

Research Article

Development of Geopolymer Cement Using Sugarcane Bagasse Ash for Application in Oil and Gas Well Cementing

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Abstract

As the oil and gas industry moves towards sustainable solutions, eco-friendly alternatives to traditional Portland cement, a major CO₂ emitter, are essential. Sugarcane bagasse ash-based geopolymer presents a promising option, also addressing agricultural waste management issues. In this work, sugarcane bagasse was collected, washed, dried and ashed to obtain the bagasse ash required for the sample formation. A total of 24 samples were prepared and they were tested for density, rheology, pH, fluid loss and compressive strength. Eight of the samples were formed using 10M NaOH (SCBA 1–8), another set of eight samples were formed using 5M NaOH (SCBA 9–16), while the remaining set of eight were formed using ordinary Portland cement OPC (OPC 1–8). Results from slurry density and rheology tests revealed that geopolymer samples had higher density, plastic viscosity, yield point, and pH compared to Ordinary Portland Cement (OPC), but with lower fluid loss and less filter cake formation. However, geopolymers cement exhibited rapid gelation at high temperatures. The compressive strength of Sugarcane Bagasse-based geopolymer cement increased with temperature, indicating stronger cement for deeper drilled holes. However, the strength decreased over time with higher NaOH concentrations, highlighting that cement must be formulated for specific applications.

Keywords

Bagasse, Compressive Strength, Eco-friendly, Geopolymer, Plastic Viscosity, Temperature

1. Introduction

The oil and gas industry seek innovative solutions to improve well integrity and sustainability. Traditional oil well cementing, primarily with Ordinary Portland Cement (OPC), faces challenges like cement degradation, limited durability, and vulnerability in acidic environments [1]. Developed by Professor Joseph Davidovits in 1972, geopolymer cement offers a potential alternative [2]. The industry's environmental impact is under increasing scrutiny, highlighting the need for sustainable practices [3]. Traditional Portland cement used in well cementing contributes significantly to carbon emis-

sions, underscoring the importance of eco-friendly alternatives [4]. Geopolymers offer a promising alternative with a reduced carbon footprint and the potential to utilize abundant waste materials [5]. This study explores geopolymer cement for wells and examines how its mechanical properties vary with curing temperatures from ambient (23 °C–80 °C), reflecting the geothermal gradient of 30 °C/km from surface to deep underground [6]. OPC-based composites suffer strength loss above 230 °F, limiting their performance in deep wells, geothermal wells, and thermally loaded wells like steam in-

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Received: 22 April 2025; **Accepted:** 3 May 2025; **Published:** 2 September 2025



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jection wells [7]. The oil and gas industry rely on cementing operations for well intervention and drilling [8]. However, Ordinary Portland Cement (OPC) faces limitations in accessibility, adaptability across diverse environments, and sustainability [9]. Cementing in injection or production wells is crucial for carbon capture and storage projects, yet OPC has shown instability in CO₂-rich environments, highlighting the need for improved preventive maintenance strategies [10].

In addition, the study adds to the current knowledge that a less cost and eco-friendly Sugarcane Bagasse based geopolymer can replace conventional cement in oil and gas well cementing in the near future. As a result, the study aims to develop environmentally sustainable geopolymer based cement formulations, utilizing sugarcane bagasse ash, for oil and gas well cementing. The integrity of the cement was examined by carrying out various physical and mechanical tests on formulated samples at relevant temperatures while comparing obtained results obtained result to that of ordinary Portland cement.

2. Materials and Methods

Sugarcane bagasse was gathered and dried under the sun to eliminate moisture. To obtain an appropriate particle size distribution, size reduction techniques, grinding or milling was also done on the sugarcane bagasse to form a powder which serve as the precursor material. The dried Sugarcane Bagasse was placed in ceramic container and positioned in a muffle furnace, at a temperature of 400 °C to obtain the ash of the bagasse, the temperature was maintained for 2 hours and after 2 hours the furnace was turned off and allowed to cool to room temperature.

The grinded or milled sugarcane bagasse powder was collected for Fourier transform infrared spectroscopy (FTIR) analysis and the analysis was done according to [11]. The analysis was performed on the sample to characterize its chemical structure, composition, organic minerals and identify the presence of specific functional groups and bonds on each geopolymer based cement that was formed.

The alkaline solution was prepared according to [12] by dissolving a measured quantity of sodium hydroxide in a distilled water and left for 24 hours for proper dissolution, The prepared alkaline solution was mixed with measured quantity of Sodium Silicate and laboratory mixer was used to blend both solutions together and the alkaline activator solution according to [12] was added to the precursor material (Sugarcane Bagasse Ash (SCBA)) while stirring continuously using laboratory mixer. The amount of activator solution added depend on the desired consistency and workability of the geopolymer paste and was mixed until a homogeneous paste or slurry was formed and left for 24 hours. Equal mass or weight of sugarcane bagasse ash was measured for the OPC using weighing balance and was mixed together with equal volume of water as that of sugarcane bagasse where the OPC formulated serve as control sample and left for 24 hours. Various tests were carried on the samples ranges from:

- 1) Rheological Testing on Slurry Samples: Using a Fann viscometer, rheological properties were measured following precise calibration and setup instructions. Temperature control was emphasized to maintain consistency, often with a temperature-controlled chamber. Each sample's Plastic Viscosity (PV) was calculated as the difference between the 600 rpm and 300 rpm readings, while the Yield Point (YP) was derived from the difference between the 300 rpm and 3 rpm readings.
- 2) Density Testing: The density test involved specific gravity determination. A 25 ml specific gravity bottle was weighed empty, then filled with slurry, weighed again, and the specific gravity was calculated.
- 3) pH Testing: The pH was measured using a calibrated pH meter, rinsing the electrode with distilled water between samples. The pH was recorded once stabilized.
- 4) Fluid Loss Test: A high-temperature, high-pressure fluid loss test was conducted at 1000 psi using an API filter press. The sample was poured into a filter press cup with a filter paper, sealed, and subjected to pressure. The fluid loss after 30 minutes was collected in a measuring cylinder.
- 5) Preparation of Core Samples: Samples of geopolymer cement were molded into 15mm x 15mm x 15mm cubes, which were left to solidify for 24 hours. Similar molds were used for OPC samples for consistency.
- 6) Curing of Samples: Molded samples were transferred to a vacuum oven with varying temperatures (100 °C, 200 °C, and 300 °C) for specified durations (6, 24, or 72 hours) to examine the feasibility of using geopolymer cement for well abandonment.
- 7) Mechanical Testing: The core samples were then subjected to a compression test using Instron electromechanical testing machine to measure their mechanical strength, enabling a comparison between SCBA-based geopolymer and OPC samples.

3. Results and Discussion

Fourier Transform Infrared (FTIR) Spectrum Test: The FTIR spectrum of sugarcane bagasse (Figure 1) was analyzed from 4000 to 450cm⁻¹, identifying four zones. Zone I (4000–2500cm⁻¹) is the single bond region; Zone II (2500–2000cm⁻¹), the triple bond region; Zone III (2000–1500cm⁻¹), the double bond region; and Zone IV (<1500cm⁻¹), the fingerprint region. Peaks were matched with reference data. A notable peak at 3250–3650cm⁻¹ indicates hydroxyl (-OH) groups, suggesting hydrogen bonding and high moisture. Carbonyl (-C=O) groups appear at 1700–1750cm⁻¹, likely from lignin and hemicellulose. Peaks at 900–1100cm⁻¹ indicate possible silicate ions, while peaks at 1000–1100cm⁻¹ suggest phosphate ions, likely from plant cellular components or soil contaminants. Other prominent peaks include C-S stretching (670–715cm⁻¹), S-S stretching (430–500cm⁻¹), and aromatic amine CN stretch (1250–1340cm⁻¹). These findings provide insight into the

chemical composition, lignin content, mineral contamination, and structural characteristics of sugarcane bagasse powder.

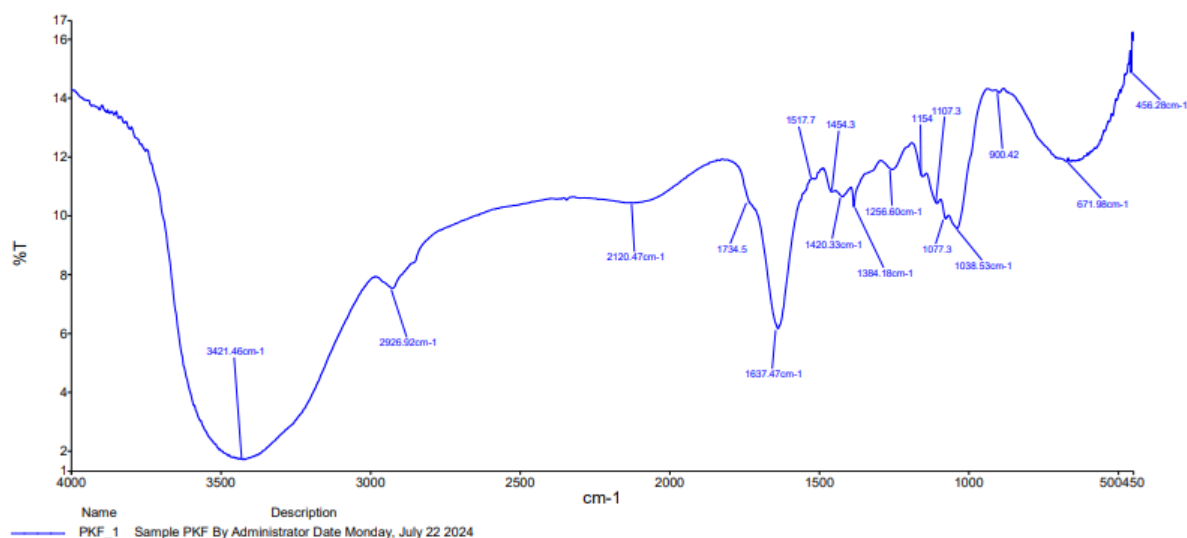


Figure 1. FTIR of sugarcane bagasse powder.

Slurry Density and Rheological Test: Cement slurries were mixed based on the geopolymer formulation. Industry standards require densities between 12.5 to 16 ppg. The density and rheological properties measured for the prepared samples are presented in Table 1. The average densities were 15.82 ppg for 10M NaOH, 14.73 ppg for 5M NaOH, and 13.09 ppg for OPC, with higher NaOH concentrations resulting in higher densities. Plastic viscosity and yield point followed the same trend, suggesting that increased NaOH enhances rheological properties. This is due to improved particle interactions and geopolymerization, which reduce circulation loss risk and improve compressive strength. Lower-density slurries may risk wellbore instability.

Table 1. Measured density and rheological properties for prepared samples.

Sample code	Density (ppg)	Specific Gravity	Yield Point (lb/ft ²)	Plastic Viscosity (cP)	Average Density
SCBA1	15.84	1.90	2.00	3.00	15.82
SCBA2	16.02	1.92	2.10	3.10	
SCBA3	15.52	0.93	2.00	3.00	
SCBA4	16.00	1.92	2.30	3.20	
SCBA5	15.90	1.91	2.50	3.51	
SCBA6	15.50	1.83	2.30	3.20	
SCBA7	15.80	1.89	2.00	3.00	
SCBA8	16.01	1.92	2.10	3.10	

Sample code	Density (ppg)	Specific Gravity	Yield Point (lb/ft ²)	Plastic Viscosity (cP)	Average Density
SCBA9	14.50	1.74	1.83	2.71	14.73
SCBA10	14.80	1.77	1.90	2.80	
SCBA11	14.42	1.73	1.96	2.91	
SCBA12	15.00	1.79	1.85	2.74	
SCBA13	15.20	1.83	1.90	2.80	
SCBA14	14.80	1.77	1.92	2.85	
SCBA15	14.60	1.75	1.87	2.77	
SCBA16	14.48	1.74	1.97	2.93	
OPC1	13.24	1.59	1.08	1.60	13.09
OPC2	13.35	1.60	1.10	1.70	
OPC3	13.10	1.57	1.09	1.60	
OPC4	12.88	1.54	1.13	1.70	
OPC5	12.68	1.52	1.20	1.80	
OPC6	13.25	1.59	1.15	1.73	
OPC7	13.30	1.60	1.08	1.60	
OPC8	12.92	1.55	1.10	1.70	

pH Test: The pH values of the three cement samples were compared: 13.55 for 10M NaOH geopolymer at 27.44 °C, 13.39 for 5M NaOH geopolymer at 26.38 °C, and 12.34 for OPC. The result is presented in Table 2. Geopolymer cements had significantly higher pH values, as expected due to the

alkaline nature of the activator, while OPC had a lower pH due to its calcium oxide content. The geopolymer samples' pH values fall within the industry standard (12-14), indicating better pH stability, making them more suitable for high-performance cement applications. This improves settling time, durability, and minimizes corrosion risk. The chart presentation for pH is as shown in Figure 2.

Table 2. pH results and temperature of each sample.

Sample code	pH Range	Temperature °C	Average pH
SCBA1	13.5	27.4	13.55
SCBA2	13.61	27.5	
SCBA3	13.52	27.4	
SCBA4	13.46	27.3	
SCBA5	13.74	27.6	
SCBA6	13.46	27.3	
SCBA7	13.40	27.1	
SCBA8	13.71	27.6	
SCBA9	13.51	26.80	

Sample code	pH Range	Temperature °C	Average pH
SCBA10	13.52	26.80	13.39
SCBA11	13.40	26.50	
SCBA12	13.38	26.00	
SCBA13	13.36	26.20	
SCBA14	13.55	26.80	
SCBA15	13.00	25.40	
SCBA16	13.42	26.50	12.34
OPC1	12.20	25.90	
OPC2	12.24	26.00	
OPC3	12.40	26.40	
OPC4	12.34	26.20	
OPC5	12.41	26.40	
OPC6	12.23	26.00	
OPC7	12.42	26.41	
OPC8	12.45	26.50	

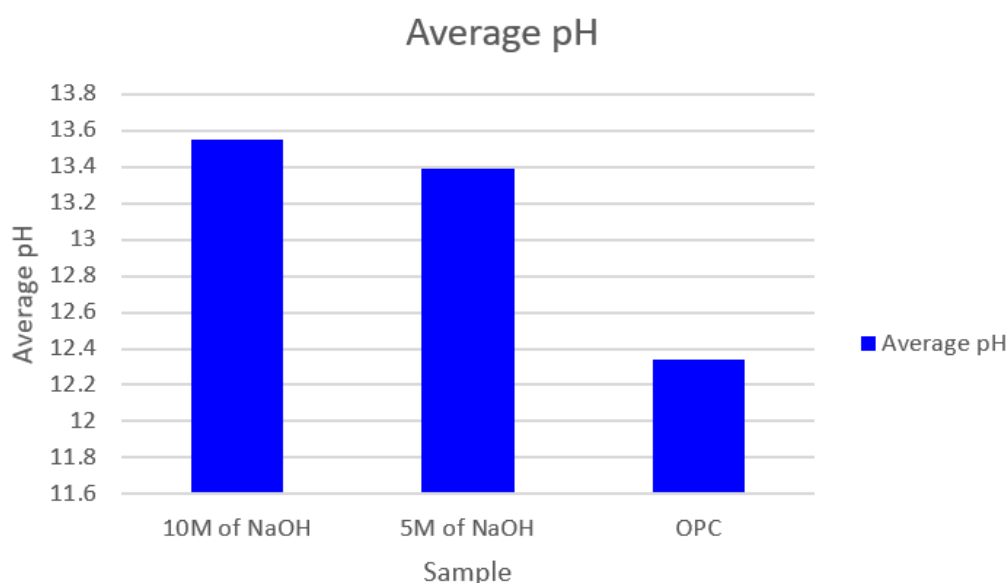


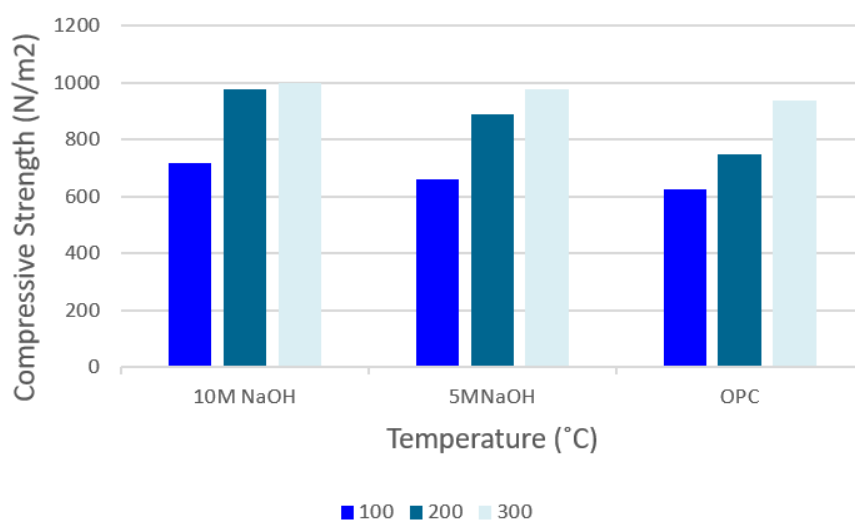
Figure 2. Chart presentation for average pH.

Effect of Temperature on Compressive Strength: The compressive strength test was performed on SCBA 4-6, SCBA 12-14, and OPC 4-6 after passing the slurry density, pH, and fluid loss tests. The cement slurry was cured for 6 hours in a high-temperature curing chamber before testing. Curing temperatures of 100 °C, 200 °C, and 300 °C were used to observe their effect on compressive strength. Results presented in Table 3 and Figure 3, shows that sugarcane ba-

gasse-based geopolymer cement generally increased in compressive strength with higher curing temperatures [13]. The 10M NaOH composition had an average compressive strength of 908.45 N/m² after 6 hours of curing at 100-300 °C, confirming that compressive strength is temperature-dependent [14]. Table 3 presents the results at various curing temperatures.

Table 3. Compressive strength of samples at various temperatures.

Sample code	Compressive Strength (N/m ²)	Temperature (°C)
SCBA4	720.41	100
SCBA12	662.23	
OPC4	626.82	
SCBA5	978.03	200
SCBA13	889.31	
OPC5	748.73	
SCBA6	1001.92	300
SCBA14	978.45	
OPC6	937.78	

**Figure 3.** Compressive strength of samples at various temperature.

Effect of Time variation on compressive strength: The compressive strength test was conducted on SCBA 7-8, SCBA 15-16, and OPC 7-8 after passing the slurry density, pH, and fluid loss tests. Cement slurry compositions were cured at 200 °C for 24 and 72 hours in a curing chamber. Results presented in Table 4 as well as Figure 4, shows that compressive strength increased with NaOH concentration at

200 °C for the 24-hour curing period [15]. However, at 72 hours, the compressive strength of the 10M NaOH sample decreased, while the 5M NaOH sample showed higher strength than both the 10M NaOH and OPC systems. This indicates that no single cement formula is universally applicable, and it must be tailored to specific operational needs, such as well plug and abandonment jobs.

Table 4. Compressive strength of samples at various times.

Sample code	Compressive Strength (N/m ²)	Time (hrs)
SCBA4	1250.34	24
SCBA12	1120.35	
OPC4	996.78	
SCBA5	1023.87	

Sample code	Compressive Strength (N/m ²)	Time (hrs)
SCBA13	1243.56	72
OPC5	1123.56	

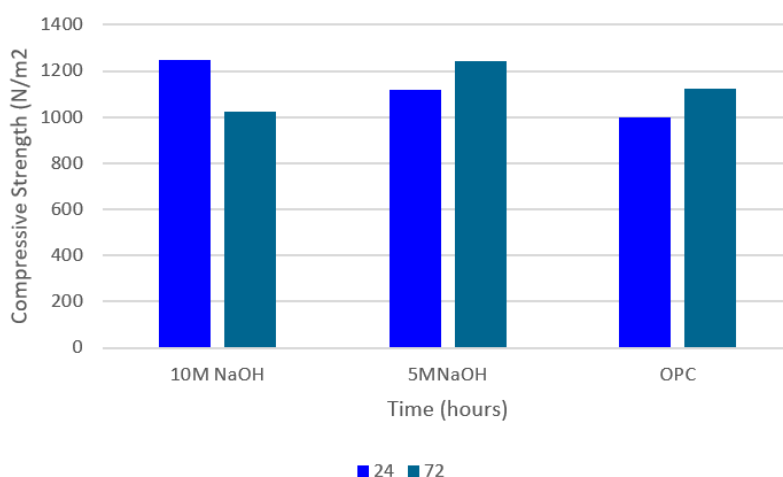


Figure 4. Compressive strength of samples at various time.

4. Conclusion

The production of geopolymer cement using agricultural waste material (Sugarcane Bagasse ash) was studied. Chemical and mineral analyses confirmed that the sugarcane bagasse ash contained the necessary functional groups for cement production. Slurry density and rheology tests revealed that geopolymer samples had higher density, plastic viscosity, yield point, and pH compared to Ordinary Portland Cement (OPC), but with lower fluid loss and less filter cake formation. Geopolymers exhibited rapid gelation at high temperatures. The compressive strength of Sugarcane Bagasse-based geopolymer cement increased with temperature, indicating stronger cement for deeper drilled holes. However, the strength decreased over time with higher NaOH concentrations, highlighting that cement must be formulated for specific applications. Overall, Sugarcane Bagasse-based geopolymer cement outperformed OPC in cementing operations due to its lower shrinkage and higher shear bond strength, making it suitable for zonal isolation and well-plugging operations. Additionally, the increased strength with temperature due to enhanced polymerization suggests its viability in steam injection wells.

Abbreviations

OPC	Ordinary Portland Cement
PV	Plastic Viscosity
YP	Yield Point

FTIR Fourier Transform Infrared

Author Contributions

Oluwasanmi Samuel Teniola: Conceptualization, Methodology, Writing – review & editing

Ebenezer Leke Odekanle: Supervision, Validation

Felix Arome Iyalla: Investigation, Writing – original draft

Mazeed Saka: Investigation, Writing – original draft

Conflicts of Interest

The authors declare no conflicts of interest.

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