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Don't Stop Drilling Operations but Use Customized Cross-Linked LCM Solution for Fractured Formations

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Abstract

Curing drilling fluids losses in fractured and sandstone formations is the most challenging scenario to drilling team. Loss zones are unpredictable, due to large vugular zones, extended and connected fracture structures or in interbedded sandstone formations. However, based on proper evaluation of the offset wells data, loss events can be anticipated. Typically, conventional lost circulation material (LCM) pills containing various particle size distributions are part of the lost circulation armory in fractured sections. However, results show variation. This cross-linked LCM is distinguished for those situations with the most-severe lost circulation, as these cross-linking polymers will produce a rubber gel structure. This chemical blend has extremely effective sealing characteristics that are used as an innovative approach to the initial response to lost circulation. Depending on the bottom hole temperature, a retarder will be used to customize the mentioned LCM solution. This paper discusses a Customized Cross-Linked LCM Solution for Fractured and Sandstone Formations, based on a customized blend of high and low molecular weight anionic polymer, reinforcing material and cross-linking agent that has an extremely effective sealing characteristic. In addition, it can be pumped through the regular bottom hole assembly without losing rig time associated with tripping and mixing conventional LCM treatment.

Introduction

Although numerous LCMs are available from different vendors in the global market, lost circulation (LC) remains a persistent and standalone challenge for the drilling industry. Operators, service companies, and academia have invested significant resources to develop solutions that address the LC challenge. However, the success rate in mitigating LC remains unsatisfactory during severe-to-total-loss scenarios in fractured formations. Use of particulate LCMs to cure losses in natural and vugular formations has shown limited success. Currently, the industry addresses losses in fractured formations using high-fluid-loss LCM pills with various particle sizes, crosslinked polymers, thixotropic surfactants, resin, gunk, reverse gunk, mud capping, and sidetracks. All of these solutions have advantages and disadvantages associated with economics, performance, and well control risks. (Abdulrazzaq et al, *AlBuraikan* et al, *Savari* et al, *Whitfill* et al, 2018). Loss circulation problems may be encountered at any depth whenever the total pressure used against the formation exceeds the formation pressure. Commonly, four types of formations and responsible for loss circulation formations with natural or induced fractures, vugular or cavernous formations, highly permeable formations and unconsolidated formations. (Ansari et al, *Pino* et al, *Knudsen* et al, *Leon* et al, *Sanabria* et al, 2015). Historically diverse procedures have been used to moderate the lost circulation problem while drilling and during workover operations.

The most common method is using combination of solid particles, fibers and flakes materials as conventional Lost Circulation Materials (LCM) to prevent or cure drilling fluid losses into the formations. Many others non-conventional LCM are used for the same purpose, those options tend to be more aggressive and with better results curing the losses. Those non-conventional LCM can be combination of high solids (granular, fibrous, blended), hydratable/swellable LCMs, nanoparticles, cement plug, polyurethane grouting, rapid setting plugs and cross-linked solutions. (Olivares et al, *Al-Zahrani* et al, *Anioke* et al, 2022).

Cross-Linked LCM solutions are formulated with a blend of high and low molecular weight anionic polymers that when combined with a cross-linking agent, the product produces a gel structure able to cure the losses. This type of LCM is very dependent of the temperature, for this reason knowing the temperature for each particular application will be critical to customize a proper formulation. Also, retarders can be used to adjust the cross-link effect depending the well conditions, hole size and formations lithology. Cross-Linked LCM solutions can be used to seal fractured, vugular and permeable formations as sandstones. There are many benefits associated to the utilization of this type of LCM in comparison with others as: are resistance to Carbon Dioxide (CO_2) and Hydrogen Sulfide (H_2S) contaminants, can be pumped through the bit and downhole tools like Logging While Drilling (LWD) or Measuring While Drilling (MWD), additionally can be used in an extensive diversity of drilling fluid applications as well as all water-based and invert emulsion systems. Through its exclusive method of action, this LCM can substitute other costly non-conventional LCM solutions as cement squeezes or rapid setting plugs, moreover prevents non-productive time relate to side tracking of the wellbore.

For the Cross-link LCM mentioned on this paper, the standard design yields within 8 hours of being pumped downhole, however, this time can be reduced or accelerated depending the requirements. The density range is from 65 to 150 pounds per cubic feet (pcf) or 8.7 to 20 pounds per gallon (ppg) and can be increased to a higher required density. In terms of temperature stability can be used in conditions up to 400 °F.

Experimental Evaluation

Cross-Linked Solution needed to be tested before the field evaluation. Therefore, extensive evaluation was done in the lab using un-weighted and weighted formulations up to 100 pcf or 13.4 ppg (based on the expected requirements) and the mixture samples properties were noted after static agent at 250 °F for a period of 6 hours and after 7 days.

Additives samples were mixed following manufacturer instructions as shown in Table 1:

Table 1—Cross Link LCM Formulation and Mixing time

CROSS-LINKED LCM COMPOSITION AND PREPARATION				
Additive	**Mix Time**	**Units**	**Unweighted**	**100 pcf (13.4 ppg)**
Fresh Water		ml	350	252
Cross-Link Retarder	1 min	ppb	10	7.2
Cross-Link Polymer	2 min	ppb	40	29
Barite	5 min	ppb	0	273

Initially the 100 pcf (13.4 ppg) weighted sample of Cross-Linked LCM produces varied results. The sample aged at 6 hours showed evidence of barite sag and the resulting polymer cross-linking had not gelled as well as the un-weighted sample. The sample aged for 7 days produced an improved gelatinous plug but again was not as firm compared with the un-weighted sample. Based on those results, the formulation was revised and customized to get better results. On the new formulation the cross-link polymer and retarder were increased as follow in Table 2:

Table 2—Revised Cross Link LCM Formulation and Mixing time

CROSS-LINKED LCM COMPOSITION AND PREPARATION				
Additive	**Mix Time**	**Units**	**Unweighted**	**100 pcf (13.4 ppg)**
Fresh Water		ml	350	252
Cross-Link Retarder	1 min	ppb	15	7.2
Cross-Link Polymer	4 min	ppb	45	29
Barite	5 min	ppb	0	273

In order to evaluate if the Cross-Link LCM pill was pumpable at the field, we did evaluate the rheology and flowability. A viscometer was used to measure the rheological properties of the Cross-Link LCM pill. The larger space between the bob and rotating four-blade sleeve lodged a greater fluid volume compared to a standard bob and sleeve used on the viscometer, which is valuable for measuring the viscosity of slurries. The rheological measurements were conducted at room temperature (RT), 120°F. and 150°F and showed acceptable results to be pumpable at the field. The Cross-Link LCM pill formulation was loaded in a HP/HT consist meter to evaluate thickening time (TT), were we did demonstrate that pill was pumpable.

After revised formulation was mixed, we did observe for both samples (aged at 6 hours and 7 days) that produce gelatinous plug which provided substantial resistance to penetration by a glass rod. Neither sample showed signs of barite sag and the resultant plug was of a homogenous appearance. Based on those results we did decide to move to the next step and try this Cross-Linked LCM solution in the field. On below Fig. 1 & Figure 2, we do have the plugs obtained after cross link polymer and retarder unweighted (65 pcf or 8.7 ppg) and weighted up to 100 pcf (13.4 ppg) respectively:

Figure 1—Cross-link LCM Plug Unweighted – 65 pcf (8.7 ppg)

Figure 2—Cross-link LCM Plug weighted – 100 pcf (13.4 ppg)

Field Evaluation

In order to properly evaluate this technology on the field, we did establish several key performance indicators (KPI's) as follow:

1. The Cross-Linked pill should be easy, fast and safe to mix.
2. The Cross-Linked pill should be pumped through the down hole equipment (No incidents of surfaces lines or Drill Pipe/BHA and/or bit plugging.)
3. The Cross-Linked pill should be compatible with the fluids in the well.
4. No events of stuck pipe or any other issue due to improper mixing or spotting Cross-Linked pill.
5. The Cross-Linked pill should create an effective seal in the thief zone as follow:
   a. Partial losses: 50 -60 % regain in circulation should be considered as success. Quantify Partial Losses as less than 100 barrel per hour (bph)
   b. Up to 2 pills will be pumped in same event.
6. No change on drilling parameters to evaluate the effectiveness of the Cross-Linked pill

A total of three field trial were executed, two of them in the same studied area X and the third application was in studied area Y.

On Well A, we were drilling intermediate hole section with 72 pcf (9.6 ppg) Invert Emulsion Fluid (IEF) with an inclination of 24 degree and partial losses of 55 bph were encountered in fractured formation. A Cross-Linked LCM Pill was customized in the lab prior to be mixed as follow: 34.6 ppb Cross-Link Polymer, 42 ppb Barite and 6.7 ppb Cross-Link retarder were mixed in the pill tank for expected Bottom Hole Temperature (BHT) 160 °F.

The Cross-Linked pill was spotted through the bit at 5 BPM in the following sequence:

- 20 bbl High Viscosity Spacer – 72 pcf (9.6 ppg)
- 57 bbl of Cross-Linked pill – 72 pcf (9.6 ppg)
- 20 bbl High Viscosity Spacer – 72 pcf (9.6 ppg)

Note: 5 bbl Cross-Linked pill was left inside the string.

The drill string was then pulled 270 ft above the theoretical top of the pill and circulated with excess Cross-Linked pill on the shakers. The string was then pulled into the nearest casing, then circulate the drill string with 1.5 string capacity volume to remove any remnants of the Cross-Linked pill. Then a hesitation squeeze was performed at 1.2 bbl at 0.3 bpm from 100 psi to a maximum of 170 psi at intervals for two hours with a total of 6.5 bbl squeezed into the formation. The Cross-Linked pill was then allowed to soak for 5.7 hours. RIH slowly to open hole free. Started reaming slowly as a precaution before top of the plug with 600 gpm and 30 rpm to bottom, eventually reaching 750 gpm to evaluate the losses at the pump rate to drill this section, which showed a reduction from 55 bph to 10 bph.

It was verified that after allowed to soak, then a hesitation squeeze was performed into the formation. losses were reduced from 55 bph to 10 bph (82% Reduction). Drilling continued with losses eventually decreasing to zero. For this first application, all the established KPI's were met as follow:

- The Cross-Linked pill was easy, fast and safe to mix.
- The Cross-Linked pill was pumped through the down hole equipment (No incidents of surfaces lines or Drill Pipe/BHA and/or bit plugging.)
- The Cross-Linked pill was compatible with the fluids in the well.
- No events of stuck pipe or any other issue were experienced due to improper mixing or spotting Cross-Linked pill.
- The Cross-Linked pill should create an effective seal in the thief zone, reducing losses from 55 bph to 10 bph (82% Reduction).
- No change on drilling parameters were used to evaluate the effectiveness of the Cross-Linked pill

On well B at same studied area X, we were drilling across intermediate hole section with 75 pcf (10 ppg) IEF with an inclination of 35 degree. The hole encountered partial losses (40 bph) after drilling through sandstone Formation.

Cross-Linked pill formulation was 37 ppb Cross-Link Polymer, 65 ppb Barite and 7.5 ppb Cross-Link retarder for expected Bottom Hole Temperature (BHT) 170 °F

Similar procedure used in well A was utilized to spot Cross-Linked LCM Pill and left to soak and performed a hesitation squeeze. Losses were totally cured (100% reduction). Drilling operations were resumed without any additional trip or non-productive time to cure losses. For the second application, all the established KPI's were met as follow:

- The Cross-Linked pill was easy, fast and safe to mix.
- The Cross-Linked pill was pumped through the down hole equipment (No incidents of surfaces lines or Drill Pipe/BHA and/or bit plugging.)
- The Cross-Linked pill was compatible with the fluids in the well.
- No events of stuck pipe or any other issue were experienced due to improper mixing or spotting Cross-Linked pill.
- The Cross-Linked pill should create an effective seal in the thief zone, reducing losses from 40 bph to 0 bph (100% Reduction).
- No change on drilling parameters were used to evaluate the effectiveness of the Cross-Linked pill

The third application was on studied area Y at well C, while drilling the curve hole section with 90 pcf (12 ppg) water base mud (WBM), total losses occurred while drilling. An attempt was made to cure the losses by pumping a 100 bbl conventional LCM pill with a concentration of 40 ppb. After pumping the LCM pill the well was still experiencing total losses and the drill pipe was pulled out to the nearest casing shoe. A 100 pcf (13.4 ppg) mud cap was pumped down the back side at 2 bpm while mixing Cross-Linked LCM solution.

A 100 bbl Cross-Linked LCM pill was mixed in the slug tank and weighted up to 90 pcf (12 ppg) with barite, this yielded 80 bbl of pumpable volume. With the bit above loss circulation zone, 50 bbl of High Viscosity Spacer loaded with 100 ppb conventional LCM was followed with 80 bbl of Cross-Linked LCM pill and displaced with 10 bbl High Viscosity Spacer and 90 pcf (12 ppg) WBM. Flow check and the well was static. The drill string was pulled out and circulated 1.5 times the string capacity with 90 pcf (12 ppg) WBM at 300 gpm and no losses were observed. Several hesitation squeezes were performed by closing the annular preventors and applying 150 psi, 11 bbl of Cross-Linked LCM were squeezed into the formation, the pill was allowed to cure/cross-link for five hours. While waiting on soak time, the well was monitored through the trip tank, again no losses were observed, therefore circulation was regained 100%.

For the third application, all the established KPI's were met as follow:

- The Cross-Linked pill was easy, fast and safe to mix.
- The Cross-Linked pill was pumped through the down hole equipment (No incidents of surfaces lines or Drill Pipe/BHA and/or bit plugging.)
- The Cross-Linked pill was compatible with the fluids in the well.
- No events of stuck pipe or any other issue were experienced due to improper mixing or spotting Cross-Linked pill.
- The Cross-Linked pill should create an effective seal in the thief zone, reducing losses from total losses to 0 bph (100% Reduction).
- No change on drilling parameters were used to evaluate the effectiveness of the Cross-Linked pill

Conclusions

Established KPI's before execute the field evaluation were successfully accomplished in the three mentioned wells (A, B & C) as follow:

- The Cross-Linked LCM pill was easy, fast and safe to mix.
- The Cross-Linked LCM pill was pumped through downhole tools.
- The Cross-Linked LCM pill was compatible with the fluids in the well (IEF and WBM).
- The Cross-Linked LCM pill created an effective seal in the thief zones
- We used same drilling parameters to evaluate the sealing effectiveness of this pill after curing the losses.

Similarly, we concluded that Cross-Linked LCM pill was effective on Fractured and Sandstone Formations, allowing to continue with programed operations and minimize the non-productive time trying to regain circulation. After the success on mentioned three field trials, we've been implementing this technology in our operations with good results.

Nomenclature

LCM	Lost Circulation Material
ppb	Pounds per barrel
ml	milliliters
min	minutes
pcf	pounds per cubic feet
ppg	pounds per gallon
bph	barrel per hour

KPI	Key Performance Indicators
IEF	Invert Emulsion Fluid
gpm	gallons per minute
bpm	barrel per minute
psi	pounds per square inch
bbl	barrel
rpm	revolutions per minute
WBM	Water Base Mud
BHT	Bottom Hole Temperature
CO_2	Carbon Dioxide
H_2S	Hydrogen Sulfide
LWD	Logging While Drilling
MWD	Measuring While Drilling
LC	Lost Circulation
TT	Thickening Time
HP/HT	High Pressure High Temperature
RT	Room Temperature

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