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# Sustainable Concrete with Waste Glass and Pond Ash: Durability and Life Cycle Assessment

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**Abstract:**

Crushed waste glass as fine aggregate (GFA) is increasingly utilised in concrete to address environmental issues from glass waste accumulation and reduce dependency on natural river sand, which is rapidly depleting and harming river systems. However, GFA presents a significant challenge due to Alkali-Silica Reaction (ASR), which causes concrete expansion and cracking, thereby limiting its broader application. Pond ash (PA), the residual ash from coal-fired power plants stored in ash ponds or silos, is employed as a supplementary cementitious material owing to its pozzolanic properties and is viewed as a potential alternative to fly ash (FA), which mitigates ASR but faces supply shortages due to coal plant closures. This study explores the viability of PA in reducing ASR expansion and enhancing the durability of GFA concrete. Concrete mixes with varying levels of GFA and PA replacements were tested for compressive strength, shrinkage, creep, moisture absorption, permeability, sorption and ASR expansion over short- and long-term curing periods, with PA performance compared to that of FA. Key findings indicate that GFA enhances both short-term and long-term strength while increasing the risk of ASR expansion. In contrast, PA effectively eliminates ASR expansion and performs similarly to FA. Furthermore, PA demonstrated comparable performance to FA in all other durability tests, confirming its viability as an alternative to FA. Life cycle assessment results reveal that while GFA alone does not substantially improve the environmental impacts of concrete, the addition of PA markedly enhances its sustainability by significantly reducing impacts in major categories.



**Keywords:** waste glass; fine aggregate; fly ash; pond ash; durability; LCA

## 1. Introduction

Glass is a crucial material in modern society, celebrated for its clarity, resilience, and versatility across a wide range of applications. However, glass waste constitutes about 7% of the world's solid waste by mass and due to its incredibly slow decomposition, it occupies long term landfill space and represents a persistent loss of a recyclable resource and of the energy invested in its production (Ling et al., 2013; Nature, 2021; Topçu and Canbaz, 2004). Recycling provides a potential solution, but it faces numerous challenges. The standard recycling process, which involves melting, cleaning, and sorting, is both energy-intensive and costly. Moreover, achieving high-quality recycled glass is challenging due to impurities and colour variations, making it difficult to adhere to strict quality standards (Guo et al., 2020; Olofinnade et al., 2017). As a result, global glass recycling rates remain low, which has led to growing interest in alternative applications for waste glass (Disfani et al., 2012). One such alternative is using crushed waste glass as fine or coarse aggregates in composite materials like concrete (Shi and Zheng 2007; Federico and Chidiac 2009; Mohajerani et al. 2017). This method not only has the potential to mitigate environmental impacts and conserve landfill space, but in regions where river sand is widely used as the main fine aggregate it could also lessen the ecological damage associated with in stream sand mining by substituting waste glass (Ali and Al-Tersawy, 2012).

However, incorporating glass into cementitious composites presents a significant challenge due to the risk of Alkali-Silica Reaction (ASR). In concrete, ASR occurs when the amorphous silica in glass reacts with cement alkalis, which may lead to deleterious expansion and cracking (Du and Tan, 2014; Pike and Hubbard, 1957; Saha et al., 2018). Previous research has consistently demonstrated that glass aggregates can exacerbate ASR expansion, with Abdallah and Fan (2014) documenting a 325% increase in ASR expansion at 20% GFA compared to a control mix. To mitigate ASR, researchers have explored the use of supplementary cementitious materials (SCM), particularly class-F fly ash (FA), which has lower lime content and has been proven effective in reducing ASR expansion by lowering the alkalinity of the concrete mix (Kim et al., 2015; Pereira De Oliveira et al., 2008; Topçu et al., 2008). Additionally, incorporating glass aggregates have shown to reduce water absorption, permeability, chloride penetration, and sulphate attack due to glass behaving as an impermeable barrier (Chen et al., 2006; Ling and Poon, 2011; Pereira De Oliveira et al., 2008; Taha and Nounu, 2008). Furthermore, studies have noted a potential reduction in shrinkage with increasing GFA content (Dumitru et al., 2010; Hunag et al., 2015). Despite extensive research on the durability of concrete with GFA, investigations into the performance of concrete containing both GFA and FA remain limited. Moreover, with the closure of coal power plants, the availability of FA is declining, underscoring the need for an alternative SCM for use in glass-based concrete.



In order to replace depleting FA, the current study introduces pond ash (PA) as an innovative waste-based SCM and compares its performance with that of FA. PA is the waste ash produced by coal power plants and is typically disposed of in outdoor ponds or storage tanks, thereby posing environmental risks (Yimam et al., 2021). Many countries, particularly in Europe and other member states of the Organisation for Economic Co-operation and Development (OECD), have adopted or announced policies to phase down or phase out coal fired power generation, which is expected to reduce future supplies of freshly produced fly ash while large volumes of legacy coal ash remain stored in existing ponds (Climate Analytics, 2019; Climate Transparency, 2019; International Energy Agency, 2021). In 2016, global coal combustion ash production was reported at 1,222 million metric tons per year, with only 64% utilised, leaving 544 million metric tons as waste (Harris et al., 2019). A 2022 survey indicated that approximately 5 million tonnes of ash waste were stored in onsite ponds awaiting potential reuse in Australia (Ash Development Association of Australia, 2023). As coal fired power plants are phased out, the production of clean, classified fly ash from run-of-station ash streams is expected to decline, reducing the availability of SCM grade FA. Coal combustion ash typically consists of a larger fly ash fraction and a smaller bottom ash fraction, with bottom ash usually making up from 10 to 20 % of the total ash (Fly Ash Australia 2023). At the same time, large volumes of legacy pond ash, containing a mixture of fly ash, bottom ash, soil and organic matter that has been exposed to rain and groundwater, will remain stored in existing ash ponds (Harris et al., 2019; Yimam et al., 2021). Prolonged storage of such material can increase the risk of leaching of trace elements and heavy metals to surrounding soil and groundwater (Harkness et al., 2016; Verma et al., 2021). In this context, harvesting and reusing pond ash as an SCM offers a means to recover a previously deposited waste while reducing the long-term environmental burden associated with ash ponds. Therefore, it is important to develop methods to reclaim and reuse this resource to minimise environmental impacts. In this study, reclaimed PA is used with minimal processing to avoid additional environmental burdens. Due to its long-term outdoor disposal and the associated exposure to impurities and moisture, PA may develop physical and chemical properties that differ significantly from those of conventional FA. Consequently, experimental investigations are necessary to establish PA as a viable SCM alternative to FA.

Previous studies by the authors demonstrated that PA can effectively mitigate ASR in glass mortar in a manner similar to FA. In that work, accelerated mortar bar test (AMBT) (ASTM International, 2023a), Thermogravimetric Analysis (TGA), pore solution analysis and Scanning Electron Microscopy (SEM) showed that replacing OPC with PA or FA reduces $Ca(OH)_2$ content and pore solution alkalinity, promotes the formation of low Ca/Si C-S-H and C-A-S-H gels, and refines the microstructure, which together limit alkali transport to the glass and suppress ASR expansion (V. Fernando et al., 2025b; W. C. V. Fernando et al., 2025). Moreover, another subsequent study by the authors has shown that PA can be successfully incorporated in concrete with GFA and RC beams without compromising compressive or flexural performance (V. Fernando et al., 2025a). However, further research is required to assess its impact on the durability of concrete with GFA. The successful incorporation of reclaimed PA in concrete with GFA could represent a significant advancement toward achieving sustainability goals in the construction industry. Moreover, in addition to investigating durability properties, a comparative life cycle assessment (LCA) was conducted to evaluate the impact of GFA and PA incorporation on the environmental performance of concrete compared to conventional mixes. This research is significant as it examines the durability and environmental impacts of concrete using two waste materials, GFA and pond ash, thereby advancing sustainability in the construction industry and supporting the practical application of these materials.



## 2. Materials And Test Methods

### 2.1. Materials

In this study, a commercially available Ordinary Portland Cement served as the primary binder, while a commercially available river sand product was used as the main fine aggregate. Crushed waste glass with a maximum nominal size of 5 mm, sourced from IQ Renew in Queensland, Australia, was integrated as an alternative to river sand, and the coarse aggregate was a commercially available gravel with a maximum nominal size of 20 mm. Additionally, commercially available Class-F fly ash and pond ash, obtained from a coal power plant in Queensland, Australia, were used as supplementary cementitious materials to partially replace OPC. Particle size analysis by laser diffraction showed that 21.7% of the pond ash particles were larger than 75 μm, indicating the presence of a coarser bottom ash-like fraction within the harvested material. The physical properties of the GFA and river sand are detailed in Table 1. Moisture content, a vital factor in material analysis, was determined according to ASTM C566 (ASTM International, 2023b), and the absorption and densities were evaluated based on ASTM C128 (ASTM International, 2022). River sand was found to have significantly higher moisture content and absorption compared to glass.

**Table 1:** Physical properties of GFA and river sand

| **Property** | **Sand** | **GFA** |
|---|---|---|
| Moisture content (%) | 3.9 | 1 |
| Water absorption (%) | 0.48 | 0.3 |
| Dry density (kg/m³) | 2627 | 2438 |

| | | |
|---|---|---|
| SSD density (kg/m³) | 2640 | 2451 |

Figure 1 provides a visual comparison of the particle size distributions of GFA and river sand, following ASTM C33 specifications (ASTM International, 2023c). The grading curves for both materials confirm their compliance with ASTM C33 standards for fine aggregates, demonstrating their suitability for concrete applications.

**Figure 1:** Particle size distributions

## 2.2. Mix design

The experimental program involved creating multiple concrete mixes with different proportions of glass and SCMs, as shown in Table 2. The control mix was targeted to achieve a 30 MPa cylinder strength at 28 days with a 5% defective rate. The conventional fine aggregates were replaced with GFA in 10% increments up to 50%. The previous mortar study demonstrated that up to 50% GFA incorporation results in minimal strength reduction (W. C. V. Fernando et al., 2025). Therefore, this study focuses on GFA utilisation up to 50%. Furthermore, to evaluate the influence of FA and PA on the mechanical properties of GFA concrete, OPC was substituted with FA and PA in 10% increments, with a maximum of 30% replacement, while keeping the GFA level at 50%. This mix ratio arrangement enables the evaluation of both the impact of increasing GFA content and the effect of incorporating FA and PA alongside GFA on the durability of the concrete. Moreover, to ensure consistent water content (205 kg/m$^3$) and water/binder ratio (0.44) across all mixtures, adjustments were made based on the moisture content and water absorption values provided in Table 1. This approach allows for a fair comparison of the different mixes, as fluctuations in water content can greatly impact the concrete's strength and workability.

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**Table 2:** Concrete mixes for evaluating mechanical properties

| **Mix designation** | **OPC (kg/m³)** | **FA (kg/m³)** | **FA %** | **PA (kg/m³)** | **PA %** | **Sand (kg/m³)** | **GFA (kg/m³)** | **GFA %** |
|---|---|---|---|---|---|---|---|---|
| 0GFA – 0FA – 0PA | 466 | – | – | – | – | 581 | 0 | 0 |
| 10GFA – 0FA – 0PA | 466 | – | – | – | – | 523 | 58 | 10 |
| 20GFA – 0FA – 0PA | 466 | – | – | – | – | 465 | 116 | 20 |
| 30GFA – 0FA – 0PA | 466 | – | – | – | – | 407 | 174 | 30 |
| 40GFA – 0FA – 0PA | 466 | – | – | – | – | 349 | 232 | 40 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 50GFA – 0FA – 0PA | 466 | – | – | – | – | 291 | 291 | 50 |
| 50GFA – 10FA – 0PA | 419 | 47 | 10 | – | – | 291 | 291 | 50 |
| 50GFA – 20FA – 0PA | 373 | 93 | 20 | – | – | 291 | 291 | 50 |
| 50GFA – 30FA – 0PA | 326 | 140 | 30 | – | – | 291 | 291 | 50 |
| 50GFA – 0FA – 10PA | 419 | – | – | 47 | 10 | 291 | 291 | 50 |
| 50GFA – 0FA – 20PA | 373 | – | – | 93 | 20 | 291 | 291 | 50 |
| 50GFA – 0FA – 30PA | 326 | – | – | 140 | 30 | 291 | 291 | 50 |



### 2.3. Slump

A slump test was conducted following AS 1012.3.1 (Standards Australia, 2014a) to assess the workability of fresh concrete, as shown in Figure 2(a). The test used a standard cone, filled in three layers, each compacted 25 times. After levelling, the cone was lifted, and the slump was measured as the height reduction of the concrete. For each mix, the slump test was performed up to three times to verify consistency. When successive measurements produced the same value, that value was recorded as the slump for the mix.

### 2.4. Compressive strength test

To assess potential reductions in compressive strength due to durability concerns with concrete containing GFA, FA, and PA, cylinder specimens with a 100 mm diameter and 200 mm height were prepared and tested according to AS 1012.9 (Standards Australia, 2014b). A minimum of three cylinders were cast for each concrete mix. The concrete was poured into moulds in three layers immediately after mixing, with each layer compacted using a vibrating table to ensure consistency. After 24 hours, the specimens were demoulded and placed in a curing chamber with 100% humidity at ambient temperature. Once the curing period was complete, compressive strength was measured by applying a progressively increasing axial load at 20 MPa/min using a compression testing machine with a capacity of 2000 kN, as shown in Figure 2(b). Strength tests were performed at 28 days, 6 months, and 1 year to evaluate the long-term effects of the supplementary materials on the concrete's strength.

### 2.5. Creep test

The creep test of concrete specimens was conducted according to AS 1012.16 (Standards Australia, 1996) as shown in Figure 2(c), which outlines the procedures for measuring concrete deformation under sustained loading. This test aimed to assess how concrete deforms over time under a constant load, providing insights into its long-term stability and performance. Concrete cylinders, each with a diameter of 100 mm and a height of 200 mm, were cast and cured in a moist environment for 24 hours before demoulding. After demoulding, the specimens were kept in a moist room for an additional 28 days before testing commenced. During the creep test, the specimens were subjected to a constant compressive load using a creep frame within a controlled environment. The load applied was 40% of the concrete's characteristic strength, as determined by testing two additional cylinders for compressive strength according to the procedure outlined in section 2.4. The deformation response of the concrete under sustained load was monitored over 8 weeks using strain gauges connected to a data logger. The recorded strain values reflect the apparent creep deformation. Only one specimen was tested for creep because the full test requires a minimum duration of three months, and time limitations prevented the preparation and testing of additional replicates.

**Figure 2:** (**a**) slump test; (**b**) compressive strength test; (**c**) creep test; (**d**) shrinkage test; (**e**) moisture absorption and permeability test; (**f**) sorption test; (**g**) ASR expansion test

### 2.6. Shrinkage test

To assess concrete shrinkage, concrete prisms with dimensions of 75 × 75 × 280 mm were prepared, incorporating studs at each end, per the ASTM C157 standard (ASTM International, 2017). After mixing and casting the concrete, the specimens were initially cured within their moulds in a controlled environment for 23.5 hours before being carefully demoulded. After demoulding, the specimens were soaked in lime-saturated water for 30 minutes before measuring their length using a vertical comparator, as shown in Figure 2(d). Initial measurements were recorded 24 hours after the addition of water to the mix. The specimens were then kept in lime-saturated water for 28 days, after which a second set of measurements was taken. After the second measurement, the specimens were air-cured, and the length changes were monitored by recording measurements at monthly intervals over six months.



### 2.7. Moisture absorption and permeability

The moisture absorption and permeability of the samples were assessed by measuring the volume of permeable voids (VPV) following ASTM C642 (ASTM International, 2013), as shown in Figure 2(e). This evaluation was performed after two distinct curing periods, specifically at 28 days and 6 months. Following curing, the concrete cylinders were sectioned into 50 mm blocks. The mass of the samples was recorded under three conditions: oven-dry, saturated surface-dry, and after water immersion followed by boiling for 5 hours. These measurements were used to calculate the volume of permeable voids in the concrete.

### 2.8. Sorption test

The sorptivity test was performed following ASTM C1585 (ASTM International, 2020). Testing was conducted after 28 days and six months of curing. Cylindrical samples were sectioned into 50 mm blocks and oven-dried to achieve a constant mass. The blocks were then immersed in water, and only their bottom surfaces were exposed, as shown in Figure 2(f). To prevent moisture ingress from the sides, they were sealed with duct tape, and grease was used to cover the top surfaces. Mass gain was recorded at specific intervals over 6 hours.

### 2.9. ASR expansion test

The ASR expansion of concrete specimens was evaluated using the miniature concrete prism test (MCPT), as specified by the AASHTO T380 standard ((American Association of State Highway and Transportation Officials, 2019). This method addresses the limitations of ASTM C1260 (ASTM International, 2023d) and ASTM C1293 (ASTM International, 2023e) test methods, which are hindered by lower accuracy and prolonged testing durations exceeding one year, respectively, while maintaining a good correlation with ASTM C1293 (Fanijo et al., 2021). The MCPT procedure involved casting concrete prism specimens with dimensions of 50 mm × 50 mm × 160 mm and curing them in a moist environment for 24 hours before demoulding. The gauge length of a specimen is 125 mm, and the length is selected based on the ASTM C490 standard (ASTM International, 2021). The specimens were then immersed in water-filled storage containers, sealed, and placed in an oven or water bath at 60°C for 24 hours. After removal, surfaces, including metal gauge studs, were dried, and zero readings were taken within 15 seconds using a vertical comparator, following calibration with a reference bar. The specimens were then immersed in a 1N NaOH solution at 60°C and returned to the oven or bath, as shown in Figure 2(g). Periodic comparator readings were conducted at 7, 14, 28, 42, and 56 days, with additional readings at 70 and 84 days for slowly reacting aggregates. According to the AASHTO T380 standard, the criteria given in Table 3 should be followed to determine the degree of reactivity of GFA. Moreover, the standard states that an SCM is effective in mitigating ASR if the 8-week ASR expansion is less than 0.020%.

**Table 3:** Criteria for characterising the aggregate reactivity in the MCPT protocol in AASHTO T380

| **Degree of reactivity** | **Expansion at 8 weeks (%)** | **Average 2-week rate of expansion from 8 to 12 weeks** |
|---|---|---|
| Nonreactive | ≤ 0.030 | – |
| Nonreactive | 0.031 – 0.040 | ≤ 0.010% per 2 weeks |
| Low/slow reactive | 0.031 – 0.040 | > 0.010% per 2 weeks |
| Moderate reactive | 0.041 – 0.120 | – |
| Highly reactive | 0.121 – 0.240 | – |
| Very highly reactive | > 0.240 | – |



## 2.10. life cycle Assessment

The environmental impact of incorporating GFA and PA into the casting of RC beams was assessed using the internationally recognised ReCiPe 2016 v1.09 midpoint (H) and endpoint (H) methodologies within the SimaPro 9.6 program. ReCiPe 2016 breaks down the environmental impacts into eighteen midpoint indexes and three endpoint indexes. These indicator scores demonstrate the relative severity of an environmental impact category. Data was presented as in characterised units and then normalised data. Normalisation of data is conducted automatically in the SimaPro software. Raw impact scores are divided by a reference value, allowing them to be compared on a common scale. Normalisation of data allows benchmarking as well as prioritisation of environmental impacts. The endpoint indicators in the ReCiPe method combine all 18 midpoint impacts into three key categories of “damage”: Human health, Ecosystems and Resources. For endpoint indicators, a higher ‘score’ indicates a higher degree of damage to the category. Furthermore, the embodied energy was assessed for each scenario using the Cumulative Energy Demand v1.12 methodology.

The ReCiPe model provides three present cultural perspectives (Individualist, Hierarchist and Egalitarian). These perspectives control how far along the cause-effect chain the model calculates impacts, and how conservative or precautionary the assumptions are. Ultimately, the perspective will impact the characterisation factors, damage models and uncertainty treatment. In LCA, uncertainty comes from gaps or limits in scientific knowledge and variability in real-world processes (like manufacturing or transport). The hierarchist perspective will incorporate moderate uncertainty into the results of the LCA, recognising that some variability in emissions and impacts is inevitable due to differences in materials, data quality, and system boundaries.

The LCA was conducted for a functional unit of 1 $m^3$ of mass concrete, the environmental impact of conventional concrete is compared with that of concrete incorporating GFA and PA from cradle-to-gate. A cradle-to-gate system boundary was selected because the primary objective was to compare the production-stage environmental burdens of concrete incorporating GFA and PA against a conventional mix. Figure 3 illustrates the system boundary and the framework for concrete production. The use phase was omitted as all mixes were designed for the same structural application and are expected to exhibit comparable service lives, meaning that the operational impacts (maintenance, energy use, in-service emissions) would not meaningfully differentiate the scenarios from an LCA perspective. End-of-life impacts were also excluded because demolition, waste handling and recycling pathways vary significantly between jurisdictions and project contexts, introducing uncertainty into the analysis.

**Figure 3:** System boundary and framework



Waste glass is collected from the Willawong waste collection facility and transported to the processing/ recycling centre at Wacol. At the recycling centre, waste glass material is crushed into an aggregate size range and then washed. Energy requirements for this process were sourced from previously published data (Hossain et al., 2016; Tushar et al., 2023). Glass aggregate is then transported to a local cement plant operated by Wagners in Pinkenba. All transportation distances for glass are included in the scope of this LCA. Since FA and PA are byproducts of power generation, their environmental burden in this study is limited to the impacts of their transportation to the beam casting site, as the power plant's environmental impacts are fully allocated to its primary product, electricity (Advanced Readymix, 2024). FA and PA products were sourced from the Millmerran power station and transported to the cement plant in Pinkenba. Table 4 provides information on the material sources and their respective distances to the beam casting site.

**Table 4:** Raw material sources and distances to the concrete mixing site

| **Materials** | **Producers** | **Distance (km)** |
|---|---|---|
| Cement | Wagners Cement Plant, Pinkenba | 54 |
| Sand | Carbrook River sand facility | 44 |
| Gravel | Keperra quarry facility | 37.6 |
| Fly ash | Millmerran power station | 217 |

| | | |
|---|---|---|
| Pond ash | Millmerran power station | 217 |
| GFA | From the Willawong waste collection facility to the Wacol glass recycling facility | 11 |
| GFA | Wacol glass recycling facility | 11.2 |

The assessment was conducted across three scenarios to comprehensively compare the environmental impacts of incorporating waste materials into concrete. Scenario 1 (S1) represents the production of 1 $m^3$ of conventional concrete, accounting for the landfilling of waste glass and coal ash, as these materials would otherwise be disposed of if not used in concrete. In Scenario 2 (S2), 50% of river sand is replaced by GFA, thereby diverting waste glass from landfills. The LCA scenarios in this study were developed based on concrete mixes that demonstrated both satisfactory mechanical performance and improved durability. The incorporation of 50% GFA resulted in increased strength and no significant negative effects on other measured durability properties, except for a substantial rise in ASR expansion.

Nevertheless, incorporating 10% PA effectively mitigated ASR without significantly affecting short or long-term strength or other durability parameters. Therefore, in Scenario 3 (S3), 10% of cement is replaced with pond ash, along with the replacement of 50% of river sand with GFA. Utilisation of these optimal performance outcomes ensures that the environmental benefits identified in the LCA are achieved without compromising the performance of the concrete. Comparing these scenarios allows for a robust evaluation of how incorporating these waste materials can improve the environmental performance of concrete.

- Scenario 1: A conventional concrete mix where waste glass and coal ash are disposed of in landfills (0GFA-0FA-0PA mix).
- Scenario 2: A mix in which 50% of river sand is replaced by processed waste glass (GFA) while pond ash is still landfilled (50GFA-0FA-0PA mix).
- Scenario 3: A mix where 50% of river sand is replaced by GFA and 10% of the cement is substituted with pond ash (50GFA-0FA-10PA mix)

Material and energy inputs for the analysis were sourced from the Ecoinvent 3 database. Allocation was “cut-off by classification – unit”. A summary of the material inputs, associated database descriptors and other information is provided in Table 5.

A sensitivity analysis of the LCA results was conducted using the Monte Carlo analysis function in Simapro. This function propagates the uncertainty information embedded within the Ecoinvent and AusLCI datasets. For each iteration, Simapro randomly samples from the probability distributions assigned to all the background inputs, such as material flows, emissions and energy use and then recalculates the full life cycle inventory and impact assessment. A total of 10,000 iterations were performed to generate a stable distribution.



**Table 5:** Material inputs

| **Inputs** | **Reference** | **Unit** | **S1** | **S2** | **S3** |
|---|---|---|---|---|---|
| Water | Tap water {RoW} \| tap water production, conventional treatment \| Cut-off, U | kg | 205 | 205 | 205 |

| | | | | | |
|---|---|---|---|---|---|
| Cement | Cement, Portland {RoW} \| cement production, Portland \| Cut-off, U | kg | 466 | 466 | 372.8 |
| Cement (transport) | Transport, freight, lorry 16–32 metric ton, EURO4 {RoW} \| market for transport, freight, lorry 16–32 metric ton, EURO4 \| Cut-off, U | tkm | 25.16 | 25.16 | 20.13 |
| Pond ash | Pond ash | kg | | | 93.2 |
| Pond ash (landfilling) | Landfilling pond ash – Hard coal ash {RoW} \| treatment of hard coal ash, residual material landfill \| Cut-off, U | kg | 93.2 | 93.2 | |
| Pond ash (transport) | Transport, freight, lorry 16–32 metric ton, EURO4 {RoW} \| market for transport, freight, lorry 16–32 metric ton, EURO4 \| Cut-off, U | tkm | | | 20.22 |
| Sand | Sand {RoW} \| gravel and sand quarry operation \| Cut-off, U | kg | 581 | 290.5 | 290.5 |
| Sand (transport) | Transport, freight, lorry 7.5–16 metric ton, EURO4 {RoW} \| market for transport, freight, lorry 7.5–16 metric ton, EURO4 \| Cut-off, U | tkm | 25.56 | 12.78 | 12.78 |
| GFA | Washing waste glass (sizes varying from 0.75–150 mm) – Tap water {RoW} \| tap water production, conventional treatment \| Cut-off, U – water 50 kg/t (Tushar et al., 2023) | kg/t | | 290.5 | 290.5 |
| GFA (processing) | Processing waste glass to produce GFA – 47 MJ/t (electricity) & 21 MJ/t (diesel) (Hossain et al., 2016) | MJ/t | | | |
| GFA (landfilling) | Landfilling waste glass – Waste glass {GLO} \| treatment of waste glass, sanitary landfill \| Cut-off, U | kg | 290.5 | | |
| GFA (transport) | Transport, freight, lor | | | | |



## 3. Results And Discussion

### 3.1. Slump

An increase in GFA content reduced workability, as shown by the slump test results in Figure 4(a). Although a GFA content of up to 30% had only a minimal effect, higher amounts led to a significant reduction in slump. Previous studies have linked the reduction in workability to the irregular angularity of GFA granules relative to the smoother surfaces of natural sand (Adaway and Wang, 2015; Bisht and Ramana, 2022; Su and Xu, 2023). Figure 5 presents SEM images that confirm GFA exhibits pronounced sharp ridges, which enhance inter-aggregate friction and consequently lower fluidity in contrast to the rounded grains of natural sand.

**Figure 4:** Impact on the slump; (**a**) by increasing GFA; (**b**) by replacing OPC with 10, 20 and 30% of PA/FA in 50% GFA concrete

The addition of both PA and FA markedly improves the workability of GFA concrete, as shown in Figure 4(b). This enhancement is primarily attributed to the morphology of the PA and FA particles. SEM images of all cementitious materials, presented in Figure 6, reveal that both PA and FA particles possess a spherical and smooth nature in contrast with OPC, which exhibits irregular and rough characteristics. The spherical and smooth texture of PA and FA particles reduces inter-particle friction and consequently improves the flowability of the concrete mix. This phenomenon has been previously reported for FA in the literature (Kurda et al., 2017; Nayak et al., 2022). Furthermore, mixes containing PA demonstrate significantly higher workability than those with FA. As shown in Figure 6(b), FA particles, despite being spherical and smooth, tend to clump together, whereas PA particles are more evenly dispersed, as observed in Figure 6(c). The agglomeration of FA particles can diminish the friction-reducing effect of their smooth surfaces, thereby explaining the lower workability of FA mixes compared to PA mixes.

**Figure 5:** SEM images of; (**a**) river sand; (**b**) GFA

**Figure 6**: SEM images of; (**a**) cement; (**b**) FA; (**c**) PA



## 3.2. Compressive strength

Figure 7(a) illustrates the strength development of GFA concrete over one year. Increased GFA content generally enhanced strength compared to the control and maintained this improvement over time. However, the 10% GFA mix exhibited lower strength than the control at 6 months and 1 year, despite showing comparable strength at 28 days. Overall, both short- and long-term trends indicate a strength increase with GFA incorporation. This improvement is likely attributed to the angular shape of GFA particles, in contrast to the smoother, rounder river sand (Figure 5), which enhances aggregate interlocking within the concrete matrix. Moreover, mixes with higher GFA content exhibited greater strength development, particularly between 28 days and 6 months, indicating that GFA contributes to long-term strength gain. This enhancement may be attributed to the pozzolanic activity of glass fines, which refines the microstructure and improves the interfacial transition zone (ITZ) between GFA and the cement matrix. This has been observed and discussed in our previous work as shown in the Figure 8 (V. Fernando et al., 2025b).

At the one-year mark, strength either continued to increase or plateaued in mixes containing up to 30% GFA. However, in mixes with 40% and 50% GFA, a noticeable decline in strength compared to 6-month results was observed. This reduction may be linked to microcracking caused by drying shrinkage, as GFA's higher friability makes it more susceptible to cracking under shrinkage stresses and to the long-term formation of ASR gels, which can weaken the concrete matrix over time (Maraghechi et al., 2012; Saccani and Bignozzi, 2010; Wu et al., 2015). This explains why the strength reduction is observed only in mixes with higher GFA content.

**Figure 7:** Strength development of concrete over 1 year: (**a**) With increasing GFA percentage; (**b**) with varying percentages of PA and FA in 50% GFA concrete

**Figure 8:** The bond between GFA and mortar matrix after (**a**) 28 days and (**b**) 91 days (V. Fernando et al., 2025b)

Figure 7(b) illustrates the effect of incorporating varying amounts of FA and PA on the strength development of concrete containing 50% GFA. Replacing 10% of OPC with PA resulted in slightly lower strength than FA. However, both PA and FA effectively mitigated the strength reduction observed in the 50% GFA-OPC mix at the one-year mark. When OPC replacement increased to 20% and 30% with either FA or PA, a significant reduction in strength was observed. This decline is attributed to the dilution of CaO, which is essential for cement hydration (W. C. V. Fernando et al., 2025). As indicated by the X-ray fluorescence (XRF) results in Table 6, the CaO content in FA and PA is considerably lower than in OPC. Consequently, increasing FA or PA replacement reduces the available CaO for hydration reactions, leading to diminished strength development.

**Table 6:** Chemical compositions of the OPC, FA and PA (W. C. V. Fernando et al., 2025)

| Material | $Al_2O_3$ | BaO | CaO | $Cr_2O_3$ | $Fe_2O_3$ | $K_2O$ | MgO | MnO | $Na_2O$ | $P_2O_5$ | $SO_3$ | $SiO_2$ | SrO | $TiO_2$ | LOI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OPC | 4.27 | 0.03 | >60 | 0.02 | 3.39 | 0.61 | 3.35 | 0.24 | 0.12 | 0.14 | 2.86 | 19.5 | 0.07 | 0.23 | 2.85 |
| FA | 25.02 | 0.10 | 4.56 | 0.01 | 6.90 | 0.88 | 1.29 | 0.09 | 0.30 | 0.61 | 0.25 | 56.28 | 0.05 | 1.34 | 2.17 |
| PA | 31.15 | 0.09 | 1.58 | <0.01 | 3.04 | 0.52 | 1.30 | 0.04 | 0.54 | 0.05 | 0.07 | 59.29 | 0.04 | 1.64 | 0.27 |



Nevertheless, at both 20% and 30% replacement levels, PA and FA exhibited similar performance at the 6-month and 1-year marks. However, at 28 days, PA consistently showed lower strength than FA across all OPC replacement levels. This can be attributed to its lower reactivity, which is influenced by its larger particle size, as illustrated in Figure 9. Unlike FA, which undergoes a comprehensive processing stage to filter out finer coal ash particles before becoming the commercially available SCM, PA is simply harvested from ash ponds without further refinement. As a result, PA retains significantly larger particle sizes compared to FA, contributing to its slower early-age reactivity. Hence, in terms of strength, PA serves as a viable alternative to FA for use in GFA concrete, particularly in long-term strength development. However, at 28 days, PA may exhibit slightly lower strength than FA due to its lower early-age reactivity.

**Figure 9:** Mean particle sizes of OPC, FA and PA

The compressive strength results are based on three cylinders per mix, and the accompanying standard deviations (SD) reflect the natural variability expected in concrete testing as presented in Table 7. The deviations are generally low to moderate, indicating consistent specimen preparation, uniform curing, and stable material behaviour across the experimental programme. These values show that repeatability was well maintained and that the observed strength trends are not influenced by random variation. The limited spread within each set confirms that three replicates were adequate to capture representative performance and ensures that the comparisons between different GFA, FA, and PA mixes are statistically reliable and reproducible.

**Table 7:** Compressive strength results

| Specimen | 28D Strength | | 6M Strength | | 1Y Strength | |
|---|---|---|---|---|---|---|
| | Result | SD | Result | SD | Result | SD |
| 0G - 0FA - 0PA | 29.7 | 2.6 | 36.3 | 1.4 | 36.8 | 2.8 |
| 10G - 0FA - 0PA | 29.7 | 1.1 | 34.4 | 1.6 | 33.9 | 0.3 |
| 20G - 0FA - 0PA | 32.2 | 2.0 | 37.5 | 4.8 | 39.2 | 1.8 |
| 30G - 0FA - 0PA | 34.1 | 1.6 | 38.7 | 0.8 | 40.7 | 0.9 |
| 40G - 0FA - 0PA | 33.5 | 1.3 | 41.5 | 3.5 | 41.3 | 0.8 |
| 50G - 0FA - 0PA | 34.6 | 0.2 | 43.6 | 2.1 | 41.5 | 0.5 |
| 50G -10FA - 0PA | 33.0 | 2.4 | 43.6 | 2.2 | 44.4 | 3.8 |
| 50G - 20FA - 0PA | 28.4 | 2.5 | 37.5 | 1.3 | 39.0 | 3.3 |
| 50G - 30FA - 0PA | 24.4 | 1.6 | 35.5 | 1.3 | 35.2 | 1.4 |
| 50G - 0FA - 10PA | 35.7 | 0.5 | 42.2 | 2.4 | 43.1 | 1.1 |
| 50G - 0FA - 20PA | 28.4 | 0.8 | 38.0 | 2.5 | 40.6 | 2.4 |
| 50G - 0FA - 30PA | 25.7 | 0.2 | 35.2 | 1.0 | 35.2 | 0.3 |

### 3.3. Creep

Figure 10 present the evolution of creep strain and the corresponding creep coefficient for the conventional concrete, the mix with 50% GFA, and the mixes in which 50% GFA is combined with FA or PA. The control shows a gradual increase in creep strain with time, which is reflected in a steadily rising creep coefficient typical of ordinary concrete. When 50% of the fine aggregate is replaced with GFA the very early age response is slightly higher than that of the control, which can be linked to local crushing of weaker glass particles under load (Polley et al., 1998). After this initial period, however, both the creep strain and the creep coefficient of the GFA mix remain consistently lower than those of the control throughout the rest of the test. This reduced time dependent deformation is attributed to the impervious and low porosity nature of the glass particles, which limits internal moisture migration and therefore drying creep (Harinadha Reddy and Ramaswamy, 2018). Microstructural studies have also shown that pozzolanic reaction around GFA produces additional C-S-H and C-A-S-H and improves the ITZ, leading to a stiffer and more deformation resistant matrix (V. Fernando et al., 2025a; Gorospe et al., 2019; Rajabipour et al., 2010; Steyn et al., 2021). He et al. (2019) reported a similar reduction in creep when glass powder was used, which they likewise attributed to microstructural densification of the paste and ITZ. At later ages the GFA specimens exhibit a lower creep rate than the control, which may be associated with the formation of ASR gel within fractured GFA particles providing a small counter expansive effect against the sustained load (Maraghechi et al., 2012; Rajabipour et al., 2015).

When PA is incorporated at a 20% level in a mix containing 50% GFA, the creep behaviour changes markedly relative to the other mixes. In terms of both creep strain and creep coefficient, the PA mix shows a slightly lower response at early age than the control, the 50% GFA mix and the FA mix, which can be linked to the higher workability of PA mixes that promotes better compaction and fewer entrapped air voids. As loading continues, however, the PA mix develops the highest time dependent deformation. This trend is consistent with the substantially larger and less reactive PA particles, which behave as weak inclusions and act as relatively large pores, increasing long term creep despite some refinement of the surrounding paste. In contrast, the FA mix exhibits higher creep at early age because many FA particles remain unreacted and function as fine pores until the pozzolanic reaction with $Ca(OH)_2$ generates secondary C-S-H that progressively stiffens the matrix and reduces further creep (Hong and Glasser, 2002, 1999). At later ages the creep coefficient of the FA mix stabilises below that of the PA mix, indicating that FA provides more effective long term microstructural densification than PA. These observations are in line with microstructural evidence for PA systems, where coarser unreacted particles and a more connected pore network have been linked to higher time dependent deformation than in comparable FA mixes (W. C. V. Fernando et al., 2025). Consequently, incorporating PA into GFA concrete increases creep even though GFA alone reduces it, and PA produces higher long-term creep than FA. Creep therefore requires particular attention when PA is used as an SCM in GFA concrete at the design stage, including careful optimisation of curing to maintain internal relative humidity and the possible use of internal curing agents or other admixtures that reduce drying related deformation in elements where long-term deflection is critical.

**Figure 10:** Creep behaviour with age; (**a**) creep strain and (**b**) creep coefficient

### 3.4. Shrinkage

Figure 11 illustrate the shrinkage behaviour of concrete with different compositions of GFA, FA, and PA over six months. The shrinkage of the control agrees with past studies (Hunag et al., 2015). During the first month, several specimens show negative shrinkage (expansion), especially those with lower GFA content. This early expansion is likely due to the immersion of specimens in lime-saturated water, which encourages moisture absorption rather than loss. In contrast, the control specimens, those with high GFA content, and specimens containing PA or FA exhibit little to no expansive behaviour. This response can be linked to the barrier effect of glass and the refined paste microstructure around glass and ash particles, which reduce water penetration and modify moisture transport paths (Chen et al., 2006; Dong et al., 2021; V. Fernando et al., 2025b; Ling and Poon, 2011). Likewise, specimens with PA or FA may experience a pozzolanic reaction in the outer regions in the presence of lime. This reaction consumes $Ca(OH)_2$ and forms additional low Ca/Si ratio C-S-H that progressively fills capillary pores and refines the connectivity of the pore network, which reduces moisture uptake and slows subsequent drying (V. Fernando et al., 2025a; W. C. V. Fernando et al., 2025; Saha, 2018; Shehata et al., 1999). After the lime-saturated water curing ends at one month, all mixes begin to exhibit positive shrinkage values. This change indicates the onset of drying shrinkage as the concrete loses moisture. The age versus length change graphs show that all specimens follow a similar slope, suggesting that the rate of shrinkage is comparable across the different mixes. Consequently, no significant differences in shrinkage emerge among the specimens as they age. The relative differences observed during the first month persist throughout the six months, with only slight deviations.



**Figure 11:** Shrinkage vs time for (**a**) varying GFA content and (**b**) varying FA/PA content

At the 6-month point, the specimens with only GFA show no clear trend in shrinkage with the increasing GFA content, as the results vary from percentage to percentage, as shown in Figure 12. Nevertheless, the inclusion of GFA shows lower values compared to the control, especially from 10 to 30% GFA, except for 40% GFA. This behaviour can be explained by the combined influence of internal relative humidity (RH) and pore structure. The essentially non-absorbent glass particles reduce the amount of paste that can lose water and act as internal barriers that interrupt capillary continuity. This limits the internal RH drop and reduces drying shrinkage. At the same time, pozzolanic reaction around GFA refines the pore system and decreases the connectivity of capillary pores, which further restrains shrinkage (Dong et al., 2021; V. Fernando et al., 2025a; W. C. V. Fernando et al., 2025). At higher GFA contents these beneficial effects compete with microcracking and local packing changes that create additional pores, which accounts for the scatter and for the less pronounced shrinkage reduction in some GFA levels.

When PA is introduced into the 50% GFA mix, the resulting specimens exhibit higher shrinkage at all PA levels compared with the 50% GFA mix alone, as illustrated in Figure 12. This increase can be attributed to the presence of relatively coarse, partially reacted PA particles, which act as weak inclusions and create additional capillary porosity that facilitates moisture loss and drying strain (V. Fernando et al., 2025a; W. C. V. Fernando et al., 2025). However, increasing the PA content results in a decreasing trend in shrinkage, whereas increasing the FA content leads to a rising shrinkage trend. As the PA content increases, shrinkage gradually decreases, indicating that the continued pozzolanic reaction of PA consumes $Ca(OH)_2$ and generates secondary C-S-H that refines the pore structure and partially compensates for the initial increase in deformability (V. Fernando et al., 2025a; W. C. V. Fernando et al., 2025; Saha, 2018; Shehata et al., 1999). In addition, specimens containing FA show significantly higher shrinkage than those with only 50% GFA or PA. Although previous studies have indicated that the inclusion of FA reduces shrinkage in conventional concrete by slowing the rate of hydration (Saha, 2018), the present study reveals that the incorporation of class-F coal ash in GFA-concrete results in an opposite effect, with both FA and PA additions substantially increasing shrinkage. Nevertheless, this shows that PA can be an effective alternative for FA when it comes to shrinkage in GFA-concrete.

**Figure 12:** Shrinkage at 6 months

Table 8 presents the shrinkage results and the corresponding six-month standard deviations, which remain low across all mixes. The small spread in values shows that the monthly measurements followed a consistent pattern and that shrinkage behaviour was reproducible within each mixture. The limited variability indicates stable testing conditions and confirms that the shrinkage trends observed for the different GFA, FA, and PA combinations are reliable.

**Table 8:** Shrinkage results and 6-month standard deviation

| Specimen | Months | | | | | | 6M SD |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | |
| 0G - 0FA - 0PA | -0.0016 | 0.009 | 0.0158 | 0.0248 | 0.0306 | 0.042 | 0.008 |
| 10G - 0FA - 0PA | -0.0104 | -0.0018 | 0.003 | 0.0122 | 0.0172 | 0.028 | 0.007 |
| 20G - 0FA - 0PA | -0.0084 | 0.0002 | 0.0102 | 0.0194 | 0.0236 | 0.038 | 0.010 |
| 30G - 0FA - 0PA | -0.0068 | 0.003 | 0.0086 | 0.0176 | 0.0224 | 0.033 | 0.009 |
| 40G - 0FA - 0PA | 0.010 | 0.0192 | 0.0272 | 0.0358 | 0.0396 | 0.048 | 0.005 |
| 50G - 0FA - 0PA | 0.0008 | 0.005 | 0.0144 | 0.0228 | 0.0268 | 0.036 | 0.007 |
| 50G -10FA - 0PA | 0.0108 | 0.0222 | 0.0308 | 0.0394 | 0.0434 | 0.055 | 0.011 |
| 50G - 20FA - 0PA | 0.0108 | 0.026 | 0.0314 | 0.0404 | 0.044 | 0.057 | 0.014 |
| 50G - 30FA - 0PA | 0.0296 | 0.0416 | 0.05 | 0.0592 | 0.0622 | 0.074 | 0.012 |
| 50G - 0FA - 10PA | 0.0092 | 0.0202 | 0.0314 | 0.042 | 0.045 | 0.058 | 0.015 |
| 50G - 0FA - 20PA | -0.0024 | 0.0128 | 0.0196 | 0.0308 | 0.0332 | 0.048 | 0.016 |
| 50G - 0FA - 30PA | -0.0012 | 0.012 | 0.0212 | 0.0316 | 0.0342 | 0.045 | 0.011 |

### 3.5. Moisture absorption and permeability

Figure 13 presents the moisture absorption and permeability test results for concrete with varying levels of GFA, FA, and PA. The inclusion of GFA slightly reduced both moisture absorption and permeability, which can be attributed to the barrier effect of GFA. The impermeable nature of GFA aggregates limits moisture penetration, while their dispersion throughout the concrete matrix increases the tortuosity of moisture migration paths, reducing moisture transport efficiency (Chen et al., 2006; Ling and Poon, 2011; Pereira De Oliveira et al., 2008; Taha and Nounu, 2008). However, by 6 months, this trend had diminished, with all GFA mixes exhibiting similar behaviour to the control, albeit with some fluctuations. Overall, the moisture absorption and permeability decreased from 28 days to 6 months due to continued cement hydration, which promoted C-S-H gel formation, refining the pore structure and further restricting moisture movement.

**Figure 13:** (**a**) Moisture absorption and (**b**) permeability test results at 28 days and 6 months

The inclusion of PA did not significantly influence moisture absorption or permeability at 28 days, as its performance remained comparable to both the control and the 50% GFA mix. Similarly, FA showed no notable impact at this stage. However, at 6 months, FA incorporation, particularly at the 10% replacement level, led to a slight reduction in both moisture absorption and permeability, whereas this effect was not observed in PA mixes. Consistent with GFA-OPC mixes, the 6-month results for both PA and FA showed lower moisture absorption and permeability due to continued hydration.

Table 9 presents the moisture absorption and permeability results together with their standard deviations at 28 days and 6 months. The standard deviation values remain low across all mixes, indicating minimal scatter among the three replicate specimens tested for each property. This limited variability shows that the test conditions were consistent and that the results are reproducible. The small spread between replicates also confirms stable material behaviour in both short-term and long-term measurements. Overall, the low SD values provide confidence that the trends observed in moisture absorption and permeability for the different GFA, FA, and PA mixtures are reliable and representative.

**Table 9:** Moisture absorption and permeability results and standard deviations

| Specimen | 28D Moisture absorption | | 6M Moisture absorption | | 28D Permeability | | 6M Permeability | |
|---|---|---|---|---|---|---|---|---|
| | Result | SD | Result | SD | Result | SD | Result | SD |
| 0G - 0FA - 0PA | 7.01 | 0.08 | 6.09 | 0.07 | 16.11 | 0.38 | 14.19 | 0.34 |
| 10G - 0FA - 0PA | 6.49 | 0.02 | 6.03 | 0.01 | 15.17 | 0.29 | 14.07 | 0.32 |
| 20G - 0FA - 0PA | 6.65 | 0.07 | 6.06 | 0.09 | 15.43 | 0.33 | 14.13 | 0.3 |
| 30G - 0FA - 0PA | 6.50 | 0.06 | 5.87 | 0.06 | 15.14 | 0.28 | 13.62 | 0.27 |
| 40G - 0FA - 0PA | 6.54 | 0.03 | 5.65 | 0.02 | 15.24 | 0.3 | 13.33 | 0.25 |
| 50G - 0FA - 0PA | 6.77 | 0.09 | 6.27 | 0.08 | 15.68 | 0.35 | 14.45 | 0.36 |
| 50G -10FA - 0PA | 6.39 | 0.01 | 5.88 | 0.01 | 14.91 | 0.26 | 13.74 | 0.28 |
| 50G - 20FA - 0PA | 6.70 | 0.07 | 6.10 | 0.06 | 15.44 | 0.31 | 14.14 | 0.31 |
| 50G - 30FA - 0PA | 7.22 | 0.1 | 6.83 | 0.09 | 16.48 | 0.4 | 15.48 | 0.42 |
| 50G - 0FA - 10PA | 6.80 | 0.01 | 6.16 | 0.02 | 15.46 | 0.32 | 14.21 | 0.33 |
| 50G - 0FA - 20PA | 6.72 | 0.06 | 5.68 | 0.05 | 15.11 | 0.27 | 12.96 | 0.24 |
| 50G - 0FA - 30PA | 7.17 | 0.09 | 6.59 | 0.07 | 16.18 | 0.37 | 14.86 | 0.39 |



### 3.6. Sorption

Figure 14 presents the sorption results for concrete with varying levels of GFA, FA, and PA at 28 days and 6 months. At 28 days, the inclusion of GFA up to 20% had no significant impact on sorption. However, at 6 months, an increase in sorption is observed in mixes containing more than 20% GFA, a trend that is not evident in the control or the 10% GFA mix. This increase may be attributed to microcracks induced by shrinkage stresses, which increase the surface area exposed to moisture during testing. Wu et al. (2015) demonstrated that pore connectivity, and consequently gas permeability, can increase due to microcracking caused by drying shrinkage. Given the higher friability of glass, drying-induced stresses may further enhance pore connectivity through the cracking of GFA particles. This mechanism explains the higher long-term sorption observed in mixes with higher GFA content. However, although Wu et al. (2015) reported an increase in gas permeability due to drying-induced microcracks, they did not observe any significant effect on water absorption, which explains the absence of an increase in the previously discussed 6-month moisture absorption results.

**Figure 14:** Sorption test results at 28 days and 6 months

The inclusion of PA increased sorption at 28 days, exhibiting a behaviour similar to that of FA. This can be attributed to the slow-reacting nature of the pozzolanic reaction in PA and FA, which results in higher porosity in the concrete matrix (Saha, 2018; Saha et al., 2018). However, at 6 months, sorption further increases in mixes containing both FA and PA, similar to the trend observed in mixes with higher GFA content. This increase may be due to microcracks caused by drying shrinkage, as the shrinkage results indicate significantly higher values in PA and FA mixes, as discussed in Section 3.4. Moreover, although the long-term pozzolanic reaction of PA and FA generates secondary C-S-H gels that refine the pore structure and reduce moisture absorption and permeability (W. C. V. Fernando et al., 2025; Saha, 2018), micro-pores may persist, maintaining pore connectivity. As previously discussed, gas permeability and moisture absorption exhibit different behaviours due to this effect, as also noted by Wu et al. (2015). Nevertheless, as an alternative to FA, PA has not exhibited any disadvantages in terms of sorption.

Table 10 presents the sorption results and their standard deviations at 28 days and 6 months. The SD values are very low across all mixes, indicating minimal variation between replicate specimens. This consistency shows that the sorptivity measurements were stable and reproducible, and that the observed trends among the different GFA, FA, and PA mixtures are reliable.

**Table 10:** Sorption results and standard deviations

| Specimen | 28D Sorption | | 6M Sorption | |
|---|---|---|---|---|
| | Result | SD | Result | SD |
| 0G - 0FA - 0PA | 0.0106 | 0.0003 | 0.0108 | 0.0004 |
| 10G - 0FA - 0PA | 0.0106 | 0.0003 | 0.0106 | 0.0003 |
| 20G - 0FA - 0PA | 0.0106 | 0.0004 | 0.0118 | 0.0005 |
| 30G - 0FA - 0PA | 0.0089 | 0.0003 | 0.0108 | 0.0004 |
| 40G - 0FA - 0PA | 0.0105 | 0.0004 | 0.0125 | 0.0006 |
| 50G - 0FA - 0PA | 0.0112 | 0.0005 | 0.0122 | 0.0005 |
| 50G -10FA - 0PA | 0.0103 | 0.0003 | 0.0121 | 0.0006 |
| 50G - 20FA - 0PA | 0.0114 | 0.0005 | 0.0136 | 0.0007 |
| 50G - 30FA - 0PA | 0.0083 | 0.0003 | 0.0138 | 0.0006 |
| 50G - 0FA - 10PA | 0.0106 | 0.0004 | 0.0122 | 0.0006 |
| 50G - 0FA - 20PA | 0.0113 | 0.0005 | 0.013 | 0.0007 |
| 50G - 0FA - 30PA | 0.0123 | 0.0006 | 0.0143 | 0.0008 |

### 3.7. ASR Expansion

Figures 15 and 16 present the MCPT expansion test results for concrete incorporating GFA, FA, and PA. Consistent with previous studies, this study also recorded a significant increase in ASR expansion with increasing GFA content (Abdallah and Fan, 2014; Ismail and AL-Hashmi, 2009; Limbachiya, 2009; Liu et al., 2022). The amorphous silica in GFA reacts with $OH^-$ and alkali metal ions, leading to the formation of an alkali-silicate gel, which absorbs water and expands in volume (Du and Tan, 2014; Pike and Hubbard, 1957). This expansion induces cracking, which progressively compromises the strength and durability of concrete over time (Rajabipour et al., 2015). According to the criteria outlined in AASHTO T380 (American Association of State Highway and Transportation Officials, 2019) and presented in Table 3, only the control mix was classified as having nonreactive aggregates. The nonreactivity of the control is further confirmed by measuring the average two-week expansion rate from 8 to 12 weeks. Based on these criteria, GFA replacement levels between 10% and 40% exhibit moderate reactivity, whereas 50% GFA is classified as highly reactive, posing a potential risk to the durability of concrete structures.

Nevertheless, the incorporation of PA and FA in 50% of GFA concrete eliminated ASR expansion, as shown in Figures 14 and 15. Even with just 10% PA/FA incorporated, the ASR expansion was significantly reduced compared to the GFA concrete containing only OPC. Increasing the PA and FA content further reduced expansion, and most notably, both materials effectively mitigated expansion to the extent that the specimens exhibited slight negative values due to regular shrinkage. Furthermore, PA demonstrated superior performance compared to FA, reinforcing its potential as a viable alternative to FA as an ASR mitigation SCM in GFA concrete. This finding aligns with our previous mortar study, in which the AMBT (ASTM International, 2023a) was used to assess ASR expansion in mixes containing GFA and PA. That study showed, using ASR expansion tests in combination with TGA, SEM and pore solution analysis, that both PA and FA can effectively suppress ASR in GFA mortar. Replacing OPC with PA or FA reduced $Ca(OH)_2$ availability, promoted the formation of C-S-H and C-A-S-H type hydrates with low Ca/Si, and improved the microstructure and ion transport resistance, which together limited the ingress of $Na^+$ and $OH^-$ to the reactive glass and prevented the formation of expansive ASR gel (W. C. V. Fernando et al., 2025).

**Figure 15:** Age vs ASR expansion results from MCPT

**Figure 16:** MCPT ASR expansion results at 8 weeks

Table 11 presents the ASR expansion results together with the 8-week standard deviations. The SD values are small across all mixes, indicating consistent readings between replicate prisms and reliable measurement stability. The limited variability confirms that the expansion behaviour observed, including both the reactive GFA mixes and the mitigated FA and PA mixes, is reproducible and representative of the actual ASR response of each mixture.

**Table 11:** ASR expansion results and 8-week standard deviation

| Specimen | Weeks | | | | | | | 8-week SD |
|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 6 | 8 | |
| 0G - 0FA - 0PA | 0 | -0.0048 | 0.0028 | 0.0044 | 0.01 | 0.0196 | 0.0368 | 0.0057 |
| 10G - 0FA - 0PA | 0 | -0.0024 | 0.0024 | 0.0064 | 0.0156 | 0.0268 | 0.0488 | 0.0011 |
| 20G - 0FA - 0PA | 0 | -0.0044 | 0.0048 | 0.0088 | 0.0176 | 0.0312 | 0.0608 | 0.0102 |
| 30G - 0FA - 0PA | 0 | -0.0032 | 0.0068 | 0.0104 | 0.0192 | 0.0348 | 0.0672 | 0.0011 |
| 40G - 0FA - 0PA | 0 | -0.004 | 0.0088 | 0.0128 | 0.024 | 0.0408 | 0.0944 | 0.0023 |
| 50G - 0FA - 0PA | 0 | -0.0028 | 0.0100 | 0.0152 | 0.0264 | 0.0528 | 0.154 | 0.0436 |
| 50G -10FA - 0PA | 0 | -0.0028 | 0.0012 | 0.0032 | 0.004 | 0.0048 | 0.0064 | 0.0011 |
| 50G - 20FA - 0PA | 0 | -0.004 | -0.0036 | -0.0028 | -0.0016 | -0.0008 | 0.0000 | 0.0000 |
| 50G - 30FA - 0PA | 0 | -0.004 | -0.0024 | -0.0012 | -0.0032 | -0.0024 | -0.0016 | 0.0011 |
| 50G - 0FA - 10PA | 0 | -0.004 | -0.002 | -0.0024 | -0.0028 | -0.004 | -0.0028 | 0.0017 |
| 50G - 0FA - 20PA | 0 | -0.004 | -0.0032 | -0.0036 | -0.004 | -0.0052 | -0.0044 | 0.0006 |
| 50G - 0FA - 30PA | 0 | -0.004 | -0.0044 | -0.0052 | -0.0092 | -0.0108 | -0.0124 | 0.0006 |

### 3.8. Life cycle assessment results

Figure 17 illustrates the percentage differences in those environmental impacts for S2 and S3 relative to S1, with S1 serving as the baseline. A comparison of S1 and S2 demonstrates the impact of incorporating GFA in concrete. Replacing 50% of river sand with GFA produces minimal changes across most environmental impact categories, with the notable exceptions of land use and water consumption. The inclusion of GFA yields slight reductions in most impacts while causing small increases in stratospheric ozone depletion, freshwater eutrophication, and marine eutrophication. The increase in eutrophication can be attributed to the washing process of waste glass, which contributes to elevated nutrient runoff. Moreover, the washing process results in a water consumption increase of 303% compared with conventional concrete. On the other hand, using GFA reduces land use by 29% because the substitution prevents waste glass from being landfilled. Furthermore, substituting GFA for river sand circumvents the harmful environmental impacts on river systems associated with river sand extraction, impacts that are not captured in this analysis.

**Figure 17:** Comparison of characterised ReCiPe 2016 midpoint results (log scale)

The coefficient of variation (CV), defined as the standard deviation divided by the mean (Montgomery and Runger, 2010) provides a measure of relative uncertainty in Monte-Carlo-based LCA results. In line with conventions used in environmental modelling and LCA uncertainty analyses (Henriksson et al., 2014; Lloyd and Ries, 2007). CV values below 5–10% are generally interpreted as low uncertainty and therefore reliable for comparative purposes. CV values between 10–50% indicate moderate to high uncertainty, whereas CV values exceeding 50% (common for toxicity- and ecotoxicity-related indicators) reflect very large variability and reduced interpretive confidence (Mendoza Beltran et al., 2018).

The CVs for characterised ReCipe midpoint results are shown in **Figure 18**. Impact categories dominated by well-characterised industrial processes such as, global warming, fossil resource scarcity, particulate matter formation, ozone formation and terrestrial acidification, showed very low coefficients of variation (CV < 5%) in all scenarios. These categories reflect emissions from cement production, electricity generation and transport, all of which are modelled using stable, high-quality datasets in Ecoinvent. As a result, these indicators are highly reliable for comparing environmental performance between mixes. In contrast, categories associated with eutrophication, land use and certain resource flows exhibited moderate uncertainty (CV 20–50%), reflecting greater variability in background data related to nutrient emissions, agricultural land occupation and extraction processes. The highest uncertainty occurred consistently in toxicity-related and water-related categories (CV > 50–110%), which is typical in LCA due to the very wide distributions used to model heavy metals, leachates and water balances. These categories are driven largely by globalised inventory assumptions with limited regional specificity, meaning that the absolute values can be reported but should not be used as primary decision-making indicators.

**Figure 18:** Coefficient of variance for characterised ReCipe 2016 midpoint results



The differences in CV values between scenarios reflect how material substitutions influence the relative contribution of stable versus highly variable processes in the life cycle inventory. Introducing 50% glass fine aggregate in S2 does not substantially alter uncertainty relative to the conventional mix (S1), as glass washing and crushing are well-defined processes and generally replace the equally stable extraction of natural river sand. However, S2 does exhibit slightly reduced uncertainty in freshwater and marine ecotoxicity because replacing natural sand removes variability associated with quarrying emissions and land disturbance. The largest shifts in uncertainty occur in S3, where 10% of cement is replaced with pond ash. Reducing cement content decreases the contribution of a highly stable and well-modelled process, while introducing pond ash, an industrial by-product with greater inherent variability in composition and trace metal emissions, adds uncertainty to toxicity-related categories. Accordingly, S3 shows increased uncertainty in human toxicity metrics but reduced uncertainty in ecotoxicity and several resource-related categories, as cement reduction outweighs the variability introduced by pond ash. Overall, the sensitivity analysis demonstrates that while the magnitude of environmental impacts decreases in S2 and S3, particularly due to reduced cement content and landfill avoidance, the underlying uncertainty structure remains dominated by the variability embedded within toxicity and water-related datasets.

The characterised results provide absolute impact values in their designated units; however, they do not convey the relative significance of each impact category. Normalised results address this limitation by relating each impact to a common reference, thereby revealing which categories are most critical. This approach facilitates clearer comparisons across diverse impact types and helps identify environmental hotspots. Figure 19 presents the normalised ReCiPe 2016 midpoint results, which indicate that human carcinogenic toxicity, freshwater eutrophication, freshwater ecotoxicity, and marine ecotoxicity are the most significant. Notably, human carcinogenic toxicity exhibits an exceptionally large impact. Moreover, while the characterised results show a considerable increase in water consumption, the normalised perspective demonstrates that this impact is negligible within the broader environmental context.

**Figure 19:** Normalised ReCiPe 2016 midpoint results

Replacing 10% of cement with PA exerts a significant influence on all impact categories, as shown in Figure 17. Land use experiences a further reduction of 3% compared to S2, primarily due to the avoidance of coal ash disposal in ash ponds. Water consumption decreases by 22% compared with S2, although it remains 281% higher than in S1. Freshwater eutrophication, human carcinogenic toxicity, and human non-carcinogenic toxicity are reduced by more than 80% compared to S1, while freshwater ecotoxicity and marine ecotoxicity decrease by over 59%. All other impacts show reductions of up to 11% when PA is incorporated compared with conventional concrete. The normalised results in Figure 19 and the summary in Table 12 show that human carcinogenic toxicity is the dominant impact category, followed by freshwater eutrophication and freshwater ecotoxicity. Scenario 3, which combines GFA with PA and avoids coal ash landfilling, achieves markedly lower normalised scores in all three categories compared with the control scenario and the GFA only scenario. These reductions are primarily associated with clinker substitution and the diversion of coal ash from long term pond storage, which together decrease emissions and leaching related burdens. From a practical perspective, this suggests that, where harvested PA is available, GFA PA concrete should be preferred over conventional concrete and GFA only concrete in applications where human toxicity and aquatic impacts are of particular concern, and that policies encouraging pond ash recovery and performance based SCM specifications can deliver tangible environmental benefits.

**Table 12:** Top four impact categories based on normalised midpoint results

| Impact category | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| Human carcinogenic toxicity | 1.6E+01 | 1.5E+01 | 2.6E+00 |
| Freshwater eutrophication | 7.4E-01 | 7.5E-01 | 1.3E-01 |
| Freshwater ecotoxicity | 6.5E-01 | 6.3E-01 | 2.5E-01 |
| Marine ecotoxicity | 5.5E-01 | 5.4E-01 | 2.2E-01 |



Figure 20 visualises the ReCiPe 2016 endpoint results. Comparing S1 with S2 shows that replacing river sand with GFA yields only marginal improvements in normalised damage endpoints, with reductions of 0.9% for human health, 1.6% for ecosystems, and 4.8% for resources. In contrast, the incorporation of PA in S3 results in substantial reductions across all damage categories. Specifically, human health impacts drop by 48%, ecosystem damage decreases by 21%, and resource impacts are reduced by 11% relative to S1. These pronounced reductions in S3 underscore the significant environmental benefits achieved by integrating PA alongside GFA, markedly enhancing the overall sustainability profile of the concrete.

**Figure 20:** Normalised ReCiPe 2016 endpoint results

Table 13 presents the cumulative energy demand for each scenario across various impact categories. The replacement of river sand with GFA did not significantly reduce total energy demand due to the energy-intensive crushing and washing processes associated with GFA. However, compared to S1, S3 reduced total energy demand by 9%, whereas S2 achieved only a 2% reduction. This indicates that replacing 10% of OPC with PA has nearly proportionally reduced energy demand, primarily due to the energy-intensive nature of cement production, whereas PA remains unprocessed.

**Table 13:** Cumulative energy demand for each scenario

| Impact category | Unit | S1 | S2 | S3 |
|---|---|---|---|---|
| Non-renewable, fossil | MJ | 2.7E+03 | 2.6E+03 | 2.4E+03 |
| Non-renewable, nuclear | MJ | 7.4E+01 | 7.3E+01 | 6.8E+01 |
| Non-renewable, biomass | MJ | 9.8E-02 | 9.1E-02 | 8.5E-02 |
| Renewable, biomass | MJ | 4.1E+01 | 4.1E+01 | 3.7E+01 |
| Renewable, wind, solar, geothermal | MJ | 3.0E+01 | 3.1E+01 | 2.9E+01 |
| Renewable, water | MJ | 6.3E+01 | 6.3E+01 | 5.9E+01 |
| **Total Energy demand** | MJ | **2889.1** | **2831.4** | **2633.2** |

## 4. Conclusions

- Replacing conventional fine aggregates with up to 50% GFA in concrete demonstrated favourable performance across various properties, including strength, strength development, creep, shrinkage, moisture absorption, permeability, and sorption, without causing significant adverse effects. However, shrinkage exhibited considerable variability. Despite these benefits, the inclusion of even 10% GFA resulted in a marked increase in ASR expansion, indicating potentially severe long-term ASR-related deterioration.

- To mitigate ASR caused by GFA, PA was used as an SCM and compared with FA. The inclusion of PA resulted in a strength reduction due to the dilution effect; however, PA effectively eliminated ASR expansion in GFA concrete. Additionally, PA performed well in terms of strength development, moisture absorption, permeability, and sorption, reinforcing its viability as an ASR-mitigating SCM for use in GFA concrete. This demonstrates that PA can be effectively utilised as an ASR-mitigating SCM in combination with reactive aggregates.

- Given that the inclusion of 10% PA had an insignificant impact on the strength of GFA concrete and was able to reduce ASR expansion to levels even lower than the conventional concrete, 10% PA can be considered an optimal measure for ASR mitigation in concrete. However, PA has shown relatively poor performance in creep compared to both OPC and FA, which should be addressed during the design stage. In terms of shrinkage, PA performed worse than OPC but better than FA, making it a viable alternative to FA.

- Incorporating GFA in concrete may provide modest environmental benefits relative to conventional mixes, primarily by reducing landfilling of waste glass and lowering the demand for natural sand, although additional water may be required for glass washing. Within the limits of the present LCA assumptions and system boundaries, the addition of PA to GFA concrete appears to further improve the overall sustainability profile, with lower impacts in several midpoint categories and reduced energy demand compared with the conventional and FA based mixes.

The durability tests indicate that GFA is a viable alternative to river sand, although its use may cause significant ASR expansion. To mitigate this, PA was incorporated as an ASR-mitigating SCM in concrete containing GFA and compared with FA. PA demonstrated promising durability performance by eliminating ASR expansion and performing well in most other durability tests while showing similar performance to FA. Additionally, PA offers substantial sustainability advantages by significantly reducing environmental impacts and energy demand. Therefore, replacing up to 50% of river sand with GFA is feasible when 10% of OPC is optimally replaced by PA. Nevertheless, considering the significant environmental and sustainability benefits, using PA at levels above 10% is feasible despite a moderate reduction in strength, especially for non-structural applications as pavements, precast blocks and masonry walls, where load demands are limited. In such cases, PA rich GFA concrete should be adopted only after verifying compliance with relevant design and durability provisions in current standards, for example AS 2758.1 (Standards Australia, 2014c) for concrete aggregates, AS/NZS 3582.1 (ASTM International, 2016) and ASTM C618 (ASTM International, 2023f) for fly ash type SCMs, and, where possible, confirming performance through targeted field trials.

While the findings of this study demonstrate the potential of GFA and PA to enhance both the durability and environmental performance of concrete, several limitations should be acknowledged. The LCA was restricted to a cradle-to-gate boundary and did not consider the use or end-of-life phases, which may affect the overall sustainability assessment. Additionally, durability tests were conducted under controlled laboratory conditions and may not fully reflect performance under variable field exposures. Although the reuse of GFA and PA supports circular economy objectives by reducing reliance on virgin materials and landfill disposal, the recyclability of the resulting concrete was not assessed. Future research should explore the reusability of such concrete as recycled coarse aggregate, particularly considering the implications of ASR-related microcracking on mechanical reprocessing.



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## Author contributions

**VF** conducted the investigation, performed the formal analysis, curated the data, conceptualised the study, and wrote the original draft. **WL**, the principal supervisor, led the conceptualisation and methodology, provided overall supervision and project administration, validated the work, supplied resources, and was a major contributor in reviewing and editing the manuscript. **HS** contributed to the methodology and resources, validated the work, and assisted with reviewing and editing the manuscript. **HW** contributed to the conceptualisation and methodology, provided supervision, validated the work, and reviewed and edited the manuscript. **CG** contributed to the conceptualisation and methodology, provided supervision and validation, and assisted in reviewing and editing the manuscript. All authors read and approved the final manuscript.

## Data Availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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## Declarations

## Competing interests

The authors declare that they have no competing interests.

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