Al <sub>2</sub> O <sub>3</sub> )  | 15.10                          | 19.9                       | 25.0                           | 26.00                     |
| Iron Oxide (Fe <sub>2</sub> O <sub>3</sub> )                                       | 9.30                           | 8.93                       | 4.0                            | 0.63                      |
| SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> | 86.77                          | 91.23                      | 81.0                           | 97.18                     |
| Lime (CaO)   | 1.97                           | 2.4                        | 5.0                            | 0.22                      |
| Potassium Oxide (K <sub>2</sub> O)   | 1.45                           | 1.26                       | 1.0                            | 0.22                      |
| Titanium Oxide (TiO <sub>2</sub> )   | 0.58                           | 0.82                       | 2.0                            | 1.43                      |
| Sulphur Trioxide (SO <sub>3</sub> )  | 0.17                           | 0.03                       | 0.0                            | 0.07                      |
| Chloride (Cl)  | 0.10                           | 0.01                       | -                              | -                         |
| Loss on ignition (LOI)   | 5.61                           | 0.98                       | 2.0                            | 1.44                      |

#### 8.2.4.2 *Regulatorions and Standards*

The major obstacle in the national or industrial adoption of FBA in concrete is that of assuring quality and ensuring products meet Australian building codes, standards, and certifications [151]. This obstacle could be overcome by systematic research with stakeholders from government and the construction sector. Thorough guidelines based on research are required to develop standards and specifications. In addition, training and guidance of staff is required to ensure the quality of FBA to be used to manufacture eco-friendly concrete.

#### 8.2.4.3 *Economic*

The use of FBA in concrete requires pre-treatment before incorporation in concrete or cement composites. These treatments mostly involve drying, sieving and grinding of FBA to required particle sizes [11,16]. The grinding of FBA prior to use as a replacement of cement increases the compressive strength of mortar mixes [54]. Khan et al. [152] reported that ground FBA showed improved resistance against acid and sulphate attacks. Capital investment is needed to encourage the preparation and use of FBA on a national or mass scale. Such preparation is needed to ensure uniform quality and properties. Preparation facilities could be established at/or near power plants where FBA could be obtained directly from power plants or ash dams. After preparation, storage presents additional challenges. FBA is prone to rates of high water absorption so the prepared FBA must be stored to prevent this occurring. In addition, the successful transition of FBA as a research topic to industry applications requires awareness campaigns to ensure that stakeholders understand its benefits and implementation strategies. This could be achieved by arranging workshops and seminars targeting stakeholders from the construction sector.

#### 8.2.4.4 *Logistics*

Another challenge limiting the use of FBA in the construction sector is that of the availability of the material as well as supply chain issues. This challenge could be easily overcome by partnering with local suppliers of FBA/coal power plants. For instance, the Hunter region of New South Wales, Australia could source FBA from Vales Point Power Station and from Eraring Power Station. The current available quantities of FBA and the future supply could be easily predicted by involving local suppliers and to support industry collaborations. In addition, the storage and handling of FBA which would be a market-ready product would also be a significant consideration. Standard procedures could be established at the processing facilities especially for ground FBA to avoid water absorption and human health issues.

#### 8.2.4.5 *Market and Stakeholders' acceptance*

Market acceptance would only be possible through collaboration with all stakeholders, including research representatives, FBA suppliers, FBA processors, concrete manufacturers, concrete consumers and regulatory authorities. Educational campaigns and real-world examples of the application of FBA as sand and as SCM in concrete would help develop the confidence of manufacturers and consumers. In addition, the presence of regulatory authorities like TfNSW would boost acceptance of FBA products in the market. In this regard, the NSW Government has taken the initiative to allow the use of low emissions products [153]. Furthermore, the implementation of legislation is underway to provide carbon emissions certifications for procured materials.

### **8.3 Summary**

This chapter has highlighted both the promise and the challenges of using FBA in concrete. FBA offers many benefits, including reduced use of natural resources, lower carbon emissions, and improved waste management. When used correctly, it can also enhance the performance of concrete and lower construction costs. These advantages support Australia's broader goals for sustainability and a circular economy.

However, the use of FBA also presents several challenges. Its properties can vary depending on how and where it is produced, which may affect concrete performance. The lack of specific standards, guidelines, and quality-control processes also limits its wider adoption. Economic factors, such as processing and storage needs, along with supply chain and market acceptance issues, further slow progress.

Despite these obstacles, ongoing research, industry collaboration, and strong government initiatives show that FBA has significant potential as a sustainable construction material. With appropriate standards, education, and investment, FBA can play an important role in creating low-carbon, resource-efficient concrete for future infrastructure.

# CHAPTER 9: REGULATORY FRAMEWORK AND APPLICABLE STANDARDS

## 9.1 Introduction

This chapter examines the key issues that influence the wider use of FBA in concrete, with a particular focus on standardisation, regulations, and sustainability. Although FBA has strong potential as a recycled material, its adoption depends on meeting strict technical requirements, complying with Australian standards, and ensuring consistent performance. This chapter examines the regulatory, standardisation, and sustainability considerations that govern the use of furnace bottom ash (FBA) in concrete. It first evaluates the applicability of existing Australian and international standards for FBA as a pozzolanic material and as a fine aggregate. The chapter then reviews hazard classification frameworks, leaching criteria, and end-of-waste pathways that determine whether FBA can be legally supplied as a construction material. Following this regulatory and technical assessment, the chapter analyses sustainability aspects, including economic implications, life-cycle assessment findings, carbon-footprint reductions, and broader environmental trade-offs. Together, these elements provide a comprehensive framework for assessing whether FBA can be safely, legally, and sustainably integrated into concrete production..

## 9.2 Applicable Standards for use as pozzolanic materials in concrete

In international practice, pozzolanic materials, especially FA, are regulated under ASTM C618 in the United States [154] and AS/NZS 3582.1:2016 in Australia and New Zealand [155]. These standards specify limits on loss on ignition, fineness, pozzolanic oxide content and calcium content to ensure durability and long-term performance. A recent study on ground FBA noted that the sum of the primary pozzolanic oxides  $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$  in FBA exceeds 70 wt%, reaching about 86.7 wt% [1,11]. The same study measured only 2.40 wt% CaO in the ground FBA, well below the 5 wt% limit imposed by ASTM C618 and the 10 wt% limit prescribed by AS/NZS 3582.1 [1].

These data (shown in Table 9.1) confirm that ground FBA behaves as a low-calcium Type F pozzolan and can satisfy the chemical requirements of both American and Australasian fly-ash standards when properly processed [19]. Fineness is equally important; the examined

material achieved 100% passing the 45  $\mu\text{m}$  sieve, exceeding the minimum 85% fineness requirement for special-grade pozzolans. Comparable results have been reported in this project, where the ground FBA exhibited a loss on ignition of about 3.7%, sulphate content below 1% and strength index higher than 75% [11]. However, there is still some concern about chloride content, where some samples showed higher than the maximum limit allowed in AS/NZS 3582.1 (Table 9.1). Collectively these values suggest that properly classified and milled FBA can meet the chemical criteria defined in ASTM C618 and AS/NZS 3582.1 [11].

**Table 9.1:** Compatibility of FBA properties with FA limits in AS/NZS 3582.1 standards.

| Criteria  | Special Grade          | Grade 1                 | Grade 2                      | From literature               | From this study |
|---|------------------------|-------------------------|------------------------------|-------------------------------|-----------------|
| Fineness (min. % passing 45 $\mu\text{m}$ sieve)                              | 75%                    | 55%                     | 85%                          | Various but can be controlled |                 |
| Loss on Ignition (LOI, max. %)  | 4.0%                   | 6.0%                    | 3.0%                         | 3.70                          | 4.802           |
| Moisture Content (max. %)   | 0.5%                   | 0.5%                    | 0.5%                         | 0.35 – 0.5                    | /               |
| Sulfate (as $\text{SO}_3$ ) (max. %)  | 3.0%                   | 3.0%                    | 3.0%                         | 0.79                          | 0.116           |
| Chloride Ion (max. %)   | 0.10%                  | 0.10%                   | 0.10%                        | /                             | 0.26            |
| Strength Index (min. % of control mortar)                                     | $\geq 75\%$ (required) | $\geq 105\%$ (required) | — (no requirement specified) | 85 – 102                      | 116 – 83.9      |
| Minimum Sum of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ | $\geq 70\%$            | $\geq 70\%$             | $\geq 70\%$                  | 82.47                         | 87.23           |

### 9.2.1 *Physical and mechanical criteria*

Standards also define performance tests that assess how FBA will behave in concrete mixes. For example, Australian Standard AS 1012.20 requires that chloride content in aggregates be below 0.03–0.04% to prevent corrosion of reinforcement, while AS 1141.66 limits the deleterious fines index to a maximum of 150 for manufactured aggregates. Table 9.1 shows that the FBA sourced in this project easily meets these limits. Additionally, the material must satisfy soundness, abrasion, and flakiness requirements under AS 2758.1 [112]. Water absorption is particularly critical because FBA is more porous than natural sand; the maximum water absorption allowed for fine aggregates is generally around 2%, whereas lightweight or vesicular aggregates may exhibit higher values [97]. Since raw FBA typically absorbs over 10 % water, pre-drying and sieving are mandatory to deliver a market-ready product [156]. Grinding or pretreating the ash not only reduces its particle size but also fills internal pores,

substantially lowering water absorption and improving workability [157]. Once these physical requirements are met, the strength index (activity index) of FBA-blended mortars should exceed 75% for ordinary grade and 105% for special grade; this project observed strength indices between 83% and 116%, surpassing the minimum thresholds [158].

### 9.3 Applicable standards for use as aggregate in concrete

Table 9.2 summarizes the minimum performance requirements that FBA materials must meet to satisfy Australian aggregate specifications. Meeting these criteria is essential because the physical and chemical properties of FBA can vary widely depending on coal source, combustion temperature, and handling [159]. Therefore, the FBA should meet AS 1141, AS 2758.1 and AS 1012 before being used as fine aggregate to control deleterious fines, flakiness, abrasion, water absorption and other properties before the material can be used in concrete. Without this level of quality control, the large pore structure and variable composition of raw FBA can lead to high water demand and inconsistent strength development in concrete [160].

**Table 9.2:** General requirements according to Australian standards.

| Required test                        | Method  | Limits   |
|--------------------------------------|---|--|
| <b>Chloride content</b>              | AS 1012.20.1 or AS 1012.20.2  | Cl content exceeding 0.04% shall not be used in reinforced concrete. Cl content exceeding 0.15% shall not be used in plain concrete. Total water-soluble chloride salt content < 0.03%     |
| <b>Degradation factor (Abrasion)</b> | AS 1141.25.3  | Shall not be less than 60 for all concrete exposure classifications. There are no specific procedures in AS specification  |
| <b>Deleterious fines index (DFI)</b> | AS 1141.66 / AS 1141.11 (Finer than 0.075 mm and washed grading) / AS 1141.12 (finer than 0.075 mm) | The DFI of any manufactured aggregate sample shall not exceed 150. It is allowable to use specific types of aggregates with DFI up to 200, but in specific applications and low additions. |
| <b>Flakiness index</b>               | AS 2758.1   | ≤ 35 %   |
| <b>Light particles</b>               | AS 2758.1   | ≤ 1% (fine) ≤ 3% for vesicular aggregates  |
| <b>Los Angeles value</b>             | AS 2758.1   | Maximum percent loss is 35% and 30% for concrete exposure Class A and B, and C, respectively   |
| <b>Material finer than 2 μm</b>      | AS 2758.1   | ≤ 1%   |
| <b>Material finer than 75 μm</b>     | AS 2758.1   | Coarse: ≤ 2% Fine: ≤ 20%   |

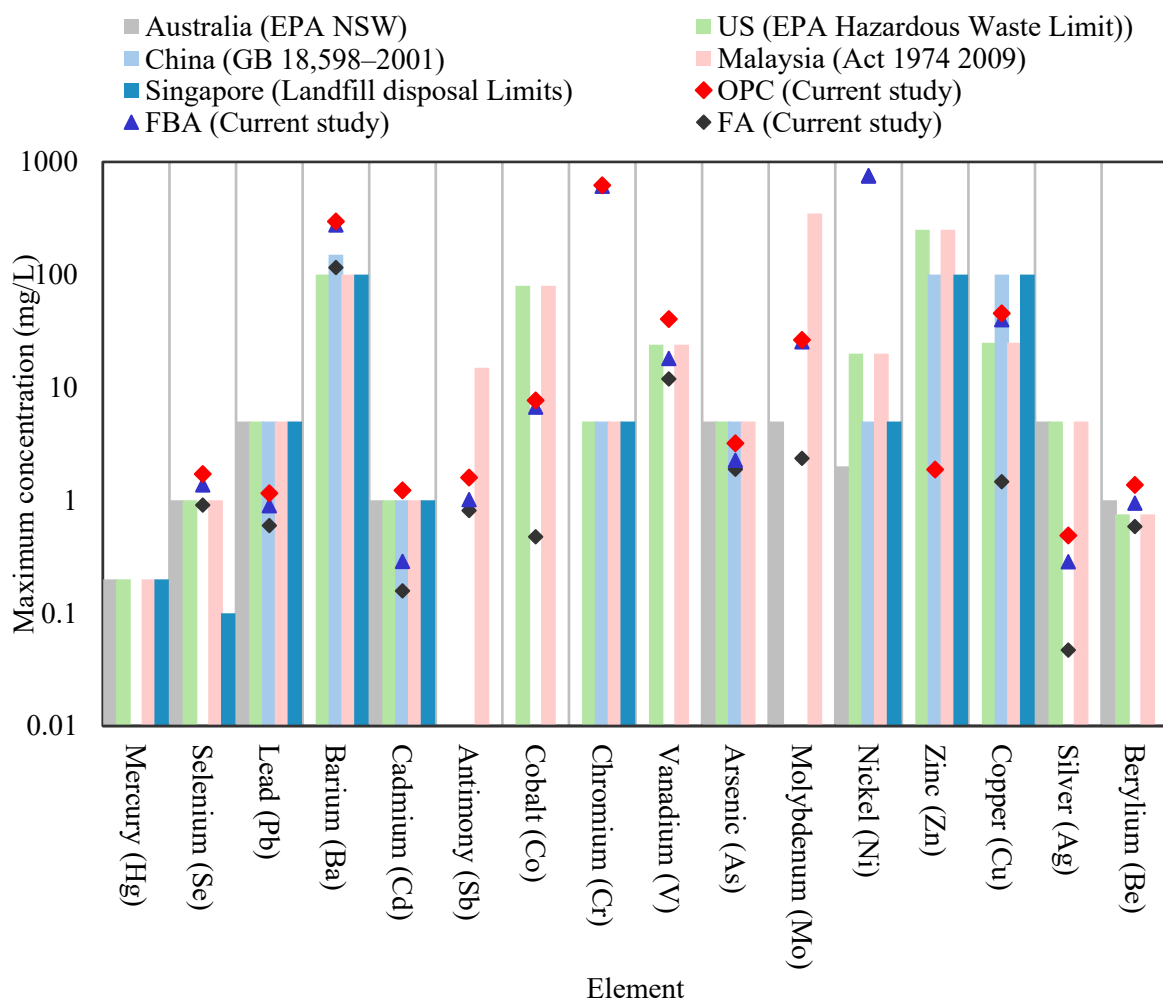
|                           |                                     |  |
|---------------------------|-------------------------------------|--|
| <b>Organic Impurities</b> | AS 1141.34                          | The colour obtained shall not be darker than the standard colour of the reference solution   |
| <b>Particle density</b>   | AS 1141.5, AS 1141.6.1              | Heavy weight > 3.2 t/m <sup>3</sup> , 3.2 t/m <sup>3</sup> > Normal weight > 2.1 t/m <sup>3</sup> , 2.1 t/m <sup>3</sup> > Light weight > 0.5 t/m <sup>3</sup> , Ultra-Light weight < 0.5 t/m <sup>3</sup> |
| <b>Soundness</b>          | AS 2758.1                           | 6% (Exposure class C)  |
| <b>Sulfates</b>           | AS 1012.20.1                        | Sulphate content of concrete mix ≤ 5% by mass of Portland cement   |
| <b>Water absorption</b>   | AS 1141.5, AS 1141.61 / AS 1141.6.2 | The avg of WA of natural aggregates is about 2%, while WA of light weight, vesicular or recycled aggregate can exceed 2 %  |

## 9.4 Hazard assessments

To date, there is no agreement on whether FBA should be classified as a hazardous substance or not. In the United States of America, the Environmental Protection Agency (EPA) classified coal ash as a nonhazardous waste under Subtitle D of the Resource Conservation and Recovery Act [74,161]. Similar to the USA, other countries such as China do not classified FBA as hazardous waste [10]. On the other hand, large concentrations of toxic metals such as Ni (175.3 mg/L) and Cr (24.25 mg/L) released from FBA, makes it fall within the hazardous waste limits according to the European Union limitations (Council Decision 2003/33/EC) [162]. Similarly, for Malaysian regulations, Hashemi et al [163] noted that the Cd, Cu, Ni and Pb concentrations in FBA exceeded the limits allowed in the Malaysian Environmental Standard, while other elements were below the toxic limit concentrations. Fig.9.1 shows the trace element concentration leached from FBA compared to the maximum limits allowed in the relevant standards for solid waste in Australia, US, China, Malaysia and Singapore standard limitations. For this study, GFBA exhibited measurable concentrations of Mn, Zn, Cr, Fe, Co, Cu, Mo, Ag, Sn, and Ba, with some elements having lower concentrations than those found in FA or OPC, or both. When comparing concentrations with the regulatory upper limits shown in Fig. 9.1, it is evident that GFBA surpasses the allowable limits for Ba, Se, Cr, and Ni. This issue is not confined to GFBA alone; certain trace elements in FA and OPC also exceeded the permissible limits. For instance, OPC exhibited concentrations of Si, Ba, Cr, and V that were higher than the allowed limits.

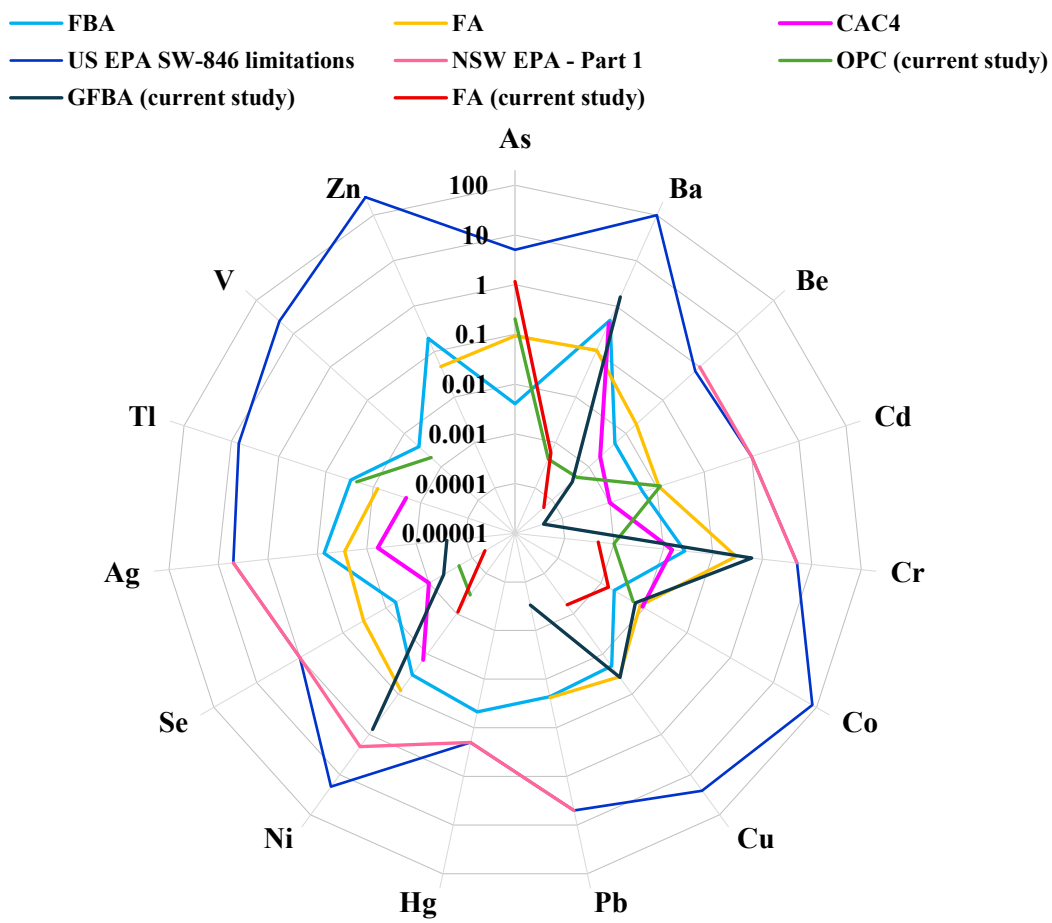
Based on literature and except for the Hg concentration noted in Wang et al.'s study [164], the concentrations of leached trace elements from FBA waste appear to be lower than the maximum limits in the relevant standards. Accordingly, it can be claimed that FBA can be

classified as non-hazardous solid waste. Oversea studies, such as those by Sutcu et al. [72] and Eliche-Quesada et al.[73] have examined the leaching characteristics of FBA-based fired bricks. Their results showed that heavy metals were effectively immobilized within the brick matrix, and the leachate concentrations were well below the maximum allowable limits specified by the USEPA. These findings demonstrate that incorporating FBA into fired bricks can significantly reduce the mobility of heavy metals. This also implies that using FBA in concrete production may offer an environmentally beneficial pathway by further stabilising heavy metals. However, while these findings provide useful background context, differences in ash sources mean that these results are not directly comparable to Australian FBA.



**Fig. 9.1:** Trace elements concentration from FBA leachate and the maximum limits allowed in the relevant standards/regulations to classify solid waste as non-hazardous waste. The raw data were collected from [74,163–169]. The maximum allowable limits for Australia [75], US [76,77], China [78], Malaysia [79] and Singapore [80,81].

Likewise, Fig. 9.2 compares the trace elements leaching from FBA, FA, OPC, and crushed concrete containing 20% FA as cement replacement and 100% FBA as sand replacement (Labeled as CAC4) compared to US EPA's SW-846 and NSW EPA- Part 1 regulation limits for classification of solid waste hazard. All of the leached concentrations are far lower than required by the US EPA's SW-846 and NSW EPA- Part 1 standard limits. The leaching of heavy metals from concrete containing 100 % FBA as sand replacement was minimal and may be ignored. From the above it can be concluded that the inclusion of coal ash as either FBA or FA in concrete composites reduced the leached heavy metals concentration remarkably compared with raw FBA and FA.



**Fig.9.2:** Trace element concentration in leachate of FBA, FA and concrete made with 100% FBA as sand replacement in (mg/l, mg/kg). Raw data were obtained from [74] and current study.

## 9.5 End-of-waste and Australian product standards

Beyond chemical and mechanical testing, regulators must determine when a by-product such as FBA ceases to be classified as waste. In Australia, several states have developed regulatory instruments such as Resource Recovery Orders and Exemptions (NSW), End-of-Waste Codes (QLD), Environment Protection Act (2017)/ Regulations (2021) (VIC) and mass balance-based resource recovery frameworks (SA) that provide practical pathways towards this determination [170]. These mechanisms typically state that materials may no longer be considered waste if they comply with approved product standards and documented factory production controls. For bound applications, these include AS 2758.1 for aggregates in concrete, AS 2758.2 for aggregates in bituminous surfacing, AS 2758.5 for pavement aggregates, AS 3582.1 for fly ash in concrete, and AS 3972 for general purpose and blended cements. Compliance with the associated AS 1141 test methods is also required to demonstrate conformity with specification limits. When FBA is processed to meet these Australian product standards and supported by documented quality assurance systems, the material may be supplied as a secondary raw material without being subject to further waste regulations under the relevant state scheme. Such end-of-waste-style rulings are significant because they provide legal certainty for suppliers and users and encourage investment in production facilities capable of delivering consistent, standards-compliant FBA [171].

## **9.6 Toward FBA-specific standardization**

Despite meeting many chemical and physical requirements, FBA is not yet explicitly covered by existing cement and aggregate standards. Most codes treat the material by analogy with fly ash or generic manufactured sands, leaving gaps for issues such as higher water absorption, variable carbon content, and delayed strength gain [172]. To facilitate broader adoption, industry and regulators need to develop FBA-specific grading classes, maximum moisture levels, and performance benchmarks. Collaboration among power station operators, materials processors, researchers, and government agencies is essential to establish consistent sampling, processing, and testing protocols. Recent Australian initiatives, such as the Environmentally Sustainable Procurement Policy, the Re-Made in Australia scheme and commitments to net-zero emissions, provide a supportive policy environment for incorporating more recycled materials in infrastructure projects. However, market confidence will only grow when clear standards exist, staff are trained in quality assurance, and end users have access to transparent data on FBA properties and performance [173].

## **9.7 Sustainability assessment and carbon footprint implications**

Sustainability is a critical lens through which the viability of furnace bottom ash in concrete must be assessed. Any substitution of Portland cement or natural aggregates should demonstrably reduce greenhouse-gas emissions, conserve raw materials and avoid transferring environmental burdens elsewhere. This section therefore synthesises life-cycle assessments (LCAs), carbon-footprint analyses and broader sustainability considerations for FBA-containing concretes [174].

### **9.7.1 *Economic benefits***

At first glance, it may seem that the expenses of reclaiming, treating, and recycling wastes, including FBA, are more costly than direct disposal strategies. However, the long-term consequences such as adverse effects on health, quality of life, and loss of green lands outweigh the financial losses incurred in treating, and recycling [175]. A case study on the cost estimate of coal ash disposal in the Paiton power plant in Indonesia has been carried out, and the total costs that incorporate land cost procurement, civil construction and auxiliary equipment, handling, treatment, and recycling process, as well as the social lost are estimated to be almost Rp 11 billion (equivalent to ~USD 800 000) per annum [175,176]. Similar reasons related to the high cost of waste disposal were reported by Kim and Lee [177].

From an economic standpoint, power plants incur substantial costs to handle and manage coal waste, often without achieving meaningful economic returns [175,178]. Therefore, recycling this waste material into value-added products is advantageous and cost-effective, as it can increase company revenue while reducing handling and disposal expenses [179]. Some reports indicate that in high-income nations, the cost of integrated waste management, including collection, transportation, treatment, and disposal, generally exceeds USD 100 per tonne [180,181], with some systems in Europe and North America reaching USD 150–200 per tonne or more for municipal solid waste services. In contrast, low-income nations often operate with much lower expenditures, in the order of USD 20–50 per tonne, reflecting less formal collection and disposal infrastructure, while rough global averages sometimes cited in literature sit near USD 70 per tonne [182,183]. Shipping/haulage alone for bulk wastes is frequently reported to range from approximately USD 20 to 50 per tonne [19,183,184]. In Australia, waste management costs reported by local councils and state regulators [185–187] reflect similarly high service expenses in developed systems: combined kerbside collection, treatment and landfill disposal fees in capital cities often range from AUD 150 to over 300 per tonne for general waste once landfill levies and gate fees are included, and hazardous or special waste streams (such as industrial by-products) can attract significantly higher costs under

contract. To date, FBA is still being discarded in landfills, and while transport costs alone may lie within the USD 20–50 per tonne range, the total disposal and management cost in Australia for industrial or bulk waste is typically higher when landfill levies, site management, monitoring, and regulatory compliance are taken into account.

Utilizing FBA in the construction industry is a viable solution for reducing those costs. However, certain treatment processes such as grinding, and oven-drying are required to adapt FBA as a construction material. Transportation costs as well as charges for grinding FBA to obtain the required fineness are among the costs concerned with FBA recycling. However, given that transportation costs are incurred while transferring all raw materials including sand and cement used to produce concrete as well, Bajare et al [16] argued that this cost factor is similar to the delivery of raw materials to the concrete plant.

Grinding is one of the most energy-intensive processes involved in preparing ash for use in concrete manufacture. Because the fineness of clinker and ash is comparable, the energy required to grind FBA to cement-level fineness is similar to that of cement grinding [16]. However, replacing cement with FBA in concrete production can still reduce overall material costs, despite the additional grinding and drying processes [19]. Abdulmatin et al [19] reported that using finely ground bottom ash as a cement replacement can reduce OPC consumption by approximately 60–80 kg/m<sup>3</sup> in typical concrete mixtures, leading to overall cost and CO<sub>2</sub> reductions, depending on local cement and processing costs. Therefore, the cost savings primarily arise from reduced clinker production rather than from aggregate substitution. Bajare et al [16] similarly found that concrete containing 20% FBA as a cement substitute achieved comparable mechanical performance while reducing production costs by approximately 9.3% compared with control concrete.

The environmental benefits come from the cost savings of cement and the savings associated with improving the quality of life, purchasing and reclamation land instead of wasting it in FBA waste dumps. Estimates of the indirect costs associated with environmental benefits may vary, but it is certain that these indirect cost benefits are as valuable and important as those related to reducing the cost of concrete production. The efficient use of energy is another crucial factor in building sustainability [113]. Huge amounts of energy are consumed annually in the process of air conditioning in residential, commercial, government and utility buildings. This increases the total amount of electricity consumed annually, which increases the cost of electricity for all residential and commercial and industrial sectors. According to

several research studies, buildings with lower thermal conductivity features can hold heat for longer periods of time, which reduces the amount of power used [113,188]. Zhang et al. [113] found that thermal conductivity decreased from 0.9 W/mK to less than 0.5 W/mK when 100% FBA was used instead of natural fine aggregates. This shows that FBA-based concrete can outperform normal aggregate concrete in terms of thermal insulation.

As FBA has a low unit weight and a high angle of shear strength, FBA-based walls required the least amount of reinforcement [20]. The lower unit weight results in lower dead load forces, leading to less reinforcing and ultimately a reduction of production costs. In addition, due to the lower nominal pricing of waste materials, it can be concluded that the cost of construction utilizing local soil as filler material is significantly higher than that of using FBA. These findings indicate that utilizing FBA as an alternative for local sand in Mechanically Stabilized Earth Wall (MSEW) can be cost-effective and efficient in reducing production costs. With its low density, low thermal conductivity values and improved thermal insulation properties, FBA can be considered a favorable building material for creating more energy-efficient buildings. Conversely, Singh et al [5] and Suaiaam et al [189] stated that using FBA either as cement or sand replacement can save construction costs as well as costs related to handling waste. Furthermore, FBA-based concrete has a lower density than ordinary concrete due to its low specific gravity. This results in lowering the structure's deadloads, thus saving a considerable portion of the reinforcement steel and foundation requirements.

### **9.7.2 *Carbon footprint of cement and the case for FBA***

Conventional concrete relies heavily on clinker-based Portland cement, the manufacture of which emits around 0.6–0.7 tonnes of CO<sub>2</sub> per tonne of cement and consumes about 1.5 tonnes of limestone [190]. These figures underline why the construction sector accounts for roughly 8 % of global anthropogenic CO<sub>2</sub> emissions [191]. The environmental rationale for incorporating FBA is twofold: as a supplementary cementitious material it can partially replace clinker, and as an aggregate it can reduce the demand for river sand and crushed rock. Because FBA is an industrial by-product generated by coal-fired power stations, using it in concrete diverts waste from landfill and leverages embodied energy that would otherwise be lost [192].

### **9.7.3 *Life-cycle assessments and environmental trade-offs***

Life-cycle assessments have examined how different design approaches influence the environmental impact of FBA-based concretes. One study compared mortars in which sand

was substituted with FBA at 0–100 wt % under two scenarios: maintaining a fixed slump versus maintaining a fixed water-to-cement ratio [193–195]. When a consistent slump was targeted, substituting sand with FBA lowered most impact indicators, including global warming potential and primary energy demand, because the ash replaced relatively high-impact river sand and improved workability without extra cement. By contrast, mixes designed with a constant water-to-cement ratio required additional water and superplasticiser to counteract the high absorption of FBA, and the environmental benefit was diminished or even reversed. These results emphasise that environmental gains depend not only on the replacement level but also on how mixtures are proportioned and what performance criteria are prioritised [196].

Another LCA focused on the integrated use of ground FBA as both a fine aggregate and a partial cement replacement. The researchers reported that the ash contained about 86.7 wt % pozzolanic oxides and only 2.40 wt % CaO; thus it behaved as a low-calcium pozzolan and enabled significant clinker substitution without compromising strength. Because the ground ash achieved 100 % passing a 45 µm sieve, it improved particle packing and reduced the need for additional cementitious binder. However, the high-water absorption ( $\approx 11\%$ ) relative to natural sand ( $\approx 1.2\%$ ) necessitated careful control of mix water. LCA modelling indicated that, when proper water adjustment and grinding energy were included, the net global warming potential remained lower than that of conventional concrete, but the margin narrowed at high replacement levels.

#### **9.7.4 *Resource conservation and circular economy benefits***

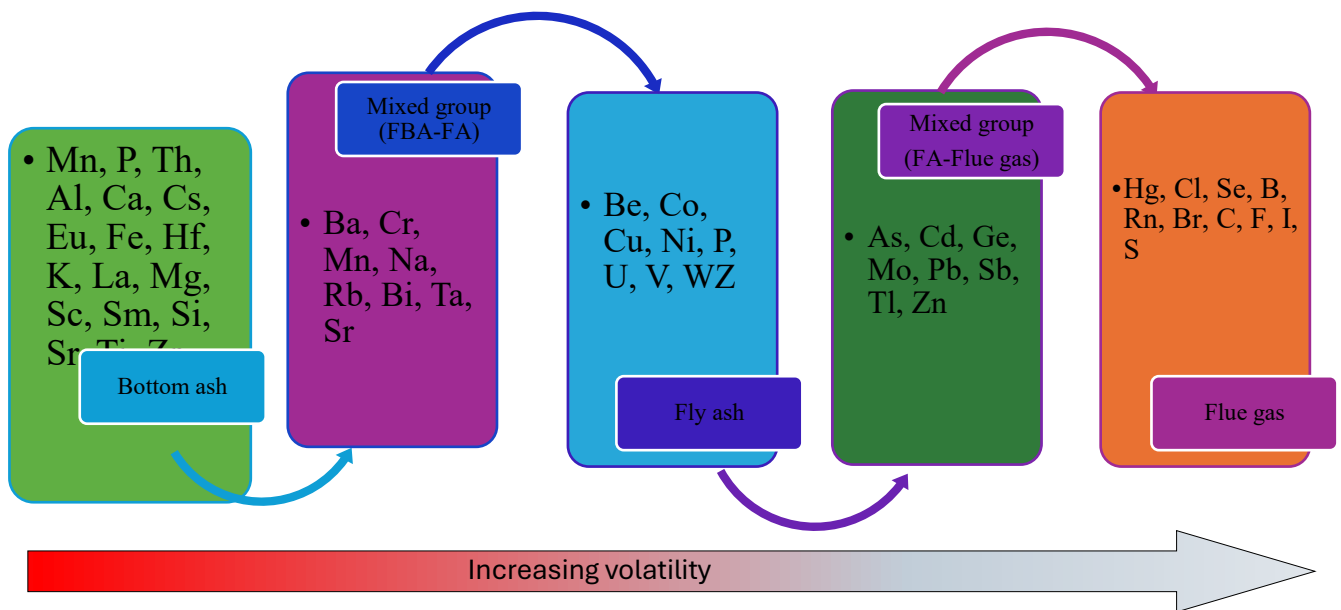
Using FBA as an aggregate or binder substitute reduces the extraction of virgin sand and limestone, both of which are finite and increasingly regulated. Sand mining has been linked to riverbank erosion, habitat destruction and depletion of aquifers; replacing even a fraction of the sand with FBA can ease pressure on these ecosystems. Similarly, by reducing clinker content, FBA mitigates the demand for raw materials and the energy-intensive calcination process. Such substitution aligns with circular-economy principles by turning a waste stream into a resource and closing material loops in the built environment [197]. It also supports national policies promoting recycled content in infrastructure projects and procurement frameworks that reward low-carbon materials [198].

#### **9.7.5 *Environmental safety and potential impacts***

FBA is a significant industrial waste product generated by coal-fired thermal power plants [177,199]. Due to the different characteristics of the discarded ash based on its source,

many studies of different regions have been conducted on their environmental impacts fr according to the relevant environmental criteria [200]. Currently, coal ashes are either stacked simply or placed in dumps or ponds [5,201]. However, these disposal techniques are not environmentally benign, if uncontrolled with no mitigation or regulation, due to the leachability, radioactivity and toxicity of coal ashes which would contaminate the soil, natural water sources and the atmosphere. Additionally, these methods of disposal deplete vast greenfield areas and distort environmental aesthetics [202,203].

The environmental impact of FBA is expected to be similar to that of fly ash (FA) due to both being from the same source and same firing furnace [204–206]. However, the risk intensity could vary due to the varying fineness of particles and combustion rate. For example, in the case of bottom ash, the concentrations of some trace elements, such as Cd, Cr, and Pb, were lower than those in FA [204]. Fig. 9.3 shows the relative volatility of elements of FBA and FA during coal combustion. As shown in Fig. 9.3, FBA has more refractory elements than FA. However, this is not always the case, as fly ash contains significant amounts of Al, Si, and Fe, while FBA has low levels of As, Hg, Pb, Cd, Cu, and Ni. Hower, et al. [207] suggest that production anomalies such as variations in boiler efficiency and combustion rates are the reasons for the relative variability of elements in FBA. A range of trace elements including Ba, Se, Cs and Zr are trapped within FBA, and consequently end up in ash dumps. Commonly, both fly and bottom ashes are disposed of in large uncovered ponds [29,55]. The large sizes of coal ash dumps makes them difficult to cover, which increases the risk of ash particles spreading further into the atmosphere.



**Fig. 9.3.** Distribution of elements among FBA, FA, and flue gas during coal incineration. Adapted with improvement from [207,208].

Recent studies have shown that transition metals such as copper and zinc, particularly when present in respirable particulate form (particles with aerodynamic diameter  $\leq 10 \mu\text{m}$ ), can contribute to oxidative stress and lung tissue injury following inhalation . [203,209]. Coal combustion residues, including FA FBA, contain trace concentrations of potentially toxic elements such as arsenic, chromium, cadmium, and lead, some of which are classified as human carcinogens depending on chemical speciation and exposure route [210,211]. However, the health risk associated with coal ash is strongly dependent on exposure pathways, particle mobility, and metal bioavailability rather than bulk elemental presence alone.. Metal release from ash matrices is governed by pH-dependent solubility and speciation. Coal ash and cementitious systems typically exhibit alkaline conditions (pH 9–12), which limit the mobility of many cationic metals (e.g., Pb, Cu, Zn) but may increase the leachability of oxyanion-forming elements such as arsenic under certain redox and pH conditions. Moreover, when FBA is incorporated into concrete or other bound applications, physical encapsulation and the high-pH cement matrix significantly reduce both particulate dispersion and leaching potential compared with unbound ash. Therefore, while coal ash contains some contaminants, risk arises primarily under scenarios involving poor dust control, long-term weathering, or inadequate containment. To mitigate airborne exposure, dust suppression practices such as surface moistening are commonly applied during storage and handling operations [212,213]..

It is important to note that the difference in the concentration of heavy metals in FA and FBA is significantly influenced by the type and origin of the coal used for combustion [214–216]. Most studies reported that FBA has a lower potential to leach trace elements than FA, due to its larger particle size and lower specific surface area [177,205]. Based on a leaching test conducted by Rafieizonooz et al. [74], the leaching of As, Be, Cd, Cr and Co in FBA was significantly lower than that in FA, whereas the concentrations of Cu and Pb were comparable in both FBA and FA, and the leachates of Ba, Hg, Ni, Se, Ag, Ti, V and Zn in FBA were higher than those in FA. Schneider et al [217] reported that the sedimentary records of spheroidal carbonaceous particles (SCPs) and the sediment metal concentrations from the Hunter and Latrobe Valleys both indicated that open-cut coal mining and the subsequent combustion of coal in power stations has most likely resulted in an increase in atmospheric deposition of metals in the local region. In particular, the metalloids As and Se showed greater concentrations compared to before coal mining commenced [217]. On other hand, across the Lake Macquarie investigations, surface sediments in the southern lake generally contained metals (including As and Se) at low bioavailable concentrations below sediment quality guideline values, toxicity tests showed minimal biological effects, and benthic community assessments did not indicate metal-driven ecosystem impairment [218–220]. Comparisons with 2011 data and newly deposited sediments indicate that metal concentrations in southern Lake Macquarie sediments have mostly decreased or remained stable over the past decade, with notable reductions in selenium, arsenic, and cadmium, suggesting no evidence of increasing recent atmospheric or ongoing inputs at a scale causing sediment quality deterioration [218,221,222].

In summary, the main environmental concern related to FBA lies in its uncontrolled storage and disposal rather than in its engineered use in construction. Although FBA contains trace elements that require monitoring, most studies show that its leaching potential is generally lower than or comparable to fly ash. When incorporated into concrete, metal mobility is significantly reduced due to physical encapsulation and the stabilizing effect of the alkaline cement matrix. When properly processed and used in bound applications, FBA should not be viewed as a hazardous material but as a manageable secondary resource. Using FBA in concrete reduces the risks associated with ash stockpiles and offers a safer and more sustainable alternative to long-term disposal.

#### **9.7.6 *Socio-economic implications and policy alignment***

Beyond environmental metrics, sustainability encompasses economic and social dimensions. Incorporating FBA into construction can lower material costs by reducing reliance

on premium sand and cement, although additional processing may partly offset these savings. Adoption also creates new markets for by-products, encourages innovation in waste management and supports jobs in the recycling sector. Policy instruments—such as carbon pricing, green procurement standards and incentives for low-carbon materials—could accelerate uptake by rewarding concrete suppliers who incorporate FBA and demonstrate life-cycle emission reductions. Conversely, inconsistent regulatory frameworks and lack of certified standards can inhibit adoption, highlighting the need for coordinated action among industry, government and research institutions [223].

### **9.7.7 *Balancing trade-offs and future directions***

Furnace bottom ash offers clear sustainability advantages when used judiciously in concrete. Its use can lower the carbon footprint of both cement and aggregate, divert waste from landfills and conserve natural resources. Life-cycle assessments reveal that environmental gains are maximised when mix designs are tailored to the material's high porosity and water demand and when processing energy is minimised. Heavy-metal leaching tests confirm that FBA does not pose significant environmental hazards, while its high aluminosilicate content allows it to meet the chemical requirements of cement standards. Future research should refine LCAs to capture regional variations in transport and energy mixes, develop low-energy processing methods and expand field trials to verify long-term durability. By embedding FBA within the broader circular-economy and decarbonisation strategies, the concrete industry can make meaningful progress toward climate goals [224].

## **9.8 Summary**

This chapter showed that standardisation and regulation play central roles in determining whether FBA can be accepted as a construction material. Meeting the chemical, physical, and mechanical requirements of Australian standards is essential for FBA to be used as a pozzolan or aggregate. The chapter has also highlighted the lack of FBA-specific standards, which remains a major barrier to industry adoption. Regulatory pathways such as end-of-waste schemes help provide clarity and confidence, but further development is needed to support consistent quality control. Sustainability assessments demonstrated that FBA can reduce carbon emissions, conserve natural resources, and support circular-economy goals when processed correctly. Overall, clear standards, strong regulatory frameworks, and sustainability-driven policies are crucial for integrating FBA into future concrete technologies.

# CHAPTER 10: SUMMARY, RECOMMENDATIONS AND FUTURE STUDIES

## 10.1 Introduction

This chapter summarizes the key findings of the comprehensive investigation into the use of FBA in concrete. It consolidates the results from material characterization, processing, laboratory testing, and industrial application. Based on these findings, the chapter provides a set of actionable recommendations for industry stakeholders and outlines directions for future research to further advance the sustainable use of FBA in the construction sector.

## 10.2 Conclusion

### *10.2.1 Properties and characterization*

This research has successfully demonstrated that FBA is a viable and valuable material for use in concrete, both as a partial replacement for fine aggregates (sand) and as a supplementary cementitious material (SCM). The study confirmed that with appropriate processing—including drying, sieving, and grinding—FBA can meet the chemical and physical requirements for concrete production. The chemical composition of the FBA samples, particularly the high content of pozzolanic oxides ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$ ), aligns with the criteria for Class F pozzolans as specified in standards like ASTM C618. While raw FBA exhibits high moisture and water absorption, these properties can be effectively managed through pre-treatment and careful mix design. The investigation also highlighted that grinding FBA for as little as 15 to 30 minutes significantly enhances its particle size distribution, making it suitable for use as an SCM.

### *10.2.2 Performance of FBA in Concrete Applications*

The performance of concrete incorporating FBA was thoroughly evaluated through laboratory tests and a real-world industrial trial. In terms of fresh properties, the use of FBA led to a reduction in slump due to its porous nature and high-water absorption, a factor that must be accounted for in mix design. However, the air content remained comparable to conventional concrete.

Regarding hardened properties, the FBA concrete exhibited slightly lower early-age compressive strength, which is typical for pozzolanic materials. Encouragingly, the 28-day compressive strength was comparable to the control mix, achieving over 31 MPa and

comfortably exceeding the 25 MPa requirement for the footpath application. The durability performance was a key highlight, with FBA concrete demonstrating superior resistance to chemical attack (acid and sulfate) compared to the control. While drying shrinkage and carbonation were slightly higher in FBA mixes, the values remained well within the acceptable limits specified by TfNSW standards. The industrial trial successfully validated these laboratory findings, confirming that FBA concrete can be produced and placed using standard equipment and practices, delivering performance that meets project specifications.

### ***10.2.3 Environmental and Economic Benefits***

The adoption of FBA in concrete presents significant environmental and economic advantages. The Life Cycle Assessments (LCAs) conducted in this study revealed that using FBA as an SCM is particularly effective in reducing the environmental footprint of concrete. Replacing just 10% of cement with ground FBA, in combination with a 25% sand replacement, resulted in a substantial reduction in embodied carbon emissions—up to 30% compared to conventional concrete. This supports decarbonization efforts and aligns with national climate goals. Economically, the use of FBA offers tangible cost savings by reducing the need for expensive primary materials like cement and natural sand. This research identified potential cost savings of approximately \$15 AUD per cubic metre of concrete with a 20% cement replacement. By diverting an industrial by-product from landfills and transforming it into a valuable resource, the use of FBA promotes a circular economy, conserves natural resources, and reduces the long-term environmental liabilities associated with ash disposal.

### ***10.2.4 Challenges and Limitations***

Despite the promising results, the widespread adoption of FBA is not without its challenges. The primary technical challenge is the inherent variability of FBA's physical and chemical properties, which depend on the coal source and combustion conditions. This variability necessitates rigorous quality control procedures and standardised laboratory testing prior to incorporation into concrete mixes. The high-water absorption of FBA requires careful management during mix design to avoid negative impacts on workability and strength. From a regulatory standpoint, the lack of specific standards for FBA as a concrete ingredient remains a significant barrier to market acceptance. Economically, the initial capital investment required for processing facilities (for drying, sieving, and grinding) may deter some producers. Finally, logistical issues related to transportation from power stations to concrete plants and the need for appropriate storage of processed FBA must be addressed to ensure a reliable supply chain

## **10.3 Recommendations**

### ***10.3.1 Recommendations for further Adoption***

To facilitate the broader adoption of FBA in the Australian construction industry, the following recommendations are proposed:

- i. **Develop Standardized Processing and Quality Control Protocols:** Concrete manufacturers, in collaboration with power generation companies, should establish standardized protocols for the drying, sieving, and grinding FBA. Implementing a consistent quality management system will ensure that the FBA supplied to the market has reliable and predictable properties, thereby building confidence among end-users.
- ii. **Invest in Centralized Processing Facilities:** To overcome the economic barrier of initial investment, consideration should be given to establishing centralized or mobile processing facilities located strategically near major power stations. This will create an economy of scale, reduce logistical costs, and ensure a steady supply of quality-assured FBA for the concrete industry.
- iii. **Advocate for FBA-Specific Standards:** Industry bodies, such as Cement Concrete & Aggregates Australia (CCAA), should lead the effort to develop a dedicated Australian Standard for the use of FBA in concrete. This standard should provide clear guidelines on material properties, testing methods, and application limits, similar to existing standards for fly ash and slag. This will remove regulatory ambiguity and provide a clear pathway for compliance.
- iv. **Promote Education and Showcase Applications:** Educational campaigns, workshops, and demonstration projects are crucial for raising awareness and building market acceptance. Showcasing successful applications, such as the footpath in this project, provides tangible proof of FBA concrete's performance and helps to overcome stakeholder reluctance.
- v. **Focus on Suitable Initial Applications:** To begin with, industry should focus on applications where the properties of FBA concrete are most advantageous, such as in non-structural elements like footpaths, kerbs, and precast blocks. As confidence and experience grow, its use can be progressively expanded to more demanding structural applications.
- vi. **Long-Term Durability Studies:** While this study provided positive short-term durability results, long-term monitoring of the industrial trial site and further laboratory studies are needed to assess the performance of FBA concrete over several years, particularly in aggressive environments.

- vii. Optimization of Co-Grinding and Ternary Blends: Further research into co-grinding FBA with other SCMs like slag or fly ash could unlock synergistic effects, potentially leading to even better performance and higher replacement levels. Investigating the optimal ratios and grinding parameters for ternary blends is a promising area of study.
- viii. Addressing Workability and Shrinkage: Research should explore the use of advanced chemical admixtures (e.g., water reducers and shrinkage-reducing admixtures) to more effectively counteract the high water demand and slightly higher shrinkage associated with FBA.
- ix. Investigating FBA from Different Sources: A comprehensive characterization of FBA from various Australian power stations is needed to create a national database of material properties. This would help in developing more robust mix design guidelines that account for regional variations in FBA.
- x. Advanced Applications: Future studies could explore the use of FBA in high-performance applications, such as in lightweight concrete, geopolymer concrete, or for 3D concrete printing, where its unique properties might offer distinct advantages.

## **10.4 Research trends and innovations in FBA concrete**

The past decade has seen a surge of research into turning FBA from a disposal problem into a useful resource. Early studies focused on characterising the ash and exploring simple replacement of sand or cement, but recent work has moved towards advanced processing, mix optimisation and performance enhancement [225].

### ***10.4.1 Enhanced processing and particle refinement***

One of the most significant innovations is co-grinding furnace bottom ash with other industrial by-products. A 2024 case study combined FBA with basic oxygen furnace (BOF) slag and ground the blend in a planetary mill [226]. Co-grinding did not alter the crystalline phases but created a finer, more homogeneous particle size distribution that improved the synergy between particles. Mortars made with the co-ground blend exhibited better flowability and compressive strength at all ages compared with those made with individually ground components. Microstructural analysis revealed a denser matrix with lower calcium-to-silica and silica-to-aluminium ratios, indicating enhanced pozzolanic reactions and more refined hydration products. Such studies demonstrate that relatively simple mechanical activation can boost the reactivity of FBA and enable higher replacement levels [227].

Chemical pre-treatments are another emerging route. A 2025 study explored the transformation of coal bottom ash into a high-performance pozzolan by soaking the ash in dilute hydrochloric acid [228]. The acid leached out deleterious minerals and heavy metals, increased the silica content and produced a much more reactive material. Mortar specimens made with the treated ash achieved a strength activity index around 20% higher than those containing untreated ash. The researchers concluded that acid pre-treatment can reduce the risk of metal leaching and enhance pozzolanic activity, although the additional chemical processing must be balanced against environmental and cost considerations [229].

#### ***10.4.2 Machine-learning-driven mix design***

Researchers are also leveraging data science to optimise mix proportions containing FBA. A 2025 study developed ensemble machine-learning models, such as Extreme Gradient Boosting (XGBoost) and gradient boosting machines (GBM), to predict the compressive strength of concrete mixes incorporating foundry sand and FBA [172]. The models achieved an  $R^2$  value of 0.983 and a root mean square error of only 1.54 MPa, outperforming traditional artificial neural networks and supporting vector regression [230]. Feature-importance analysis [230] indicated that curing duration, superplasticiser dosage and binder content were the most influential variables, while bottom ash content influenced strength in conjunction with these parameters. The authors highlighted that machine-learning tools can capture nonlinear interactions between waste materials and mix constituents, reducing the need for extensive laboratory testing and enabling tailor-made designs for specific sources of FBA [108].

#### ***10.4.3 Integrated use of FBA as binder and aggregate***

Several recent studies have explored using FBA simultaneously as a partial cement replacement and as a fine aggregate. Tang et al. (2024) processed bottom ash by oven drying and ball milling and reported that the resulting ground FBA contained about 86.7 wt%  $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$  and only 2.40 wt% CaO, meeting ASTM C618 and AS/NZS 3582.1 chemical requirements [1]. The ground FBA had a very fine particle size, with all particles passing a 45  $\mu\text{m}$  sieve and a specific surface area higher than that of ordinary Portland cement. When used to replace river sand in mortar, the material exhibited a water absorption of around 11% compared with 1.2% for natural sand. This high absorption necessitated careful control of the water–cement ratio, but the fine particle size helped improve workability and contributed to dense microstructures. Combining ground FBA with conventional fine aggregate at appropriate proportions therefore offers an integrated pathway to reuse the ash without compromising mechanical performance [231].

#### ***10.4.4 Geopolymer and alkali-activated applications***

Another growing research area is the use of FBA in alkali-activated binders and geopolymer products. Deraman et al. investigated geopolymer bricks produced with bottom ash and supplementary fly ash and reported compressive strengths up to 13.69 MPa [232]. Adding fly ash improved both the density and water absorption of the bricks, suggesting that FBA can participate in geopolymerisation when activated by alkaline solutions [233]. Similar investigations into alkali-activated concretes have demonstrated that FBA can contribute reactive alumina and silica, lowering the need for high-temperature curing and reducing greenhouse-gas emissions compared with traditional Portland cement systems [234].

#### ***10.4.5 Lightweight aggregates and composite materials***

Research has also extended to converting bottom ash into lightweight aggregates for use in structural and insulating concretes. Lo et al. reviewed green lightweight aggregate concrete and reported that sintered furnace bottom ash can produce lightweight aggregates with densities below 1.5 t/m<sup>3</sup> [235]. When these aggregates were combined with optimized cementitious matrices, the resulting lightweight concrete achieved workability and compressive strengths comparable to conventional-weight concretes. Other studies have combined FBA with basalt fibres or steel fibres to create composites with improved tensile strength and fracture toughness; milling FBA before mixing has been shown to increase compressive strength and resistance to acid and sulphate attack [236].

#### ***10.4.6 Future directions***

Taken together, these innovations signal a shift from simple substitution to engineered solutions that maximise the value of FBA. Mechanical activation, chemical treatments and AI-assisted design enable higher replacement levels and predictable performance. Researchers are also starting to combine FBA with other supplementary materials, such as rice husk ash, slag and silica fume, to tailor the chemistry and microstructure of binders. Field-scale trials and long-term durability assessments remain limited, however. Future work should address the energy and environmental costs of pre-treatment techniques, develop predictive models for durability, and standardise test methods for FBA from different sources. With continued innovation, FBA could become a mainstream component of sustainable concrete [237].

## **10.5 Concluding Remarks**

In conclusion, this report confirms that FBA is a promising sustainable material for the concrete industry. Its successful incorporation as both a fine aggregate and a supplementary cementitious material offers clear pathways to reducing the environmental impact of construction while maintaining robust performance standards. Although challenges related to variability and standardization exist, they are surmountable through targeted research, industry collaboration, and regulatory support. By embracing FBA, the construction sector can take a significant step towards a more circular, cost-effective, and environmentally responsible future.

## REFERENCES

- [1] Tang W, Onaizi AM, Onaizi SA, Sajjad U, Liu Y. Integrated Use of Furnace Bottom Ash as Fine Aggregate and Cement Replacement for Sustainable Mortar Production. *Materials (Basel)* 2024;17:3834.
- [2] ul Haq E, Padmanabhan SK, Licciulli A. Synthesis and characteristics of fly ash and bottom ash based geopolymers—A comparative study. *Ceram Int* 2014;40:2965–71.
- [3] Chindapasirt P, Jaturapitakkul C, Chalee W, Rattanasak U. Comparative study on the characteristics of fly ash and bottom ash geopolymers. *Waste Manag* 2009;29:539–43.
- [4] Muthusamy K, Rasid MH, Jokhio GA, Budiea AMA, Hussin MW, Mirza J. Coal bottom ash as sand replacement in concrete: A review. *Constr Build Mater* 2020;236:117507.
- [5] Singh M, Siddique R. Effect of coal bottom ash as partial replacement of sand on workability and strength properties of concrete. *J Clean Prod* 2016;112:620–30.
- [6] Namkane K, Naksata W, Thiansem S, Sooksamiti P, Arqueropanyo O. Utilization of coal bottom ash as raw material for production of ceramic floor tiles. *Environ Earth Sci* 2016;75:1–11.
- [7] Ge X, Zhou M, Wang H, Liu Z, Wu H, Chen X. Preparation and characterization of ceramic foams from chromium slag and coal bottom ash. *Ceram Int* 2018;44:11888–91.
- [8] Colonna P, Berloco N, Ranieri V, Shuler ST. Application of bottom ash for pavement binder course. *Procedia-Social Behav Sci* 2012;53:961–71.
- [9] Suloshini S, Ranathunga AS, Kulathilaka SAS, Gunawardana WB, Mapa M. Utilization of Bottom Ash for Clay Mine Rehabilitation. *ICSBE 2020*, Springer; 2022, p. 101–12.
- [10] Zhou H, Bhattarai R, Li Y, Si B, Dong X, Wang T, et al. Towards sustainable coal industry: Turning coal bottom ash into wealth. *Sci Total Environ* 2022;804:149985.
- [11] Onaizi AM, Tang W, Amran M, Liu Y, Sajjad U, Alhassan M. Towards increased adoption of furnace bottom ash as sustainable building materials: Characterization, standardization, and applications. *J Build Eng* 2024;82:108274. <https://doi.org/https://doi.org/10.1016/j.jobe.2023.108274>.
- [12] ADAA. About CCP's - ADAA | Ash Development Association of Australia n.d. <https://www.adaa.asn.au/about-ccps/> (accessed January 31, 2026).
- [13] Pushkar S. The Effect of Different Concrete Designs on the Life-Cycle Assessment of the Environmental Impacts of Concretes Containing Furnace Bottom-Ash Instead of Sand. *Sustainability* 2019;11. <https://doi.org/10.3390/su11154083>.
- [14] Jeon JH, Son YH, Kim DG, Kim TJ. Estimation of Life Cycle CO<sub>2</sub> emissions using oyster shells and bottom ash as materials for soil-mixing and a drainage layer. *J Clean Prod* 2020;270:122477. <https://doi.org/https://doi.org/10.1016/j.jclepro.2020.122477>.
- [15] Navaratnam S, Tushar Q, Jahan I, Zhang G. Environmental Sustainability of Industrial Waste-Based Cementitious Materials: A Review, Experimental Investigation and Life-Cycle Assessment. *Sustainability* 2023;15. <https://doi.org/10.3390/su15031873>.

- [16] Bajare D, Bumanis G, Upeniece L. Coal combustion bottom ash as microfiller with pozzolanic properties for traditional concrete. *Procedia Eng* 2013;57:149–58.
- [17] Hanafi M, Ekinici A, Aydin E. Engineering and microstructural properties of alluvium clay stabilized with Portland cement and coal bottom ash for sustainable future. *KSCE J Civ Eng* 2022;26:5049–66.
- [18] Kumar A, Bheel N, Ahmed I, Rizvi SH, Kumar R, Jhatial AA. Effect of silica fume and fly ash as cementitious material on hardened properties and embodied carbon of roller compacted concrete. *Environ Sci Pollut Res* 2022;29:1210–22.
- [19] Abdulmatin A, Tangchirapat W, Jaturapitakkul C. An investigation of bottom ash as a pozzolanic material. *Constr Build Mater* 2018;186:155–62.
- [20] Pant A, Ramana G V, Datta M, Gupta SK. Comprehensive assessment of cleaner, sustainable and cost-effective use of coal combustion residue (CCR) in geotechnical applications. *J Clean Prod* 2020;271:122570. <https://doi.org/https://doi.org/10.1016/j.jclepro.2020.122570>.
- [21] AEMO | Generation information n.d. <https://www.aemo.com.au/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/forecasting-and-planning-data/generation-information> (accessed December 4, 2025).
- [22] AEMO. 2022 Electricity Statement of Opportunities Important notice 2022.
- [23] Commonwealth Government & NSW Government. *report-of-liddell-taskforce*. 2020.
- [24] Geoscience Australia. Coal | Australia’s Energy Commodity Resources 2021 n.d. <https://www.ga.gov.au/digital-publication/aecr2021/coal> (accessed December 4, 2025).
- [25] HBM Group Pty Ltd. Ash Development Association of Australia - Annual Production and Utilisation Survey Report (January - December 2023) 2023:2–6.
- [26] Council NSWL. Costs for remediation of sites containing coal ash repositories. 2021.
- [27] Paul Winn, Johanna Lynch, Georgina Woods. *Out of the Ashes II: NSW water pollution and our aging coal-fired power stations* 2020.
- [28] Ankur N, Singh N. Performance of cement mortars and concretes containing coal bottom ash: A comprehensive review. *Renew Sustain Energy Rev* 2021;149:111361.
- [29] Singh N, Bhardwaj A. Reviewing the role of coal bottom ash as an alternative of cement. *Constr Build Mater* 2020;233:117276.
- [30] Hamada H, Alattar A, Tayeh B, Yahaya F, Adesina A. Sustainable application of coal bottom ash as fine aggregates in concrete: A comprehensive review. *Case Stud Constr Mater* 2022;16:e01109–e01109. <https://doi.org/https://doi.org/10.1016/j.cscm.2022.e01109>.
- [31] International Electrotechnical Commission. ISO/IEC 17025 General requirements for the competence of testing and calibration laboratories. *Int Stand* 2005;2005:1–36.
- [32] Gooi S, Mousa AA, Kong D. A critical review and gap analysis on the use of coal bottom ash as a substitute constituent in concrete. *J Clean Prod* 2020;268:121752.
- [33] ASTM C. C618-15, Standard specification for coal fly ash and raw or calcined natural

- pozzolan for use in concrete. West Conshohocken ASTM Int 2015.
- [34] AUSTRALIA AS-S. Supplementary cementitious materials AS 3582.2. Slag - Gr Granulated Blast-Furnace n.d.
- [35] Abdullah MJ, Beddu S, Manan TSBA, Syamsir A, Naganathan S, Mohd Kamal NL, et al. The Strength and Thermal Properties of Concrete containing Water Absorptive Aggregate from Well-Graded Bottom Ash (BA) as Partial Sand Replacement. *Constr Build Mater* 2022;339:127658. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2022.127658>.
- [36] Singh M, Siddique R. Effect of coal bottom ash as partial replacement of sand on properties of concrete. *Resour Conserv Recycl* 2013;72:20–32.
- [37] Asokbunyarat V, van Hullebusch ED, Lens PNL, Annachhatre AP. Coal bottom ash as sorbing material for Fe (II), Cu (II), Mn (II), and Zn (II) removal from aqueous solutions. *Water, Air, Soil Pollut* 2015;226:1–17.
- [38] Amran M, Onaizi AM, Fediuk R, Danish A, Vatin NI, Murali G, et al. An ultra-lightweight cellular concrete for geotechnical applications – A review. *Case Stud Constr Mater* 2022;16:e01096–e01096. <https://doi.org/https://doi.org/10.1016/j.cscm.2022.e01096>.
- [39] Nanda B, Rout S. Properties of concrete containing fly ash and bottom ash mixture as fine aggregate. *Int J Sustain Eng* 2021;14:809–19.
- [40] Singh N, Mithulraj M, Arya S. Utilization of coal bottom ash in recycled concrete aggregates based self compacting concrete blended with metakaolin. *Resour Conserv Recycl* 2019;144:240–51.
- [41] Hasim AM, Shahid KA, Ariffin NF, Nasrudin NN, Zaimi MNS, Kamarudin MK. Coal bottom ash concrete: Mechanical properties and cracking mechanism of concrete subjected to cyclic load test. *Constr Build Mater* 2022;346:128464.
- [42] Kou S-C, Poon C-S. Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates. *Constr Build Mater* 2009;23:2877–86. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2009.02.009>.
- [43] Mangi SA, Wan Ibrahim MH, Jamaluddin N, Arshad MF, Ramadhansyah PJ. Effects of ground coal bottom ash on the properties of concrete. *J Eng Sci Technol* 2019;14:338–50.
- [44] Lakhiar MT, Bai Y, Wong LS, Paul SC, Anggraini V, Kong SY. Mechanical and durability properties of epoxy mortar incorporating coal bottom ash as filler. *Constr Build Mater* 2022;315:125677. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.125677>.
- [45] Abbas S, Arshad U, Abbass W, Nehdi ML, Ahmed A. Recycling untreated coal bottom ash with added value for mitigating alkali–silica reaction in concrete: A sustainable approach. *Sustainability* 2020;12:10631.
- [46] Mangi SA, Ibrahim MHW, Jamaluddin N, Arshad MF, Memon SA, Shahidan S. Effects of grinding process on the properties of the coal bottom ash and cement paste. *J Eng Technol Sci* 2019;51:1–13.
- [47] Ibrahim AH. Influence of coal bottom ash on properties of Portland cement mortar. *Int*

- [48] Boral Quarries. Fly Ash Safety Data Sheet. Boral n.d.
- [49] Yu Q, Nagataki S, Lin J, Saeki T, Hisada M. The leachability of heavy metals in hardened fly ash cement and cement-solidified fly ash. *Cem Concr Res* 2005;35:1056–63. <https://doi.org/https://doi.org/10.1016/j.cemconres.2004.03.031>.
- [50] Giergiczny Z, Król A. Immobilization of heavy metals (Pb, Cu, Cr, Zn, Cd, Mn) in the mineral additions containing concrete composites. *J Hazard Mater* 2008;160:247–55. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2008.03.007>.
- [51] Mangi SA, Ibrahim MHW, Jamaluddin N, Arshad MF, Jaya RP. Short-term effects of sulphate and chloride on the concrete containing coal bottom ash as supplementary cementitious material. *Eng Sci Technol an Int J* 2019;22:515–22.
- [52] Australia Standards. Aggregates and rock for engineering purposes. AS 27587-96 1996.
- [53] Cook FJ, McLachlan G, Leyden E, Mosley L. Physical properties of soils/sediments of Lower Murray Lakes and modelling of acid fluxes 2011.
- [54] Jaturapitakkul C, Cheerarot R. Development of bottom ash as pozzolanic material. *J Mater Civ Eng* 2003;15:48–53.
- [55] Kim H-K. Utilization of sieved and ground coal bottom ash powders as a coarse binder in high-strength mortar to improve workability. *Constr Build Mater* 2015;91:57–64.
- [56] Pormmoon P, Abdulmatin A, Charoenwaiyachet C, Tangchirapat W, Jaturapitakkul C. Effect of cut-size particles on the pozzolanic property of bottom ash. *J Mater Res Technol* 2021;10:240–9.
- [57] Wongkeo W, Thongsanitgarn P, Pimraksa K, Chaipanich A. Compressive strength, flexural strength and thermal conductivity of autoclaved concrete block made using bottom ash as cement replacement materials. *Mater Des* 2012. <https://doi.org/10.1016/j.matdes.2011.08.046>.
- [58] Cheriaf M, Rocha JC, Péra J. Pozzolanic properties of pulverized coal combustion bottom ash. *Cem Concr Res* 1999;29:1387–91. [https://doi.org/https://doi.org/10.1016/S0008-8846\(99\)00098-8](https://doi.org/https://doi.org/10.1016/S0008-8846(99)00098-8).
- [59] Cheah CB, Liew JJ, Khaw Le Ping K, Siddique R, Tangchirapat W. Properties of ternary blended cement containing ground granulated blast furnace slag and ground coal bottom ash. *Constr Build Mater* 2022;315:125249. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.125249>.
- [60] Ong TS, Yang H. Effect of atmosphere on the mechanical milling of natural graphite. *Carbon N Y* 2000;38:2077–85.
- [61] Delogu F, Gorrasi G, Sorrentino A. Fabrication of polymer nanocomposites via ball milling: Present status and future perspectives. *Prog Mater Sci* 2017;86:75–126.
- [62] Liu D, Hao Z, Zhao X, Su R, Feng W, Li S, et al. Effect of physical and mechanical activation on the physicochemical structure of coal-based activated carbons for SO<sub>2</sub> adsorption. *Processes* 2019;7:707.
- [63] Hisseine OA, Tagnit-Hamou A. Development of ecological strain-hardening cementitious composites incorporating high-volume ground-glass pozzolans. *Constr*

- Build Mater 2020;238:117740.
- [64] Arowojolu O, Fina J, Pruneda A, Ibrahim A, Mahmoud E. Feasibility study on concrete performance made by partial replacement of cement with nanoglass powder and fly ash. *Int J Civ Eng* 2019;17:1007–14.
- [65] Kim HK, Lee HK. Use of power plant bottom ash as fine and coarse aggregates in high-strength concrete. *Constr Build Mater* 2011;25:1115–22. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2010.06.065>.
- [66] Onaizi AM, Lim NHAS, Huseien GF, Amran M, Ma CK. Effect of the addition of nano glass powder on the compressive strength of high volume fly ash modified concrete. *Mater Today Proc* 2022;48:1789–95.
- [67] Aydin E. Novel coal bottom ash waste composites for sustainable construction. *Constr Build Mater* 2016;124:582–8. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2016.07.142>.
- [68] Ali T, Buller AS, Abro F ul R, Ahmed Z, Shabbir S, Lashari AR, et al. Investigation on Mechanical and Durability Properties of Concrete Mixed with Silica Fume as Cementitious Material and Coal Bottom Ash as Fine Aggregate Replacement Material. *Buildings* 2022;12:44.
- [69] Günay G, Cihan MT, Güneş E. Evaluation of mechanical properties and leaching tests results of mortars containing waste bottom ash as replacement of cement. *J Mater Cycles Waste Manag* 2024. <https://doi.org/10.1007/s10163-024-01976-w>.
- [70] Guan X, Wang L, Mo L. Effects of ground coal bottom ash on the properties of cement-based materials under various curing temperatures. *J Build Eng* 2023;69:106196. <https://doi.org/https://doi.org/10.1016/j.jobe.2023.106196>.
- [71] Cheah CB, Liew JJ, Kevin KLP, Siddique R, Tangchirapat W. Influence of milling parameters on the properties of ground coal bottom ash and its blended cement. *Constr Build Mater* 2023;363:129745. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2022.129745>.
- [72] Sutcu M, Erdogmus E, Gencel O, Gholampour A, Atan E, Ozbakkaloglu T. Recycling of bottom ash and fly ash wastes in eco-friendly clay brick production. *J Clean Prod* 2019;233:753–64.
- [73] Eliche-Quesada D, Leite-Costa J. Use of bottom ash from olive pomace combustion in the production of eco-friendly fired clay bricks. *Waste Manag* 2016;48:323–33. <https://doi.org/https://doi.org/10.1016/j.wasman.2015.11.042>.
- [74] Rafieizonooz M, Salim MR, Mirza J, Hussin MW, Khan R, Khankhaje E. Toxicity characteristics and durability of concrete containing coal ash as substitute for cement and river sand. *Constr Build Mater* 2017;143:234–46.
- [75] EPA NSW. New South Wales Environmental Protection Agency. *Waste Classif Guidel Part 1 Classifying Waste* 2009.
- [76] Victorian EPA. Leaching test - Recommended acceptance criteria for suitability of industrial wastes for landfill disposal. *Epa* 1986:399.
- [77] Contaminants EPADW. EPA 816-F-09-0004. US Environ Prot Agency (US EPA) Washing DC, USA 2009.

- [78] Li J, Zhuang X, Querol X, Font O, Moreno N. A review on the applications of coal combustion products in China. *Int Geol Rev* 2018;60:671–716.
- [79] Berhad PAA. Report on literature study and laboratory testing on characteristics of water treatment plants residuals for DOE consideration to declassify residuals as non-scheduled waste under Environment Quality Act 1974 2009.
- [80] Abdullah MH, Rashid ASA, Anuar UHM, Marto A, Abuelgasim R. Bottom ash utilization: A review on engineering applications and environmental aspects. *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 527, IOP Publishing; 2019, p. 12006.
- [81] Patra S, Whaung ST, Kwan WL. Analysis of heavy metals in Incineration Bottom Ash in Singapore and potential impact of pre-sorting on ash quality. *Energy Procedia* 2017;143:454–9.
- [82] AS-1379-Supp-1. Specification and supply of concrete - Commentary. 2008.
- [83] AS 1012.2. Methods of testing concrete: Preparing concrete mixes in the laboratory. Updat 2022-09-29 2014. <https://au.i2.saiglobal.com/management/display/index/0/830677/-/5622a5974c35027f51c29eebabc515a4> (accessed June 4, 2025).
- [84] AS 1012.4.1. Methods of testing concrete: Determination of air content of freshly mixed concrete - Measuring reduction in concrete volume with increased air pressure. Updated 2022-09-29 2014. <https://au.i2.saiglobal.com/management/display/index/0/663651/-/e373f10839f137b041580a0d58a39c4b> (accessed June 4, 2025).
- [85] AS 1012.3.1. Methods of testing concrete: Determination of properties related to the consistency of concrete - Slump test. Updated 2022-09-29 2014. <https://au.i2.saiglobal.com/management/display/index/0/663207/-/03d86dd6a2cad5e1e1b7a6c735f535f9> (accessed June 4, 2025).
- [86] AS 1012.9. Methods of testing concrete: Compressive strength tests - Concrete, mortar and grout specimens. Updated 2022-11-23 2014. <https://au.i2.saiglobal.com/management/display/index/0/831002/-/78e09fee7d5fabdca50411fd7f19dc2e> (accessed June 4, 2025).
- [87] AS 1012.11. Methods of testing concrete: Determination of the modulus of rupture (Reconfirmed 2014). Updated 2023-02-15 2000. <https://au.i2.saiglobal.com/management/display/index/0/662340/-/e59b63fb2fc5421048742d12efe199ea> (accessed June 4, 2025).
- [88] AS 1012.10. Methods of testing concrete: Determination of indirect tensile strength of concrete cylinders (“Brazil” or splitting test) (Reconfirmed 2014). Updated 2022-09-28 2000. <https://au.i2.saiglobal.com/management/display/index/0/662292/-/b18aacfeae54c87db49998701de2c7f5> (accessed June 4, 2025).
- [89] AS 1012.17. Methods of testing concrete: Determination of the static chord modulus of elasticity and Poisson’s ratio of concrete specimens (Reconfirmed 2014). Updated 2023-03-23 1997. <https://au.i2.saiglobal.com/management/display/index/0/662598/-/c2d15372fec0f01b19e90bbdf91522ab> (accessed June 4, 2025).
- [90] AS 1012.21. Methods of testing concrete: Determination of water absorption and apparent volume of permeable voids in hardened concrete (Reconfirmed 2014). Updated 2023-02-15 1999. <https://au.i2.saiglobal.com/management/display/index/0/662776/->

/2a6254c9409ddcb5d150e73e162f5f74 (accessed June 4, 2025).

- [91] ASTM C. 944, Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method. Am Soc Test Mater USA 2007:1–10.
- [92] Cao R, Yang J, Li G, Zhou Q, Niu M. Durability performance of nano-SiO<sub>2</sub> modified OPC-SAC composites subjected to sulfuric acid attack. *Constr Build Mater* 2023;371:130802. <https://doi.org/10.1016/j.conbuildmat.2023.130802>.
- [93] Sata V, Sathonsaowaphak A, Chindaprasirt P. Resistance of lignite bottom ash geopolymer mortar to sulfate and sulfuric acid attack. *Cem Concr Compos* 2012;34:700–8.
- [94] Huseien GF, Sam ARM, Shah KW, Mirza J, Tahir MM. Evaluation of alkali-activated mortars containing high volume waste ceramic powder and fly ash replacing GBFS. *Constr Build Mater* 2019;210:78–92. <https://doi.org/10.1016/j.conbuildmat.2019.03.194>.
- [95] Huseien GF, Shah KW. Durability and life cycle evaluation of self-compacting concrete containing fly ash as GBFS replacement with alkali activation. *Constr Build Mater* 2020;235:117458. <https://doi.org/10.1016/j.conbuildmat.2019.117458>.
- [96] Pedersen KH, Jensen AD, Skjøth-Rasmussen MS, Dam-Johansen K. A review of the interference of carbon containing fly ash with air entrainment in concrete. *Prog Energy Combust Sci* 2008;34:135–54. <https://doi.org/10.1016/j.pecs.2007.03.002>.
- [97] Aygun BF, Bilir T, Uysal M. Coal bottom ash and its applications in cement and concrete technologies: a review. *Discov Civ Eng* 2024;1:86. <https://doi.org/10.1007/s44290-024-00090-y>.
- [98] Zhang D, Zhu T, Yang Q, Vandeginste V, Li J. Influence of ground granulated blast furnace slag on recycled concrete powder-based geopolymer cured at ambient temperature: Rheology, mechanical properties, reaction kinetics and air-void characteristics. *Constr Build Mater* 2024;438:137190. <https://doi.org/10.1016/j.conbuildmat.2024.137190>.
- [99] Kostrzanowska-Siedlarz A, Gołaszewski J. Rheological properties and the air content in fresh concrete for self compacting high performance concrete. *Constr Build Mater* 2015;94:555–64. <https://doi.org/10.1016/j.conbuildmat.2015.07.051>.
- [100] Haddadian A, Ahmed Mahmoud A, U. Johnson A, Mo Kim H, Muhammad S. I. I, and Ayough P. Mechanical and microstructural properties of structural and non-structural lightweight foamed concrete with coal bottom ash as cement and sand replacement material. *J Sustain Cem Mater* 2024;13:622–44. <https://doi.org/10.1080/21650373.2023.2295505>.
- [101] Schack T, Haist M. Performance assessment of eco-efficient concrete with ternary blended cementitious materials considering the effect of binder component fineness. *Case Stud Constr Mater* 2024;20:e03154. <https://doi.org/10.1016/j.cscm.2024.e03154>.
- [102] Hasim AM, Shahid KA, Ariffin NF, Nasrudin NN, Zaimi MNS. Properties of high volume coal bottom ash in concrete production. *Mater Today Proc* 2022;48:1861–7. <https://doi.org/10.1016/j.matpr.2021.09.250>.

- [103] Dvořák K, Dolák D, Dočkal J. Comparison of Separate and Co-grinding of the Blended Cements with the Pozzolanic Component. *Procedia Eng* 2016;151:66–72. <https://doi.org/https://doi.org/10.1016/j.proeng.2016.07.376>.
- [104] Tadier S, Le Bolay N, Rey C, Combes C. Co-grinding significance for calcium carbonate–calcium phosphate mixed cement. Part I: Effect of particle size and mixing on solid phase reactivity. *Acta Biomater* 2011;7:1817–26. <https://doi.org/https://doi.org/10.1016/j.actbio.2010.12.010>.
- [105] Rafieizonooz M, Mirza J, Salim MR, Hussin MW, Khankhaje E. Investigation of coal bottom ash and fly ash in concrete as replacement for sand and cement. *Constr Build Mater* 2016;116:15–24.
- [106] Meena A, Singh N, Singh SP. Shear strength and microstructural investigation on high-volume fly ash self-compacting concrete containing recycled concrete aggregates and coal bottom ash. *Mater Construcción* 2024;74:e333–e333.
- [107] Rathee M, Singh N. Durability properties of copper slag and coal bottom ash based I-shaped geopolymer paver blocks. *Constr Build Mater* 2022;347:128461. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2022.128461>.
- [108] Ashraf MW, Tu Y, Khan A, Siddiqui AS, Mubarak S, Sufian M, et al. Experimental and explainable machine learning based investigation of the coal bottom ash replacement in sustainable concrete production. *J Build Eng* 2025;104:112367. <https://doi.org/https://doi.org/10.1016/j.job.2025.112367>.
- [109] Sow M, Hot J, Tribout C, Cyr M. Improving circular economy by the valorization of non-conventional coal fly ashes in composite cement manufacturing. *Constr Build Mater* 2021;300:124053. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.124053>.
- [110] Garces-Vargas JF, Díaz-Cardenas Y, Zunino F, Ribalta-Quesada J, Scrivener K, Martirena F. The Challenge of Grinding Ternary Blends Containing Calcined Clays and Limestone. *Minerals* 2022;12. <https://doi.org/10.3390/min12091170>.
- [111] Annex M, Notes G. TRANSPORT FOR NSW ( TfNSW ) QA SPECIFICATION R53 CONCRETE FOR GENERAL WORKS 2021.
- [112] Chindasiriphan P, Meenyut B, Orasutthikul S, Jongvivatsakul P, Tangchirapat W. Influences of high-volume coal bottom ash as cement and fine aggregate replacements on strength and heat evolution of eco-friendly high-strength concrete. *J Build Eng* 2023;65:105791. <https://doi.org/https://doi.org/10.1016/j.job.2022.105791>.
- [113] Zhang B, Poon CS. Use of furnace bottom ash for producing lightweight aggregate concrete with thermal insulation properties. *J Clean Prod* 2015;99:94–100.
- [114] Huseien GF, Hamzah HK, Sam ARM, Khalid NHA, Shah KW, Deogrescu DP, et al. Alkali-activated mortars blended with glass bottle waste nano powder: Environmental benefit and sustainability. *J Clean Prod* 2020;243:118636.
- [115] Prakasan S, Palaniappan S, Gettu R. Study of energy use and CO<sub>2</sub> emissions in the manufacturing of clinker and cement. *J Inst Eng Ser A* 2020;101:221–32.
- [116] Commission NT. Carbon dioxide emissions intensity for new Australian light vehicles 2019 2020.

- [117] DCCEE. Australian National Greenhouse Accounts, National Greenhouse Gas Inventory. accounting for the Kyoto Target. 2010.
- [118] Regulator AE. State of the energy market 2023 2023.
- [119] Sheet PD. Sika ® ViscoCrete ® -4100 2019:3–4.
- [120] Hadi MNS, Farhan NA, Sheikh MN. Design of geopolymer concrete with GGBFS at ambient curing condition using Taguchi method. *Constr Build Mater* 2017;140:424–31.
- [121] Chi Y, Qiao Z, Zhou W, Zhang M, Zhang X. The impact of ultra-high voltage projects on carbon emissions in China. *Environ Sci Pollut Res* 2023;30:92135–45.
- [122] Xing W, Tam VWY, Le KN, Butera A, Hao JL, Wang J. Effects of mix design and functional unit on life cycle assessment of recycled aggregate concrete: Evidence from CO2 concrete. *Constr Build Mater* 2022;348:128712.
- [123] Baite E, Messan A, Hannawi K, Tsobnang F, Prince W. Physical and transfer properties of mortar containing coal bottom ash aggregates from Tefereyre (Niger). *Constr Build Mater* 2016;125:919–26. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2016.08.117>.
- [124] Hossain MU, Poon CS, Lo IMC, Cheng JCP. Comparative LCA on using waste materials in the cement industry: A Hong Kong case study. *Resour Conserv Recycl* 2017;120:199–208.
- [125] Flower DJM, Sanjayan JG. Green house gas emissions due to concrete manufacture. *Int J Life Cycle Assess* 2007;12:282–8.
- [126] Gan VJL, Chan CM, Tse KT, Lo IMC, Cheng JCP. A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters. *J Clean Prod* 2017;161:663–75.
- [127] Turk J, Cotič Z, Mladenović A, Šajna A. Environmental evaluation of green concretes versus conventional concrete by means of LCA. *Waste Manag* 2015;45:194–205.
- [128] Hossain MU, Poon CS, Lo IMC, Cheng JCP. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resour Conserv Recycl* 2016;109:67–77.
- [129] Anh LH, Mihai F-C, Belousova A, Kucera R, Oswald K-D, Riedel W, et al. Life cycle assessment of river sand and aggregates alternatives in concrete. *Materials (Basel)* 2023;16:2064.
- [130] Wiranata DY, Yang S-H, Akgul CM, Hsien HY, Nugraha MZP. Use of coal ash cement stabilized material as pavement base material: Laboratory characterization and field evaluation. *Constr Build Mater* 2022;344:128055. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2022.128055>.
- [131] Ibeto CN, Obiefuna CJ, Ugwu KE. Environmental effects of concretes produced from partial replacement of cement and sand with coal ash. *Int J Environ Sci Technol* 2020;17:2967–76.
- [132] UON Team. LCA (Life Cycle Assessment) of FBA concrete. 2024, The University of Newcastle. 2024.
- [133] Kurama H, Kaya M. Usage of coal combustion bottom ash in concrete mixture. *Constr*

- [134] Fediuk R, Makarova N, Kozin A, Lomov M, Petropavlovskaya V, Novichenkova T, et al. Nanomodified basalt fiber cement composite with bottom ash. *J Compos Sci* 2023;7:96.
- [135] Bang JW, Ganesh Prabhu G, Jang Y Il, Kim YY. Development of ecoefficient engineered cementitious composites using supplementary cementitious materials as a binder and bottom ash aggregate as fine aggregate. *Int J Polym Sci* 2015;2015:681051.
- [136] Phutthananon C, Tippracha N, Jongpradist P, Tunsakul J, Tangchirapat W, Jamsawang P. Investigation of strength and microstructural characteristics of blended cement-admixed clay with bottom ash. *Sustainability* 2023;15:3795.
- [137] Chowdhury R, Apul D, Fry T. A life cycle based environmental impacts assessment of construction materials used in road construction. *Resour Conserv Recycl* 2010;54:250–5. <https://doi.org/https://doi.org/10.1016/j.resconrec.2009.08.007>.
- [138] Moretti L, Caro S. Critical analysis of the life cycle assessment of the Italian cement industry. *J Clean Prod* 2017;152:198–210.
- [139] Zuo J, Zhao Z-Y. Green building research—current status and future agenda: A review. *Renew Sustain Energy Rev* 2014;30:271–81.
- [140] Circular Australia. Environment Sustainable Procurement Policy. 2023. 2023 n.d. <https://circularaustralia.com.au/article/australian-government-releases-environmentally-sustainable-procurement-policy/> (accessed November 11, 2025).
- [141] DCCEEW. ReMade in Australia n.d. <https://www.dcceew.gov.au/environment/protection/waste/consumers/remade-in-australia> (accessed November 11, 2025).
- [142] CSIRO. A concrete step forward: Australia’s ambitious plan to cut cement and lime emissions 2023. <https://www.csiro.au/en/news/all/articles/2023/november/ccus-roadmap> (accessed November 10, 2025).
- [143] CCAA. Ambition to deliver net zero cement and concrete by 2050. 2024. p. 1-3. n.d.
- [144] Al Biajawi MI, Embong R, Muthusamy K, Ismail N, Obianyo II. Recycled coal bottom ash as sustainable materials for cement replacement in cementitious Composites: A review. *Constr Build Mater* 2022;338:127624. <https://doi.org/10.1016/j.conbuildmat.2022.127624>.
- [145] Kim H-K, Jeon JH, Lee H-K. Flow, water absorption, and mechanical characteristics of normal-and high-strength mortar incorporating fine bottom ash aggregates. *Constr Build Mater* 2012;26:249–56.
- [146] Mangi SA, Wan Ibrahim MH, Jamaluddin N, Arshad MF, Mudjanarko SW. Recycling of coal ash in concrete as a partial cementitious resource. *Resources* 2019;8:99.
- [147] Oruji S, Brake NA, Nalluri L, Guduru RK. Strength activity and microstructure of blended ultra-fine coal bottom ash-cement mortar. *Constr Build Mater* 2017;153:317–26.
- [148] Menéndez E, Álvaro AM, Hernández MT, Parra JL. New methodology for assessing the

- environmental burden of cement mortars with partial replacement of coal bottom ash and fly ash. *J Environ Manage* 2014;133:275–83.
- [149] UON Team. Preliminary test results on the characteristics of refined FBA and their effects on fundamental properties of cementitious composites. 2024.
- [150] Xie T, Ozbakkaloglu T. Behavior of low-calcium fly and bottom ash-based geopolymer concrete cured at ambient temperature. *Ceram Int* 2015;41:5945–58. <https://doi.org/https://doi.org/10.1016/j.ceramint.2015.01.031>.
- [151] Heidrich C, Feuerborn H-J, Weir A. Coal combustion products: a global perspective. *World coal ash Conf.*, vol. 22, 2013, p. 25.
- [152] Khan RA, Ganesh A. The effect of coal bottom ash (CBA) on mechanical and durability characteristics of concrete. *J Build Mater Struct* 2016;3:31–42.
- [153] NSW Government website. Low emission building materials n.d. <https://www.energy.nsw.gov.au/business-and-industry/programs-grants-and-schemes/low-emission-building-materials> (accessed November 26, 2025).
- [154] Suraneni P, Burris L, Shearer CR, Hooton RD. ASTM C618 fly ash specification: Comparison with other specifications, shortcomings, and solutions. *ACI Mater J* 2021;118:157–67. <https://doi.org/10.14359/51725994>.
- [155] Pourkhorshidi AR, Najimi M, Parhizkar T, Jafarpour F, Hillemeier B. Applicability of the standard specifications of ASTM C618 for evaluation of natural pozzolans. *Cem Concr Compos* 2010;32:794–800.
- [156] Schackow A, Andrade Neto J da S, Hack L, Folgueras MV, Kirchheim AP, Rodríguez Martínez ED, et al. Coal Bottom Ash as Supplementary Cementitious Material: Optimizing Reactivity Through Particle Grinding. *Sustainability* 2025;17:5031.
- [157] Hammoud O, Blanc D, Lupsea-Toader M, de Brauer C. Influence of chemical pre-treatment on the leaching behaviour of bottom ash. *5th Int. Conf. Sustain. Solid Waste Manag.*, 2017.
- [158] Tuntisukrarom K, Cheerarot R. Prediction of compressive strength behavior of ground bottom ash concrete by an artificial neural network. *Adv Mater Sci Eng* 2020;2020:2608231.
- [159] Lin KL, Chang WC, Lin DF. Pozzolanic characteristics of pulverized incinerator bottom ash slag. *Constr Build Mater* 2008;22:324–9.
- [160] Kalina RD, Al-Shmaisani S, Ferron RD, Juenger MCG. False positives in ASTM C618 specifications for natural pozzolans. *ACI Mater J* 2019;116:165–72.
- [161] Rules C. Hazardous and solid waste management system; disposal of coal combustion residuals from electric utilities: Final rule. United States Environ Prot Agency, Washington, DC 2015.
- [162] Di Bella M, Italiano F, Magazù S, Mottese AF, Interdonato M, Gentile F, et al. Risk assessment of bottom ash from fuel oil power plant of Italy: mineralogical, chemical and leaching characterization. *Environ Earth Sci* 2018;77:1–9.
- [163] Hashemi SSG, Mahmud H Bin, Ghuan TC, Chin AB, Kuenzel C, Ranjbar N. Safe disposal of coal bottom ash by solidification and stabilization techniques. *Constr Build*

Mater 2019;197:705–15.

- [164] Wang Z, Dai S, Zou J, French D, Graham IT. Rare earth elements and yttrium in coal ash from the Luzhou power plant in Sichuan, Southwest China: Concentration, characterization and optimized extraction. *Int J Coal Geol* 2019;203:1–14.
- [165] Arenas C, Leiva C, Vilches LF, Cifuentes H. Use of co-combustion bottom ash to design an acoustic absorbing material for highway noise barriers. *Waste Manag* 2013;33:2316–21. <https://doi.org/https://doi.org/10.1016/j.wasman.2013.07.008>.
- [166] Rafieizonooz M, Khankhaje E, Rezania S. Assessment of environmental and chemical properties of coal ashes including fly ash and bottom ash, and coal ash concrete. *J Build Eng* 2022;49:104040. <https://doi.org/https://doi.org/10.1016/j.job.2022.104040>.
- [167] Ginés O, Chimenos JM, Vizcarro A, Formosa J, Rosell JR. Combined use of MSWI bottom ash and fly ash as aggregate in concrete formulation: Environmental and mechanical considerations. *J Hazard Mater* 2009;169:643–50. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2009.03.141>.
- [168] Llorens JF, Fernandez-Turiel JL, Querol X. The fate of trace elements in a large coal-fired power plant. *Environ Geol* 2001;40:409–16.
- [169] Ketris MP, Yudovich YE. Estimations of Clarkes for Carbonaceous biolithes: World averages for trace element contents in black shales and coals. *Int J Coal Geol* 2009;78:135–48. <https://doi.org/https://doi.org/10.1016/j.coal.2009.01.002>.
- [170] Poranek N, Łaźniewska-Piekarczyk B, Lombardi L, Czajkowski A, Bogacka M, Pikoń K. Green Deal and circular economy of bottom ash waste management in building industry—Alkali (NaOH) pre-treatment. *Materials (Basel)* 2022;15:3487.
- [171] Oyejobi DO, Firoozi AA, Fernández DB, Avudaiappan S. Integrating circular economy principles into concrete technology: Enhancing sustainability through industrial waste utilization. *Results Eng* 2024;24:102846.
- [172] Paruthi S, Verma R, Sharma N, Khan AH, Hasan MA. Ensemble machine learning models for predicting strength of concrete with foundry sand and coal bottom ash as fine aggregate replacements. *Sci Rep* 2025;15:38331.
- [173] Khan K, Salami BA, Iqbal M, Amin MN, Ahmed F, Jalal FE. Compressive strength estimation of fly ash/slag based green concrete by deploying artificial intelligence models. *Materials (Basel)* 2022;15:3722.
- [174] Pushkar S. Life-cycle assessment of the substitution of sand with coal bottom ash in concrete: two concrete design methods. *Appl Sci* 2019;9:3620.
- [175] Rashidi NA, Yusup S. Overview on the Potential of Coal-Based Bottom Ash as Low-Cost Adsorbents. *ACS Sustain Chem Eng* 2016;4:1870–84. <https://doi.org/10.1021/acssuschemeng.5b01437>.
- [176] Kurniawan AR, Maryati S, Dote Y, Sekito T. The environmental assessment and cost benefit analysis of utilization of indonesian coal combustion products (CCPs). *J Perenc Wil Kota* 2014;3:127–34.
- [177] Kim HK, Lee H-K. Coal bottom ash in field of civil engineering: A review of advanced applications and environmental considerations. *KSCE J Civ Eng* 2015;19:1802–18.

- [178] Jorat ME, Marto A, Namazi E, Amin MFM. Engineering characteristics of kaolin mixed with various percentages of bottom ash. *Electron J Geotech Eng* 2011;16:841–50.
- [179] Ramme BW, Tharaniyil MP. *Coal combustion products utilization handbook* 2004.
- [180] Wilson DC, Rodic L, Scheinberg A, Velis CA, Alabaster G. Comparative analysis of solid waste management in 20 cities. *Waste Manag Res* 2012;30:237–54.
- [181] Hajar HAA, Tweissi A, Hajar YAA, Al-Weshah R, Shatanawi KM, Imam R, et al. Assessment of the municipal solid waste management sector development in Jordan towards green growth by sustainability window analysis. *J Clean Prod* 2020;258:120539.
- [182] Rissman J, Bataille C, Masanet E, Aden N, Morrow WR, Zhou N, et al. Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Appl Energy* 2020;266:114848. <https://doi.org/10.1016/j.apenergy.2020.114848>.
- [183] Kaza S, Yao L, Bhada-Tata P, Van Woerden F. *What a waste 2.0: a global snapshot of solid waste management to 2050*. World Bank Publications; 2018.
- [184] Prurapark R, Asavaritikrai P, Prurapark R, Asavaritikrai P. *Environmental Impacts. Assess Coal Use Thail Curr Futur Trends* 2020:37–44.
- [185] Resource recovery centres | Rubbish tip | Brisbane City Council n.d. [https://www.brisbane.qld.gov.au/bins-waste-and-recycling/waste-and-recycling-facilities/resource-recovery-centres?utm\\_source=chatgpt.com](https://www.brisbane.qld.gov.au/bins-waste-and-recycling/waste-and-recycling-facilities/resource-recovery-centres?utm_source=chatgpt.com) (accessed January 31, 2026).
- [186] Chapter 4 – Parliament of Australia n.d. [https://www.aph.gov.au/Parliamentary\\_Business/Committees/Senate/Environment\\_and\\_Communications/WasteandRecycling/Report/c04?utm\\_source=chatgpt.com](https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Environment_and_Communications/WasteandRecycling/Report/c04?utm_source=chatgpt.com) (accessed January 31, 2026).
- [187] Fees and Charges 25/26 » Eastern Metropolitan Regional Council n.d. [https://www.emrc.org.au/our-services-and-products/our-services/fees-and-charges.aspx?utm\\_source=chatgpt.com](https://www.emrc.org.au/our-services-and-products/our-services/fees-and-charges.aspx?utm_source=chatgpt.com) (accessed January 31, 2026).
- [188] Akçaözöğlü S, Akçaözöğlü K, Atiş CD. Thermal conductivity, compressive strength and ultrasonic wave velocity of cementitious composite containing waste PET lightweight aggregate (WPLA). *Compos Part B Eng* 2013;45:721–6.
- [189] Sua-iam G, Makul N. Utilization of high volumes of unprocessed lignite-coal fly ash and rice husk ash in self-consolidating concrete. *J Clean Prod* 2014;78:184–94. <https://doi.org/https://doi.org/10.1016/j.jclepro.2014.04.060>.
- [190] Pazouki G, Tao Z, Saeed N, Kang W-H. Using artificial intelligence methods to predict the compressive strength of concrete containing sugarcane bagasse ash. *Constr Build Mater* 2023;409:134047.
- [191] Olsson JA, Miller SA, Kneifel JD. A review of current practice for life cycle assessment of cement and concrete. *Resour Conserv Recycl* 2024;206:107619.
- [192] Allegrini E, Vadenbo C, Boldrin A, Astrup TF. Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash. *J Environ Manage* 2015;151:132–43.

- [193] Galvín AP, Ayuso J, García I, Jiménez JR, Gutiérrez F. The effect of compaction on the leaching and pollutant emission time of recycled aggregates from construction and demolition waste. *J Clean Prod* 2014;83:294–304.
- [194] Asmara YP. *Green Engineering Materials: Innovations and Applications for Sustainable Construction*. CRC Press; 2025.
- [195] Bansal D, Ramana G V, Datta M. Sustainable utilization of incineration bottom ash in pavement construction: Environmental impacts and life cycle assessment. *Sci Total Environ* 2024;931:172890.
- [196] Cheng L, Jin H, Liu J, Xing F. A comprehensive assessment of green concrete incorporated with municipal solid waste incineration bottom: Experiments and life cycle assessment (LCA). *Constr Build Mater* 2024;413:134822.
- [197] Pérez-Villarejo L, Bonet-Martínez E, Eliche-Quesada D, Sánchez-Soto PJ, Rincón-López JM, Castro-Galiano E. Biomass fly ash and aluminium industry slags-based geopolymers. *Mater Lett* 2018;229:6–12.
- [198] Reddy MY, Harihanandh M. Experimental studies on strength and durability of alkali activated slag and coal bottom ash based geopolymer concrete. *Mater Today Proc* 2023.
- [199] Nikbin IM, Rahimi S, Allahyari H, Damadi M. A comprehensive analytical study on the mechanical properties of concrete containing waste bottom ash as natural aggregate replacement. *Constr Build Mater* 2016;121:746–59.
- [200] Singh G, Paul BC. Assessment of groundwater quality impacts due to use of coal combustion byproducts to control subsidence from underground mines. *Environ Int* 2001;26:567–71.
- [201] Valeev D, Kuniilova I, Alpatov A, Mikhailova A, Goldberg M, Kondratiev A. Complex utilisation of ekibastuz brown coal fly ash: Iron & carbon separation and aluminum extraction. *J Clean Prod* 2019;218:192–201. <https://doi.org/https://doi.org/10.1016/j.jclepro.2019.01.342>.
- [202] Wang N, Sun X, Zhao Q, Yang Y, Wang P. Leachability and adverse effects of coal fly ash: A review. *J Hazard Mater* 2020;396:122725. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2020.122725>.
- [203] Singh N, Mithulraj M, Arya S. Influence of coal bottom ash as fine aggregates replacement on various properties of concretes: A review. *Resour Conserv Recycl* 2018;138:257–71.
- [204] Levandowski J, Kalkreuth W. Chemical and petrographical characterization of feed coal, fly ash and bottom ash from the Figueira Power Plant, Paraná, Brazil. *Int J Coal Geol* 2009;77:269–81.
- [205] Sauer JJ, Benson CH, Edil TB. *Metals leaching from highway test sections constructed with industrial byproducts*. University of Wisconsin-Madison; 2005.
- [206] Kasaniya M, Thomas MDA, Moffatt EG. Pozzolanic reactivity of natural pozzolans, ground glasses and coal bottom ashes and implication of their incorporation on the chloride permeability of concrete. *Cem Concr Res* 2021;139:106259.
- [207] Hower JC, Henke KR, Dai S, Ward CR, French D, Liu S, et al. Generation and nature of coal fly ash and bottom ash. *Coal Combust. Prod.*, Elsevier; 2017, p. 21–65.

- [208] Hower JC, Fu B, Dai S. Geochemical partitioning from pulverized coal to fly ash and bottom ash. *Fuel* 2020;279:118542. <https://doi.org/https://doi.org/10.1016/j.fuel.2020.118542>.
- [209] Ruhl L, Vengosh A, Dwyer GS, Hsu-Kim H, Deonarine A, Bergin M, et al. Survey of the potential environmental and health impacts in the immediate aftermath of the coal ash spill in Kingston, Tennessee. *Environ Sci Technol* 2009;43:6326–33.
- [210] Munawer ME. Human health and environmental impacts of coal combustion and post-combustion wastes. *J Sustain Min* 2018;17:87–96.
- [211] Zierold KM, Odoh C. A review on fly ash from coal-fired power plants: chemical composition, regulations, and health evidence. *Rev Environ Health* 2020;35:401–18.
- [212] Baba A, Gurdal G, Sengunalp F, Ozay O. Effects of leachant temperature and pH on leachability of metals from fly ash. A case study: Can thermal power plant, province of Canakkale, Turkey. *Environ Monit Assess* 2008;139:287–98.
- [213] Svoboda P, Kurth H. Environment effects-Dust pollution and soil protection. *Appl. Mech. Mater.*, vol. 843, Trans Tech Publ; 2016, p. 111–7.
- [214] Ranjbar N, Kuenzel C. Cenospheres: A review. *Fuel* 2017;207:1–12.
- [215] Aggarwal Y, Siddique R. Microstructure and properties of concrete using bottom ash and waste foundry sand as partial replacement of fine aggregates. *Constr Build Mater* 2014;54:210–23.
- [216] Hashemi SSG, Mahmud H Bin, Djobo JNY, Tan CG, Ang BC, Ranjbar N. Microstructural characterization and mechanical properties of bottom ash mortar. *J Clean Prod* 2018;170:797–804.
- [217] Schneider L, Rose NL, Lintern A, Sinclair D, Zawadzki A, Holley C, et al. Assessing environmental contamination from metal emission and relevant regulations in major areas of coal mining and electricity generation in Australia. *Sci Total Environ* 2020;728:137398.
- [218] Assessing the health of Lake Macquarie results | EPA n.d. <https://www.epa.nsw.gov.au/Working-together/Community-engagement/Regulation-of-power-stations/Coal-ash-dams/Monitoring-environmental-condition-Lake-Macquarie/Results> (accessed January 31, 2026).
- [219] Nsw S, Change C. Surface sediment quality – toxicity assessment n.d.
- [220] Faelnar K. Benthic Community Composition – Lake Macquarie Final Report June 2024 2024:1–105.
- [221] Nsw S, Change C. Synthesis report n.d.
- [222] Nsw S, Change C. Surface sediment quality – chemical assessment n.d.
- [223] Kang M-C, Ju S, Oh T, Yoo D-Y, Pyo S. Novel treatment method of coal bottom ash for strain-hardening alkali-activated composite. *Cem Concr Compos* 2024;151:105598.
- [224] Júnior LUDT, Tabora-Barraza M, Cheriaf M, Gleize PJP, Rocha JC. Effect of bottom ash waste on the rheology and durability of alkali activation pastes. *Case Stud Constr Mater* 2022;16:e00790.

- [225] Li H, Chung H, Li Z, Li W. Compressive Strength Prediction of Fly Ash-Based Concrete Using Single and Hybrid Machine Learning Models. *Buildings* 2024;14:3299.
- [226] Onaizi AM, Tang W, Liu Y. 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 Stud Constr Mater* 2024;CSCM-D-23-.
- [227] Hamada HM, Abed F, Al-Sadoon ZA, Alashkar A. Enhancing pozzolanic activity of fly ash via dry and wet milling: A comparative study for sustainable construction material enhancement. *J CO2 Util* 2024;83:102811.
- [228] Embong R. Transforming coal bottom ash into a high-performance pozzolan: effects of acid treatment on material properties. *Innov Infrastruct Solut* 2025;10:1–17.
- [229] Yahya AA, Ali N, Kamal NLM, Shahidan S, Beddu S, Nuruddin MF, et al. Reducing heavy metal element from coal bottom ash by using citric acid leaching treatment. *MATEC Web Conf.*, vol. 103, EDP Sciences; 2017, p. 1004.
- [230] Siddique R, Aggarwal P, Aggarwal Y. Prediction of compressive strength of self-compacting concrete containing bottom ash using artificial neural networks. *Adv Eng Softw* 2011;42:780–6.
- [231] Kiruthiga P, Dave N, Guduru RK, Choudhary L. Investigation of coal bottom ash as pozzolan in binder and mortar along with strength prediction using machine learning model. *Innov Infrastruct Solut* 2025;10:184.
- [232] Adelizar AS, Olvianas M, Adyithia DM, Syafiyurrahman MF, Pratama I, Astuti W, et al. Fly ash and bottom ash utilization as geopolymers: Correlation on compressive strength and degree of polymerization observed using FTIR. *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 742, IOP Publishing; 2020, p. 12042.
- [233] Affandhie BA, Kurniasari PT, Darmawan MS, Subekti S, Wibowo B, Husin NA, et al. The effects of bottom ash on setting time and compressive strength of fly ash geopolymer paste. *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 267, IOP Publishing; 2017, p. 12002.
- [234] Tan Y, He Y, Cui X, Liu L. Design and performance optimization of alkali-activated waste coal bottom ash/slag porous concrete. *Constr Build Mater* 2022;359:129413.
- [235] Balapour M, Zhao W, Garboczi EJ, Oo NY, Spatari S, Hsuan YG, et al. Potential use of lightweight aggregate (LWA) produced from bottom coal ash for internal curing of concrete systems. *Cem Concr Compos* 2020;105:103428.
- [236] Somani P, Gaur A, Dhemia P. Impact of Sintered Fly Ash Aggregate on Mechanical, Durability, and Thermal Performance of Concrete. *J Struct Des Constr Pract* 2025;30:4024072.
- [237] Křížová K, Bubeník J, Sedlmajer M. Use of lightweight sintered fly ash aggregates in concrete at high temperatures. *Buildings* 2022;12:2090.

# Appendix A: Checklist for Control Concrete at Site

## Concrete Placement Checklist/inspection

| Date: <b>20/02/2025</b> Location: <b>Tom Barney oval</b> Section: <b>Middle Section (6 m)</b>  |  |    |     |         |
|--|--|----|-----|---------|
| Concrete Mix: <b>Control</b> Quantity: <b>1 m<sup>3</sup></b> Start time: <b>08:09 a.m.</b> Temperature: <b>21°C</b>                       |  |    |     |         |
| Humidity/Wind: <b>84%/19 km/hr</b> End Time: <b>08:25 a.m.</b>   |  |    |     |         |
| Description  | Yes  | No | N/A | Remarks |
| <b><u>Pre-Pour Checks</u></b>  |  |    |     |         |
| Is the excavation size correct?  | x  |    |     |         |
| Is the excavation base compacted correctly?  | x  |    |     |         |
| Is the excavation dry?   | x  |    |     |         |
| Is the formwork bracing adequate?  | x  |    |     |         |
| Has mould oil been applied evenly and thoroughly?  | x  |    |     |         |
| Is formwork vertically and horizontally aligned?   | x  |    |     |         |
| Are the rebars free from rust?   | x  |    |     |         |
| Is the spacing and concrete cover, correct?  | x  |    |     |         |
| Is the pore site clean and free from all debris?   | x  |    |     |         |
| <b><u>Concrete Placement Observations</u></b>  |  |    |     |         |
| Is there any bleeding?   |  | x  |     |         |
| Is there any segregation?  |  | x  |     |         |
| Are the joints properly spaced?  |  | x  |     |         |
| Are the joints provided properly?  |  | x  |     |         |
| <b><u>Compaction and Finishing</u></b>   |  |    |     |         |
| What is the vibration/compaction method?<br><b>Started with shovel and then finalized with portable electric vibrator</b>                  | What is the quality of compaction?<br><b>Very good</b>           |    |     |         |
| What is the quality of surface finish?<br><b>Good</b>  | What is the appearance of the finished product?<br><b>Smooth</b> |    |     |         |
| <b><u>Post-Pour Observations</u></b>   |  |    |     |         |
| Are there any surface anomalies?<br><b>At start there were no surface anomalies. Later, slight air pockets were found after finishing.</b> |  |    |     |         |
| <b><u>Sample Preparation for Testing</u></b>   |  |    |     |         |
| Number of samples for compressive strength test at 7, 28 & 56 days: <b>9 samples</b><br>(Cylinder 100 mm dia. & 200 mm ht.)                |  |    |     |         |
| Number of samples for flexural strength test at 28 days: <b>3 samples</b><br>(Prism 350 x 100 x 100 mm):                                   |  |    |     |         |
| Number of samples for shrinkage test at 3-56 days: <b>3 samples</b><br>(Prism with side studs 285 x 75 x 75 mm):                           |  |    |     |         |

Slump value = **At plant (125 mm) Before casting (160 mm)**

Air content (at batching plant) = **2.6%**

Time taken for finishing = **~14 minutes**

Remarks on workability during placing and finishing: **Good place ability, workable, normal.**

Temperature of concrete before casting = **18°C**

Other observations (if any): **Not any.**

## Appendix B: Checklist for FBA Concrete at Site

### Concrete Placement Checklist/inspection

| Date: 20/02/2025   | Location: Tom Barney oval                                 | Section: Last Section (10 m)             |     |         |
|--|---|--|-----|---------|
| Concrete Mix: FBA  | Quantity: 2 m <sup>3</sup>                                | Start time: 09:09 a.m. Temperature: 21°C |     |         |
| Humidity/Wind: 84%/19 km/hr  |   | End Time: 09:36 a.m.                     |     |         |
| Description  | Yes   | No                                       | N/A | Remarks |
| <b><u>Pre-Pour Checks</u></b>  |   |  |     |         |
| Is the excavation size correct?  | x   |  |     |         |
| Is the excavation base compacted correctly?  | x   |  |     |         |
| Is the excavation dry?   | x   |  |     |         |
| Is the formwork bracing adequate?  | x   |  |     |         |
| Has mould oil been applied evenly and thoroughly?  | x   |  |     |         |
| Is formwork vertically and horizontally aligned?   | x   |  |     |         |
| Are the rebars free from rust?   | x   |  |     |         |
| Is the spacing and concrete cover, correct?  | x   |  |     |         |
| Is the pore site clean and free from all debris?   | x   |  |     |         |
| <b><u>Concrete Placement Observations</u></b>  |   |  |     |         |
| Is there any bleeding?   |   | x  |     |         |
| Is there any segregation?  |   | x  |     |         |
| Are the joints properly spaced?  |   | x  |     |         |
| Are the joints provided properly?  |   | x  |     |         |
| <b><u>Compaction and Finishing</u></b>   |   |  |     |         |
| What is the vibration/compaction method?<br>Started with shovel and then finalized with portable electric vibrator   | What is the quality of compaction?<br>Good                |  |     |         |
| What is the quality of surface finish?<br>Good   | What is the appearance of the finished product?<br>Smooth |  |     |         |
| <b><u>Post-Pour Observations</u></b>   |   |  |     |         |
| Are there any surface anomalies?<br>There were some air bubbles after finishing.                                     |   |  |     |         |
| <b><u>Sample Preparation for Testing</u></b>   |   |  |     |         |
| Number of samples for compressive strength test at 7, 28 & 56 days: 9 samples<br>(Cylinder 100 mm dia. & 200 mm ht.) |   |  |     |         |
| Number of samples for flexural strength test at 28 days: 3 samples<br>(Prism 350 x 100 x 100 mm):                    |   |  |     |         |
| Number of samples for shrinkage test at 3-56 days: 3 samples<br>(Prism with side studs 285 x 75 x 75 mm):            |   |  |     |         |

Slump value = At plant (110 mm) Before casting (88 mm)

Air content (at batching plant) = 2.8%

Time taken for finishing = ~14 minutes

Remarks on workability during placing and finishing: Workable, slightly stickier than control.

Temperature of concrete before casting = 18°C

Other observations (if any): Dark colour compared to control.