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Removal Efficiency of Water-Based Drill-In Fluid Filter Cake Using Polylactic Acid

S.M. Elkatatny, and H.A. Nasr-El-Din, Texas A&M University, All SPE members

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Abstract

Water-based drilling fluids consisting of xanthan gum, starch, sized calcium carbonate and salt particles have been used to drill horizontal wells. Available chemical methods of removing filter cake like mineral acids, esters, oxidizers, and chelating agents are limited at certain conditions.

Drilling fluid was designed based on calcium carbonate particles and an ester of lactic acid. The objective of the latter is to remove calcium carbonate once the drilling operation is complete and there is a need to remove the filter cake. Extensive lab work was done to: 1) determine thermal stability of the drilling fluid (70-72 pcf) for 24 hrs, 2) characterize the filter cake using computer tomography, 3) assess potential formation damage for different rock types (limestone and sandstone) using a modified HPHT filter press, and 4) determine the removal efficiency of the filter cake and the return permeability.

The results obtained showed that the drill-in fluid has stable rheological properties up to 250°F over 24 hrs. A CT scan showed that the filter cake contained two layers, one layer close to the rock surface, which contained a mixture of calcium carbonate and acid-precursor, and one layer close to the drilling fluid that contained a mixture of XC-polymer and starch. The polymer layer was removed by using 10% solution of alpha amylase. The rest of the filter cake was removed by lactic acid that was produced from the hydrolysis of the ester. The removal efficiency of the filter cake was nearly 100% and the return permeability was about 100%, when using a ratio of polylactic acid to calcium carbonate 3 to 1. The decrease in the CT number of the core after the removal process indicated that the filter cake was completely removed and no formation damage occurred. This paper will discuss the development of this new drilling fluid and will give recommendations for field applications.

Introduction

Water-based drill-in fluid used to drill most of the target zone is composed of XC-polymer, starch, potassium chloride, and calcium carbonate. XC-polymer provides non-Newtonian behavior, which is required to provide the viscosity in annular flow, which is important for efficient cutting lifting in normal density mud. Potassium chloride is added for clay control and to minimize problems associated with fines migration. Starch is used to control fluid loss into the formation and calcium carbonate is used as a bridging material to minimize the filtration of drilling fluid into the formation.

Drill-in fluids are typically formulated to deposit a thin, relatively impermeable filter cake, which will seal the wellbore and minimize fluid leak off into the formation, Nasr-El-Din et al. (2005). The level of the near-wellbore formation damage caused by drill-in fluids depends on the drilling fluid characteristics, formation properties, and operation conditions; such as overbalance pressure, temperature, and solid loading, Ding et al. (2006).

Calcium carbonate-based filter cake cleanup fluids could be composed of acids, chelating agent, oxidizers, enzyme treatments, or combinations of these materials. Acid will react with calcium carbonate very rapidly at downhole conditions and will cause rapid consumption of calcium carbonate at the point at which acid is introduced to the wellbore. This can lead to localized cleanup, excessive local losses, and an inability to circulate acid to the rest of wellbore section, Buijse et al (2004). Ryan et al. (1995) and Burnett (1998) stated that large volume of acid is usually lost into the formation due to leak off.

Parlar et al. (1998) mentioned that it is not recommended to use acids in long horizontal wells because of the large volume of acid required to remove the filter cake. Hodge at al. (1997) studied the effect of using oxidizers to remove calcium carbonate filter cake. They concluded that oxidizers were not effective to remove the polymer damage, especially in horizontal intervals.

Enzymes have some limitations; for example, they will only attack specific polymer chains, and the calcium carbonate components will be not completely removed, Battistel et al., (2005). Hembling at al., (2000) mentioned that enzyme did not completely remove the filter cake. Al-Otabi et al., (2004) concluded that specific enzymes were effective in removing most of drill-in fluid filter cake and they were able to break XC-polymer and starch that is used in the drill-in fluid.

Bradshaw et al., (2006) used chelating agents as a breaker to remove filter cake damage and they found that the soaking time for different wells ranged from 15 to 110 days. Collins et al., (2011) mentioned that chelating agents such as EDTA, HEDTA, DTPA, and NTA have been used to remove calcium carbonate filter cake, but these chelating agents have some environmental and safety issues. EDTA and HEDTA are not readily biodegradable; while NTA is really biodegradable, it is potentially hazardous to humans and therefore creates handling and environmental discharge concerns, Frenier et al., (2003).

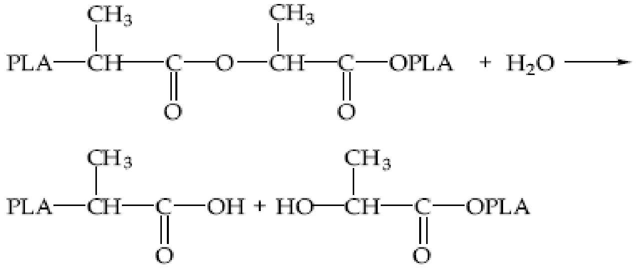
Theory and background of polylactic Acid (PLA)

Poly (lactic acid) (PLA) belongs to the family of aliphatic polyesters commonly made from α-hydroxy acids, which are considered biodegradable and compostable. PLA is a thermoplastic, high-strength, high-modulus that can be made from annually renewable resources to yield articles for use in either the industrial packaging field or the biocompatible/bioabsorbable medical device market, Hartmann (1998). PLA is not new to the world of polymers. Carothers et al. (1932) investigated the production of PLA from the cyclic dimer (lactide) of lactic acid. PLA undergoes thermal degradation at temperatures above 200°C (392°F), by hydrolysis or lactide reformation. PLA degradation is dependent on time, temperature, low-molecular-weight impurities, and catalyst concentration, Jamshidi et al. (1998). PLA has a degradation time in the environment in the order of six months to two years, which compares to 500 to 1000 years for conventional plastics such as polystyrene and polyethylene, Sinclair (1996).

The basic building block for PLA is lactic acid (2-hydroxypropionic acid), which is highly water-soluble. **Fig. 1** shows the known routed to high-molecular weight PLA; condensation/coupling, azeotropic dehydrative condensation, or ring-opening polymerization of lactide, Datta et al. (1995). Lactic acid is condensation polymerized to yield a low-molecular weight, brittle, glass polymer, which is unusable for any applications unless external coupling agents are used to increase the molecular weight of the polymer. The second route of producing PLA is to collect and ring-open polymerize (ROP) lactide to yield high-molecular weight of an average of 100,000.

Witzke (1997) and Tsuji et al. (1999) mentioned that PLA can be either amorphous or semicrystalline, depending on the stereochemistry and thermal history. For amorphous PLAs, the glass transition (Tg) determines the upper use temperature for most commercial applications. For semicrystalline PLAs, both the Tg (~58°C) and melting point (Tm), 130–230°C (depending on structure) are important for determining the use temperatures across various applications. Bigg (1996) mentioned that PLA quickly losses its thermal stability when heated above the melting point. A significant level of molecular degradation occurred when PLA was held 10°C above its melting point (160°C). Migliares et al. (1991) has shown that thermal degradation was due to chain splitting and not hydrolysis.

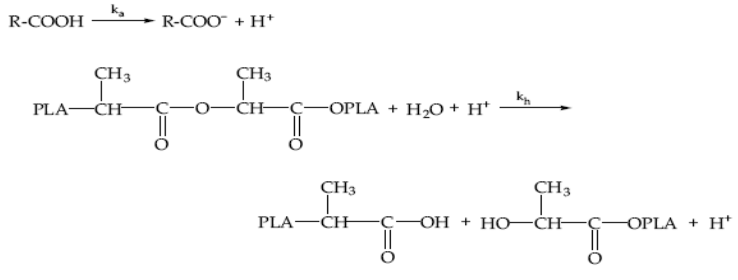
Spinu (1993) and Kylma et al. (1997) stated that due to the impermeability of the crystalline region highly crystalline PLA will take months or years to hydrolyze fully to lactic acid, where an amorphous sample is degraded in weeks. Degradation of PLA is primarily due to hydrolysis of the ester linkages, which occurs more or less randomly along the backbone of the polymer. It requires the presence of water according to the following reaction:



$$\mathrm{PLA{-}\overset{CH_3}{CH}{-}\underset{O}{\overset{\|}{C}}{-}O{-}\overset{CH_3}{CH}{-}\underset{O}{\overset{\|}{C}}{-}OPLA} + H_2O \longrightarrow$$

$$\mathrm{PLA{-}\overset{CH_3}{CH}{-}\underset{O}{\overset{\|}{C}}{-}OH} + \mathrm{HO{-}\overset{CH_3}{CH}{-}\underset{O}{\overset{\|}{C}}{-}OPLA}$$

Hydrolytic degradation of PLA is autocatalytic due to the production of carboxylic acid end groups that catalyze further hydrolysis, Joziasse et al. (1998). The rate of degradation is strongly influenced by the number average molecular weight, Vert et al. (1997). The presence of lactide also increased the rate of hydrolytic degradation, Hyon et al. (1998). The autocatalytic hydrolysis reaction is the following:



$$\mathrm{R{-}COOH} \xrightarrow{k_a} \mathrm{R{-}COO^-} + H^+$$

$$\mathrm{PLA{-}\overset{CH_3}{CH}{-}\underset{O}{\overset{\|}{C}}{-}O{-}\overset{CH_3}{CH}{-}\underset{O}{\overset{\|}{C}}{-}OPLA} + H_2O + H^+ \xrightarrow{k_h}$$

$$\mathrm{PLA{-}\overset{CH_3}{CH}{-}\underset{O}{\overset{\|}{C}}{-}OH} + \mathrm{HO{-}\overset{CH_3}{CH}{-}\underset{O}{\overset{\|}{C}}{-}OPLA} + H^+$$

Willberg and Dismuk (2009) introduced a new method to remove calcium carbonate filter cake, in which polylactic acid was used as a solid-acid precursor. They mentioned that lactic acid which was generated from PLA is effective for dissolution of calcium carbonate. The rate of hydrolysis of PLA depends on; temperature, surface area, molecular weight, and degree of crystallinity. Rostami and Nasr-El-Din (2010) stated that PLA did not change the drilling fluid properties and this approach has a removal efficiency of 70% for calcium carbonate filter cake with a particle size of PLA 150 of micron.

The objective of this study are; 1) measure the thermal stability of a drill-in fluid that contains PLA, 2) obtain the optimum ration of PLA to calcium carbonate, 3) characterize the filter cake using computer tomography, 4) calculate the removal efficiency, and 5) assess the retained permeability of different cores to determine the formation damage probability.

Experimental Work

Material

Water-based drill-in fluid was prepared and mixed as shown in **Table 1**. Calcium carbonate (D_{50} = 50 µm) was used as a weighting material, KCl was used for clay stabilization, XC-Polymer was used to adjust the viscosity, starch was used for filtration control, and solid polylactic acid (D_{50} =150 µm) was used as a solid-acid precursor.

The PLA was obtained from ICO Polymers and it has molecular weights up to about 100,000. PLA's specific gravity is 1.24 g/cm^3. The available PLA has a high ratio of amorphous to crystal particles with particle sizes of 150 µm. α-amylase enzyme was obtained from Baker Hughes. This type of enzyme contains stabilizer that can be used up to 250 °C, Samuel et al. (2010).

Table 2 shows properties and types of the cores which were used to simulate the reservoir formation. Indiana limestone core were cut from a block with an average porosity of 23 vol% and an average permeability of 100 md. Berea sandstone cores were obtained from a block with an average porosity of 18 vol% and an average permeability of 50-60 md.

Properties of Drilling Fluid

Table 3 summarizes the properties of the drill-in fluid. The drill-in fluid has a density of 72 pcf, which was measured at 75°F, plastic viscosity of 11 cp, which was measured at 120°F, yield point of 18 lb/100ft^2, which was measured at 120°F, Gel strength of 3 and 4 was measured at 120°F for 10 s and 10 min, respectively, and pH of 10 - 11, which was measured at 75°F. All the properties were measured at atmospheric pressure.

Table 4 shows sieve analyses results, which were made for the solid components in the drill-in fluid. **Fig. 2** shows that the D_{50} = 85 µm.

Thermal Stability of the Drill-in Fluid

In order to measure the thermal stability of the drill-in fluid that contained PLA as a solid-acid precursor, the following procedure was done:

1. The drill-in fluid was prepared and mixed as shown in **Table 1**
2. The drill-in fluid was put in a steel aging cell, which was pressurized to 300 psi
3. The cell was placed in the oven under rolling at a temperature of 250°F for a required time
4. The cell was taken and cooled down and the drill-in fluid properties were measured
5. The above procedure was repeated for a new drill-in fluid for a new time step

Results and Discussion

Thermal Stability of the Drill-in Fluid

The properties of the drill-in fluid were measured after hot rolling for 4, 8, 12, 16, 20, and 24 hrs. It was noticed that there was no phase separation even after 24 hrs. **Table 5** summarizes the change of the properties with time. **Fig. 3** shows that the density of the drill-in fluid slightly increased from 72 to 74 pcf after 4 hrs only. This was because all the bubbles went out from the drill-in fluid under the effect of temperature. Drill-in fluid viscosity was constant for 12 hrs at 11cp and it was decreased to 9 cp due to the initial hydrolysis of PLA, **Fig. 4**. The yield point and gel strength properties were constant for 8 hrs and increased by a small amount after partial hydrolysis of PLA and some of the water was consumed in the chemical reaction, **Fig. 5**. The drill-in fluid pH value was continuously decreased until it reached a near constant value after 12 hrs, which indicated that a certain amount of PLA was hydrolyzed form lactic acid and the rate of hydrolysis was small and became near constant after 12 hrs, **Fig. 6**.

HPHT Filter Press

A modified cell was used to perform the filtration process, in which a core of 1 in. length and 2.5 in. diameter was used to simulate the reservoir section, **Fig. 7**. The drilling fluid was prepared and put in the modified cell. The cell was placed in the heating jacket, temperature was adjusted at 225°F, and differential pressure was applied at 300 psi. **Fig. 8** shows a high amount of filtration was found when using $CaCO_3$ to PLA ratio of 1:1. The spurt loss was 4.4 cm^3 and the total amount of filtration was 18 cm^3.

The formed filter was soaked with 200 cm^3 of water for 24 hrs at 225°F and 300 psi. **Fig. 9** shows that there was not any reaction and the filter cake was not removed from the rock surface. The experiment was repeated under dynamic conditions

(150 RPM) and the same result was obtained. In order to figure out what happened, a CT scan was made to characterize the filter cake.

Fig. 10 shows that the filter cake was heterogonous that contained two layers. The layer closer to rock surface has an average CTN (number) of 1100 and it contained the solid particles of CaCO3 and PLA. The layer closer to drilling fluid has an average CTN of 400 and it contained mainly a mixture of starch and polymer, which completely isolated the contact between water and PLA and hence there was no reaction.

To remove the polymer layer, it was decided to use 10 wt% α-amylase enzyme solution, **Table 5**. This type of enzyme with stabilizer can be used to remove the polymer layer at 250°F. **Fig. 11** shows that the polymer layer was completely removed after soaking with the enzyme solution for 20 hrs; while most of the layer closer to rock surface was removed.

By using PLA to $CaCO_3$ ratio 1:1, there were two issues; a high amount of filtration (18 cm^3) and low removal efficiency 65%. To decrease the amount of filtration it was decided to use a mixture of calcium carbonate particle sizes. The ratio of fine (25 µm) to medium (50 µm) was 2:1. **Fig. 8** shows reduction of spurt loss to 2.3 cm^3 and a reduction in the total filtration amount to 12.6 cm^3 when using a mixture of calcium carbonate particles. To increase the removal efficiency, it was decided to increase the amount of PLA to be equal to double the amount of calcium carbonate.

Removal efficiency

The removal efficiency was increased to 90% by increasing the ratio of PLA to $CaCO_3$ (2:1), **Fig. 12**. The soaking time with 10 wt% α-amylase enzyme was 20 hrs. There was no improvement of removal efficiency when increasing the soaking time to 25 hrs. The removal efficiency was calculated using Eq. 1.

$$Efficiency = \frac{W_2 - W_3}{W_2 - W_1}, \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where

W_1 = the weight of the disk saturated with water, g
W_2 = the weight of the disk with filter cake, g
W_3 = the weight of the disk after removal process, g

Table 7 summarizes the calculation of removal efficiency of limestone and sandstone cores based on Eq. 1. In order to obtain higher removal efficiency, the ratio of PLA to $CaCO_3$ was increased to 3:1. **Fig. 13** shows that the surface of the limestone core was very clean when increasing the ratio of PLA to $CaCO_3$ to 3:1 with 10 wt % α-amylase enzyme for 24 hrs. The removal efficiency was 100%.

In order to minimize the cost of enzyme, the concentration was decreased to 5 wt%. It was noticed that there was a residue of calcium carbonate particles on the limestone core surface after soaking for 24 hrs, **Fig. 14**. It can be concluded that the amount of enzyme was not enough to remove the polymer layer and some of the generated lactic acid was consumed with reaction with this layer. **Fig. 15** shows continuous increase of the removal efficiency by increasing the ratio of PLA to $CaCO_3$, while there was a reduction in the removal efficiency when decreasing the enzyme concentration.

Retained Permeability

The initial permeability of each core used in these experiments was measured using Darcy's law, Eq. 2.

$$\mathrm{k} = \frac{122.812 * q * \mu * h}{\Delta p * d^2}, \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where

d = diameter through which water flow, in. (2.25)
h = disk thickness, in.
K = permeability of the disk, md
q = flow rate, cm^3/min (150)
µ = fluid viscosity, cp (1)
Δp = differential pressure, psi (60)

The time required to flow of 150 cm^3 at a constant pressure (60 psi) was recorded. The same procedure was performed after the removal of the filter cake to calculate the final permeability. The retained permeability was calculated based on Eq. 3

$$k_r = \frac{k_f}{k_i} x100, \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where

k_f = final permeability, md
k_i = initial permeability, md

k_r = retained permeability

Table 8 summarizes the calculation of the retained permeability. **Fig. 16** shows continuous increase of the retained permeability by increasing the ratio of PLA to $CaCo_3$. To explain the increase of the retained permeability a CT scan analysis was performed.

CT Analysis

A CT scan was performed for a limestone core saturated with DI water and the average CTN was 2215. After the filtration process, CT scan was performed and the average CTN became 2290 due to the invasion of fine solid particles and filtrate fluid into the core. The average CTN after soaking with 10 wt% α-amylase enzyme for 24 hrs was 2272, which indicated poor removal of the invaded solid and filtrated fluid, **Fig. 17**. This can explain the reason that the retained permeability was 60% when using a ratio of PLA to $CaCO_3$ = 2:1. The amount of generated lactic acid was not enough to remove the invaded solid particles.

By increasing the ratio of PLA to $CaCO_3$ to 3:1, the average CTN of the cleaned core was 2260 which was very close to average CTN of the saturated core, **Fig. 18**. The amount of lactic acid generated from the PLA at this ratio was enough to remove the filter cake and the invaded solid from inside the core. The retained permeability was 100%, which confirm the CT results.

Sandstone Cores

After optimizing the PLA to $CaCO_3$ ratio and the enzyme concentration, it was decided to use these optimum conditions to test sandstone cores. **Fig. 19** shows that the amount of filtration for sandstone core was smaller than the amount of filtration in the case of limestone core. This was due to the fact that the average permeability of sandstone cores (60 md) was smaller than the average permeability of limestone cores (100 md). **Fig. 20** shows that the removal efficiency was 100% after soaking with 10 wt% α-amylase enzyme solution for 24 hrs, and the retained permeability was close to 100%, **Fig. 16**.

Conclusions

To obtain better distribution of the breaker fluid, especially in horizontal drilling, PLA was used with the drilling fluid components to form the filter cake. Based on the experimental results, the following conclusions can be drawn:

1. The drill-in fluid has stable reheological properties up to 250°F over 24 hrs.
2. PLA has a removal efficiency of 100% for Indiana limestone and Berea sandstone cores in 24 hrs.
3. 10 wt% α-amylase enzymes was the optimum concentration to remove the polymer layer.
4. PLA to $CaCO_3$ ratio 3:1 was the optimum for completely removal of the filter cake.
5. The ratio of fine to medium $CaCO_3$ was 2:1 and was adequate to reduce the amount of filtration.
6. The retained permeability is 100% for Indiana limestone and Berea sandstone cores.
7. CT shows that no formation damage was observed inside the cores.

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Table 1: Drilling fluid formula for lab scale.

Material	Quantity	Units	Mixing Time
Distilled Water	308	g	-------
Defoamer	0.33	cc	30 sec
XC-polymer	1.5	g	20 min
Starch	6.00	g	20 min
KCl	97.6	g	20 min
KOH	0.30	g	1 min
Sodium sulfide	0.25	g	1 min
$CaCO_3$ (D_{50} =50 µm)	13	g	10 min
Acid Precursor (D_{50} = 150 µm)	10	g	10 min

Table 2: Properties of the cores that were used to simulate the reservoir section.

Property	Sandstone	Limestone
Porosity, vol%	18	23
Permeability, md	50-60	100
Length, in.	1	1
Diameter, in.	2.5	2.5

Table 3: Properties of the drill-in fluid.

*Property	Temperature, °F	Value	Units
Density	77	72	lb/ft^3
Plastic viscosity	120	11	cp
Yield point		18	$lb/100\ ft^2$
10 s gel strength		3	$lb/100\ ft^2$
10 min gel strength		4	$lb/100\ ft^2$
pH	77	10 - 11	………

*all the properties were measured at atmospheric pressure (14.7 psi)

Table 4: Sieve analysis of different solid mixes that were used to prepare the drilling fluids.

Sieve Number	Sieve Size (mm)	Retained Weight Percent %	Cumulative Weight Percent %
20	> 0.85	2.4	2.4
30	0.85 - 0.6	5.7	8.1
40	0.6 - 0.425	4.3	12.4
50	0.425 - 0.3	1.2	13.6
70	0.3 - 0.212	1.7	15.3
100	0.212 - 0.15	3.4	18.7
140	0.15 - 0.106	21.2	39.9
170	0.106 - 0.09	5.3	45.3
200	0.09 - 0.075	11.1	56.4
325	0.075 - 0.045	17.4	73.8
Pan	< 0.04	26.2	100.0

Table 5: Change of the drill-in fluid properties with time.

Time (hr)	Density, pcf	pH	Plastic Viscosity, cp	Yield Point, lb/100ft^2	Gel 10 s, lb/100ft^2	Gel 10 min, lb/100ft^2
0	72	10.43	11	18	3	4
4	74	9.00	11	19	3	4
8	74	7.29	11	20	3	4
12	74	6.31	11	20	4	6
16	74	6.00	10	20	4	6
20	74	5.96	9	20	4	6
24	74	5.66	9	20	4	6

Table 6: Composition of α-amylase solutions.

Additive	Core Type	Concentration, wt %
DI-Water	Limestone	90
α-amylase		10
KCl		0
DI-Water	Sandstone	85
α-amylase		10
KCl		5

Table 7: Filter cake removal efficiency for different core types.

	Core Type	**Condition**	**W_1* (g)**	**W_2*(g)**	**W_3*(g)**	**Efficiency %**
LM1*	Limestone	$CaCO_3$ to PLA ratio = 1:1	182.12	186.41	186.41	66
LM2			182.95	187.4	187.4	65
LM3		$CaCO_3$ to PLA ratio = 1:2	182.85	187.4	183.25	91
LM5			182.7	186.6	183.1	90
LM6		$CaCO_3$ to PLA ratio = 1:3	181.75	194	181.75	100
LM8			181.59	191.11	181.59	100
LM10		5 wt% enzyme solution	182.47	192.1	183.4	90
LM11			179.14	190.34	180.5	88
SD2*	Sandstone	$CaCO_3$ to PLA ratio = 1:3	184.9	191.2	184.9	100

*W_1 = the weight of the disk saturated with water
*W_2 = the weight of the disk with filter cake
*W_3 = the weight of the disk after removal process
*LM = limestone core
*SD = sandstone core

Table 8: Calculation of the retained permeability of the used cores at different conditions.

Code	**Core Type**	**Condition**	**Leakoff Time Before Filtration, s**	**Leakoff Time After Removal, s**	**Retained permeability, %**
LM1	Limestone	$CaCO_3$ to PLA ratio = 1:1	7	17	41
LM2			9	17	53
LM3		$CaCO_3$ to PLA ratio = 1:2	8	14	57
LM5			8	12	67
LM6		$CaCO_3$ to PLA ratio = 1:3	15	16	94
LM8			17	17	100
SD2	Sandstone	$CaCO_3$ to PLA ratio = 1:3	23	23	100

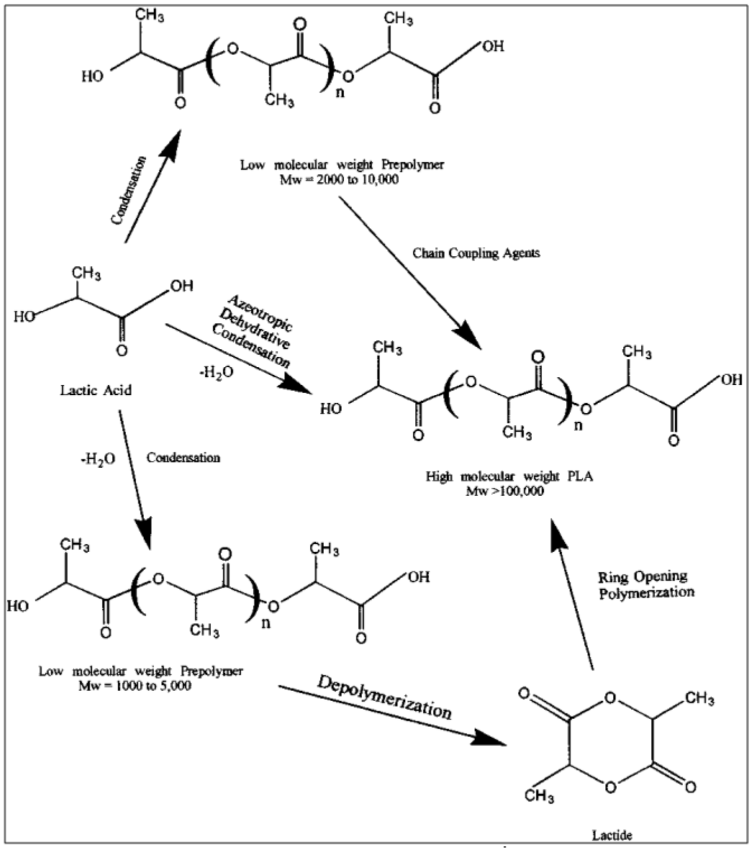


Fig. 1: Synthesis method for high-molecular weight PLA.

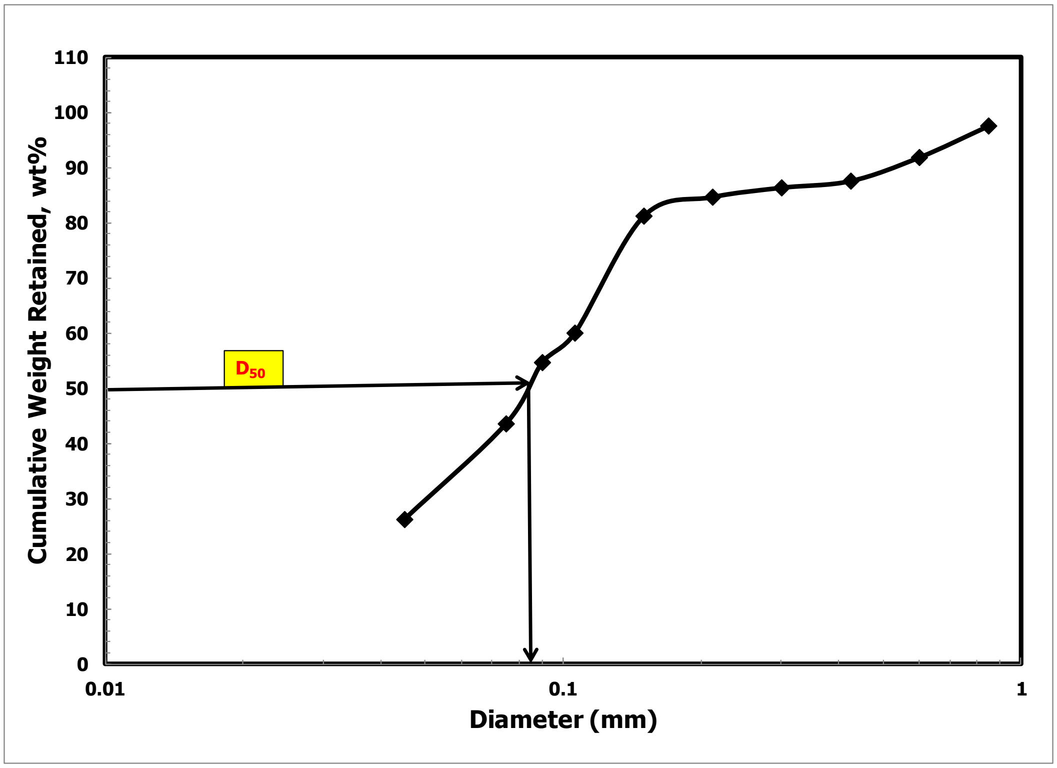


Fig. 2: Sieve analysis of the solid particles that were used to form the drilling fluid. $D_{50} = 0.085$ µm.

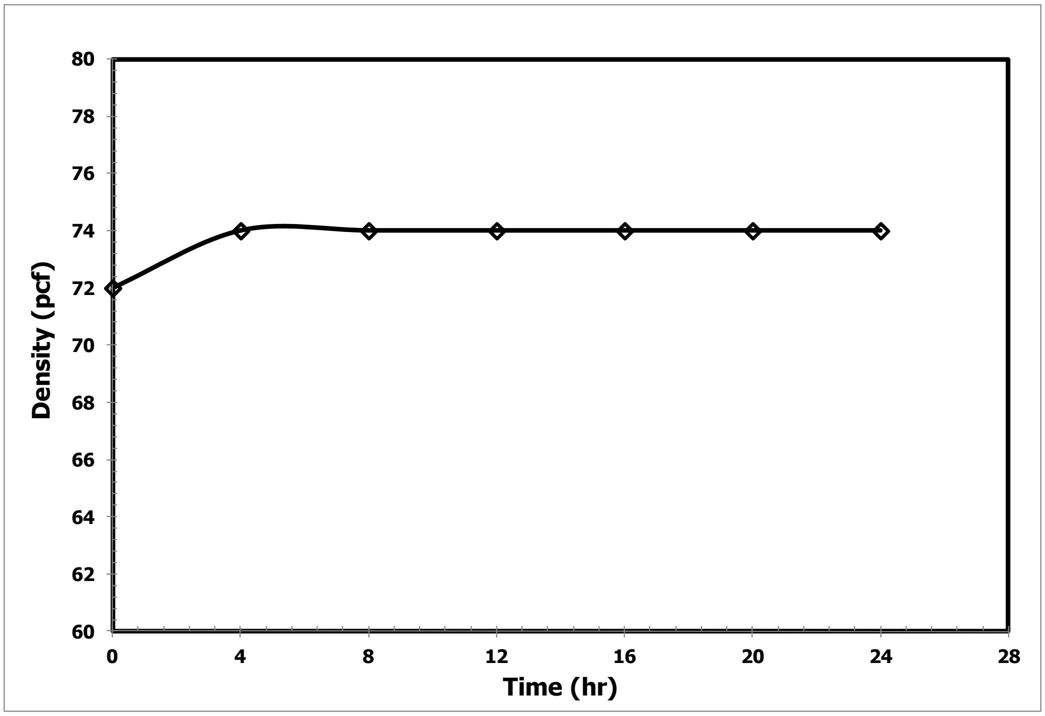


Fig. 3: Drill-in fluid density was near constant for 24hrs after hoot rolling at 250°F.

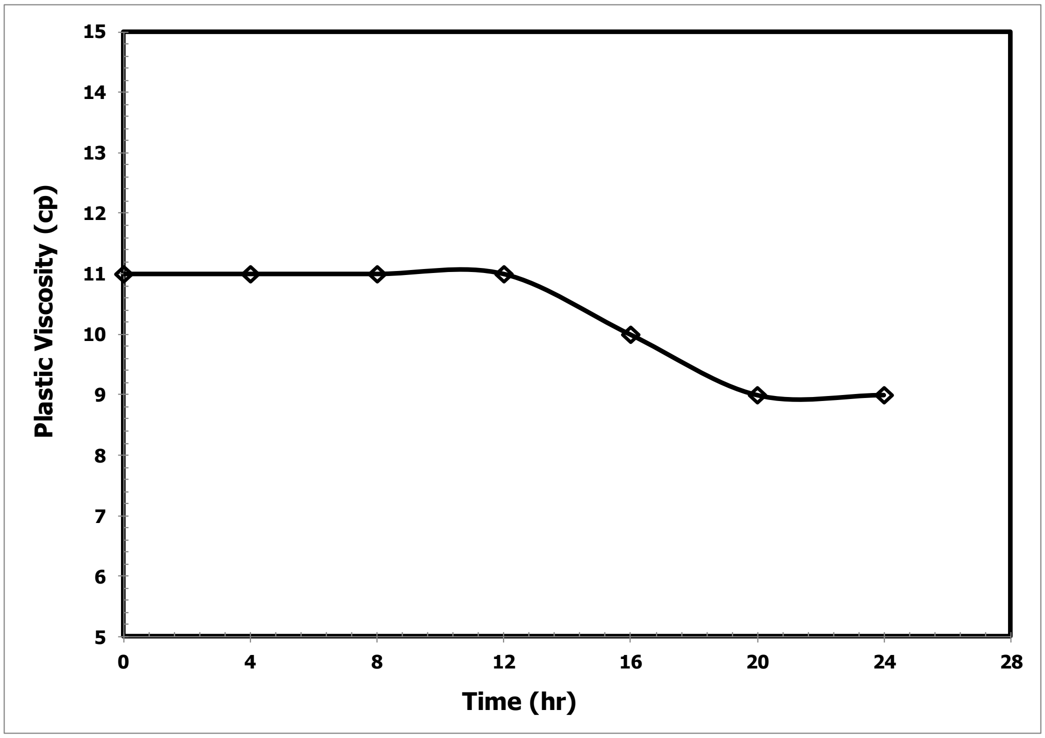


Fig. 4: Plastic viscosity of the drill-in fluid was constant at 11 cp for 12 hrs and then decreased to 9 cp at 24 hrs due to the effect of temperature, 250°F and initial hydrolysis of PLA.

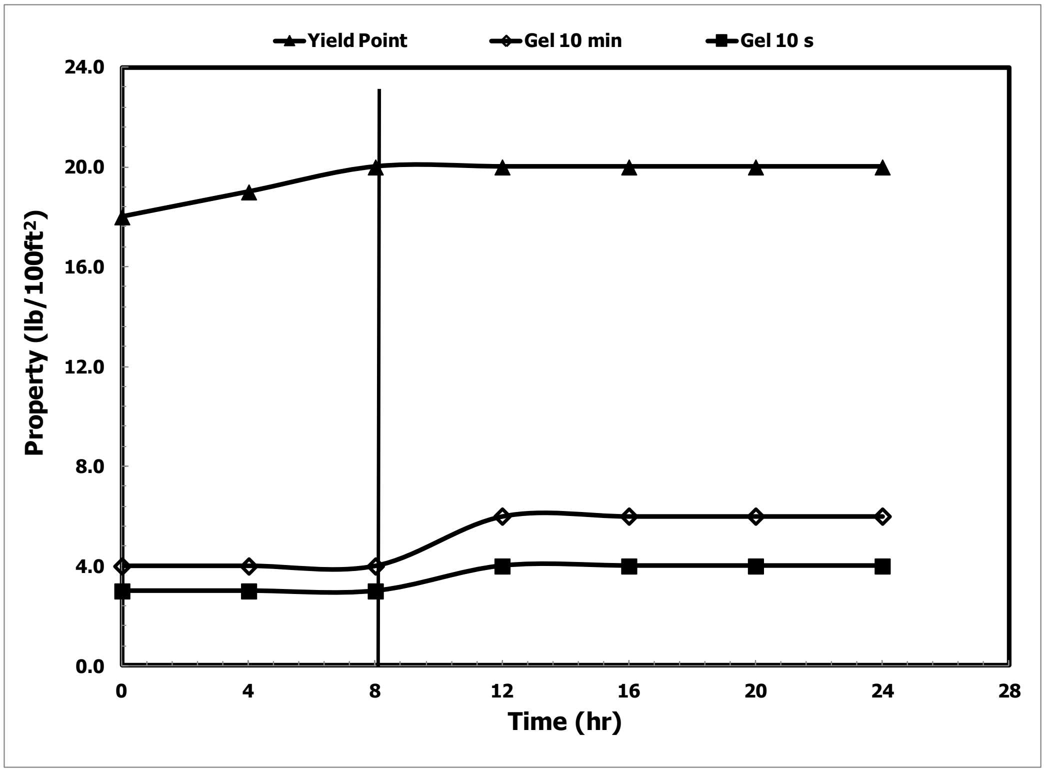


Fig. 5: Increase in the drill-in fluid yield point, 10 s and 10 min gel strength after 8 hrs due to the hydrolysis of PLA under high temperature.

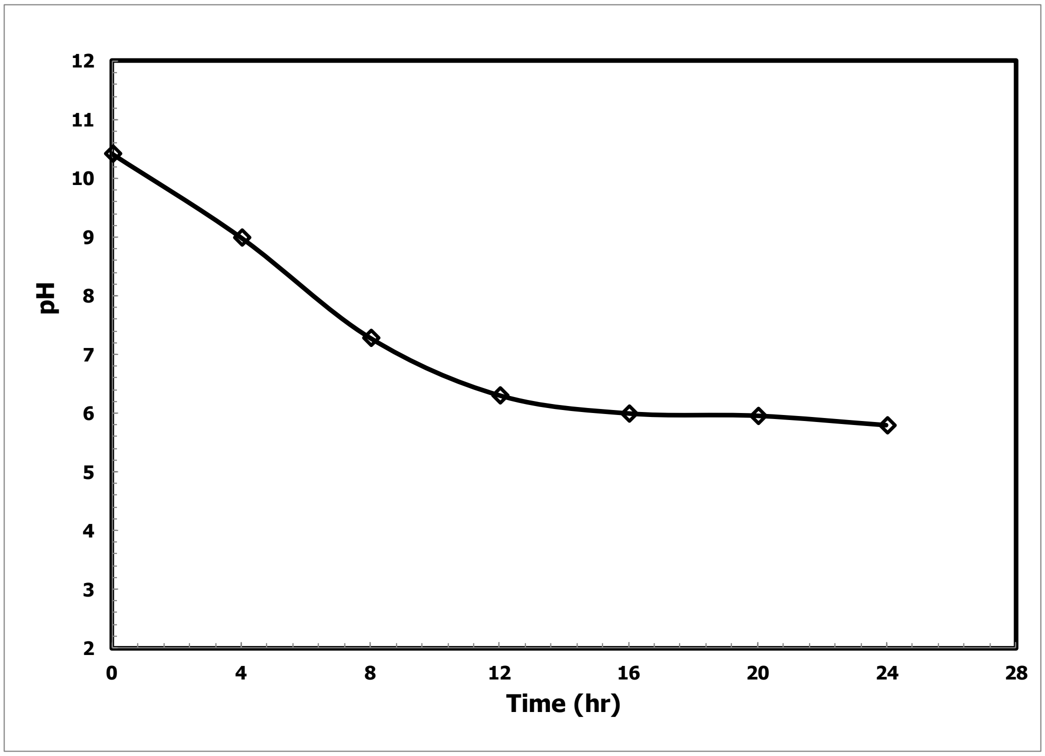


Fig. 6: Decrease in pH until it reached 6 after 12 hrs indicated that PLA hydrolyzed by certain amount under the effect of temperature, 250°F.

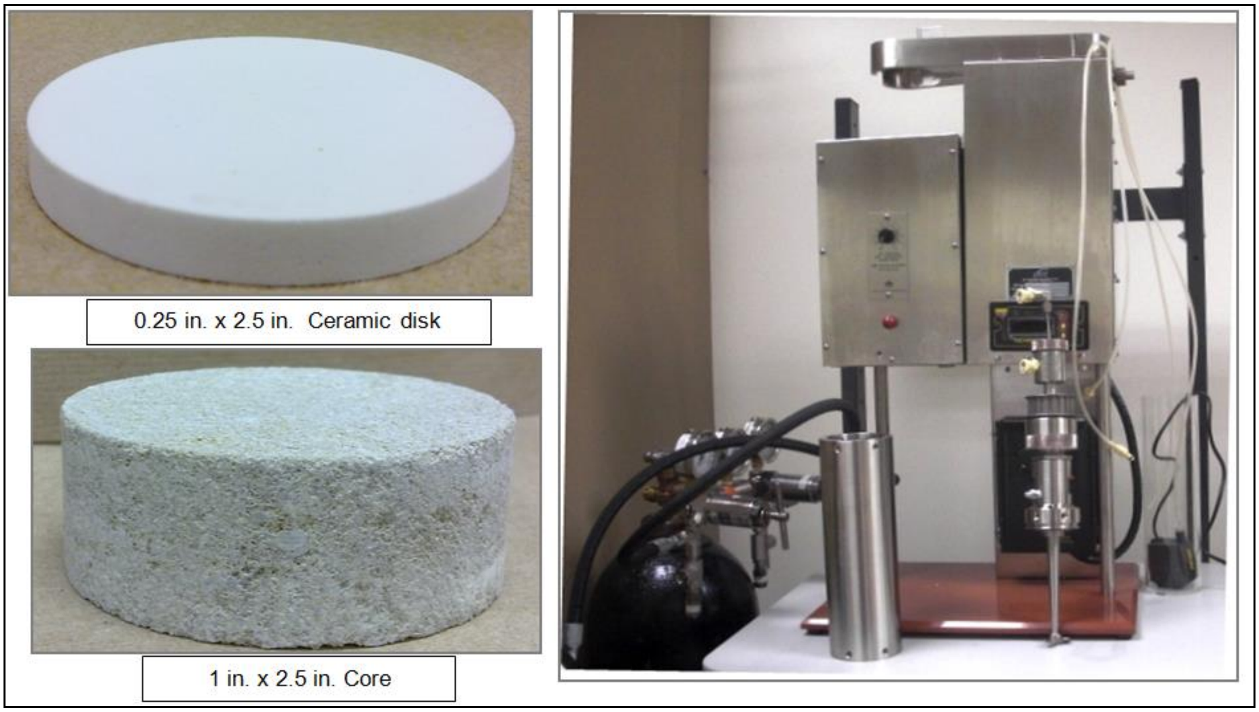


Fig. 7: A modified HPHT filter press cell.

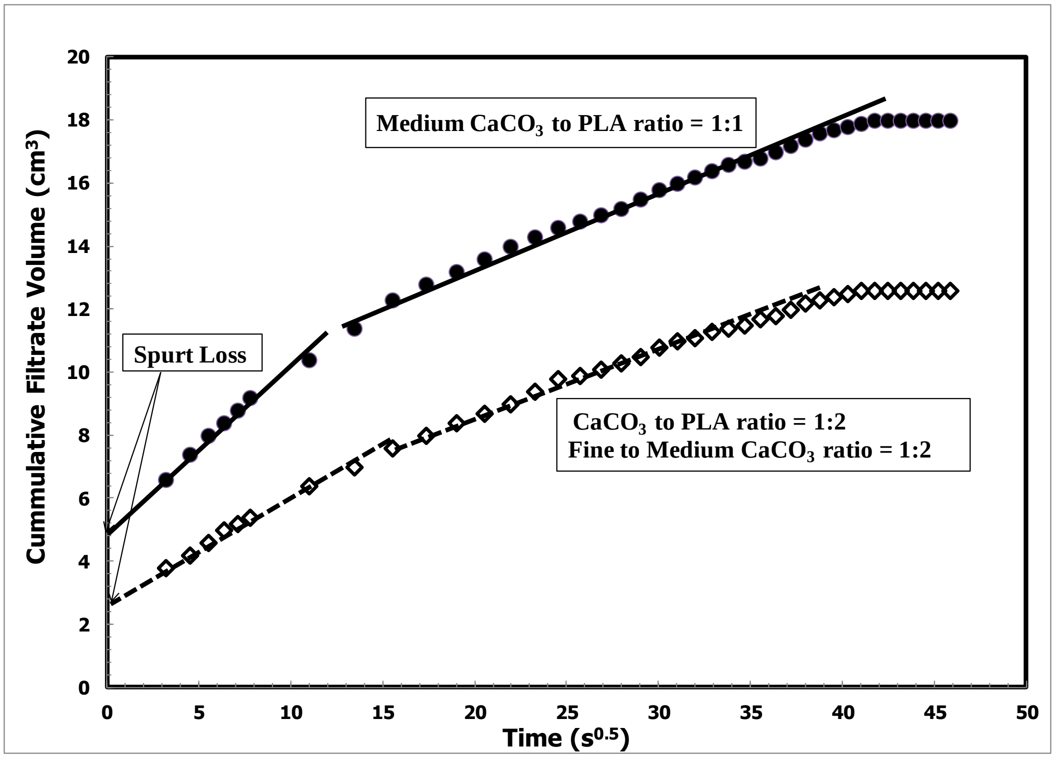
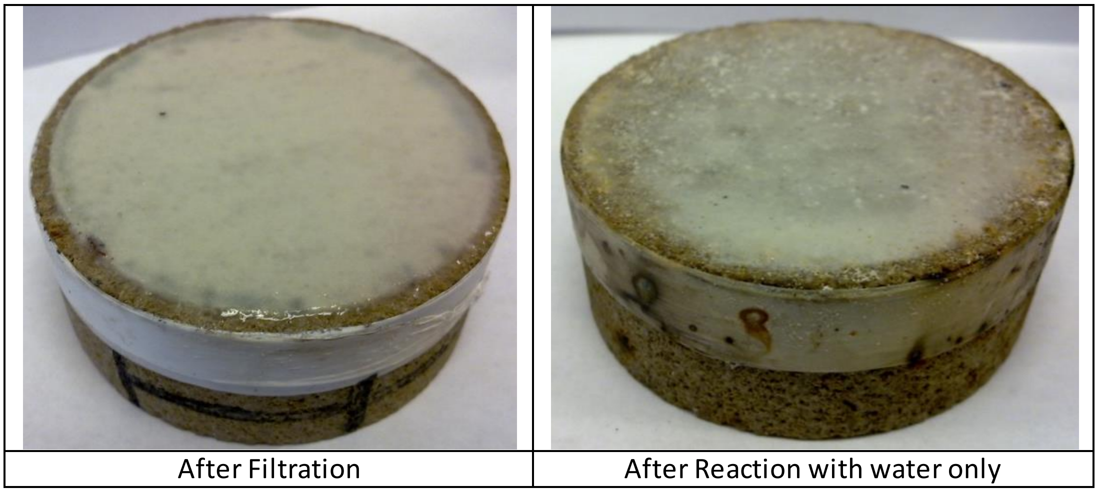


Fig. 8: Reduction of amount of filtration when increasing the amount of calcium carbonate particles with fine particles.



After Filtration | After Reaction with water only

Fig. 9: No removal of the filter cake after soaking with water for 20hrs.

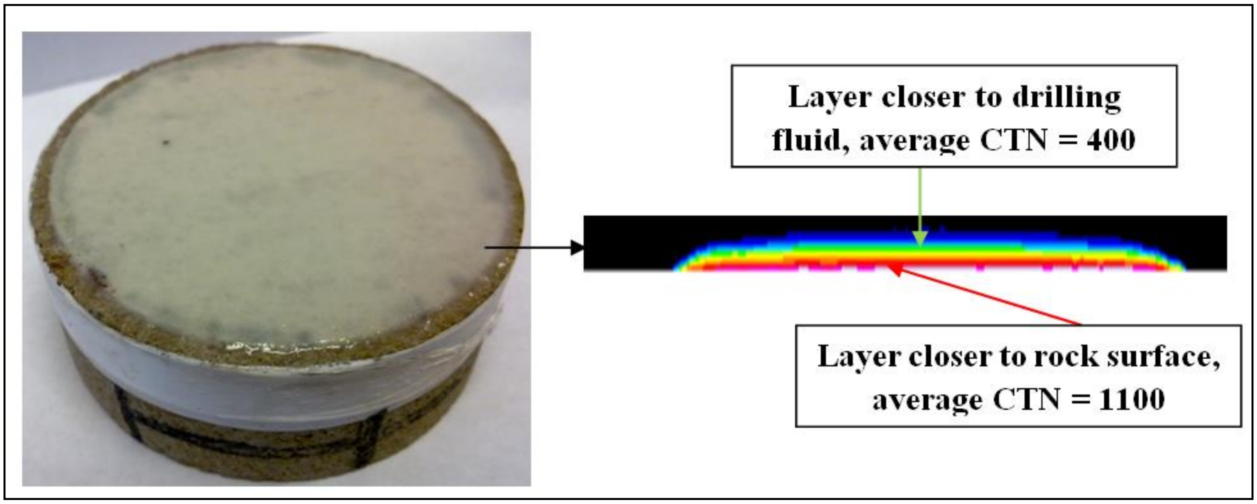
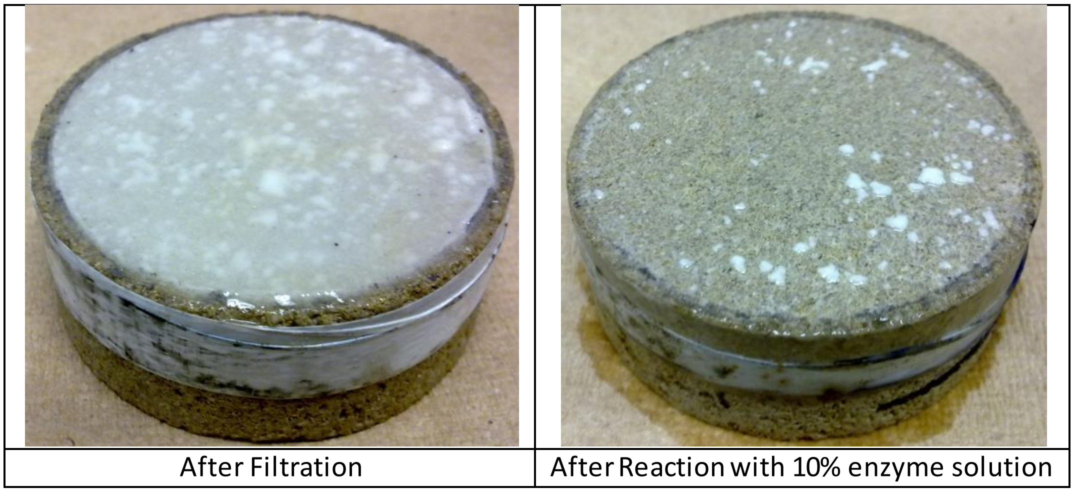


Fig. 10: CT scan shows heterogeneity of the formed filter cake.

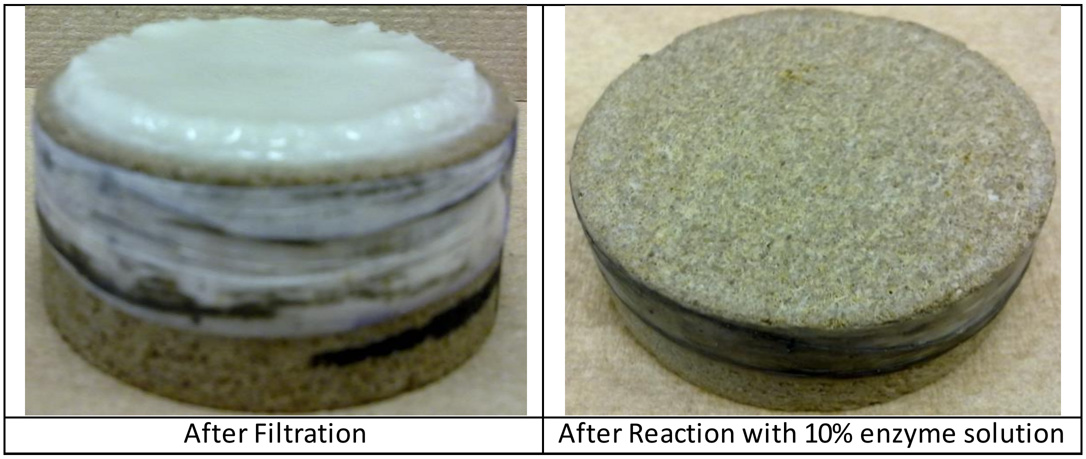


After Filtration | After Reaction with 10% enzyme solution

Fig. 11: Lower filter cake removal efficiency using $CaCO_3$ to PLA ratio 1:1.

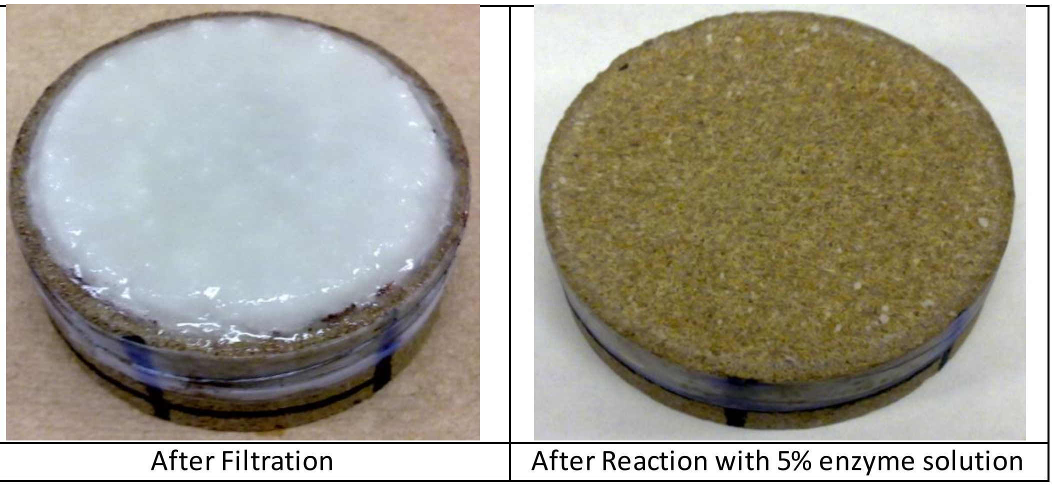
After Filtration | After Reaction with 10% enzyme solution

Fig. 12: High filter cake removal efficiency (90%) using $CaCO_3$ to PLA ratio 1:2.



After Filtration | After Reaction with 10% enzyme solution

Fig. 13: Completely removal of the filter cake using the ratio of $CaCO_3$ to PLA 1:3.



After Filtration | After Reaction with 5% enzyme solution

Fig. 14: reduction in filter cake removal efficiency when decreasing the enzyme concentration to 5 wt%.

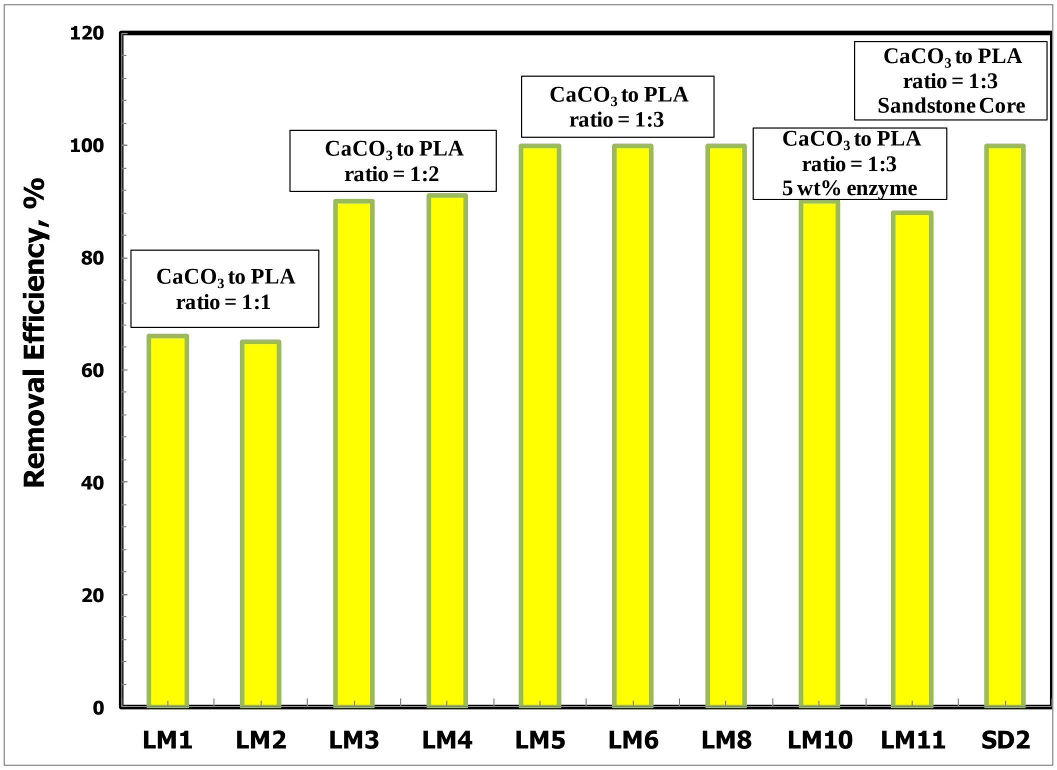


Fig. 15: Increase of filter cake removal efficiency by increasing PLA to $CaCO_3$ ratio.

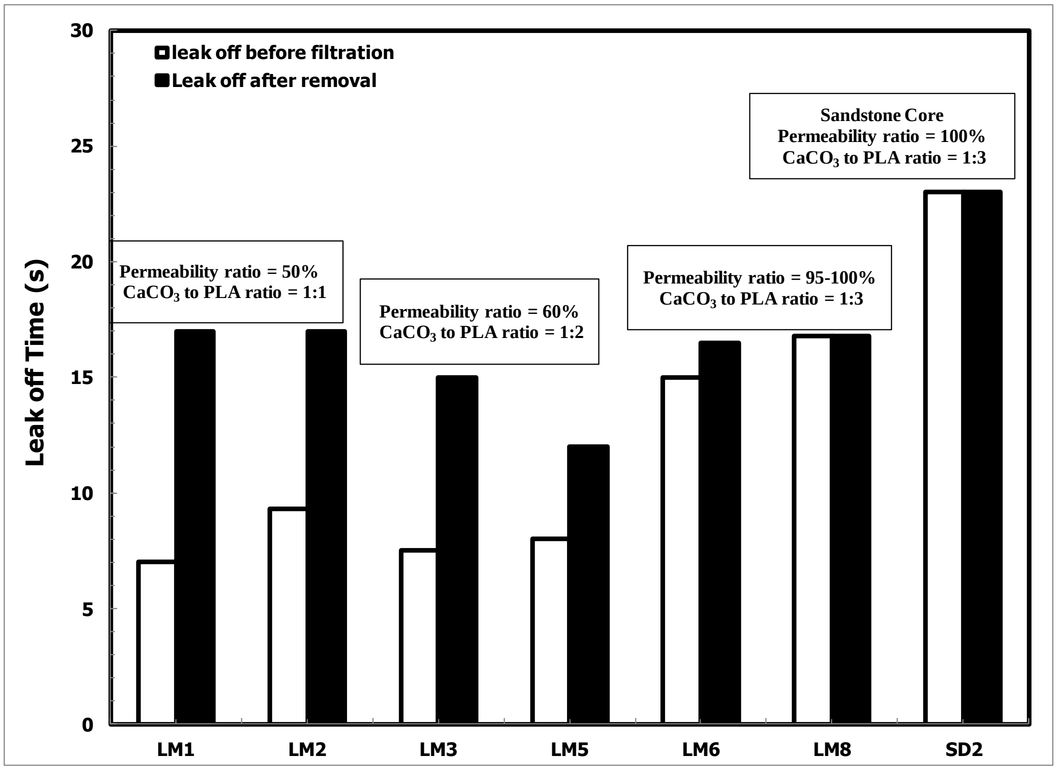


Fig. 16: Continuous increase of the retained permeability with increasing the PLA to $CaCO_3$ ratio.

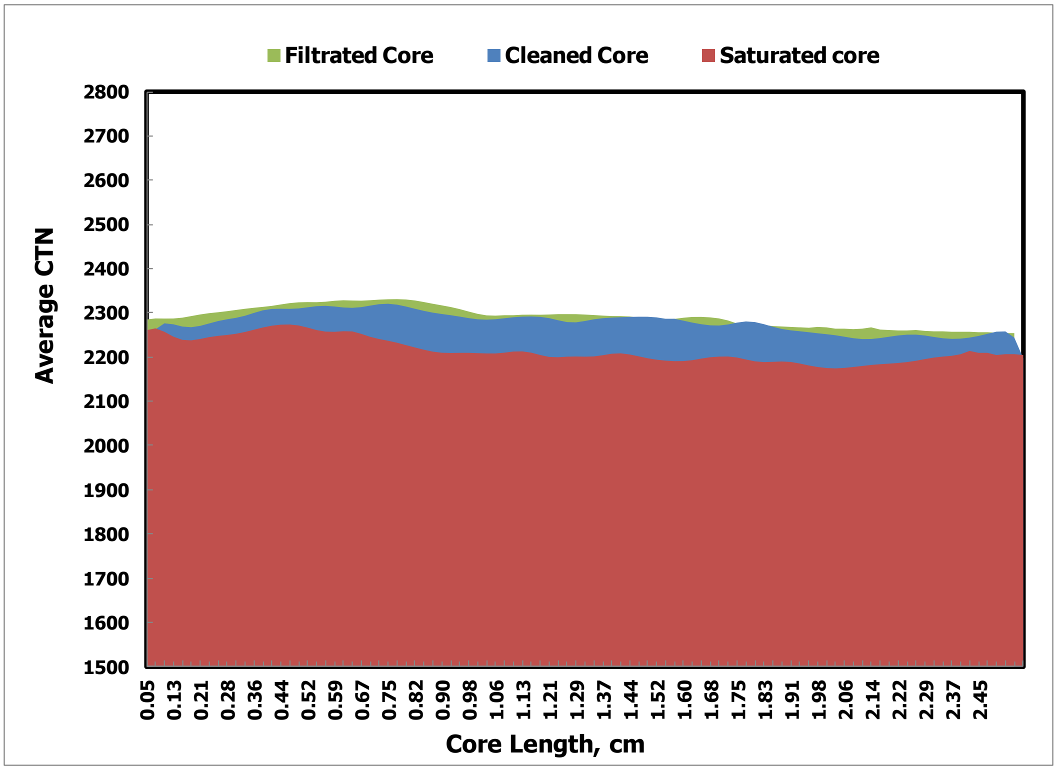


Fig. 17: Increase in average CTN after removal process indicated poor removal of invaded particles and reduction in retained permeability.

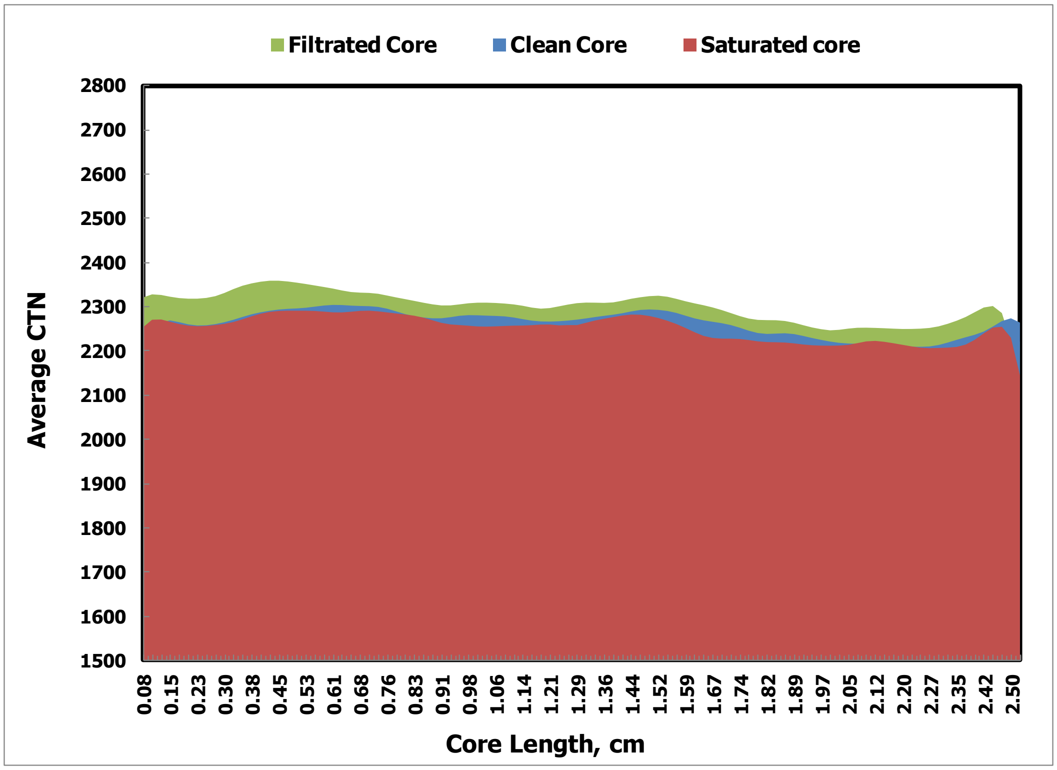


Fig. 18: The average CTN for saturated core was close to average CTN of cleaned core indicated that most of the invaded solid particles were removed.

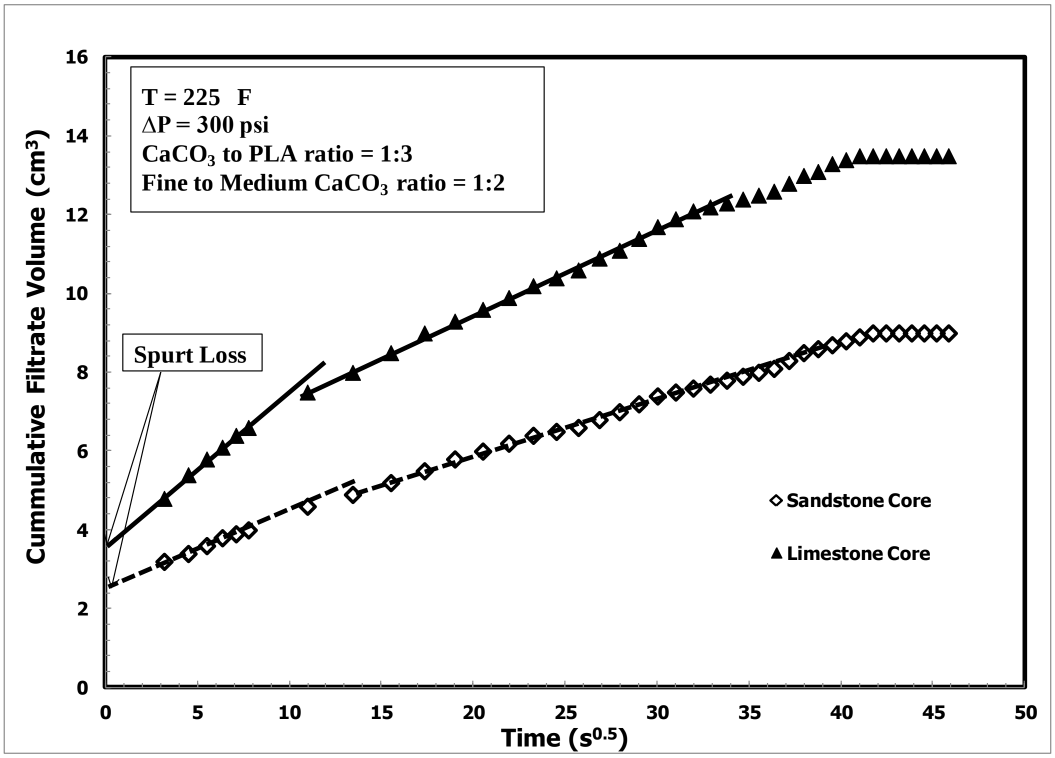
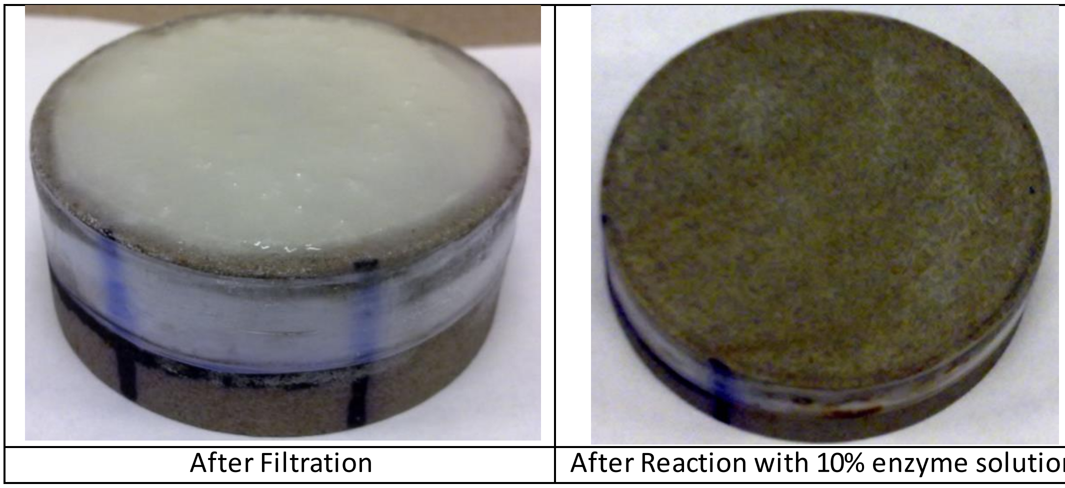


Fig. 19: Decrease in the amount of filtration in the case of sandstone core.



After Filtration

After Reaction with 10% enzyme solution

Fig. 20: Complete removal of the filter cake from sandstone core after soaking for 24 hrs with 10 wt% α-amylase enzyme.