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Nanoparticle-Enhanced Polymeric Fluid for Sand Control in Unconsolidated Petroleum Wells

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Abstract

Sand production remains a critical challenge in petroleum engineering, particularly in unconsolidated sandstone reservoirs where reservoir pressure decline disrupts the stress equilibrium around the wellbore. Progressive depletion of reservoir pressure increases effective overburden stress, frequently inducing formation failure and mobilization of sand grains. Conventional mechanical sand-control methods, such as gravel packing and screens, are widely used but are costly, operationally complex, and less adaptable under harsh downhole conditions. Consequently, chemical consolidation using polymeric resins has attracted increasing attention as a more economical and technically flexible alternative.

This study evaluates the performance of a furan-based polymer system for chemical consolidation of sandstone formations. At an optimized formulation of 20% CF and 18% CLA, the polymer demonstrated strong bonding capability, providing effective grain-to-grain adhesion while maintaining compatibility with reservoir brines, preserving initial rock wettability, and resisting thermal degradation. To further enhance consolidation efficiency, SiO_2 nanoparticles were incorporated into the chemical at concentrations ranging from 0.25 to 1.0 wt%.

Experimental core tests revealed that nanoparticle inclusion significantly increased unconfined compressive strength, achieving values up to 2130 psi, while retaining as much as 81% of initial permeability. In addition, thermal stability was markedly improved, with high-temperature weight loss at 500 °C reduced from ~50% to ~30%. Scanning electron microscopy confirmed enhanced polymer adhesion to sand particle surfaces .

These findings demonstrate that nanoparticle-modified furan polymers represent a technically robust and field-viable alternative for chemical sand consolidation, with the potential to improve wellbore stability and reduce operational costs in unconsolidated petroleum reservoirs.

Keywords: Chemical sand consolidation, Wellbore stability, Sand production control, Nano-fluid

1. Introduction

The strength of sandstone formations is influenced by compaction, cementation, and dissolution of cement between sand grains at contact points. The cement between particles in sandstone reservoirs is often of quartz type, and in some environments that make up the reservoir rock, this amount is lower than in other places (Dewprashad et al. 1993). An increase in the production rate leads to a pressure difference near the wellbore, which results in pressure on the reservoir rock in this area (Haavind et al. 2008). The increase in production also leads to a decrease in the pore pressure, which causes the overburden pressure to overcome the pore pressure and ultimately can lead formation failure (Kotlar et al. 2005). In general, the set of factors leading to sand production in sandstone reservoirs can be considered as the strength of the formation, viscous force, pressure drop in the wellbore, and overburden pressure (King, Wildt, and O'Connell 2003). Sand production has brought many problems, the most important of which are the erosion of equipment inside the well, instability of the borehole,

erosion of the surface facilities, reduction of production rate due to the accumulation of sand particles in the borehole, cost of sand disposal, environmental problems, etc. (Farias et al. 2007).

Sand control methods generally fall into two categories: mechanical and chemical methods. In the mechanical methods of controlling sand production, the goal is to prevent sand particles from entering the well using existing equipment (Morgan et al. 2005). The main challenge of mechanical methods of sand production control is the cost of installing and operating these systems and also, the damage of the tools used during the time (Chuah et al. 1994). The mechanism of operation of chemical methods of controlling sand production is different from mechanical methods. In this method, by injecting polymer materials such as various resins, the loose particles of the formation around the wellbore stick to each other and their movement during fluid production is prevented. Chemical methods can be divided into two general categories: in-situ consolidation and agglomeration (Haavind et al. 2008; Rike 1966). The injection of polymers leads to the fact that the strength of the formation in the injected areas increases and the sand particles can withstand more pressure (Smith 1969).

In general, in the research and studies carried out so far, chemical materials such as polymers, polymer gels, organosilanes, and some enzymes have been used for the chemical consolidation of sandstone reservoirs (Shahsavari and Khamehchi 2018). Studies have shown that among the available chemicals, polymers will have a much better performance in chemical consolidation because of their high thermal stability, chemical stability when in contact with formation fluids, and also environmental considerations (Soter et al. 2005). Among the polymers used in sand production control, furan polymers (Fader et al. 1992; Karian et al. 1999; Kotlar et al. 2005; Parker Jr, Treadway, and Brandt 1967), epoxy (Tabbakhzadeh et al. 2020; Talaghat, Esmaeilzadeh, and Mowla 2009), phenol formaldehyde (Talaghat, Esmaeilzadeh, and Mowla 2009), acrylic polymers (Talaghat, Esmaeilzadeh, and Mowla 2009), and urea formaldehyde (Mishra and Ojha 2016b) can be mentioned. In 2022, Vaidya et al. were able to increase the compressive strength to 910 psi with the help of amino resin, while the core contained 30% clay(Vaidya et al. 2022). Also, in 2023, Rico et al. were able to increase the compressive strength to 600 psi with a new base resin, while the remaining permeability was about 60%(Recio et al. 2023).

One of the main reasons for using furan polymer in the chemical consolidation of sandstone reservoirs is that this material is economical compared to other existing polymers (Karian et al. 1999). Also, the studies conducted on furan polymer show that this material can increase the compressive strength up to 550 psi, with the permeability reduction rate being in the range of 10% (Fader et al. 1992; Talaghat, Esmaeilzadeh, and Mowla 2009). Also, another reason that caused Furan polymer to be considered in the chemical control methods of sand production is the success of this material in field operations (Karian et al. 1999; Parker Jr, Treadway, and Brandt 1967).

Furan resins are derived from vegetable cellulose, a renewable resource (Coppock 1996; Gonsalves and Chen 1996). Furan resin is the general term of synthetic resin containing furan ring (**Fig. 1**) in the molecular structure. Because their molecular structures all have furan ring, this group of resins share many common characteristics, such as prominent alkali, acid, solvent resistance and excellent heat-resistant properties (Wang, Zheng, and Zheng 2011).

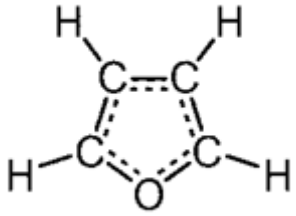


Fig. 1. Chemical structure of furan ring

Cured furan resin have excellent chemical resistance. This is probably because, although the resin has some reactive groupings, most of the reactions occurring do not result in the disintegration of the polymer molecules. Therefore, whilst surface layers of molecules may have undergone modification they effectively shield the molecules forming the mass of the resin. In these respects, they are similar to, and often slightly superior to, the epoxide resins (Brydson 1999). Furan resin formulations can be used for in situ chemical sand consolidation (Shu 1996). According to research, furan resin can increase Young's modulus and compressive strength (Tabbakhzadeh et al. 2024).

One of the main requirements of using polymers in chemical consolidation is the dynamic viscosity of polymers. To reduce the viscosity of the polymer, the consolidating chemical is a combination of polymer and solvent so that the viscosity of the polymer is within the appropriate range for injection. In this regard, polymer chemicals can be divided into two categories: solvent-based polymer (Alakbari et al. 2020; Tabbakhzadeh et al. 2020) and aqueous-based polymer (George C, Nguyen D, and Patil 2019; Nguyen and Rickman 2012; Villesca et al. 2010). The addition of the solvent to the primary polymer leads to a decrease in the concentration of the polymer in the injection chemical and, as a result, a decrease in the volume of empty spaces between the pores occupied by the polymer. This issue leads to the reduction of the permeability of the consolidated area to a lesser extent.

One of the materials that are added as an additive to the consolidation chemical is different types of Nanoparticles (Du et al. 2024). The used Nanoparticles reduce the electrostatic repulsion leading to sand particles getting closer to each other and maintaining the integrity of the formation rock, and prevents the migration of fines (Yuan, Ghanbarnezhad Moghanloo, and Pattamasingh 2015). SiO_2-Nanoparticles is one of the materials that has been used in various research. Based on the studies conducted, SiO_2-Nanoparticles lead to an increase in the compressive strength of the consolidated sample and an increase in the strength of the consolidation fluid in contact with the formation fluid by creating two, which includes the bond of SiO2-Nanoparticles with sand and the bond of SiO2-Nanoparticles with resin (Mishra and Ojha 2016b). Based on the studies conducted, Nanoparticles such as SiO_2, MgO, and Al_2O_3 are mostly used as additives to improve the properties of polymer chemicals in controlling sand production (Mishra and Ojha 2016b). In recent years, Nanoparticles have been used along with resins to compensate for the decrease in permeability caused by the use of resins. In 2023, Nejati et al. were able to maintain the residual permeability up to 86% using SiO_2-Nanoparticle and epoxy resin(Nejati et al. 2023). Also, in 2024, Banashooshtari et al used SiO_2-Nanoparticle, epoxy resin and SDS surfactant for chemical consolidation and were able to obtain a compressive strength of 1888 psi and a remaining permeability of 89%(Banashooshtari et al. 2024).

In this study, the performance of furan polymer in increasing the rock's compressive strength and finally its effect on the sand production control was investigated. The experiments were performed in three phases: before the injection of the chemical, the injection of the chemical and the investigation of the effect of Nanoparticles, where in the pre-injection phase by combining furan polymer, isopropyl alcohol, and the crosslinking agent the minimum concentration of each of these substances was determined. At first, to reduce the concentration and viscosity of furan polymer, it was diluted using isopropyl alcohol. A crosslinking agent was used to facilitate and speed up the curing process as well as to improve the properties of the chemical, which leads to an increase in its strength after curing. The curing process of the chemical was done at 90 ˚C and in two atmospheric and 3000 psi pressure conditions. Next, to perform the chemical injection phase, the chemical sample was prepared in three different concentrations of the furan polymer and also in five different percentages of the cross-linking agent. After examining the results obtained from the chemical injection, the optimal concentration was determined using regression with Python. Then, the effect of adding Nanoparticles on the chemical compound with optimal concentration was investigated and it was observed that adding SiO_2-Nanoparticles leads to an increase in the compressive strength of the consolidated core sample. Then, the effect of furan polymer on creating in-situ consolidation in the existing sand sample was investigated. The observations showed that by increasing the amount of polymer in combination with the formation sand, the compressive strength of the obtained sand core samples increased. Also, to investigate the performance of the chemical more precisely, mineralogy, TGA (Thermogravimetric Analysis), FESEM (Field Emission Scanning Electron Microscope), and wettability analyses were performed.

2. Materials and Procedure

2.1. Materials

Materials used in this study include furan polymer (CF), cross-linking agent (CLA), SiO_2-Nanoparticles powder (the distribution of nanoparticle size was between 10 to 20 nm), isopropyl alcohol to dilute and reduce fluid viscosity, and diesel as a pre-flush fluid. Crude oil (29.55 ˚API) and formation water with pH 5.4 and salinity of more than 180000 ppm (mg/lit) were obtained from the Ahvaz oil field in southwest Iran. **Fig. 2** shows the analysis of the SARA test of crude oil and **Table 1** shows the analysis of formation water.

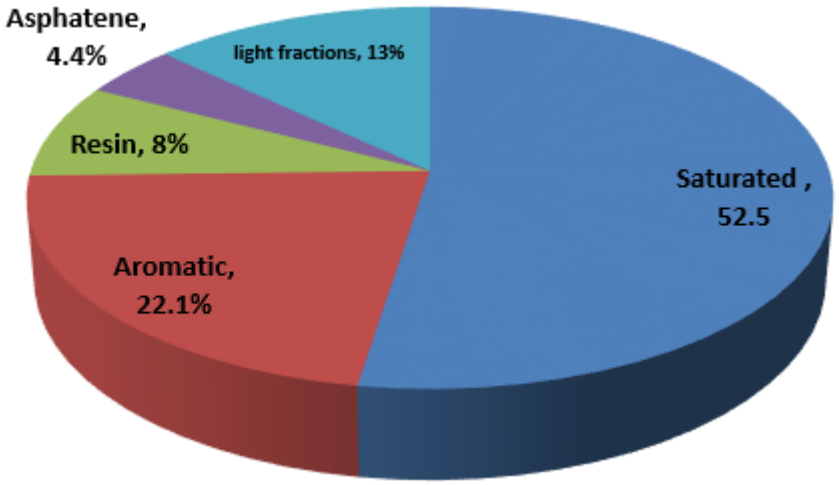


Fig. 2. The analysis of the SARA test of crude oil

Table 1. The analysis of formation water

Ion type	Na^+	K^+	Ca^{2+}	Mg^{2+}	NO_3^-	Cl^-	SO_4^{2-}	HCO_3^-
Concentration (ppm)	59800	1184	7531.4	1085.9	15	105640	185	7323.7

A formation sand sample was prepared from one of the sand production wells in the Ahvaz field to evaluate the compressive strength caused by the different concentrations of the chemical and its stability. The mineralogical analysis of the formation sand sample can be seen in **Table 2**.

Table 2. The mineralogical analysis of the formation sand sample

Mineral type	Weight percentage (%)
Quartz	83
Calcite	9
Dolomite	4
Albite	1
Potassium Feldspar	2
Illite	1

To determine the particle distribution of sand particles, sieve analysis was also performed on the production sand sample, and the distribution diagram of the particles is presented in **Fig. 3**.

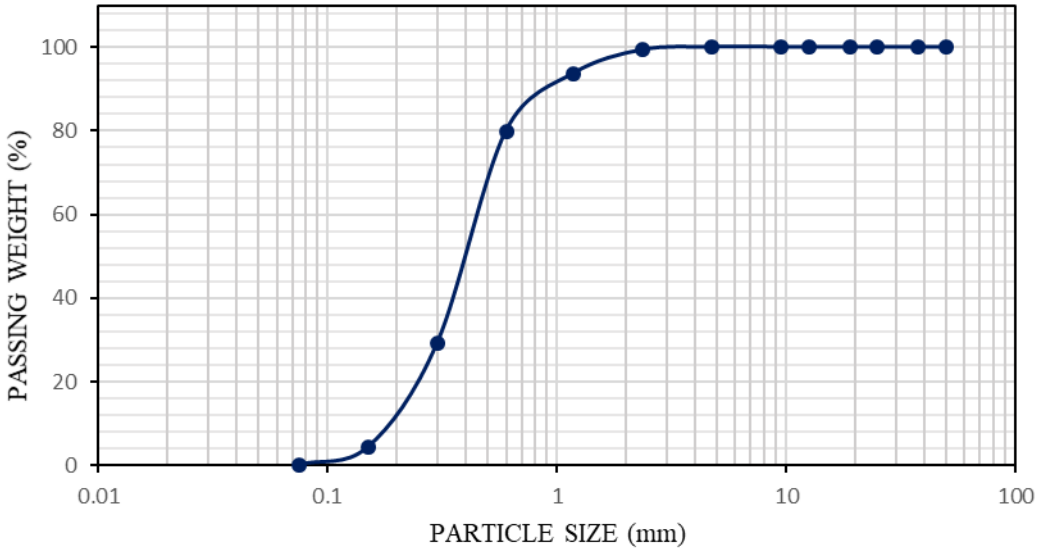


Fig. 3. The distribution diagram of the sand particles

According to **Fig 3** and Eq.1, the uniformity coefficient of sand particles is equal to 2.67.

$$Cu = {}^{D_{60}}/_{D_{10}} \quad (1)$$

where,

D_{60} = Weight of the size opening that just 60% of the sand particles pass.

D_{10} = Weight of the size opening that just 10% of the sand particles pass.

In this study, because of unavailability of formation cores to perform injection tests, to obtain test conditions as close as possible to the real state and to investigate the effect of the presence of clay minerals, samples from the outcrop of the production formation in Ahvaz field were also used. Mineralogical analysis was done to identify the minerals that make up the outcrop and the presence of shale and its type on the outcrop. The mineralogical analysis can be seen in **Table 2** by weight percentage.

Table 3. The mineralogical analysis of the outcrop sample

Mineral type	Weight percentage (%)
Quartz	42
Calcite	30
Dolomite	4
Albite	5
Potassium Feldspar	3
Chlorite	9
illite	7

The characteristics of the outcrop cores obtained are given in **Table 4**. The diameter of the outcrop cores was 3.73 inch.

Table 4. The characteristics of the outcrop cores

Core No.	Length(cm)	Permeability(md)
1	6.90	220.7
2	6.18	123.4
3	5.58	117.3
4	6.03	174.2
5	6.80	214.7
6	6.89	114.8
7	6.78	107.1
8	6.10	134.9
9	6.17	232.9
10	5.91	188.1
11	6.89	183.1
12	6.81	117.8
13	6.70	153.1
14	6.26	148.1
15	6.26	157.2
16	5.99	168.0
17	6.29	170.7

18	6.41	165.3
19	6.42	166.8
20	6.27	174.6
21	6.45	170.7
22	6.60	184.2
23	6.60	166.8
24	6.72	178.4

2.2 Experimental Equipment

To perform preliminary tests before injection at atmospheric pressure to check the compatibility of the chemicals with rock and reservoir fluids and to determine the minimum amount of CF and CLA in the chemical, a mold with two steel shells and two screw caps was used, a view of which is shown in **Fig 4**.

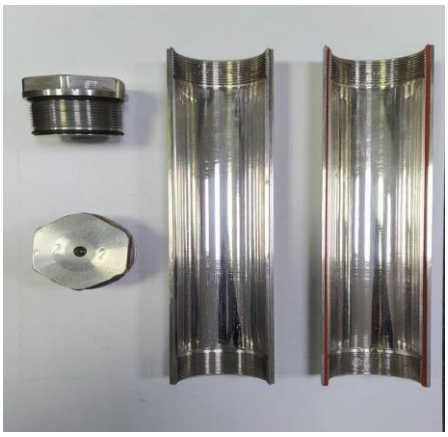


Fig 4. The steel mold for performing preliminary tests

To apply temperature and pressure during the curing of the chemical (the stage where all cross-links between polymer chains are established and polymer networks are formed and the polymer system turns into solid state) injected into the cores, a reactor with a high-pressure (5000 psi) and high-temperature (480°F) capacity was used, the image of which can be seen in **Fig 5**.

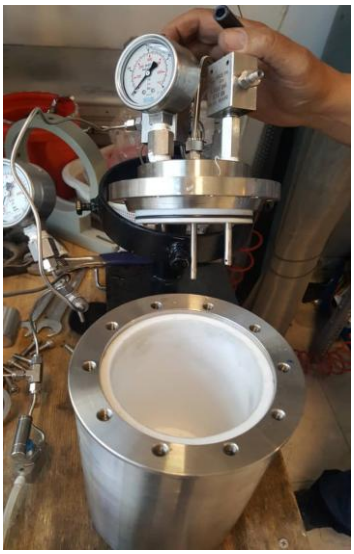


Fig 5.The reactor for applying pressure and temperature

Also, the VINCI FDS350 device was used to inject the chemicals into the cores. This instrument can be used for the evaluation of the effect of different fluids on rock permeability. The system can be used to simulate and measure the degree of near well bore permeability impairment caused by chemicals, drilling mud systems or other well bore fluids. Tests can be conducted using reservoir or outcrop core material at specified temperatures and pressures. A diagram of which can be seen in **Fig. 6**.

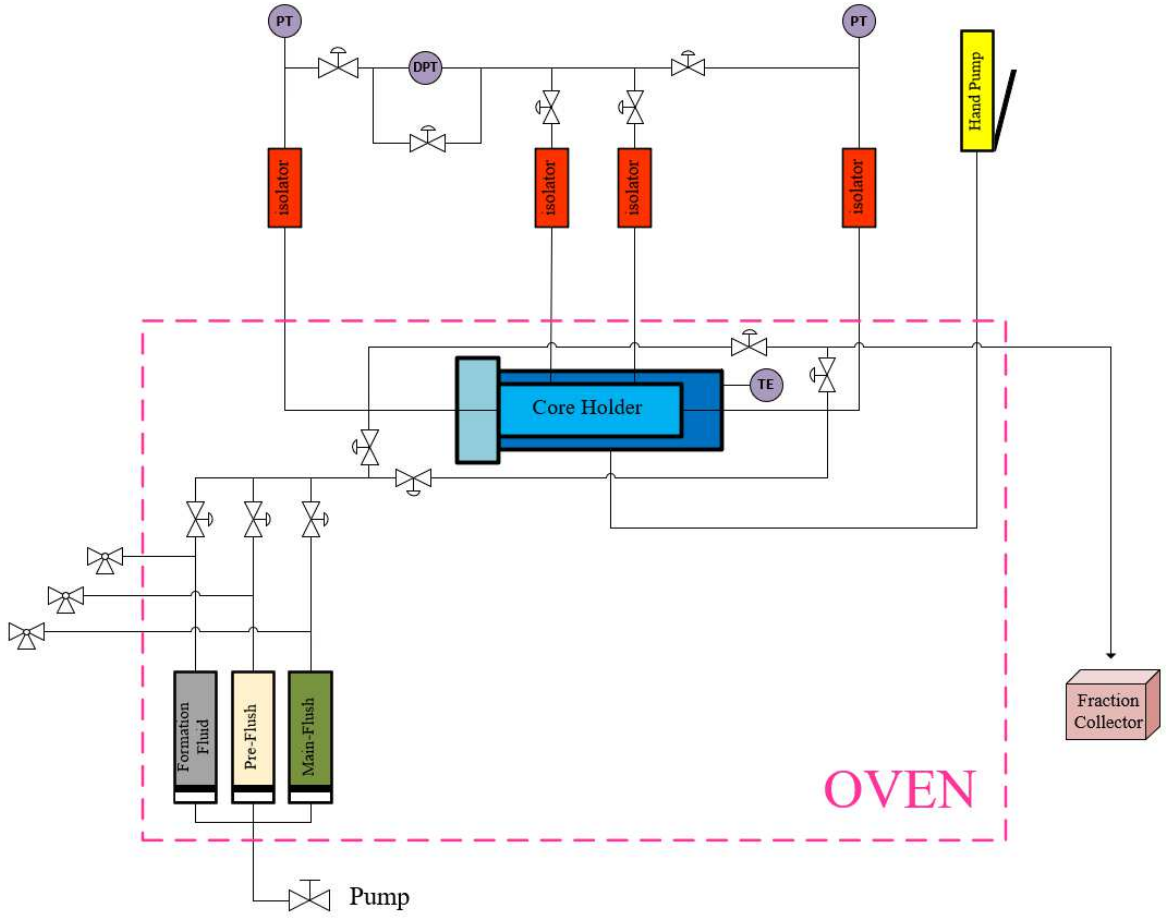


Fig. 6. Diagram of core injection device

2.3 Experimental procedure

This study was conducted in three phases. The first phase) before core injection of the chemicals, the second phase) core injection of the chemicals, and the third phase) investigating the effect of SiO_2-Nanoparticles. All experiments were performed at least three times to confirm reproducibility and accuracy of the results.

First, in the pre-injection phase, the minimum amounts of materials were determined and the compatibility of materials was surveyed. After the first stage, in the second phase, chemicals were injected into the cores in different concentrations and the results were evaluated. In the end, in the third phase, the effect of SiO_2-Nanoparticles on the compressive strength and retained permeability was investigated.

Fig. 7 shows the chart of the steps of conducting experiments.

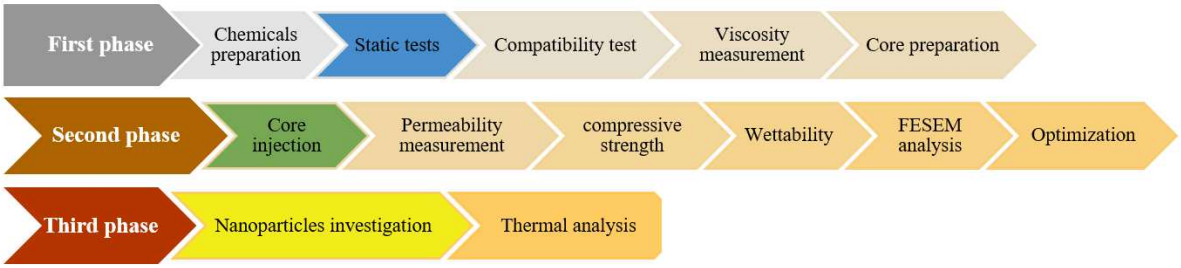


Fig. 7. Experimental procedure

2.3.1 First phase) before injection of the chemical

Determining the minimum amount of CF

At first, solutions with different concentrations were prepared by mixing isopropyl alcohol and CF in different amounts. To identify the minimum concentration of the CF in the solution, the amount of isopropyl alcohol as a solvent was increased at each step, and the addition of isopropyl alcohol continued until the solution did not leave the homogeneous and uniform condition and did not form sediment

Determining the minimum amount of CLA

To determine the minimum amount of CLA, first, small amounts of CLA along with a chemical solution were combined with sand and formation fluids and then transferred to the mold to be placed in contact with heat for curing at atmospheric pressure. This process continued each time by increasing the CLA amount until the curing process was done well. After increasing the amount of CLA and checking it, the minimum amount of CLA was determined at atmospheric pressure. To investigate the effect of pressure and identify the minimum amount of CLA under high-pressure conditions (3000 psi), the mentioned steps were carried out under pressure in the reactor until the minimum amount of CLA was determined under high-pressure conditions.

Compatibility test

Sometimes the formation fluids are incompatible with the treatment fluids, which can cause formation damage and loss of treatment fluid properties. To check the compatibility of the chemicals with formation water and oil before conducting the injection test, the chemical was placed in contact with the formation fluid, and its compatibility was evaluated.

Viscosity measurement

In this study, the viscosity of each of the prepared solutions was measured by the viscometer device which is made by The Brookfield CAP 2000+ viscometer. The measurements were done in the temperature range of 30 to 75 ˚C and the shear rate 100 1/s. The curves related to the flow ability of each chemical in different temperature conditions were obtained. Also, at the end, viscosity of chemical with optimal concentrations of CF, CLA and, nanoparticle was measured with variation in shear rate between 3.5 and 250 1/s and constant temperature of 50 ˚C.

Cores preparation

At first, four cores (core No. 7, 8, 9, and 23 refer to **Table 3**) were selected from the obtained outcrop cores to measure the average initial compressive strength, and the compressive strength of each one was measured.

The remaining cores were placed in contact with the formation water for one week to saturate with the formation water. After a week, the cores were saturated with formation water and placed in contact with crude oil for three weeks to saturate with oil.

2.3.2 Second phase) core injection of the chemicals

Core injection steps of the chemicals.

1. After saturating the cores with formation fluids, the core was placed in the sleeve and the sleeve was transferred to the core holder for the injection test.
2. To start the injection test, a pressure of 800 psi was applied with the help of hydraulic pressure.
3. Diesel was injected into the core as a pre-flush fluid for the initial washing of the pore space filled with formation fluids and removing them from the core space until the amount of remaining oil in the core reached its residual value.
4. Four pore volume of the chemical were injected into the core at a rate of 5 cc/s.
5. The core was removed from the core holder and sleeve and was cured for 24 hours in an HPHT reactor under a pressure of 3000 psi and a temperature of 90 ˚C.
6. After 24 hours, the core was removed from the reactor and the retained permeability and also compressive strength was measured after chemical consolidation.
7. From the consolidated core, a thin section was prepared to measure wettability alteration after chemical consolidation, and its contact angle was also measured.

Retained permeability**.** The retained permeability of the cores after the injection test was measured by Helium. The retained permeability of cores was calculated using Eq.2.

$$\mathbf{K = \frac{2000 P_a \mu_a q L}{A(P_2^2 - P_1^2)}} \quad (2)$$

Compressive strength. The compressive strength of cores was measured by the Uniaxial Compressive Strength device. The compressive strength of cores was calculated using Eq.3.

$$\mathbf{CS = \frac{F_{max}}{A}} \quad (3)$$

FESEM analysis

When the chemical enters the pore spaces of the core, the surfaces of the formation sandstone particles are covered by the chemical, so the more the surfaces of the particles are covered by the chemical, the greater the connection between the sand particles and the grains are better placed next to each other. This can make chemical consolidation more effective. For this reason, FESEM (Field Emission Scanning Electron Microscope) analysis was used to survey the quality of covering the surfaces of sand particles with the chemical.

Wettability alteration

The surface of the formation sandstone may undergo wettability alteration by coming into contact with chemicals. Therefore, to survey the changes in the contact angle of the formation sandstone with oil, the contact angle was measured using the obtained thin sections.

The obtained thin section was placed horizontally under the formation water, then an oil droplet was gently placed under the thin section. Later, the contact surface between the oil droplet and the thin section was photographed and the contact angle was measured using Digimizer software. Digimizer is an easy-to-use and flexible image analysis software package that allows precise manual measurements as well as automatic object detection with measurements of object characteristics.

Determining the optimal concentration of CLA

To identify the optimal amount of CLA and the concentration of CF, the objective function was considered, which was equal to the product of the maximum value of the percentage of retained permeability and the percentage of increase in compressive strength, and regression was performed on the obtained results using Python.

2.3.3 Third phase) investigating the effect of SiO_2-Nanoparticles

Preparation of chemical with SiO_2-Nanoparticles. After determining the optimal values of CF concentration and CLA, solutions with 0.0, 0.25, 0.5, 0.75, and 1.0 weight percent Nanoparticles were made. Nanoparticles were added to the solution and then stirred for 15 minutes at a constant temperature of 30 ˚C. An ultrasonic stirrer was used for 8 hours to prevent the agglomeration of Nanoparticles. It was left alone for two days and in the end, it was observed that no Nanoparticles were deposited and all of them remained suspended in the solution. Each of the solutions was injected into the cores and after measuring the compressive strength and retained permeability, they were evaluated to determine the optimal amount of Nanoparticles.

Injecting Nano-fluid into the cores

1. The optimal value of CF concentration and CLA of the chemical solution was determined.
2. With the specified optimal amounts, five solution compounds with five different amounts of SiO_2-Nanoparticles were prepared for injection into the cores.
3. Each of the obtained Nano-fluids was injected into the cores and placed under temperature and pressure for curing.
4. Their compressive strength and retained permeability were measured and according to the obtained results, the optimal amount of SiO_2-Nanoparticles was determined.

Steps of chemical consolidation of formation sand core sample. After determining the optimal amount of CF, CLA, and Nanoparticle to check the ability of the chemical to create in-situ consolidation and also check the effect of the presence of shale, chemical consolidation was done using the chemical made with optimal amounts on the formation sand sample using the sand core sampling method. Using the volume of the mold, mass, and average density of the formation sand, the porosity of the sand core was calculated, by which the volume of the chemical required for chemical consolidation was determined. To prepare formation sand for chemical consolidation, the sand sample was placed in contact with formation fluids for a week and dried, then the sand sample was mixed with the chemical for 10 minutes, and after the sand particles were completely impregnated, the mixture of sand and the chemical was transferred to the mold and placed inside the heater at a temperature of 90 ˚C. After curing the chemical, the compressive strength of the consolidated sand core was measured.

TGA/DTA

It is a method of thermal analysis in which the change in mass of a sample with temperature change is observed and analyzed and can be used to evaluate the thermal stability of materials. To determine the thermal stability of the chemical and observe the effect of Nanoparticles on its improvement, the thermal resistance was studied using the Pyris Diamond Perkin Elmer device. A small amount of the desired material was placed in the device and

heated under nitrogen gas from ambient temperature to a temperature of 500 ˚C. Thermal stability of the chemical was evaluated using TGA/DTA diagrams.

3. Result and Discussion

3.1. Determination of optimal concentration of CF and CLA

The results of the experiments of determining the optimal concentration amount of CF showed that the CF concentration between 20 and 30 weight percent is the optimal amount for forming polymer networks and creating compressive strength in loose sands. The results indicated that the optimal amount of CLA at atmospheric pressure was 9%. But the tests at 3000 psi showed that the amount of 9% CLA was not able to cure. Next, the percentage of CLA was increased and it was found that curing with less than 15% CLA does not take place. With a CLA above 25%, curing is fast caused by the rapid formation of polymer networks, and as soon as the CLA is mixed with the polymer, the curing takes place, and it is not possible to inject the chemical. Therefore, the optimal amount of CLA was specified between 15 and 25 weight percent.

3.2. Compatibility test

The results of the compatibility test can be seen in **Fig 8**. In **Fig 8a**, the chemical is mixed with the formation water. As it is clear in part b, after 48 hours, no deposits were observed and this material is compatible with formation water. The box shown in part b of **Fig 8b** shows the complete curing of the polymer, revealing that formation water properties don't prevent the curing of the chemical.

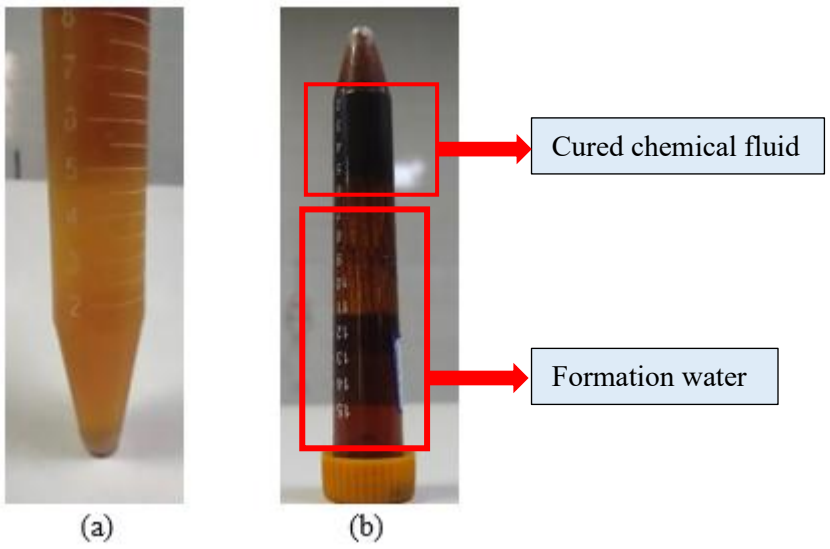


Fig 8. Compatibility of the chemical with formation water: a) The chemical and formation fluid before curing b) The chemical and formation water in contact with each other after 48 hours.

3.3. Viscosity measurement

Measuring the viscosity of the chemical is very important for the effective injection of polymer base chemicals and their placement in the formation. High viscosity can prevent the injection and penetration of the chemical into the loose sand. Viscosity is one of the main requirements for the use of CF in the chemical consolidation. Accordingly, the viscosity value should not be above 0.02 Pa.s (Talaghat, Esmaeilzadeh, and Mowla 2009). The viscosity of the chemical was measured with CF weight concentrations of 20%, 25%, 30% and CLA weight concentrations of 0.0%, 15%, 20%, and 25% at different temperatures (30 to 75°C) and a constant shear rate of

100 1/s. **Fig. 9** shows the diagram of viscosity change with temperature for the chemicals of different percentages of CF and CLA concentration. The result shows that the viscosity of chemicals is strongly affected by temperature (30 to 75 °C) and follows a decreasing trend with increasing temperature and decreasing the concentration of CF and CLA. Also, the viscosity of the chemicals shows that it has good rheological properties for chemical consolidation, and the viscosity of all the chemicals is below 6 cP. Under the different ranges of Temperature, the viscosities were observed in the acceptable range (Fuller et al. 2011; Mishra and Ojha 2016b).

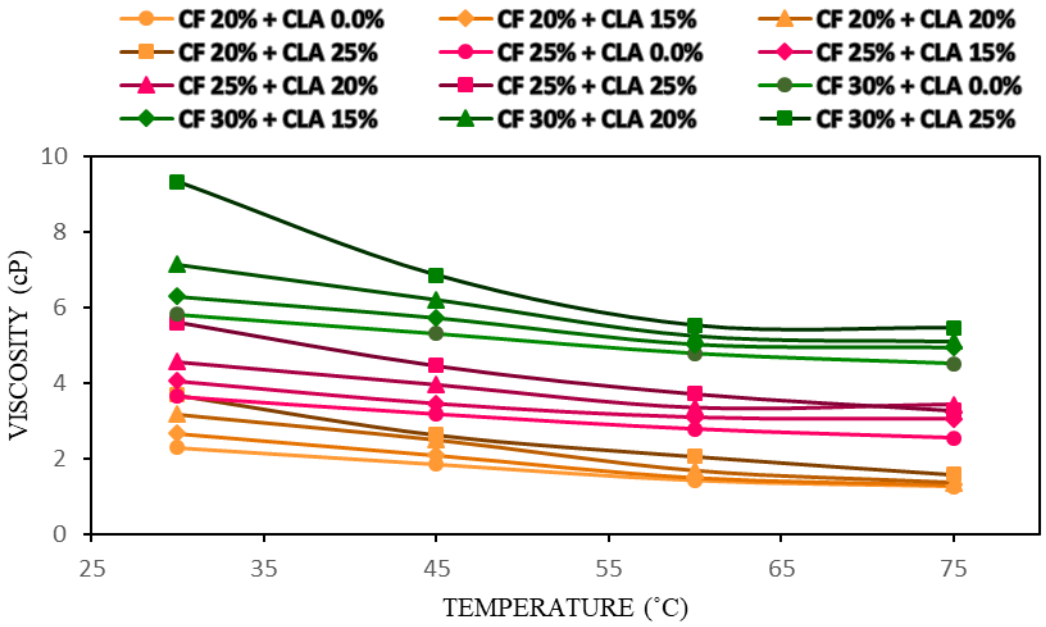


Fig. 9. Viscosity of the chemicals with different concentrations of CF and CLA at different temperatures

The viscosity of the optimal chemical (20% CF+18% CLA+ 0.75% SiO_2) was measured at the various conditions of shear rate and constant temperature of 50 ˚C. **Fig. 10** shows the variation in viscosity with different shear rates. The result shows that the viscosities of the chemical is affected by the shear rate (3.5 to 250 1/s) and follow a decreasing trend with the increase in shear rate. The viscosities were recorded in the range of 12.53 to 1.27 cP at the various shear rates 1/s.

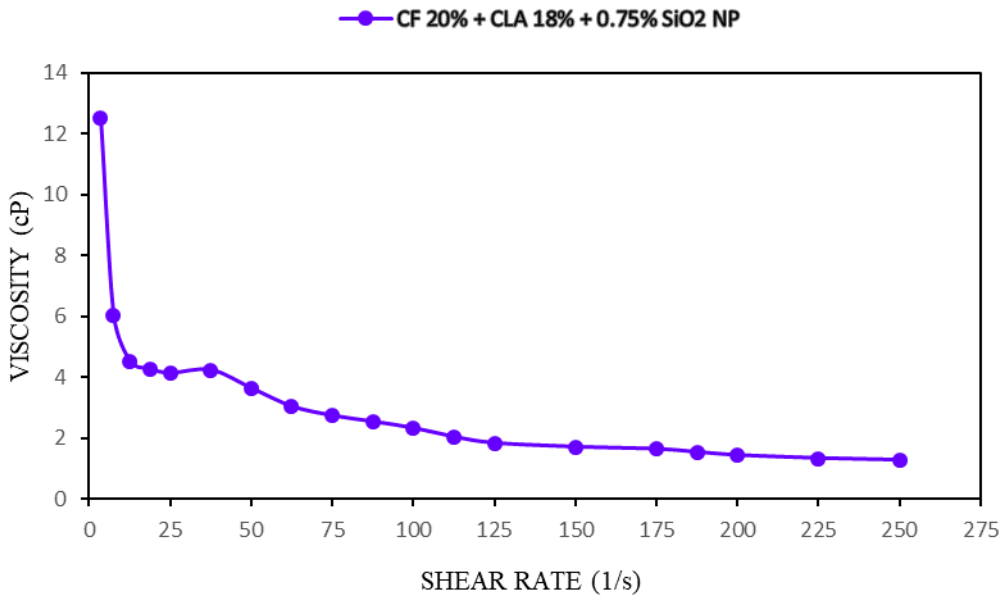


Fig. 10. Viscosity of the chemical with optimal concentrations of CF, CLA and, nanoparticle as a function of shear rate (1/s) at constant temperature of 50 ˚C.

3.4. Core injection stage

Initial compressive strength. At first cores number 7, 8, 9, and 23 were selected to measure the average initial compressive strength and the compressive strengths of the cores were equal to 938, 925, 979, and 964 psi, respectively. The average compressive strength of the selected cores was calculated at 952 psi. Therefore, the initial compressive strength of all cores was considered to be 952 psi.

3.5. Core injection with the chemical

This experiment was conducted in two phases. In the first phase, according to **Table 5**, injecting was done on 15 cores with different weight percentages of CF concentration and CLA.

Table 5. Core No. And Properties of injection fluid

Core No.	CF concentration (%)	CLA (%)
1	20	15
2	20	17
3	20	20
4	20	23
5	20	25
6	25	15

10	25	17
11	25	20
12	25	23
13	25	25
14	30	15
15	30	17
21	30	20
22	30	23
24	30	25

There are two key parameters in chemical consolidation: (1) compressive strength, and (2) retained permeability after chemical consolidation, which is critical to the effectiveness of consolidation operations in the target formation. The compressive strength must be sufficient against the forces caused by the high velocity of the reservoir fluid flow, while the reduction in permeability must be so minimal that it does not prevent oil production after chemical consolidation.

3.6. Compressive strength after chemical consolidation

During the fluid flow in the porous medium, compressive strength is one of the effective factors in controlling sand production. Also, high compressive strength and retained permeability is always preferred for chemical sand consolidation over other characteristics (Alakbari et al. 2020). **Fig. 11** shows a core sample with uniaxial compressive strength measured after fluid injection.



Fig. 11. Image of the injected core sample after the uniaxial compressive strength test

Fig. 12 shows the changes in the compressive strength of the cores after chemical consolidation with different percentages of CF concentration and CLA. In general, furan is the type of CF of thermoset materials that are

exposed to heat and irreversibly change from a liquid to a solid state. This category of polymers has a relatively low molecular weight. After injecting this material in the formation and placing it between the loose sand and adding the CLA, the curing process, i.e. the transformation from the liquid state to the solid state, happens with the polymer chains linking to a single molecule and the sand particles joining together. As can be seen, with the increase in polymer concentration, because of the formation of larger polymer networks, the compressive strength has increased. Also, by increasing the CLA, curing is done faster and better, and with the higher number of polymer networks, the compressive strength increases.

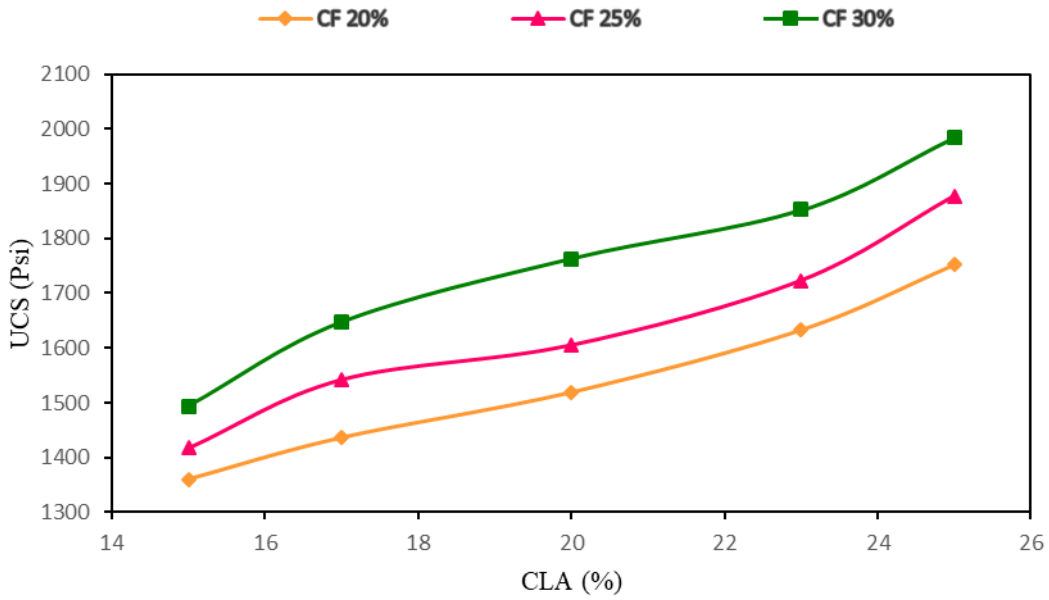


Fig. 12. Compressive strength after chemical consolidation

As can be seen in **Fig. 12**, the compressive strength has increased by between 408 and 1032 psi (Difference between initial and final compressive strength) with the injection of the chemical. The biggest increase is related to the chemical of 30 weight percentage CF concentration and 25 weight percent CLA.

Retained permeability. Permeability is a vital factor in investigating chemical consolidation after core injection. **Fig. 13** shows the percentages of retained permeability of cores after chemical consolidation by the chemicals with different percentages of CF concentration and CLA. As can be seen, with the increase in the concentration of CF and CLA, the permeability has decreased. With the increase in CF concentration and when the thickness of the CF on the surface of the sand grains and the formation of polymer networks become larger, the pore throat through which the fluid passes becomes narrower or closed. Also, by increasing the CLA, polymer networks are formed faster with higher CLA concentration, the number of networks contacts increases, and the rate of permeability reduction increases.

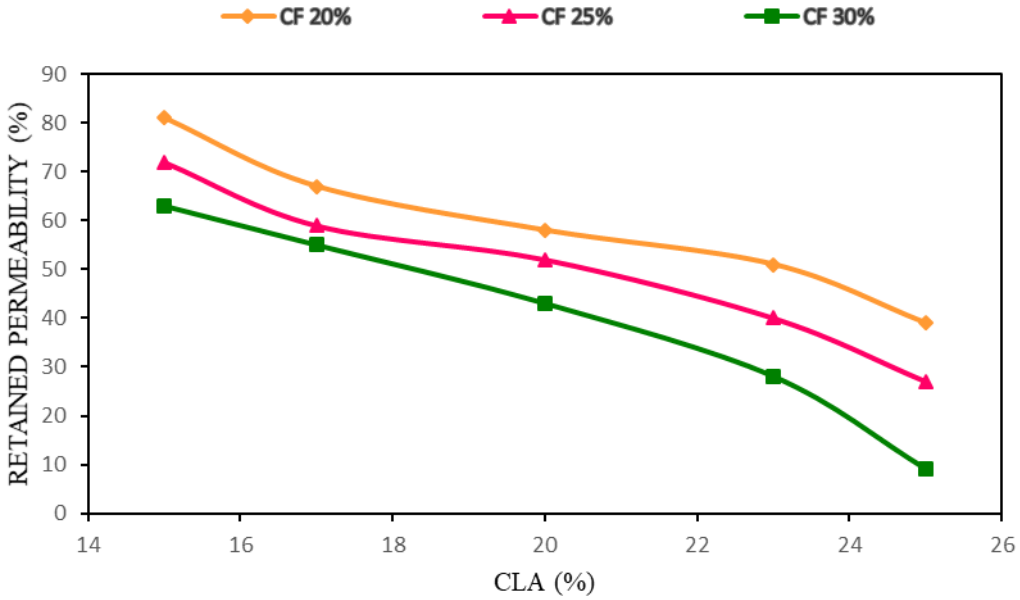


Fig. 13. Retained permeability after chemical consolidation

The retained permeability of the cores after chemical consolidation can be seen in **Fig 10**, which is between 81% and 9%. The lowest permeability reduction is related to the chemical solution of 20% CF concentration and 15% CLA.

To facilitate comparison between the findings of present study and those of previous research, **Table 6** presents the compressive strength and permeability values reported in earlier studies alongside the results obtained in the current investigation.

Table 6. Comparison with results of previous research

No.	Researcher and year	Chemical used	Regained permeability (%)	Compressive strength (psi)
1	(Fader et al. 1992)	Furan resin	85	600
2	(Parlar et al. 1998)	Furan resin	80	1200
3	(Osman et al. 2000)	Low-Temperature Oxidation(LTO)	82	980
4	(Mishra and Ojha 2016a)	Urea–formaldehyde, potassium silicate and Ammonium chloride	70	1300
5	(Vaidya et al. 2022)	New resin-based sand consolidation fluid	75	1000
6	(Recio et al. 2023)	New base resin composition	90	600
7	(Mishra, Chauhan, and Ojha 2024)	a blend of organic and inorganic silicates	64	2021

3.7. Determining the optimal concentration of CF and CLA

Considering the simultaneous increase in compressive strength with the decrease in permeability, an optimal concentration of the chemical should be found so that both important factors in chemical consolidation in loose sandstone formations are in their best state. In the second phase, the optimal percentage for the concentration of CF and the CLA was determined by optimization with the help of Python. Given that with the increase in the concentration of CF and CLA, the permeability decreases but the compressive strength increases, it is necessary to find an optimal amount of CLA and CF concentration. In this study, quadratic regression was employed to model the relationship between furan resin (CF) and crosslinker (CLA) concentrations (independent variables) and unconfined compressive strength (UCS) or permeability (dependent variables). This approach was selected

to account for potential nonlinear interactions between the variables, which preliminary data analysis suggested were critical to the system's behavior.

The quadratic regression model is expressed as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 + \varepsilon \quad (4)$$

Where:

x_1 = CF concentration

x_2 = CLA concentration

y = UCS or permeability

βi = regression coefficients,

ϵ = error term.

The optimization framework aimed to maximize UCS while minimizing permeability reduction. Realistic concentration ranges for CF and CLA were enforced as constraints to ensure practical applicability.

Optimization was done and the optimal amount of CLA was 18% and the CF concentration was 20%.

The effect of Nanoparticle

Injection of Nano-fluid into cores. At this phase, different weight percentages of SiO_2-Nanoparticles were added to the optimal weight concentration of the chemical. The final composition fluid was chemical solution of 20% CF concentration, 18% CLA and 0.0-1.0 %wt. of SiO_2 nanoparticles.

Permeability and compressive strength of cores after injecting the Nano-fluid

Fig. 14 shows the effect of SiO_2-Nanoparticles on the performance of the chemical on permeability and compressive strength. Nanoparticles can form a layer of integrated materials on the surface of loose sand to control sand production while retained permeability at an appropriate condition. This layer can bring the sand grains together and increase the compressive strength to facilitate oil production. In this study, because of the significant decrease in permeability in the previous phase by CF, SiO_2-Nanoparticles were added to the chemical. As it is known, by increasing the amount of SiO_2-Nanoparticles in the chemical, the compressive strength increased significantly, but the decrease in permeability was not noticeable. SiO_2-Nanoparticles are placed between the surface of the sand particle and the polymer network and make a better bonding between the surface of the sand particles and the polymer material and better consolidation and increase compressive strength (Alakbari et al. 2020).

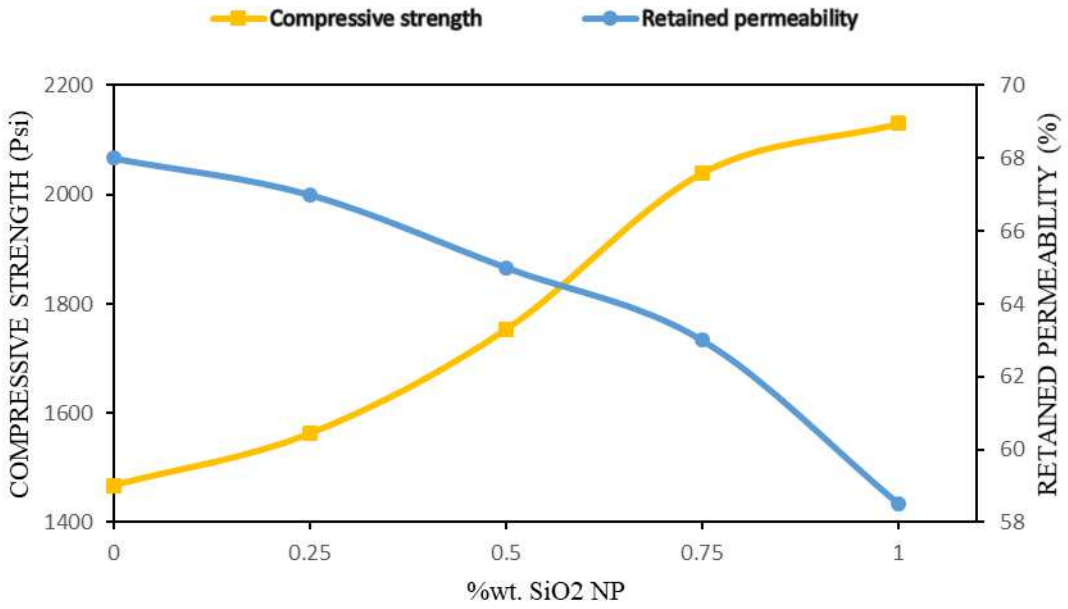


Fig. 14. The effect of change in SiO_2-Nanoparticles percentage on permeability and compressive strength

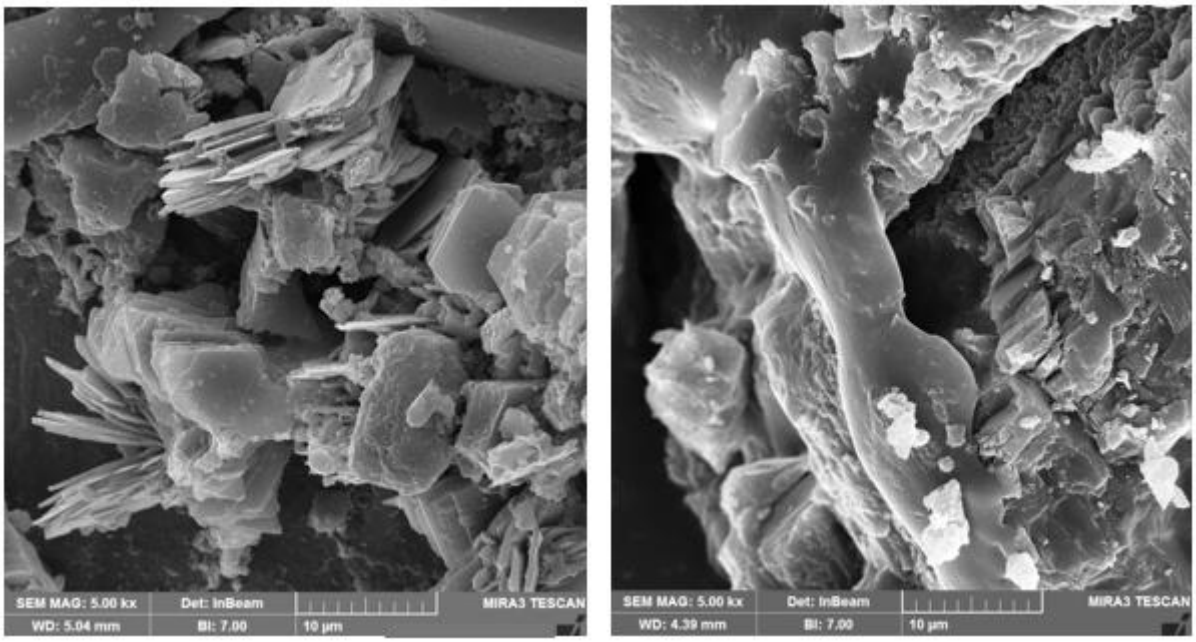
As can be seen in **Fig 14**, the final unconfined compressive strength (UCS) increased by between 515 and 1178 psi by injecting the Nano-fluid (The final UCS of consolidated cores ranged from 1,467 (952 + 515) psi to 2,130 (952 + 1,178) psi, where 952 psi is initial compressive strength). The biggest increase is related to the percentage of 1.0 %wt. Also, the retained permeability of cores after consolidation can be seen in **Fig 14**, which is between 68% and 58%. The results show that Nanoparticles can significantly increase the compressive strength while the permeability reduction is less significant. In 1992, a study showed that every 1000 psi increase in compressive strength can cause loose formations to resist 1700 psi of viscous force(Penberthy and Shaughnessy 1992). According to the trend of changes in compressive strength and permeability (**Fig 14**), the increase in compressive strength from 0.0 to 0.75% wt is larger than 0.75% to 1.0% wt, while the decrease in permeability from 0.75% to 1.0% wt is greater than 0.0 to 0.75% wt, so the optimal weight percentage of SiO_2-Nanoparticles was considered to be 0.75 %wt.

3.8. FESEM analysis

Fig. 15a presents the Field Emission Scanning Electron Microscopy (FESEM) image of the outcrop sample in its pre-consolidation state, displaying the original morphology of unconsolidated sand particles. **Fig. 15b** depicts the post-consolidation microstructure, where a cured polymer network film uniformly coats the particle surfaces. This film:

- Enhances intergranular bonding through adhesive forces, improving mechanical integrity.
- The polymer film bridges adjacent grains, reinforcing grain-to-grain connections and increasing the sample's Unconfined Compressive Strength (UCS).
- Despite consolidation, pore throats remain open, maintaining hydraulic conductivity for fluid flow.

Fig. 15b highlights the interconnected particle network, where the bonding between the grains have been strengthened while the connection between the pore throats and void spaces had been maintained, so this process exemplifies targeted consolidation to strengthen loose formation while retaining permeability for fluid flow.



(a) **(b)**

Fig. 15. a) FESEM image of the outcrop sample before chemical consolidation, b) FESEM analysis related to consolidated outcrop sample

3.9. Chemical consolidation of formation sand core sample

For investigating the ability of the Nano-fluid to create in-situ consolidation, four sand core samples with optimal concentrations of CF, CLA, and SiO_2-Nanoparticle were made. The compressive strength of the four sand core samples is shown in **Fig. 16**. The highest compressive strength of sand core samples was 1704 psi and the lowest compressive strength was 1645 psi. The average compressive strength obtained from the sand core samples was calculated to 1679 psi, which shows that the selected Nano-fluid can create in-situ consolidation. The difference in compressive strength between the four sand core samples could be caused by placement of sand particles. Moreover, as the used sands are free of clay and shale materials are not present on the surface of the sand, the chemical has created stronger chemical bonds with higher strength between the sand particles, and hence, a higher compressive strength compared to the case with shale has been achieved. Also, the impregnation of all sand particles with the chemical, a higher compressive strength has been obtained compared to the case of injecting the chemical.

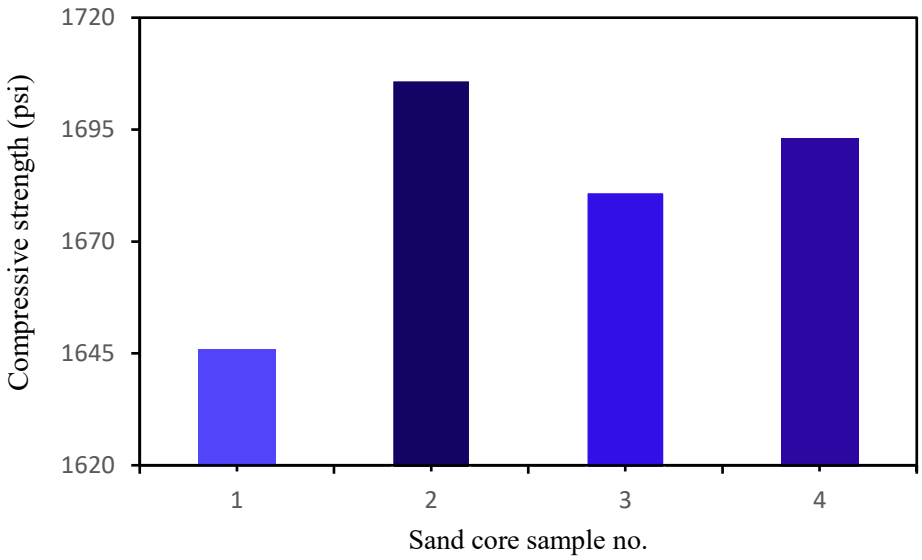
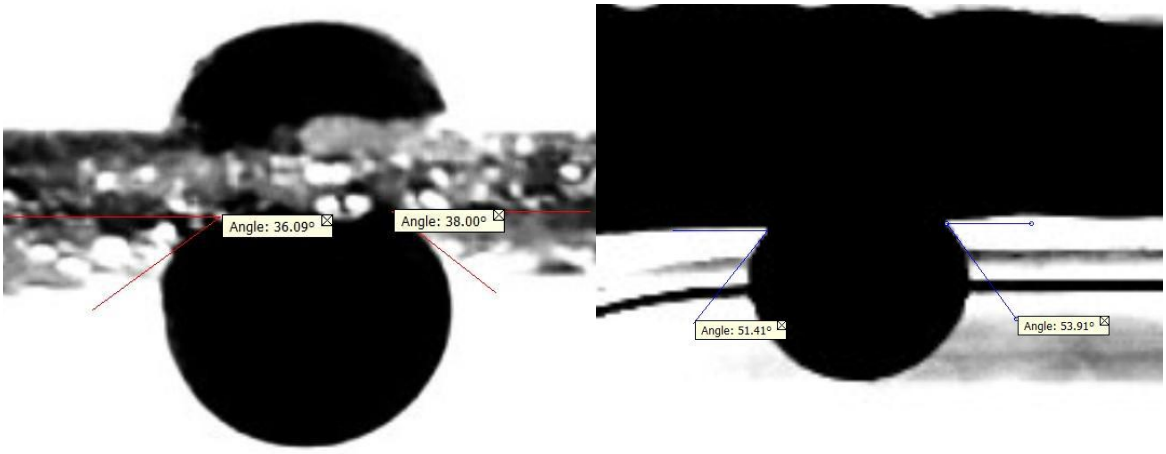


Fig. 16. Compressive strength of the man-made formation sand core samples

3.10. Wettability alteration

In this study, wettability has been measured with the help of contact angle in 2 states: 1. Before chemical consolidation, 2. After chemical consolidation with the optimal concentration of the chemical. **Fig. 17** shows the contact angles of the oil droplet with the surface of a thin section in the presence of the formation water in the two cases mentioned.



(A) (B)

Fig. 17. The contact angle of the oil droplet with the surface of the thin section A) before chemical consolidation and B) after chemical consolidation)

Fig. 17b shows the contact angle of the oil droplet with the consolidated thin section. The contact angle of the oil droplet in the presence of formation water in this case is in the range of 126.09° to 128.59°. By comparing it with the state before chemical consolidation (**Fig. 17a**), where the contact angle of the rock sample with the oil droplet

is in the range of 142° to 143.91°, it can be understood that by injecting the chemical solution into the core, its water-wet state has reduced, but still, it is completely water-wet.

3.11. TGA/DTA

To measure the thermal stability, TGA and DTA analysis were performed. **Fig. 18** shows the difference between two chemical states with and without nanoparticles. As can be seen from **Fig. 18a**, the addition of nanoparticle to the desired chemical has increased its thermal resistance so that its mass loss has decreased from about 50% to less than 28%.

From **Fig. 18b**, three main thermal degradations for the chemical without nanoparticle and two main degradations for the chemical with the nanoparticle can be identified, at which points the slope of the TGA plot has changed and a hump has been created in the DTA diagram. For both analyzed chemicals, one of these changes is observed between 90 and 110 ˚C and the other is observed in the temperature range of 300 and 310 ˚C, and in addition, according to **Fig. 18b**, in the range of 380 to 390 ˚C, the chemical without nanoparticle also has another temperature degradation. The first basic degradation is the result of the release of volatile compounds, existing water and gases trapped in polymer networks, while the next basic degradations are related to the breaking of polymer networks and the destruction of polymer chain bonds. The three-stage degradation of the chemical without nanoparticle in comparison with the two-stage degradation of the Nano-fluid, and also, as can be seen from **Fig. 18b**, the changes in mass with respect to temperature changes in the chemical where nanoparticle are used are more than in the chemical without nanoparticle.

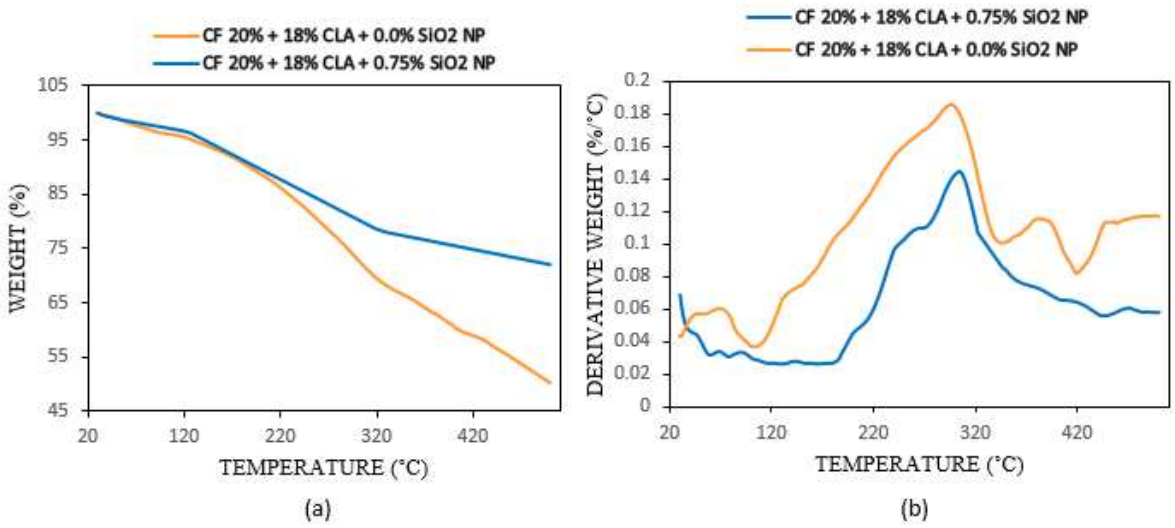


Fig. 18. Effect of SiO_2-Nanoparticle addition on thermal stability. a) TGA diagram, b) DTA diagram

Two reasons are mentioned are acceptable justification for the greater reduction in the mass of the chemical without nanoparticle compared to the Nano-fluid and as a result the increase in thermal resistance due to the addition of nanoparticle.

4. Conclusion

Based on this study, the following results were obtained concerning the potential performance of the selected in controlling sand production:

- The results of the curing process at atmospheric pressure and high pressure showed that the amount of pressure has an effect on curing and its quality.
- The chemical obtained from the CF is compatible with the formation fluids and also the results show that the characteristics of the formation fluid affect the minimum amount of CLA.
- The results of measuring the compressive strength of the cores showed that the compressive strength of the cores increases with the increase in the concentration of CF, and CLA.
- The measurement of the permeability of the cores after the chemical consolidation process showed that with the increase in the concentration of CF and percentage of CLA, the retained permeability of the cores decreases too much.
- The contact angle of the formation fluids with the surface of the thin section after the chemical consolidation process showed that the chemical has no significant effect on rock wettability and the rock surface remains water wet.
- The addition of SiO_2-Nanoparticle to the composition of the chemical had such a substantial effect on its performance that the compressive strength of the outcrop cores increased greatly and was accompanied by a slight decrease in the permeability compared to the composition without Nanoparticle.
- The results showed that the Nano-fluid has the good ability to create compressive strength.

Data availability: The datasets generated and/or analysed during the current study are not publicly available due [REASON WHY DATA ARE NOT PUBLIC] but are available from the corresponding author on reasonable request.

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References

Alakbari, Fahd Saeed, Mysara Eissa Mohyaldinn, Ali Samer Muhsan, Nurul Hasan, and Tarek Ganat. 2020. 'Chemical sand consolidation: From polymers to nanoparticles', Polymers, 12: 1069.

Banashooshtari, Hooman, Ehsan Khamehchi, Fariborz Rashidi, and Matin Dargi. 2024. 'An experimental study of epoxy-based nanocomposite for chemical consolidation in a sandstone reservoir with high clay content', Journal of petroleum exploration and production technology: 1-16.

Brydson, John Andrew. 1999. Plastics materials (Elsevier).

Chuah, Beng-Swee, AR Hasumi, Noren Samsudin, and Ahmadbazlee Matzain. 1994. "Formation Damage in Gravel Packed and Non-Gravel Packed Completions: A Comprehensive Case Study." In SPE International Conference and Exhibition on Formation Damage Control, SPE-27360-MS. SPE.

Coppock, Kathleen Marie Pittman. 1996. Durable wood adhesives from furfural-based diols, diamines, and diisocyanates (The University of Wisconsin-Madison).

Dewprashad, Brahmadeo, HH Abass, DL Meadows, JD Weaver, and BJ Bennett. 1993. "A method to select resin-coated proppants." In SPE Annual Technical Conference and Exhibition?, SPE-26523-MS. SPE.

Du, Juan, Qisheng Huang, Pingli Liu, Yangyang Fu, Jinming Liu, Xiang Chen, and Yaoshun Yuan. 2024. 'Review of Recent Advances in Chemical Sand Production Control: Materials, Methods, Mechanisms, and Future Perspectives', Energy & Fuels, 38: 21845-72.

Fader, PD, BW Surles, NJ Shotts, and BA Littlefield. 1992. "New low-cost resin system for sand and water control." In SPE Western Regional Meeting, SPE-24051-MS. SPE.

Farias, Rodrigo, Jeff Li, A Vilela, and R Aboud. 2007. "Openhole horizontal gravel packing offshore Brazil: best practices and lessons learned from 72 operations." In SPE Latin America and Caribbean Petroleum Engineering Conference, SPE-107190-MS. SPE.

Fuller, Michael J, Ricardo A Gomez, Joel Gill, Cesar Guimaraes, Ardestya Ferta Abdurachman, Vladimir Chaloupka, and Rio Descapria. 2011. "Development of new sand consolidation fluid and field application in shallow gas reservoirs." In SPE Asia Pacific Oil and Gas Conference and Exhibition, SPE-145409-MS. SPE.

George C, Shoy, Philip Nguyen D, and Prajakta Patil. 2019. "Novel Non-Damaging Hybrid System for Sand Consolidation Application." In International Petroleum Technology Conference, D021S23R01. IPTC.

Gonsalves, KE, and X Chen. 1996. 'The Polymeric Materials Encyclopaedia: Synthesis, Properties and Applications', Salamone, JC, Ed: 3256.
Haavind, Frode, Sissel Solberg Bekkelund, Arild Moen, Hans Kristian Kotlar, Jamie Stuart Andrews, and T Håland. 2008. "Experience with chemical sand consolidation as a remedial sand-control option on the Heidrun Field." In SPE International Conference and Exhibition on Formation Damage Control, SPE-112397-MS. SPE.
Karian, Mohd Awallizam, Alias Salleh, Jamaludin Haron, Mohamed Adzman Mohamed Sura, and Ruziean A Rashid. 1999. "Resin Sand Consolidation In Baram Delta, Sarawak. Case Study On Resin Performance versus Internal Gravelpacking With Acid Prepacking." In SPE International Improved Oil Recovery Conference in Asia Pacific, SPE-57314-MS. SPE.
King, George E, Pat J Wildt, and Eamonn O'Connell. 2003. "Sand control completion reliability and failure rate comparison with a multi-thousand well database." In SPE Annual Technical Conference and Exhibition?, SPE-84262-MS. SPE.
Kotlar, Hans Kristian, Frode Haavind, Martin Springer, Sissel Solberg Bekkelund, and Ole Torsaeter. 2005. "A new concept of chemical sand consolidation: From idea and laboratory qualification to field application." In SPE Annual Technical Conference and Exhibition?, SPE-95723-MS. SPE.
Mishra, Saurabh, Geetanjali Chauhan, and Keka Ojha. 2024. 'An experimental study on optimizing parameters for sand consolidation with organic-inorganic silicate solutions', Petroleum, 10: 483-93.
Mishra, Saurabh, and Keka Ojha. 2016a. 'Application of an improvised inorganic–organic chemical mixture to consolidate loose sand formations in oil fields', Journal of Petroleum Science and Engineering, 137: 1-9.
———. 2016b. 'Nanoparticle induced chemical system for consolidating loosely bound sand formations in oil fields', Journal of Petroleum Science and Engineering, 147: 15-23.
Morgan, Quentin Peter, James Elliott Phillips, Gareth Lyle Innes, Drew E Hembling, Alistair Russell Macarthur, and Ibrahim Meselh Refai. 2005. "Expandable Sandface Completions—A Journey From Single-Zone Applications to Next-Generation Multizone Systems." In International Petroleum Technology Conference, IPTC-10284-MS. IPTC.
Nejati, Hamed, Ehsan Khamehchi, Ali Ashraf Derakhshan, and Saeed Shad. 2023. 'Synthesis and optimization of a Novel epoxy-based nanofluid for sand consolidation in oil wells', Geoenergy Science and Engineering, 230: 212217.
Nguyen, Philip Duke, and Richard Dale Rickman. 2012. "Foaming Aqueous-Based Curable Treatment Fluids Enhances Placement and Consolidation Performance." In SPE International Conference and Exhibition on Formation Damage Control, SPE-151002-MS. SPE.
Parker Jr, P Harold, BR Treadway, and H Brandt. 1967. 'Oil well sand consolidation. I. Resins for a three-step process', Journal of Applied Polymer Science, 11: 1667-82.
Parlar, M, SA Ali, R Hoss, DJ Wagner, L King, C Zeiler, and R Thomas. 1998. "New Chemistry and Improved Placement Practices Enhance Resin Consolidation: Case Histories From the Gulf of Mexico." In SPE International Conference and Exhibition on Formation Damage Control, SPE-39435-MS. SPE.
Penberthy, WL, and CM Shaughnessy. 1992. 'Sand control', (No Title).
Recio, Antonio, Denise N Benoit, Michael W Sanders, and Philip D Nguyen. 2023. "Long Interval Chemical Consolidation of Failing Clay Laden Formations: A Departure from Epoxy-Based Resins." In SPE International Conference on Oilfield Chemistry. OnePetro.
Rike, JL. 1966. 'Review of sand consolidation experience in South Louisiana', Journal of Petroleum Technology, 18: 545-50.
Shahsavari, Mohammad Hossein, and Ehsan Khamehchi. 2018. 'Optimum selection of sand control method using a combination of MCDM and DOE techniques', Journal of Petroleum Science and Engineering, 171: 229-41.
Shu, Paul. 1996. "Water compatible chemical in situ and sand consolidation with furan resin." In.: Google Patents.
Smith, TK. 1969. "Sand consolidation through production tubing." In Drilling and Production Practice. OnePetro.
Soter, K, J Malbrough, D Mayfield, and Jeff Holland. 2005. "Medusa Project: Integrated Planning for Successful Deepwater Gulf of Mexico Completions." In SPE Annual Technical Conference and Exhibition?, SPE-97144-MS. SPE.
Tabbakhzadeh, Mohammad Nabi, Feridun Esmaeilzadeh, Dariush Mowla, and Reza Zabihi. 2024. 'Effects of reservoir fluids on sand packs consolidated by furan and epoxy resins: Static and dynamic states', Journal of Rock Mechanics and Geotechnical Engineering, 16: 4504-14.
Tabbakhzadeh, Mohammad Nabi, Feridun Esmaeilzadeh, Reza Zabihi, and Dariush Mowla. 2020. 'Experimental study of chemical sand consolidation using epoxy and furan resins for oil wells: Experimental design models', International Journal of Rock Mechanics and Mining Sciences, 135: 104486.
Talaghat, MR, F Esmaeilzadeh, and D Mowla. 2009. 'Sand production control by chemical consolidation', Journal of Petroleum Science and Engineering, 67: 34-40.
Vaidya, Nirupama, Rasika Prabhu, Juan-Carlos Santamaria, Patrice Abivin, and Josh Susmarski. 2022. "A Sustainable Fluid System for Sand Consolidation." In SPE International Conference and Exhibition on Formation Damage Control, D011S01R04. SPE.
Villesca, Josue, Santiago Loboguerrero, Jesse Gracia, Ann Hansford, Philip Duke Nguyen, Richard Dale Rickman, and Ronald Glen Dusterhoft. 2010. "Development and field applications of an aqueous-based consolidation system for proppant remedial treatments." In SPE International Conference and Exhibition on Formation Damage Control, SPE-128025-MS. SPE.
Wang, Ru-Min, Shui-Rong Zheng, and Yujun George Zheng. 2011. Polymer matrix composites and technology (Elsevier).
Yuan, Bin, Rouzbeh Ghanbarnezhad Moghanloo, and Purachet Pattamasingh. 2015. "Applying method of characteristics to study utilization of nanoparticles to reduce fines migration in deepwater reservoirs." In SPE European Formation Damage Conference and Exhibition, SPE-174192-MS. SPE.