

Framework for the integration of coal ash–brine encapsulation into cemented paste backfill design

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Abstract

The incorporation of coal ash and saline brines into cemented paste backfill (CPB) presents an opportunity to combine underground structural support with the secure disposal of high-volume industrial wastes. This paper outlines a practical framework for assessing, designing, and implementing coal ash–brine encapsulation within CPB, with the dual objective of meeting backfill performance requirements and immobilising dissolved salts. The approach draws on established mineralogical, geochemical, and engineering principles, and is adaptable to site-specific materials and operational constraints.

The framework begins with systematic characterisation of coal ash and brine, including chemical composition, mineralogy, and leach potential, to evaluate reactivity and compatibility. Encapsulation mechanisms are linked to pozzolanic and cementitious reactions, with the formation of secondary phases such as calcium silicate hydrates, layered double hydroxides, and Friedel's salt contributing to long-term stability. Mix design development considers ash–brine ratios, binder type and dosage, water–binder ratios, and additive use. Laboratory testing for unconfined compressive strength, permeability, and leachate chemistry supports optimisation of mix performance.

This integrated approach is relevant to coal-fired power stations seeking to reduce surface storage of ash and brine, and to coal mines with suitable underground workings for placement. By functioning both as a structural fill and a secure containment medium, CPB can deliver operational, environmental, and cost benefits. Although the focus is on coal ash–brine systems, the methodology can be extended to other compatible industrial by-products and saline waste streams.

Keywords: cemented paste backfill, coal ash, saline brine, encapsulation, co-disposal, waste management

1 Introduction

Coal combustion processes generate two major waste streams of concern: solid residues, such as coal ash, and saline liquid effluents, including brines from cooling and treatment circuits. These wastes are generated in large volumes annually, placing considerable demand on disposal infrastructure (American Coal Ash Association [ACAA] 2015). The management of these wastes presents both environmental and operational challenges, particularly where surface disposal facilities are constrained or where long-term seepage risks are unacceptable (Carlson & Adriano 1993; Mattigod et al. 1990; Eary et al. 1990). Conventional strategies for ash disposal have largely relied on engineered landfills or surface impoundments (Roy et al. 1984; Warren & Dudas 1985), while saline brines are typically stored in evaporation ponds or discharged under regulated permits (Sakata 1987; Pretorius 1995; Mahlabi 2002). Both approaches carry significant risks in terms of land use, water quality, and long-term liability (Adriano et al. 1980; Swaine 2000).

Cemented paste backfill (CPB) has been widely applied in underground mining to provide structural support to stopes and pillars while reducing surface deposition of tailings (French & Ward 2009). Its flexibility in

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accommodating a range of waste-derived materials makes it an attractive option for integrated waste management. The co-disposal of coal ash-brines within CPB systems represents a novel approach, enabling the use of underground workings as a secure repository while ensuring that the backfill continues to meet geotechnical and operational performance standards (Mukherjee 2011). This approach is particularly relevant where coal mines and power stations operate in close proximity, creating opportunities for integrated waste management solutions.

The purpose of this paper is to outline a framework for the assessment, design, and implementation of coal ash–brine encapsulation in CPB. The framework integrates mineralogical, geochemical, and engineering considerations to ensure both short-term placement performance and long-term immobilisation of dissolved salts and associated trace constituents (Fruchter et al. 1990; Zevenbergen et al. 1999). By adopting this approach, coal-fired power stations and coal mines can reduce reliance on surface waste facilities, optimise the use of backfill operations, and achieve broader environmental and cost benefits.

To support the framework with evidence while protecting confidentiality, included is an anonymised case example. Results are presented without site or operator identifiers to illustrate typical strength development and leach behaviour for coal ash–brine CPB systems.

2 Background

Coal ash is produced in large volumes from combustion processes, with global estimates exceeding hundreds of millions of tonnes annually (ACAA 2015). Its mineralogy is dominated by amorphous aluminosilicate phases, often supplemented by crystalline quartz, mullite, and minor iron oxides (Roy et al. 1984; Warren & Dudas 1985). The relative proportions vary depending on the source, with Class F ashes typically more siliceous and Class C ashes richer in calcium, which directly influences pozzolanic reactivity (Zevenbergen et al. 1999; Fruchter et al. 1990). These characteristics underpin the use of coal ash as a partial replacement for cementitious materials (Mukherjee 2011). While this is well established in construction applications, its deliberate integration into mine backfill systems is still less commonly described in the literature (French & Ward 2009). Recent CPB research has increasingly focused on how secondary waste streams influence microstructure evolution and transport properties, particularly where the binder system is expected to provide both mechanical competence and chemical containment (Wang et al. 2023).

In parallel, saline brines are an inevitable byproduct of many industrial processes, including power generation, cooling, and water treatment circuits. The chemistry can vary, with some brines dominated by chlorides and others enriched in sulphates or bicarbonates, which makes site-specific assessment unavoidable (Mahlaba 2002; Pretorius 1995). Management typically relies on surface evaporation ponds or discharge under regulated conditions (Sakata 1987). Both approaches can carry long-term liabilities, including seepage risk, salinisation of groundwater, and limited opportunities for beneficial reuse (Carlson & Adriano 1993; Adriano et al. 1980). Incorporating brines into CPB provides a potential pathway to reduce freshwater demand while placing dissolved salts in an underground environment designed for containment.

The combination of coal ash-brine in CPB presents a dual challenge: maintaining mechanical strength and flowability for backfilling operations, while limiting the mobility of soluble salts over long timescales. Solidification and stabilisation studies indicate that secondary mineral formation, including calcium silicate hydrates (C–S–H), aluminate-hydrates and related phases, can influence both strength development and ionic retention (Portland Cement Association [PCA] 1998; Lothenbach & Winnefeld 2006). In cement chemistry terms, chloride-binding and sulphate-binding is commonly discussed in relation to aluminate hydrate families, including AFm (alumina, ferric oxide, monosulphate) phases and AFt (alumina, ferric oxide, trisulphate) phases, with the latter including ettringite-group minerals. Recent reviews emphasise that chloride retention reflects coupled mechanisms, namely physical binding in C–S–H type gels and chemical binding through AFm phase evolution (including Friedel's and Kuzel's salts), with sensitivity to porewater composition and competitive anion effects (Lv et al. 2025; Georget et al. 2025). Where layered double hydroxides are discussed, they are best treated as potential auxiliary sinks unless directly confirmed for the specific binder system (Mir et al. 2020). Translating these concepts into CPB systems under operational and

geomechanical constraints remains underdeveloped, with limited published case studies (French & Ward 2009; Liu et al. 2005).

This paper frames coal ash–brine encapsulation within CPB as an integrated waste management strategy that connects conventional surface disposal challenges with backfill operations. The workflow builds on established geochemical, mineralogical, and engineering principles and adapts them for practical application in underground mining environments (Zhu & Anderson 2002; Parkhurst & Appelo 2013). The emphasis is on decision-ready evidence rather than theory, recognising that brine variability and operational controls are usually what determine whether a promising laboratory concept holds up in practice (Georget et al. 2025).

3 Conceptual framework

The encapsulation of coal ash–brine in CPB must consider processes operating over different timescales. These processes govern both the short-term placement behaviour and the long-term geochemical stability of the system. The framework distinguishes between short-term, medium-term, and long-term mechanisms, each contributing to the development of mechanical strength and the immobilisation of dissolved salts (Zevenbergen et al. 1999; Fruchter et al. 1990).

3.1 Short-term processes

Immediately after placement, hydration reactions dominate. The dissolution of cementitious binders releases calcium and hydroxyl ions, initiating the precipitation of early hydration products such as calcium hydroxide and C–S–H (PCA 1998; Lothenbach & Winnefeld 2006). The chemistry of the brine influences these reactions by introducing high concentrations of sodium, chloride, and sulphate. While these ions can interfere with the normal hydration sequence, notably through ionic competition at exchange sites, they also promote the precipitation of secondary chloride and sulphate phases such as Friedel’s salt (Möschner et al. 2008). Short-term reactions therefore determine the initial setting time, early strength gain, and compatibility of the brine with the paste matrix.

3.2 Medium-term processes

Over weeks to months, pozzolanic reactions between amorphous aluminosilicate phases in coal ash and calcium hydroxide released during binder hydration become more significant. These reactions generate additional C–S–H gels, contributing to strength development and reduced porosity (Roy et al. 1984; Warren & Dudas 1985). The progressive consumption of calcium hydroxide lowers porewater alkalinity, which stabilises secondary phases while reducing leachate aggressiveness (Mattigod et al. 1990). In parallel, the elevated ionic strength of the brine encourages the formation of layered double hydroxides (LDHs), which can intercalate chloride and sulphate ions within their structures (Adriano et al. 1980; Möschner et al. 2008). These medium-term processes are important for stabilising porewater chemistry and for improving the durability of the backfill matrix.

3.3 Long-term processes

Over extended timescales, secondary mineralisation processes dominate. Friedel’s salt and other complex calcium aluminate hydrates can form, providing a long-term sink for chloride (Zhu & Anderson 2002; Möschner et al. 2008). LDHs may continue to evolve, offering sustained binding capacity for anions (Eary et al. 1990). Carbonate phases such as calcite may also precipitate, further refining pore structure and contributing to chemical stability (Swaine 2000). The gradual reduction in permeability through pore refinement further limits the potential for salt migration. Collectively, these mechanisms underpin the geochemical stability of the encapsulated system and support the viability of CPB as a long-term disposal pathway for ash and brine.

3.4 Framework application

By considering these time-dependent processes, the framework ensures that both operational and environmental objectives are met. In the short term, CPB must remain pumpable and develop sufficient strength for mine backfill applications. In the medium term, continued pozzolanic reactivity enhances mechanical properties. In the long-term, secondary mineral formation and reduced permeability provide containment of dissolved salts (French & Ward 2009). Equally important, the staged framework highlights potential risks at each stage, providing a structured means of identifying and mitigating failure mechanisms before implementation. Table 1 summarises the framework across short-term, medium-term, and long-term horizons, linking operational test work, predicted mineral phases, and performance verification.

Table 1 Coal ash–brine cemented paste backfill framework across short-term, medium-term and long-term processes

Description	Short-term (0–28 days)	Medium-term (1–12 months)	Long-term (>12 months)
Inputs	Class F ash	Residual brine salts	Groundwater interaction
	RO brine	Ongoing curing	Stress history
	OPC/binder dosage	Temperature/humidity	Time-dependent chemistry
	Target solids %		
Key processes	Rheology and pumpability	Pozzolanic reactivity	Pore refinement
	Early hydration (CSH/Aft)	Secondary phase formation	Reduced permeability
	Bleed control	Microstructure build-out	Diffusion-limited transport
Performance focus	Placement behaviour	Strength gain	Containment of dissolved salts
	Early UCS (7–28 days)	Stiffness and dimensional stability	Low hydraulic conductivity
	Stability for re-entry	Reduced permeability	Low mass flux
Risks and controls	Sulphate ettringite:	Microcracking:	Long-term leach/flow:
	Control binder chemistry	Curing control	Monitoring plan
	Brine envelope selection	Binder optimisation	Triggers & thresholds
Verification tests	Slump/flow, bleed	UCS @ 28–90 days	EPA 1315 monolith leach
	UCS @ 7–28 days	XRD/SEM mineralogy	Hydraulic testing
	ASLP (screening)	Lab permeability (k)	Periodic audit

RO = reverse osmosis; OPC = Ordinary Portland Cement; CSH = calcium silicate hydrate; Aft = alumina, ferric oxide, trisulphate; UCS = unconfined compressive strength; ASLP = Australian standard leaching procedure; XRD = X-ray diffraction; SEM = scanning electron microscopy; EPA = Environmental Protection Agency

4 Geochemical modelling

Predictive modelling is an essential component of assessing the long-term stability of coal ash–brine encapsulation in CPB. Numerical models allow for the simulation of mineralogical evolution, porewater chemistry, and salt immobilisation under stope conditions, providing insight into performance well beyond the time frame of laboratory tests (Zhu & Anderson 2002).

4.1 Modelling approach

Geochemical modelling was undertaken using PHREEQC, a widely applied equilibrium speciation and reactive transport code (Parkhurst & Appelo 2013). The model was configured to represent ash–brine–binder systems

under typical CPB conditions, with parameters for porosity, water-to-binder ratios, and brine chemistry derived from laboratory testing. Input parameters for binder composition, ash mineralogy, and brine chemistry were constrained using characterisation results to ensure realistic boundary conditions. Simulations were performed for different ash–brine ratios and binder dosages to assess the sensitivity of mineralisation pathways to mix design (Lothenbach & Winnefeld 2006).

4.2 Database selection and limitations

The choice of thermodynamic database is a key factor in modelling cementitious systems. While general-purpose databases such as LLNL provide coverage for many aqueous and mineral phases, they often lack the cement hydrate species essential for predicting encapsulation performance (Zhu & Anderson 2002). Databases such as CEMDATA07 include these phases, but their applicability under hypersaline conditions is limited (Matschei et al. 2007; Lothenbach et al. 2008). To address this gap, additional solubility data for chloride- and sulphate phases were incorporated where available (Möschner et al. 2008). A further limitation arises from ionic strength effects: activity correction models (e.g. Debye–Hückel or Pitzer) are not always adequate for highly saline solutions, introducing uncertainty into stability predictions (Appelo & Postma 2005). This highlights the broader challenge of simulating highly saline systems, where ionic strength effects and phase stability are less well constrained.

4.3 Model predictions

To illustrate typical model behaviour under hypersaline conditions, two representative outputs are included for an RO-brine and Class F fly ash paste. Figure 1 shows the evolution of secondary phases predicted with increasing cement addition, while Figure 2 shows the shift in major solutes before and after encapsulation. These outputs are used to visualise mineralogical and porewater trends that guide mix design before laboratory optimisation.

Simulation results indicated that initial cement hydration is not significantly inhibited at moderate brine substitution levels (PCA 1998). With increasing brine content, early-stage porewater chemistry reflects elevated sodium and chloride, but progressive precipitation of Friedel’s salt and LDHs reduces the dissolved load over time (Möschner et al. 2008). Longer-term predictions show continued development of C–S–H gels, associated with refinement of pore structure and reduced permeability (Lothenbach & Winnefeld 2006). Sulphate introduced via the brine is partly incorporated into ettringite and AFm phases, with stability governed by the calcium-to-alumina balance of the blend (Matschei et al. 2007).

While these trends are broadly consistent with experimental observations, the stability fields of LDHs and Friedel’s salt under elevated chloride concentrations remain sensitive to thermodynamic uncertainties. As such, caution is required when extrapolating predictions beyond calibrated compositional ranges (Zhu & Anderson 2002).

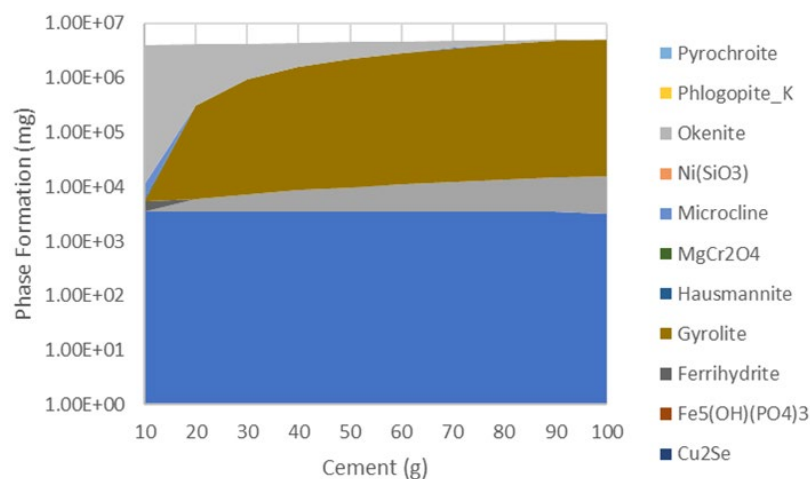


Figure 1 Predicted phase formation as a function of cement addition for an ash–brine paste scenario

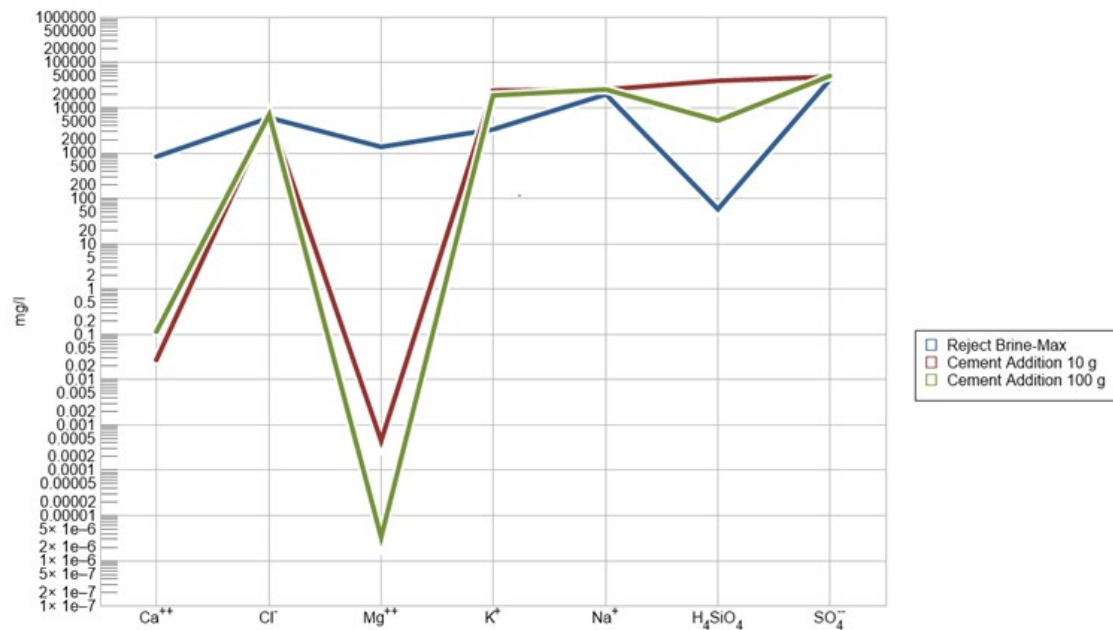


Figure 2 Predicted change in brine chemistry before and after encapsulation for major solutes

4.4 Practical role of modelling

The application of geochemical modelling provides a means of screening mix designs before extensive laboratory testing. Models can identify the conditions under which chloride and sulphate immobilisation are maximised, guide the selection of binder types, and anticipate long-term chemical stability (Lothenbach et al. 2008). While limitations in databases constrain absolute predictions, the relative trends produced are valuable for optimising the encapsulation framework. In addition, coupling equilibrium speciation with reactive transport simulations allows for assessment of diffusion-driven leaching scenarios, providing further assurance of long-term containment performance (Zhu & Anderson 2002; Parkhurst & Appelo 2013).

5 Analytical mineralogy and laboratory testing

The integration of coal ash and saline brine into CPB requires verification that both mechanical and environmental performance objectives are met. Laboratory testing and analytical mineralogy provide the necessary tools to evaluate mix behaviour, validate model predictions, and refine design parameters (Mukherjee 2011).

5.1 Mineralogical characterisation

Detailed mineralogical characterisation forms the basis of the framework. Standard techniques such as X-ray diffraction (XRD) are used to identify crystalline phases within coal ash, binders, and cured backfill samples (Roy et al. 1984; Fruchter et al. 1990). Emphasis is placed on quantifying amorphous content, as this fraction controls pozzolanic reactivity and long-term strength development (Zevenbergen et al. 1999). Scanning electron microscopy (SEM) and electron microprobe analysis provide insight into microstructural features, including hydration products, pore networks, and brine interaction with cementitious phases (Warren & Dudas 1985).

Automated methods such as QEMSCAN or other mineral liberation analysers enable quantitative mapping of mineral phases and their associations, which is important for confirming the presence and distribution of secondary chloride-binding and sulphate-binding minerals (Van Alphen 2007; Liu et al. 2005; French & Ward 2009). The ability to detect and quantify phases such as LDHs and Friedel's salt is particularly important for assessing long-term immobilisation mechanisms (Möschner et al. 2008).

5.2 Mechanical testing

Mechanical stability of the backfill is assessed primarily through unconfined compressive strength (UCS) testing. Mixes containing coal ash-brine are assessed at multiple curing intervals (7, 28, and 90 days) to establish strength development trends (PCA 1998). Results are compared against minimum requirements for slope stability. In most cases, the inclusion of coal ash contributes to pozzolanic strength gain over extended curing periods, partially offsetting the dilution effects of brine (Zevenbergen et al. 1999; Roy et al. 1984).

Permeability testing provides complementary information on microstructural refinement, with SEM evidence of pore narrowing and reduced connectivity correlating with reductions in hydraulic conductivity (Warren & Dudas 1985). Low permeability is a critical indicator of long-term salt containment (Mattigod et al. 1990).

5.3 Leachate testing

Leachate chemistry testing under controlled laboratory conditions evaluates the mobility of chloride, sulphate, and trace metals from cured mixes. Leachate is sampled over extended contact periods, with comparison to baseline brine composition providing a measure of immobilisation efficiency (Mahlaba 2002; Pretorius 1995). In CPB applications, this distinction is important because crushed or high liquid-to-solid screening tests tend to exaggerate early wash-off, whereas intact monolith behaviour is governed by mass-transfer limitations and progressive matrix densification with curing. For this reason, diffusion-influenced methods are particularly valuable where the material is placed and cured as a monolith underground, and the semi-dynamic tank leaching approach of SW-846 Method 1315 provides an established basis for assessing time-dependent release from cementitious matrices (Environmental Protection Agency [EPA] 2013). Recent LEAF-based demonstrations further show how semi-dynamic datasets can be used to distinguish short-lived surface wash-off from longer-term, diffusion-influenced release trends and to support screening-level assessments (Garraabrants et al. 2021). Observed reductions in dissolved salt concentrations are typically consistent with progressive secondary hydrate development and associated changes in pore connectivity. Where mineralogical support is required, chloride retention is most defensibly linked to AFm-type hydrate evolution and related aluminate phases, rather than assumed LDH control unless those phases are directly confirmed for the specific binder system (Lv et al. 2025; Georget et al. 2025; Mir et al. 2020).

5.4 Integrated role of testing

Together, mineralogical analysis, mechanical testing, and leachate assessment provide a multi-dimensional evaluation of coal ash–brine CPB performance. Laboratory methods validate predictions from geochemical modelling, confirm immobilisation mechanisms, and guide optimisation of ash-to-binder ratios and brine substitution levels (Mukherjee 2011). More importantly, the integration of these datasets allows for mechanistic interpretation: linking strength development, permeability trends, and leachate chemistry directly to the underlying mineralogical transformations (French & Ward 2009). This triangulated approach ensures that mix designs are both operationally viable and environmentally robust.

5.5 Anonymised case example: quantitative performance indicators

To ground the framework in measured performance, an anonymised RO-brine and Class F fly ash case is included. Two mixes were prepared with different brine contents (5 and 10%), while other constituents were held constant. The intent is not to present a full case history, but to illustrate the type of acceptance indicators typically evaluated in practice: strength development and leach behaviour. In CPB applications, these indicators are typically assessed as a linked set because strength gain, microstructure development, and mass-transfer behaviour evolve together with curing time (Wang et al. 2023).

Table 2 summarises the UCS results for the 2 mixes over 21–42 days. These values reflect operational curing windows commonly used for CPB and show that both mixes develop strengths within the MPa range over this period.

Table 2 Unconfined compressive strength of cemented ash–brine paste

Mix	Brine content	21 days (MPa)	28 days (MPa)	35 days (MPa)	42 days (MPa)
Mix 1	5%	3.1	2.3	3.1	3.8
Mix 2	10%	2.6	2.2	4.3	2.7

To screen readily soluble constituents, a short-term leach test Australian Standard Leaching Procedure (ASLP, 1:20 S:L) was undertaken on the fly ash and both mixes. Selected indicators are listed in Table 3. As expected, chloride, sodium and potassium concentrations increase with brine content, while calcium decreases due to reaction with aluminosilicates in the ash matrix.

Table 3 Selected short-term leachate indicators (ASLP, 1:20 solid:liquid)

Parameter	Fly ash	Mix 1 (5% Brine)	Mix 2 (10% Brine)	Unit
pH	12.2	11.5	11.5	pH
TDS	832	310	354	mg/L
EC	126	39	53	mS/m
Chloride	<0.25	6.03	10.9	mg/L
Sulphate	68.2	51.3	51.1	mg/L
Aluminium	0.45	5.47	5.42	mg/L
Calcium	447	80.5	68.6	mg/L
Sodium	1.44	28.9	59.4	mg/L
Potassium	1.73	22.6	29.7	mg/L

Because CPB is placed and cured as a monolith, Environmental Protection Agency (EPA) Method 1315 (EPA 2013) was used to better represent in situ behaviour. Table 4 lists the ranges measured over cumulative leaching intervals (2 hours to 28 days). Results show an initial surface wash-off phase, followed by a rapid decline in release rates, consistent with diffusion-controlled behaviour in a maturing cemented matrix. This interpretation is consistent with recent LEAF demonstrations where semi-dynamic monolith datasets are used to separate short-lived wash-off from longer-term diffusion-influenced release and to support screening-level leaching assessments (Garraabrants et al. 2021).

Table 4 Selected monolith leach ranges (Environmental Protection Agency Method 1315) over 2 hours to 28 days

Parameter	Mix 1 (5% Brine)	Mix 2 (10% Brine)	Unit
pH	9.4–10.4	9.3–10.5	pH
TDS	20–120	22–150	mg/L
Chloride	0.48–7.45	0.66–9.07	mg/L
Sulphate	6.21–25.0	7.76–37.7	mg/L
Aluminium	0.10–1.92	0.05–2.10	mg/L
Sodium	4.41–26.8	5.04–36.9	mg/L
Potassium	1.69–17.0	1.38–16.6	mg/L

The observed pattern, early surface wash-off followed by lower, diffusion-controlled release, is consistent with the monolithic backfill form and aligns with the modelling trend of progressive secondary phase formation. More generally, recent reviews emphasise that chloride retention in cementitious matrices is controlled by coupled physical and chemical binding mechanisms, including AFm phase evolution, and that competing anions and porewater composition can shift the balance between retained and mobile fractions. (Lv et al. 2025; Georget et al. 2025)

The triangulated relationship between mineralogical confirmation, modelling predictions, and performance testing is summarised in Figure 3.

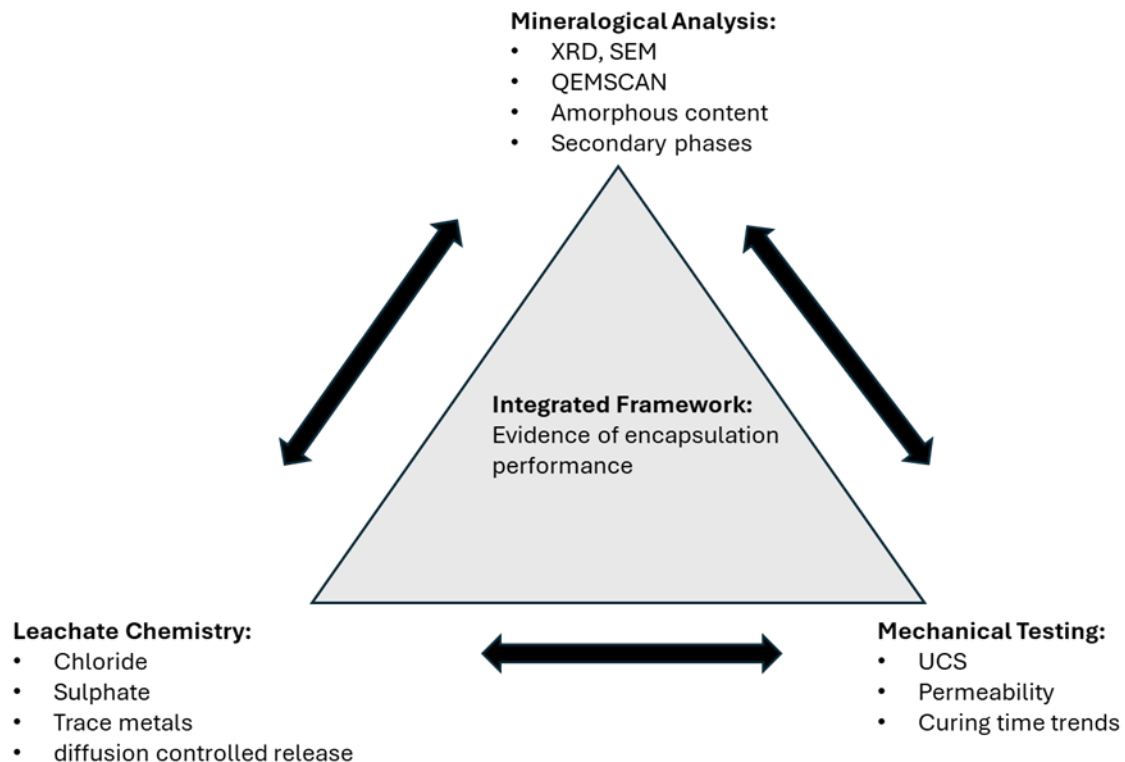


Figure 3 Triangulated framework for evaluating cemented paste backfill performance, integrating mineralogical, geochemical, and mechanical datasets

6 Discussion

The anonymised case example in Section 5.5 shows how the framework translates into practical acceptance checks: MPa-level UCS development over standard curing windows and markedly lower leach loads under monolithic assessment relative to crushed screening tests. In practice, this distinction is important, as CPB behaves as a solid mass in situ and its leach profile is governed primarily by surface wash-off followed by diffusion-controlled release.

The integration of coal ash-brine into CPB requires balancing operational performance with long-term geochemical stability. The framework presented in this paper demonstrates that both objectives can be met when systematic characterisation, predictive modelling and laboratory validation are combined. Results from the modelling illustrate how early-age porewater chemistry responds to brine addition and how secondary minerals, particularly C–S–H, AFm phases and LDHs, support progressive containment over time. Corresponding laboratory results confirm that strengths within operational ranges can be achieved and that monolithic leach rates decline rapidly after initial exposure.

Together, these elements show that coal ash–brine CPB can perform as both a structural material and a containment system when mix design is tuned to brine chemistry, binder demand, and the reactive potential of the ash. The staged approach provides a practical means of identifying risks early in the design process

and of demonstrating, with measurable evidence, that both geotechnical and environmental performance requirements can be satisfied.

6.1 Operational benefits

The incorporation of coal ash reduces demand for conventional binders, contributing to lower costs and improved sustainability of backfill operations (Adriano et al. 1980). The use of saline brine as mix water decreases reliance on freshwater resources, which is an important advantage in regions where water scarcity constrains mining activities (Carlson & Adriano 1993). Furthermore, CPB prepared with ash–brine mixes have shown to retain pumpability and early strength development within acceptable operational ranges, ensuring that underground placement is not compromised (Zevenbergen et al. 1999). The reactivity of amorphous ash phases further supports strength gain over time, offering operational resilience beyond initial curing (Fruchter et al. 1990).

6.2 Environmental advantages

Co-disposal of coal ash–brine in underground workings provides a secure alternative to surface storage. Laboratory leachate testing and geochemical modelling confirm that the precipitation of secondary phases such as LDHs and Friedel's salt effectively immobilises chloride and sulphate ions (Möschner et al. 2008; PCA 1998). Reduced permeability over curing time further limits migration of dissolved salts (Mattigod et al. 1990). By integrating mineralogical, geochemical, and mechanical evidence, a clear demonstration of containment performance is possible (Liu et al. 2005; Van Alphen 2007). Relocating waste streams underground significantly reduces the risks of seepage, dam failure, and long-term monitoring liabilities associated with surface facilities (Pretorius 1995; Mahlaba 2002).

6.3 Technical challenges

The differing UCS trajectories at 5 and 10% brine underscore the role of brine chemistry in early-age reactions. Sulphate species can promote secondary formations that temporarily depress strength if the binder-to-alumina balance is not well controlled, and these effects can become more pronounced as brine concentration increases. In practical terms, this often shows up as a transient sensitivity during early curing, followed by recovery as continued reaction and microstructural densification become dominant. The timing and magnitude of that response is brine-specific and should not be assumed to be monotonic.

Despite the advantages demonstrated in this study, several challenges remain. Brine chemistry is inherently variable, and elevated concentrations of certain ions can shift hydration pathways or influence strength gain (Sakata 1987). Predictive modelling under high ionic strength conditions also carries uncertainty, particularly where thermodynamic databases are incomplete or where kinetic effects differ from equilibrium assumptions (Zhu & Anderson 2002; Parkhurst & Appelo 2013). Long-term stability of immobilising phases under changing redox or thermal conditions still requires validation to ensure that retention mechanisms persist throughout the life of the backfill (Eary et al. 1990). Recent guidance also highlights that apparent binding and release behaviour can be sensitive to test conditions and reporting basis, which strengthens the case for consistent documentation of brine chemistry, curing regime, and leach methodology when results are used for screening or compliance arguments (Georget et al. 2025).

From an operational perspective, managing high-salinity water in reticulation systems may necessitate adjustments to pumping strategy, solids concentration, or dispersant use to maintain flowability (French & Ward 2009). These considerations reinforce the need for site-specific characterisation and staged testing so that mix designs can be tuned to brine chemistry and performance requirements. Where monolith leaching is used to support decision-making, semi-dynamic datasets are also increasingly applied to separate short-lived wash-off from longer-term, diffusion-influenced behaviour, which helps define practical acceptance indicators for scale-up (Garraabrants et al. 2021).

6.4 Regulatory considerations

Implementation of ash–brine CPB systems must align with both mining and environmental regulations. Regulators typically require evidence that waste encapsulation does not compromise underground water quality or structural stability (EPA 1993; Zhu & Anderson 2002). In practice, the most persuasive evidence is simple and transparent: mechanical acceptability within the operational curing window, paired with leaching behaviour that reflects the monolithic form of CPB (EPA 2013).

Given the analytical challenges posed by highly saline solutions, single data streams are rarely sufficient. Mineralogical confirmation, leachate testing, and modelling outputs need to be read together to build an evidence base that can be audited and defended (Mukherjee 2011; French & Ward 2009). Recent technical reviews also stress that leaching and binding outcomes can be sensitive to test conditions and reporting basis, which makes documentation of brine composition, curing regime, and leach methodology essential when results are used for screening or compliance arguments (Georget et al. 2025). Where semi-dynamic monolith tests are applied, they are increasingly used to distinguish short-lived wash-off from longer-term diffusion-influenced release trends, helping translate laboratory results into practical acceptance indicators (Garraabrants et al. 2021).

Engagement with regulators and stakeholders early in the planning process is essential to demonstrate that environmental and operational risks are being managed (Carlson & Adriano 1993). At a minimum, early engagement should agree the brine screening suite, the acceptance indicators to be applied (strength, permeability where available, and monolith leaching), and the decision triggers for staged testing or mix adjustment.

6.5 Broader applicability

While the framework was developed with coal ash–brine in mind, the same logic can be applied to other industrial byproducts and saline effluents where underground placement is technically and operationally feasible. Examples include tailings with elevated salinity, desalination brines, and process waters from water treatment or cooling circuits, provided the material compatibility, and backfill performance requirements are demonstrated through staged testing (Adriano et al. 1980).

The value of the framework is less about a single waste pair and more about the discipline it imposes. It forces early characterisation, makes the mix design assumptions explicit, and links acceptance indicators to the form and curing conditions expected underground. That adaptability broadens its relevance across sectors and supports more sustainable integration of waste streams into backfill operations, particularly where surface storage options are constrained or carry long-term liability (Mukherjee 2011).

In practical terms, extension to other waste streams should be treated as a managed scale-up rather than a direct substitution exercise. Brine composition, variability, and operational constraints can dominate performance, so the same staged workflow remains essential when moving from conceptual development to operational deployment.

7 Conclusion

The framework presented in this paper shows that co-disposal of coal ash–brine within CPB is a practical route to both operational performance and long-term containment. By staging systematic characterisation, predictive modelling and laboratory validation, the approach provides a structured basis for application in underground mining environments.

Key conclusions are:

- Feasibility demonstrated within operational windows: in the anonymised case example, cemented ash–brine pastes achieved MPa-level UCS between 21 and 42 days, within typical scheduling windows for placement and early exposure to load (Table 2). This supports the practical feasibility of coal ash–brine CPB in stope stability contexts.

- Assess encapsulation in the form you will place: short-term leach tests remain useful as conservative screening tools, but monolith leaching (EPA 2013) better represents in situ CPB behaviour. The case example shows early surface wash-off followed by markedly lower release with time (Tables 3 and 4), supporting monolith testing as the primary basis for leach performance decisions. This interpretation aligns with recent LEAF demonstrations distinguishing short-lived wash-off from longer-term diffusion-influenced release trends (Garraabrants et al. 2021).
- Modelling narrows the search space for design: geochemical modelling under hypersaline conditions is effective for anticipating secondary phase formation and porewater trends. Phase stability and ‘before and after’ brine chemistry outputs help define binder and brine envelopes prior to laboratory optimisation (Figures 1 and 2).
- Mechanisms align with field objectives: predicted and observed microstructural evolution, including cement hydrates, aluminosilicates and related secondary phases, supports strength development and reduced leachability with curing, consistent with the targeted reduction in permeability during service.
- A triangulated workflow reduces project risk: integrating mineralogical confirmation, modelling predictions and performance testing provides an evidence-based path to design sign-off and regulatory alignment (Figure 3), while enabling practical benefits such as reduced freshwater demand and diversion of wastes from surface storage.

In summary, encapsulating coal ash-brine within CPB is a technically feasible, environmentally sound, and operationally beneficial option when guided by the proposed workflow and validated with site-specific data.

8 Recommendations

To advance the framework into practice, the following steps are proposed:

1. Site-specific characterisation: profile ash and brine chemistry and mineralogy, with emphasis on amorphous content.
2. Pilot trials: validate mix performance under field conditions, including pumping and in situ strength gain.
3. Database refinement: enhance geochemical models with improved thermodynamic data for cement hydrates under hypersaline conditions.
4. Performance monitoring: implement long-term monitoring of leachate, pore structure, and stope water chemistry.
5. Wider application: extend the framework to other saline or pozzolanic by-products such as tailings or desalination brines.

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