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Engineered Reinforced Composite Mat Pills to Effectively Combat Losses While Drilling in Qatar

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Abstract

Drilling into fractures and fissures in carbonate reservoirs with lateral pore pressure variations is a major challenge. Accurately predicting and managing fracture initiation and fracture closure pressure is not practically feasible in naturally fractured carbonate rocks. Local fracture closure pressure (FCP, minimum in situ stress) around fractures are much lower than the mean value of FCP for the area, as observed in the Al Shaheen field. Drilling operators are experiencing massive lost circulation resulting in potential formation damage; and cost overruns. To address these lost circulation instances, modern lost circulation pills must be implemented.

Drilling through the natural fractures within parts of the Shuaiba limestone reservoir usually results in significant drilling fluid losses, up to 50 m^3/h. Lateral pore pressure variation causes dynamic inflow conditions within the wellbore, which make plugging fractures difficult. In addressing these lost circulation challenges, various approaches were previously used, notably reducing the hydrostatic pressure of fluids column, utilizing lighter weight drilling fluids, reducing the penetration of fluids into fractures with the use of various lost circulation materials, and the use of thixotropic cement slurries and lightweight high-solids-content cement slurries. Conventional lost circulation treatments provided very limited success under these conditions.

An engineered composite fiber-based lost circulation pill with an innovative blend of fibers and sized solids to bridge and plug thief zones has been developed to address these lost circulation challenges. This pill was designed to be pumped through either a dummy bottomhole assembly (BHA) or through bypass circulation ports above the BHA with total flow area of 1.571 in^2. These pills have been successfully used to mitigate losses while drilling as well as to achieve an incremental equivalent static density up to 144 kg/m^3 to drill and cement the section. An impermeable grid created by this system was able to withstand the additional pressures. As a result, all the wells treated with these pills in the field were successfully drilled and cemented.

After establishing the field specific guidelines over 2 years, continuous success was replicated in other wells for all the operator's rigs in Qatar.

Introduction

An operator has been drilling through one of the largest and most complex reservoirs of its kind in the world, Block 5 in Al Shaheen field **(Fig. 1).** It is in Qatari waters, 80 km north of Ras Laffan, and has facilities consisting of 33 platforms and more than 300 wells. Al Shaheen is Qatar's largest offshore oil field and one of the largest offshore oil fields in the world.

Wells are primarily drilled and completed horizontally in four formations, namely the Upper Mauddud limestone, Nahr Umr sandstone, the Shuaiba limestone, and the Kharaib limestone.

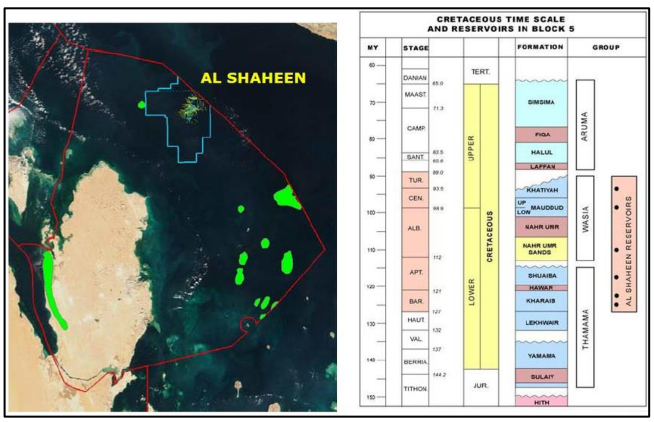

Fig. 1—Left, Al Shaheen field offshore Qatar and right, stratigraphy of Al Shaheen field (Finlay et. al. 2014).

A typical profile of these wells **(Fig. 2)** has a hammered driven 20" conductor pipe (CP), a 16" section secured by a 13-⅜" casing, a 12-¼" section with 9-⅝" production casing landed in the reservoir from 4,500 ft measured depth (MD) to 8,500 ft MD with an inclination of 90° at ±3,400 ft true vertical depth (TVD). The 8-½" reservoir section is drilled horizontally to depths ranging from 20,000 ft MD to 40,000 ft MD. Both producer and injector wells are drilled through platforms, and the wells are typically spaced from 600 ft in the tight carbonate formations to more than 5000 ft in permeable sandstones. The drilling and cementing of these wells especially in carbonate formations is prone to lost circulation challenges due to natural fractures. Challenges related to non-conformance issues are also common due to undesired direct connections between injectors and producers via natural fractures. Typical losses from 15 bbl/hr to 300 bbl/hr of drilling fluids usually occur while drilling, tripping into the hole, running casing, or cementing. The lost circulation issues result in increasing the cost of footage drilled due to the additional cost of material to treat losses and in unwanted drilling events such as abandoning and sidetracking the section. Further, the losses in horizontal sections complicate the placement of lost circulation material and reduce the effectiveness of the lost circulation material used to treat losses.

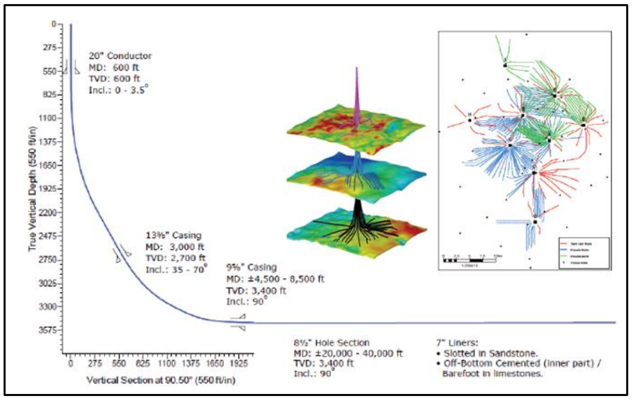

Fig. 2—Al Shaheen field well design (Hoch et al. 2010)

Several lost circulation solutions, such as particulate material, bridging agents, and reactive (surface mixed and downhole mixed) systems have been used to treat losses. Treatments were initially based on trial, resulting in multiple inefficient treatments and consequential additional cost, increased rig time, and remedial cementing operations. However, a step change was noticed when specific engineered composite mat pills were used to treat losses. This paper aims to discuss the challenges related to losses encountered while drilling these extended reach wells and evolution of the lost circulation treatments using the composite mat pills to overcome those challenges. The best practices and lessons learned are subsequently applied to the planning, designing, and execution of the hundreds of wells to be drilled in Al Shaheen field over the coming years.

Engineered Reinforced Composite Mat Pills

Typical solutions used globally for curing losses include the use of particulate or bridging materials mixed in the mud either as a pill or to the whole mud volume. These are expected to physically plug the fractures based on the particle size. Although they show some success, these sized materials alone fail to provide positive results when the size of the fractures increases. Usually, the aperture of the fractures in which the losses are happening is not known. Therefore, the particles used to plug them can either be too small and flow through or too big and may not penetrate the fractures, as shown in **Fig 3**. Additionally, the formation is not uniform, and the fracture apertures can vary with depth, which make it difficult to plug the fractures using the particulate approach. Consequently, a different approach is required to enhance the performance of lost circulation treatments.

An engineered reinforced composite mat pill has been designed to be used in the water-based fluids and can be pumped as a pill during drilling as well as cementing. This innovative composite mat pill combines fibers and solids into a specially engineered pill that can plug fractures as big as 0.2 in (0.5 cm). The reinforced composite mat pill design combines fibers with different mechanical properties and high solids content. This engineered design makes it less sensitive to fracture sizes because the particle size of the solids is optimized to plug the network fibers. The treatment pill fibers form a network at the mouth of the fracture. The solid particles then reach the fiber network and fill up the spaces to either stop the flow of drilling fluid or build integrity. **Fig. 3** demonstrates the principle of plugging and its validation, which is independent of the fracture width.

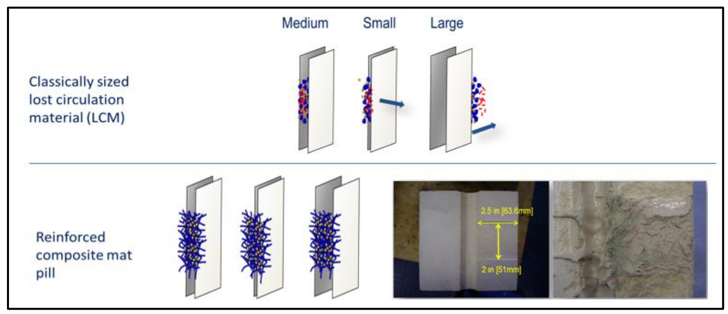

Fig. 3—Plugging mechanism, conventional vs. reinforced composite material-based pill.

There are three main components of the pill:

- A base fluid serves to suspend and evenly distribute the fibers and solids.
- The composite fibers are a blend of two uniquely different types of fibers, with the blend engineered to maximize the plugging efficiency and to improve performance robustness. The black fiber is relatively thick and stiff whereas the white fiber is soft and significantly more flexible. The thick and stiff fiber initiates the building of the fiber network across the loss zone. The soft and flexible fibers entangles with the stiff fibers and works with the solids to reduce the permeability of the network.
- The solids package is a blend of coarse or extra-coarse, medium, and fine granules that plugs the fibers' network.

The innovative system is based on a four-step plug mechanism (de Andrade et al. 2012; Kefi et al. 2010), as illustrated in **Fig. 4** and described below:

- Disperse: Composite fibers are chemically coated to ensure proper dispersion in the base fluid. This creates a 3D network with many contact points enhancing the bridging efficiency.

- Bridge: Fibers are designed to bridge across the loss zone. The composite package consists of hard and soft fibers that allow for partial penetration into fracture along with surface bridging. The stiffness of hard fibers is precisely selected to support the plugging solids, so they do not bend excessively or to rupture in front of the fractures.
- Plug: The optimized solids package efficiently plugs the bridge formed by composite blend of fibers and prevents any fluid loss across the bridge. Computer-aided design software is used to optimize the solid package, which consists of extra-coarse, coarse, medium, and fine materials. The particle size distribution for each material is used as an input to optimize the solid volume fraction of the package.
- Sustain: After the losses are controlled or the integrity is built, subsequent operations require the drilling to continue. Therefore, the plug must sustain surge and swab, pressure fluctuation, elevated equivalent circulating density, elevated differential pressure and remain stable under downhole conditions. The mesh formed by composite fibers allows the plug to resist erosion and mechanical tear. The part of the mesh that penetrates the fracture stays intact even if the surface get eroded during flow of mud.

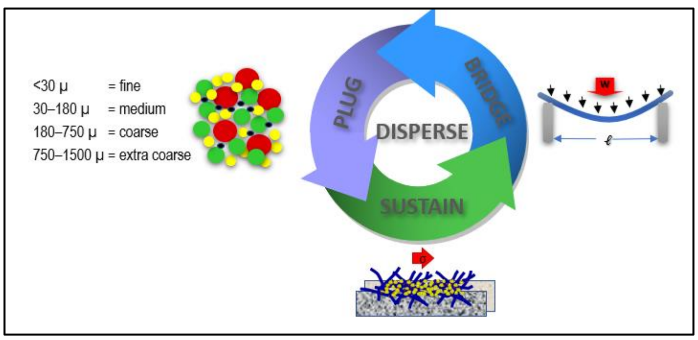

Fig. 4—Four-step approach to build integrity using engineered reinforced composite mat pill.

Lost Circulation Pill Designer Software

To effectively plug the fibers' network in these pills, the added solids package must match the size distribution of the voids in between fibers. These voids are filled by using a solid package of fine, medium, coarse and extra-coarse particles. The effectiveness of the composite mat pills depends on both the blend of fibrous package and the particle size distribution of the solid particles. The fibers used in composite mat pills are compatible with a wide range of the solids. The chemical nature of the sized solid particles is irrelevant to the pill efficiency, providing they are inert and do not change size and shape after mixing in the base fluids. Sized calcium carbonate particles (fine, medium, coarse and extra-coarse) were used as the solid particles in Al Shaheen field due to the readiness of the solids at rig site, although they are known to change in size while drilling.

The composition of this pill is designed using a unique lost circulation pill designer software that helps in matching the particle size to the pores of the fibers' network with greater efficiency. The software tool incorporates locally available particles and tunes the granule sizes to match holes in the fibers' network. The optimizer software is based on patented fiber pore plugging algorithm (Kefi et al. 2010). The size distribution of granules is optimized for a given solid volume fraction and a given fiber system. Kefi et al. (2010) describe the performance index as a permeability indicator: the lower the permeability of the fibers' network plugged by the lost circulation material granules, the better the performance index.

As input for loss-zone characterization, the software uses loss rate severity; loss zone information such as formation depth, bottomhole static temperature, and pore pressure; and wellbore information such as drilling fluid details, openhole size, etc. The particle size distribution (PSD) for the solids available on the rig site was uploaded in the software. To maintain the robustness of the pills, the minimum solid volume fraction of 25% was used, and the minimum volume percentage for the fine granules had to be equal to or greater than 10% of the total particle volume.

The typical classification of sized particles used for designing the pill is as follows:

- Fine particles: $d50 \leq 30$ µm
- Medium particles: 30 µm $< d50 \leq 180$ µm
- Coarse particles: 180 µm $< d50 \leq 750$ µm

Based on the information provided and particles selected, the software provides an optimum ratio **(Fig. 5)** of the particles to plug the fiber network and thereby fill up the spaces to either stop the flow of drilling fluid through the fiber package. After the optimum ratios are calculated, the pill design is validated in the laboratory.

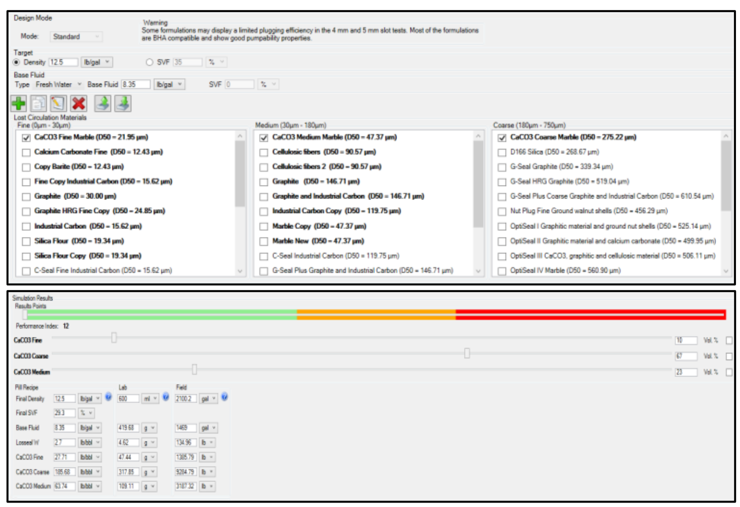

Fig. 5—Lost circulation pill designer software showing selection of different particle sizes and simulation results, based on optimized ratio.

Laboratory Validation

A laboratory setup was created to validate the plugging concept of the reinforced composite mat pill. As usual in lost circulation experiments (Low et al. 2003), the plug tests used a modified static fluid loss cell **(Fig. 6).** The cell is equipped with a grid having a predefined slot or hole geometry to simulate the loss zone. In this case, both 3-mm and 5-mm slots were used to simulate the fracture width. The aim of experiments was to confirm plugging performance against different flow areas and geometries. Pressures were applied across the slots to check the plugging efficiency. The pill was tested successfully up to 500 psi differential pressure, as shown in **Table 1.**

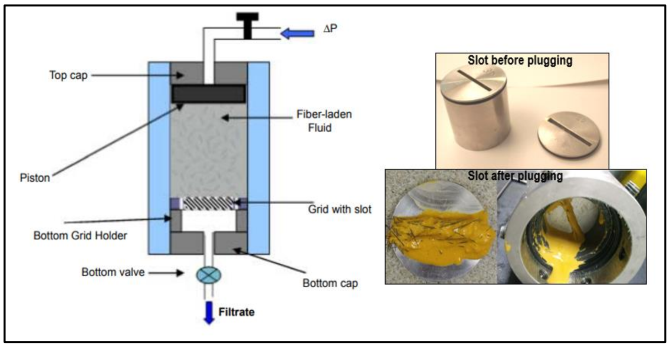

Fig. 6—Modified static fluid loss cell and slotted discs to validate plugging efficiency.

The suspension ability of the pill was tested by checking the fluid rheology of the base pill before adding fibers, and stability of the pill was checked by a free fluid test. Furthermore, compatibility of the pill was confirmed using the drilling fluid sample from the field and spacer to be pumped ahead and behind the pill. In case of any need to pump the pill ahead of cement slurry, additional compatibility tests were done between both lead and tail slurries. The pill has also proved to withstand erosion, as observed by Kefi et al. (2010).

Pill Density	12.5 ppg
Solid Volume Fraction	30.7 %
Plugging Test Results	
Grid Geometry & Test Temperature	Result
3mm slot @ 25° C [77°F]	Plugged
5mm slot @ 25° C [77°F]	Plugged

Table 1 – Plugging efficiency test results.

Placement Mechanism

Composite Mat Pill placement mechanism is fined tuned based on conventional LCM pill pumping technique. The decision to spot composite mat pill is depending on the loss rate after hitting the loss zone.

- Step 1: once the loss zone is encountered during drilling, stop drilling, and establish the loss rate (static / dynamic) based on the pumping rate up to 550 gpm (**Fig.7**)

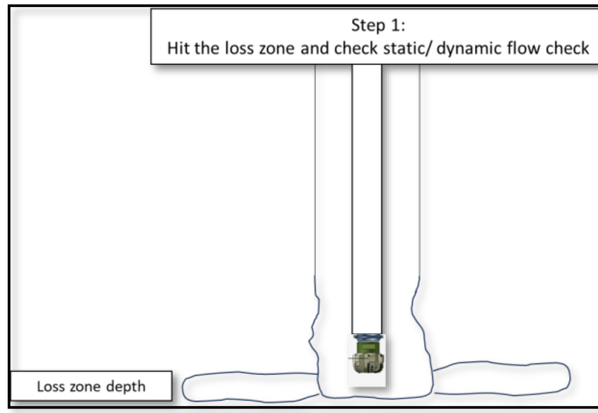

Fig. 7—Step 1: Hitting loss zone.

- Step 2: once the loss rate is confirmed at loss zone depth, drill minimum 100 ft more to access on the loss zone. Then establish again loss rate ranging from 100 gpm to 550 gpm (**Fig.8**).
  - If loss rate is <50 bph @ 550 gpm, continue drilling.
  - If loss rate is > 50 bph @ 100 gpm (>120 gpm @ 550 gpm), spot engineered composite mat pill

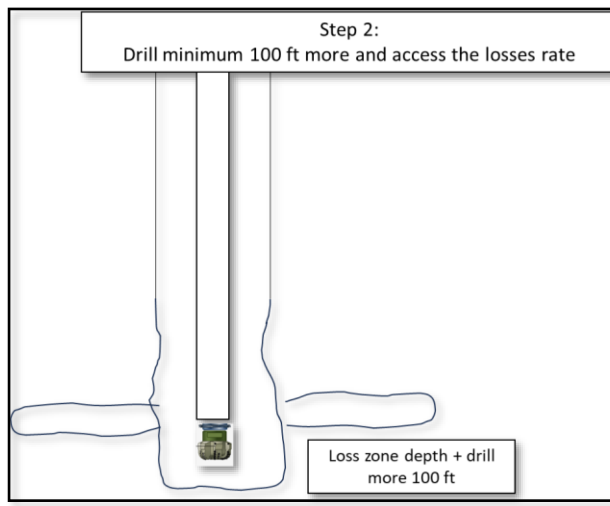

Fig. 8—Step 2: Access the loss rate.

- Step 3: Once the loss rate is confirmed and decided to spot the pill, position the bit 10 ft above loss zone (circulating sub depth +/- 190 ft from loss zone). Activate to open the circulating sub. Once the circulating sub is confirmed open, pump and squeeze composite mat pill as per pumping techniques (**Fig.9**):
  - Pump the pill at maximum allowable pumping rate (never stop pumping)
  - Do not pump fresh or sea water ahead or behind of the engineered composite mat pill.

  - Displace composite mat pill out of circulating sub by pumping surface line (1) + string volume to ports (2) + BHA/OH annulus (3) + 1 bbls of drilling fluid.
  - Rotate the string occasionally with 5 – 10 rpm.
  - Close annular and choke on the fly prior to composite mat pill exiting the circulating sub.
  - Composite mat pill needs to be completely displaced out of the string.
  - Pump rate needs to be adjusted depending on MASP.

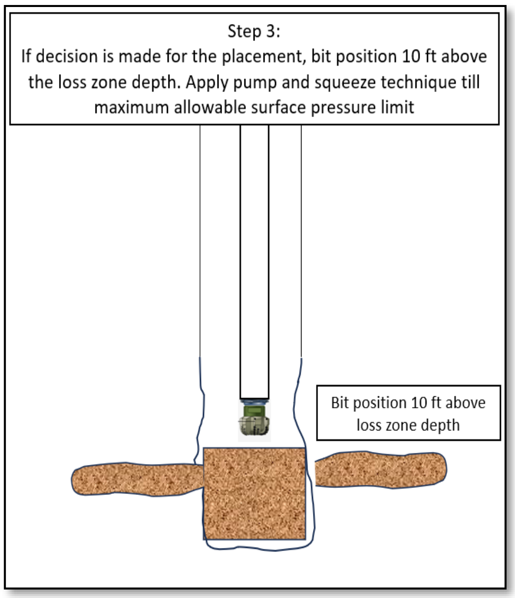

Fig. 9—Step 3: Placement technique

- Step 4: After the pill is spotted, POOH for 5 stands. Soaked the pill for 60 mins. Check dynamic loss rate ranging from 100 to 550 gpm. After checking, run back in hole to drilled depth, check again the loss rate (**Fig.10**):
  - If loss rate is <50 bph @ 550 gpm, continue drilling.
  - If loss rate is > 50 bph @ 100 gpm (>120 gpm @ 550 gpm), spot engineered composite mat pill again

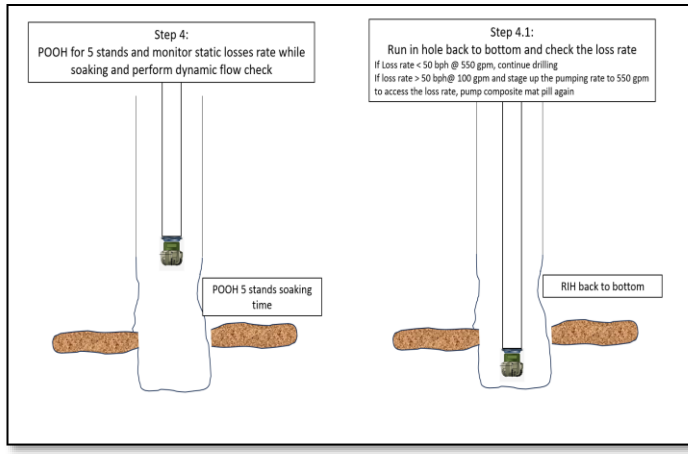

Fig. 10—Step 4: Post placement technique

Field Application

Application of the composite mat pills in the field provided the final validation of the above concept. The pills were successfully used to cure losses across both the 12-¼" and 8-½" hole sections in more than 10 wells. Well details of the typical loss circulation zones are provided in **Table 2**.

Hole Section	12-¼" Section	8-½" Section
Formation Type	Carbonate	Carbonate
Deviation	~ 90°	~ 90°
BHA Configuration	Circulating Sub	Circulating Sub
Ports of Circulation Sub	2 ports of 1 in. each	4 ports of 24/32 in. each
Depth (MD/TVD)	~5,300 ft / 3,300 ft	~6,000 ft / 3,300 ft
Temperature (BHST)	135°F	135°F
Mud Density	10.2 ppg	9.8 ppg

Table 2 – Well details of field cases.

The following case study describes the operations in one well. While drilling an 8-½" section across carbonate formation in a horizontal section, 256 bbl/hr of static losses were observed at 6,024 ft. At this point, a decision was made to spot a sized calcium carbonate material to control the losses. The pill was spotted using a circulation sub that was placed 136 ft above the drilling assembly. The circulation sub had four ports of 24/32 in that could be opened or closed by dropping a ball. The first lost circulation treatment was performed by spotting a 100 bbl of sized calcium carbonate material with bottomhole assembly (BHA) above the loss circulation zone at 5,848 ft and circulation sub at 5,712ft. However, it was noticed that the rate of losses remained unchanged after the first treatment. At this point, it was decided to spot a composite mat pill of 80 bbl through the circulation sub used above. The pill was spotted by placing the BHA ~ 150 ft above the lost circulation zone and was displaced completely out of the drill-string. It was noticed that as the pill entered the loss zone, the pumping pressures started to increase, which indicated the plugging of fractures, as shown in **Fig 11**. The pill was left static for approximately 1 hour after placing the treatment to soak in the fracture zone, and the static and dynamic losses were reassessed by staging up the flow rate to drilling rate by placing the bit above the loss zone.

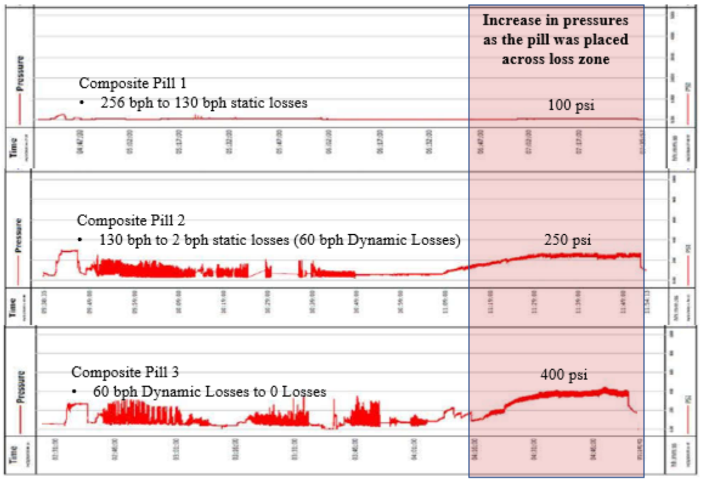

Fig. 11—Pressure profiles during placement.

After the first treatment, the loss rate dropped down from 256 bbl/hr of static losses to 130 bbl/hr of static losses, and the pumping pressures were at 100 psi while circulating on top of the loss zone. The treatment was repeated, and the losses dropped from 130 bbl/hr static losses to 2 bbl/hr static losses (60 bbl/hr dynamic losses).

The pumping pressures on top of the loss zone increased from 100 psi to 250 psi, indicating a clear improvement with each pill both in terms of loss rate and pumping pressures.

A third pill was spotted using similar procedures as the first two pills, and it was noticed that all the losses were completely cured after spotting the pill. The pumping pressures increased from 250 psi to 400 psi; this is equivalent to an increase of approximately 1.12 ppg of equivalent static density.

Similar procedures have been followed to successfully to cure losses in multiple sections, as shown in **Fig. 12.** The pills have been spotted by using either an open-ended drill pipe or circulation subs depending on the nature of operations at the time of the losses. All the wells treated were later successfully cemented with no major losses.

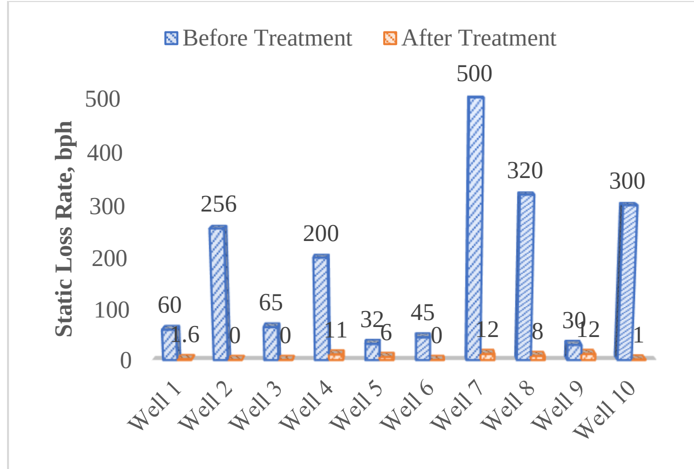

Fig. 12—Track record of engineered composite mat pills.

Due to the effectiveness of the pill on this case study well, the Loss Management Plan decision tree has been created with engineered composite mat pills as the primary option for upcoming wells (**Fig. 13**).

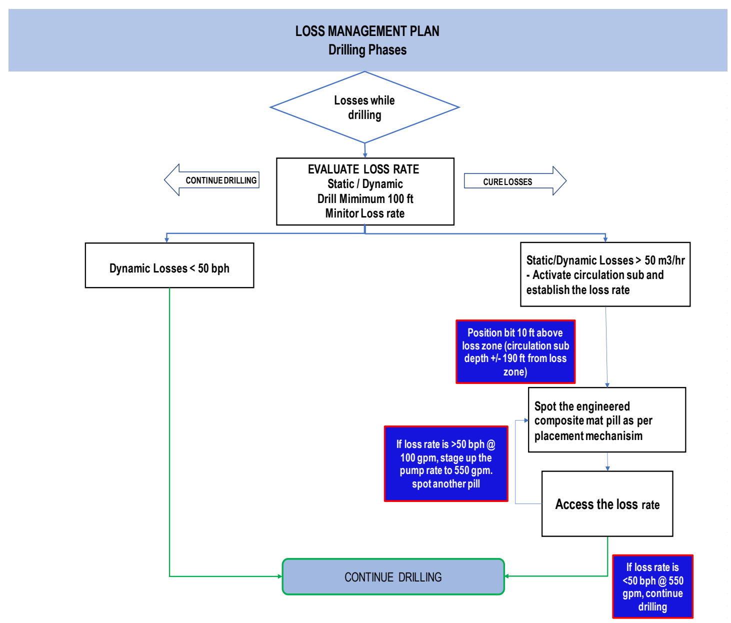

Fig. 13—Loss Management Plan

Conclusions

An engineered composite fiber-based lost circulation pill was successfully developed to bridge and plug thief zones in horizontal carbonate sections. The ability of the pills to bridge and plug the fractures was seen in the laboratory and was further demonstrated in the lost circulation treatments performed over various sections. A clear increase in the pumping pressures while circulating on top of the loss zones indicated that the pills were able to increase the equivalent static density. The engineered composite pills allowed successful drilling and cementing of wells with minimum nonproductive times and thus proved its value to the operator.

Acknowledgments

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Nomenclature

m^3/h = *Metric cube per hour*

kg/m^3 = *Kilogram per metric cube*

in^2 = *Inch Square*

MD = *Measure Depth*

TVD = *Total Vertical Depth*

bbl/hr = *barrel per hour (bph)*

ft = *feet*

in = *inch ('')*

µm = *micron*

gpm = *gallons per minute*

ppg = *pound per gallon*

°C = *Degree Celsius*

°F = *Degree Fahrenheit*

BHST = *Bottom Hole Static Temperature*

bbl = *barrel*

psi = *pound per square inch*

rpm = *Rotations per minute*

MASP = *Maximum Allowable Surface Pressure*

LCM = *Lost Circulation Material*

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