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Application of a Synthetic Polymer Nanocomposite Latex in a Wellbore Cement Slurry for Gas Blockage Functions

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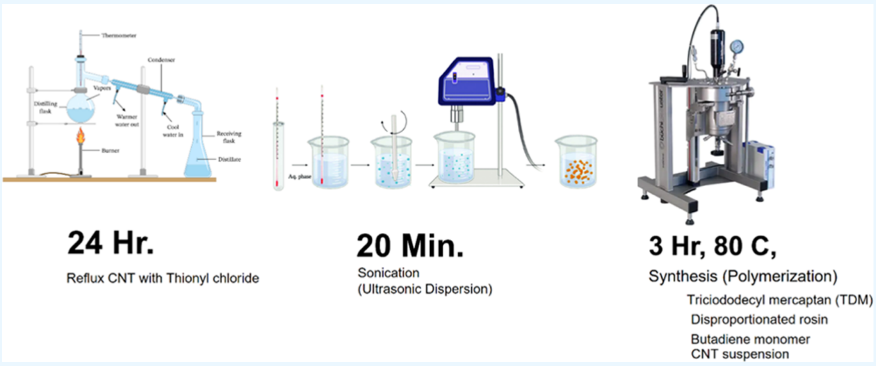

ABSTRACT: Commercial synthetic polymers are a professional approach to creating versatile new materials with high-performance classes. This research focuses on controlling gas migration within cement in the early stages of cement setting through a newly synthesized butadiene−carbon nanotube (CNT) polymer nanocomposite latex. The optimized cement in these experiments exhibits the inherited combination behavior from the flexible characteristics of the polymer matrix and the mechanical features from the carbon nanotubes. The feedback of the superelastic behavior of carbon nanotubes is indicated by a 75% increase in the modulus of elasticity and a 48% increase in the flexural strength in cementitious samples reinforced with the polymer nanocomposite latex. The improvement of surface tension by the polymer latex in the slurry and enough tensile strength during cement hydration have positive control and compensatory effects in early shrinkage and resistance to the development of fissures and cracks in the hardening cement. Optimized cement slurries containing polymer nanocomposite additives dramatically reduce the critical transfer time window to about 40 min for gelatinized cement, thereby reducing the risk of gas migration during the mentioned critical period for the cement slurry.

1. INTRODUCTION

The structure of oil and gas wells is a reinforced set of protected steel casings with a surrounding strong cement sheath, which offers a durable channel for the safe and controlled extraction of hydrocarbon fluids.[1] Due to the exorbitant costs of wellbore construction, the practical implementation of the wellbore structure is planned with the prospect of long-term durability and sustainable production.[1] The excellent role of the cement sheath in isolating the wellbore from nonproductive subsurface layers and establishing an exclusive link between the wellbore and the target pay zone layer is a requirement for establishing sustainable production.[2] The failure of the cement sheath in performing its sealing job allows for unrestricted gas invasion, which might pose severe human and financial risks by increasing the possibility of gas migration to the surface.[3] Performing the sealing task of wellbore cement by considering the conditions of subsurface threats, implementation defects, and the poor placement of the cement slurry behind the steel casing space has been associated with many difficulties and challenges. The most critical aspect of implementing a successful cement program is to address the concerns raised about possible cement defects in the face of gas invasion and discuss gas migration control through the cement-filled annular space.[4]

Micro annulus passageways and microchannels produced in annular cement serve as gas invasion paths. The micro annulus is a very thin circular marginal area generated by the debonding of hardened cement from the steel sheath face or the formation wall in the wellbore annular space.[5,6] The micro annulus is a type of cement sheath inefficiency challenge that

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can occur in the medium or long term through various mechanisms. In the medium term, after cementing and hydration process of the cement in which the cement slurry becomes stiff, it undergoes a slight volumetric change due to the autogenous shrinkage of the cement texture, which is the inherent behavior of the cementitious material. This microscale change may create a debonded marginal space around the hardened cement block.[7] In the long term, intense tectonic interactions and salt rock creep phenomena due to differences in the capacities of elastic−plastic properties between rocks of different formations and cement provide the necessary potential for the development of debonding in the interfacial margins of annular cement.[5,8] In addition, development measures such as implementing EOR techniques, which are realized using mechanical interactions, might be considered a threat to the cement sheath bond's inefficiency. Pressure cycling in the hydraulic fracturing process applies excessive hydraulic pressure to the steel sheath accompanied by repeated shocks, and expansion−contraction to the casing wall is known as a serious debonding mechanism for the outer side of the casing cement.[9]

Microchannels are the connected heterogeneous network paths that form within the cementitious matrix or at the interface of cement casing or cement formation and provide potential conduits for gas migration through the hardened annular cement.[10] Microchannels can be formed due to the upward movement of natural gas bubbles within the gelatinized cement slurry in the annular space.[11] When the slurry is faced with a narrow-allowed density margin window, the movement of gas bubbles inside the cement gel (transition phase from the slurry state to the hardened cement) will be more likely. In the gelatinous cement phase, which is referred to as the transient region, the cement slurry becomes gelatinized and gradually loses the ability to transfer the weight of the overburdened hydrostatic column. By weakening the deterrent force of gas invasion into the cement, the gas bubbles will have the opportunity to enter the gelatinous cement. Extending the transient time frame for the cement slurry will allow gas bubbles to penetrate deeper into the cement texture and develop microchannel traces as they pass through it. Structural fissures and microcracks associated with autogenous shrinkage in cement texture are also among the most likely structural defects contributing significantly to interconnected microchannel networks' growth.[12]

Table 1 summarizes some research backgrounds on the use of chemicals to control gas migration through oil well cement.

Table 1. Summary of Research Conducted to Control Gas Migration into Well Cement

researchers	chemicals	mechanism
Rod et al.[13]	polymer	improve sealing performance: creates self-healing properties for adhesion to steel pipe walls
Todorovic et al.[14]	polymer resin	remediation of leakage through annular cement
Santos et al.[15]	expandable polymer	using an expandable polymer to improve zonal isolation
Bayanak et al.[16]	nanosilica (SiO_2)	optimizing particle size and improving the structural strength of the hardened cement mass
Murtaza et al.[17]	hybrid silicate system	application of a hybrid silicate system to strengthen well cement and control gas migration
Jafariesfad et al.[18]	nano MgO	utilizing the volumetric expansion properties of magnesium cement
Chen et al.[19]	magnesia	a comprehensive review on the use of magnesia to strengthen and expand wellbore cement
Alkhamis[20]	graphene nanoplatelets	prevent the destruction of cement in oil wells and the durability of the structure

Polymers are magical molecular structures that have become more efficient alternatives to their traditional materials due to their unique physical and chemical properties. The industrial application pervasiveness of the polymers has created an unrivaled position for them in engineering and industry. The application advent of polymers in construction cement and concrete dates back to about 1950 when cement and concrete met expectations beyond hardness and toughness.[21] Polymers mainly increase the tensile strength of hardened cement, so in most executive studies, the performance evidence related to strengthening tensile strength using various types of plastic polymers in cement has been reported.[22] Improving the adhesion of cement paste to different external surfaces and the incorporated reinforcing materials is an effective solution for the optimization of reinforced concrete, which has been achieved using polymer latexes.[23] The improvement of lubrication property and curing cement paste with polymer additives is also evident.[24] Extensive research has also been conducted to study the long-term stability of cement by increasing the chemical resistance to water of invasive solutions.[25] Commercially, polymers like carboxymethyl cellulose (CMC) are widely used in oil and gas wells for applications to improve the rheological properties and control the liquid phase filtration of the cement slurry.[26] Applications of polymeric materials as additives to improve the mechanical properties of wellbore cement have been the subject of many research projects.[27] Polymer latexes have also recently been evaluated as candidates for controlling gas migration by optimizing gelatinous properties and increasing the surface tension of molecular liquids in the cement slurry phase.[28]

A better understanding of how to use technology to maximize the effective reaction surface in materials has paved the path for the practical production of nanomaterials. The super performance of nanoparticles is much higher than similar traditional materials due to their higher reaction surface.[29] Benefiting from the unique properties of nanomaterials in applications related to the cement of oil and gas wells has attracted much attention. Silica nanoparticles have proven their effectiveness in enhancing compressive strength and reducing porosity in hardened cement, so the increase in the compressive strength of up to about 20% compared to benchmark samples has been seen in some reports.[17,30,31] Magnesium nanoparticles have shown significant performance in compensating for the intrinsic shrinkage of oil and gas well cement.[19,32] Carbon nanotubes, famous for their outstanding mechanical properties, have also been tested as reinforcing microstructures in wellbore construction cement. Extracting the potential mechanical properties of hydrophobic carbon nanotubes in aqueous substrates, especially cement and concrete, has been a fundamental challenge for researchers.[33] Realizing the maximum mechanical strength potential of carbon nanotubes, like other nanoparticles, really demands the uniform dispersion of nanostructures in the aqueous polar environment. Various techniques have been proposed for uniform dispersion of carbon nanotubes in aqueous substrates, the most effective of which include sonication with powerful ultrasonic waves,[34] functionalization with anionic groups,[35] emulsification by surfactants, and emulsion polymeriza-

Table 2. Cement Slurries' Formulation

slurry sample	water to cement ratio	poly(butadiene−CNT) latex (vol %)	fluid loss control (B.W.O.C)	dispersant additive (B.W.O.C)	retarder additive (B.W.O.C)
benchmark	0.41		0.65	0.89	0.08
PN-LTX-1	0.37	1	0.65	0.89	0.08
PN-LTX-2	0.37	2	0.65	0.89	0.08
PN-LTX-3	0.38	3	0.65	0.89	0.08
PN-LTX-4	0.38	4	0.65	0.89	0.08

tions.[35,36] Musso et al. adequately described the advantage of the factorization process for introducing carbon nanotubes to aqueous cement matrices and its final effect on the mechanical results of cement samples.[37] Their study examined how the functional groups attached to carbon nanotubes affect concrete reinforcement using raw (nonfunctional) carbon nanotubes and carboxylic acid-functionalized carbon nanotubes, respectively. Carbon nanotube coagulation in the aqueous paste of the concrete sample treated with raw carbon nanotubes resulted in a significant reduction in the compressive strength and rupture modulus, whereas the broader distribution of functionalized nanotubes in the concrete matrix resulted in an increase of ∼14% in the compressive strength and 7% in the rupture modulus.

The idea of using carbon nanotubes in wellbore cement was pursued in several investigations, where they were blended into the cement slurry as a dry additive, with no preprocessing or dispersion procedures. The findings given in these studies described the increase in compressive strength in hardened cement.[38] However, Santra et al. published a disappointing description of using unmodified carbon nanotube additives (at concentrations of 1 and 2 wt %) for cementing application in oil and gas wells. Their results included a 10 and 30% drop in compressive strength and tensile strength, respectively.[39]

Some research has focused on improving cement properties to control gas migration from annular cement. Abbas et al. introduced the hydroxypropyl methylcellulose polymer as an effective additive to reduce gas migration.[40] McDaniel et al. tested slurry samples with gypsum accelerator agents at different concentrations to reduce the thickening time and thinning of the transient time window to minimize gas migration in Marcellous shale play.[41] Velayati et al. used gas migration control and gelatin strength industrial additives to shorten slurry thickening time and found a considerable reduction in the gas migration rate using the fluid migration analyzer apparatus.[42] Elkatatny et al. employed a propylene fiber in oil well cement, which enhanced the tensile and compressive strength of hardened wellbore cement and shortened the slurry thickening time.[43] Bayanak et al. used silicon dioxide nanoparticles to reduce slurry thickening time without adversely affecting other cement properties.[44]

The material selection process was planned with in-depth insights into solutions that control gas migration mechanisms within the cement column. A butadiene superelastic polymer can provide a reasonable basis for improving the adhesion of internal cement components and increasing the internal tensile strength in hardened cement. Carbon nanotubes with proper distribution throughout the cement texture and the function of mechanical strength will contribute to the integrity of the cement mass by reducing the possibility of breaking cement bonds inside the matrix and at the external contact surface.

2. MATERIALS AND METHODS

2.1. Wellbore Cement Composition and Quality Testing Methods.

The main component of an oil wellbore cement slurry in this study is Portland cement grade G, which is employed without further processing during manufacturing. The common practical additives for oil well cement slurries such as a retarder, dispersant, and fluid loss control agent at the same concentration ratios were used to formulate all samples during slurry preparation to achieve more realistic findings. Mixing, molding, curing, and performance tests were performed on all cement slurry samples following the API-10B recommended practice.[45] All cement slurries are designed with a density of 120 PCF, and formulations of the slurries made are given in Table 2. The quality of the samples required for the tests is confirmed by selecting quality raw materials and following the practical method of performing the test and the standard devices described in the API-10B standard framework.

Mechanical tests of compressive strength were performed by uniaxial stress apparatus equipped with linear variable differential transformer (LVDT) sensors, and the flexural test was carried out utilizing the third point loading method to achieve cement specimens' flexural strength following ASTM C-78.[46] The beam specimens with dimensions of 15 cm × 15 cm × 55 cm were tested after 24 h. Mechanical tests on each sample were repeated to validate the results, and the statistical distribution of the data was 0.1 for the modulus of elasticity and 0.01 for the Poisson ratio and flexural strength.

Annular cement gas migration and the gel strength changes measurement during the transition time window were evaluated by the OFITE cement gas migration tester coupled with a static gel strength measurement (SGSM) apparatus.

2.2. Synthesis of a Butadiene−CNT Polymer Nanocomposite Latex.

A polymer latex with concentrations of 1, 2, 3, and 4 volume percentages (in the aqueous phase) consists of a butadiene monomer, and a carbon nanotube composite is synthesized. The dispersion process of carbon nanotubes in the aqueous phase is realized through anionic functionalization and sonication mechanisms. Through the mini-emulsion polymerization approach, the incorporative system of carbon nanotubes in the polymer matrix employs an emulsion dispersion mechanism. For this purpose, carboxylic acid-functionalized carbon nanotubes are refluxed for 24 h with a solution of thionyl chloride to replace the chlorine ion and create an anionic edge. The anionic repulsive force between the nanotubes greatly helps to disperse and prevent them from clotting in water. An ultrasonic homogenizer sonicated the resulting solution for 20 min. Noncontinuous polymerization of a butadiene emulsion and its combined synthesis with carbon nanotubes was performed in a cylindrical double-walled stainless steel reactor (Buchi pressure reactor) equipped with a heater and a U-shaped mechanical stirrer. In each test,

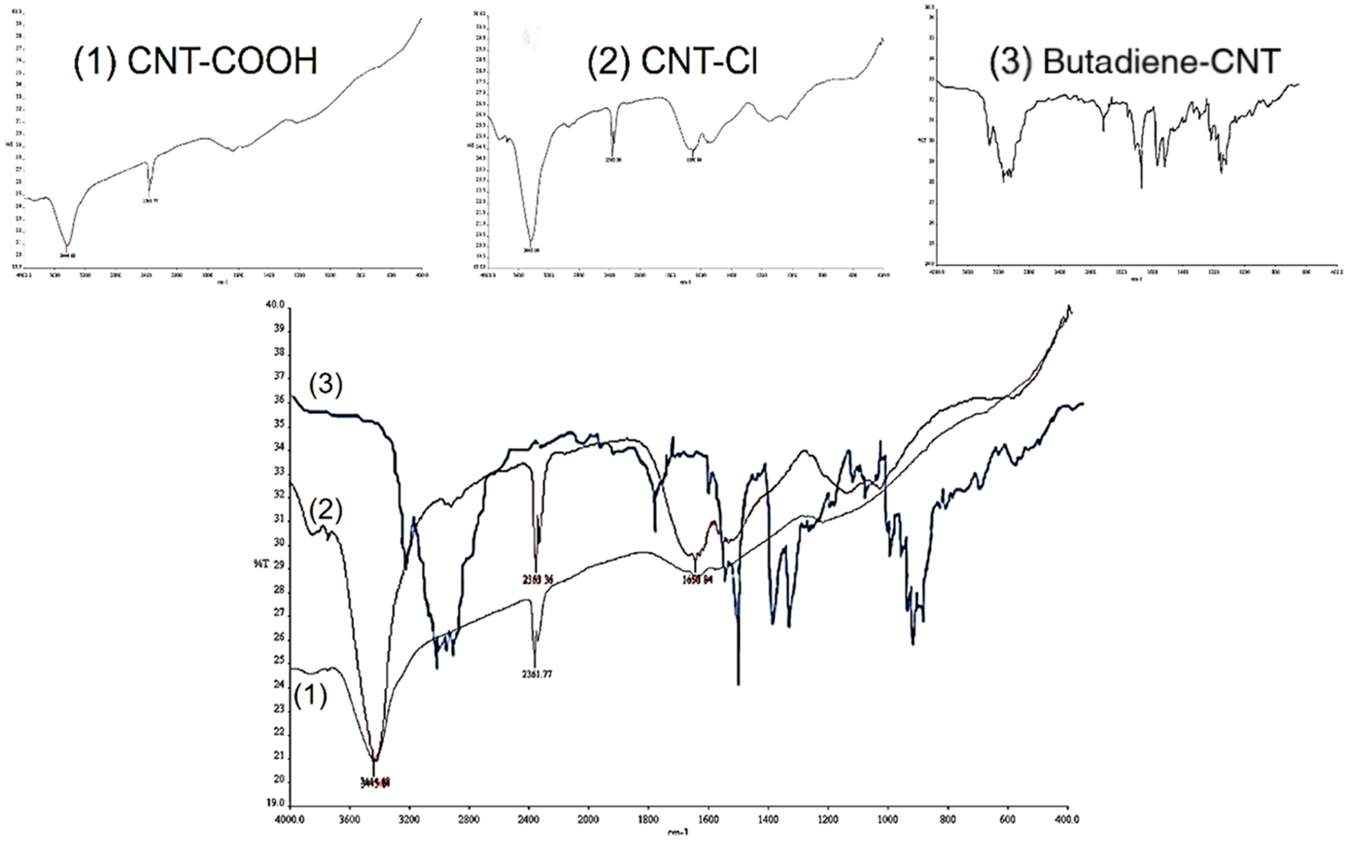

Figure 1. Matching graph obtained from the FTIR experiment in the three stages of latex nanopolymer synthesis shows the successful carbon nanotubes' functionalization process and their compositing with the butadiene polymer.

triciododecyl mercaptan (TDM) as a reaction initiator and disproportionated rosin as an anionic emulsifier were dissolved in some water and were added to the reactor. Then, other emulsion polymerization components were introduced into the reaction reactor except for the butadiene monomer and a homogenized suspension of carbon nanotubes. To discharge oxygen gas inside the reactor, nitrogen gas with a purity of 99.9% was passed through the upper space of the liquid inside the reactor (including initiator, emulsifier, chain transfer agent, and other materials) for about 30 min. Finally, after redraining the nitrogen gas above the solution, the whole system was sealed.

After isolating the system from the outside environment, a particular volumetric concentration of carbon nanotubes and a butadiene suspension were fed into the reaction reactor. To complete the polymerization process, the temperature inside the reactor was increased to 80 °C and maintained for 3 h. The polymerization process was stopped by injecting 1 mL of a 1% hydroquinone solution into the reactor.

2.3. Molecular Structure Detection. Molecular recognition techniques are valuable tools for understanding structural identity and intermolecular bonds. The Fourier transform infrared (FTIR) test tracked structural conversion targets during the polymer composite synthesis process. Also, polymer nanocomposites and hardened cement treated with it were explored to analyze the microscopic structure using a scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

3.1. Polymer Nanocomposite Molecular Characterization. Figure 1 shows the FTIR spectrum of polybutadiene carbon nanotubes nanocomposites. Carbon nanotubes are distinguished in step 1 by the carboxylic acid functional group with O−H and C═O stretching bond indices in the absorption range of 2400−3000 and 1710 cm^{-1}, respectively. The anionic functionalization step is detected with a C−Cl stretching bond index of 750 cm^{-1} in step 2.[47] Polybutadiene can be formed with three different microstructures, namely, 1,4-*cis*, 1,4-*trans*, and 1,2-vinyl. Depending on the content of each of these microstructural configurations, the polybutadiene can have plastic or rubber properties. Polybutadiene with plastic properties mainly contains a 1,2-vinyl microstructure used in packaging films. On the other hand, polybutadiene with the mentioned 1,4-cis configuration has rubber properties and is used in rubber products such as tires and belts. The polybutadiene synthesized using emulsion polymerization has all three configurations of 1,4-*cis*, 1,4-*trans*, and 1,2-vinyl; however, the microstructure of 1,4-trans with a ratio of roughly 60% is the dominating microstructure that offers better elastic qualities. The polybutadiene synthesized by the emulsion polymerization method has all three configurations of 1,4-*cis*, 1,4-*trans*, and 1,2-vinyl, but the microstructure of 1,4-*trans* with a ratio of about 60% is the predominant microstructure that promises more elastic properties. This molecular growth model is available in two forms of cis or trans in which both models the 1,2-X double bond branch also remain in the butadiene structural unit (other uncommon forms of butadiene polymer molecular growth configuration). The cis and trans bonds are characterized in step 3, in the absorption range of 720 and 970 cm^{-1}, respectively. It can be inferred that the significant increase in the butadiene monomer to the growing chain is of the 1,4-*trans* increase type.

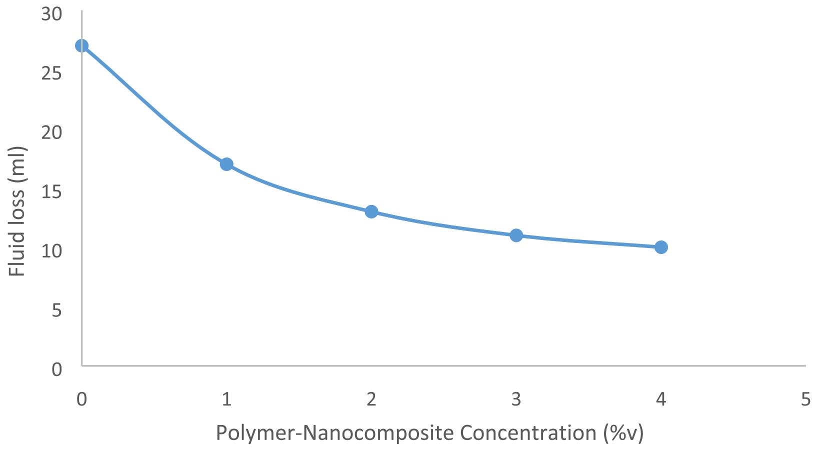

Figure 2. Effect of the butadiene−carbon polymer nanocomposite latex concentration on filtration properties of cement slurry samples (the defined concentrations belong to the samples: benchmark: 0, PN-LTX-1: 1, PN-LTX-2: 2, PN-LTX-3: 3, and PN-LTX-4: 4).

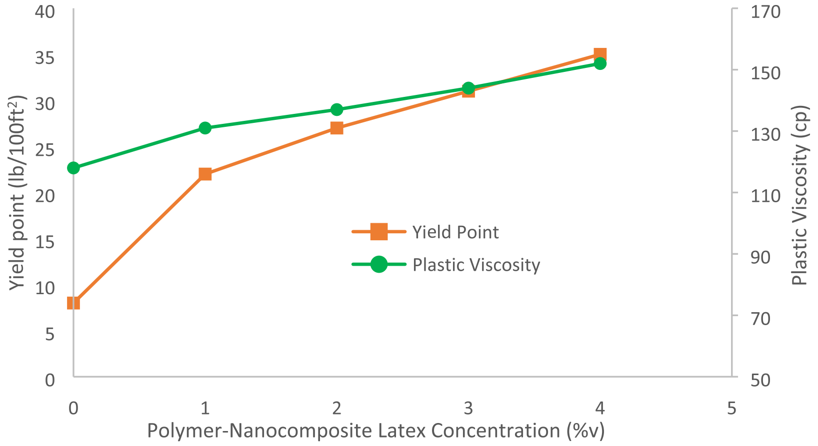

Figure 3. Effect of the butadiene−CNT polymer-nanocomposite latex concentration on rheological characteristics of cement slurry samples (the defined concentrations belong to the samples: benchmark: 0, PN-LTX-1: 1, PN-LTX-2: 2, PN-LTX-3: 3, and PN-LTX-4: 4).

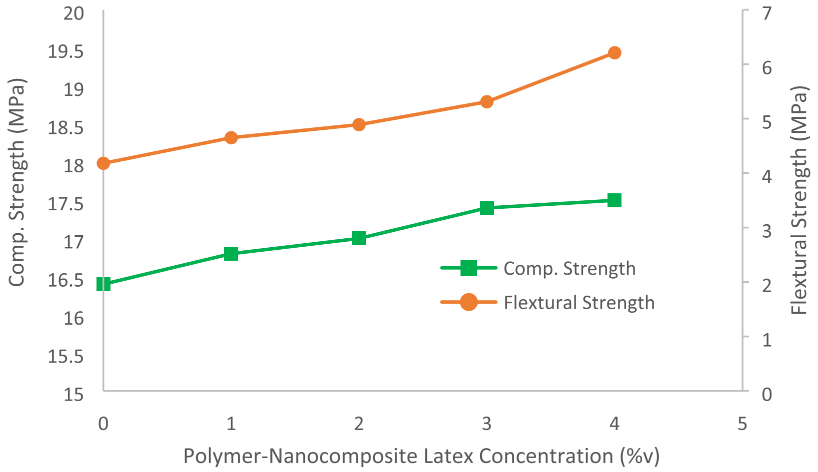

Figure 4. Effect of the butadiene−CNT polymer-nanocomposite latex content on compressive and flexural strength of hardened cement samples under mechanical tests (the defined concentrations belong to the samples: benchmark: 0, PN-LTX-1: 1, PN-LTX-2: 2, PN-LTX-3: 3, and PN-LTX-4: 4).

3.2. Filtration and Rheology Properties. A benchmark sample of a cement slurry with four samples containing concentrations of 1, 2, 3, and 4% by volume of a butadiene−CNT polymer nanocomposite in three modes of slurry, gelatin, and hardened cement, passed standard slurry tests, gas migration, and mechanical test.

The effects of increasing the content of the butadiene−CNT nanocomposite latex on the filtering control of cement slurries are clearly shown in Figure 2. In a simulation experiment of a

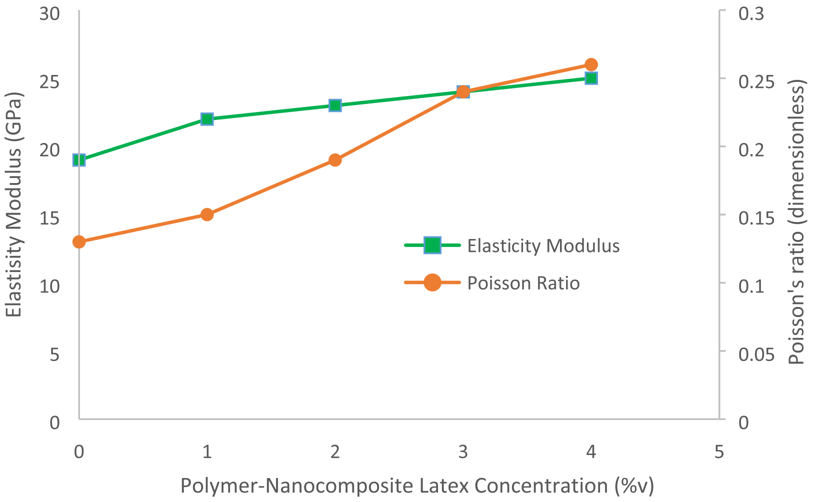

Figure 5. Effect of the butadiene−CNT polymer-nanocomposite latex content on the Poisson's ratio and the modulus of elasticity for hardened cement samples under mechanical tests (the defined concentrations belong to the samples: benchmark: 0, PN-LTX-1: 1, PN-LTX-2: 2, PN-LTX-3: 3, and PN-LTX-4: 4).

cement liquid phase loss under a differential pressure, the cement slurry loses a fraction of its liquid content as a filtrate. Cement slurries with uncontrolled high filtration reduce the cement slurry column in the wellbore and may cause the loss of sufficient moisture resources for complete hydration of the cement.[48] Incomplete hydration due to insufficient moisture inside the cement will intensify the shrinkage effects of the cement texture.

The absorption of water in the polymer's molecular structure will be accompanied by swelling and repulsion of its lateral branches due to the electrical charge created during the interaction with the polar environment of water. This process will increase the shear strength of fluid layers in the face of external shear and mechanical forces, which is seen as an increase in the fluid viscosity and yield point.[49] The laboratory evidence presented in Figure 3 shows that increasing the concentration of the polymer nanocomposite latex leads to an increase in the viscosity and yield point of the cement slurry.

3.3. Mechanical Properties. Evidence from mechanical test results in Figure 4 indicates a significant increase in flexural strength of up to about 48% for a reinforced hardened cement sample (for 4% by volume of additive) and a slight increase of 7% in compressive strength in the same sample. As shown in Figure 5, the modulus of elasticity increases significantly with increasing concentration of the latex polymer nanocomposite in cement. At the highest concentration of the additive tested, it has promoted the modulus of elasticity by about 75%. A 12% increase in the Poisson's ratio, along with an increase in the modulus of elasticity, provides a higher axial strain in the very high elastic form for hardened cement.

For a better insight into the performance of the reinforcing mechanisms of the butadiene−CNT polymer nanocomposite at the microscopic scale within the cementitious texture, a broken cement cross section was explored by the SEM probe.[50] Figure 6 provides microstructural evidence of the tissue-reinforcing mechanism of cement hardened by polymer nanocomposites. The top row images belong to carbon nanotubes with an average diameter of 20 nm. The middle row images belong to the pure latex polymer nanocomposite with a 50−80 nm droplet diameter. Bottom row images belong to the fractured side of a hardened cement sample optimized with the butadiene−CNT polymer-nanocomposite latex. A polymer latex matrix as the primary emulsifying substrate of nanotubes has achieved their proper dispersion in cement. The wide distribution of carbon nanotubes in the structure of the cement bulk can be seen in the microscopic images taken from its texture. Therefore, feedback on the superelastic behavior of carbon nanotubes in strengthening the tensile strength and modulus of elasticity of cement samples is evident. Intrinsic tensile strength of the butadiene polymer ensures the integrity of the cement mortar by adhesion of the cementitious components and better bonding with nonhydrophilic carbon nanotubes, which dramatically enhances the flexural behavior of the hardened cement specimens in the mechanical test. These claims are characterized by the scattered distribution of carbon nanotubes in cement and the creation of resistance bridges over the emerging fissures or fractured cracks.

3.4. Shrinkage Assessment for Gas Migration Control. As shown in Figure 7, measurement of shrinkage of cement samples after 24 h showed that early shrinkage during the hydration process of cement in samples treated with the butadiene−CNT polymer nanocomposite latex had been compensated satisfactorily. The fresh cement texture does not have sufficient tensile strength during the hydration process, so the gel structure of C−H−S cement dries and cracks during the rapid hydration.[51] During the cement hydration, the higher surface tensile property and structural adhesion of the polymer nanocomposites latex create greater resistance throughout the cementitious gel, which prevents rapid cracking and the growth of microscopic fissures in the hardening cement. The polymer nanocomposite latex also allows a complete hydration process with sufficient moisture sources within the cement texture by holding free water inside the gelatinous cement structure and significantly limiting the cement samples' shrinkage effects.

3.5. Static Gel Strength Assessment for Gas Migration Control. The gel strength development has been accepted as an efficient control lever to limit gas migration within annular cement in the early stages of setting.[52] During this period, the cement slurry is transformed from a viscous fluid form into a hard material with high compressive strength. When the hydration process is undergoing, the interactions of

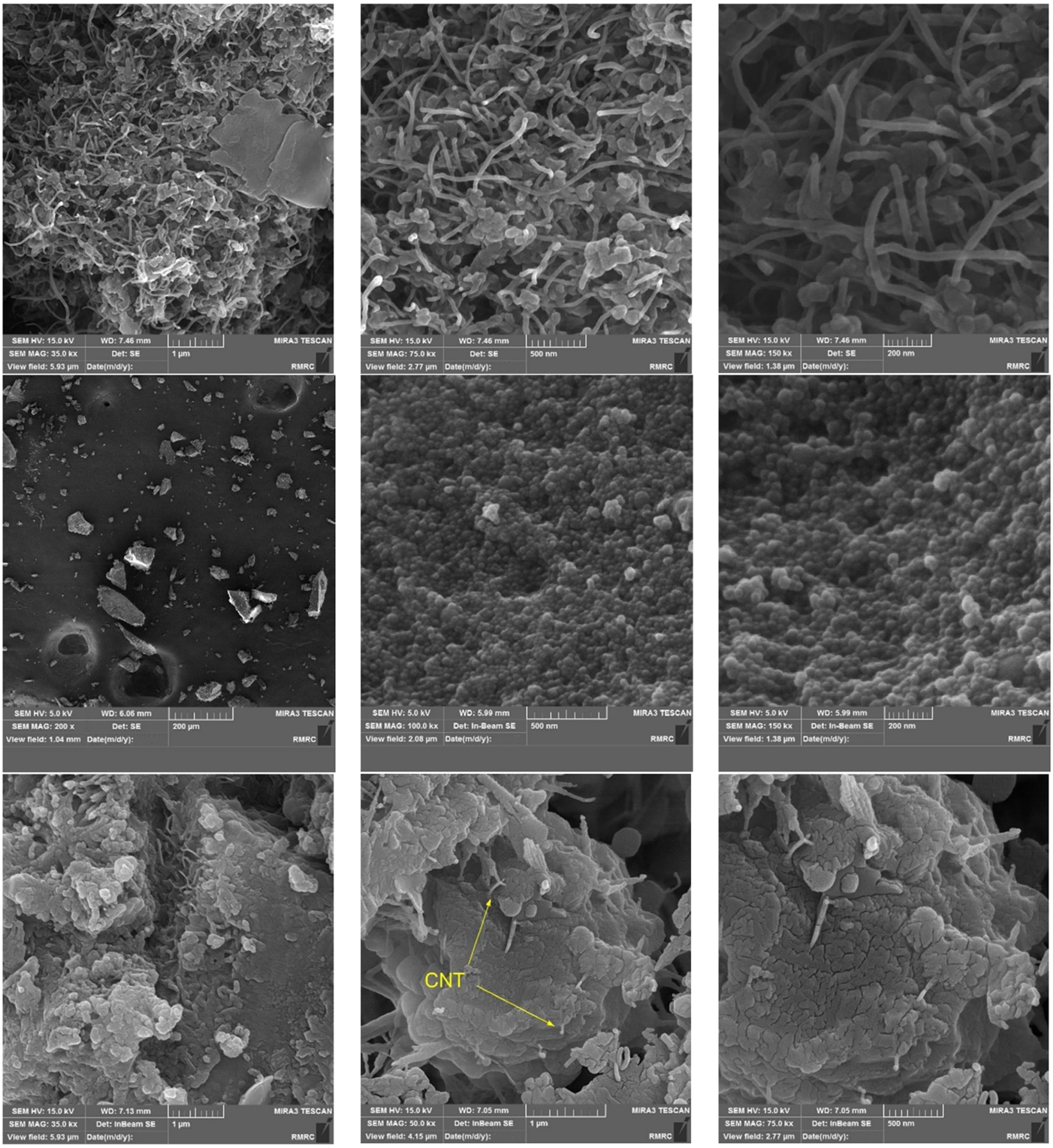

Figure 6. Micrographs recorded at different magnification scales by the SEM probe: the top row images belong to carbon nanotubes with an average diameter of 20 nm. The middle row images belong to the pure latex polymer nanocomposite with a 50−80 nm droplet diameter. Bottom row images belong to the fractured side of a hardened cement sample optimized with the butadiene−CNT polymer-nanocomposite latex.

cement silicates with water form C−S−H and Ca(OH) microcrystalline.[30,53] Development of the formation of hydrated silicate and calcium crystals (C−S−H gel) is accompanied by gelation of the slurry, in which the cement slurry loses the ability to transmit hydrostatic pressure. The inability of gelatinous slurry to transfer hydrostatic pressure reduces its pore pressure in the vicinity of the gas zone, and as a result, the gas will seize the provided opportunity for aggression.[54] The progress period of the strength of hydrated cement gel, known as the phase transfer window, is defined as 100−500 lb/100 ft^2 (48−240 Pa).[55] Most efforts to meet the challenge of rapid gas migration are related to limiting the critical cement phase transition critical window.

The OFITE static gel strength device was used in this research to investigate the temporal SGS development phase in cement slurries. The test results for measuring the development of static gel strength for four samples containing the butadiene−CNT polymer nanocomposite latex and the

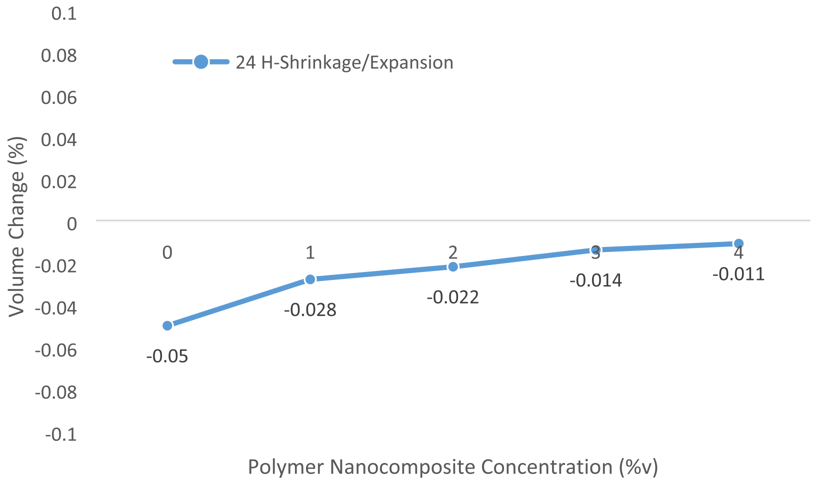

Figure 7. Volumetric dimension changes of dried cement samples after 24 h (measured by OFITE circular cement expansion mold).

benchmark sample are presented in Table 3. Examination of the rheology of slurries treated with polymer nanocomposites shows a pattern of thixotropic behavior. The time-dependent thixotropic properties of polymer nanocomposite latex slurries give them the property that the slurry remains fluid as long as it undergoes shear stress in dynamic conditions and immediately begins to gel when the cement is completely displaced and pumping is stopped. Further experiments in previous research have shown that the temporal profile of gel strength development is related to the nature of the cement slurry structure and not to the time of thickening.[55]

Table 3. Cement Slurry Gel Strength Development (@212 F, 1000 psi Condition)

slurry sample	time to 48 Pa (100 lb/100 ft^2)	time to 240 Pa (500 lb/100 ft^2)	thickening time
benchmark	00:35	01:48	07:40
PN-LTX-1	00:18	01:02	05:10
PN-LTX-2	00:15	00:54	04:58
PN-LTX-3	00:12	00:45	04:40
PN-LTX-4	00:10	00:40	04:27

The SGS critical time range was significantly reduced in four samples of nanocomposite latex-modified cement compared to the benchmark sample (for the highest concentration used, up to 41% reduction was observed in the critical transition time window compared to the benchmark sample).

4. CONCLUSIONS

The synthesized nanocomposite polymer latex is contrived to consider the known principles of gas migration mechanisms in a cement slurry and to handle known mechanisms by new engineering techniques. The problem-solving method in this research is based on controlling the gas migration driving mechanisms in wellbore annular cement, especially in the early hours of cement setting time. The following three practical steps are taken to curb gas migration mechanisms in the cement slurry:

- Controlling the rate of the fluid loss to maintain hydrostatic pressure and sufficient moisture for hydration.
- Increasing the surface tension of the cement slurry and the flexural strength of the hardening cement texture to control the early shrinkage in fresh hydrating cement.
- Reduction of the critical cement transfer time window (modification of static gel strength development).

The measures taken led to a reduction of 45 min in the critical period of transfer of the cement slurry from a liquid to rigid state and significantly limited the possibility of gas invasion into the cement slurry in the gelly phase. The mini-emulsion polymerization technique was used to respond to the challenge of dispersion of hydrophobic carbon nanotubes in an aqueous cement medium. The mechanical properties of cement samples modified with the CNT−butadiene polymer nanocomposite have experienced significant improvement. The flexural strength increased by 48% and compressive strength increased by 7%. A 75% increase in the modulus of elasticity, accompanied by a 12% increase in the Poisson's ratio, has significantly improved the flexibility of the elastic range of hardened cement.

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Notes

The authors declare no competing financial interest.

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