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Sustainable Cementing Solutions for Geothermal Wells: Harnessing Industrial By-Products to Enhance Well Integrity

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ABSTRACT

Geothermal energy represents a renewable and sustainable solution to global energy challenges, offering a pathway to meet energy demands while reducing carbon emissions. The Williston Basin in North Dakota, characterized by extensive sedimentary layers, presently holds significant geothermal potential, with subsurface temperatures ranging from 60°C to 150°C at depths of 2–3 kilometers (Gosnold et al., 2015). However, current geothermal well operations face critical challenges, including high temperatures, pressures, and corrosive environments, which can compromise well integrity. This explores the use of industrial by-products, such as pumice and eggshell powder, in improving the durability and efficiency of geothermal well cement under thermal stress. It highlights the environmental and economic benefits of utilizing waste materials for developing advanced cement technologies in geothermal energy production. The research addresses critical challenges in geothermal well integrity under extreme temperature conditions (150-300°C). Through systematic experimentation and analysis, we evaluated four cement formulations: a control sample and three blends with different pumice/eggshell powder (PMC/ESP) ratios (75%/25%, 50%/50%, and 25%/75%). The optimal PMC/ESP (75%/25%) blend demonstrated exceptional performance, exhibiting a 341% increase in compressive strength (12.96 MPa vs. 2.93 MPa for control) at 300°C, significantly lower porosity (0.53% vs. 13.07%), and enhanced permeability resistance (0.0019 mD vs. 0.01 mD) compared to conventional cement. XRD analysis revealed that this superior performance correlates with reduced C-S-H formation and increased thermal stability through the formation of xenotolite phases. The findings present a novel approach to enhancing geothermal cement stability, offering a sustainable solution for improving well integrity in high-temperature geothermal applications by utilizing industrial by-products such as pumice and eggshell. The optimized cement formulation offers extended well lifespans, reduced maintenance costs, and improved economic viability while addressing environmental concerns associated with traditional cementing practices.

1. INTRODUCTION

Geothermal energy has garnered increasing attention as a sustainable alternative to fossil fuels, with projections indicating a growing share in the global energy mix. As this transition occurs, investments in geothermal resource exploration and drilling operations are set to expand, highlighting the importance of understanding the numerous factors influencing geothermal production (Gyimah et al 2024; Ojo and Fadairo 2024). Among these, wellbore integrity stands as a critical parameter, directly affecting the efficiency and longevity of geothermal wells. A global study revealed that over 380,000 wells worldwide have experienced wellbore integrity issues, underscoring the urgency of addressing this challenge (Davies et al., 2014; Zang & Wang, 2017). In the context of geothermal energy, where wells typically operate under high-temperature and high-pressure (HTHP) conditions, wellbore integrity becomes even more vital. A 2015 study on technological gaps in HTHP wells identified cement design as the area with the most significant research voids. Geothermal wells, with temperatures ranging from 150°C to 400°C, present unique challenges, as the high heat can induce cement sheath failure, leading to costly and time-consuming production shutdowns and repairs. To mitigate these challenges, extensive research has been dedicated to enhancing the performance of Ordinary Portland Cement (OPC) and developing alternative materials for cementing geothermal wells. Notable advancements include the development of phosphate-bonded cements (Sugama, 2006), organic and semi-organic cement materials, as well as foam cement formulations (Bour et al., 2003). Furthermore, recent innovations have explored incorporating self-healing materials into cement systems to address the issue of cement degradation. Childers et al. (2017) demonstrated that integrating self-healing polymers into cement slurry enhances bonding properties, thereby improving cement integrity over time. In a similar vein, Pyatina and Sugama (2019) developed a Thermal Shock Resistant Cement (TSRC) composite with self-healing properties, achieving a remarkable 86% recovery of compressive strength after thermal shock, compared to just 36% for conventional Portland cement under similar conditions. These advancements underscore the potential for self-healing and thermally stable cement formulations to significantly enhance wellbore integrity in geothermal energy production. Early studies by Ostroot and Walker (1961) highlighted silica's role in enhancing cement performance under high-temperature conditions, while Philippacopoulos and Berndt (2002) demonstrated its stabilizing effects on cement structure. Additionally, Hole (2008b) recommended incorporating 15–20% silica into cement formulations to mitigate strength retrogression, a common issue in geothermal wells operating at elevated temperatures. Beyond silica, other additives have shown promise in improving cement performance. Research by Buntoro et al. (2000) revealed that supplementing API Class G HSR-type cement with 3–5% magnesium oxide (MgO) significantly enhances compressive and shear strength at temperatures as high as 250°C. Similarly, Southon and James (2005) found that optimizing cement slurry compositions bolsters cement resistance, enabling it to maintain structural integrity throughout the well's operational lifespan. However, the success of a geothermal cementing job is influenced not only by the composition of the cement slurry but also by the application of appropriate cementation techniques in the field. Olatunji (2024) emphasized the importance of completing wells with a fully cemented annulus, advocating for the top squeeze method as an effective strategy to enhance cement placement and extend geothermal well longevity. Eggshell (ES) is an eco-friendly and versatile additive with diverse applications in the oil and gas industry, geothermal drilling, and construction. Its unique properties, such as excellent thermal resistance and stability under extreme conditions, make it a promising material for challenging environments. Compositional analysis reveals that eggshells are predominantly composed of calcium carbonate ($CaCO_3$, ~94%), with minor constituents such as organic matter (1%) and magnesium carbonate (1%). Calcium carbonate, a key component of ES, has been shown to enhance the compressive strength of cement by stabilizing ettringite and mono-carbonate phases (Lothenbach et al., 2017; Deweerdt et al., 2011). Extensive research has explored the potential of ES as a sustainable additive in cement and concrete. Pliya et al. (2015) demonstrated that incorporating ES improves the mechanical properties of concrete, such as compressive, tensile, and flexural strengths. Similarly, Olarewaju et al. (2011) evaluated the use of ES as a stabilizer for subgrade soils in highway construction, finding significant improvements in soil properties. In the oil and gas sector, Fadairo and Oni (2024) investigated the effects of eggshell nanoparticles on the thermal stability of co-polymers used in water-based drilling muds. Their findings revealed substantial enhancements in rheological behavior at elevated temperatures, underscoring the potential of ES as a valuable additive in geothermal drilling fluids. Pumice, a lightweight aggregate of volcanic origin, complements the properties of ES due to its low density, cellular structure, and excellent insulating capabilities. Its widespread use in construction stems from these attributes, as noted by Aydın and Baradan (2007). The combination of ES and pumice in cement formulations presents an innovative approach to improving the thermal and mechanical stability of Class G cement for geothermal well applications. Given the extreme conditions in geothermal wells, where temperatures can exceed 250°C, such enhancements are essential for maintaining cement integrity and ensuring long-term operational success.

Considering these qualities, the inclusion of eggshell powder in Class G cement is hypothesized to enhance thermal stability and maintain strength under the elevated temperatures encountered in geothermal wells. Similarly, the addition of pumice could further optimize the material's performance by leveraging its insulating properties. According to recent data, global volcanic pumice (VP) production stands at approximately 19.6 million tons annually, with Turkey leading the way at 4.2 million tons per year, followed by Italy, Chile, and the United States (Crangle, 2010). The abundant availability of pumice, coupled with its unique physical and chemical properties, has made it a valuable material in various construction applications. Incorporating pumice as a partial substitute for Portland cement in blended cement production offers significant benefits, particularly in mitigating greenhouse gas emissions and promoting sustainable construction practices (Hossain, 1999; 2003). Several studies have highlighted the performance advantages of pumice in high-temperature applications. Research by Türker et al. (2001), Remzi et al. (2003), and Aydin and Baradan (2007) demonstrated that mortars incorporating pumice aggregates exhibited enhanced thermal resistance compared to quartzite and limestone-based mortars. These pumice-aggregated mortars retained compressive strength effectively within the 400–600°C range, making them suitable for high-temperature environments. Furthermore, the inclusion of pumice in cement and concrete formulations has been shown to improve freeze-thaw resistance, enhancing durability under cyclic freezing conditions (Litvan, 1985; Gündüz and Ugur, 2005). The lightweight and porous nature of pumice makes it particularly advantageous in lightweight concrete production. Hossain (1999, 2003, 2005) demonstrated that pumice-based concrete exhibits excellent mechanical properties, while patented a pumice-containing cement blend designed for subterranean wells, particularly in oil and gas applications. This patented composition leveraged fine pumice particles to enhance thermal and mechanical stability, ensuring the integrity of cement under extreme subsurface conditions. Pumice's potential extends to improving the performance of blended cement through its pozzolanic activity, which reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H). This reaction enhances the mechanical properties and durability of cementitious systems. Hossain et al. (2010) explored the performance of a novel lightweight concrete produced using both coarse and fine volcanic pumice aggregates (VPAs), as well as pumice-based blended cement. The results confirmed its suitability for applications requiring high strength and low density, further underscoring the versatility of pumice in sustainable construction. Given these attributes, the incorporation of pumice in cementitious materials presents an eco-friendly solution to the challenges of high-temperature and extreme environmental conditions. Its thermal stability, durability, and sustainability make it a promising additive for diverse applications, including geothermal wells, oil and gas well cementing, and lightweight construction. These findings highlight pumice's potential to contribute significantly to advancing sustainable and high-performance construction practices. These synergistic improvements have the potential to address critical challenges in geothermal cementing, offering sustainable and effective solutions for the energy industry.

2. METHODOLOGY.

2.1 Materials used for this Study.

The research investigated three key cementitious materials: Class G Cement from Dyckerhoff Company, Pumice from Hess Pumice and Eggshell powder gathered from the University of North Dakota's dining center and student apartments. The eggshell preparation followed a meticulous process beginning with thorough tap water cleaning and membrane removal, followed by oven drying at 90°C for 2 hours. The dried shells were then ground and sieved through a twenty-micron mesh to achieve uniform particle size conforming to ASTM specifications. Nouryon Pulp and Performance Chemicals Inc. provided supplementary materials, including defoamer, retarder, water, fluid loss additive, and silica solution. The chemical composition of these cementitious materials was reported by weight percentage in a supporting Table 1.

2.2 Cement slurry preparation.

The cement slurry preparation adhered to API RP 10B guidelines. The process began with carefully weighing and combining dry ingredients before adding any additives. A consistent water-to-cement ratio of 0.44 was maintained throughout the mixing process, with the liquid components added to a sturdy mixing vessel. A Festool mixer operating at 1000 rpm was used to blend the materials, beginning with liquid additives like defoamer and silica solution. The solid additives were pre-blended with water to ensure even distribution before being incorporated into the mixture. The cement powder blend was then carefully added while maintaining consistent mixing speeds to create a uniform slurry. The study explored four distinct formulations: a base slurry serving as the control sample (CS), and PMC/ESP (75%/25%), PMC/ESP (25%/75%) and PMC/ESP (50%/50%) variations using different proportions of pumice and eggshell powder as cement replacements. These alternative mixtures substituted the primary cement with pumice (PMC) and eggshell powder (ESP) combinations at varying ratios of 25%, 50%, and 75% by weight of cement (BWOC), as outlined in Tables 2.

2.3 Molding and Curing the Sample

For the curing process, the slurry was carefully poured into pre-greased 2X2X2 in^3 cube molds and tapped to remove air bubbles. The initial curing took place at temperature at 87°C for 24 a day, after which the samples were removed from their molds. Further curing occurred in an autoclave reactor under at 150°C and 2000psi for 30 days, 200°C and 2000psi for 30 days, 260°C and 2000psi for 30 days, and 300°C and 2000 psi for 30 days in Figure 1. After naturally cooling to room temperature, the samples were divided for various testing purposes, including compressive strength testing and other analyses.

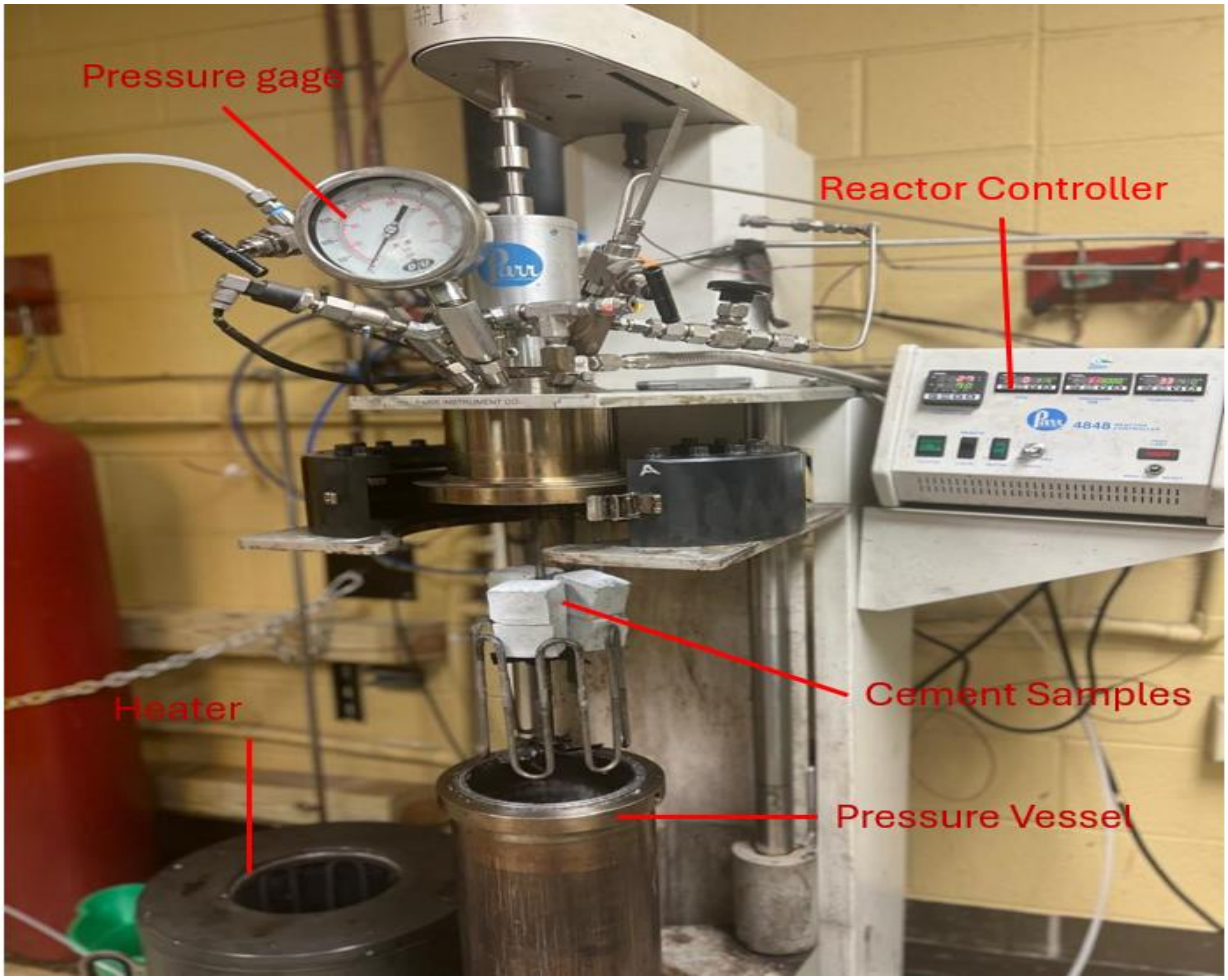

Figure 1: The autoclave reactor used to cured the cement sample, simulating geothermal well condition (Aluah et al 2024a).

2.4 Preparation of Samples

Sample preparation consisted of preparing cylindrical cores and powder specimens. For NMR Porosity, permeability and mechanical testing, cylindrical cores measuring 1 inch in diameter and 2 inches in length were drilled from the cube samples, with their end surfaces precision-cut and polished using a diamond polisher on a high-precision variable-speed tabletop grinder. For XRD analysis to examine mineralogy, separate samples were pulverized into fine powder

Table 1. Chemical Composition of eggshell powder and pumice.

Component	**Class G Cement**	**Pumice Mass (%)**	**Eggshell powder Mass (%)**
TiO_2	-	0.07	-
Fe_2O_3	5.05	1.30	-
SiO_2	20.12	72.4	0.05
MgO	0.95	0.08	1.12
Al_2O_3	4.46	12.2	0.05
SO_3	2.21	0.02	0.49
P_2O_5	-	0.01	0.1
CaO	62.73	0.56	98
K_2O	-	4.87	0.11
Na_2O	-	1.63	-
LOI	-	6.9	-
MnO	-	0.03	0.11

Table 2. Cement slurry formulation composition

Components	**Control Sample**	**PMC/ESP (75/25)**	**PMC/ESP (25/75)**	**PMC/ESP (50/50)**
Cement (% BWOC)	100	100	100	100
Silica solution	35	35	35	35
Water (% BWOC)	44	44	44	44
Defoamer (% BWOC)	7	7	7	7
Dispersant (% BWOC)	0.25	0.25	0.25	0.25
Fluid Loss ((% BWOC)	0.5	0.5	0.5	0.5
Retarder (% BWOC)	1.5	1.5	1.5	1.5
Eggshell Powder (% BWOC)	0	75	25	50
Pumice (% BWOC)	0	25	75	50

2.5 XRD and XRF Analysis

The chemical composition was analyzed using a RIGAKU Supermini 200 WDXRF apparatus. Class G cement contained mainly CaO (62.73%) and SiO2 (20.12%), with smaller quantities of Fe2O3 (5.05%) and Al2O3 (4.46%). Pumice showed high SiO2 (72.4%) and Al2O3 (12.2%) content, plus K2O (4.87%) and Na2O (1.63%). Eggshell powder was predominantly CaO (98%) with minor MgO (1.12%). For XRD analysis, cement samples were ground to powder, dried at 140°C for 1 hour, and analyzed using a Rigaku MiniFlex 6000 diffractometer. The scan parameters were 3-90° range, 0.030° step size, 0.18°/min speed, 40 kV voltage, and 15 mA current over 8 hours and 3 minutes. Data processing used PDXL software with baseline correction, peak identification, and profile integration, followed by manual processing to ensure complete peak inclusion. Phases were identified by matching peaks with reference patterns from the instrument's database.

2.6 Measurement of Elastic properties using AutoLab 1500

The testing used an NER AutoLab 1500 system to measure dynamic elastic properties through P-waves and S-waves. The process involved encasing the cement sample in a rubber jacket, applying shear gel to the sonic components, and connecting the sample to source and receiver caps in Figure 2. The system underwent verification through pressure testing and wave pattern monitoring. After assembly placement and mineral oil introduction, the setup followed strict leak testing protocols. The measurement process involved cycling confining pressure from 10 MPa to 40 MPa in 15 MPa increments, with a 0.01 MPa/s change rate. Each pressure level included a two-minute stabilization period before recording "p", "s_1", and "s_2" wave data. The system calculated dynamic elastic properties using relationships between P-wave velocity, S-wave velocity, and material density to determine Poisson's ratio, Young's modulus, and bulk compressibility under various pressure conditions.

The dynamic elastic properties are calculated using specific relationships.

The dynamic Poisson's ratio (ν_{dyn}):

$$\mathrm{V}_{\mathrm{dyn}} = \frac{V_p{}^2 - 2v_s{}^2}{2(v_p{}^2 - v_s{}^2)} \tag{1}$$

The dynamic Young's modulus (E_{dyn}):

$$\mathrm{E}_{\mathrm{dyn}} = \frac{\rho V_s{}^2(3V_p{}^2 - 4V_s{}^2)}{v_p{}^2 - v_s{}^2} \tag{2}$$

Bulk compressibility is calculated using (C_{dyn}):

$$\mathrm{Vdyn} = \frac{1}{\rho V_p{}^2 - \frac{4}{3}\rho V_s{}^2} \tag{3}$$

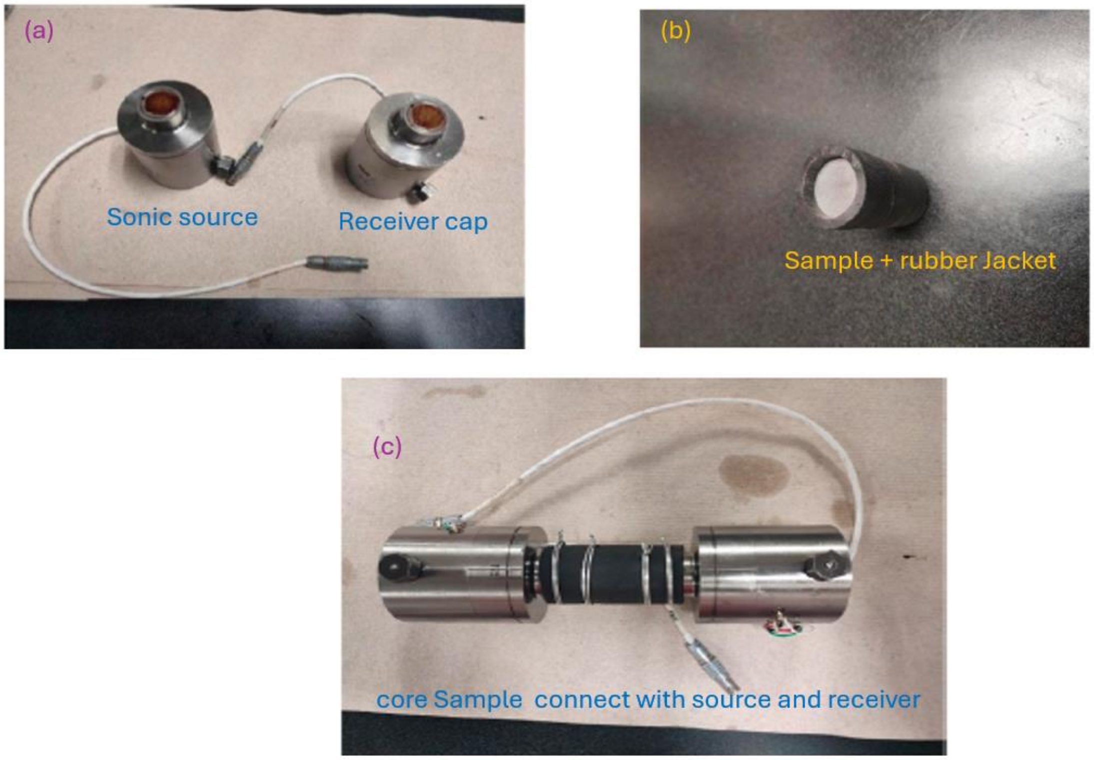

Figure 2: Show ultrasonic measurement (a)the shear gel applied on both caps, b) cement sample in the rubber jacket, and c) connecting the cement sample with receiver cap and sonic source.

2.7 Compressive Strength Testing

A detailed study was conducted to understand how adding pumice and eggshell powder affects cement slurry properties, particularly its strength under pressure. Cubic cement specimens with dimensions of 2 × 2 × 2 in^3 were subjected to compressive strength testing to determine the ultimate load-bearing capacity of varying cement formulations prior to failure. This experimental methodology proved critical for assessing wellbore cement integrity in geothermal applications where pumice and eggshell powder additives are incorporated into the cement matrix.

The cement specimens were subjected to elevated temperature curing conditions at 150°C, 200°C, 260°C, and 300°C for a duration of 30 days, facilitating enhanced compressive strength development through accelerated hydration reactions relative to ambient curing protocols. Compressive strength evaluations were performed utilizing a Forney 920 Series Universal Testing Machine incorporating Automatic Variable Frequency Drive controls (Figure 3). In accordance with ASTM C39 standards, a continuous compressive load was applied at a rate of 100 psi/s until specimen failure was achieved. The compressive strength values were derived from the maximum sustained load prior to failure. To establish statistical validity, a minimum of two replicate samples were tested for each cement formulation, with the reported strength values representing the mean of these measurements. This comprehensive testing methodology enables detailed analysis of the structural integrity of modified cement formulations under simulated downhole conditions.

Figure 3: Compressive Strength test was performed on cement samples at curing temperatures using Forney 920 Series Universal Testing Machine.

2.8 Permeamility Measurement

Permeability measurements were conducted using the Autolab 1500 system equipped with pulse-decay methodology and nitrogen gas injection in Figure 4. The system's measurement capabilities range from 0.01 µD to 500 mD, with operational parameters including maximum confining and pore pressures of 5,000 psi and 2,000 psi, respectively. The experimental protocol commenced with dimensional verification of the cured cement specimens and parallel end preparation. Specimens were encased in a rubber jacket and interfaced with the pressure system via downstream sensor and upstream cap connections. The core holder assembly was positioned within the pressure chamber and integrated with the upstream vessel and reservoir. Mineral oil served as the pressure control medium within the chamber. Confining pressure was incrementally elevated while maintaining a differential above pore pressure to prevent gas circumvention. Following nitrogen gas introduction and leak verification through valve isolation, pressure parameters were adjusted to test specifications. System equilibration was maintained until downstream-upstream pressure equivalence was achieved, typically requiring a thirty-six-hour stabilization period. Subsequently, pulse-decay parameters were established, and pressure decay monitoring was initiated. Permeability calculations incorporated decay curve data, specimen dimensions, and fluid properties in accordance with Darcy's law.System decommissioning procedures included pressure stability verification, controlled pressure release, vessel disconnection, and specimen extraction following established safety protocols. A constant net effective stress of 20.8 MPa was maintained throughout testing, with continuous monitoring of pressure and temperature conditions. This methodology demonstrates particular efficacy in characterizing tight formation permeability and permeability anisotropy in heterogeneous formations.

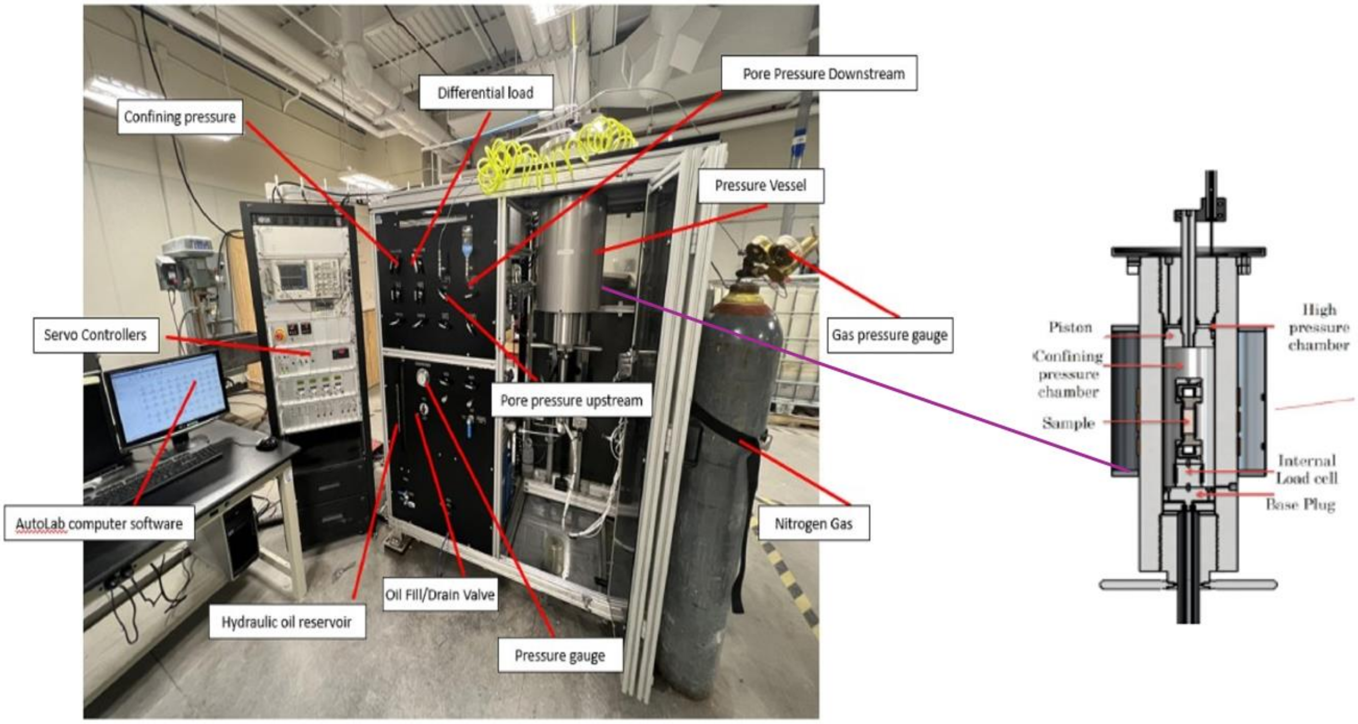

Figure 3: Autolab 1500 for measuring Permeability and ultrasonic of the cement samples (Aluah et al., 2024b).

2.9 Porosity measurement.

The porosity of the geothermal cement samples was measured using Nuclear Magnetic Resonance (NMR) techniques. The cured cement specimens were analyzed both before and after thermal exposure at various temperatures (150°C, 200°C, 260°C, and 300°C) to investigate the effect of elevated temperature on the porosity development. Prior to NMR analysis, the cement samples underwent a systematic preparation protocol. Initially, the specimens were placed in a vacuum chamber for 2 hours to evacuate entrapped air and moisture from the pore network. Subsequently, the samples were saturated with distilled water for three days to ensure complete saturation of the pore structure. To optimize the saturation process, the specimens were transferred to a core flooding accumulator and subjected to 2000 psi pressure before NMR testing. NMR analysis, a non-destructive methodology, utilizes the magnetic properties of hydrogen nuclei to determine porosity characteristics and pore size distribution within cement matrices. Upon exposure to a strong magnetic field, the hydrogen nuclei align with the applied field. Through the application of radio frequency pulse sequences, the NMR instrument quantifies the relaxation times of the hydrogen nuclei, which correlate directly to the pore size distribution and total porosity of the cement specimens. This technique provides comprehensive characterization of the pore network evolution in cement samples subjected to geothermal conditions.

3. DISSCUSION AND RESULTS

3.1 Compressive Strength

The compressive strength tests presented in Figure 5 highlight the performance of cement samples under varying geothermal well conditions. The study indicates that temperature plays a pivotal role in influencing the mechanical properties of cement formulations, particularly under high-temperature geothermal conditions (150°C–300°C). At 150°C, the control cement sample exhibits a compressive strength of 4.54 MPa, which is significantly lower than the PMC/ESP (75%/25%) blend's 11.03 MPa. This suggests that conventional Class G cement lacks the necessary mechanical strength to maintain zonal isolation at even moderate geothermal conditions, whereas the addition of pumice and eggshell powder enhances performance through pozzolanic reactions. As the temperature increases to 260°C, the performance gap widens further. The control sample deteriorates to 3.23 MPa, while the 75%/25% blend achieves 11.9 MPa. This highlights the critical role of the PMC/ESP additives in improving thermal stability. Similarly, the 50%/50% blend demonstrates moderate performance (7.52 MPa), while the 25%/75% blend drops to 4.28 MPa, signifying a lower thermal resilience with higher eggshell content. At the highest tested temperature of 300°C, the 75%/25% blend achieves its peak performance with a compressive strength of 12.96 MPa, whereas the control sample's degradation to 2.93 MPa reaffirms its unsuitability for deep geothermal operations. These findings underline the superior thermal stability and durability of the optimized PMC/ESP formulation, making it suitable for challenging geothermal environments. The results have critical implications for geothermal well design and operations. The exceptional performance of the 75%/25% blend suggests its potential to ensure long-term well integrity, reduce maintenance costs, and minimize risks associated with cement failure. Furthermore, the utilization of industrial by-products like pumice and eggshell aligns with sustainability goals by promoting waste valorization and reducing environmental impacts.

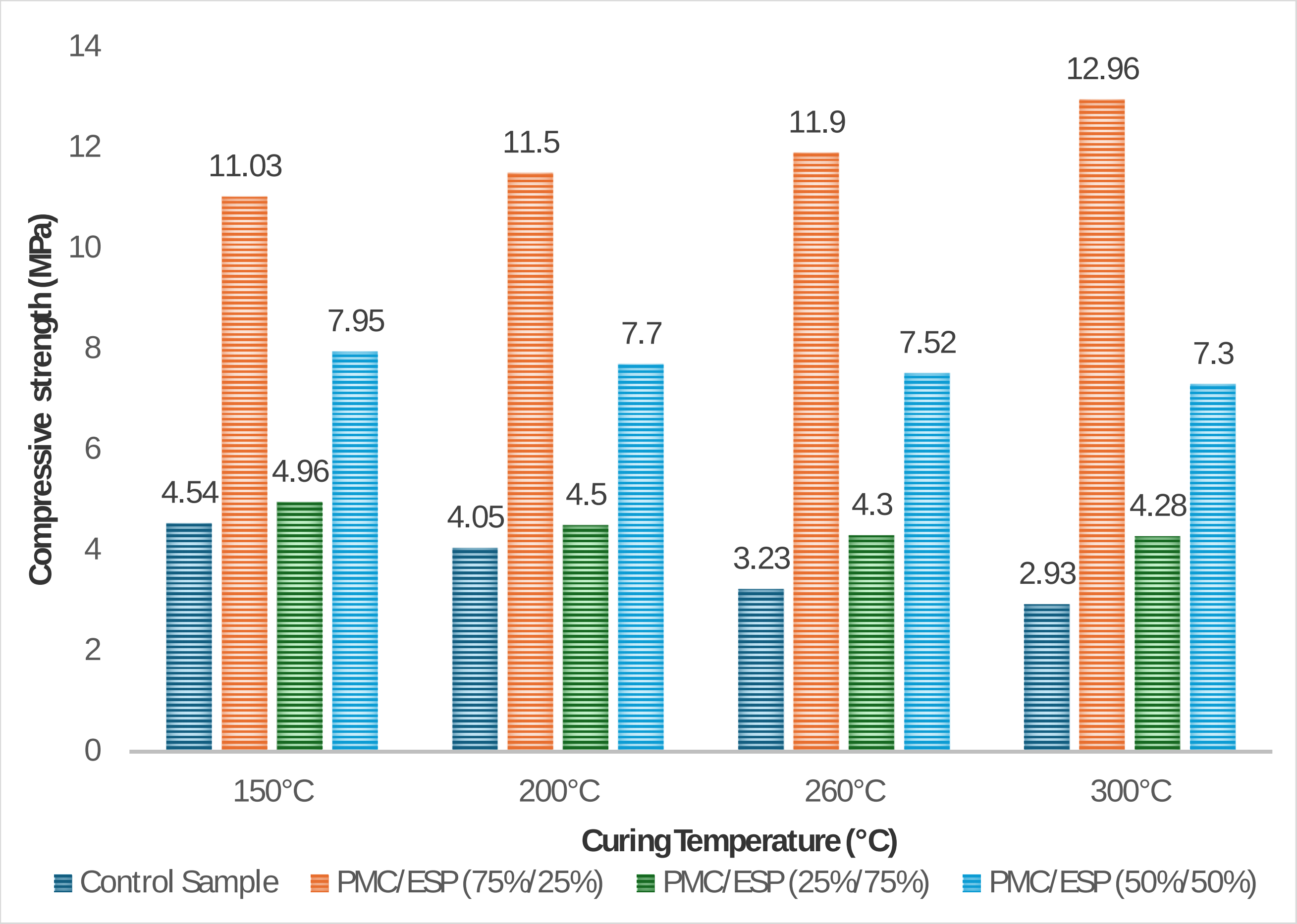

Figure 5: Compressive Strength test was performed on cement samples at a curing temperature: 150°C, 200°C, 260°C and 300°C.

3.2 Young's Modulus Analysis

The systematic evaluation of Young's modulus across varying temperature regimes reveals critical insights into the behavior of cement systems under geothermal well conditions. Figure 6 highlights distinct performance patterns, essential for maintaining wellbore integrity across the geothermal gradient. The PMC/ESP (75%/25%) blend exhibits superior elastic properties, achieving a Young's modulus of 73.6

GPa at 150°C, significantly outperforming the control sample's 39.5 GPa. This enhanced elastic response is indicative of superior microstructural development, providing robust zonal isolation capabilities and resistance to stress variations in upper well sections. As temperature increases, the PMC/ESP (75%/25%) blend demonstrates remarkable thermal resilience, with minimal variation in Young's modulus (73.7–72.9 GPa) from 200°C to 260°C. This stability is critical for maintaining phase integrity and ensuring consistent mechanical performance in geothermal environments. Conversely, the control sample shows a substantial decline in Young's modulus, dropping from 34.2 GPa to 32.5 GPa, signaling its inadequate resistance to thermal effects and limited suitability for geothermal applications. At 300°C, the 75%/25% blend continues to outperform all other formulations, with a Young's modulus of 72.5 GPa, compared to the control sample’s 30.5 GPa. This confirms its ability to withstand extreme geothermal conditions and sustain long-term well integrity. The superior elastic stability of the PMC/ESP (75%/25%) blend across all temperature ranges underscores its suitability for geothermal wells, offering consistent zonal isolation and resistance to thermal cycling. These properties are critical for preventing inter-zonal fluid migration and ensuring well compartmentalization during operational fluctuations.

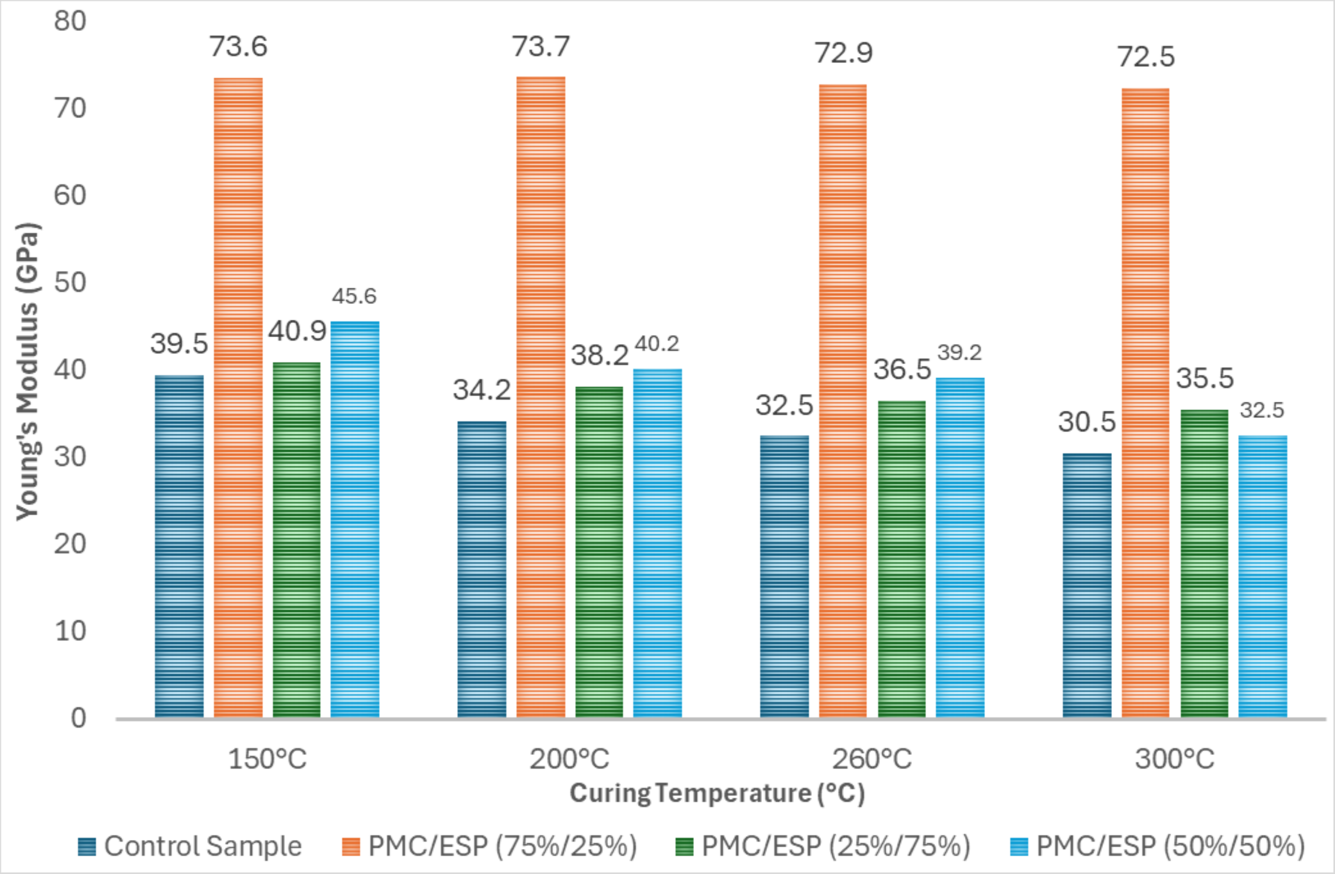

Figure 6 Young’s modulus test was performed on cement samples at a curing temperature: 150°C, 200°C, 260°C and 300°C.

3.2 Poisson’s Ratio Analysis.

Poisson’s ratio (PR) analysis of cement blends under geothermal well conditions (150°C to 300°C) provides valuable insights into the lateral deformation properties critical for maintaining wellbore integrity. The results, as depicted in Figure 7, highlight the superior performance of the PMC/ESP (75%/25%) blend compared to the control sample and other formulations across the temperature range. At 150°C, the PMC/ESP (75%/25%) blend achieves the highest PR value of 0.294, reflecting its superior ability to accommodate lateral strain under shallow well conditions. This elasticity is vital for managing stress variations near the surface, where thermal and mechanical loads are less severe but still significant. The control sample, with a PR of 0.201, demonstrates limited capacity to adapt to radial deformations, which could lead to early-stage cracking or stress accumulation. As the temperature increases to 200°C and 260°C, the 75%/25% blend exhibits further improvement in PR values, reaching 0.301 and 0.350, respectively. This trend indicates its exceptional capacity to distribute thermal stresses and maintain structural integrity in intermediate zones. The control sample’s PR declines to 0.150 at 260°C, signifying a critical loss of lateral strain capacity, which poses a high risk of failure in these zones. At 300°C, typical of deep geothermal reservoirs, the 75%/25% blend achieves its peak PR of 0.365, demonstrating robust stress accommodation and resilience under extreme conditions. The control sample, in contrast, deteriorates to 0.124, underscoring its unsuitability for high-enthalpy geothermal environments. Intermediate blends (PMC/ESP 50%/50% and 25%/75%) show moderate PR stability across all temperatures but do not match the performance of the 75%/25% blend. The results emphasize the superior lateral deformation capability of the PMC/ESP (75%/25%) blend across all geothermal conditions, ensuring enhanced wellbore stability and reduced risk of cement sheath failure. The blend’s consistent PR improvement and thermal resilience make it ideal for geothermal well applications, particularly in high-pressure, high-temperature zones. These findings underscore the critical role of optimizing cement formulations to improve mechanical and elastic properties for long-term geothermal well integrity.

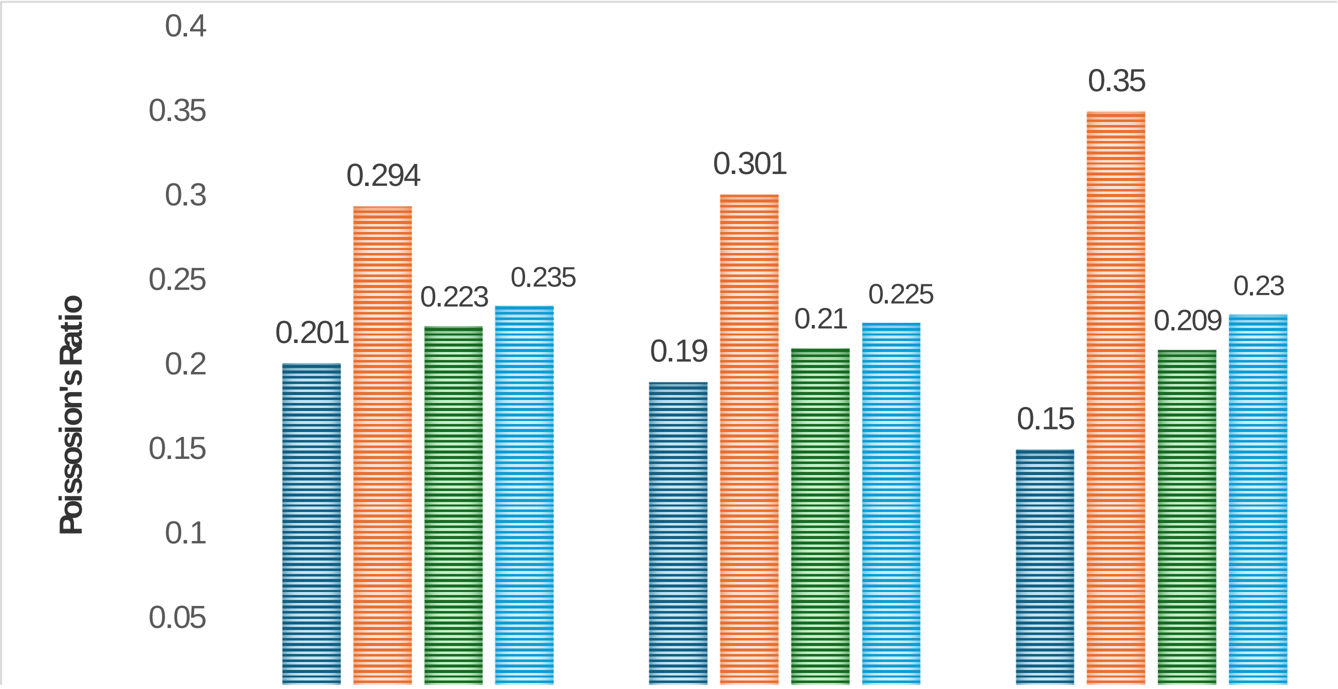

Figure 7 Poisson's Ratio test was performed on cement samples at a curing temperature: 150°C, 200°C, 260°C and 300°C.

3.4 Permeability Analysis.

The permeability analysis of cement samples at curing temperatures ranging from 150°C to 300°C, as depicted in Figure 8, underscores the importance of tailored cement blends for geothermal well applications. Permeability is a critical factor in ensuring wellbore integrity, with lower permeability being essential for maintaining zonal isolation and long-term durability under extreme thermal conditions. At 150°C, the PMC/ESP (75%/25%) blend demonstrates exceptional performance, exhibiting a remarkably low permeability of 0.00192 mD. This result reflects refined pore structure, which is crucial for effective zonal isolation in geothermal wells. In contrast, the control sample's higher permeability (0.008 mD) raises concerns about its suitability for such conditions, as it indicates potential leakage risks. The intermediate blends (50%/50% and 25%/75%) show moderate permeability values of 0.0041 mD and 0.0072 mD, respectively, revealing incremental improvements over the control. At elevated temperatures (200°C to 260°C), the 75%/25% blend maintains remarkable stability, with permeability values between 0.00183 mD and 0.00185 mD, indicating resistance to thermal degradation. Conversely, the control sample experiences a significant permeability increase, reaching 0.009 mD, while the 50%/50% blend shows moderate stability (0.0063 mD). At 300°C, the 75%/25% blend again outperforms, with minimal permeability increase (0.0019 mD), demonstrating its superior thermal resilience. The control sample, however, reaches its highest permeability (0.01 mD), reflecting severe thermal degradation. The 50%/50% blend shows a 73% increase in permeability across the temperature range, and the 25%/75% blend experiences a 32% increase, further underscoring the limitations of these configurations. The consistent low permeability of the 75%/25% blend across all temperatures highlights its potential as a robust material for geothermal wells, ensuring reliable zonal isolation and reduced thermal degradation. This study emphasizes the importance of optimizing cement formulations for geothermal environments to enhance wellbore integrity and operational safety.

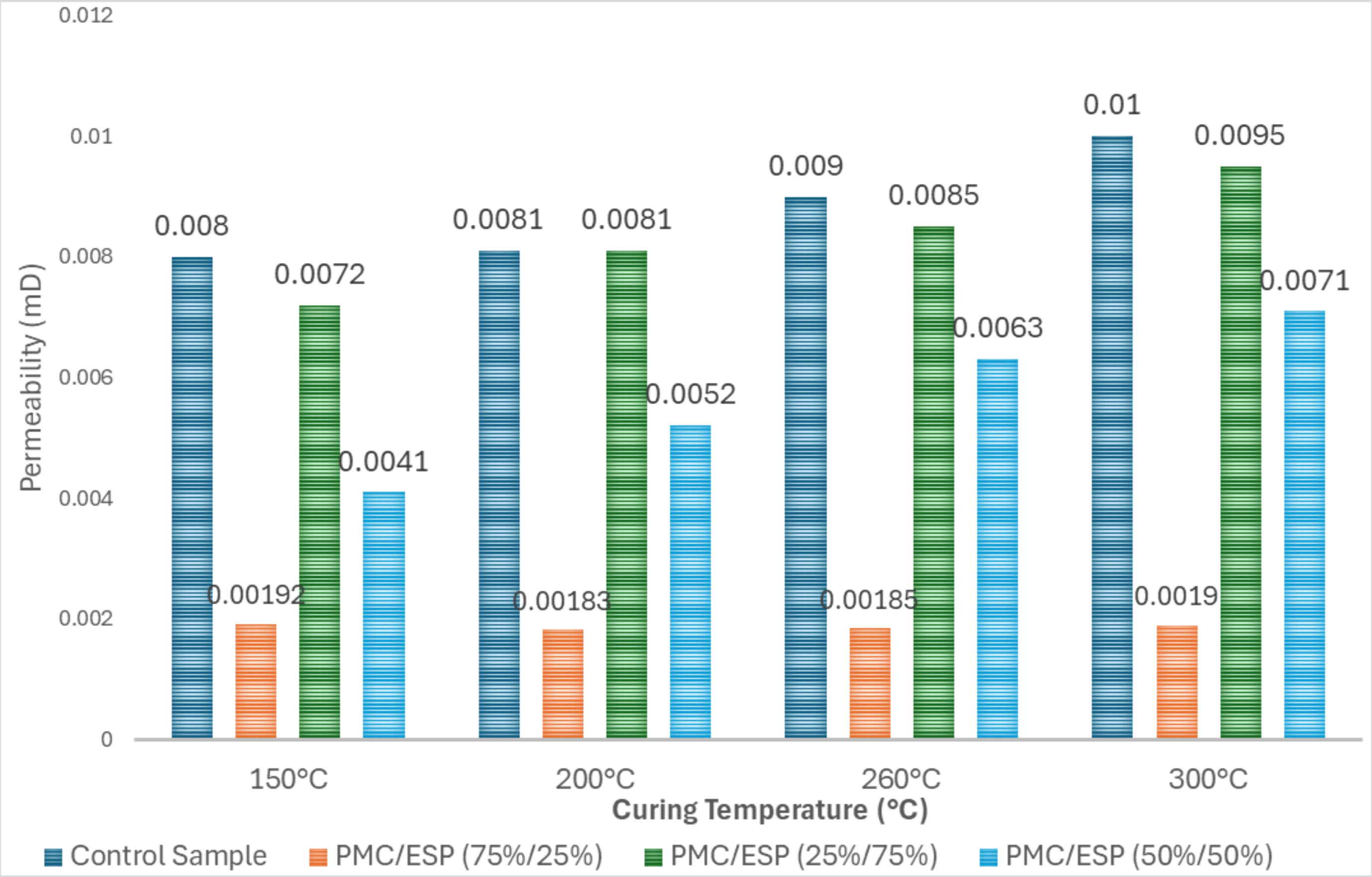

Figure 8: Permeability analysis was performed on cement samples at a curing temperature: 150°C, 200°C, 260°C and 300°C.

3.5 NMR Porosity analysis.

The NMR porosity analysis across curing temperatures (150°C to 300°C) provides key insights into the thermal stability and pore structure evolution of various cement blends under geothermal conditions. Figure 10 and Table 3 reveal a significant increase in porosity for the control sample, from 9.14% at 150°C to 13.07% at 300°C, representing a concerning 43% increase. This behavior suggests progressive thermal decomposition of hydration products and matrix degradation, raising doubts about the long-term integrity of conventional cement systems in high-temperature geothermal environments. Such increased porosity compromises the cement’s zonal isolation capability, leading to potential fluid migration and operational challenges. In stark contrast, the PMC/ESP (75%/25%) blend exhibits exceptional performance (Figure 11, Table 3), maintaining porosity values consistently below 1% across all temperatures. The porosity variation from 0.51% at 150°C to 0.84% at 260°C, followed by a decrease to 0.53% at 300°C, demonstrates remarkable thermal stability. This low and stable porosity indicates effective pore structure refinement, likely due to synergistic interactions between pumice and eggshell powder, which enhance the formation of stable hydration products. Such behavior highlights the blend's capability to resist thermal degradation and maintain robust zonal isolation in geothermal wells. The PMC/ESP (50%/50%) blend shows moderate performance, with porosity ranging from 3.29% at 150°C to 3.55% at 300°C (Figure 12, Table 3). This relatively stable trend indicates adequate thermal resistance, albeit with higher porosity than the 75%/25% blend. Meanwhile, the PMC/ESP (25%/75%) blend exhibits greater thermal sensitivity, with porosity increasing from 4.12% at 150°C to 7.92% at 300°C (Figure 13, Table 3). This suggests that a higher proportion of eggshell powder reduces the blend's ability to resist pore structure degradation at elevated temperatures. The findings emphasize the importance of optimizing the pumice-to-eggshell ratio in cement formulations for geothermal applications. The dramatic porosity reduction observed in the 75%/25% blend translates to enhanced mechanical properties, ensuring superior durability and zonal isolation. These attributes make it a viable candidate for geothermal wells, offering improved performance under extreme thermal conditions compared to conventional systems. The study underscores the need for tailored cement formulations to address the challenges posed by high-temperature geothermal environments, promoting long-term wellbore integrity and operational efficiency.

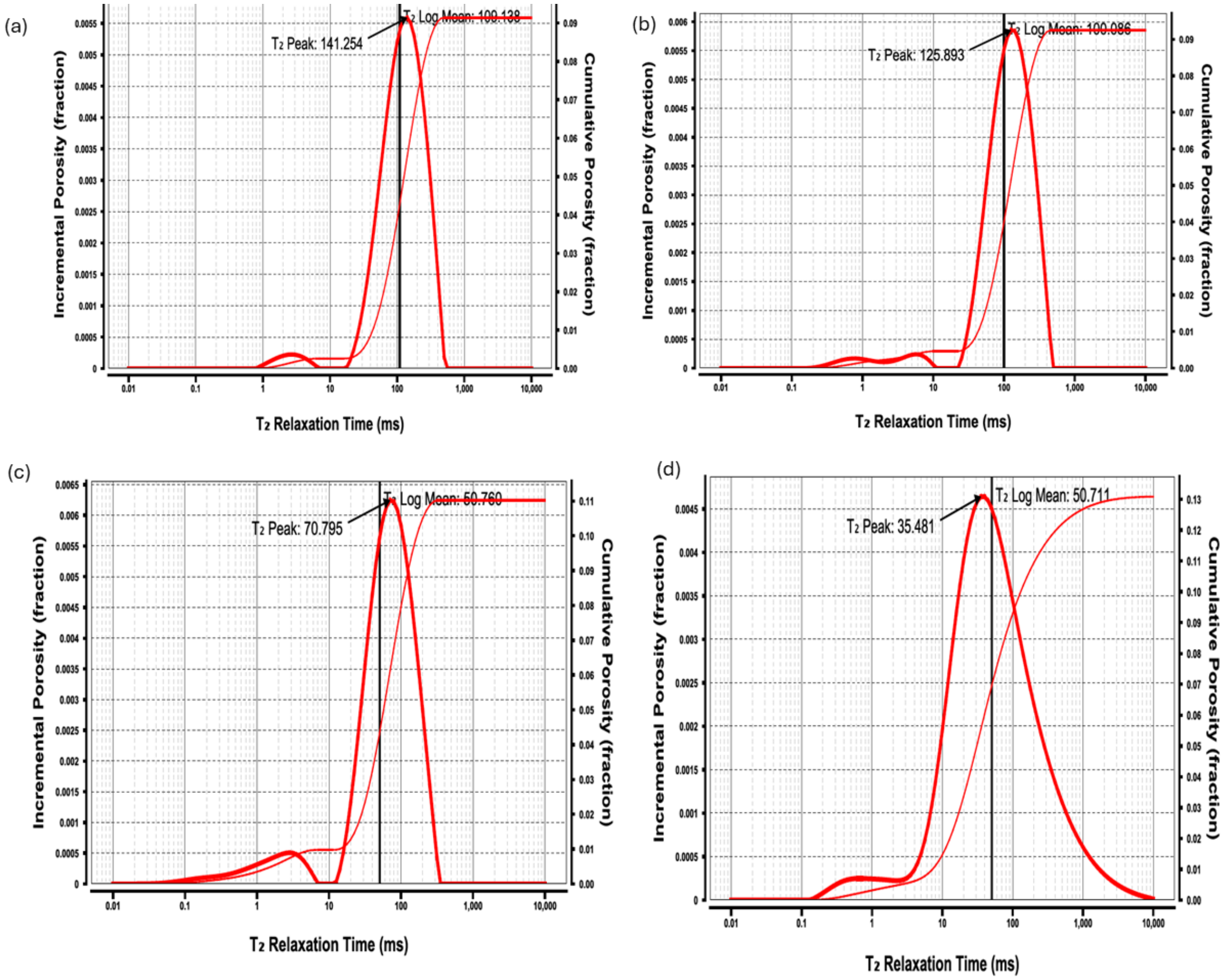

Figure 10: NMR porosity for control samples at curing temperature for 30 days: (a) 150°C with porosity of 9.14%; (b) 200°C with porosity of 9.25%; (c) 260°C with porosity of 11.02% and (d) 300°C with porosity of 13.07%.

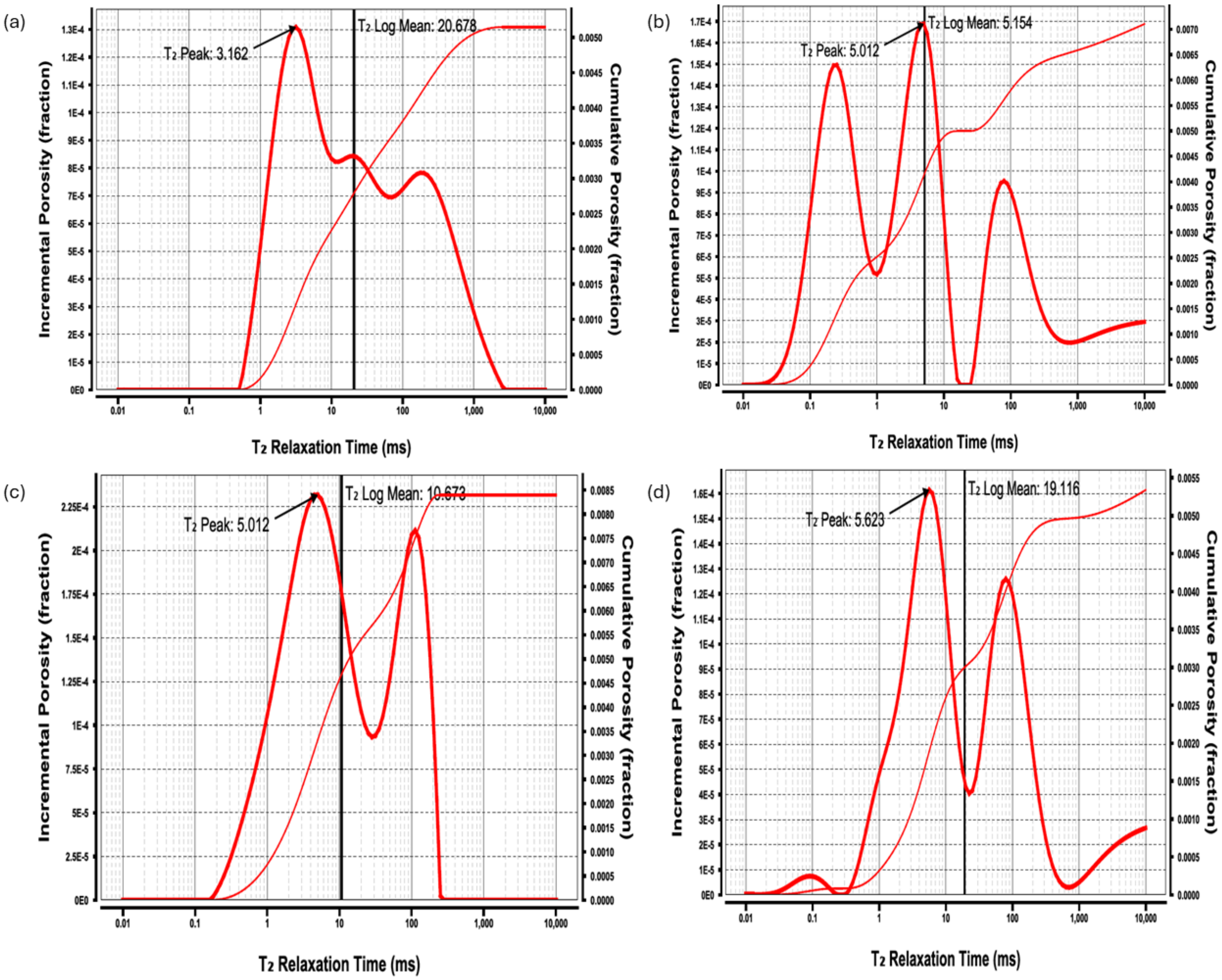

Figure 11: NMR porosity for 75% PMC/25% ESP samples at curing temperature: (a) 150°C with porosity of 0.51%; (b) 200°C with porosity of 0.71%; (c) 260°C with porosity of 8.84% and (d) 300°C with porosity of 0.53%.

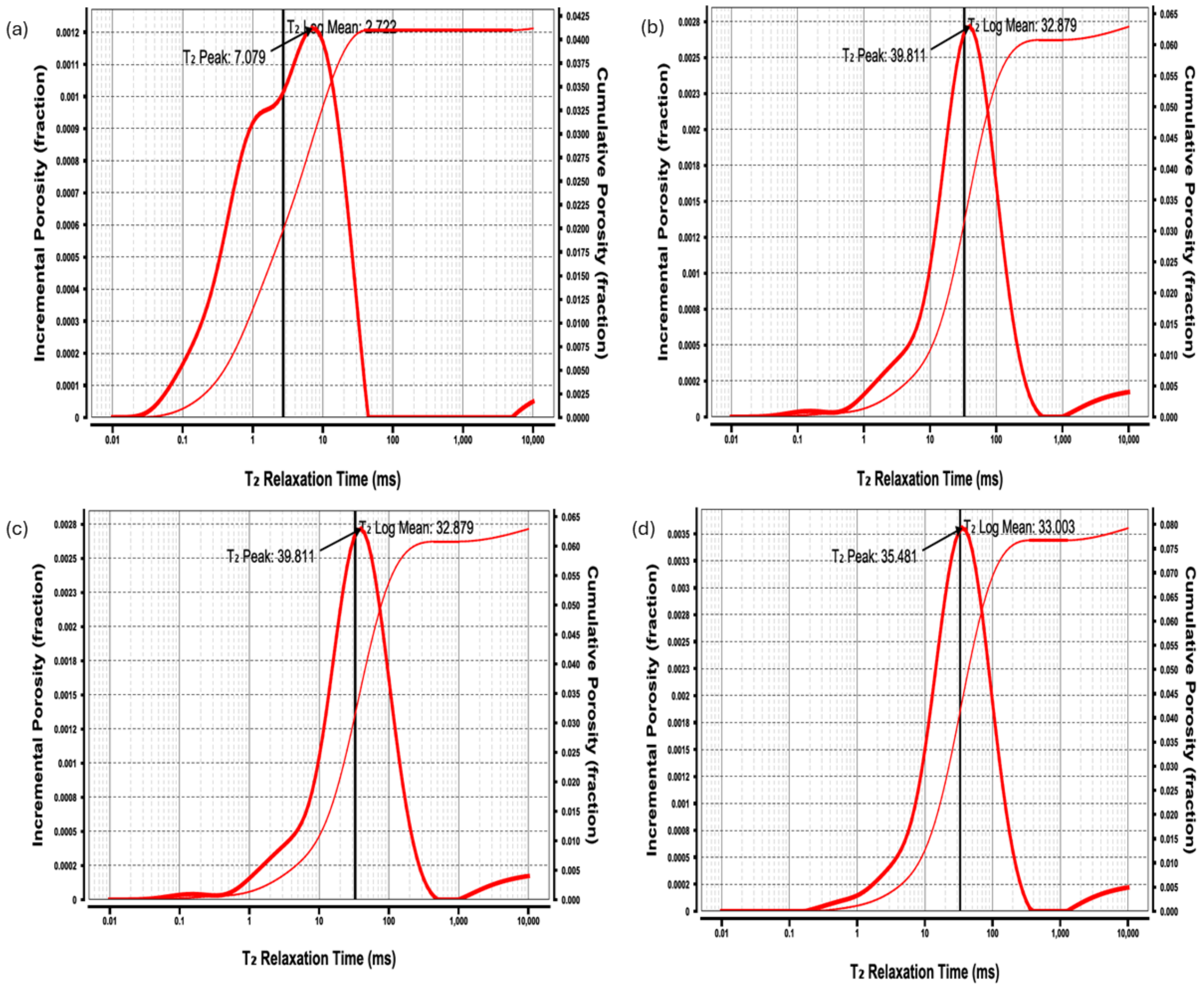

Figure 12: NMR porosity for 25% PMC/75% ESP samples at curing temperature: (a) 150°C with porosity of 4.12%; (b) 200°C with porosity of 6.26%; (c) 260°C with porosity of 6.29% and (d) 300°C with porosity of 7.92 %.

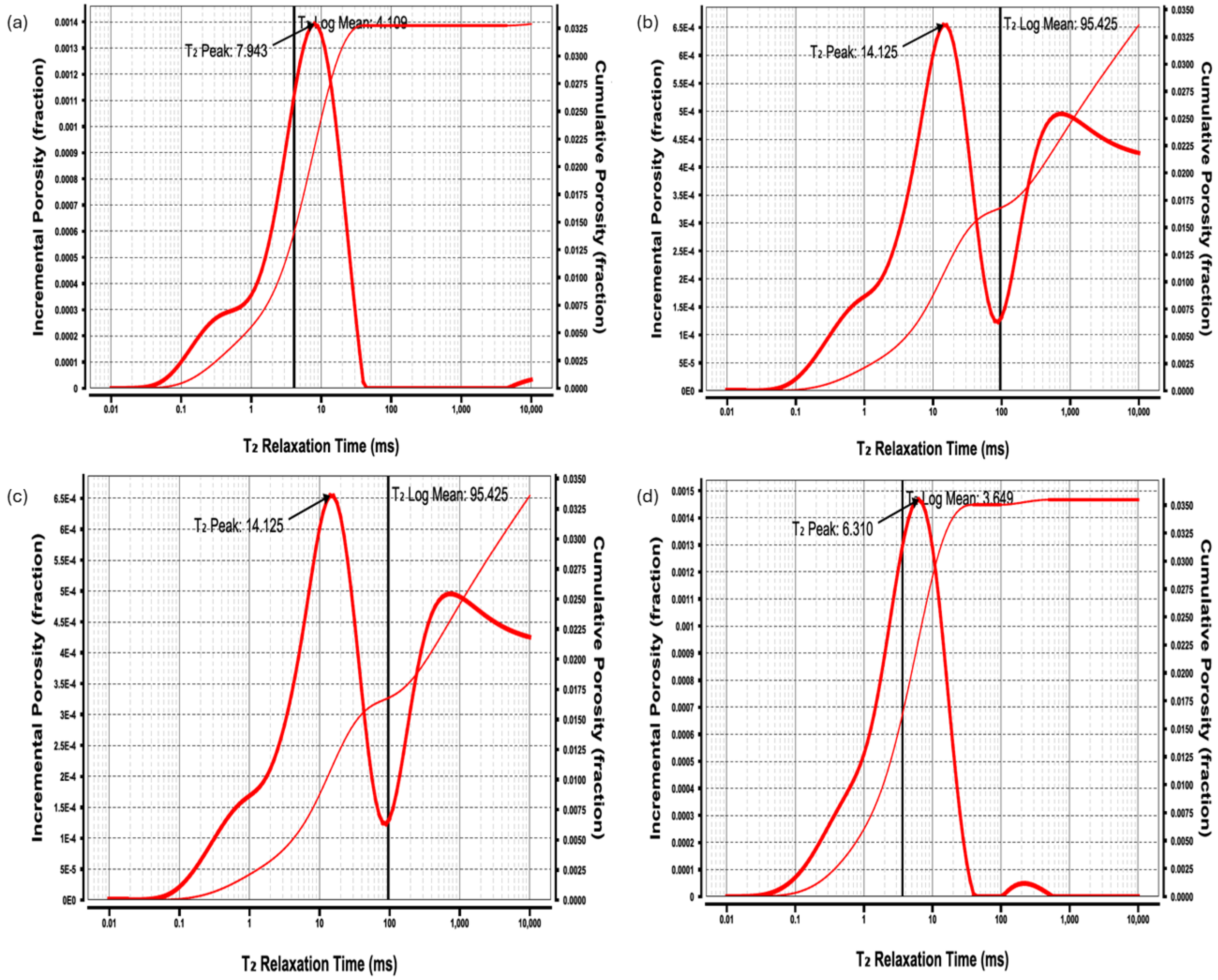

Figure 13: NMR porosity for 50% PMC/50% ESP samples at curing temperature: (a) 150°C with porosity of 3.29%; (b) 200°C with porosity of 3.35%; (c) 260°C with porosity of 3.36% and (d) 300°C with porosity of 3.55%.

Table 3: Summary of NRM porosity for the curing temperature samples.

Cement Formulation	Porosity @ 150°C (%)	Porosity @ 200C (%)	Porosity @ 260C (%)	Porosity @ 300C (%)
Control Sample	9.14	9.25	11.02	13.07
PMC/ESP (75%/25%)	0.51	0.71	0.84	0.53
PMC/ESP (25%/75%)	4.12	6.27	6.29	7.92
PMC/ESP (50%/50%)	3.29	3.35	3.36	3.55

3.5: XRD Analysis.

The XRD analysis offers valuable insights into the mineralogical transformations of cement blends incorporating PMC/ESP under curing conditions of 150°C to 300°C over 30 days. In the control cement samples, alite (Ca_3SiO_5), a critical phase for early strength development, decreases significantly from 40.6% at 150°C to 30.91% at 300°C, highlighting structural instability at higher temperatures. The brownmillerite content in these samples shows moderate thermal stability, increasing from 10.6% to 16.76%, while other phases exhibit signs of thermal decomposition. These findings suggest that the control sample may experience performance degradation in high-temperature geothermal environments due to phase instability. The PMC/ESP (75%/25%) blend demonstrates remarkable thermal stability, with the formation of xenotolite, ranging from 28.5% to 32.8%, providing structural robustness under extreme conditions. Brownmillerite remains stable (21.96-24.9%), while calcite content increases moderately from 6.3% to 10.42%, reflecting controlled carbonation processes. Notably, the reduced formation of C-S-H phases (7.4-9.78%) minimizes susceptibility to thermal degradation, autogenous shrinkage, and cracking, making this blend highly suitable for geothermal applications. In contrast, the PMC/ESP (25%/75%) blend shows higher C-S-H content (34.5-37.2%), which raises concerns about its thermal stability. This high content is associated with increased porosity and a higher likelihood of thermal cracking under prolonged exposure to elevated temperatures. Brownmillerite exhibits greater temperature sensitivity (28.33-32.2%), and pavlovskite degrades significantly (18.65-11.3%), compromising the blend's structural integrity. The PMC/ESP (50%/50%) blend strikes a balance, with moderate C-S-H formation (30.4-34.6%) and stable larnite content (18.5-20.3%). Although pavlovskite content decreases from 31.7% to 22.5%, suggesting controlled pozzolanic reactions, the high C-S-H content still poses risks of shrinkage and thermal cracking. This blend provides moderate strength development and phase stability but remains less ideal than the 75%/25% blend for high-temperature applications. The implications of these findings emphasize the critical role of blend ratio optimization in ensuring cement integrity under geothermal conditions. Excessive C-S-H formation in the control sample and certain PMC/ESP ratios leads to thermal cracking, autogenous shrinkage, and potential strength retrogression during long-term exposure to high temperatures. Conversely, the PMC/ESP (75%/25%) blend's reduced C-S-H formation, combined with stable xenotolite and brownmillerite content, offers superior thermal stability and durability. The PMC/ESP (75%/25%) blend is the most promising formulation for geothermal well cementing, providing enhanced resistance to thermal degradation, improved structural integrity, and reduced risk of long-term failure in extreme geothermal environments. These results underscore the importance of mineralogical control and phase optimization in cement design for geothermal applications.

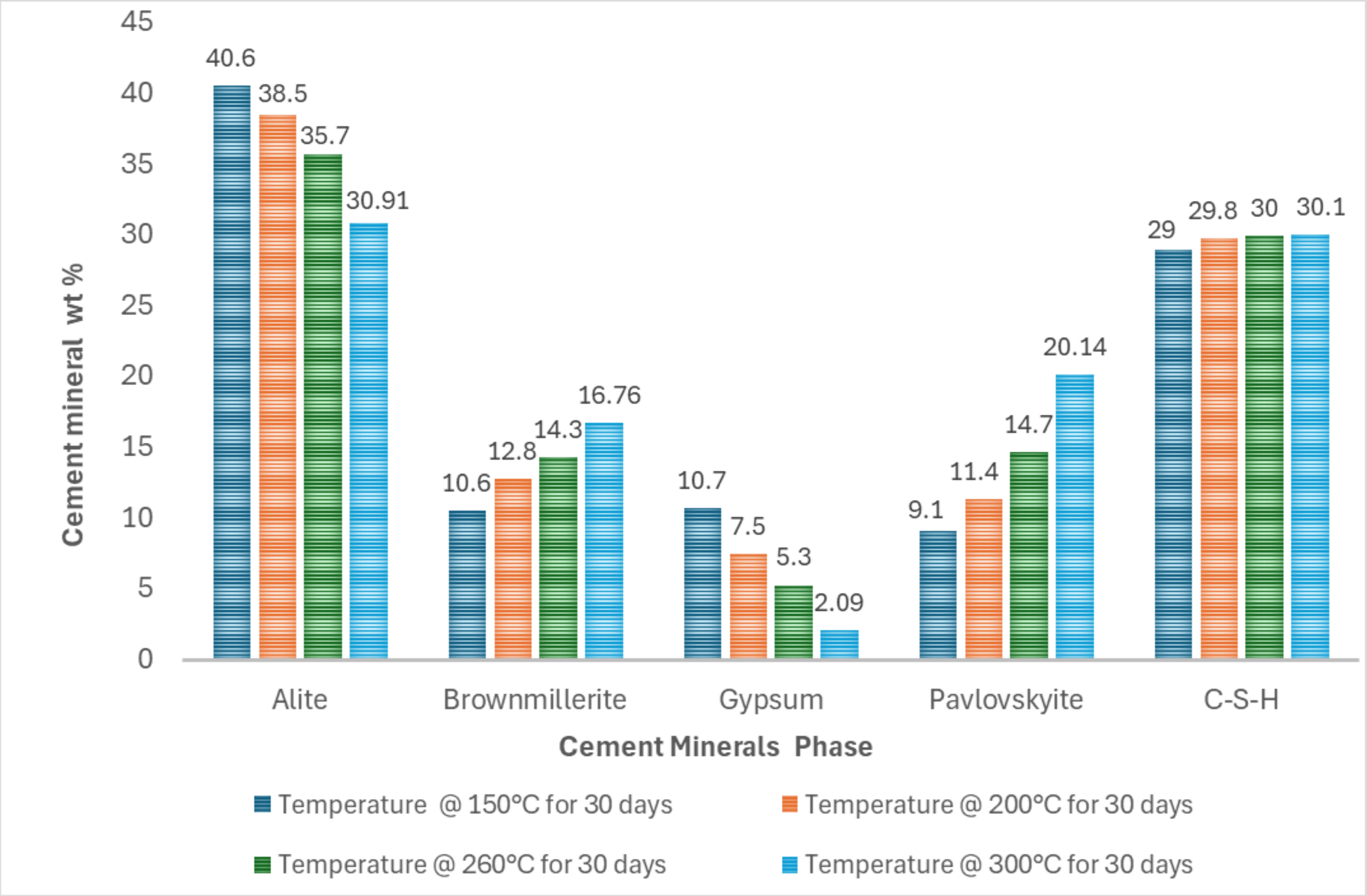

Figure 14: XRD experiments performed on cement control samples cured at temperatures of 150°C, 200°C, 260°C and 300°C for 30 days.

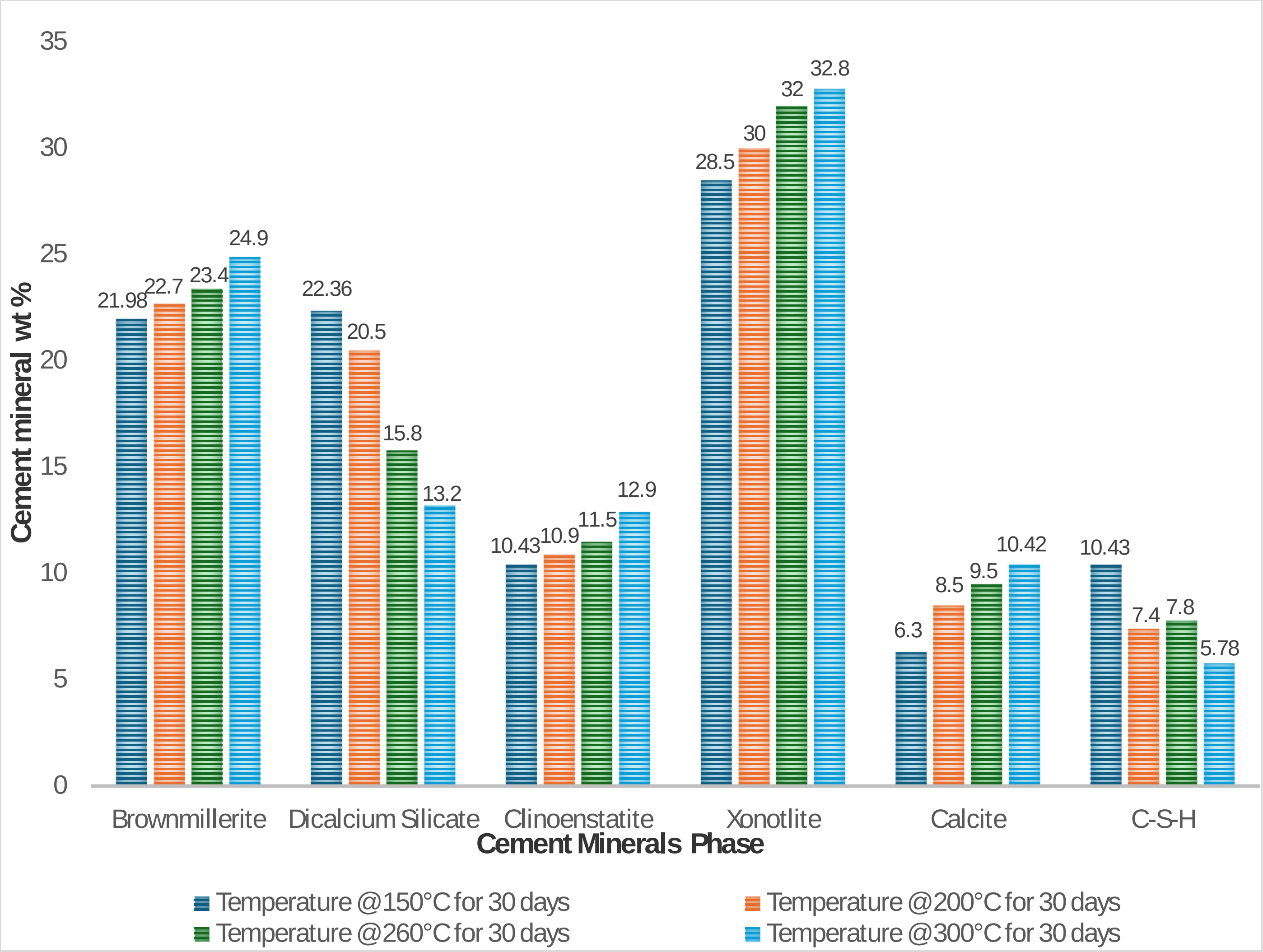

Figure 15: XRD experiments performed on cement PMC/ESP (75%/25%) samples cured at temperatures of 150°C, 200°C, 260°C and 300°C for 30 days.

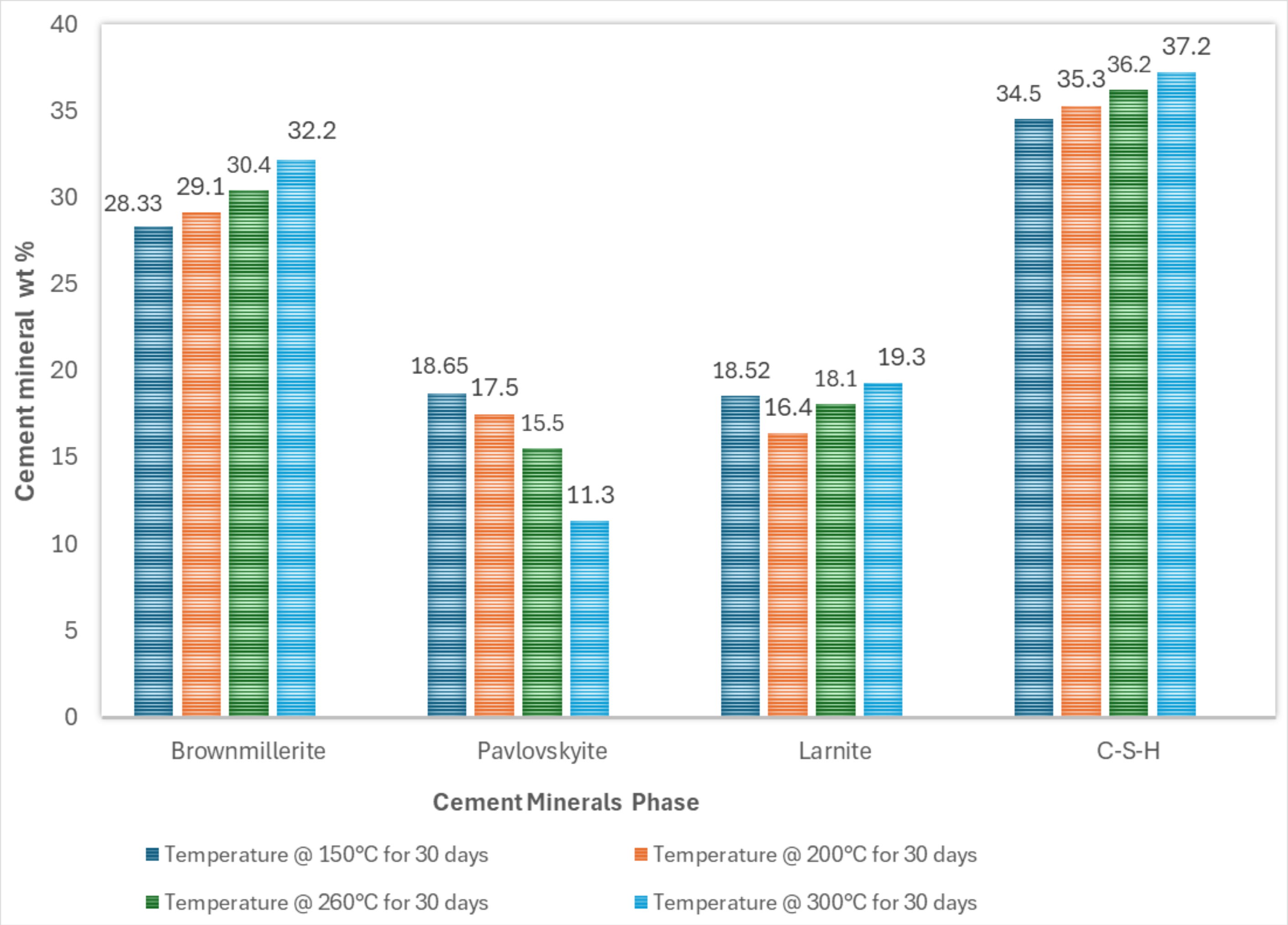

Figure 10: XRD experiments performed on cement PMC/ESP (25%/75%) samples cured at temperatures of 150°C, 200°C, 260°C and 300°C for 30 days.

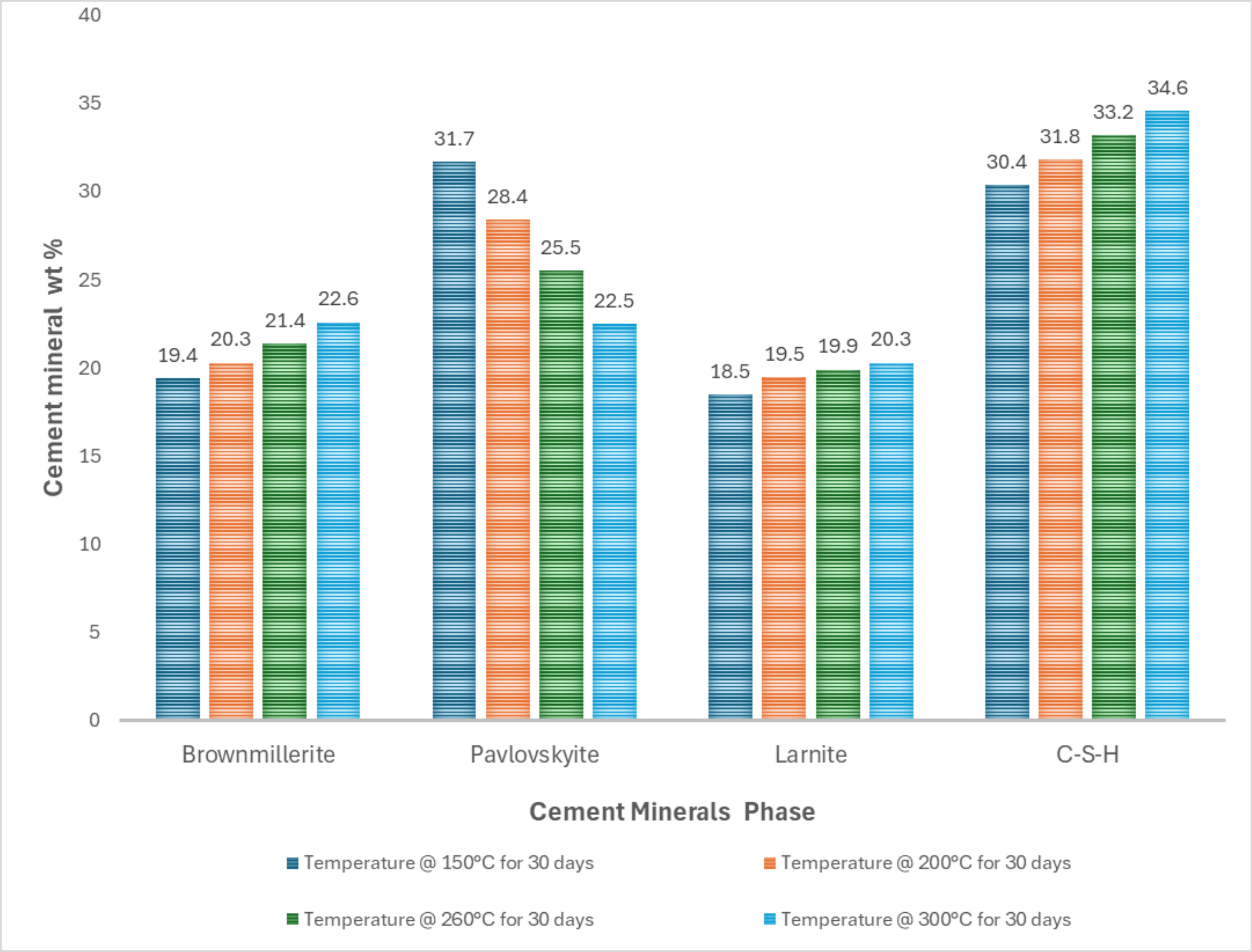

Figure 17: XRD experiments performed on cement PMC/ESP (50%/50%) samples cured at temperatures of 150°C, 200°C, 260°C and 300°C for 30 days.

2. CONCLUSION

This comprehensive investigation into PMC/ESP-modified Class G cement demonstrates significant advancements in geothermal well cementing technology. The accompanying conclusions can be drawn from this undertaking:

This study demonstrates the effectiveness of PMC/ESP cement blends in overcoming the limitations of conventional cement systems in geothermal wells. The 75%/25% blend exhibits outstanding compressive strength and thermal stability, making it a viable solution for maintaining zonal isolation in high-temperature geothermal applications. The findings advocate for the adoption of enhanced cement formulations as a sustainable and cost-effective approach to improving geothermal well integrity.

The 75%/25% PMC/ESP cement blend demonstrates exceptional performance across the tested temperature range, combining mechanical stability, thermal resilience, and elastic consistency. These attributes position it as a robust and reliable solution for geothermal well integrity, ensuring long-term operational efficiency.

The optimized PMC/ESP (75%/25%) blend exhibits exceptional thermal stability, maintaining porosity below 1% across high temperatures, outperforming other formulations and the control sample. This demonstrates its potential for enhanced durability and zonal isolation in geothermal applications, ensuring long-term well integrity and addressing challenges posed by extreme geothermal conditions effectively.

The study highlights the superior thermal stability and structural integrity of the PMC/ESP (75%/25%) blend, making it ideal for geothermal applications. Its reduced C-S-H formation and stable mineral phases minimize thermal cracking and shrinkage. Optimizing PMC/ESP ratios is crucial for enhancing cement performance and ensuring long-term well integrity under extreme conditions

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NOMENCLATURE

E_{dyn} = the dynamic Young's modulus [GPa]

ESP= Eggshell Powder

C_{dyn} = the Bulk compressibility [Pa^{-1}]

PMC = Pumice

V_p = compressional P-wave velocity [m/s]

V_s = shear S-wave velocity [m/s]

V_{dyn} = the dimensionless dynamic Poisson's ratioρ = density [g/cm^3]

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