



Article

Mechanical and Chemical Durability of a Fly Ash–Epoxy Composite Cement for Extreme Oil and Gas Well Conditions

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Abstract

Oil and gas well cement is routinely exposed to aggressive chemical and mechanical environments that can compromise long-term zonal isolation. Conventional Portland cement systems, which rely on hydration products such as calcium silicate hydrate (C–S–H), are particularly vulnerable to acid attack, carbonation, high salinity, and thermal stress. This study investigates a polymer–mineral composite cement in which Class F fly ash is incorporated into an epoxy resin matrix at 0, 25, and 50 weight percent (wt%) loading. The composite samples were exposed for ten days to harsh downhole-representative environments, including hydrochloric acid (HCl, 15–28 wt%), sodium hydroxide (NaOH, 15–28 wt%), sodium chloride (NaCl) brines (20 wt%), crude oil, elevated temperatures up to 100 °C, and high-pressure carbon dioxide (CO₂). Compressive strength was evaluated using a universal testing machine, capturing both deformation strength and ultimate failure strength to assess elastic and structural performance. Across most conditions, the composite maintained strengths exceeding 5000 psi, demonstrating strong chemical resistance. Acidic and CO₂ exposures primarily reduced elastic deformation rather than ultimate strength, suggesting localized interaction with the polymer matrix. Elevated temperature reduced strength to ~2800 psi and diminished elasticity, marking the material's upper thermal limit. Acetone exposure progressively degraded the polymer network, highlighting potential controlled removability. These findings indicate that embedding industrial fly ash in a polymer matrix produces a mechanically resilient and chemically robust cement alternative with up to 50 wt% industrial waste incorporation. This hybrid system offers a promising approach for wells exposed to acidic, CO₂-rich, or high-salinity environments, where conventional Portland cement may fail.

Keywords: resin; sustainable; fly ash cement; compressive strength; cementing



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1. Introduction

Cementing is one of the most critical operations in the life cycle of an oil or gas well. Beyond securing the casing, well cement serves as the primary barrier that ensures zonal isolation, prevents fluid migration, and protects freshwater aquifers from contamination. Loss of cement integrity can result in sustained casing pressure, interzonal communication, or, in severe cases, catastrophic failure. Historical well integrity incidents have repeatedly demonstrated that cement failure is not merely a materials issue, but a systemic risk to operational safety and environmental protection. Research has addressed chemical formulations for cement slurries and the mechanical behavior of well materials under stress [1–3], the influence of various fluids on rock and cement properties [4–8], and advanced imaging

or characterization techniques for pore structures and erosion testing [5–11]. Additionally, novel methods such as in situ gravel packs and polymer injection strategies have been explored to improve operational efficiency and promote sustainability in oil and gas wells [7–19].

The downhole environment presents a uniquely complex combination of stressors. Cement sheaths are exposed to fluctuating mechanical loads resulting from casing expansion and contraction, pressure cycling during production and injection, and long-term reservoir depletion effects. Chemically, the cement may encounter acidic fluids, carbon dioxide, hydrogen sulfide, high salinity brines, and crude oil components [20–25]. Thermally, elevated temperatures accelerate degradation mechanisms and induce thermal stresses that can generate microcracks [26–28]. Moreover, mechanical and hydraulic challenges such as fracture height growth, fracture propagation, and leakoff effects can exacerbate cement and formation integrity issues [13,14,16,19]. Conventional Portland cement systems, which rely on hydration products such as calcium silicate hydrate (C–S–H), are particularly susceptible to acid dissolution, carbonation, shrinkage, and reduced long-term durability under such complex downhole conditions [15–18,21–23,27].

To address these limitations, alternative cement systems have been investigated. Geopolymer cements derived from fly ash and alkaline activators have demonstrated improved chemical resistance and reduced carbon footprint. However, their performance remains sensitive to fly ash variability and activator composition, leading to concerns regarding reproducibility and field reliability [29–33]. Polymer-based materials, particularly epoxy resins, have also been used in well remediation, sand consolidation, and coating applications due to their chemical resistance and high mechanical strength. Nevertheless, polymer systems are typically deployed as repair materials rather than primary cementing systems [34–42].

The present study explores a different approach: the development of a hybrid polymer–mineral composite in which fly ash particles are embedded within an epoxy matrix. In this configuration, the polymer phase provides chemical resistance and elasticity, while the mineral filler reduces material cost and enhances stiffness [43–55]. Unlike geopolymer systems, this composite does not rely on hydration chemistry, thereby eliminating acid-sensitive cementitious phases. At the same time, incorporating up to 50 wt% fly ash improves sustainability by valorizing industrial waste material [56–61].

Despite extensive research on geopolymer cements and polymer-based well remediation materials, there remains a lack of systematic evaluation of hybrid polymer–mineral composite systems as primary cementing alternatives for chemically aggressive well environments. Conventional Portland cement systems are inherently vulnerable to acid dissolution, carbonation reactions, and microcracking under cyclic mechanical loading. While additives can improve specific properties, they do not fundamentally alter the calcium-based hydration chemistry governing degradation mechanisms [62–70].

Previous studies have investigated epoxy resins primarily for sand consolidation, casing repair, or remedial sealing operations rather than as structural cement matrices incorporating mineral fillers. Furthermore, most reported studies evaluate isolated exposure conditions rather than simultaneous benchmarking across acidic, alkaline, saline, thermal, and CO₂-rich environments relevant to oil and gas operations [70–88].

The objective of this research is to systematically evaluate the mechanical durability and chemical resilience of a fly ash–epoxy composite under aggressive downhole conditions, including acidic, alkaline, high-salinity, CO₂-rich, thermal, and pressurized environments typical of oil and gas wells. Particular emphasis is placed on distinguishing between elastic deformation strength, the material's capacity to sustain loads without permanent deformation, and ultimate failure strength, providing a more complete characterization of

the material's load-bearing behavior. By assessing performance across multiple extreme conditions, this study aims to define the operational envelope and identify potential applications for this composite cement system.

This study addresses several gaps in current cementing and resin-based systems by:

- Developing a hybrid fly ash–epoxy composite that incorporates up to 50 wt% industrial by-product material, thereby promoting resource efficiency and partial replacement of high-energy polymer content.
- Systematically evaluating mechanical durability under a range of chemically aggressive, thermal, and high-pressure conditions that are relevant to wellbore integrity.
- Benchmarking performance against conventional American Petroleum Institute (API) Class G cement, highlighting differences in chemical resistance, ductility, and long-term stability.
- Distinguishing between deformation strength and failure strength, allowing the characterization of semi-ductile behavior that conventional cement tests often fail to capture.

While epoxy resins have been widely applied in well repair, sand consolidation, and temporary plugging, the present composite system is distinct in both design and performance. Unlike conventional resin-based materials, this fly ash–epoxy system leverages industrial by-products to achieve a mechanically resilient, chemically stable matrix that can partially replace high-energy polymer without sacrificing performance [7,88]. Compared with geopolymer cement systems, which rely on alkali activation of aluminosilicate precursors, the epoxy–fly ash composite provides superior resistance to acid, CO₂, and high-salinity conditions commonly encountered in aggressive reservoirs [67,77,84,86,88]. This unique combination of semi-ductile mechanical behavior, chemical resistance, and waste material incorporation positions the composite as a novel alternative for specialized applications such as acidizing-prone wells, CO₂ injection projects, and high-salinity formations, where traditional Portland cement or geopolymer systems may exhibit accelerated degradation.

By defining the operational envelope, performance trade-offs, and environmental advantages of this composite system, the study contributes to the development of next-generation cementing materials tailored for chemically aggressive, CO₂-intensive, and thermally constrained well environments.

2. Experimental Description

2.1. Materials

2.1.1. Fly Ash

Class F fly ash was used as the mineral filler phase in the composite cement. The material was obtained from a cement production facility in Egypt. Class F fly ash was selected due to its low calcium content and chemical stability, which reduces the likelihood of secondary hydration or acid-reactive phases forming within the composite [84–87]. Prior to mixing, the fly ash was oven-dried at 60 °C for 24 h to eliminate moisture that could interfere with polymer curing. The chemical composition of Class F fly ash used in this research:

- **Silicon dioxide (SiO₂):** 50–60 wt%—major glassy phase contributing pozzolanic activity;
- **Aluminum oxide (Al₂O₃):** 20–30 wt%—provides pozzolanic properties;
- **Iron oxide (Fe₂O₃):** 5–10 wt%—minor component; can influence color and reactivity;
- **Calcium oxide (CaO):** <10 wt% (usually 1–5)—low calcium content distinguishes Class F from Class C fly ash;
- **Magnesium oxide (MgO):** 1–5 wt%—can affect minor expansion;
- **Sulfur trioxide (SO₃):** <1–3 wt%—depends on coal and cement kiln source;

- **Alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$):** 0.5–3 wt%—low levels preferred to reduce alkali-silica reaction risk;
- **Loss on ignition (LOI, unburned carbon):** 1–6 wt%—higher LOI can reduce workability and affect polymer bonding.

2.1.2. Epoxy Resin System

A commercially available two-component epoxy system consisting of a base resin and amine hardener was used as the polymer matrix. The resin was supplied as a moderately viscous, light-yellow liquid, while the hardener was a low-viscosity transparent liquid. The manufacturer-recommended resin-to-hardener ratio was strictly maintained to ensure complete crosslinking and consistent mechanical performance. The ratio of epoxy resin to hardener was 4:1 by weight.

The epoxy system was selected due to:

- High compressive strength after curing;
- Chemical resistance to acids and brines;
- Low permeability;
- Proven use in downhole repair and consolidation operations.

2.1.3. Chemical Exposure Media

To simulate aggressive downhole environments, the following exposure fluids were prepared:

- Hydrochloric acid (15 wt% and 28 wt%);
- Sodium hydroxide solution (15 wt% and 28 wt%);
- Sodium chloride brine (15 wt% and 20 wt%);
- Distilled water (baseline control);
- Crude oil (450 cp at ambient conditions, Gulf of Suez origin);
- Carbon dioxide (500 psi and 1200 psi at 60 °C);
- Acetone (for degradation study).

All chemical solutions were prepared using analytical-grade reagents and distilled water.

2.2. Composite Cement Preparation

The composite cement consisted of epoxy resin as the continuous matrix phase and fly ash as the dispersed filler phase. Three formulations were prepared:

- 0 wt% fly ash (pure epoxy control);
- 25 wt% fly ash;
- 50 wt% fly ash.

Fly ash loading was selected to investigate the effect of mineral filler content on strength retention and elastic behavior while maintaining workability. Increasing the fly ash concentration beyond 50% by weight resulted in a significant decrease in sample workability. This had a negative impact on the slurry viscosity which made it almost impossible to inject. Also, increasing the fly ash concentration resulted in a significant increase in the slurry density, which also impacted workability and injectivity negatively.

The preparation procedure was as follows:

1. The required mass of fly ash was weighed using a precision balance.
2. The epoxy resin component was placed in a clean mixing container.
3. Fly ash was gradually added to the resin under continuous mechanical stirring to ensure homogeneous dispersion and prevent agglomeration.
4. After achieving uniform particle distribution, the hardener was added according to the manufacturer's specified ratio.

5. The mixture was stirred for an additional 3–5 min to ensure complete blending.
6. The slurry was poured into cubic molds (dimensions: $5 \times 5 \times 5 \text{ cm}^3$).
7. Samples were allowed to cure at ambient laboratory conditions for 24 h (22 °C, and 14.7 psia, and 43% humidity).
8. After demolding, specimens were conditioned for an additional 48 h prior to exposure testing.

All samples were visually inspected to ensure absence of macro-voids or segregation. The chemicals used are presented in Figure 1.



Hardener



Epoxy Resin



Fly Ash

Figure 1. Components of Novel Cement.

2.3. Exposure Conditions

To evaluate chemical and thermal durability, cured specimens were fully submerged in the designated exposure media for 10 consecutive days. The conditions under which the evaluation conducted was selected based on industry considerations. The 15% and 28% HCl and NaOH represent the most severe conditions that could be present in hydrocarbon wells. Additionally, the salinity selected was based on the concentrations of the formation water associated with oil and gas wells, which can reach more than 25 wt%. Finally, the temperature and CO₂ were selected based on different reservoir temperatures and the pressures required to represent gaseous CO₂ and supercritical CO₂ phases.

Exposure conditions included:

- Acidic environment (15% and 28% HCl);
- Alkaline environment (15% and 28% NaOH);
- High salinity brine (15% and 20% NaCl);
- Elevated temperature (20, 40, 60, 100 °C water bath);
- Carbon dioxide at 60 °C under:
 - 500 psi (gaseous CO₂);
 - 1200 psi (supercritical CO₂);
- Crude oil at ambient conditions;
- Acetone for degradation testing.

During exposure:

- Samples were visually inspected daily.
- Mass measurements were recorded to monitor fluid uptake or degradation.
- For CO₂ experiments, samples were placed inside a sealed high-pressure vessel equipped with a pressure regulator.

All exposure durations were maintained at 10 days to ensure consistent comparative evaluation across environments.

2.4. Compressive Strength Testing

Compressive strength was measured using a calibrated universal testing machine (UTM) (obtained from HST, Shanghai, China). Each formulation and exposure condition was tested in triplicate to ensure reproducibility. Figure 2 presents the universal testing compressive strength machine. The universal testing compressive was obtained from HST-China strength machine, (obtained from HST, Shanghai, China, used in this research had a capacity of 2000 kN and an accuracy of two decimal places.

The loading protocol included:

- Axial compressive loading applied at a constant displacement rate of 40 kg_f/cm²/min.
- Load continuously recorded until structural failure.

Because the composite exhibited significant elastic deformation prior to fracture, two strength metrics were defined:

1. **Deformation Strength**—The stress at the onset of noticeable macroscopic deformation. The point at which the deformation strength was determined was when the sample exhibited plastic deformation, but did not yet fail. It was determined as the yield point of the sample from the stress–strain plot.
2. **Failure Strength**—The maximum stress recorded immediately prior to structural failure. This was determined as the tensile strength of the samples and was determined from the stress–strain plot.

Compressive strength was calculated based on Equation (1):

$$\sigma = \frac{F}{A} \quad (1)$$

where:

- F = applied load at deformation or failure (lbf or N)
- A = cross-sectional area of the specimen

Results are reported as mean values of three replicates.



Figure 2. Universal Testing Compressive Strength Machine.

2.5. Statistical Considerations

All experiments were conducted using three independent specimens per condition. Average compressive strength values are reported, and variability among samples was monitored to assess homogeneity of mixing. Deviations between replicates remained within acceptable laboratory variation limits, indicating reproducible composite fabrication.

Figure 3 shows an illustration of the experimental workflow and the cement preparation procedure to highlight the exact steps followed to conduct the experiments.

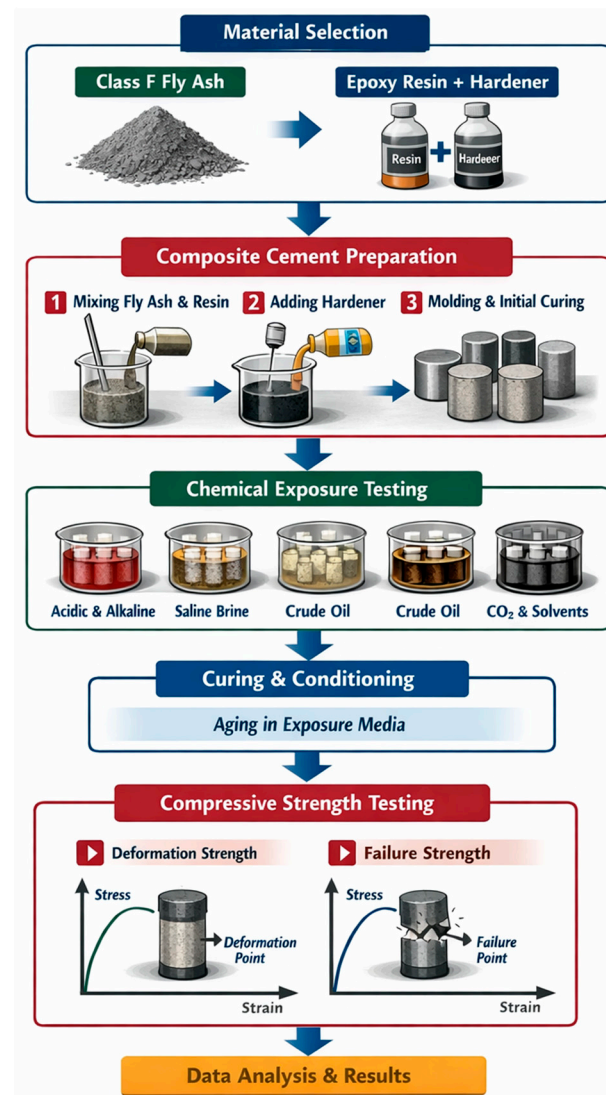


Figure 3. Experimental Workflow.

3. Results and Analysis

The compressive strength results for both the deformation strength and the failure strength of the novel fly ash resin cement under different conditions is presented. For all conditions, three samples were tested including a sample with no fly ash, a sample with 25% fly ash, and a sample with 50% fly ash. For each experiment three samples were tested and the average compressive strength for all three samples was recorded to ensure that the cement was mixed homogeneously. The tests include acid, alkaline resistance, high salinity, high temperature, high pressure, carbon dioxide, and crude oil resistance. The results also present tests for decomposition of the cement using acetone.

3.1. Baseline Mechanical Performance (Distilled Water Conditioning)

The baseline compressive strength of the composite specimens was evaluated after 10 days of immersion in distilled water to establish a reference for subsequent environmental exposure comparisons, shown in Figure 4.

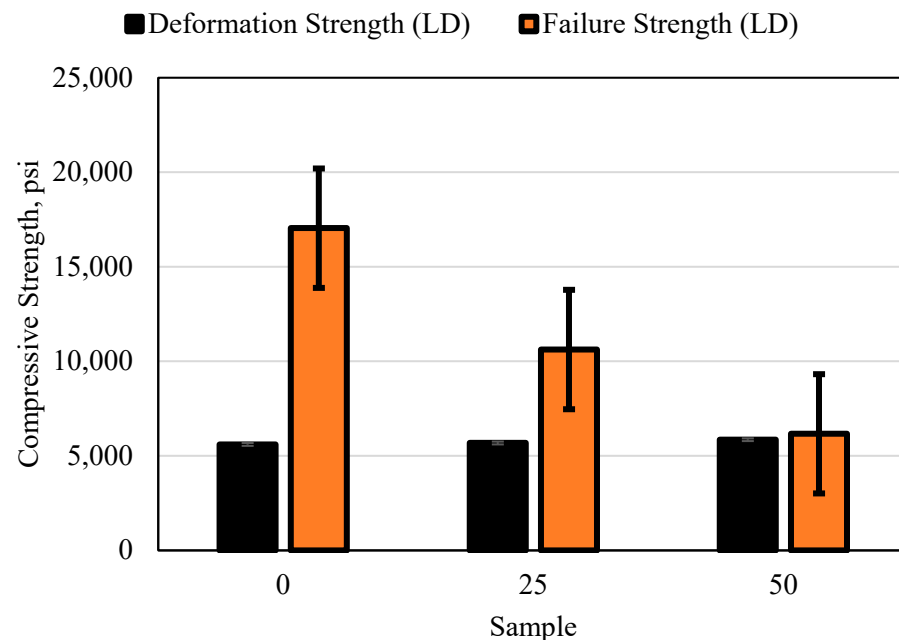


Figure 4. Deformation and Failure Strength of the 0, 25, and 50 wt% Fly Ash Samples Placed in Distilled Water for 10 Consecutive Days.

Across all formulations (0, 25, and 50 wt% fly ash), deformation strength remained approximately 5500–5800 psi. The ultimate failure strength, however, exhibited a clear dependence on fly ash content. The 0 wt% sample (pure epoxy matrix) demonstrated the highest failure strength, while increasing fly ash loading progressively reduced ultimate failure stress and reduced elastic deformation prior to fracture.

This behavior reflects the transition from a polymer-dominated ductile response to a more particle-constrained semi-brittle composite response as filler loading increases. The fly ash particles act as rigid inclusions within the polymer matrix, restricting chain mobility and reducing strain capacity before failure.

For comparison, conventional API Class G cement cured under similar laboratory conditions typically exhibits compressive strengths in the range of 3000–5000 psi after 7–14 days, depending on curing temperature and additives. The composite cement therefore meets or exceeds the minimum compressive strength requirements typically specified for primary cementing operations.

Importantly, unlike Portland cement systems that exhibit brittle fracture at peak load, the composite demonstrated measurable deformation prior to structural failure. This ductility may provide tolerance against microcrack propagation caused by casing expansion, thermal cycling, and pressure fluctuations.

3.2. Performance Under Acidic Conditions

Exposure to 15 wt% and 28 wt% HCl did not significantly reduce ultimate compressive strength for any formulation. Deformation strength remained above 5500 psi across fly ash loadings, with only moderate reductions observed in the pure epoxy formulation, as is shown in Figure 5.

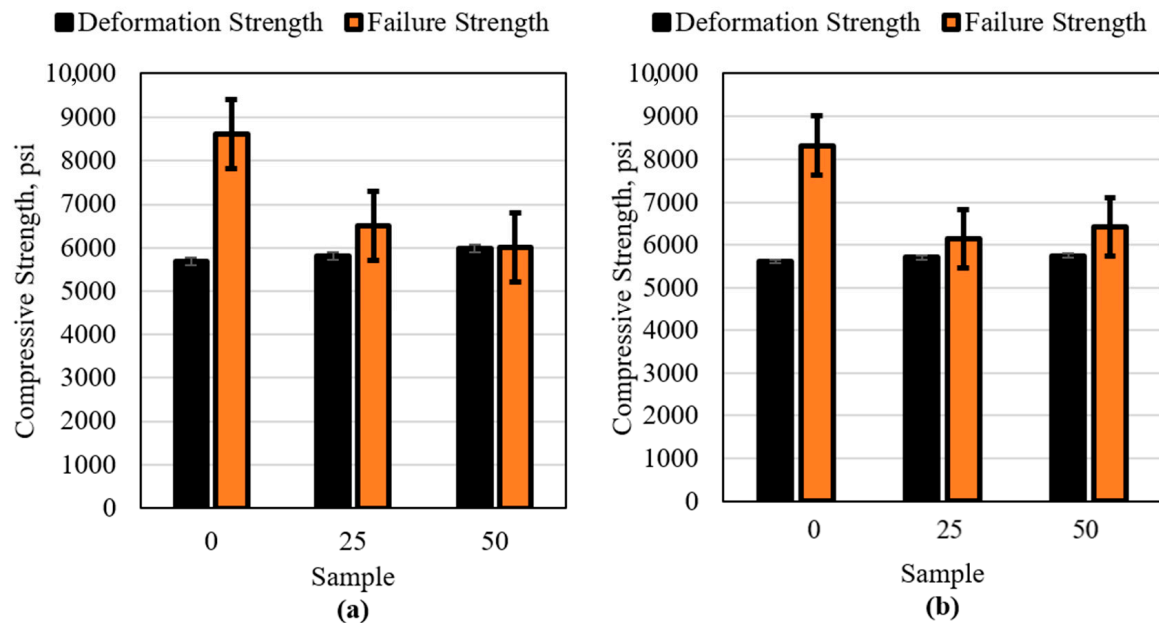


Figure 5. Deformation and Failure Strength of the 0, 25, and 50 wt% Fly Ash Samples Placed in (a) 15 wt% HCl and (b) 28 wt% HCl for 10 Consecutive Days.

In contrast, conventional Portland cement systems are highly vulnerable to hydrochloric acid exposure due to dissolution of calcium hydroxide and decalcification of C–S–H phases. Even short-term exposure to strong acid can reduce compressive strength by more than 30–60%, depending on concentration and exposure duration.

The composite's resistance to acid degradation can be attributed to its polymer-based matrix. Because the material does not rely on hydration products or calcium-based binding phases, there are no acid-reactive mineral components susceptible to rapid dissolution. The slight reduction in deformation strength observed in the 0 wt% sample suggests surface-level polymer softening or plasticization rather than structural degradation.

The addition of fly ash appeared to slightly stabilize elastic response under acid exposure, likely due to reduced polymer fraction and increased mechanical confinement of the matrix phase.

The resistance of epoxy–fly ash cement composites to acid degradation is closely tied to how well the solid particles are bonded within the polymer matrix. When strong interfacial bonding exists between the epoxy resin and the fly ash particles, the composite forms a more continuous and tightly integrated structure, which limits the penetration of acidic fluids and slows down chemical attack. This improved bonding reduces microvoids and weak interfaces, typically the first points of acid ingress, thereby enhancing durability. In contrast, weaker bonding leads to interfacial gaps and pathways that allow acids to infiltrate more easily, accelerating degradation and material breakdown. In essence, the better the adhesion within the polymer matrix, the more resistant the composite is to acid-induced damage [81].

Overall, under extreme acid concentrations (28 wt% HCl), the composite maintained compressive strength values exceeding those typically reported for acid-exposed Class G cement systems.

3.3. Alkaline Stability

Under high-pH exposure (15 wt% and 28 wt% NaOH), compressive strength remained close to baseline values, with less reduction in deformation strength compared to acid exposure, shown in Figure 6.

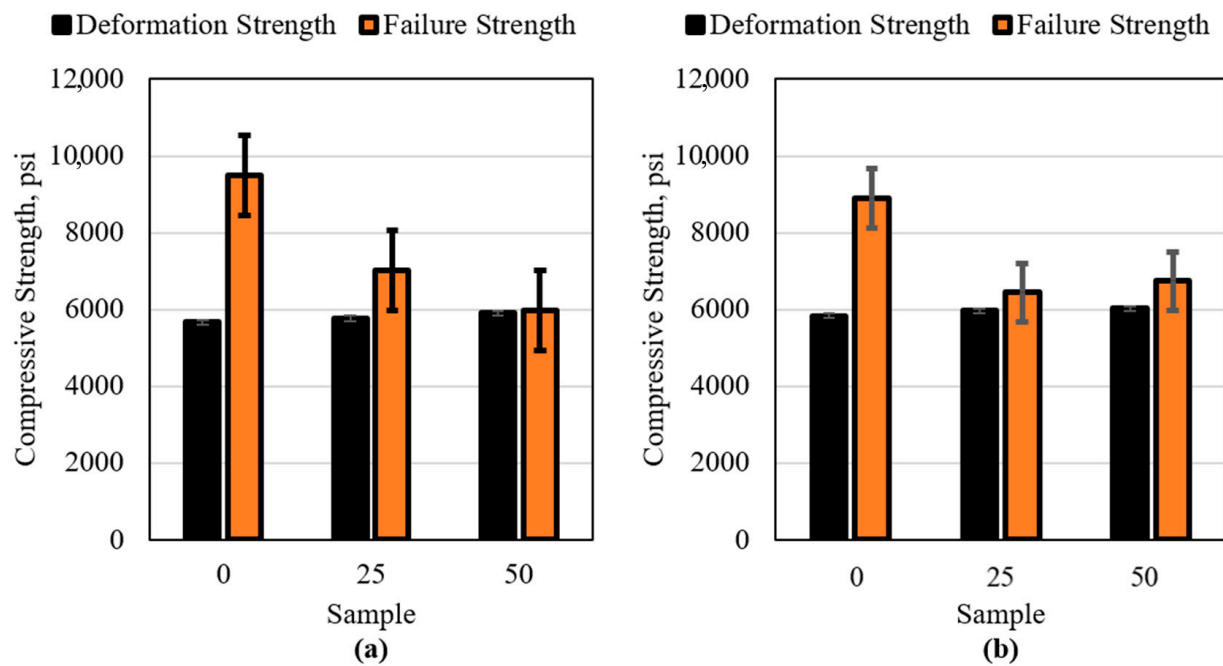


Figure 6. Deformation and Failure Strength of the 0, 25, and 50 wt% Fly Ash Samples Placed in (a) 15 wt% NaOH and (b) 28 wt% NaOH for 10 Consecutive Days.

Epoxy systems are generally resistant to alkaline attack over short exposure periods, although prolonged hydroxide exposure may induce chain scission in some resin systems. The limited impact observed over 10 days suggests that hydroxide diffusion into the crosslinked network was minimal under the test conditions.

Conventional cement systems are inherently alkaline and typically tolerate high-pH exposure; however, extreme alkaline injection fluids used in enhanced oil recovery can still alter cement microstructure over time. The composite system demonstrated mechanical stability under these aggressive alkaline conditions, indicating its potential suitability for chemically enhanced oil recovery wells.

3.4. High Salinity Exposure and Fluid Uptake

Exposure to 15 wt% and 20 wt% NaCl brine resulted in negligible reduction in compressive strength for all formulations, as is evident in Figure 7. However, minor fluid expulsion was observed during compression in some specimens.

This phenomenon suggests limited brine imbibition into micro voids or interfacial regions between fly ash particles and the polymer matrix. Possible sources of such micro voids include:

- Entrapped air during mixing;
- Incomplete particle wetting;
- Localized filler clustering.

Despite evidence of limited fluid uptake, strength retention indicates that these voids are isolated and non-percolating. In contrast, conventional cement systems possess interconnected pore networks that readily allow brine penetration, salt crystallization, and long-term permeability evolution.

The polymer matrix likely serves as a diffusion barrier, significantly restricting brine transport compared to hydrated cement systems. This characteristic may improve long-term resistance to saline formation water environments.

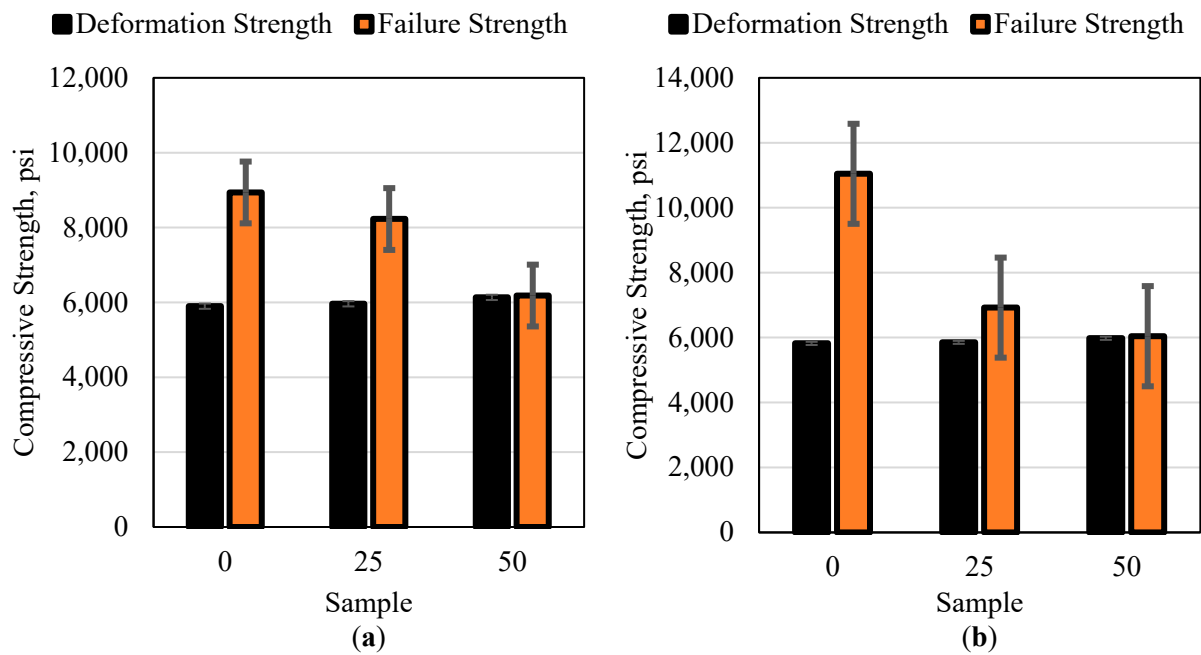


Figure 7. Deformation and Failure Strength of the 0, 25, and 50 wt% Fly Ash Samples Placed in (a) 15 wt% NaCl and (b) 20 wt% for 10 Consecutive Days.

3.5. Thermal Exposure

Temperature had the most pronounced influence on composite performance, shown in Figure 8. As exposure temperature increased from 20 °C to 100 °C, both deformation and failure strengths decreased progressively.

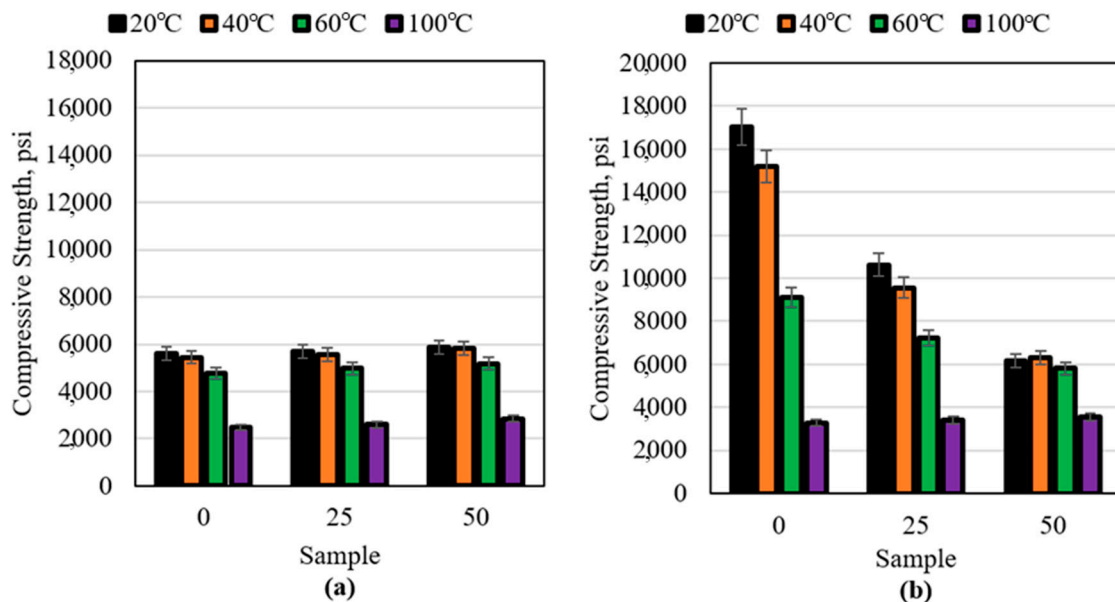


Figure 8. (a) Failure Strength and (b) Deformation Strength of the 0, 25, and 50 wt% Fly Ash Samples Placed in 20 °C, 40 °C, 60 °C, and 100 °C Water for 10 Consecutive Days.

At 100 °C, failure strength decreased to approximately 2800 psi, representing a substantial reduction relative to baseline. Additionally, deformation strength and failure strength converged, indicating loss of elastic deformation capacity.

This behavior is consistent with thermally induced softening of the polymer matrix as temperature approaches its glass transition temperature (T_g). Above T_g , polymer chain mobility increases significantly, reducing modulus and strength.

Conventional Portland cement systems, in contrast, often gain strength when cured at elevated temperatures due to accelerated hydration. However, at very high temperatures or under thermal cycling, shrinkage-induced cracking may occur.

The composite's temperature sensitivity therefore represents a key design limitation. Future optimization using high-T_g epoxy formulations could expand the operational envelope for high-temperature wells.

3.6. Carbon Dioxide Exposure

Exposure to CO₂ at 60 °C under 500 psi (gaseous) and 1200 psi (supercritical) resulted in modest reductions in deformation strength but minimal change in ultimate failure strength, shown in Figure 9.

In conventional cement systems, CO₂ reacts with calcium hydroxide to form calcium carbonate, potentially reducing alkalinity and altering microstructure. Over extended exposure periods, carbonation may lead to permeability changes and strength variation.

The composite cement lacks reactive calcium phases, fundamentally altering its interaction with CO₂. The observed reduction in deformation strength may be attributed to:

- CO₂ diffusion into the polymer matrix;
- Mild plasticization effects;
- Interfacial stress redistribution under pressure.

Notably, performance under supercritical CO₂ was only slightly inferior to gaseous exposure, suggesting limited phase-dependent degradation under the test duration.

Strength values remained above 5000 psi, supporting potential application in CO₂ injection or storage wells, although long-term studies would be required to assess extended exposure effects.

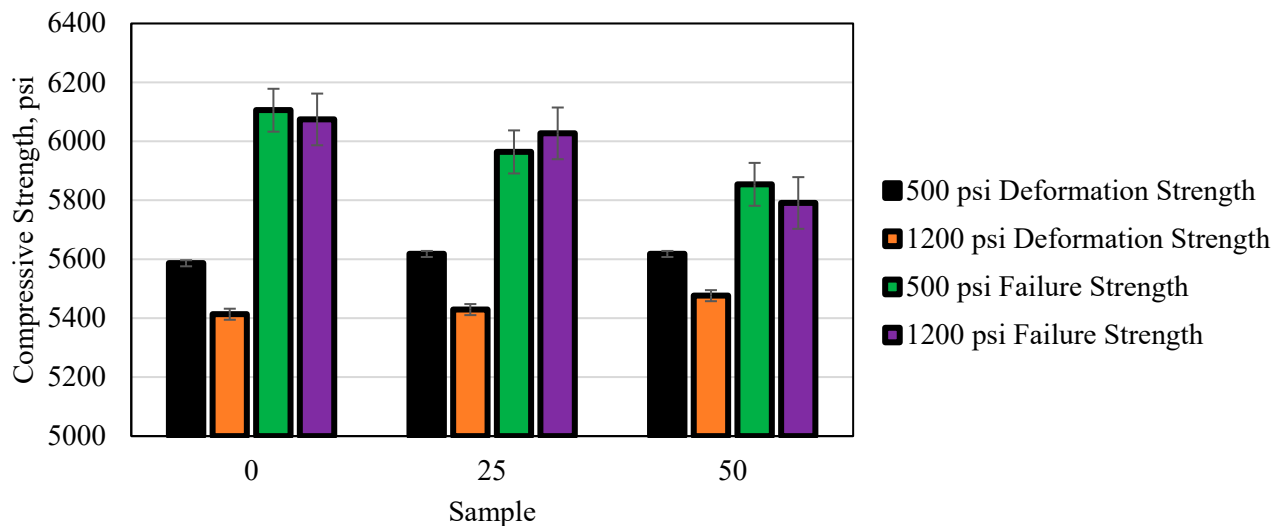


Figure 9. Deformation and Failure Strength of the 0, 25, and 50 wt% Fly Ash Samples Placed in Gaseous and Supercritical Carbon Dioxide for 10 Consecutive Days.

3.7. Crude Oil Exposure (Expanded Analysis)

Exposure to heavy crude oil (450 cp) did not produce measurable reductions in deformation or failure strength across all fly ash loadings. Mechanical performance remained statistically comparable to distilled water baseline values, shown Figure 10.

This stability can be attributed to several material characteristics:

1. **Hydrophobic Polymer Matrix:** The epoxy matrix exhibits low affinity for non-polar hydrocarbon molecules, limiting crude oil penetration into the bulk material.

2. **Absence of Hydration Phases:** Conventional cement contains capillary pores that may allow hydrocarbon infiltration over long exposure periods. Although hydrocarbons do not chemically degrade cement as aggressively as acids, prolonged exposure can alter wetting characteristics and permeability. The composite's lower intrinsic permeability likely restricts such interactions.
3. **High Viscosity of Crude Oil:** The heavy crude's viscosity (450 cp) further limits diffusion into microstructural voids.
4. **Stable Polymer–Particle Interface:** No evidence of debonding between fly ash particles and the resin matrix was observed during mechanical testing, suggesting that oil exposure did not compromise interfacial adhesion.

These findings indicate that the composite cement maintains mechanical integrity in hydrocarbon-rich environments and may be particularly suitable for production zones where prolonged oil contact is expected.

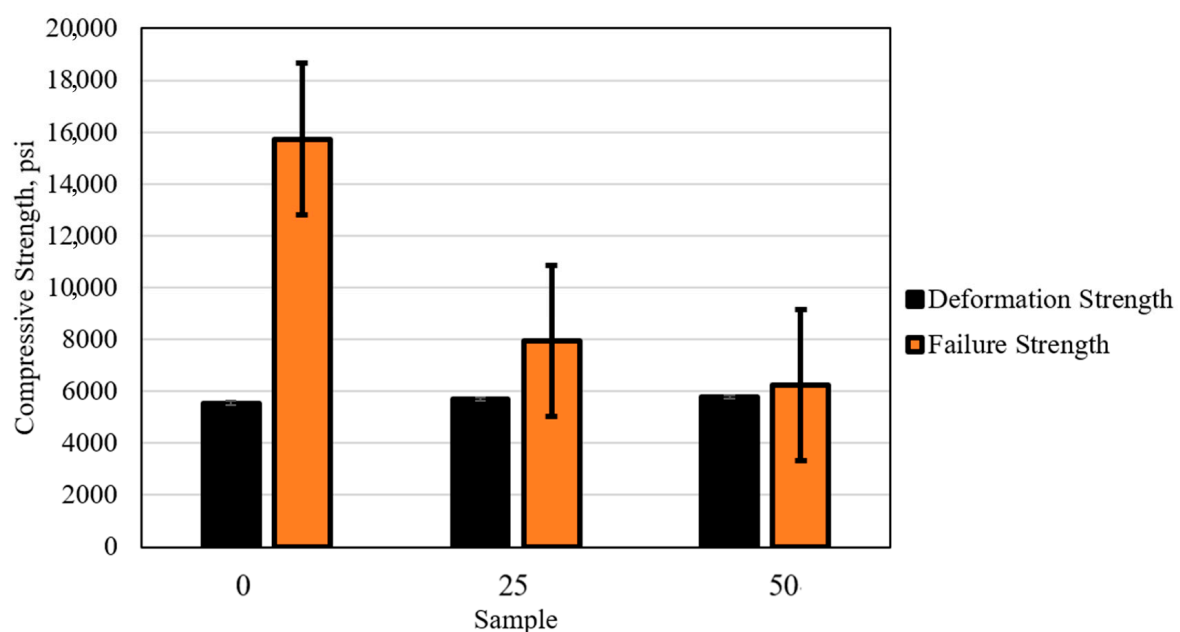


Figure 10. Deformation and Failure Strength of the 0, 25, and 50 wt% Fly Ash Samples Placed in Crude Oil for 10 Consecutive Days.

3.8. Acetone-Induced Degradation

Acetone exposure resulted in progressive softening, swelling, and eventual structural degradation of the composite. Both deformation and failure strengths decreased substantially, and elastic behavior was eliminated. A sample of the cement sample subjected to acetone is presented in Figure 11.

This confirms that structural integrity is governed primarily by the polymer network, which is susceptible to organic solvent dissolution. Higher fly ash content slightly improved residual strength due to increased inorganic fraction.

From an operational perspective, this property introduces the possibility of controlled removal in remedial operations—a capability not available in conventional cement systems, which require mechanical milling for removal.

Figure 12 shows the deformation and the failure strengths of the 0, 25, and 50 wt% fly ash samples after being placed in acetone for 10 consecutive days. The first observation from the results shows that the samples lost all of their elastic properties, and therefore the deformation strength was identical to the failure strength of all three samples. The compressive strength of the samples decreased significantly compared to all other experi-

ments due to the decomposition and weakening of the cement samples. The highest fly ash weight percent sample resulted in the highest compressive strength after being subjected to the acetone. This is an indication that the acetone had no impact on the fly ash and only worked to degrade the resin.



Figure 11. Novel Cement Sample After Placement in Acetone for 10 Consecutive Days.

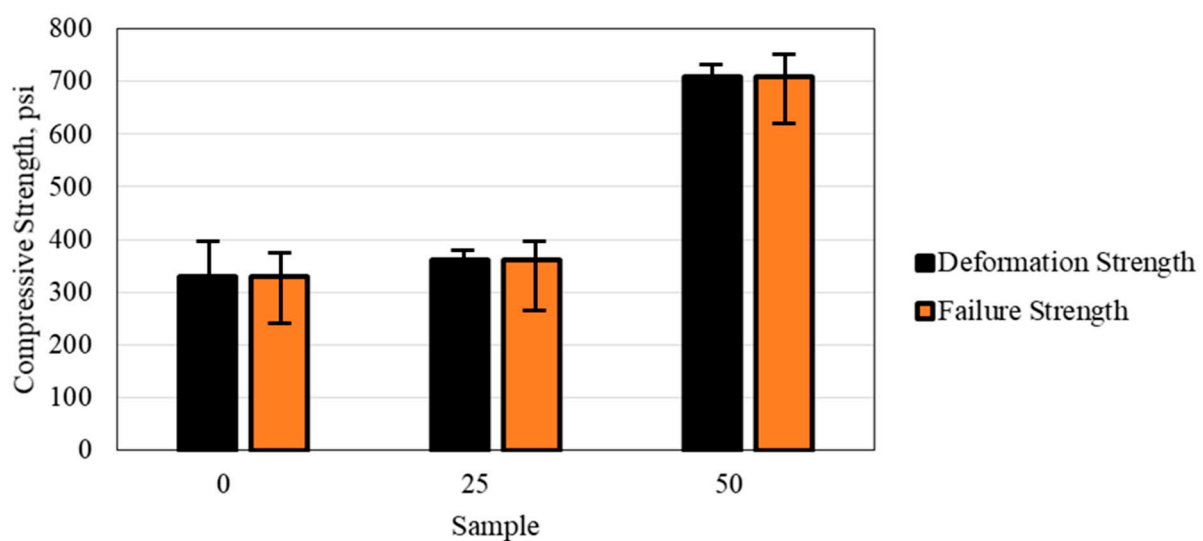


Figure 12. Deformation and Failure Strength of the 0, 25, and 50 wt% Fly Ash Samples Placed in Acetone for 10 Consecutive Days.

Recent studies have highlighted the critical role of matrix densification and interfacial bonding in enhancing the durability of fly ash-based composites, particularly under aggressive environmental conditions. For instance, the incorporation of mineral additives such as limestone powder has been shown to accelerate hydration reactions, promote the formation of additional binding phases, and refine pore structure, ultimately improving resistance to chemical degradation. These findings align with the behavior observed in polymer-modified systems, where stronger interfacial adhesion between the binder and filler phases reduces permeability and limits the ingress of harmful agents such as acids. Accordingly, the improved performance of epoxy–fly ash composites can be attributed not only to the intrinsic chemical resistance of the polymer matrix but also to the enhanced microstructural integrity arising from better particle–matrix interaction [82,83].

4. Microstructural and Mechanistic Interpretation

4.1. Load Transfer Mechanism

In the composite system, compressive load is primarily carried by the continuous epoxy matrix, while fly ash particles act as rigid fillers that contribute to stiffness enhancement and stress redistribution. Under applied load, stress is transferred from the deformable polymer matrix to the stiffer mineral particles through interfacial shear stresses.

At low fly ash loading (0 wt%), the material behaves as a highly ductile polymer network. As fly ash content increases, particle–particle interactions become more significant, leading to reduced strain capacity and earlier fracture initiation. This explains the observed narrowing of the gap between deformation strength and failure strength with increasing filler content.

The relatively stable compressive strength at 50 wt% loading suggests effective interfacial bonding between fly ash particles and the epoxy matrix. Poor interfacial adhesion would have manifested as premature debonding and significant strength loss.

4.2. Chemical Resistance Mechanism

The superior acid and CO₂ resistance of the composite compared to conventional Portland cement can be attributed to fundamental differences in binding chemistry.

Portland cement relies on hydration products (C–S–H gel and Ca(OH)₂), which are susceptible to:

- Acid dissolution;
- Decalcification;
- Carbonation reactions.

In contrast, the composite's structural integrity depends on a crosslinked organic polymer network. Acidic or carbonic environments do not directly dissolve this network. Instead, degradation mechanisms are diffusion-limited and primarily affect surface regions.

The relatively small reduction in deformation strength under acidic and CO₂ exposure suggests localized polymer softening rather than bulk structural compromise. Fly ash particles, composed largely of aluminosilicate phases, remain chemically stable under these conditions and contribute to mechanical reinforcement.

4.3. Fluid Transport and Porosity Considerations

Minor brine expulsion observed during high salinity testing indicates the presence of isolated micro voids. These may originate from:

- Air entrapment during mixing;
- Incomplete wetting of filler surfaces;
- Particle packing heterogeneity.

However, because compressive strength remained stable, these voids likely form a non-percolating pore structure.

Conventional cement systems typically exhibit interconnected capillary porosity, which facilitates fluid transport, salt crystallization, and chemical attack. The polymer matrix in the composite likely significantly reduces effective permeability, thereby limiting fluid diffusion and enhancing durability.

Future work including permeability testing and microstructural imaging (e.g., SEM or micro-CT) would further quantify this effect.

4.4. Thermal Softening Behavior

The strength reduction at 100 °C is consistent with polymer thermomechanical behavior. As temperature approaches the epoxy glass transition temperature (T_g), molecular mobility increases, reducing stiffness and compressive strength.

Unlike cement hydration systems, which may gain strength with elevated curing temperature, polymer-based composites are constrained by thermal softening thresholds. Therefore, the composite's operational temperature window is governed by resin formulation.

Selection of high- T_g epoxy systems could significantly improve high-temperature performance without altering composite architecture.

5. Engineering Applicability and Operational Envelope

While laboratory-scale mechanical testing provides insight into material durability, translation to field deployment requires evaluation within an operational framework. Based on the experimental findings, the fly ash–epoxy composite cement demonstrates distinct performance characteristics that define its potential application envelope.

5.1. Suitable Downhole Environments

The composite exhibited strong resistance to:

- High acid concentrations (up to 28 wt% HCl);
- High salinity brines (up to 20 wt% NaCl);
- Alkaline environments (up to 28 wt% NaOH);
- Carbon dioxide exposure (gaseous and supercritical);
- Direct crude oil contact.

These characteristics suggest suitability for:

- Acidizing-prone wells;
- Carbon capture and storage (CCS) injection wells;
- CO₂ enhanced oil recovery (EOR) operations;
- High-salinity formation environments;
- Production zones with prolonged hydrocarbon exposure.

Conventional Portland cement systems often require specialized additives to achieve comparable acid or CO₂ resistance. The composite achieves this without reliance on hydration chemistry, reducing susceptibility to calcium leaching and carbonation degradation.

5.2. Temperature Limitations

Thermal exposure results indicate that compressive strength declines significantly at 100 °C due to polymer softening. Therefore, the current formulation is best suited for:

- Low- to moderate-temperature wells (<90–100 °C)

For high-temperature reservoirs, material optimization through high-glass-transition epoxy systems would be necessary. This highlights that the composite is not a universal replacement for Class G cement, but rather a specialized alternative for chemically aggressive, moderate-temperature environments.

5.3. Mechanical Behavior Compared to Conventional Cement

One of the most significant differences between the composite and conventional oilwell cement lies in deformation behavior.

Portland cement is inherently brittle, failing abruptly once peak compressive stress is reached. In contrast, the composite demonstrated measurable elastic deformation prior to failure. This semi-ductile response may:

- Improve resistance to microannulus formation;

- Enhance tolerance to casing expansion/contraction;
- Reduce crack propagation under cyclic loading.

Such characteristics may be particularly beneficial in injection wells experiencing pressure cycling.

5.4. Sustainability and Material Efficiency

The fly ash–epoxy composite cement system represents a strategic integration of industrial by-products into advanced polymer matrices, with significant implications for sustainability and resource efficiency. By incorporating up to 50 wt% Class F fly ash into the polymer network, this composite simultaneously addresses material cost, mechanical performance, and environmental stewardship [67,77,85]. Partial replacement of epoxy with fly ash reduces the demand for virgin polymer, which carries high embodied energy, while maintaining structural integrity in aggressive downhole environments [7,88]. This approach aligns with circular economy principles by diverting significant quantities of fly ash from landfills and repurposing them as functional construction material [85,88].

From an environmental perspective, conventional Portland cement production is a major source of CO₂ emissions, energy consumption, and natural resource depletion. In contrast, the composite system leverages the pozzolanic and filler properties of fly ash, which contribute to reduced CO₂ intensity and lower lifecycle energy demands per unit of material applied [77,84,88]. Research on fly ash-based geopolymers and polymer-fly ash composites has demonstrated that incorporating up to 50% fly ash can lower CO₂ emissions by 20–40% relative to conventional Class G cement while simultaneously improving resistance to acid, CO₂, and high-salinity exposure [67,77,84,86,88]. These enhancements extend service life and reduce the likelihood of frequent remedial operations, further decreasing the long-term environmental footprint of well completion and maintenance activities [86,88].

Economically, the use of fly ash significantly lowers raw material cost due to its availability as an industrial by-product, without compromising mechanical performance [67,85]. The semi-ductile behavior of the composite enhances its ability to accommodate casing deformation and cyclic loading, potentially preventing microannulus formation and associated production losses. This mechanical resilience may translate into fewer workovers and lower operational expenditures over the well’s life [86,88]. Additionally, partial polymer replacement with fly ash reduces overall polymer consumption, which has both cost and sustainability benefits, as polymer production is energy-intensive [7].

Table 1 provides a comparative overview of economic and sustainability-related performance metrics for the fly ash–epoxy composite versus conventional Class G cement, integrating both literature-based estimates and material property considerations.

Table 1. Comparative Economic and Sustainability Metrics for Fly Ash Epoxy Composite and Class G Cement.

Factor	Class G Cement	Fly Ash–Epoxy Composite	Notes/Impact
Raw material cost	Medium	Low–Medium	Fly ash substitution reduces polymer volume and overall material cost [67,85]
Embodied energy (MJ/kg)	~4–5	Higher per kg polymer, ~5–6	Offset by extended service life and reduced remedial operations [7,88]
CO ₂ emissions (kg CO ₂ /kg material)	Baseline	20–40% reduction	Partial cement replacement and lower frequency of remediation contribute [77,88]

Table 1. *Cont.*

Factor	Class G Cement	Fly Ash–Epoxy Composite	Notes/Impact
Waste diversion	Low	High	Up to 50 wt% fly ash utilized, reducing landfill disposal [85,88]
Service life in aggressive environments	Moderate	Extended	Enhanced chemical resistance to acid, CO ₂ , and brines [84,86,88]
Mechanical resilience	Brittle	Semi-ductile	Accommodates casing deformation, mitigates microannulus formation [86,88]
Long-term remediation needs	Moderate	Reduced	Reduced maintenance and intervention requirements [86,88]
Potential water savings	Low	Moderate	Reduced leachate and washout from chemically resistant matrix [7,88]

5.5. Remedial Potential

The acetone degradation experiments demonstrated that the composite can be chemically weakened if necessary. Although acetone is not naturally present in reservoirs, this property introduces a potential advantage in controlled remedial scenarios where partial removal of cement is required.

Conventional cement systems typically require mechanical milling for removal, which can be operationally complex and costly.

5.6. Cost–Benefit Analysis

From an operational perspective, Class G cement remains the simplest to deploy, with low placement complexity and predictable curing behavior; however, this simplicity comes at the cost of higher failure risk, particularly in aggressive environments such as CO₂ or acidic conditions, which can lead to significant remediation expenses and only moderate long-term well integrity. In contrast, epoxy-based systems introduce slightly more complexity during placement, especially at higher fly ash loadings, but offer clear advantages in performance. The epoxy with 25 wt% fly ash system strikes a balance, providing faster curing, reduced failure risk, and improved well integrity with relatively low remediation needs. Increasing the fly ash content to 50 wt% further enhances durability and significantly lowers both failure risk and remediation costs, ultimately delivering very high well lifetime integrity, albeit with moderately more complex handling and curing behavior. This is summarized in Table 2.

Table 2. Operational Cost-Benefit Analysis of the Epoxy Resin Cement vs. Portland Cement Class G.

Factor	Class G	Epoxy with 25% FA	Epoxy with 50% FA
Placement complexity	Low	Medium	Medium–high
Curing time	Predictable	Faster (polymer)	Moderate
Failure risk	Higher (especially CO ₂ /acid)	Low	Very low
Remediation cost	High	Low	Very low
Well lifetime integrity	Moderate	High	Very high

6. Conclusions

This study demonstrates that a fly ash–epoxy composite cement can maintain mechanical integrity under a wide range of chemically aggressive downhole conditions, including

acidic, alkaline, high-salinity, and carbon dioxide (CO₂)-rich environments. The material consistently retained compressive strength above 5000 psi under most conditions, with degradation primarily affecting elastic deformation rather than ultimate strength. Unlike conventional Portland cement systems, the composite showed strong resistance to acid attack and carbonation, as well as stability in crude oil environments, highlighting the advantages of its polymer-based matrix. However, thermal exposure at 100 °C significantly reduced strength due to polymer softening, defining the primary operational limitation of the system. The composite also exhibited a semi-ductile response, which may improve resistance to microannulus formation and cyclic loading. Overall, the incorporation of up to 50 wt% fly ash provides a chemically resilient and mechanically adaptable alternative cement system for moderate-temperature wells in aggressive environments. Future work should focus on long-term durability, permeability characterization, and performance under cyclic loading to further establish field applicability.

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