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RESEARCH

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Application of Qusaiba Kaolinite Clays as Secondary Cementitious Material in Oil Well Cementing

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Abstract

The oil and gas industry, constituting 90% of Saudi Arabia's exports, relies on essential operations, including oil-well cementing. This crucial process ensures zonal isolation and wellbore structural support. While traditional cementing involves Saudi Class G cement, water and additives, recent attention focuses on secondary cementitious materials for enhanced mechanical properties and durability. Kaolinite is a type of clay mineral investigated as a supplementary cementitious material in various applications, including concrete and mortar. The objective of this study is to use Qusaiba kaolinite as a secondary material in oil and gas wells cementing. Six heavyweight cement samples with different kaolinite concentrations were prepared under high pressure and high temperature (HPHT) conditions. The effects of incorporating several kaolinite dosages on the cement's segregation, microstructure, mechanical, elastic, and petrophysical properties were assessed. The results of this study revealed that 1% by weight of cement (BWOC) is the optimum concentration of kaolinite to be used. Using kaolinite improved the mechanical strength of the cement, where both the compressive and tensile strengths of the cement were increased by 13% and 73%, respectively, when adding kaolinite. It also resulted in a 6.4% reduction in Young's modulus and a minor increase in Poisson's ratio, indicating improved cement elasticity. Cement segregation was also reduced by 74.4% after adding kaolinite, as noted in the direct density variation method and confirmed by the CT scan. As indicated by the SEM images, the ability of the kaolinite to fill the pore spaces reduced the cement permeability by 74.4% for the samples prepared with kaolinite.

Keywords Qusaiba kaolinite, Cementitious material, Oil well cement, Strength

1 Introduction

The global energy demand continues to grow, prompting an increased exploration and production of oil and gas resources. In this quest for sustainable energy solutions, the oil and gas industry faces numerous challenges, including those related to well integrity, zonal isolation and deep, high-pressure, high-temperature (HPHT) wells (Davies et al., 2014; Kiran et al., 2017).

Oil wells' successful operation and longevity heavily rely on the quality and effectiveness of the cement used in well construction. In the realm of petroleum engineering, oil-well cement plays a pivotal role in drilling operations, serving as a cornerstone material for well integrity and performance (El-Gamal et al., 2017). Oil-well cement is a type of Portland cement specifically designed for use in the cementing processes of oil and gas wells. The conditions in which Oil-well cement is used are typically

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challenging, as many remaining oil and gas reserves are located in deep formations with high temperatures.

Once a well has been drilled, this specialized cement is meticulously injected into the annular space between the formation walls and the casing, creating a critical barrier. The multifaceted functions of oil well cement can be broadly categorized into primary and secondary roles, each contributing significantly to the well's stability and productivity (Ahmed et al., 2020). The primary tasks of oil-well cement are preventing crossflow between highly porous formations and disparate zones, providing crucial support for the substantial weight of the casing, and bearing any additional loads that may be imposed on the well structure (Kmieć et al., 2018). Beyond these fundamental roles, the cement serves several secondary yet equally vital purposes. It acts as a formidable barrier against the production of unwanted downhole fluids, offers essential protection to the casing against corrosive elements, and plays a critical role in managing anomalous pore pressures that could otherwise compromise well integrity (Ahmed et al., 2022; Mahmoud et al., 2022).

Nelson and Guillot (2006) underscored the paramount importance of a well-formulated cement slurry. They posit that the failure to isolate problematic zones effectively could significantly impair a well's ability to achieve its maximum production potential, thereby underscoring the cement's role in optimizing well performance and economy. However, conventional oil well cements often exhibit limitations in their mechanical strength, durability, and resistance to aggressive environments and harsh downhole conditions, including high temperature, high pressure, and exposure to corrosive fluids, which compromise the well's integrity (Moroni et al., 2009; Wilcox et al., 2016). These issues have spurred research into developing innovative cement formulations incorporating various additives to improve the cement's mechanical properties, stability, and resistance to aggressive environments.

Kirgiz (2014, 2015a, 2015b, 2015c) investigated the improvement of Class C fly ash cement systems using carbon flakes and nanographite. He showed that adding nanographite accelerates setting times and increases strength gains in pure cement and fly ash-blended systems while positively affecting water absorption, apparent volume, and density characteristics. Kirgiz (2015b, 2015c) brought supernatant nanographite solutions, improving the handling of these cement systems. Later work by Kirgiz et al. (2021) concentrated on synthesizing and characterizing new materials doped with carbon flakes and colloidal carbon. They revealed that these additives greatly improve the physico-mechanical properties of eco-friendly adhesives and grouts, including enhanced compressive strength and optimal particle packing.

The formulation of cement slurry in oil-well applications is a complex and nuanced process involving the careful integration of various additives and materials (Ahmed et al., 2023; Chen et al., 2021). These components must not only be compatible with one another but also work synergistically to fulfill diverse functions, yielding high-quality cement matrices that meet the demanding requirements of downhole environments (Kremieniewski et al., 2016). Among the many additives employed, silica flour stands out for its crucial role in enhancing the strength properties. This material significantly boosts the strength of the cement matrix while simultaneously reducing its permeability, thereby improving its overall performance and longevity in challenging well conditions.

Weighting material such as hematite is incorporated into the slurry composition to achieve the precise density required for specific well depths and pressure regimes. This material allows engineers to increase the slurry's weight, ensuring optimal performance and preventing issues, such as formation fracturing or fluid influx. The cement setting process is controlled using accelerators and retarders. These chemical agents enable engineers to adjust the cement's setting time, accommodating variations in well depth, temperature, and other environmental factors that can significantly impact the curing process.

Furthermore, a range of specialized additives is employed to modify key properties of the cement slurry. Extenders and dispersants alter the density and viscosity, allowing precise control over the slurry's flow characteristics. Fluid loss agents are critical in controlling the aqueous phase's leakage and maintaining the cement's integrity during placement. In addition, defoamers are incorporated to prevent foam formation, which could otherwise compromise the cement's strength and uniformity (Kremieniewski, 2020). This sophisticated approach to cement slurry composition underscores the intricate balance required to produce a high-performance cement system capable of withstanding the extreme conditions encountered in oil and gas wells.

Recent advancements in oil-well cementing technology have emphasized the critical importance of optimizing cement formulations through rigorous laboratory experimentation (Calvert & Smith, 1990). This methodical approach is crucial for enhancing the cement's key properties and ensuring its performance under the harsh conditions encountered in downhole environments. Innovative research has delved into the intricate effects of diverse materials on cement characteristics, aiming to develop formulations that exhibit superior strength, durability, and adaptability to varied well conditions. These investigations have paved the way for innovative cement compositions that can withstand extreme temperatures, pressures, and chemical environments, contributing to improved well integrity and longevity. Among these materials, kaolinite, a naturally occurring clay mineral, has emerged as a promising candidate due to its unique physical and chemical properties (Adjei et al., 2022).

With the chemical formula $Al_2Si_2O_5(OH)_4$, Kaolinite belongs to the kaolin group of minerals and is one of Earth's most abundant clay minerals. It is formed through the weathering of aluminum silicate rocks such as feldspar and has found widespread applications across various industries, including ceramics, paper, rubber, and paints. In recent years, kaolinite has gained considerable attention as an additive in oil well cement due to its favorable properties, such as low shrinkage, high thermal stability, and a high surface area, which enhances its reactivity (Alujas et al., 2015; Hollanders et al., 2016; Kunther et al., 2017).

Based on previous studies conducted in the field of construction, when kaolinite is utilized as an additive for cement slurry, it serves as a favorable factor in enhancing both peat sedimentation and shear strength (Kazemian, 2015; Kazemian et al., 2011, 2013). The presence of kaolinite significantly impacts the rheological attributes and the progressive strengthening in limestone calcined clay cement (Scrivener et al., 2018). Harnessing both kaolin and metakaolin as supplementary cementitious components presents a prospective solution for mitigating the challenges linked to cement consumption pressures, concurrently bolstering the holistic performance of concrete (Borg et al., 2018; Fan et al., 2014; Hamzaoui et al., 2019; Mitrovic et al., 2009; Taylor-Lange et al., 2015).

This research aims to provide valuable insights into using kaolinite as an additive to oil well cement, focusing on its influence on cement performance, microstructure, and durability. The findings from this study could have significant implications for the oil and gas industry, leading to the development of more resilient and efficient cement formulations for oil well construction.

2 Materials and Methods

2.1 Materials

This study primarily employed Saudi Class G cement and Qusaiba kaolinite, supplemented by several additives. These additives were used to enhance the performance of the oil well cement, ensuring its suitability for a range of wellbore conditions; in addition, hematite was used to increase the weight of the cement and make it applicable for high-pressure, high-temperature applications. Qusaiba kaolinite was obtained as a raw material from Saudi Arabia. Saudi Class G and other additives were obtained from a local service company. In addition, deionized water was used in the experiments for making the cement slurries.

Qusaiba kaolinite was obtained from the Silurian age Qusaiba Member of the Qalibah Formation. This member is in the Qassim Region, central Saudi Arabia (Fig. 1). Its exposed thickness is approximately 30m. It is characterized by gray-to-green color mudstones with some rare mica-rich sandstone alternation towards the top of the section. It is conformably overlined by the sand-rich Sharawra Member of the same Formation and locally erosively overlined by the Tawil Formation. The base of the Qusaiba Member is not exposed in the Qassim Region (also informally known as the hot shale).

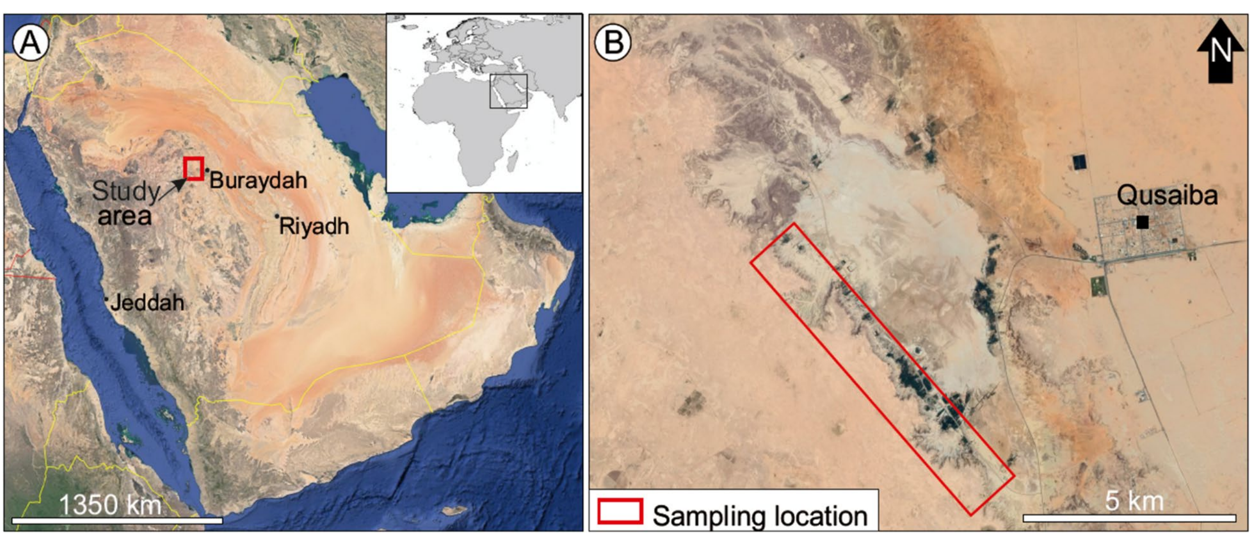

Fig. 1 Study area map **A** and sample location **B** of Saudi kaolinite in the Qassim region

2.2 Characterization

The elemental makeup of Saudi Class G cement, Qusaiba kaolinite, and hematite was analyzed using X-ray Fluorescence (XRF) techniques. According to Table 1, XRF results reveal the primary elements in the kaolinite, cement, and hematite. The results indicate that cement predominantly comprises calcium, accounting for 73% of its content, with silicon and iron making up 11% and 7%, respectively. This analysis helps understand the elemental distribution within these materials, which is crucial for their application in various industrial processes.

Table 1 XRF analysis of Saudi Class G cement, Qusaiba kaolinite, and hematite, %

Element	Cement	Kaolinite	Hematite
Al	2.2	45.6	0.7
Si	10.6	45.0	0.4
Mg	1.4	5.3	0.0
Fe	6.9	2.2	95.6
K	0.8	1.7	0.1
Ca	72.7	0.1	0.0
S	4.8	0.1	0.0
Cl	0.0	0.0	0.2
Ti	0.3	0.0	0.0
Rh	0.0	0.0	2.8

The kaolinite contains mainly aluminum (Al = 47%) and silicon (Si = 45%), while the hematite is totally iron (Fe = 97%). Because of the high calcium concentration in cement, the elements in kaolinite (aluminum and silicon) will cause a pozzolanic reaction. Calcium silicate hydrates (CSH) are formed during the hydration process from a reaction between silicon and calcium ions; these CSH have the potential to increase the compressive and tensile strength of the cement (Amin et al., 2020; Donelien et al., 2016). In this case, aluminum enters the cement's CSH unrestrictedly, and its replacement extensively impacts the cement's chemical performance across various characteristics (Brough et al., 2001; Hong & Glasser, 2002; Richardson, 1999; Schneider et al., 2001).

The particle size distribution (PSD) of kaolinite, cement, and hematite was measured to find their average particle sizes, as presented in Fig. 2. The data from this figure reveal that the average particle size (D_{50}) of kaolinite is notably small, with fine particles, less than 3.6 µm. At the same time, the D_{50} of the cement and hematite are greater than kaolinite (12.2 and 9.4 µm, respectively). These very fine kaolinite particles can reduce the cement specimens' petrophysical properties by filling the pore spaces and minimizing the particles' settling.

The material was deeply investigated to determine its main components by quantitative evaluation of materials scanning (QEMscan), as presented in Fig. 3. The

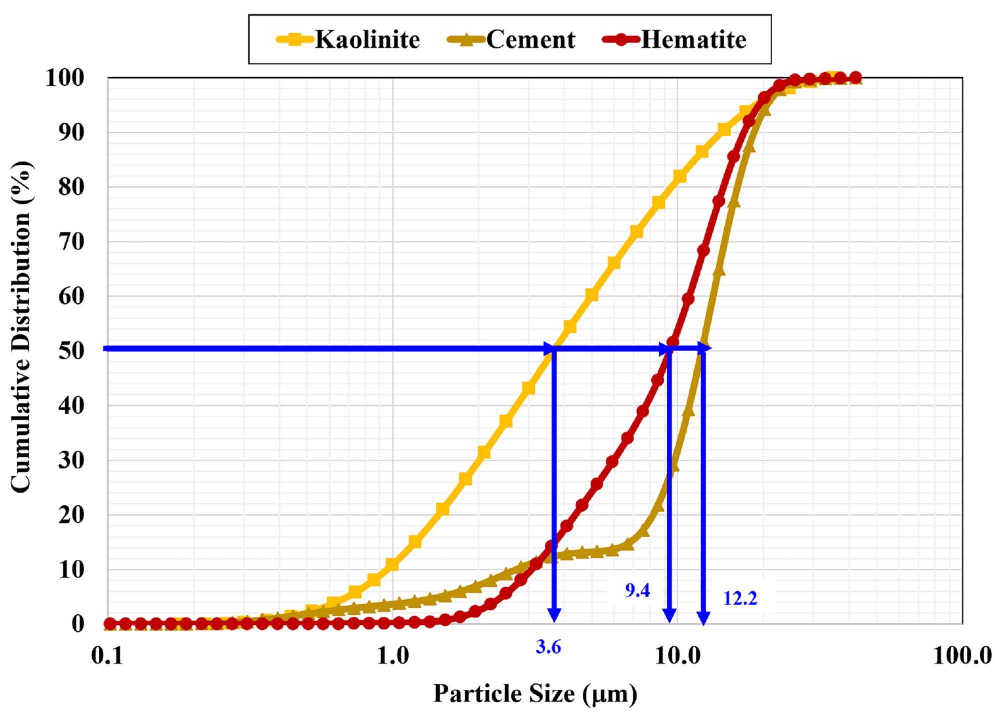

Fig. 2 Results of PSD for cement, Qusaiba kaolinite, and hematite

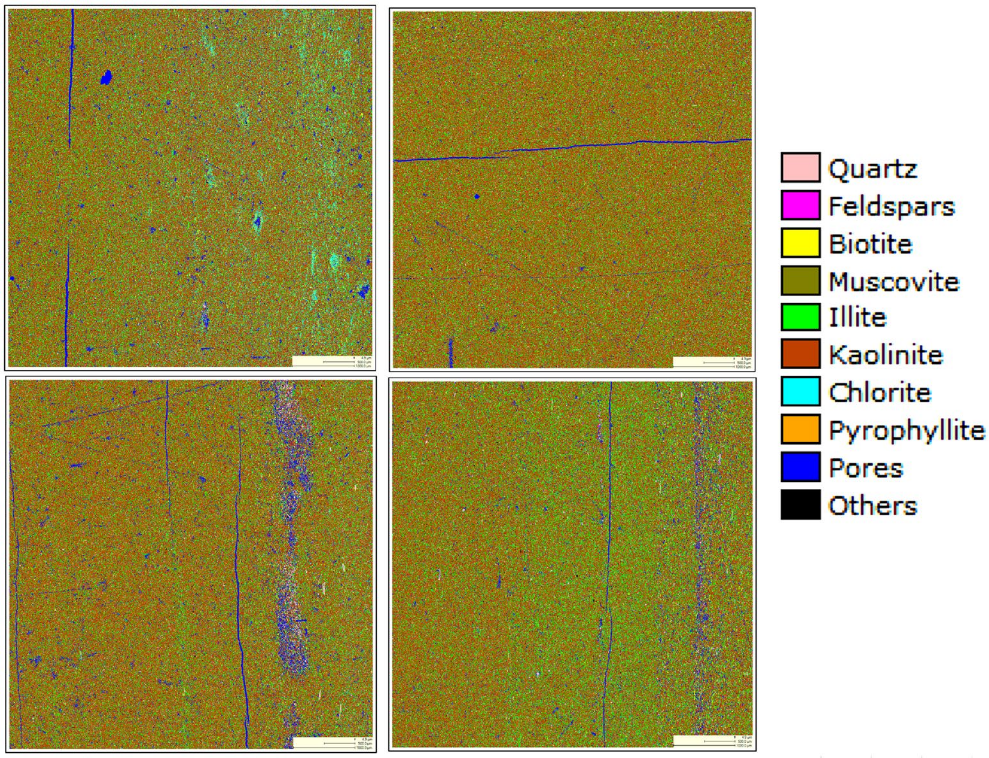

Fig. 3 QEMScan results of kaolinite

results indicate that kaolinite represents approximately 61% of the rock samples. In contrast, illite and quartz represent around 27% and 6%, respectively.

2.3 Slurries Preparation

Several cement samples were formulated following the API's standard (API, 1997). The constituents of the cement mixtures are summarized in Table 2. The only

Table 2 Compositions of cement slurries (%BWOC)

Components	Base Cement	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Cement	100	100	100	100	100	100
Silica Flour	35	35	35	35	35	35
Hematite	32.9	32.9	32.9	32.9	32.9	32.9
Water	44	44	44	44	44	44
Defoamer	5×10^{-3}	5×10^{-3}	5×10^{-3}	5×10^{-3}	5×10^{-3}	5×10^{-3}
Fluid Loss Controller	0.5	0.5	0.5	0.5	0.5	0.5
Dispersant	0.25	0.25	0.25	0.25	0.25	0.25
Retarder	0.5	0.5	0.5	0.5	0.5	0.5
Kaolinite	0	0.25	0.50	1.00	2.00	4.00

inconstant between the specimens is the percentage of kaolinite. In other words, all cement mixtures have the same components, but the amount of kaolinite varies. Six cement slurries with kaolinite range from 0 to 4% by weight of cement (BWOC) were formulated as indicated in Table 2. The first sample has no kaolinite (base sample), the second sample has 0.25% BWOC of kaolinite, the third sample has 0.5% BWOC of kaolinite, the fourth, fifth and sixth samples have 1%, 2% and 4% BWOC kaolinite, respectively. The hematite was used as a weighting material for all slurries to obtain a highly dense cement slurry of 18 lb/gal.

For the mixing, the cement, silica flour, and hematite were thoroughly mixed as a dry mix before any fluids were introduced. Then, water was poured into the mixing blender, which was operated at 4000 rpm. Defoamer was added first to the water, followed by fluid loss agents, dispersant, retarder, and kaolinite. The dry mix was then gradually added. After that, the cement slurries were poured inside a digital atmospheric consistometer to condition the slurries at a temperature of 194 °F for 30 min. Then, the samples were ready to prepare the required samples with the required dimensions.

After conditioning, the slurries were placed inside different molds of different dimensions to prepare the cement samples for the measurements of the evaluated properties in this study, such as strength, elasticity, cement segregation, permeability, and microstructures. The dimensions of the molds vary based on the test to which the sample will be subjected. The samples were prepared for compressive strength testing with cubical molds of 2×2×2 inches. For preparing the samples for the other tests, cylindrical molds of 4 and 1.5 inches in length and diameter were used. Then, the cement specimens were subjected to curing in a high-pressure, high-temperature (HPHT) curing chamber, maintained at 294°F and 3000 psi, for 24 h.

2.4 Properties Evaluation

2.4.1 Measurement of Strength Properties

To evaluate the impact of kaolinite on cement strength, two types of strength tests were conducted on every cement specimen: compressive and tensile strength. Compressive strength was assessed by crushing cubic samples of 2 inches edges using a crushing machine, following the ASTM standard (ASTM, 2020) explained by Chang et al. (2022). While, cylindrical specimens with a length of approximately 0.75 inches and a diameter of 1.5 inches were subjected to tensile strength testing following ASTM guidelines using the same crushing machine (ASTM, 2016). These strength properties are important to prevent cracks as these cracks can appear on the cement paste with stress exceeding the tensile or compressive strength of the cement.

2.4.2 Measurement of Elastic Properties

The cement specimens' elastic properties, specifically Young's modulus and Poisson's ratio, were measured by the scratch machine utilizing the whole cylindrical cement specimens. The measurement process involved measuring the ultrasonic velocities of shear and compressional waves. Young's modulus and Poisson's ratio were calculated by determining the time these waves traveled between probes.

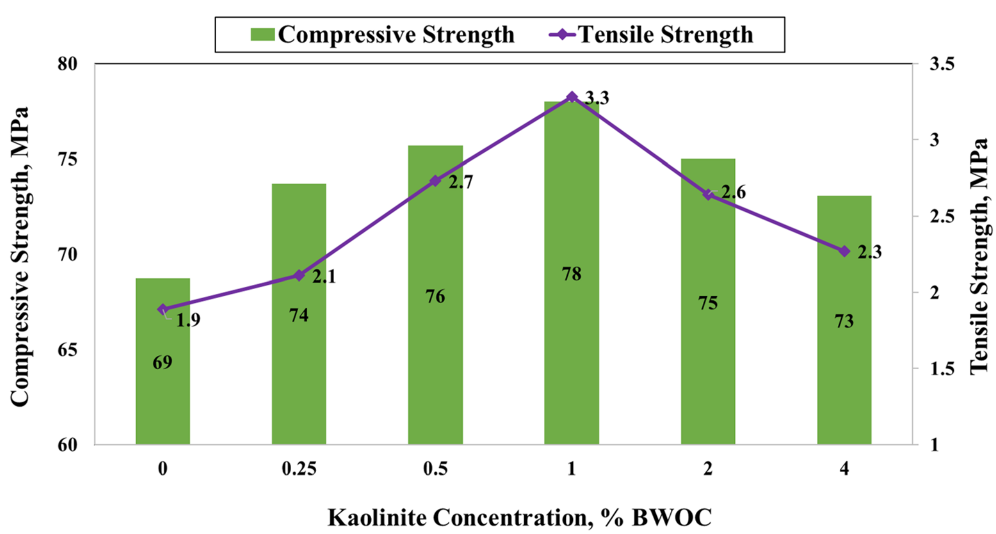

Fig. 4 Effect of kaolinite on the strength of the cement specimens

2.4.3 Measurement of Cement Segregation

A common challenge with heavy-weight cement is the variation in density across the cement length, leading to a denser bottom section than the top. This issue arises due to the settling of weighting agents like hematite. Two methods were employed to assess the density variation in this study: the direct density variation method and computerized tomography (CT) scanning.

Cylindrical cement specimens containing varying amounts of kaolinite (0%, 0.25%, 0.5%, 1%, 2%, and 4% BWOC) were segmented into three segments to represent every sample's bottom, middle, and top portions. Each segment was uniformly sized, with a diameter of 1.5 inches and a length of 0.5 inches, to ensure a fair comparison. The density of every section was calculated by dividing its weight by volume. This involved calculating the weight-to-volume ratio for each part. Subsequently, the density variation along the specimen was assessed by comparing the density of the top section to that of the bottom section. This comparison was made by calculating the ratio of the difference in density between the top and bottom sections to the density of the bottom section.

Six cylindrical samples, each corresponding to a different cement formulation, were examined using a medical CT scan to assess density variations. The CT scan employed imaging techniques to measure the density directly, with scans taken at intervals of approximately 1.2 mm and a voxel resolution of 1 mm.

2.4.4 Measurement of Permeability

Permeability is one of the most essential petrophysical characteristics of the cement matrix. 0.7-inch cylindrical cement specimens representing all six formulations under study were utilized to measure permeability. The permeability was determined using nitrogen gas under a confining pressure of 1000 psi, adhering to the principles of the Hagen–Poiseuille law. This process followed the methodology outlined by Sanjuán and Muñoz-Martialay (1995).

2.4.5 Microstructural Analysis

Scanning electron microscopy (SEM) was applied to analyze the impact of kaolinite on the changes in the microstructure of the studied specimens incorporating 0.5%, 1.0%, and 2.0%BWOC kaolinite.

3 Results and Discussion

This section examines how adding kaolinite affects various properties of oil well cement, including strength, elasticity, cement segregation, permeability, and microstructures.

3.1 Influence of Kaolinite on the Strength Properties

The strength of the cement sheath is a crucial property in the design of cementing operations. This study analyzed cement samples' compressive and tensile strength with different kaolinite concentrations. Compressive strength refers to the maximum force that the cement sheath can endure before it fails, whereas tensile strength denotes the maximum tensile force the cement can withstand without breaking (Xiao et al., 2022).

The effect of adding kaolinite on the cement's compressive and tensile strengths can be seen in Fig. 4. The results show that adding kaolinite increased the compressive strength. It is observed that the compressive strength increased with the increment of kaolinite in

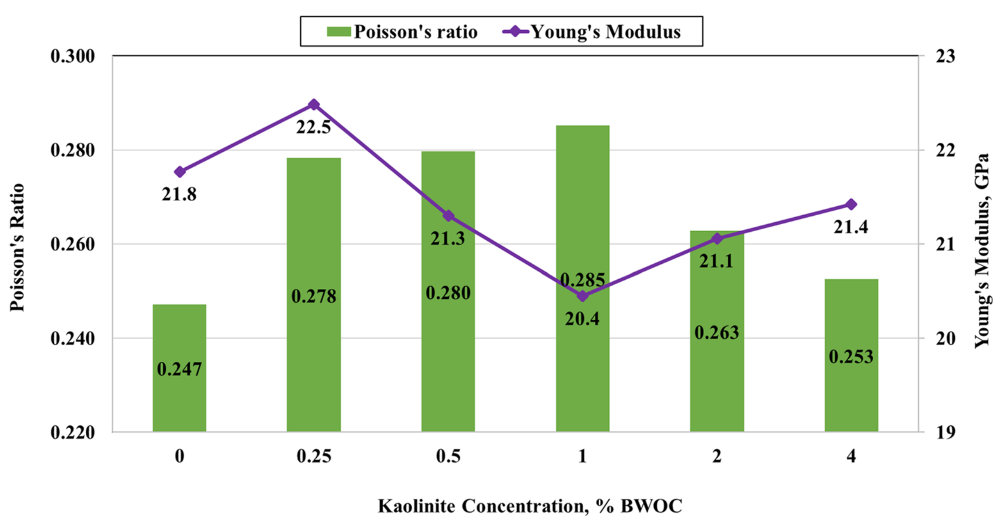

Fig. 5 Effect of kaolinite on the Poisson's ratio and Young's modulus of the cement samples

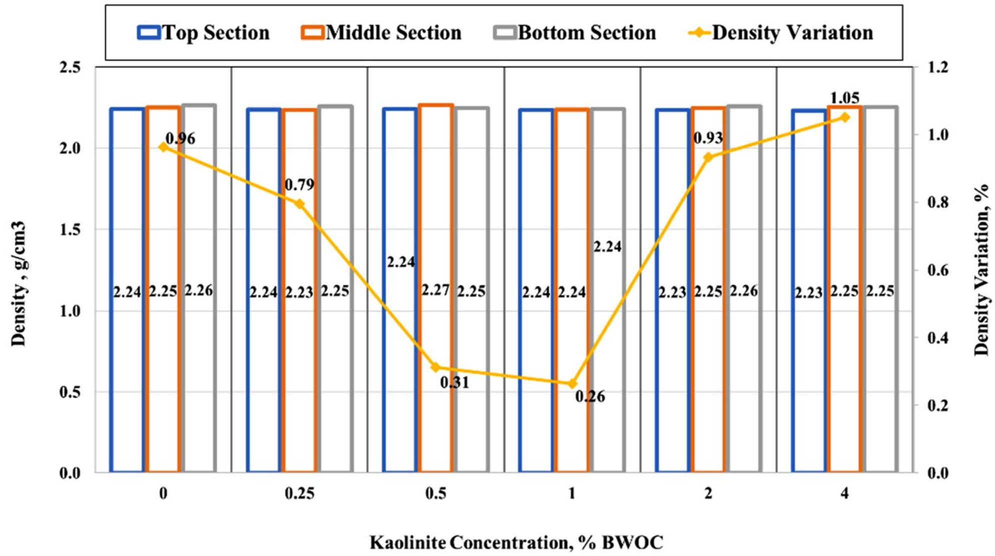

Fig. 6 Effect of kaolinite on cement segregation

the slurry. Increasing the kaolinite increased the compressive strength until it reached its optimum value and decreased. For example, the compressive strength of the control cement sample (with 0% kaolinite) was 69 MPa. Using 0.25% BWOC of kaolinite increased the compressive strength by 7.25% compared to the base cement sample to reach 74 MPa. The compressive strength continued increasing when more kaolinite was added to reach its maximum strength of 78 MPa at 1% kaolinite, with an increase of 13% compared to the sample without kaolinite. The compressive strength decreased to 75 and 73 MPa when 2% and 4% BWOC of kaolinite were utilized, respectively. The cement's ability to withstand greater compressive forces will help to prevent it from collapsing or cracking, which could damage the casing and wellbore.

Tensile strength changes followed a trend similar to that of compressive strength. Fig. 4 shows that the increase in kaolinite concentration results in an increase in cement's tensile strength. For example, the base specimen had a tensile strength of 1.9 MPa. In the 0.25% and 0.5% BWOC of kaolinite samples, tensile strength increased by approximately 10.5% and 42.1% to be 2.1 and 2.7 MPa, correspondingly. The tensile strength continued its increase to 3.3 MPa when 1% BWOC of kaolinite was incorporated. Then, the tensile strength began to drop to 2.6 and 2.3 MPa when the kaolinite percentage increased to 2% and 4% BWOC, respectively. Notably, the highest tensile strength was achieved using a 1% BWOC of kaolinite, with an increase of 73.7% compared to the control cement. The stronger cement will be better able to carry the weight of the casing, which is especially important in deviated sections of the well, where the cement is under greater load.

The main reason for this increase in compressive and tensile strength is that kaolinite is considered a source of pozzolanic material. This means that it reacts with the calcium hydroxide ($Ca(OH)_2$) that is formed during the hydration process of cement, forming additional calcium silicate hydrate (C–S–H) gel, which can increase the overall strength and durability of the cement. When higher kaolinite concentrations were used (i.e., 2% and 4% BWOC), the strengths were reduced due to the weight of particles agglomeration of kaolinite.

3.2 Influence of Kaolinite on the Elastic Properties

The cement sheath's elastic properties significantly influence the wellbore's integrity. The flexible cement sheath with a high Poisson's ratio and a low Young's modulus is believed to maintain the wellbore integrity over the long term. Fig. 5 shows the impact of adding kaolinite on Poisson's ratio. The figure explains that the increase in the concentration of kaolinite increased the Poisson's ratio to its maximum value and then decreased. For example, the control cement specimen had Poisson's ratio of 0.247 and then increased by 12.6% for the 0.25% BWOC kaolinite sample. For the samples of 0.5% and 1% BWOC kaolinite, Poisson's ratio increased to 0.280 and 0.285. Then, the 2% BWOC of kaolinite showed a sharp reduction to 0.263. Poisson's ratio decreased to 0.253 at 4% BWOC kaolinite sample. It is noted that the highest Poisson's ratio was found at a kaolinite concentration of 1% BWOC, with an increase of 15.8% compared to the base cement. The rise in Poisson's ratio indicates that the kaolinite-based

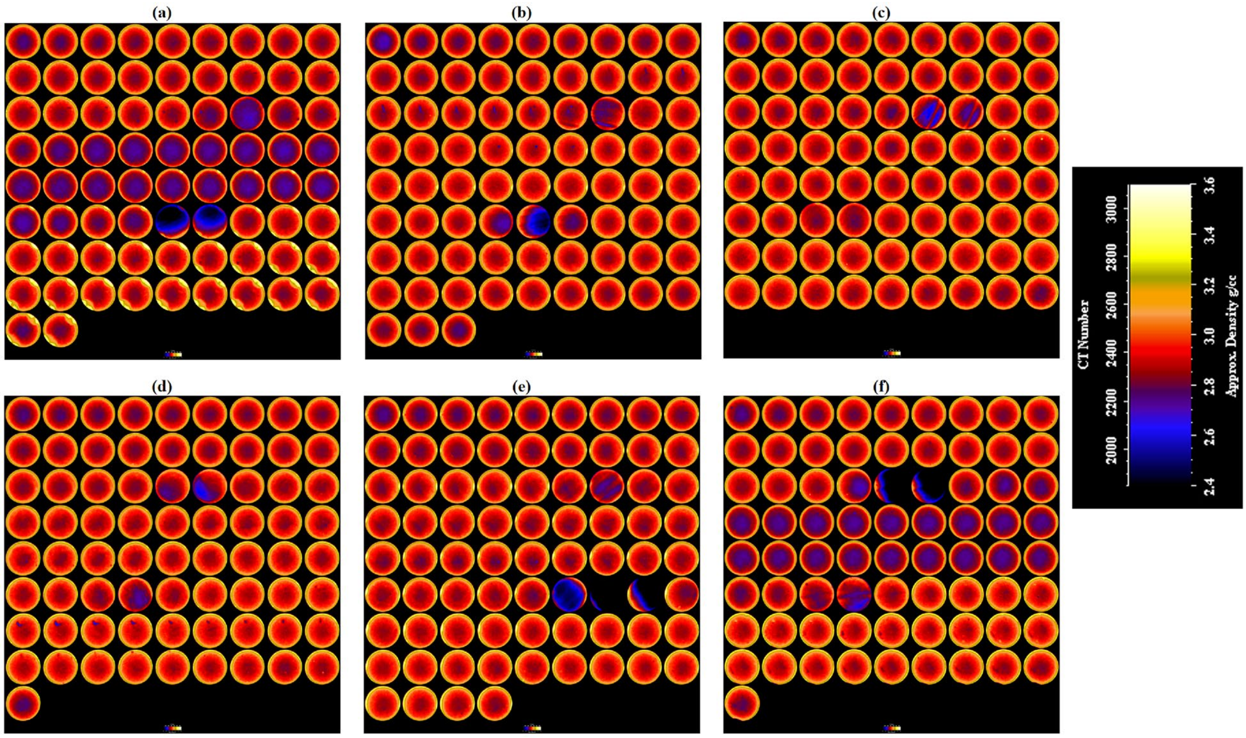

Fig. 7 CT scan images for kaolinite dosages at **a** 0%, **b** 0.25%, **c** 0.5%, **d** 1%, **e** 2%, and **f** 4%

cement was less likely to compress, allowing it to expand more easily around the casing.

Fig. 5 shows the influence of different dosages of kaolinite on the Young's modulus of the cement samples. It can be seen that the five used concentrations of kaolinite had lower Young's modulus than the control cement sample (0% kaolinite). As the kaolinite is added to the cement mixture, Young's modulus increases from 21.8 GPa for the base cement to 22.5 GPa for the 0.25% BOWC kaolinite. The addition of more concentration of kaolinite (i.e., 0.5% and 1% BWOC) decreased Young's modulus by 2.3% and 6.4%, respectively, compared to the base cement. Then, the Young's modulus increased to 21.1 and 21.4 GPa when 2% and 4% BWOC kaolinite were used. It is noteworthy that adding 1% BWOC of kaolinite decreased Young's modulus to its minimum value of 20.4 GPa, which is a reduction of 6.4% compared to the cement specimen with no kaolinite. It is advisable to have a lower Young's modulus to create a more stable cement sheath when subjected to shear deformation. This lower modulus helps the cement better absorb and adapt to the stresses without cracking or failing, enhancing the overall stability and durability of the cement structure. Young's modulus can be influenced by several aspects, such as cement's moisture amount, strength, density, and aggregate volume percentage (Jurowski & Grzeszczyk, 2015).

Because kaolinite has a higher value of Poisson's ratio and a lower value of Young's modulus at 1% BWOC, the cement matrix becomes more flexible and capable of withstanding heavy stresses throughout the well's lifetime. When higher kaolinite concentrations were used (i.e., 2% and 4% BWOC), the Poisson's ratio was reduced, and Young's modulus was increased due to the weight of particles agglomeration of kaolinite.

3.3 Influence of Kaolinite on Cement Segregation Through Direct Measurement

Cement segregation poses a significant issue during cementing operations, as it can compromise the wellbore's durability. Heavier components tend to migrate towards the lower part of the mixture due to their high density, leaving lighter particles at the top. Fig. 6 illustrates the results from the direct method used to measure density variation across each cement sample, indicating densities at the top, middle, and bottom portions. In the base case with no kaolinite, density variation was notably high. However, with the introduction of kaolinite, the density variation initially reduced to its lowest value before increasing again. For example, the control cement specimen showed a density variation of 0.96%, with densities of 2.24 g/cm^3 at the top, 2.25 g/cm^3 in the middle, and 2.26 g/cm^3 at the bottom. Adding 0.25% BWOC of

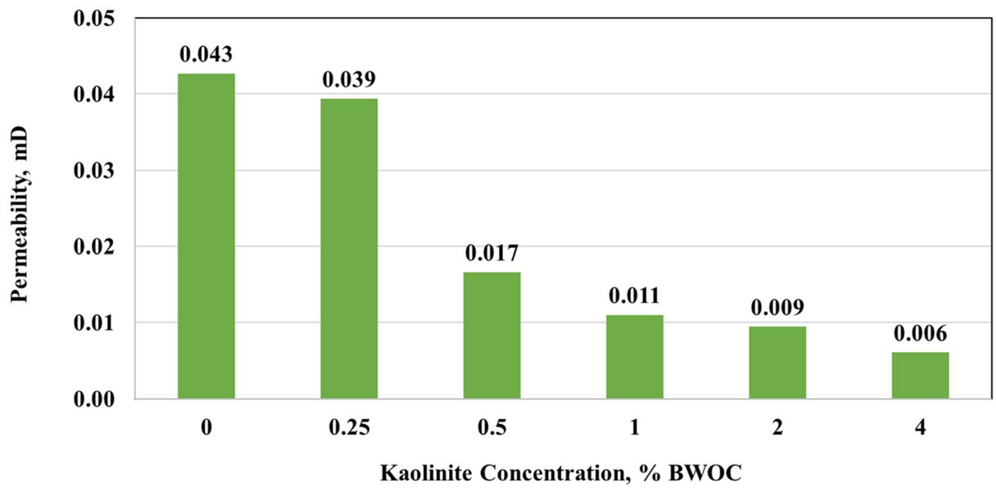

Fig. 8 Effect of kaolinite on the permeability of the cement specimens

kaolinite reduced the density variation to 0.79%, with section densities of 2.24, 2.23, and 2.25 g/cm^3, respectively. Further incorporation of 0.5% BWOC of kaolinite resulted in a density variation decrease to 0.31%. The cement sample of 1% kaolinite was the optimum as it provides the lowest density deviation of 0.26%, represented by almost the same density in the three sections of 2.24 g/cm^3. Nevertheless, by increasing the concentration of kaolinite to 2% and 4%, BWOC increased the density variation to 0.93% and 1.05%, correspondingly. The cement sample of 4% BWOC of kaolinite had the highest density variation of 1.05% with top, middle, and bottom densities of 2.23, 2.25, and 2.25 g/cm^3, respectively. This is due to the weight of particles agglomeration of kaolinite, where they began to settle, and the density variation increased.

From the results of density variation, it can be found that kaolinite reduced segregation in the oil well cement. This might be because kaolinite has a large surface area and high surface area to volume ratio, which means it can absorb water and other fluids. This helps to keep the water content of the cement consistent, which can also help to reduce particle settling. When kaolinite is added to cement, its particles can interlock and form a network, which helps to prevent the movement of larger cement particles during the mixing and placement of cement.

3.4 Influence of Kaolinite on Cement Segregation Through CT Scan

Computed tomography (CT) scans were used to evaluate the density changes in the prepared cement specimens. The CT scan images can be used to visualize cement segregation. The different colors represent different densities, with blue representing low density, red representing medium density, and yellow representing high density. The appearance of multiple colors in an image indicates a significant change in density, while fewer colors indicate a slight density variation. CT scan results emphasized the results of the direct measurement in which the control cement specimen had a high tendency of cement segregation and using kaolinite minimized the segregation problem, as shown in Fig. 7. It can be seen in Fig. 7 that the largest difference in density is across the column of the control cement sample and the 4% BWOC kaolinite sample, as represented by considerable color changes in Fig. 7a, f, respectively. Fig. 7c, d validates that 0.5% and 1% BWOC of kaolinite concentration showed almost no color changes, which means they could reduce the density distribution to the minimum. They showed a more homogeneous cement with fewer color changes than the base cement. As the concentration of kaolinite increased, the cement segregation was minimized to its lower value at 1% BWOC of kaolinite. Then the cement segregation increased as more amount of kaolinite was added.

3.5 Influence of Kaolinite on the Permeability

Permeability is an extremely important factor of the cement's petrophysical properties to guarantee the wellbore's durability throughout the production period. They play an important part in preventing fluids from migrating behind the casing (Ridha et al., 2014). The evaluation of these properties in cement sheaths is, therefore, essential because failing to do so may result in the need for secondary cementing, which will result in additional expenses for the companies and, in the worst-case scenario, may cause damage to the wells. The current investigation analyzed the cement permeability to determine how different kaolinite concentrations affected each

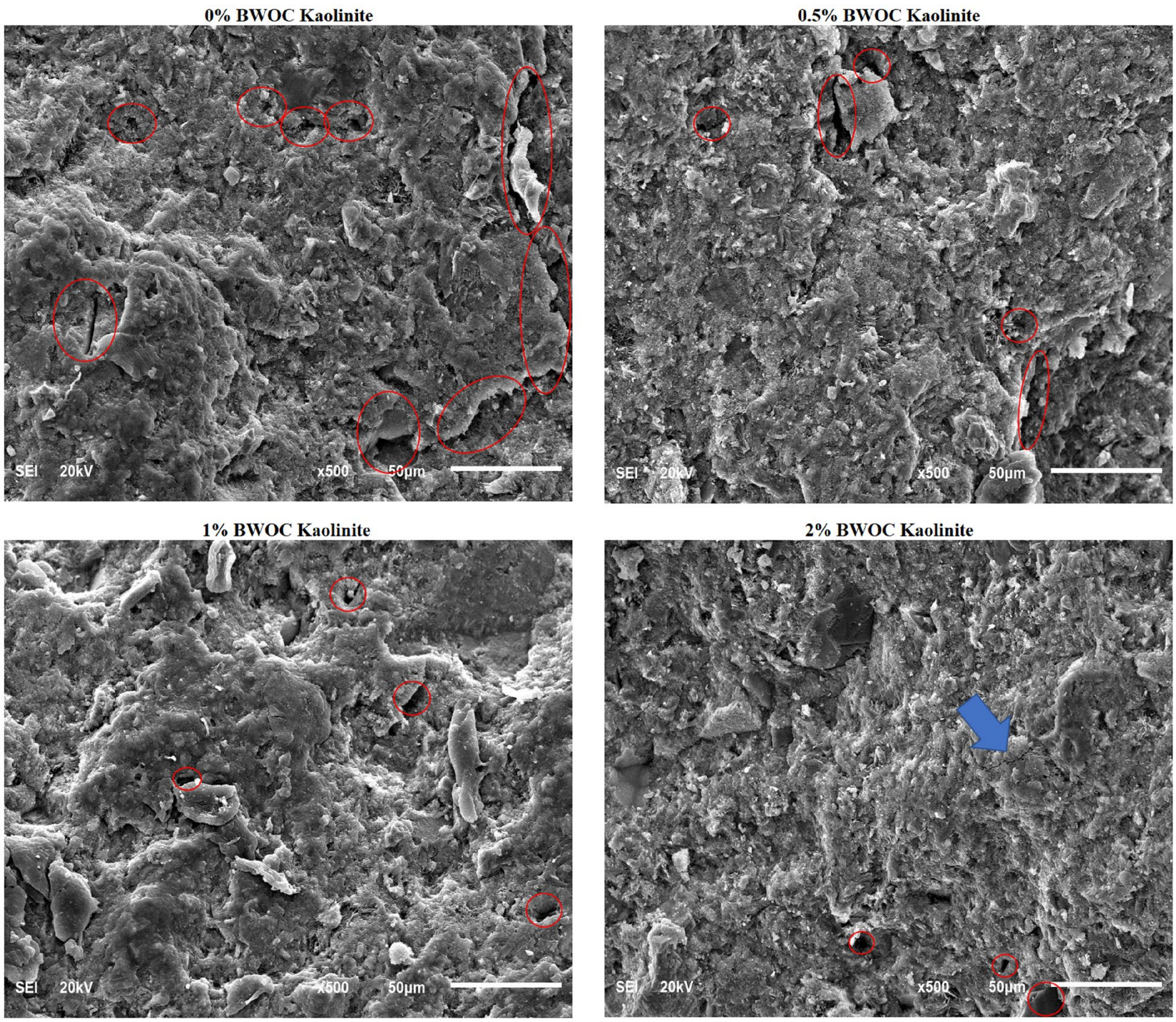

Fig. 9 SEM images showing the microstructure of the cement samples. The red circles determine the presence of the void spaces

variable. Fig. 8 shows the permeability change with the increased kaolinite amount in the slurry.

It can be observed that adding kaolinite up to a concentration of 4% BWOC reduced the permeability of cement. The base sample had an initial permeability of 0.043 mD. Then, the permeability was gradually decreased to 0.039 mD when 0.25% BWOC of kaolinite was added to the cement. Including 0.5% BWOC of kaolinite resulted in a sharp decrease in the permeability by 60.5% compared to the specimen with no kaolinite. Moreover, a further increase in the kaolinite concentration gradually decreased the permeability. For example, the cement samples of 1%, 2%, and 4% BWOC of kaolinite had permeability 74.4%, 79.1%, and 86.1% less than the control sample, respectively.

The decreased permeability of the cement matrix will make it more difficult for fluids to flow through the cement, which can help prevent fluid migration between different zones in the wellbore. This decrease in permeability is due to the very fine particles of kaolinite, which can fill in the gaps between the cement particles, form a more compact structure, and reduce the amount of space available for fluid to penetrate.

3.6 Influence of Kaolinite on the Microstructure of the Cement

Microstructural analysis was performed to identify the hydration products of various slurries to understand the strength and petrophysical results better. The final values in terms of strength and petrophysical properties are affected by the hydration products and the structures they take (Bu et al., 2016). Different curing temperatures produce different cement hydration products. Scanning electron microscopy (SEM) analysis was carried out by gold plating the unexposed surface of cement samples that had been cured for 24 h at 290°F before being fractured to reveal the underlying surface.

Fig. 9 shows how kaolinite influences the microstructure of the hardened cement samples. It can be seen that the base sample (0% BWOC) had many large void spaces, as specified by the dark spaces (red circle). However, the cement samples with kaolinite had fewer small pore spaces. As the concentration of kaolinite increased (0.5%, 1%, and 2% BWOC), void spaces were decreased, as indicated by the red circles. This shows the ability of kaolinite to fill the pores, which confirms the permeability reduction with the increase of kaolinite concentrations and validates the increase of both strengths with the rise of kaolinite. However, the 2% BWOC of the kaolinite cement specimen had some microcracks indicated by a blue arrow, which could explain its compressive and tensile strength reduction.

4 Conclusion

This work investigates the ability to use kaolinite as an oil well cement additive. Characterizations of the kaolinite particles were performed by X-ray fluorescence, quantitative evaluation of materials scanning, and particle size analyzer. Various concentrations of kaolinite were examined to select the optimum concentrations, and it was found that 1% BWOC of Kaolinite was the optimum concentration to be used. Moreover, adding kaolinite particles to the oil well cement showed promising results in enhancing the cement properties, as summarized below:

1. Incorporating kaolinite particles increased the strength properties of the cement by increasing the compressive strength and tensile strength by 13% and 73%, respectively.
2. Adding kaolinite to the cement enhanced the elastic properties of the cement by causing a minor increase in Poisson's ratio from 0.247 to 0.285 and reducing Young's modulus by 6.4% compared to the base cement with no kaolinite.
3. Using kaolinite in the cement slurry minimized the problem of cement segregation due to the heavy-weight material (hematite) to a minimum value of 0.26% compared to 1% in the base sample with zero % kaolinite).
4. CT scan images confirmed the kaolinite's ability to minimize the cement segregation by showing a uniform density along the column of the kaolinite cement sample.
5. The kaolinite could fill the pores, which was reflected by the reduced permeability with increased kaolinite concentration.
6. SEM images showed many large void spaces in the base cement sample and few small void spaces in the kaolinite-based cement samples, confirming kaolinite's capability to fill the pores, increasing the strengths and decreasing the permeability.

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Author contributions
AA: methodology, formal analysis, visualization, writing—original draft, and writing—review and editing; AM: visualization, validation, investigation, review and editing; SE: conceptualization, investigation, supervision; DA: supervision, and project administration; KA: resources, and review and editing.

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Availability of Data and Materials
All the data sets associated with this study are available from the corresponding author upon request.

Declarations

Ethics Approval and Consent to Participate
All authors of the manuscript confirm the ethics approval and consent to participate following the Journal's policies.

Consent for Publication
All authors of the manuscript agree on the publication of this work in the International Journal of Concrete Structures and Materials.

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