Final Project Report

R1P4- Using drinking water treatment alum sludge to make greener and durable concrete

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Acknowledgements and Project Team

We gratefully acknowledge the support and collaboration of all partner organisations and team members who have contributed to the success of this project, as summarised by Table 1. This work was led by Professor Yan Zhuge (University of South Australia, UniSA), who had overall responsibility for the project and guided the development and testing of AS-based mortar and concrete materials. Professor Christopher Chow (UniSA) provided expert leadership on sludge and wastewater characterisation, including assessment of potential environmental and regulatory issues associated with the reuse of alum sludge. We sincerely thank Professor Rameez Rameezdeen (UniSA) for his leadership on life cycle costing, life cycle assessment, reverse logistics and broader circular-economy framing, which enabled the project to move beyond materials development to systems-level impact. Dr Tom Benn (UniSA), as Chief Investigator, provided strategic oversight, research guidance and continuous support across all phases of the project.

Our industry partner, the South Australian Water Corporation (SA Water), has been critical to the practical relevance of this work. In particular, we thank Dr Alexandra Keegan (Industry lead) and Amanda Mussared for providing industry insight, coordinating access to AS samples and plant information, and facilitating engagement with key SA Water stakeholders.

The project has also been strongly supported by a committed research team at UniSA. Dr Yue Liu (Research Associate – feasibility and durability) and Dr Weiwei Duan (PhD student – feasibility and durability) played central roles in experimental design and testing related to fresh and hardened properties, long-term durability, alkali-silica reaction (ASR), acid corrosion, microbiologically induced corrosion (MIC) performance and elevated-temperature behaviour. Dr Jiarui Liu (Research Associate – quality control) led the development of the quality-control framework for AS-derived SCMs, including multi-source sampling, reactivity assessment and correlation with performance.

On the systems and modelling side, Dr Bin Huang (Research Associate – embedded carbon assessment) led the integrated carbon analysis for AS-derived concretes, and Dr Li Luo (Research Associate – supply chain model) developed the national-scale supply-chain optimisation framework for AS valorisation in the concrete sector. Finally, we thank the SmartCrete CRC and broader teams within UniSA and SA Water for their logistical, technical and administrative support, and for providing access to facilities, data and operational insights. Their collective efforts have been essential in progressing this project from concept to a robust body of evidence supporting the safe, durable and low-carbon use of AS in concrete.

Table 1. Project team and roles

Contact	Organisation	Role in Project
Yan Zhuge	UniSA	Overall responsibility for the project with an emphasis on mortar material development
Christopher Chow	UniSA	Sludge and wastewater characterisation, assessment of potential environmental issues
Rameez Rameezdeen	UniSA	Life cycle costing and life cycle assessment; reverse logistics; circular economy
Alexandra Keegan	South Australian Water Corporation (SA Water)	Providing industry insight and coordinating SA Water sample/site provision

Tom Benn	UniSA	Chief investigator
Yue Liu	UniSA	Research associate-feasibility and durability
Jiarui Liu	UniSA	Research associate-quality control
Bin Huang	UniSA	Research associate- embedded carbon assessment
Weiwei Duan	UniSA	PhD student-feasibility and durability

Executive Summary

This project set out to convert a problematic waste—drinking water treatment alum sludge (AS)—into a reliable, low-carbon resource for concrete. Water utilities generate large volumes of AS that are typically landfilled at significant cost, while the concrete industry faces increasing pressure to reduce clinker-related CO_2 emissions and dependence on finite natural sand and fly ash. The central question was therefore: can AS be safely and consistently used to replace part of the cement and sand in concrete, while delivering robust durability and tangible carbon benefits at scale?

To address this, the project was structured into four phases: (1) Feasibility and basic performance evaluation of a new type of mortar lining material developed with AS; (2) Durability in aggressive environment; (3) Integrated carbon assessment and supply-chain optimisation; and (4) Variability assessment and quality control for commercialisation. Across 12 publications (10 journal papers and 2 conference papers), 9 progress reports and 1 PhD thesis, the project met—and in several areas exceeded—these objectives.

Experimentally, the work demonstrated that, with standardised pre-treatment (dewatering, grinding and calcination at ~800 °C), AS behaves as a reactive supplementary cementitious material (SCM) and/or fine filler. Binary and ternary binders with 10–20% cement replacement (and up to 30% in slag/limestone blends) achieved equal or higher 28–90-day strengths than reference mixes. AS was also successfully used as a partial sand replacement in dry-mix blocks, particularly when combined with early-age CO_2 curing.

Durability testing yielded several notable outcomes. In ordinary Portland cement (OPC) systems, AS mitigated ASR with recycled glass aggregates and improved elevated-temperature performance. In slag-based alkali-activated materials (AAMs), alum-rich AS significantly enhanced resistance to ASR, sulfuric-acid attack and MIC, positioning these binders as strong candidates for sewer and other CO_2-rich environments. Toxicity Characteristic Leaching Procedure (TCLP) tests consistently showed that heavy metals remain well immobilised.

At the systems level, integrated life-cycle assessment indicated that treated AS emits approximately 80 % less CO_2 per tonne than general purpose (GP) cement. Replacing only 10 % of cement with AS reduces concrete life-cycle emissions by around 9 %, with additional savings achievable when renewable electricity or low-carbon fuels are used. A national mixed-integer optimisation study further demonstrated that regional sludge-processing hubs can deliver substantial greenhouse gas (GHG) savings, positive net present value and regional job creation.

Given the high variability of AS, no single test is sufficient to qualify such unconventional SCMs. The project therefore developed a practical multi-parameter quality-control (QC) framework based on R^3 bound water, fineness and simple strength tests to classify AS into reactivity classes and define safe, application-appropriate replacement ranges. In parallel, a “blending and calcination” protocol was shown to effectively reduce performance variability between sources. When combined with limiting AS replacement to around 10% in most structural applications, this approach constrains fluctuations in mechanical and durability performance to levels considered acceptable for industry use.

1. Industry Problem, Needs and Relevance

Global cement production reached approximately 4,100 million tonnes in 2019, and annual production is projected to increase by about 50% by 2050 [1]. Cement manufacture currently contributes up to 8% of global anthropogenic CO_2 emissions, making it one of the most carbon-intensive bulk materials in use [2]. To mitigate this impact, there is a strong international drive to partially replace clinker with low-carbon supplementary cementitious materials (SCMs), including industrial by-products and residues.

In parallel, rapid population growth, economic development and changing consumption patterns have increased the demand for treated water. Mainland Australia alone operates around 400 drinking water treatment plants, with individual facilities generating up to 2,000 tonnes (dry mass) of AS per year [3]. AS, a residual sludge from coagulation–flocculation and filtration processes, is commonly disposed of to landfill without beneficial reuse, incurring substantial financial and environmental costs. In metropolitan Adelaide, for example, landfill levies of ~AUD 140/t, combined with handling costs, result in total disposal costs of ~AUD 200–250/t (excluding transport) [3]. Preliminary assessments indicate that one large Victorian water utility spends more than AUD 1.5 million per year on AS disposal, and another more than AUD 6 million per year [3], highlighting strong economic incentives for valorisation.

The market potential of AS as an SCM is therefore significant. AS is rich in reactive aluminium phases and, when appropriately processed, can contribute to cementitious systems with enhanced acid resistance at lower cost than conventional calcium aluminate cements, given that AS is currently a cost liability. Under such circumstance, the UniSA team has, for the first time in Australia, developed durable mortar and concrete block products that incorporate AS as sand replacement, supplementary cementitious material (SCM) and precursor for alkali-activated materials (AAM). Valorisation of AS as building material provides both an economical and environmentally beneficial route for AS management, while preserving diminishing natural resources. The environmental benefits are twofold: (i) significant quantities of AS are diverted from landfill, and (ii) demand for virgin raw materials for cement and concrete production is reduced. This work aligns directly with SmartCrete CRC's objectives on improving competitiveness and sustainability through utilisation of AS as novel construction materials, and represents a practical, scalable example of circular-economy principles being applied to critical infrastructure sectors.

2. Project Objectives and Impact Pathways

2.1. Project objectives

The project seeks an environmentally acceptable and economically viable solution to the AS disposal issue faced by water utilities, while enabling lower-carbon concrete products. The four phases were designed not only to answer technical questions, but also to reduce the key barriers to adoption by concrete suppliers, asset owners, end users, and policy stakeholders. Together, they establish a pathway from feasibility, to durability confidence, to system-level implementation, and finally to quality assurance and commercial readiness.

Phase 1: Feasibility and basic performance

The objective of Phase 1 was to determine whether AS could be processed and incorporated into cementitious systems in a practically workable manner, including as an SCM in OPC systems and as a precursor component in AAM systems. The target applications were lower-risk, factory-controlled products such as mortar products, blocks, pavers, precast elements, and selected concrete mixes. These applications shaped the experimental focus on processability, fresh properties, strength development, and basic durability-related performance. For concrete suppliers, this phase addressed the first adoption question: can AS become a usable feedstock rather than remain a waste material? For end users, it established initial confidence that AS could be used in real products rather than only in laboratory formulations.

Impact pathway: supports early adoption in lower-risk concrete products where suppliers can trial AS under controlled production conditions and end users need evidence of basic performance and manufacturability.

Phase 2: Durability in aggressive environment

The objective of Phase 2 was to determine whether the most promising AS-based binders and products could remain reliable under service conditions relevant to infrastructure, particularly aggressive chemical and biologically active environments. The target applications were sewer and wastewater assets, reactive-aggregate systems, and other infrastructure exposed to harsh degradation conditions. These applications shaped the experiments toward identifying critical degradation mechanisms, defining the design parameters that must be controlled, and generating the durability evidence needed before field translation. For end users such as utilities and asset owners, this phase was essential because adoption depends on confidence in long-term service behaviour, not only initial strength. For suppliers, it helped define the higher-value applications where AS-based systems may offer the strongest case for uptake.

Impact pathway: supports targeted adoption in durability-driven applications, especially where sewer, wastewater, acid-prone, or reactive environments determine material selection.

Phase 3: Integrated carbon assessment & industrial symbiosis

The objective of Phase 3 was to evaluate whether AS valorisation delivers meaningful environmental, economic, and logistical benefits beyond laboratory-scale performance. This phase placed AS reuse within a broader industrial system linking sludge generation in the water sector with material demand in the concrete sector. The target applications were product pathways that could realistically be deployed at scale through regional processing and local manufacture, particularly lower-strength and commodity concrete markets where large volumes can generate strong circular-economy impact. In this phase, the 12.5 MPa “business-as-usual” concrete was used as a benchmark for carbon and supply-chain modelling. It provides a practical reference case for evaluating implementation potential in applications such as mortar linings, blocks, pavers, and other non-structural elements. For utilities, manufacturers, and procuring agencies, this phase addressed whether AS reuse can be delivered at realistic cost, useful scale, and credible environmental benefit.

Impact pathway: informs where AS reuse should be implemented first, which product classes are most scalable, and how regional processing, logistics, and procurement can support uptake.

Phase 4: Variability assessment and quality control

The objective of Phase 4 was to address the main commercial barrier to implementation: the intrinsic variability of AS between sources and over time. This phase aimed to determine how differences in chemistry, mineralogy, fineness, impurities, and processing history affect performance, and to translate that understanding into a practical framework for quality control, acceptance, and specification. The target applications were those most likely to move toward production, including mortar, blocks, pavers, precast products, and conservative use in selected concrete systems. These applications shaped the experiments toward what must be measured, controlled, and documented so AS can be incorporated into industrial production with acceptable consistency and risk. For concrete suppliers, this phase underpins feedstock qualification, batching reliability, and process compatibility. For end users, asset owners, and regulators, it provides confidence that AS-based products can be manufactured consistently and used within clearly defined application boundaries.

Impact pathway: supports the transition from research outcomes to auditable industrial practice by providing the quality-control basis needed for supplier acceptance, specification development, and repeatable production.

3. Project Methodology and Key Activities

This project advanced an innovative methodology, combining in-depth qualitative and quantitative approaches to achieve the objectives in four designated phases, as summarised in Table 2 and Figure 1. Phase 1 established the feasibility of using DWT in a range of green-concrete products by combining systematic material characterisation, microstructural analysis and basic performance testing. Phase 2 extended the methodology to evaluate durability of the most promising AS-derived systems under aggressive exposure conditions relevant to real infrastructure, with a particular focus on sewer environments and reactive aggregates. Phase 3 shifted from laboratory testing to systems-level modelling, integrating life-cycle carbon assessment with national-scale supply-chain design for AS-derived SCMs and concretes. Phase 4 focused on quality control (QC) and standardisation to enable industrial upscaling, with a dedicated experimental programme on multiple AS sources to develop practical acceptance criteria for use as SCM.

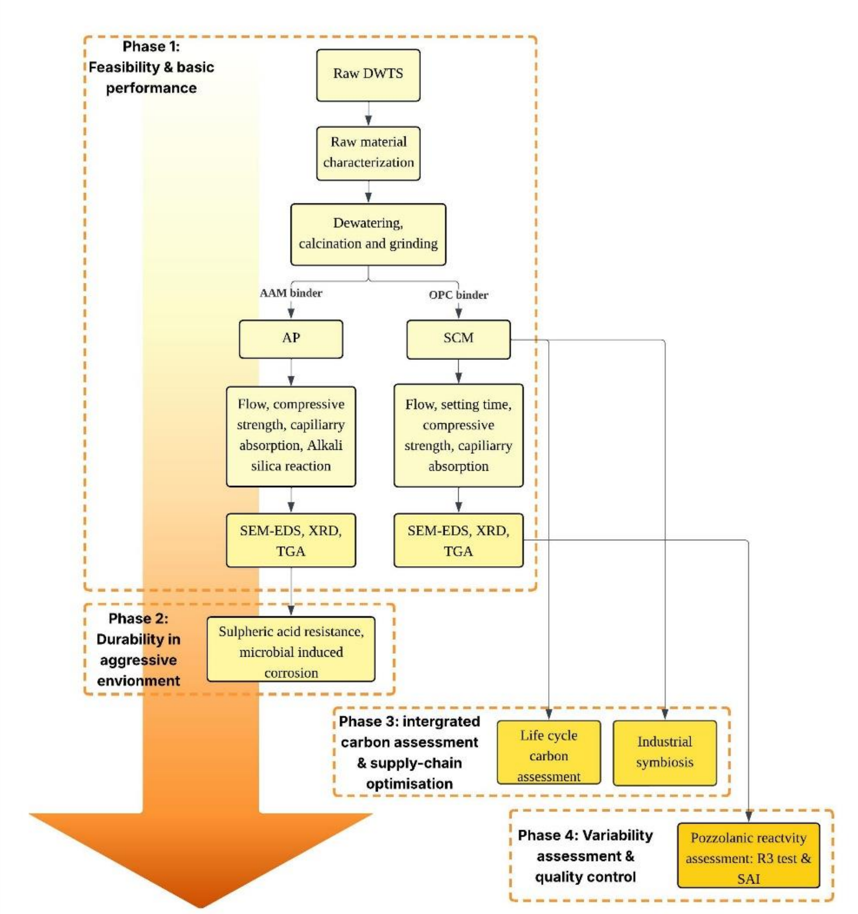

Figure 1. Flow chart of project methodology and key activities

3.1. Phase 1 – Feasibility & basic performance

First, representative AS samples from multiple drinking water treatment plants were collected and pre-treated (drying, grinding, calcination) under controlled conditions. Comprehensive raw-material characterisation was undertaken to quantify chemical and physical variability. Chemical composition and oxide ratios were determined by X-ray fluorescence (XRF), mineralogy by X-ray diffraction (XRD), and loss on ignition (LOI) using ASTM D7348 [4] and

AS 3583.3 [5]. Physical properties such as specific gravity, water absorption, morphology and PSD were measured using ASTM D854 [6], AS 1141.5 [7], scanning electron microscopy (SEM) and laser diffraction, respectively.

To understand reaction mechanisms, reaction product characterisation was carried out on hydrated pastes and mortars. Mineralogy evolution was monitored by XRD and thermogravimetric analysis (TGA), while Fourier transform inferred spectroscopy (FTIR) was used to identify changes in chemical bonds. Scanning electron microscopy - energy dispersive spectroscopy (SEM–EDS) were used to link hydrate assemblage and pore structure gel with macroscopic behaviour.

Finally, the basic performance of AS-derived products (as SCM or aluminosilicate precursor (AP)) was assessed. Fresh properties (flow/consistency) were measured using ASTM C1437 [8]. Mechanical properties (compressive and flexural strength) were evaluated according to AS 1012.9/AS4456.4 and ASTM C348/C293. Physical properties such as Capillary absorption, Water absorption, and Porosity were was assessed using ASTM C1585 [9], AS 1012.21 [10]/ASTM C642, and ASTM C597 [11]/ mercury intrusion porosimetry (MIP). Lastly, ASR performance was assessed on mortars with recycled glass aggregates and AS as SCM/AP using AS 1141.60.1 [12]. Expansion was monitored under accelerated conditions, with complementary microstructural observations (SEM–EDS) to characterise ASR products and crack patterns.

3.2. Phase 2 – Durability in aggressive environment

For chemical durability aggressive environment, sulfuric-acid resistance of both OPC and AAM systems incorporating AS was evaluated using ASTM C267 [13], with periodic measurements of mass loss, strength loss and depth of neutralisation. Further, MIC was investigated using both controlled laboratory corrosion chambers and in situ exposure at real sewage facility. Mortar coupons were exposed to cultures of Thiobacillus ferrooxidans or mixed sulphur-oxidising bacteria (ASTM C1904 [14]), as well as real wastewater environments. Chamber conditions (temperature, relative humidity, H_2S concentration) were controlled, and corrosion progression was monitored via surface pH, H_2S uptake rate, neutralisation depth, density and porosity. Periodic sampling of corrosion layers allowed high-throughput DNA sequencing of 16S rRNA genes to track microbial communities, while Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) was used to quantify sulfur species and dissolved ions. Photogrammetry and 3D surface reconstruction (Photomodeler®) were applied to determine material loss and derive corrosion rates.

3.3. Phase 3 – Integrated carbon assessment & supply chain optimisation

For the integrated carbon assessment, a cradle-to-grave model was developed for sludge-derived concrete products. The system boundary included AS dewatering, transport, calcination and grinding, SCM production, concrete batching and curing, operational service (including carbonation), and end-of-life. Life-cycle inventory (LCI) data were collected from plant records, literature, and industry databases, covering energy consumption, fuel types, material flows and transport distances. The model compared a 12.5 MPa "business-as-usual" GP cement concrete with mixes where 10–20 % of cement was replaced by treated AS. Scenario analyses investigated the effects of varying cement replacement levels, alternative fuel options, renewable electricity penetration, curing regimes and carbonation rates on embodied and life-cycle CO_2-e.

In parallel, a multi-objective mixed-integer linear programming (MILP) model was formulated to design a national waste-to-resource supply chain for AS-derived SCM. Decision variables included locations and capacities of processing facilities (drying, calcination, grinding), allocation of AS from drinking water treatment plants to these facilities, and distribution of SCM to concrete production sites. Constraints captured supply–demand balance, plant capacities, technology options, and transport networks. Three objectives were optimised simultaneously:

(i) maximise greenhouse-gas savings (relative to landfilling and GP cement use),

(ii) maximise net present economic benefit (revenues minus capital and operating costs), and

(iii) maximise social benefit (job creation, especially in employment-vulnerable regions).

The optimisation produced Pareto-optimal configurations, highlighting trade-offs between environmental, economic and social goals. Sensitivity analyses on energy prices, landfill levies, transport costs, and clinker replacement rates explored robustness and informed practical recommendations for utilities and cement producers.

3.4. Phase 4 – Variability assessment & quality control

Eight types of alum-based sludges from different drinking water treatment plants were selected to capture realistic variability in chemical composition, LOI, mineralogy, fineness and impurity levels (e.g. Fe, Cu, Ti). All samples were processed using a standardised activation protocol (dewatering → grinding → calcination at 800 °C), to decouple inherent material variability from processing effects. Comprehensive characterisation included XRF for bulk chemistry, quantitative XRD (QXRD) for crystalline and amorphous phase quantification, specific gravity measurements and particle-size distribution (PSD) analysis.

To quantify pozzolanic reactivity, the ASTM C1897 R^3 test [15] was applied to pastes containing each AS as SCM. Bound water and CH consumption at 7 d were measured via TGA to identify secondary hydrate formation (particularly hydrogarnet-type C–A–H). In parallel, conventional SAI tests (ASTM C311 [16]) were conducted on mortars with fixed replacement levels of OPC by each sludge, measuring UCS at standard ages. Fresh properties (flow) and basic mechanical performance (UCS, AS 1012.9 [17]) were also recorded to capture practical workability and strength effects.

Microstructural and elemental analyses (SEM–EDS, QXRD, TGA) were used to interpret differences between ASs in terms of hydrate assemblage, CH content and pore structure. Statistical correlations were then developed between (i) rapid indices (R^3 bound water, amorphous content, PSD, impurity levels) and (ii) performance indicators (SAI, strength development). This allowed differentiation between “chemical reactivity” and “strength contribution” driven by filler/nucleation effects.

The outcome was a multi-parameter QC framework rather than reliance on a single test. The project identified 7d R^3 bound water, amorphous content and fineness as primary indices for ranking AS reactivity, with SAI and simple physical tests used as secondary, performance-based checks. Conceptually, this enables AS from different plants to be categorised into high-, medium- and low-reactivity classes, with corresponding recommended replacement ranges for cement-based systems.

Table 2. Methodologies and key activities in four phases.

Phase	Role of AS	Property	Tests and activities	Standard/ method	Ref.
1	Raw material characterization	Chemical properties	Chemical composition	XRF	[18-23]
			Mineralogy	XRD	[20, 23]
			LOI	AS3583.3 [5]	[23]
			Morphology	Scanning electron microscopy (SEM)	[20]
			PSD	Laser particle diffraction	[18-20, 22, 23]
	Reaction product characterisation	Chemical properties	Mineralogy	XRD	[19-23]
			Chemical bond	FTIR	[22, 23]
			Microstructure & elemental mapping	SEM-EDS	[19-23]
	Basic performance	Fresh properties	Flow/ consistency /fluidity	ASTM C1437 [8]	[20]
		Mechanical properties	UCS	AS 1012.9 [17]	[18-23]
			Flexural strength	ASTM C348 [24]	[18, 19]
				ASTM C293 [25]	[18]
		Physical properties	Capillary absorption	ASTM C1585 [9]	[18-20]
			Water absorption	AS 1012.21 [10]	[21]
				ASTM C642	[23]
			ASR	AS1141.60.1 [12]	[18, 19, 21]
			Porosity	UPV (ASTM C597) [11]	[18]
				MIP	[20]
2	Durability in aggressive environment	Acid aggression	Sulphuric acid resistance	ASTM C267 [13]	[22]
		MIC	Sulphur-oxidizing bacteria	ASTM C1904 [14]	[23]
3	LCA and carbon assessment	industrial symbiosis	Gabi software	As detailed by ref.	[26]
		Integrated carbon assessment	Model for carbon footprint of sludge-derived concrete products	As detailed by ref.	[27]
4	Raw material characterization	Chemical properties	Chemical composition	XRF	[28, 29]
			Mineralogy	QXRD	
		Physical properties	PSD	Laser particle diffraction	
		Pozzolanic reactivity	R3 test	ASTM C1897 [15]	
			SAI	ASTM C311 [16]	
	Reaction product characterization	Chemical properties	Thermal gravimetric analysis	TGA	
			Microstructure & elemental mapping	SEM-EDS	
			Mineralogy	QXRD	

4. Deliverables & Analysis of Key Results

4.1. Deliverables

4.1.1. Progress reports

Over the three and half year's project period (Jan 2023-Dec 2025), the nine quarterly reports trace a clear progression from materials development and proof-of-concept, through durability testing and systems-level decarbonisation modelling, to quality control and scale-up strategies for valorising AS in concrete. The full progress reports can be found in Attachment A.

Technically, the project pursued two main material pathways. First, AS was incorporated as a precursor in AS-AAMs. Mortars with up to ~40–60% AS achieved high UCS and significantly reduced ASR. Systematic 1% H_2SO_4 testing showed that replacing high-Ca binders with AS-rich AAMs reduced strength loss from ~48% to ~27%, linked to the formation of a more stable, Si-rich aluminosilicate layer rather than expansive gypsum. Parallel microbially induced corrosion (MIC) work refined test protocols using sulphur-oxidising bacteria, elemental sulphur and an HCl pre-leach step to overcome high initial alkalinity. Under these improved conditions, mixes with around 20% AS consistently outperformed slag-rich systems, pointing to genuine durability benefits in sewer environments.

Second, the project examined AS as a manufactured pozzolan and sand replacement in conventional cement concretes, framed against AS 3582.4. A metropolitan sampling campaign collected AS from multiple water treatment plants, with standardised drying, grinding and calcination. Extensive characterisation (chemistry, LOI, PSD, mineralogy, TGA) revealed high amorphous contents but substantial variability in organics and heavy metals. Performance testing using the R^3 method and SAI showed a wide reactivity spectrum: some calcined ASs comfortably met Grade 1 requirements at 20% replacement, while others were strongly retarding. Blending multiple sources prior to calcination and fine grinding markedly reduced variability, demonstrating a viable quality-control strategy. The work also highlighted that AS 3582.4 alone is insufficient for AS, and proposed additional indicators (amorphous content, bound water, CH consumption, heavy-metal profiles) for industrial QC.

In parallel, a comprehensive decarbonisation and reverse-logistics stream quantified the environmental and economic value of AS valorisation. Life-cycle assessment showed that treated AS has roughly one-seventh the embodied carbon of Portland cement, and that 10–30% cement replacement can reduce concrete emissions by ~9–27% per tonne, with much larger savings at national scale. A genetic-algorithm optimisation tool was developed to select supplying water plants, locate integrated sludge treatment facilities and design truck routes under different technical and policy scenarios. Results indicate that treating AS at water plants is most energy- and carbon-efficient, while using existing equipment at concrete plants is often most cost-effective once avoided landfill fees are included.

4.1.2. Publications

In addition to progress reports, 9 journal papers (8 published and 1 in submission) and 2 conference papers have been completed, as summarised by Table 3. By mapping all project publications to the four phases by clarifying the role of AS, the product type and the performance tests or models applied, the table demonstrates how the publications collectively progress from material feasibility to durability, decarbonisation potential and practical QC for industrial implementation. A full publication list is presented in Section 8. As shown in the table, phases 1 and 2 jointly capture the transition from basic performance characteristics to durability, where AS is incorporated in OPC pavers (ambient and CO_2-cured), mortars and AAMs; performance is probed through ASR expansion, sulphate and sulfuric-acid attack, MIC, elevated-temperature exposure, sorptivity, TCLP and other durability indicators. In Phase 3, AS acts purely as an SCM within system-level tools, namely a multi-objective MILP supply-chain model and an integrated carbon assessment framework for AS-derived concrete. Finally, Phase 4 focuses on AS as an SCM in OPC mortars, linking R^3 reactivity tests, SAI and fresh/mechanical properties to quality control and upscaling.

Table 3. Publications and their corresponding themes.

Phase	**Role of AS**	**Product**	**Performance tests/model**	**Ref.**
1	SCM	OPC Mortar	UCS, flexural strength, ASR, water absorption	[18]
			UCS, flexural strength, sorptivity, ASR	[19]
	AP	AAM mortar	UCS, flow, water absorption	[20]
			UCS, water absorption, ASR	[21]
2	AP	AAM mortar	UCS, Sulfuric acid corrosion	[22]
			UCS, MIC, water absorption	[23]
3	LCA	Integrated carbon assessment	Model for carbon footprint of AS-derived concrete products	[27]
		Industrial symbiosis	Gabi	[26]
4	SCM	Quality control of SCM	R3 test, SAI, flow	[28, 29]

4.2. Key results

4.2.1. Phase 1 – Feasibility & basic performance evaluation

The Phase 1 established that AS—after milling and calcination—can be incorporated into cementitious binders in two principal ways: as a SCM in Portland-cement systems and as an AP blended with slag in AAMs. The work therefore focused on practical feasibility (strength and workability windows), early durability indicators (transport and ASR resistance), and the associated reaction products/mechanisms that rationalise performance trends. A consistent theme is that AS contributes through both physical effects (particle packing, nucleation, filler action) and chemical effects (pozzolanic reaction in OPC; participation in alkali-activation chemistry), but the balance depends strongly on dosage and system alkalinity.

Duan et al. (2020) [18] showed that calcined AS can behave as a reactive SCM when used at modest replacement levels. When ≤10% of cement was replaced, both compressive and flexural strength improved, with 10% identified as the optimum for maximum strength. The durability-relevant transport response also improved: calcined AS reduced capillary water absorption, interpreted as pore refinement caused by additional C–S–H formed via pozzolanic reaction and concurrent portlandite (CH) consumption. Importantly, AS improved resistance to alkali–silica reaction (ASR): at 20% replacement, ASR was effectively prevented (Figure 2). The proposed mitigation mechanisms were multi-factor: (i) formation of secondary C–S–H (densification), (ii) CH consumption (reducing alkalinity and Ca availability for ASR gel evolution), (iii) aluminium-mediated control of reactive silica dissolution, and (iv) reduced permeability limiting transport of alkalis and moisture. This paper is foundational because it shows AS can be more than an inert filler: at the right level and treatment, it simultaneously improves mechanical performance and suppresses a key durability failure mode.

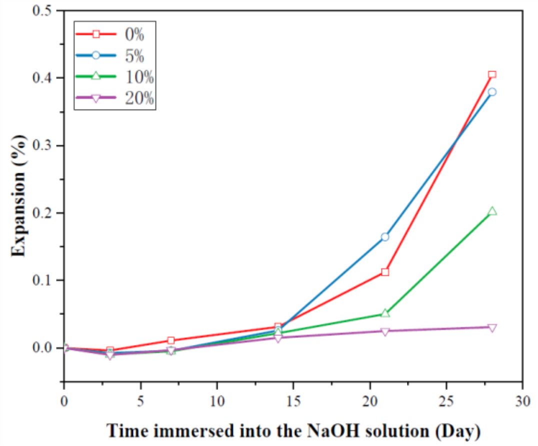

Figure 2. Expansion of the mortars with 0%, 5%, 10%, and 20% cement replaced by the calcined AS [18].

Duan et al. (2022a) [20] evaluated AS–GGBFS binary AP activated by sodium hydroxide/sodium silicate, varying both AS content and the sodium silicate/sodium hydroxide ratio (SS/SH). The study highlighted processing constraints: higher AS/GGBFS (and lower SS/SH) reduced mortar consistency because AS is porous and water-absorptive, while higher SS/SH can also increase activator viscosity. Despite these fresh-mix penalties, a clear performance window emerged: AS additions up to about 40% (with SS/SH up to ~1.5) improved mechanical performance relative to neat GGBFS-AAM; further increasing AS beyond ~40% tended to reduce strength due to limited available calcium and "excess aluminium" effects (Figure 3). The microstructural/chemical key finding was the confirmation of hybrid binding gels: coexistence of C-(A)-S-H and N-A-S-H. A mechanistic explanation was articulated in Figure 4: a suitable amount of dissolved Al from AS promotes geopolymerisation and C-(A)-S-H development, but excessive alumina can hinder silica dissolution from precursors, producing incomplete reaction and a more porous product. Raising SS/SH helps offset this by supplying more soluble silica from the activator. This paper effectively defined a "design space" for AS-bearing AAMs where gel chemistry and calcium balance are tuned rather than assumed.

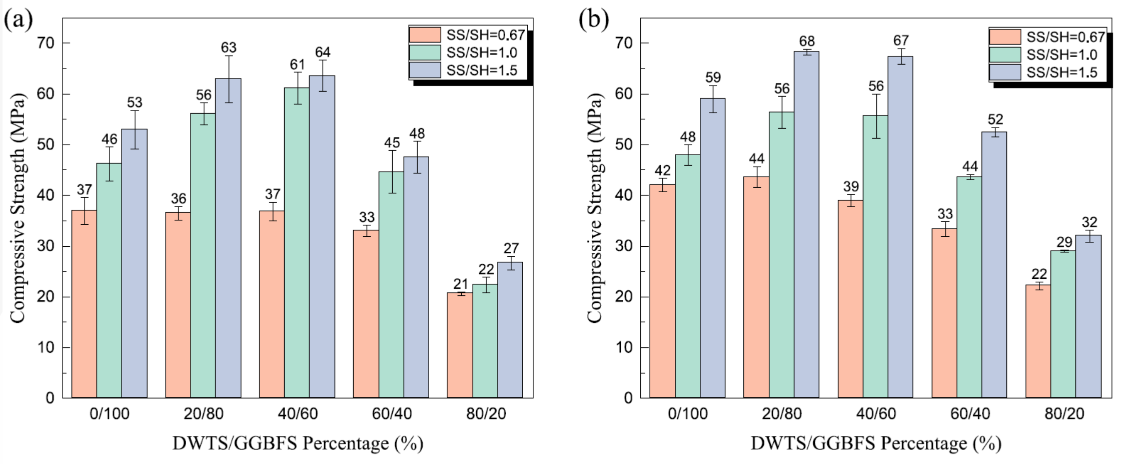

Figure 3. Compressive strength of the mortars curing at (a) 60 °C for 24 h and (b) 23 °C for 28 d [20].

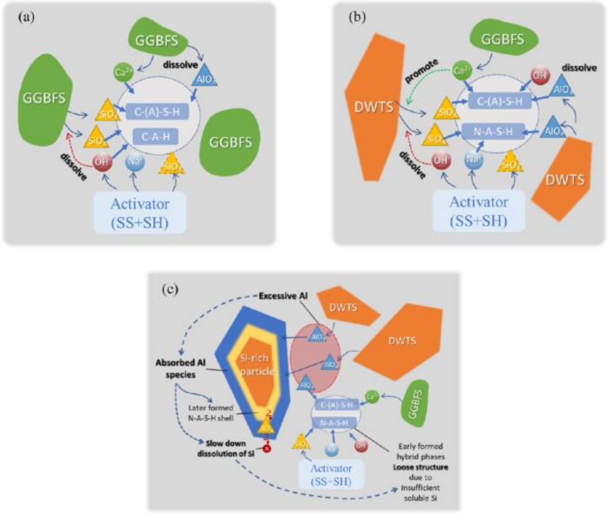

Figure 4. Schematic representation of phases precipitated in the AAM with (a) neat GGBFS as the precursor, (b) suitable Al concentration, and (c) excessive Al concentration [20].

Duan et al. (2022b) [19] shifted the feasibility question to a high-risk application—recycled glass aggregates—where ASR mitigation is critical. Using AS and GGBFS together as SCMs produced a synergy that allowed higher replacement while retaining strength: at 20% total replacement in ternary blends, compressive strength reached ~40 MPa (vs ~34 MPa in the reference), and at 30% replacement strength remained ~37 MPa. In contrast, binary blends with more than ~10% replacement suffered notable strength loss (dilution dominating). Microstructural analysis suggested ASR initiates at the glass–binder interface and within pre-existing microcracks in glass particles; the ternary system modifies ASR gel chemistry and the surrounding C–S–H/secondary hydrates, restricting crack growth and changing ion uptake (e.g., Ca/Si and Na/Si characteristics in ASR products). The practical message is that AS can be most effective when paired with a complementary SCM (slag) that stabilises strength while AS contributes Al-rich reactivity and pore refinement.

Beyond SCM in OPC system, Duan et al. (2023) [21] demonstrated that ASR risk can still be severe in AAMs. As shown in Figure 5 neat GGBFS-based AAM mortar with recycled glass aggregate exhibited expansion of ~0.82%, exceeding the 0.3% limit in AS 1141.60.1. Incorporating AS up to ~40% improved mechanical performance while keeping water transport similar to neat slag AAM, and crucially limited expansion to <0.3%, reducing mechanical damage. Higher AS contents increased water absorption, attributed to unreacted porous AS. This study extends the Phase-1 thesis: AS-type materials can mitigate ASR in both OPC and AAM routes, but only when replacement levels do not introduce excessive porosity or undermine reaction completeness.

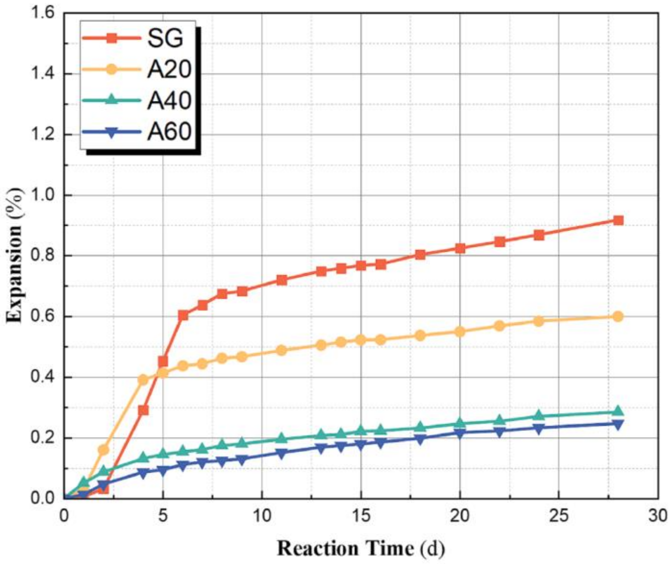

Figure 5. ASR-induced expansion of the AAM mortars (SG - reference AAM sample consisted of neat GGBFS, A20, A40, A60 – sample with 20%, 40%, 60% GGBFS replaced by AS). The replacement of GGBFS by AS mitigates the ASR expansion of AAM incorporating glass sand [19].

4.2.2. Phase 2 – Durability in aggressive environment

With feasibility established, Phase-2 targeted service environments where conventional concrete often fails rapidly: sulfuric-acid exposure and MIC in sewer conditions. The unifying hypothesis was that incorporating AS into GGBFS-based AAMs can improve chemical durability by reducing “free calcium” vulnerability (gypsum formation and decalcification), refining pore structure, and promoting corrosion-front passivation via silica-/aluminosilicate-rich layers. Across both acid and MIC studies, the durability improvements are consistently strongest at moderate AS contents (typically 20–40%), while too much residue increases porosity and weakens resistance.

Duan et al. (2024) [22] assessed acid corrosion resistance of AAM mortars made from binary AS–GGBFS precursors, examining mixes containing up to 60% AS. As shown in Figure 6, samples were immersed in 1 w/w% sulfuric acid for 56 days and evaluated via residual compressive strength, ion leaching (Ca, Si, Al, Na), phase identification, and microstructural mapping. A clear improvement window was identified: incorporating AS reduced acid-induced strength loss substantially, from ~40.3% in neat-GGBFS AAM mortar to ~22% when 40% AS was used. This indicates that AS can “re-engineer” the degradation pathway such that mechanical integrity is better preserved under strong acid exposure.

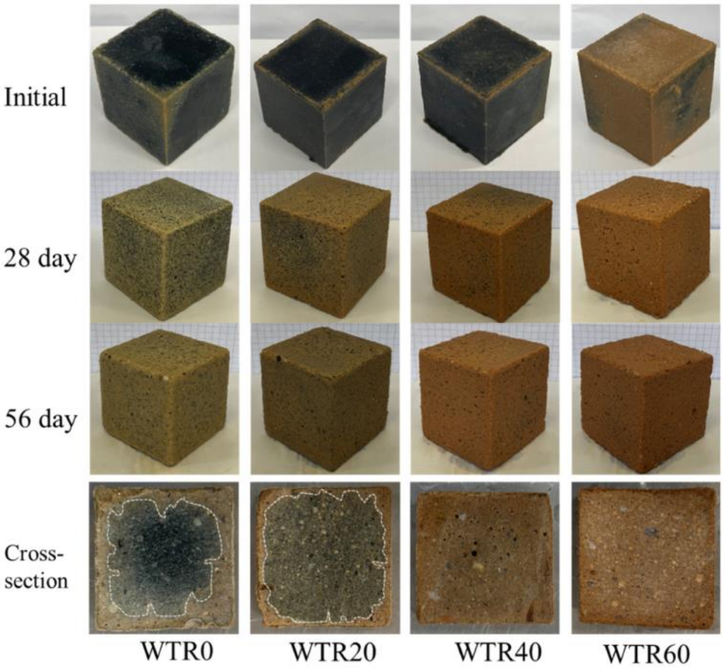

Figure 6. Appearance and cross-section of AAM mortars before and after 28- and 56-day sulfuric acid corrosion (WTR0 – reference AAM sample consisted of neat GGBFS, WTR20, WTR40, WTR60 – sample with 20%, 40%, 60% GGBFS replaced by AS) [22].

The durability mecha e dominant corrosion product (Ca/S ~1.0). Importantly, the study links strength loss reduction to: (i) reduced leachable Ca reservoir (less gypsum precipitation driving disintegration), and (ii) a modified corrosion front where silica-/aluminosilicate-rich remnants are less soluble than Ca-rich hydrates. However, increasing AS too far (>40% toward 60%) risks higher initial porosity/unreacted residue, which can raise permeability and reduce the net benefit—hence the performance maximum around moderate replacement.

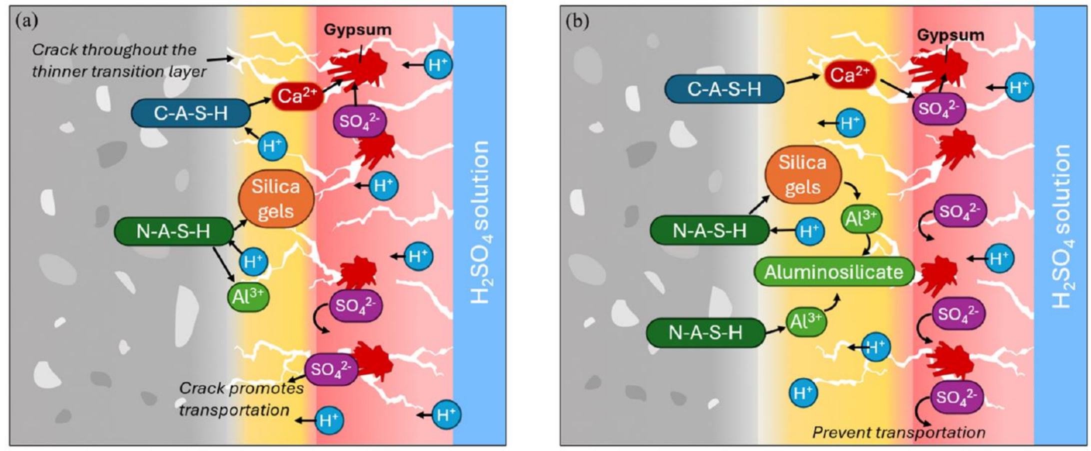

Figure 7. Illustration of sulfuric acid degradation mechanism on (a) GGBFS-based AAM and (b) high-AS AAM [22].

Duan et al. (2025) [23] extended the durability assessment from purely chemical acid exposure to biologically driven corrosion, evaluating MIC resistance of AAMs incorporating AS with GGBFS. This is important because MIC involves coupled processes—biofilm colonisation, sulfur-oxidising bacteria (SOB) activity, biogenic sulfuric acid generation, and mineral transformation—so "acid resistance" alone is not sufficient. The study showed that AS incorporation significantly improved MIC resistance: AS reduces free calcium content in the matrix, lowering the propensity for gypsum formation and acid-induced degradation. Specimens containing 20–40% AS retained satisfactory residual strength after MIC exposure (Figure 8), whereas neat-GGBFS AAMs were more susceptible due to higher available Ca.

A mechanistic picture was proposed that complements the Phase-2 acid study while adding microbial transport considerations. MIC was described to initiate with decalcification of C-A-S-H, producing a silica gel layer. Under microbial activity, SOB can penetrate this silica layer, attach to intact matrix beneath, and generate biogenic acids that facilitate further corrosion and gypsum formation. AS improved performance through two coupled effects: (i) chemical—reducing the free Ca reservoir and thus limiting gypsum-driven damage, and (ii) physical—lower porosity at 20–40% AS (relative to neat slag AAM in this system) limiting SOB penetration and slowing acid transport. In contrast, samples with 60% AS exhibited higher porosity, allowing deeper acid penetration and greater strength reduction. This establishes a clear durability trade-off: AS contributes beneficial chemistry but can become detrimental if it introduces excessive unreacted porous particles.

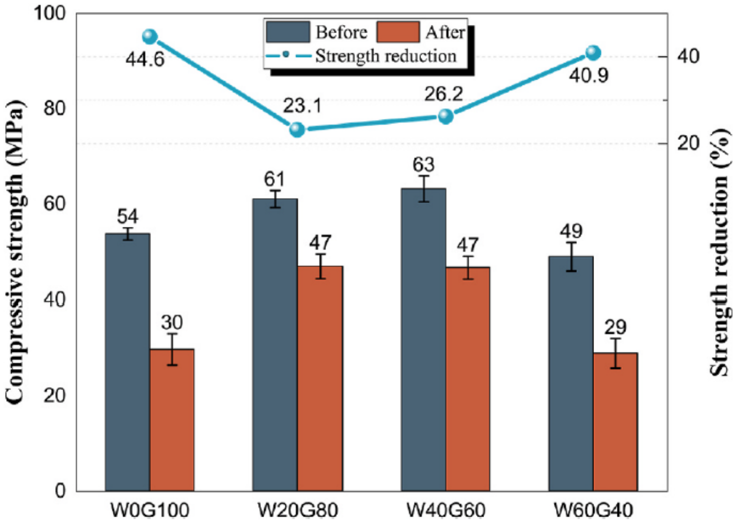

Figure 8. Compressive strength and strength reduction percentage before and after 56-day MIC exposure (W0G100 - control sample with neat GGBFS, W20G80, W40G60, W60G40 - AS-based samples with 20–60% of GGBFS replaced by calcined AS by weight). W20G80 and W40G60 retained the highest strength after MIC, followed by W60G40 and W0G100. The enhanced durability of samples with 20 %–40 % AS can be attributed to its reduced porosity and the limited free Ca content, which lowered the acid transformation rate and reduced susceptibility to acid-induced gypsum formation. [23].

4.2.3. Phase 3 – Integrated carbon assessment & supply-chain optimisation

Phase-3 extended the project from materials performance to systems performance: carbon intensity, energy demand, logistics, and cross-sector resource coupling between the water industry (sludge generation) and the concrete industry (cement demand). The outputs developed modelling frameworks that (i) quantify cradle-to-gate and life-cycle carbon impacts of sludge-derived concrete, and (ii) optimise industrial symbiosis (IS) configurations to maximise environmental and economic benefits. A key message is that the carbon advantage of sludge-derived SCMs is real but conditional on processing energy and supply-chain design; therefore, decarbonisation should be treated as an integrated optimisation problem rather than a single-material substitution.

Huang et al. (2024) [27] developed an integrated carbon assessment model with a widened system boundary that accounts for sludge treatment (including energy for processing), transport, concrete production, and electricity/fuel choices. Using comparative scenario analysis, the study contrasted a “business-as-usual” 12.5 MPa concrete with a sludge-derived low-carbon concrete pathway. A central quantitative finding was that treated alum sludge is a desirable greener “cementitious component,” with ~83.48% lower carbon emissions compared to general-purpose (GP) cement on a like-for-like binder basis. At the concrete level, replacing 10% of GP cement with treated alum sludge reduced the carbon intensity of concrete by ~9.14%. This magnitude is meaningful because it comes from a modest substitution rate that is consistent with Phase-1 feasibility windows (where moderate SCM additions can preserve or improve performance).

The paper further explored decarbonisation strategies through sensitivity and scenario analyses, showing that the treatment energy’s carbon intensity is a dominant driver. In the modelling, complete reliance on renewable energy sources delivered a ~41.97% reduction in carbon emissions across the assessed process, while a combined strategy of photovoltaic electricity and biogas heating delivered a ~30.57% reduction, as shown in Figure 9. The implication is that “low-carbon SCM production” is not only about the material itself but also about how it is processed and powered. The study also explicitly discussed carbonation over the service life of concrete: accounting for carbonation can change the net carbon picture and should be included in robust carbon accounting frameworks rather than treated as an afterthought.

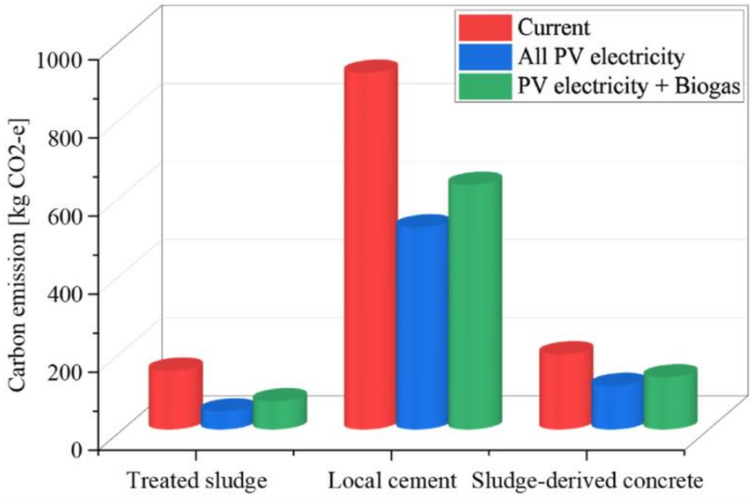

Figure 9. Selected DWTPs for sludge supply [27].

Huang et al. (2025) [26] advanced from carbon accounting to resource-system optimisation, proposing an innovative framework to optimise logistics and processing of sludge SCMs at regional scale while improving both environmental and economic performance. The model fosters industrial symbiosis between the water and concrete sectors: treated alum sludge is repurposed for green concrete manufacturing, reducing sludge disposal costs and associated emissions while lowering the carbon footprint of concrete production. The work used a dual-layer genetic algorithm (GA) optimisation and validated the approach with case studies in South Australia.

A key output from the optimisation was supply potential and matching: eight drinking water treatment plants (Figure 10) selected through optimisation collectively produce approximately 16,107 tonnes/year of sludge suitable for SCM use, meeting ~7.4% of regional demand. Scenario analysis highlighted that configuration of treatment capacity dominates outcomes. A representative scenario (S6) that leverages existing sludge treatment facilities achieved carbon and cost reductions of ~86.24% and ~52.04%, respectively, and energy savings of ~65.16% compared with business-as-usual. When landfill avoidance was included, sustainability outcomes improved further (energy savings ~70.97%, carbon reduction ~84.57%, and cost reduction >100%), indicating that disposal diversion can be a decisive economic lever and can shorten payback periods for treatment technology investments. The study also emphasised that sludge treatment is energy-intensive, but renewable energy integration (photovoltaics and biogas) can reduce operational costs and associate carbon emissions by up to ~69.21%. Finally, logistics optimisation mattered: certain configurations (e.g., S2 and S6) outperformed others primarily by minimising transportation costs and emissions.

Figure 10. Selected DWTPs for sludge supply [26].

4.2.4. Phase 4 – Variability assessment & Quality control

Phase-4 tackled the biggest barrier to industrial uptake: variability. Even within one water treatment plant, AS can vary in mineralogy, amorphous content, organics, and trace metals due to raw-water chemistry, coagulant dosage, seasonal changes, and operational drift. Phase-4 therefore shifted the project question from “can AS work?” to “how do we ensure reproducible performance and manage risk at scale?”. The papers propose quality-control (QC) metrics that connect intrinsic variability to pozzolanic reactivity, cement hydration response, and practical concrete performance.

Liu et al. (2025) [28, 29] presented a case study on manufacturing calcined AS in the Adelaide metropolitan area. The central finding was that AS exhibits substantial variability in particle size and mineralogical/amorphous phase content even when sourced from the same plant

(Figure 11), which propagates into variability in specific gravity, grindability, and performance-based tests (Figure 12) after calcination. Calcination was confirmed as effective for impurity removal, with organics as the primary impurity; however, the work emphasised that calcination parameters must be tuned to the feed (e.g., longer durations for higher-organic sludges) to reliably reduce LOI.

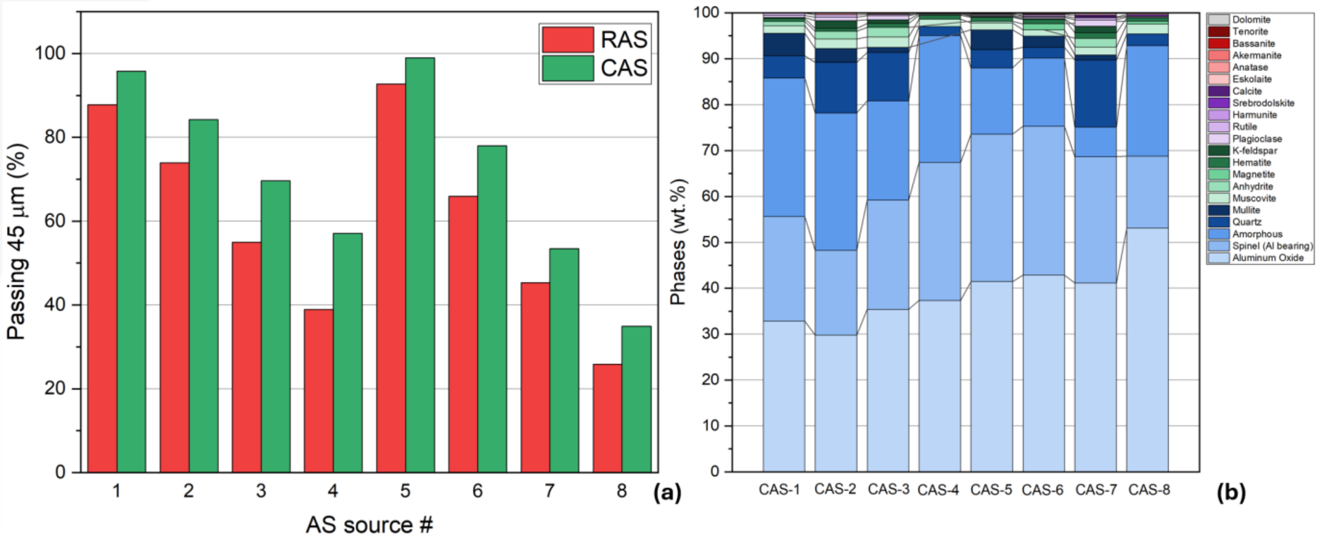

Figure 11. Percentage of raw AS (RAS) and calcined AS (CAS) passing 45 µm (a) and crystalline & amorphous phases (b).

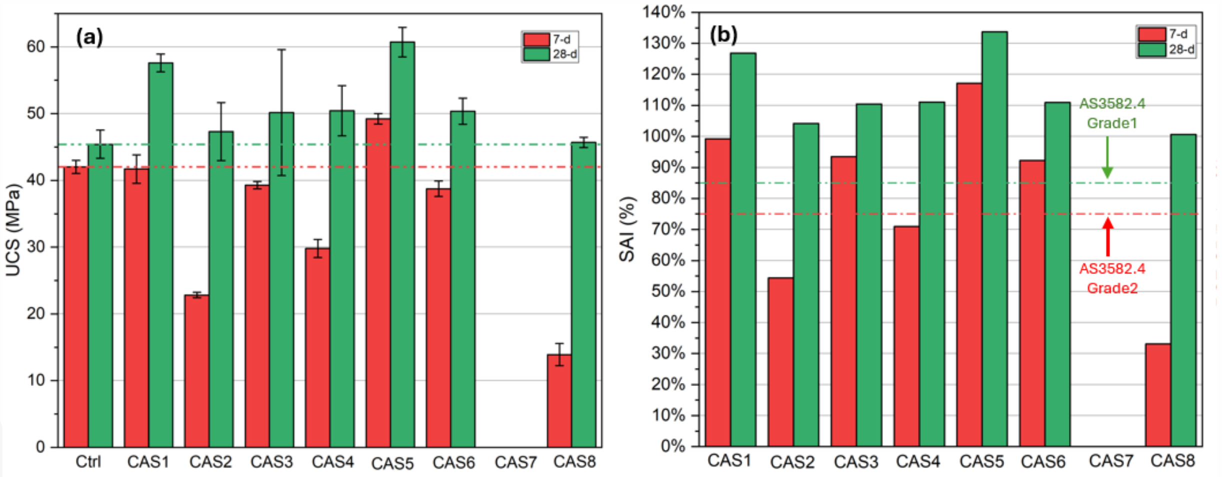

Figure 12. 7-day and 28-day UCS (a), SAI (b) of standard CAS mortar, PCE-SP usage and mortar flow (c) (error bars in UCS bar charts represent standard deviation).

Beyond intrinsic variability, admixture compatibility—particularly with polycarboxylate ether superplasticisers (PCE-SP)—emerged as a critical issue at 20% CAS replacement (Figure 13 In OPC systems (pH ≈ 12.5–13), PCE adsorption relies on Ca^{2+} bridging between negatively charged carboxylate groups ($–COO^{-}$) and cement particle surfaces, generating electrosteric dispersion [39], as shown by Figure 14 (a). However in Al-rich systems containing CAS, dissolved aluminium predominantly exists as $[Al(OH)_4]^{-}$, which competes with PCE for Ca^{2+}. This reduces the availability of Ca-bridging sites and weakens PCE adsorption (Figure 14 (b)), leading to reduced dispersion efficiency and increased admixture demand. Excess free PCE in solution can further complex Ca^{2+} [13]. delaying C–S–H nucleation and prolonging the induction period. In extreme cases (e.g., CAS-7), this results in severe retardation or complete setting failure.

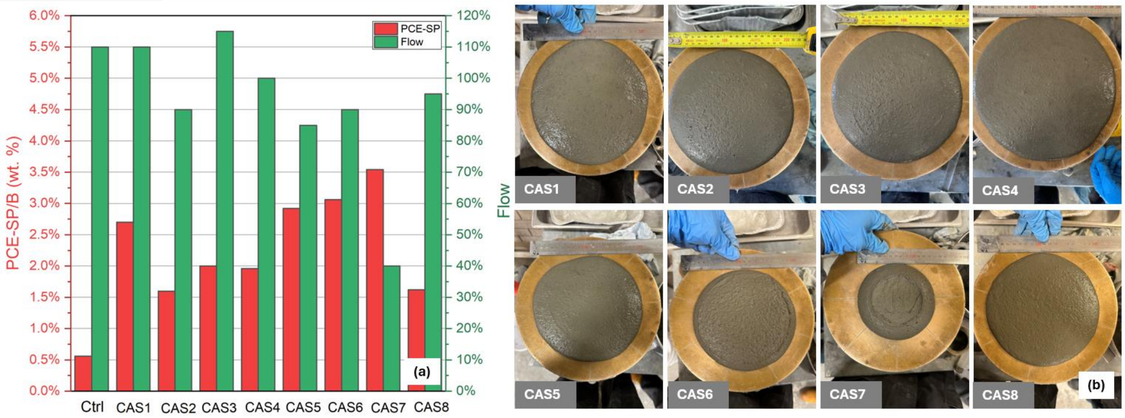

Figure 13. Flow of CSA-OPC mortar (20% replacement by wt.) with their PCE-SP dosage (by wt. of total binder). The usage of PCE-SP in CAS groups is significantly higher than Ctrl group (pure OPC) and varied across sources.

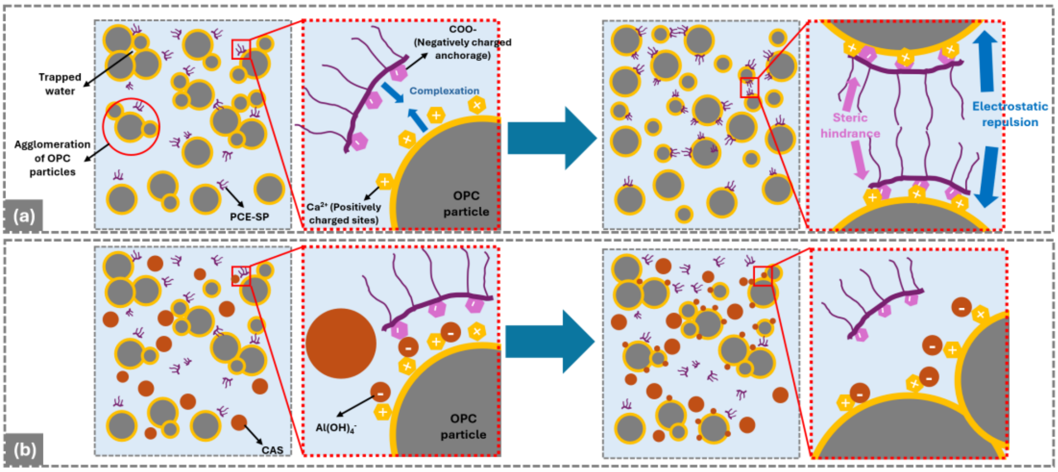

Figure 14. Comparison of working environment (pore solution) of PCE-SP in neat OPC (a) and OPC with CAS (b)

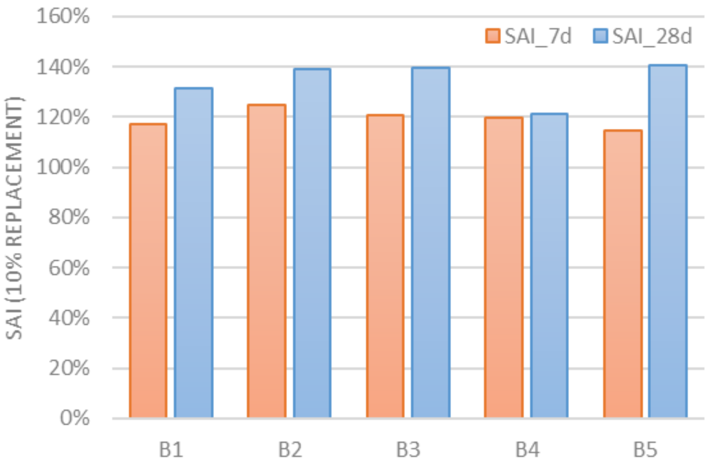

Figure 15. Strength activity index (SAI) of blended group (B1-B5 are equally blended of CAS1-8 with 12.5% wt. of each)

Therefore, to mitigate both variability and compatibility challenges, a combined strategy of feed blending, controlled calcination, and limiting replacement levels (~10%) was proposed, which significantly reduced performance variability (Figure 15). At the production level, three primary QC indicators are identified: fineness, which governs packing, nucleation, and admixture demand; LOI, a key risk parameter linked to residual organics and setting instability; and phase assemblage, where higher amorphous content correlates with pozzolanic reactivity, while crystalline phases remain largely inert. Additional control of alkalis and heavy metals (e.g., Fe, Cu, Ti) is required due to their combined influence on hydration and durability.

Within this framework, calcination acts as a necessary but insufficient control step: it reduces LOI but does not eliminate intrinsic feedstock variability. Moreover, chemical reactivity and strength are partially decoupled—R^3 reactivity metrics capture pozzolanic behaviour, whereas strength is also influenced by filler and nucleation effects—necessitating multi-parameter QC. Impurities exhibit a dual role, being detrimental or beneficial depending on composition and fineness, reinforcing the need for compositional “windows” rather than strict limits. Ultimately, particle size serves as a master control parameter, governing both physical and chemical processes and providing a key lever to stabilise performance in variable AS-derived systems.

5. Next Steps – Commercialisation & Impact Plan

This chapter outlines how project outputs will be transferred to partners, how data and tools will be hosted and maintained, and how intellectual property (IP), commercialisation and follow-up activities will be managed beyond the life of the project.

5.1. Handover of Outputs

At project completion, the following core outputs will be provided to project partners:

(i) **Final Wrap-up Report** (this document), including Executive Summary and conclusions; Detailed methodology and results; Phase-based findings and recommendations.

(ii) **Technical deliverables**, including progress reports (Attachment A), publications (Attachment B), and a doctoral thesis (

Publications_compressed.zip

(iii)

(iv) Attachment C) generated throughout the projects.

(v) **Digital files** (to be provided via UniSA's secure data transfer system), including parameterised LCA models (e.g. spreadsheets or scripts) for AS-derived concrete; MILP model formulation and example data sets for the national supply-chain optimisation. Where minor formatting or anonymisation is required (e.g. removal of site identifiers, alignment with internal document templates), this will be completed before handover.

5.2. Hosting and Access to Project Outputs

Project partners: UniSA will host the core digital outputs (reports, data, models) on an institutional repository or secure cloud workspace, with controlled access granted to SA Water and other project partners. The chief investigators will be responsible for nominating custodians and ensuring that file structures and metadata are sufficiently clear for ongoing internal use.

Broader audience: Public-facing outputs (journal papers, conference presentations, selected figures and summary datasets) will be made available through:

(i) Open-access and subscription journal platforms

(ii) UniSA's institutional research repository

(iii) Partner websites or knowledge portals (e.g. SmartCrete CRC, SA Water, where appropriate).

(iv) Any additional guidance documents or short "industry notes" developed from this project can also be hosted by partner organisations to support internal adoption.

5.3. Project Data, Materials and Equipment

Data: Raw and processed experimental data will be archived within UniSA's research data management system, following institutional policies on retention and access. Aggregated or de-identified data can be shared with partners for internal analysis, benchmarking and future project development.

Materials: Any remaining AS samples, activated ASs and reference binders will be retained at UniSA for follow-up research where storage space and condition allow; or appropriately disposed of in accordance with SA Water and UniSA safety and waste-management procedures.

Equipment: All equipment purchased or used under this project (e.g. laboratory rigs, moulds, small-scale curing chambers) will remain with UniSA and will be available for follow-up experimental and demonstration work in collaboration with project partners.

5.4. Intellectual Property (IP) Management

Foreground IP generated by the project includes, in particular: indicative binder formulations and mix-design envelopes (binary and ternary systems); parameterised LCA and supply-chain modelling approaches customised for AS valorisation; and the AS SCM quality-control framework (testing protocol, indicator thresholds and decision logic).

IP will be managed in accordance with the existing project and collaboration agreements between UniSA, SA Water and other parties. At this stage, no immediate patent filings are proposed, but the following actions are recommended:

(i) Document key algorithms, methods and decision frameworks in internal technical notes.

(ii) Review, with partner IP offices, whether any aspects of the QC framework or specific binder formulations warrant protection (e.g. know-how, trade secrets or formal IP registration).

(iii) Ensure that any new software tools or scripts are licensed appropriately (e.g. internal use only, or open-source with agreed conditions).

(iv) Ongoing oversight of IP use and protection should be coordinated through the chief investigators and the respective research/innovation offices of partner organisations.

5.5. Commercialisation Pathways

The environmental benefits of reusing waste resources such as AS are acknowledged. Significant quantities could be diverted from landfill, and demand for virgin raw materials for cement and concrete production could be reduced. The SmartCrete CRC Project Using drinking water treatment alum sludge to make greener and durable concrete (R1P4) is a step towards identifying a reuse option for AS. This work represents a practical, scalable example of circular-economy principles being applied to critical infrastructure sectors.

It is agreed that future work with industry partners should focus on integrated demonstration projects that combines:

1. **AS processing at or near water treatment plants**: Local processing activity is fundamental to an effective circular economy because it shortens material loops, strengthens community resilience, and reduces environmental impact. SA Water operates approximately 30 water treatment plants across in regions across South Australia. The majority of DWTS are produced from treatment activities that occur

across the Adelaide Hills and River Murray catchments. SA Water could provide support for the local processing of DWTS in a number of ways including (but not limited to) site infrastructure, land, in-kind resourcing and financial support for future work at one (or more) of its water treatment plants. A trial plan will need to be developed, in addition to the necessary agreements/contracts being put in place to progress any support.

2. **Local production of AS-based concrete products (e.g. blocks, precast):** SA Water acknowledges that collaborating with local businesses and building partnerships is critical to establishing a circular economy. By keeping processing and production of DWTS-based concrete products close to where DWTS are produced, transportation emissions can be minimised, the value of materials can be retained for longer, and local jobs can be supported. Several concrete batching facilities and manufacturers of concrete products exist across the Adelaide Hills and Riverland regions which could be investigated. There may be opportunities to engage with local re-processors/manufacturers that are aligned with SA Water sustainability aspirations and a future that values circularity, responsible resource use, and long-term environmental resilience.
3. **Supportive procurement, standards and landfill/diversion policies:** With waste resource recovery/reuse activities, it is essential to build confidence among regulators, asset owners, designers and end users to enable market uptake. This will apply to DWTS-based concrete products. The procurement process provides a significant opportunity to increase the use of products that contains recycled content such as SCM. Procurement guidelines need to identify areas where recycled materials and products should be the default option before the virgin equivalent is considered. Risk aversion can prevent the adoption of new products. Creating specifications that explicitly allow for recycled materials with proven performance can increase the uptake of recycled materials. SA Water is proactively seeking to take an environmental leadership role in sustainable infrastructure, circular procurement and waste resource management and continues to identify opportunities to embed circular practices into its business. SA Water aims to become a zero-waste organisation by 2040, meaning no waste is sent to landfill wherever possible by avoiding waste, extending asset life, and recycling materials at end of life.

5.6. Dissemination

All project parties have a role in communicating outcomes: UniSA will lead academic dissemination through journal publications, conference papers and technical workshops, and support industry-focused summaries and seminars. SA Water and other industry partners will lead communication within operational teams and to broader stakeholders (e.g. asset owners, regulators and consultants), using concise briefing notes, case studies and internal presentations. Lastly, Joint presentations at relevant industry forums (e.g. water, concrete, infrastructure and sustainability conferences) are strongly encouraged to demonstrate the partnership and enhance impact.

6. Education and Training

This project has supported substantial education and training across materials, environmental and systems engineering. At UniSA, Professors Yan Zhuge, Christopher Chow, Rameez Rameezdeen and Tom Benn worked closely with research associates and PhD candidates to build capability in several key technology areas: pre-treatment and activation of AS (dewatering, grinding, calcination), mix design and testing of AS-based mortars and concretes, durability assessment under aggressive exposures, and advanced life-cycle and supply-chain modelling.

Research associates Yue Liu, Danda Li, Jiarui Liu, Li Luo and Bin Huang received hands-on training in concrete mixing and curing, durability test methods (ASR, MIC, acid and elevated-temperature resistance), AS quality-control protocols (R^3, SAI, fineness-based classification), and quantitative LCA/MILP tools.

PhD candidate Weiwei Duan played a central role in the experimental and analytical work on feasibility and durability, gaining advanced skills in experimental design, microstructural characterisation and scientific communication, evidenced by multiple peer-reviewed publications. His thesis, titled “Utilising alum-based water treatment residue in producing highly durable alkali-activated material” (submitted in December 2024 and included in Section 0), was successfully examined, and he was awarded his PhD in July 2025. In recognition of his contribution, he received the Student Water Prize from the Australian Water Association in June 2025 for his work on reusing alum-based water treatment residue to develop highly durable, acid-resistant construction materials.

7. Conclusions, Implications and Recommendations

7.1. Challenges overcome & highlights

At project inception, a central question was whether a heterogeneous, alum-based waste such as AS could be used as a reliable, safe and durable component in cementitious systems. The project has substantially addressed this challenge at four levels:

- **Technical feasibility:** It was demonstrated that, following appropriate pre-treatment (dewatering, grinding and calcination at ~800 °C), alum-based AS consistently behaves as a reactive SCM and/or fine filler. Across multiple studies, AS was shown to replace approximately 10–20% of cement (and locally higher levels in ternary blends) and small portions of sand without compromising, and often improving, 28–90-day strength and pore structure.
- **Durability and environmental safety:** A second major concern was that AS-bearing products might exhibit poor durability or excessive leaching when exposed to aggressive environments (ASR, sewer, sulfate, acid, elevated temperature). A comprehensive test matrix in both OPC and AAM systems showed that AS can significantly mitigate ASR, enhance resistance to sulfuric acid and MIC in sewer-like exposures, and maintain acceptable leaching and high-temperature performance. In several cases, AS-derived SCMs and AS-based AAMs outperformed conventional reference mixes in key durability metrics.
- **System-level decarbonisation and economics:** A further objective was to determine whether AS valorisation delivers meaningful benefits at product and system scales. Integrated life-cycle assessment showed that treated AS emits ~80% less CO_2 per tonne than GP cement, and that ~10% cement replacement can reduce concrete life-cycle emissions by about 9%, with larger gains when low-carbon energy is adopted. Complementary national supply-chain optimisation demonstrated that regional AS processing hubs can simultaneously achieve substantial GHG savings, positive net present value and significant regional job creation, confirming strong economic drivers for implementation.
- **Variability and qualification:** The fourth key challenge was the high feedstock variability between AS sources. The dedicated quality-control study in Phase 4 developed a practical, multi-parameter framework based on R^3 bound water, fineness and SAI to categorise different AS sources into reactivity classes and define safe replacement ranges. This converts “sludge variability” from a generic concern into a measurable, manageable parameter. In parallel, adopting a “blending and calcination” protocol effectively reduces performance variability between sources; when combined with limiting AS replacement to around 10% in most structural applications, the resulting fluctuation in mechanical and durability performance can be constrained to an acceptable level for industry use.

7.2. Recommendations for future research and commercialisation

The project has generated several important learnings that should inform future research directions and commercial deployment, as outlined below:

- **Standardisation, quality control and co-blending strategies**: There is currently no dedicated standard for AS-derived SCMs. A priority is to translate the proposed QC framework into formal test methods and acceptance criteria (e.g. within AS 3582 or equivalent). For unconventional SCMs, a single index is insufficient: R^3 bound water is valuable for ranking chemical reactivity of Al-rich residues but does not capture filler/nucleation effects or the influence of Fe/Cu/Ti on strength. Future frameworks should combine rapid chemical indices (R^3, amorphous content) with physical metrics (PSD, specific surface area) and simple performance-based indicators (e.g. SAI, short-age mortar strength, water demand). Ternary co-blending strategies (e.g. cement–slag–AS, cement–limestone–AS), and co-blending–calcination of AS with other powders, have proven effective at both enhancing performance and reducing variability, and should be further developed as practical QC tools.
- **Admixture compatibility in Al-rich systems.** In Phase 4, several mixes exhibited abnormal setting or failed to reach target strength when combined with PCE-based superplasticisers, despite showing normal behaviour in raw material characterisation and reactivity tests. This likely reflects interactions between high Al-speciation in AS and the positively charged anchoring groups of PCEs. Future work should systematically investigate AS–admixture compatibility (including alternative PCE chemistries and dosage strategies) and develop admixture formulations or guidelines tailored to Al-rich SCM systems.
- **Al enrichment as a deliberate design lever:** The project has shown that Al-rich AS modify hydrate assemblages (increased C-A-S-H, carboaluminates, hydrogarnet and alumina gels) in ways that enhance ASR resistance, acid/MIC performance and, in some cases, fire resistance. Future research should treat such residues as functional “Al-modifiers”, not just cement replacers, and intentionally design binders for aggressive exposure conditions (e.g. sewers, acid-prone industrial floors, sulphide-rich soils).
- **Field validation and application-driven durability testing:** Most performance data are from laboratory or pilot-scale studies. Long-term field trials in relevant applications (sewer pipes, precast elements, pavements, low-rise structural units) are required to validate ASR, MIC and acid resistance, as well as carbonation and service-life performance. Future projects should start from clearly defined exposure scenarios (e.g. marine, freeze–thaw, sulfate/sulfide-rich environments) and design both binder chemistries and test programmes to suit those conditions.
- **Process integration, energy and systems thinking:** LCA and MILP results highlight that technology, logistics and policy are tightly coupled: cement replacement alone provides substantial carbon reductions, but the major step-change arises when AS valorisation is combined with low-carbon energy and optimised facility siting. Future work with industry partners should focus on integrated demonstration projects that combine:

  (i) AS processing at or near WTPs,

  (ii) Local production of AS-based concrete products (e.g. blocks, precast), and

  (iii) Supportive procurement, standards and landfill/diversion policies.
- **Perception and regulatory acceptance:** A residual perception risk remains around “sludge concrete”. Clear, transparent communication of performance, durability and TCLP

data, supported by well-documented field trials and high-visibility demonstration projects, will be essential to build confidence among regulators, asset owners, designers and end users, and to enable broader market uptake.

8. Publication List

The publications resulted from this project can be summarised below (sorted by year). A zip file containing all publications is attached in Attachment B.

1. Duan, W., et al. (2020). "Utilization of Drinking Water Treatment Sludge as Cement Replacement to Mitigate Alkali–Silica Reaction in Cement Composites." Journal of Composites Science 4(4). https://doi.org/10.3390/jcs4040171
2. Duan, W., et al. (2022). "A ternary blended binder incorporating alum sludge to efficiently resist alkali-silica reaction of recycled glass aggregates." Journal of Cleaner Production 349. https://doi.org/10.1016/j.jclepro.2022.131415
3. Duan, W., et al. (2022). "Mechanical performance and phase analysis of an eco-friendly alkali-activated binder made with sludge waste and blast-furnace slag." Journal of Cleaner Production 374. https://doi.org/10.1016/j.jclepro.2022.134024
4. Duan, W., Zhuge, Y., Chow, C.W.K., Keegan, A., Liu, Y., Merta, I., 2023. Mitigation of alkali-silica reaction in blast-furnace slag-based alkaline activated material through incorporation of alum water treatment residue. Construction and Building Materials 406. https://doi.org/10.1016/j.conbuildmat.2023.133383
5. Duan, W., Zhuge, Y., Liu, Y., Chow, C.W.K., Keegan, A., Jiang, G., 2024. Enhancing acid corrosion resistance in alkaline-activated materials with water treatment residue and blast-furnace slag. Construction and Building Materials 447. https://doi.org/10.1016/j.conbuildmat.2024.138105
6. Huang, B., Zhuge, Y., Rameezdeen, R., Xing, K., Huang, G., Liu, Y., 2024. Integrated carbon assessment for sludge-derived concrete: Modelling and a comparative study. Journal of Cleaner Production 435. https://doi.org/10.1016/j.jclepro.2023.140304
7. Duan, W., Liu, Y., Chow, C.W.K., Keegan, A., Zhuge, Y., 2025. Evaluating microbiologically influenced corrosion in alkali-activated materials incorporating alum sludge. Journal of Building Engineering 106. https://doi.org/10.1016/j.jobe.2025.112682
8. Liu, J., Liu, Y., Zeng, J., & Zhuge, Y., 2025. A comprehensive review of mechanisms, techniques, and precursors in enforced carbonation for low-carbon concrete. Journal of Building Engineering, 112. https://doi.org/10.1016/j.jobe.2025.113685
9. Huang, B., Zhuge, Y., Rameezdeen, R., Xing, K., & Liu, Y., 2025. Optimizing resource efficiency in regional industrial symbiosis: Integrated modelling and scenario analysis. Journal of Cleaner Production, 489. https://doi.org/10.1016/j.jclepro.2025.144744
10. Liu, J., Liu, Y., Bu, F., Zeng, J., Chow, C.W.K., & Zhuge, Y., 2026. Quality-control metrics for Al-rich calcined alum sludge: linking intrinsic variability, pozzolanic reactivity, and cement hydration performance, submitted to journal.

List of conference presentations

1. Liu, J., Liu, Y., Zeng, J., & Zhuge, Y., 2025. Assessing the Variability and Performance of Drinking Water Treatment Sludge as a Supplementary Cementitious Material. International Conference on Resource Sustainability (icRS 2025), July 16-18, 2025, Adelaide, Australia.

2. Liu, J., Liu, Y., Zeng, J., & Zhuge, Y., 2025. Quality control for production of manufactured calcined pozzolan using drinking water treatment sludge – a case study in Adelaide metropolitan area. Concrete Institute of Australia’s 32nd Biennial conference, Sep 7-10, 2025, Adelaide, Australia.

Acronyms and Abbreviations

Table 4. Table of acronyms and abbreviations.

Acronym	Full term
AAM	Alkali-Activated Material
ASR	Alkali–Silica Reaction
AS	Alum Sludge
BAU	Business As Usual
CH	Calcium Hydroxide
C-A-H	Calcium Aluminate Hydrate
C-A-S-H	Calcium Aluminosilicate Hydrate
C-(A)-S-H	Calcium (Aluminium) Silicate Hydrate
C-S-H	Calcium Silicate Hydrate
DNA	Deoxyribonucleic Acid
AS	Drinking Water Treatment Sludge
EDS	Energy Dispersive Spectroscopy
FTIR	Fourier Transform Infrared Spectroscopy
GHG	Greenhouse Gas
GP cement	General Purpose cement
ICP-OES	Inductively Coupled Plasma – Optical Emission Spectrometry
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LOI	Loss on Ignition
MIC	Microbiologically Influenced Corrosion
MILP	Mixed-Integer Linear Programming
MIP	Mercury Intrusion Porosimetry
MPa	Megapascal
N-A-S-H	Sodium Aluminosilicate Hydrate
NPV	Net Present Value
OPC	Ordinary Portland Cement
PV	Photovoltaic
PSD	Particle Size Distribution
QC	Quality Control
rRNA	Ribosomal Ribonucleic Acid
SAI	Strength Activity Index
SCM	Supplementary Cementitious Material
SEM	Scanning Electron Microscopy
TCLP	Toxicity Characteristic Leaching Procedure
TGA	Thermogravimetric Analysis
UPV	Ultrasonic Pulse Velocity
WTP	Water Treatment Plant
XCT	X-ray Computed Tomography
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
QXRD	Quantitative X-ray Diffraction

References

1. Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., Le Quéré, C., Li, H., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Arneth, A., Arora, V., Bates, N. R., Becker, M., Bellouin, N., Berghoff, C. F., Bittig, H. C., Bopp, L., Cadule, P., Campbell, K., Chamberlain, M. A., Chandra, N., Chevallier, F., Chini, L. P., Colligan, T., Decayeux, J., Djeutchouang, L., Dou, X., Duran Rojas, C., Enyo, K., Evans, W., Fay, A., Feely, R. A., Ford, D. J., Foster, A., Gasser, T., Gehlen, M., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Heinke, J., Hurtt, G. C., Iida, Y., Ilyina, T., Jacobson, A. R., Jain, A., Jarníková, T., Jersild, A., Jiang, F., Jin, Z., Kato, E., Keeling, R. F., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Lauvset, S. K., Lefèvre, N., Liu, Z., Liu, J., Ma, L., Maksyutov, S., Marland, G., Mayot, N., McGuire, P., Metzl, N., Monacci, N. M., Morgan, E. J., Nakaoka, S.-I., Neill, C., Niwa, Y., Nützel, T., Olivier, L., Ono, T., Palmer, P. I., Pierrot, D., Qin, Z., Resplandy, L., Roobaert, A., Rosan, T. M., Rödenbeck, C., Schwinger, J., Smallman, T. L., Smith, S., Sospedra-Alfonso, R., Steinhoff, T., Sun, Q., Sutton, A. J., Séférian, R., Takao, S., Tatebe, H., Tian, H., Tilbrook, B., Torres, O., Tourigny, E., Tsujino, H., Tubiello, F., van der Werf, G., Wanninkhof, R., Wang, X., Yang, D., Yang, X., Yu, Z., Yuan, W., Yue, X., Zaehle, S., Zeng, N., and Zeng, J., *Global Carbon Budget 2024.* Earth Syst. Sci. Data, 2024: p. 1-191.
2. Andrew, R.M., *Global CO2 emissions from cement production.* Earth System Science Data, 2018. **10**(1): p. 195-217.
3. *Report for Smart Water Fund - 10OS-42 Alum Sludge Reuse Investigation*. 2015, GHD.
4. *ASTM D7348 – 21 Standard Test Methods for Loss on Ignition (LOI) of Solid Combustion Residues*. 2021, American Society for Testing and Materials.
5. *AS 3583.3:1991: Determination of loss on ignition – supplementary cementitous materials*. 2016, Standards Australia.
6. *ASTM D854–23 Standard Test Methods for Specific Gravity of Soil Solids by the Water Displacement Method*. 2023, American Society for Testing and Materials.
7. *AS 1141.5: Method for sampling and testing aggregates, Method 5: Particle density and water absorption of fine aggregate*. 2018, Standards Australia.
8. *ASTM C1437-20: Standard Test Method for Flow of Hydraulic Cement Mortar*. 2020, American Society for Testing and Materials.
9. *ASTM C1585-20: Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes*. 2020, American Society for Testing and Materials.
10. *AS 1012.21-1999: Methods of testing concrete Determination of water absorption and apparent volume of permeable voids in hardened concrete*. 2014, Standards Australia.
11. *ASTM C597-22: Standard Test Method for Ultrasonic Pulse Velocity Through Concrete*. 2022, American Society for Testing and Materials.
12. *AS 1141.60.1:2014 : Methods for sampling and testing aggregates, Method 60.1: Potential alkali-silica reactivity - Accelerated mortar bar method*. 2014, Standards Australia.
13. *ASTM C267-20: Standard Test Methods for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacings and Polymer Concretes*. 2020, American Society for Testing and Materials.
14. *ASTM C1904-22: Standard Test Methods for Determination of the Effects of Biogenic Acidification on Concrete Antimicrobial Additives and/or Concrete Products*. 2022, American Society for Testing and Materials.
15. *ASTM C1897-20 Standard Test Methods for Measuring the Reactivity of Supplementary Cementitious Materials by Isothermal Calorimetry and Bound Water Measurements*. 2020, American Society for Testing and Materials.
16. *ASTM C311/C311M−24 Standard Test Methods for Sampling and Testing Coal Ash or Natural Pozzolans for Use in Concrete*. 2024, American Society for Testing and Materials.

17. *AS 1012.9:2014: Methods of testing concrete, Method 9: Compressive strength tests - Concrete, mortar and grout specimens*. 2014, Standards Australia.
18. Duan, W., et al., *Utilization of Drinking Water Treatment Sludge as Cement Replacement to Mitigate Alkali–Silica Reaction in Cement Composites.* Journal of Composites Science, 2020. **4**(4).
19. Duan, W., et al., *A ternary blended binder incorporating alum sludge to efficiently resist alkali-silica reaction of recycled glass aggregates.* Journal of Cleaner Production, 2022. **349**.
20. Duan, W., et al., *Mechanical performance and phase analysis of an eco-friendly alkali-activated binder made with sludge waste and blast-furnace slag.* Journal of Cleaner Production, 2022. **374**.
21. Duan, W., et al., *Mitigation of alkali-silica reaction in blast-furnace slag-based alkaline activated material through incorporation of alum water treatment residue.* Construction and Building Materials, 2023. **406**.
22. Duan, W., et al., *Enhancing acid corrosion resistance in alkaline-activated materials with water treatment residue and blast-furnace slag.* Construction and Building Materials, 2024. **447**.
23. Duan, W., et al., *Evaluating microbiologically influenced corrosion in alkali-activated materials incorporating alum sludge.* Journal of Building Engineering, 2025. **106**.
24. *ASTM C348-21: Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars*. 2021, American Society for Testing and Materials.
25. *ASTM C293/C293M-16: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading)*. 2016, American Society for Testing and Materials.
26. Huang, B., et al., *Optimizing resource efficiency in regional industrial symbiosis: Integrated modelling and scenario analysis.* Journal of Cleaner Production, 2025. **489**.
27. Huang, B., et al., *Integrated carbon assessment for sludge-derived concrete: Modelling and a comparative study.* Journal of Cleaner Production, 2024. **435**.
28. Liu, J., et al., *Quality control for production of manufactured calcined pozzolan using drinking water treatment sludge – a case study in Adelaide metropolitan area*, in *the Institute's 32nd Biennial National Conference (Concrete 2025)*. 2025: Adelaide, Australia.
29. Liu, J., et al., *Assessing the Variability and Performance of Drinking Water Treatment Sludge as a Supplementary Cementitious Material*, in *International Conference on Resource Sustainability (icRS 2025)*. 2025: Adelaide, Australia.

Attachments

Attachment A: Progress reports

Progress Reports_UniSA.zip

Attachment B: Publications

Publications_compressed.zip

Attachment C: PhD thesis (Dr Weiwei Duan)

PhD thesis_Dr
Weiwei Duan_comp