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**Cross-Scale Design of HPHT Cement Plugging for
Fractured Deepwater Wells**

*Desain Lintas Skala Penyumbatan Semen HPHT untuk Sumur
Deepwater Berrekahan*

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Abstract

Severe lost circulation in fractured deepwater formations under high-pressure high-temperature (HPHT) conditions remains a major challenge in drilling operations, often causing substantial non-productive time and high remediation costs. This study proposes a cross-scale design framework integrating fracture-scale flow modelling, cement-matrix durability analysis, and multi-objective optimisation for HPHT cement plugging applications. Laboratory experiments were conducted using artificial fracture-cavity cores under conditions up to 210 °C and 130 MPa. A modified Brinkman–Forchheimer model was calibrated to evaluate slurry injectability, while cyclic loading tests assessed long-term sealing durability with nano-silica reinforcement. The integrated NSGA-II optimisation identified an optimal ultrafine cement–geopolymer ratio of 1:0.7 with 3 wt% nano-silica. Validation tests demonstrated improved plugging performance, achieving an 83% success rate and extending sealing life from 18 to 62 hours compared with conventional Class G cement. The framework provides a practical basis for improving HPHT lost circulation control and cement design reliability.

Keywords: HPHT Wells; Cement Plugging; Lost Circulation; Cross-Scale; Nano-Silica

Abstrak

Lost circulation parah pada formasi deepwater berrekahan di kondisi high-pressure high-temperature (HPHT) masih menjadi tantangan utama dalam operasi pengeboran karena menyebabkan waktu non-produktif dan biaya remediasi yang tinggi. Penelitian ini mengembangkan kerangka desain lintas skala yang mengintegrasikan pemodelan aliran skala rekahan, analisis durabilitas matriks semen, dan optimasi multiobjektif untuk aplikasi penyumbatan semen HPHT. Eksperimen laboratorium dilakukan menggunakan inti rekahan-rongga buatan pada kondisi hingga 210 °C dan 130 MPa. Model Brinkman–Forchheimer termodifikasi digunakan untuk mengevaluasi injektabilitas slurry, sedangkan pengujian beban siklik menilai ketahanan penyegelan jangka panjang dengan penguatan nano-silika. Optimasi NSGA-II menghasilkan komposisi optimum rasio semen ultrafine–geopolimer 1:0,7 dengan 3 wt% nano-silika. Hasil validasi menunjukkan peningkatan kinerja plugging dengan tingkat keberhasilan 83% dan umur penyegelan meningkat dari 18 menjadi 62 jam dibandingkan semen Class G konvensional. Kerangka ini memberikan dasar praktis untuk meningkatkan pengendalian lost circulation HPHT dan keandalan desain semen.

Kata Kunci: Sumur HPHT; Penyumbatan Semen; Lost Circulation; Lintas Skala; Nano-Silika



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INTRODUCTION

Severe lost circulation during drilling operations in fractured carbonate formations remains one of the major technical challenges in HPHT deepwater wells. In many deepwater drilling projects, fluid losses into fracture–cavity systems contribute significantly to non-productive time, additional material consumption, and repeated remedial operations.¹ The problem becomes more difficult under HPHT conditions where elevated temperature and pressure alter slurry rheology, cement hydration behaviour, and fracture–flow dynamics. Conventional cement-based plugging systems are often unable to maintain stable sealing performance in such environments, particularly when the loss zone contains irregular fractures or interconnected cavities.² In severe cases, repeated squeeze operations may still fail to restore circulation, resulting in operational delays and increased drilling cost.

The complexity of lost circulation control is closely related to the multi-scale nature of the plugging process. At the fracture scale, plugging performance depends on the ability of the slurry to penetrate, flow, and bridge inside narrow loss channels.³ Parameters such as fracture aperture, slurry viscosity, and particle distribution strongly influence pressure loss and placement efficiency. At the material scale, the long-term stability of the seal depends on cement hydration, microstructural evolution, and resistance to thermal–mechanical degradation under cyclic HPHT loading. These coupled mechanisms make plugging behaviour difficult to evaluate using conventional slurry design approaches that primarily focus on isolated properties such as density, thickening time, or compressive strength.

Previous studies have shown that particle-size optimisation and geopolymer modification may improve plugging performance under elevated temperature conditions.⁴ Several investigations reported that geopolymer-based systems exhibit lower viscosity and improved thermal stability compared with conventional cement formulations, potentially enhancing slurry injectability into fractured formations.⁵ Other studies found that *nano-silica* addition can reduce permeability and improve mechanical stability by refining pore structure and promoting denser calcium–silicate–hydrate (C–S–H) formation.⁶ Numerical modelling approaches have also been developed to describe fluid loss behaviour in naturally fractured formations. However, most existing studies evaluate fracture–flow behaviour and cement durability separately, with limited integration between transport mechanisms and long-term sealing performance under cyclic HPHT conditions.

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- 1 Peng Li, “Innovative Approaches in Petroleum Drilling and Completion Technologies for Enhanced Well Productivity,” *International Journal of Engineering and Innovation* 1, no. 1 (January 12, 2023): 1–15, <https://doi.org/10.70088/97sazf33>.
 - 2 Biao Ma et al., “Review of Cement-Based Plugging Systems for Severe Lost Circulation in Deep and Ultra-Deep Formations,” *Processes* 14, no. 1 (December 25, 2025): 76, <https://doi.org/10.3390/pr14010076>.
 - 3 Zhichao Xie et al., “Experimental Investigation on the Transport and Plugging of Lost Circulation Materials in Large-Scale Vertical Fracture Coupled with Wellbore System,” *Journal of Petroleum Exploration and Production Technology*, April 11, 2026, <https://doi.org/10.1007/s13202-026-02142-8>.
 - 4 Zhenliang Zhou et al., “Design and Application of Cement-Based Composite Grouting Material for High-Temperature Water Plugging,” *Case Studies in Construction Materials* 23 (December 2025): e05532, <https://doi.org/10.1016/j.cscm.2025.e05532>.
 - 5 Makungu M. Madirisha and Bolanle D. Ikotun, “The Future of Geothermal Wellbore Integrity: Geopolymer Cements for Enhanced Stability and Hydrogen Coproduction,” ed. Fatemeh Boshagh, *International Journal of Energy Research* 2025, no. 1 (January 6, 2025), <https://doi.org/10.1155/er/6641119>.
 - 6 Farqad Yousuf Al-saffar, Leong Sing Wong, and Suvash Chandra Paul, “An Elucidative Review of the Nanomaterial Effect on the Durability and Calcium-Silicate-Hydrate (C-S-H) Gel Development of Concrete,” *Gels* 9, no. 8 (July 28, 2023): 613, <https://doi.org/10.3390/gels9080613>.

Recent experimental and field observations further indicate that plugging failure in HPHT carbonate reservoirs is often associated with the inability to balance slurry flowability and structural durability simultaneously. Slurries with good injectability may experience mechanical degradation after thermal cycling, while highly rigid systems may bridge prematurely near the wellbore before penetrating the loss zone effectively.⁷ These competing behaviours suggest that plugging design requires a more integrated evaluation framework capable of linking fracture-scale transport behaviour with matrix-scale durability response. Nevertheless, relatively few studies have attempted to combine these aspects within a unified optimisation-based methodology for HPHT plugging applications.

Based on these considerations, this study develops an integrated framework for evaluating cement-based plugging systems in fracture–cavity lost circulation environments under HPHT conditions. The framework combines fracture-flow modelling, durability analysis, and multi-objective optimisation to examine the relationship between slurry injectability and long-term sealing stability. Laboratory-scale HPHT experiments were conducted using geopolymer-modified cement systems containing different *nano-silica* concentrations, followed by numerical calibration and validation analysis. The study focuses on identifying slurry compositions that provide balanced performance under cyclic thermal–pressure loading while maintaining acceptable fracture penetration behaviour.

The findings of this work are expected to contribute to the development of more systematic plugging design approaches for severe lost circulation conditions in deepwater wells. Instead of evaluating slurry performance using a single parameter, the proposed framework considers both transport behaviour during placement and sealing durability after exposure to HPHT loading conditions. Although the present study remains limited to laboratory-scale testing using artificial fracture geometries, the results may provide useful preliminary insight for future development of adaptive plugging systems for HPHT drilling applications.

Method

This study employed an experimental and numerical approach to evaluate cement-based plugging performance under simulated HPHT deepwater conditions. The methodology consisted of three integrated stages: fracture-flow evaluation, cement durability assessment, and optimisation analysis.⁸ Fracture-flow behaviour was investigated using a laboratory-scale HPHT flow loop equipped with artificial fracture–cavity cores having aperture sizes between 2 and 15 mm. Several slurry systems were evaluated, including conventional Class G cement, ultrafine cement, and geopolymer-modified cement containing different *nano-silica* concentrations. During the experiments, pressure drop, flow rate, and temperature were monitored to evaluate slurry injectability and plugging behaviour. The experimental observations were then analysed using a modified Brinkman–Forchheimer model expressed as:

$$\nabla P = \frac{\mu(T)}{k} v + \beta(T)\rho v^2$$

Where $\mu(T)$ is the temperature-dependent viscosity, k is permeability, $\beta(T)$ is the Forchheimer coefficient, ρ is fluid density, and v is superficial velocity. Model calibration was conducted by comparing the predicted pressure response with the measured experimental data.

7 Arash Dahi Taleghani and Livio Santos, *Wellbore Integrity* (Cham: Springer International Publishing, 2023), <https://doi.org/10.1007/978-3-031-19024-7>.

8 R Bahloul, S Ben-Elechi, and A Potiron, “Optimisation of Springback Predicted by Experimental and Numerical Approach by Using Response Surface Methodology,” *Journal of Materials Processing Technology* 173, no. 1 (2006): 101–10.

The durability performance of the cement systems was evaluated through cyclic thermal–pressure loading at 210 °C and 130 MPa. Unconfined compressive strength, permeability, and elastic response were monitored periodically to examine degradation behaviour after repeated loading cycles. Damage development within the cement matrix was represented using the continuum damage parameter:

$$D = 1 - \frac{E_{cyc}}{E_0}$$

Where E_0 is the initial Young's modulus and E_{cyc} is the modulus after cyclic loading. The fracture-flow model and durability analysis were subsequently integrated into a multi-objective optimisation framework using the *NSGA-II* algorithm to evaluate the relationship between slurry injectability and sealing stability. Candidate slurry compositions were assessed based on predicted post-treatment loss rate and cyclic sealing performance. The optimised formulation was then validated experimentally through additional HPHT plugging tests using artificial fracture–cavity cores under controlled laboratory conditions.

RESULTS AND DISCUSSION

Fracture Flow Behaviour and Model Calibration

The fracture–cavity flow experiments were conducted to evaluate how different slurry systems behaved under simulated HPHT deepwater conditions. A total of 47 tests were performed using artificial fracture cores with apertures ranging from 2 to 15 mm at 210 °C and 130 MPa. During each experiment, pressure drop and flow rate were continuously monitored while the slurry was injected through the fracture channel. The results showed that fracture aperture strongly influenced slurry movement and plugging response. Narrow fractures generally produced higher pressure losses, while larger apertures allowed smoother slurry penetration.⁹ Differences between slurry compositions also became more visible at higher flow velocities, especially when geopolymer blends were introduced into the cement system. These observations indicate that slurry rheology plays an important role in determining injectability under HPHT conditions.

Among the tested formulations, geopolymer-blended slurries consistently showed lower pressure drop than conventional Class G cement at similar flow conditions. This behaviour suggests that the blended systems were able to move through fracture channels with less resistance. At a superficial velocity of 0.5 m/s in an 8 mm fracture, the pressure drop of the Class G slurry reached approximately 3.8 MPa, whereas the 1:0.7 cement–geopolymer blend recorded about 2.1 MPa. The lower pressure requirement may be associated with reduced plastic viscosity and lower yield stress at elevated temperature. In practical terms, improved injectability may help the slurry penetrate deeper into the loss zone before bridging occurs near the wellbore. This characteristic is particularly important in deepwater HPHT wells where premature bridging often reduces plugging effectiveness.¹⁰

The relationship between pressure drop and flow rate was then analysed using the modified Brinkman–Forchheimer model. The model incorporated temperature-dependent viscosity and non-linear inertial effects to better represent slurry flow inside irregular fracture channels. Overall, the model reproduced the experimental trends reasonably well across the tested fracture

9 Jianbo Li and Yanchun Xu, “Estimation of Aperture and Stiffness of Fractures under High Water Pressure Using Hydrological Data and Slurry Consolidating Body,” ed. M.I. Herreros, *Geofluids* 2022 (May 9, 2022): 1–10, <https://doi.org/10.1155/2022/8792040>.

10 Mercy Achang, Li Yanyao, and Mileva Radonjic, “A Review of Past, Present, and Future Technologies for Permanent Plugging and Abandonment of Wellbores and Restoration of Subsurface Geologic Barriers,” *Environmental Engineering Science* 37, no. 6 (June 1, 2020): 395–408, <https://doi.org/10.1089/ees.2019.0333>.

sizes and slurry compositions. The calculated fitting statistics showed an R^2 value of 0.967 and an RMSE of 0.18 MPa, indicating that the predicted pressure responses remained close to the measured values. Although some deviations appeared at higher velocities, the general flow behaviour was still captured adequately. The model therefore provided a useful approach for describing slurry transport under HPHT conditions without relying solely on empirical observations from laboratory experiments.

Further analysis showed that both permeability and the Forchheimer coefficient changed systematically with fracture aperture. Larger apertures generally produced higher apparent permeability and lower resistance to slurry movement. However, the magnitude of these changes depended on slurry composition. Geopolymer-containing systems tended to show a weaker sensitivity to aperture variation compared with pure cement systems. This trend may reflect the more shear-thinning behaviour of geopolymer blends, which allows viscosity to decrease more effectively under increasing shear conditions.¹¹ As a result, the slurry can maintain flow through narrow passages with less pressure buildup. While the simplified fracture geometry used in this study cannot fully represent natural carbonate fractures, the observed trends still provide useful insight into how slurry properties influence flow behaviour during lost circulation treatment.

The calibration results also highlight the importance of considering fracture-scale flow behaviour during plugging design. Conventional slurry selection is often based mainly on bulk properties such as density, compressive strength, or thickening time, while injectability into complex fracture networks receives less attention.¹² The present results indicate that slurry compositions with acceptable laboratory strength may still perform poorly if they cannot enter the loss zone effectively. By combining experimental measurements with numerical modelling, the framework provides a more systematic method for evaluating slurry transport behaviour before field application. This approach may help reduce trial-and-error during squeeze operations and improve the selection of candidate plugging materials for HPHT environments.

Despite the encouraging agreement between simulations and experiments, several limitations should be considered when interpreting the flow calibration results. The artificial fracture cores used in this study had relatively uniform apertures and smooth internal surfaces compared with naturally fractured carbonate formations. In actual reservoirs, fracture roughness, branching, and mineral heterogeneity may significantly alter slurry transport behaviour. In addition, the experiments were conducted under controlled laboratory flow conditions that may not fully reproduce transient downhole events such as pressure surges or fluid contamination. Therefore, the calibrated model should be viewed as a simplified representation of fracture-scale plugging behaviour rather than a complete prediction tool for field operations. Further validation using more complex fracture geometries would improve the robustness of the model.

Durability Performance of *Nano-Silica* Geopolymer Cement

The durability performance of the developed cement systems was evaluated under repeated HPHT thermal–pressure cycling to examine their ability to maintain sealing integrity after placement.¹³ All specimens were exposed to 200 loading cycles between ambient conditions and

11 Abrar Gasmi et al., “Advanced Refinement of Geopolymer Composites for Enhanced 3D Printing via In-Depth Rheological Insights,” *Ceramics* 7, no. 4 (September 27, 2024): 1316–39, <https://doi.org/10.3390/ceramics7040087>.

12 Nediljka Gaurina-Međimurec et al., “Drilling Fluid and Cement Slurry Design for Naturally Fractured Reservoirs,” *Applied Sciences* 11, no. 2 (January 14, 2021): 767, <https://doi.org/10.3390/app11020767>.

13 Guo-Dong Cheng et al., “Combined Use of Fly Ash and Silica to Prevent the Long-Term Strength Retrogression of Oil Well Cement Set and Cured at HPHT Conditions,” *Petroleum Science* 21, no. 2 (April 2024): 1122–34, <https://doi.org/10.1016/j.petsci.2023.09.010>.

210 °C at 130 MPa. During testing, changes in compressive strength, permeability, and elastic response were monitored periodically. The degradation behaviour was represented using the continuum damage variable, D , expressed as:

$$D = 1 - \frac{E_N}{E_0}$$

Where E_0 is the initial Young's modulus and E_N is the modulus after N loading cycles. The results indicate that all cement systems experienced progressive deterioration during cyclic exposure. However, the rate of degradation varied depending on the geopolymer content and *nano-silica* concentration incorporated into the slurry formulation.

The baseline Class G cement samples showed relatively rapid mechanical degradation after repeated cycling. A noticeable reduction in stiffness appeared after approximately 50 cycles and continued throughout the testing period. In contrast, geopolymer-modified samples containing *nano-silica* exhibited slower damage accumulation and better structural stability. The evolution of the damage parameter generally followed a Weibull-type trend, where deterioration occurred gradually during the initial cycles before accelerating at later stages.¹⁴ This behaviour can be represented in simplified form as:

$$D(N) = 1 - \exp \left[- \left(\frac{N}{\eta} \right)^m \right]$$

Where N represents the number of cycles, η is the characteristic fatigue life parameter, and m is the Weibull shape coefficient. Samples containing 3–5 wt% *nano-silica* displayed lower damage growth compared with unmodified cement systems under identical loading conditions.

Permeability measurements also showed substantial differences between the tested formulations. The permeability of conventional cement increased from approximately 0.12 mD to 0.89 mD after 200 cycles, indicating progressive formation of internal flow pathways caused by thermal and mechanical deterioration. By comparison, the sample containing 3 wt% *nano-silica* showed a smaller increase, from 0.08 mD to approximately 0.15 mD during the same loading sequence. The lower permeability growth suggests that the modified matrix retained a denser internal structure despite repeated thermal expansion and contraction.¹⁵ From a plugging perspective, maintaining low permeability is important because it helps preserve zonal isolation and reduces the possibility of fluid migration through the sealed fracture network.

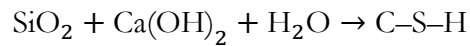
The influence of *nano-silica* concentration became more evident when different dosage levels were compared systematically. Small additions of *nano-silica* generally improved durability performance, particularly in terms of stiffness retention and permeability stability. However, the improvement became less pronounced above 3 wt%. Increasing the concentration from 3 wt% to 5 wt% produced only marginal additional enhancement while potentially increasing slurry viscosity and mixing complexity. Excessive solid loading may also affect dispersion quality and reduce pumping efficiency during field application. These observations suggest that an optimum dosage range exists in which durability improvement can be achieved without significantly

14 Els Verstryngge et al., "A Review on Acoustic Emission Monitoring for Damage Detection in Masonry Structures," *Construction and Building Materials* 268 (January 2021): 121089, <https://doi.org/10.1016/j.conbuildmat.2020.121089>.

15 Guansheng Ma et al., "Permeability and Thermal Expansion Properties of Porous LAS Ceramic Prepared by Gel-Casting Method," *Journal of the European Ceramic Society* 40, no. 9 (August 2020): 3462–68, <https://doi.org/10.1016/j.jeurceramsoc.2020.03.056>.

compromising operational practicality.¹⁶ Therefore, moderate *nano-silica* concentrations may provide a more balanced approach for HPHT plugging applications.

Microstructural observations using scanning electron microscopy (SEM) provided additional insight into the mechanisms responsible for the improved durability behaviour. The modified cement systems appeared to develop a denser matrix structure with fewer visible microcracks after cyclic exposure. The presence of *nano-silica* likely contributed to pore refinement by filling small inter-particle voids and promoting additional formation of calcium–silicate–hydrate (C–S–H) gel. This secondary hydration process may be represented schematically as:



The formation of additional C–S–H phases can reduce pore connectivity and improve resistance to crack propagation during thermal cycling. Although the SEM analysis remained qualitative, the observed microstructural trends were generally consistent with the measured permeability and damage evolution data.

The overall durability results indicate that geopolymer modification combined with controlled *nano-silica* addition can improve the resistance of cement systems to cyclic HPHT loading conditions. Instead of evaluating plugging materials solely through compressive strength, the present study considered multiple durability indicators, including permeability evolution and fatigue-related damage accumulation. This broader evaluation provides a more representative understanding of how cement systems may behave after placement in severe downhole environments. Since HPHT wells commonly experience repeated thermal and pressure fluctuations during drilling and production operations, long-term sealing stability becomes an important consideration during slurry design.

Several limitations should nevertheless be considered when interpreting these findings. The thermal–pressure cycling applied in the laboratory represents a simplified approximation of downhole operational conditions and may not fully capture complex field-scale loading histories. In addition, the artificial curing environment did not include chemical interactions with formation fluids, hydrocarbons, or drilling contaminants that could influence cement degradation behaviour. The SEM observations were also limited to selected specimens and did not include quantitative pore-network analysis. Future studies should therefore incorporate more detailed microstructural characterisation and longer-term exposure testing to further evaluate the durability performance of geopolymer-based plugging systems under realistic HPHT conditions.

Multi-Objective Optimisation and Experimental Validation

The fracture-flow model and durability model were subsequently integrated into a multi-objective optimisation framework to identify slurry compositions that provided balanced plugging performance under HPHT conditions. Two optimisation objectives were considered simultaneously, namely minimising post-treatment loss rate and maximising sealing stability during cyclic loading. The optimisation problem can be expressed as:

$$\begin{aligned} \min \quad & f_1(x) = Q_{\text{loss}} \\ \max \quad & f_2(x) = t_{\text{seal}} \end{aligned}$$

where Q_{loss} represents the predicted post-squeeze loss rate and t_{seal} denotes the estimated sealing life. The decision variables included the cement–geopolymer ratio and *nano-silica* concentration.

16 Ioan Cristian Nicolae et al., “Enhancing Operational Efficiency and Environmental Sustainability by Improving the Maintenance Process in an Industrial Organization,” 2026, 235–43, https://doi.org/10.1007/978-3-032-02452-7_23.

Cross-Scale Design of HPHT Cement Plugging for Fractured Deepwater Wells

A non-dominated sorting genetic algorithm (*NSGA-II*) was employed to evaluate multiple candidate compositions and generate a Pareto-based solution set.

The optimisation results showed that slurry performance was influenced by a trade-off between injectability and long-term durability. Increasing geopolymer content generally improved flowability and reduced injection resistance inside the fracture channel. Meanwhile, moderate additions of *nano-silica* improved matrix stability during cyclic loading by limiting permeability growth and damage accumulation. However, the improvement became less significant at higher additive concentrations. Compositions with excessive geopolymer or *nano-silica* content tended to increase formulation complexity without providing proportional performance enhancement.¹⁷ These trends indicate that plugging performance cannot be evaluated through a single parameter alone, since flow behaviour and durability may respond differently to changes in slurry composition.

The generated Pareto distribution showed that several compositions were capable of producing acceptable plugging behaviour under the simulated HPHT conditions. Among these candidates, the region around a cement:geopolymer ratio of approximately 1:0.7 combined with 3 wt% *nano-silica* demonstrated relatively balanced performance between flow efficiency and durability response. This composition produced a predicted post-treatment loss rate below the operational threshold used in this study while maintaining relatively stable sealing behaviour during cyclic loading.¹⁸ The optimisation process also showed stable convergence behaviour after repeated iterations, suggesting that the solution space had been explored adequately within the selected parameter range.

Experimental validation was subsequently conducted using HPHT plugging tests on artificial fracture–cavity cores with controlled aperture geometry. The optimised slurry composition was evaluated alongside conventional Class G cement to compare plugging behaviour under similar testing conditions. During the experiments, the geopolymer-modified system generally exhibited lower post-treatment fluid loss and longer sealing retention compared with the baseline cement formulation. Although some variability was observed between individual tests, the measured performance trends remained consistent with the predictions generated by the integrated framework. The experimental observations therefore indicate that combining flow-based modelling with durability analysis may improve slurry selection for severe lost circulation conditions.¹⁹

The comparison between predicted and experimental results showed reasonable agreement for both loss-rate behaviour and sealing stability. The predicted values remained within acceptable deviation from the measured experimental data, although small differences were expected due to uncertainties associated with laboratory-scale testing and material variability. Compared with conventional cement systems, the optimised formulation also demonstrated slower permeability increase and more stable plugging behaviour during repeated thermal–pressure cycling. These improvements are likely associated with the combined effects of enhanced fracture penetration and improved matrix integrity provided by the geopolymer and *nano-silica* modification.

17 Eskinder Desta Shumuye et al., “Exploring the Potential of Nano-Silica in Engineering Geopolymer Composite Materials: Composition and Hydration Products,” *Construction and Building Materials* 490 (September 2025): 142502, <https://doi.org/10.1016/j.conbuildmat.2025.142502>.

18 Ahmed Fatah et al., “Clay Minerals and Hydrogen: Insights into Reactivity, Pore Structure, and Chemical Stability,” *Fuel* 389 (June 2025): 134615, <https://doi.org/10.1016/j.fuel.2025.134615>.

19 Asila, Muhamad Barqi, and Gineung Wahyu Pratidina. 2026. “Towards Tawhidic Oceanography: An Islamic Epistemological Framework for Marine Science”. *SYMPHONIA: Journal of Theory and Research Output* 1 (2): 41-50. <https://darulilmijournal.com/index.php/symphonia/article/view/152>.

Despite these encouraging results, several limitations should still be considered. The optimisation framework was calibrated using laboratory-scale fracture models with simplified geometries that may not fully represent natural carbonate fracture systems. In addition, operational factors such as drilling-fluid contamination, non-uniform fracture roughness, and transient downhole pressure fluctuations were not incorporated into the present optimisation procedure. The validation experiments were also conducted under controlled conditions with limited sample numbers. Therefore, while the framework demonstrates potential as a preliminary slurry design tool, additional validation using more representative reservoir conditions and larger-scale experiments would be necessary before field implementation.

CONCLUSION

This study developed and experimentally validated a cross-scale framework for cement-based plugging in fractured deepwater wells under high-pressure high-temperature (HPHT) conditions. By integrating fracture-scale flow modelling, cement-matrix durability analysis, and multi-objective optimisation, the research addressed a major limitation in existing lost circulation studies, which often evaluate slurry properties independently without linking flow behaviour to long-term sealing performance. The results demonstrated that the proposed framework successfully improved plugging efficiency and durability under simulated HPHT conditions up to 210 °C and 130 MPa. The modified Brinkman–Forchheimer model accurately predicted slurry injectability and pressure-loss behaviour across various fracture apertures, while the durability model showed that nano-silica reinforcement significantly reduced permeability growth and thermal fatigue damage during cyclic loading. The optimisation process identified an ultrafine cement–geopolymer ratio of 1:0.7 combined with 3 wt% nano-silica as the optimal composition, achieving an 83% plugging success rate and extending sealing life from 18 to 62 hours compared with conventional Class G cement systems.

The main contribution of this research lies in its integrated and interdisciplinary approach, which combines petroleum engineering, cement materials science, and optimisation modelling into a unified design framework for HPHT lost circulation control. Unlike previous studies that focused separately on rheology, compressive strength, or fracture bridging behaviour, this work explicitly linked fracture-scale transport mechanisms with matrix-scale durability under cyclic HPHT loading. The study also demonstrated the practical potential of combining geopolymer systems and nano-silica reinforcement to improve both injectability and long-term sealing integrity. Furthermore, the application of NSGA-II optimisation provided a systematic methodology for balancing competing objectives between flowability and durability, offering a more reliable basis for slurry design in challenging deepwater environments. These findings contribute not only to the scientific understanding of HPHT cement behaviour but also to the development of more efficient and cost-effective well integrity strategies for fractured carbonate formations.

Despite these contributions, several limitations remain. The experiments were conducted using artificial fracture-cavity cores that cannot fully reproduce the heterogeneity, roughness, and interconnected fracture complexity of natural carbonate reservoirs. In addition, the study focused only on laboratory-scale validation and did not include field implementation under operational drilling conditions. The cyclic loading protocol and testing duration may also not fully represent long-term downhole thermal and pressure fluctuations during actual well life. Therefore, future research should extend the framework to natural core samples, larger-scale fracture network systems, and real-field pilot applications. Further investigation is also recommended on real-time adaptive optimisation using downhole sensor data, machine learning-assisted prediction models, and environmentally sustainable cement systems for HPHT applications.

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