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Loss circulation prevention in geothermal drilling by shape memory polymer

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ABSTRACT

Geothermal formations are naturally fractured with large fracture openings and networks. This can often lead to frequent drilling fluid loss events which is a major contributor to the cost and non-productive time in geothermal drilling. Development of smarter technologies and methods to tackle problem lost circulation is vital for geothermal drilling cost reduction required for geothermal energy to be recognized as a competitive alternative energy source. Mitigation of this problem and other drilling problems such as stuck pipe can minimize overall project cost.

In this paper, a thermoset shape memory polymer that can be activated by formation natural heat was assessed to seal near wellbore fractures in geothermal wells. The performance of the shape memory polymer (SMP) was evaluated using artificial fractures created in aluminum discs and cylindrical granite cores. Rheology and particle size distribution were considered. A novel testing setup was built for this work, which allows testing of sealing efficiency under dynamic conditions at high temperature. Analysis showed that the SMP has efficiently succeeded in forming a strong plug inside the fractures and stopped fluid loss at high sealing pressure. This smart loss circulation material can expand within the fractures to reduces non-drilling time and strengthen the wellbore in high-temperature drilling operations.

1. Introduction

The cost of geothermal drilling is prohibitive without new technologies to address the challenges associated with the type of rock found in a geothermal well. Lost circulation complications are accountable for about 10 % of well costs in mature geothermal fields and often more than 20 % of exploration well costs in the United States (Lavrov, 2016). Lukawski et al. (2016) analyzed the cost of drilling for 8000−15,000 ft geothermal wells. They found that assumptions used to estimate geothermal drilling may not always be valid because of varied volumes of drilling mud and its high cost, which is often a symptom of significant loss of circulation (Lukawski et al., 2016). However, currently the traditional geothermal wells do not exceed 10,000 feet and most are between 4000−8000 ft. Geothermal formations are typically naturally fractured with large fractures and complex networks, in addition to the thermally induced fractures (Rossi et al., 2020). According to Cole et al. (2017), most of the lost circulation problems in geothermal well drilled between 2009 and 2017 were due to natural fractures (Cole et al., 2017). Compared to lost circulation in oil and gas wells, in addition to high temperature challenges, the geothermal formations can be cavernous with low pressure which complicate the loss situation.

For instance, in Reykjanes a scientific well was drilled in geothermal field in southwest Iceland. The major unsolved problem was a complete loss of circulation that could not be cured with lost circulation materials or by multiple attempts to seal the loss zone with cement (Friðleifsson and Elders, 2017). Pálsson et al. (2014) described a sequence of lost circulation events while drilling a geothermal well in the Krafla field in Iceland. Multiple sidetracks were drilled due to repeatedly occurring total loss at every time attempting to enter the geothermal formations. The high temperature, big fractures, and hard rocks made it difficult to drill through the zone and worsen the loss circulation problem. At some point, the losses could not be cured and cement plug was placed (Pálsson et al., 2014). Another dramatic sequences of lost circulation events occurred and concluded in a blowout during drilling of an exploration well at Wairakei Geothermal Field in New Zealand. When a major loss started, the rig's crew attempted multiple times to cure the losses by using increasingly coarser lost circulation materials. However, it was unsuccessful. After the loss and stopping the drilling and shutting down

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the pumps, formation fluids influx occurred and subsequently buildup of temperature and pressure in the hole led to a blowout (Bolton et al., 2009). A Geothermal well located in Indonesia faced a sequence of severe lost circulation (>50 bbl/hr.), more than 6,500,000 bbl. of mud were lost to the formation causing about 30 % of the NPT. In addition, the lost circulation added troubles in the casing and cementing operations which contributed to 36 % of the NPT (Nugroho et al., 2017).

To prevent lost circulation, sealing materials are added to the mud to strengthen the wellbore by increasing the minimum horizontal stress of the fracture, and therefore, preventing fractures from getting larger and causing loss circulation. This method is known by the term wellbore strengthening (WS) which is conducted to increase the fracture gradients of formations. Salehi and Nygaard (2010) compared the existing theories of WS models and found that although wellbore hoop stress cannot be increased to a higher value than its ideal case, the fracture gradient can be increased significantly by enhancing the propagation pressure of fractures (Salehi and Nygaard, 2011). When a proper size and concentration of loss circulation materials were mixed with the mud, the fractures can be plugged and sealed (Cook et al., 2011). Ma et al., 2019 conducted a laboratory study on core fracturing simulations for wellbore strengthening. They used a self-developed experimental fracture equipment to study the performance of different plugging materials, their results concluded that the kinds and gradation of drilling fluids had obvious effects on fracturing pressure (Ma et al., 2019).

Alsaba et al. in 2014 reviewed and classified the most recent developments in lost circulation materials (LCM). They grouped lost circulation materials into seven categories based on their appearance and application: flaky, fibrous, granular, mixture, acid/water-soluble, high fluid loss squeeze, swellable/hydratable combinations, and nanoparticles (Alsaba et al., 2014). In addition to the type and shape of the LCM, Collins et al., 2010 emphasized the importance of the amount of plugging materials in drilling fluid, and noted that it is vital to consider the volume density of the plugging materials, rather than the weight density only, which resulted in a better plugging efficiency (Collins et al., 2010).

Many researchers proposed and tested different types of LCMs, such as cellulosic fibers and particles that were developed by Friedheim (Friedheim et al., 2012), blends of nanomaterials and graphite (Contreras et al., 2014; Nwaoji, 2012), and crosslinked polymers (Magzoub et al., 2020a; Shamlooh et al., 2019). However, even with the advances and development in the last couple of decades, lost circulation materials still have lots of limitations such as failing to seal complex large fractures, causing plugging of the drill string, or damaging production zones. In general, strengthening the wellbore and keeping the integrity of the sealing inside the fracture are essential to prevent further losses.

In a recent development, Mansour et al. (2017) proposed a smart expandable material made from thermoset shape memory polymers (SMPs) that are capable of sealing fractures and treat loss circulation (Mansour et al., 2017). The expandable polymer was found to be capable of forming strong seals and increase wellbore strengthening as a preventive method for loss circulation. The SMP can work as lost circulation material that seals and plugs fractures to stop losses. Another advantage of SMP illustrated by Mansour et al., is that it can release 13 MPa of stress which will increase the hoop stress around the wellbore and strengthen it. Using the SMP as smart loss circulation materials has great potential for geothermal drilling applications since thy can be activated by geothermal temperatures to prevent the loss of fluid in fractured rocks near the wellbore. The programmed smart SMP is proven to have high performance in fracture sealing since it can be deployed with various particle size distributions. It has the ability to be programed to activate and change in shape at certain temperatures in order to seal different fractures sizes (Mansour and Taleghani, 2018).

Another successful application of the smart expandable polymers can be found in cement formulations, where SMP can act as smart additives for cement loss in fractured formations. Dahi Taleghani et al., 2017 proposed use of an expandable cement additive made of SMP, and conducted mechanical evaluation tests that confirmed the expandable polymer-based additives do not have any deterioration effect or alter thickening time of the cement, rather than providing better slurry properties to prevent cement channeling, debonding, and fluid migration to the upper formations (Dahi Taleghani et al., 2017). Their study showed that SMP can provide sustainable integrity in naturally fractured formations.

1.1. Shape memory polymers

SMPs can be defined as polymers that have the ability to be deformed and fixed into a temporary shape, and then able to recover to their original permanent shape if they are exposed to a specific external stimulus such as light, magnetic field, temperature, moisture, or pH. When the shape memory polymers are deformed under any load they have the ability to trap mechanical energy as internal energy, and release this energy whenever an external stimulus causes a change in the molecular relaxation rate or in material morphology (Li, 2014). The common external stimuli are, temperature (Mansour et al., 2017; Srivastava et al., 2017), change in light which known as light induced or photo responsive materials (Lendlein et al., 2005), and change in electricity (Ratna and Karger-Kocsis, 2008). Other known stimuli are magnetic fields, moisture, and pH (Li, 2014). The most common stimulus is temperature, where change in shape takes place with respect to a certain critical temperature (T_c) (Ratna and Karger-Kocsis, 2008). This type is known as thermally induced SMP. The shape memory materials can be deformed and fixed into a temporary shape before they are put in service and later, they recover their original permanent shape by heating to above their transition temperature, which is the glass transition temperature (T_g) for amorphous thermoset SMPs. An example of deformation and shape recovery is depicted in Fig. 1.

The first discovery of shape memory phenomena was made by Chang and Read in 1932 (Chang and Read, 1951). At the beginning it was metallic shape memory alloys (SMA), and later in 1984 the Chime Company France (CDF) developed the first shape memory polymers (SMP) (Behl and Lendlein, 2000). Then throughout the last decades, the shape memory materials have found growing interest because of the rise of new applications and materials. The metallic alloys and polymers are the two major types of developed shape memory materials. Both types have been used in many applications and have their advantages and limitations. For instance, the (SMA) exhibit remarkable properties such as high strength and high recovery stress, and their wide technical applications (Wei et al., 1998). However, the SMA have many noticeable disadvantages, such as high cost of manufacturing, limited recoverable deformation, and high degree of toxicity (Hornbogen, 2006; Uo et al., 2001).

On the other hands, the SMP offer more flexibility and wide scope of applications, which is due to the variety of mechanical properties compared to SMA. Moreover, the SMP can be turned into biocompatible and nontoxic materials in addition to other advantages such as high shape recoverability, easy manufacturing and manipulating compared to alloys, which make them more economical compared to SMAs (Fakirov, 2006; Hisaaki et al., 1996; Liu et al., 2007).

The polymers basically comprised of two phases, frozen phase, and active or reversible phase. The frozen phase remains hard during shape

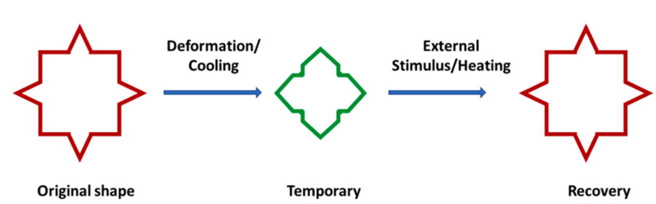

Fig. 1. Deformation and shape recovery of shape memory materials.

changing process, while the reversible phase is subjected to softening and hardening upon removal and applying of the stimulus (Kim et al., 1998). In other words, in a thermoset SMP, the soft phase acts as a device to store energy during programming either through the reduction in entropy or increase in enthalpy of both (Fan and Li, 2018), and release the energy when the temperature is above the glass transition temperature. The hard phase is formed by crosslinked netpoints which restrict the neighboring chains from slipping past each other during deformation and consequent stress build up (Srivastava et al., 2017). The mechanism of the shape memory depends on material design principles. Polymers can be crystalline or amorphous, and the type of crosslinking, whether it is chemically crosslinked, physically crosslinked or composite (Li et al., 1998; Ratna and Karger-Kocsis, 2008). However, the shape memory effect is not attributed to a specific material property of single polymers; it rather results from a combination of the polymer structure and the polymer morphology in addition to the applied manufacturing and programming technology.

The programing of an SMP is a process involving deforming the polymer to give it a temporary shape before it retains its original permanent shape through the application of external stress. The classical programming method of thermoset SMP consist of four thermo-mechanical cycles, involving changes in temperature, and provoking stress and strain. The first cycle runs at temperatures above T_g, which applies high deformation, and this is known as the pre-deformation step. The second step is to maintain pre-deformation while reducing the temperature to lower than T_g. The third step is to remove pressure at lower temperature. In the last step, the SMP is to be reheated to its initial temperature without applying any restrictions, hence the pre-stress step will return to zero, the SMP regains its original and permanent shape (Li and Xu, 2011). This programing process can also be conducted at temperatures below the glass transition temperature or the so called cold programing shown in Fig. 2 (Lendlein and Kelch, 2002), which happens in the glassy state and is far below T_g. In the cold programming the process depends on the structural and stress relaxation condition. During this process of cold programming, the segments freeze in imbalance state and maintain a temporary shape. This includes a reversible plastic deformation which is mainly stored in the form of active force, that allow it to be reversibly recoverable when heated up to the Tg (Li, 2014; Li and Wang, 2016).

The previous studies on SMP showed that they can be programmed to activate at certain temperature, which gives them great potential of making a programable expandable polymers for loss circulation prevention in geothermal drilling. In this paper a more reliable method of LCM performance evaluation is introduced: the SMP was evaluated in term of rheology, particle size distribution (PSD), and fracture sealing efficiency. The fracture sealing experiments were conducted at high temperature using actual granite cores for better resemblance of geothermal reservoir conditions. The objective of this study is to investigate SMP performance as a reliable method of loss circulation prevention in geothermal drilling to reduce the cost of geothermal projects.

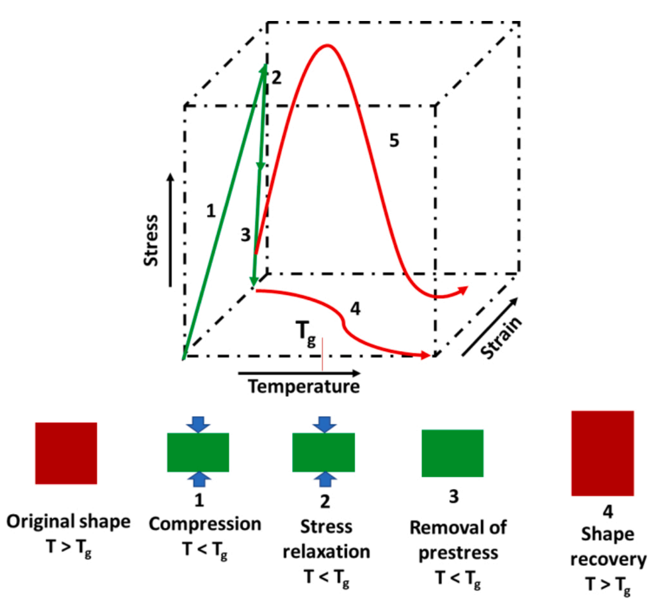

Fig. 2. Cold-Programming of thermoset SMPs (Modified after Li, 2014).

2. Design of experiment

2.1. Materials

The SMP used in this study, shown in Fig. 3 is a thermoset temperature triggered polymer. This high enthalpy storage thermoset SMP has high compressive strength (320 MPa) and high stiffness (1.05 GPa) at room temperature, high glass transition temperature of 300 °F, and high recovery stress of 17 MPa and energy output of 2.12 MJ/m^3 in rubbery state and in bulk form (Fan and Li, 2018). Just like other thermoset polymers, this SMP also has high stiffness, high strength, high thermo-stability, high dimensional stability and high corrosion resistance. The SMP used as LCM in this study has a density of 59.3 lb/ft3, Poisson's ratio of 0.4, and Young's modulus of 37,710 and 350 psi at temperatures of 73 and 176 °F, respectively (Mansour et al., 2019).

For comparison, two types of LCM were tested. One is a commonly used fiber as LCM, and the other is a mixture of the fiber and the SMP. A cedar fiber was used in a mixture with the SMP to improve its performance. The fiber was obtained from a local supplier which is a blend of specially processed wood fibers of controlled length in order to give it proper size distribution and is usually used to treat lost circulations in concentrations from 1 to 30 %.

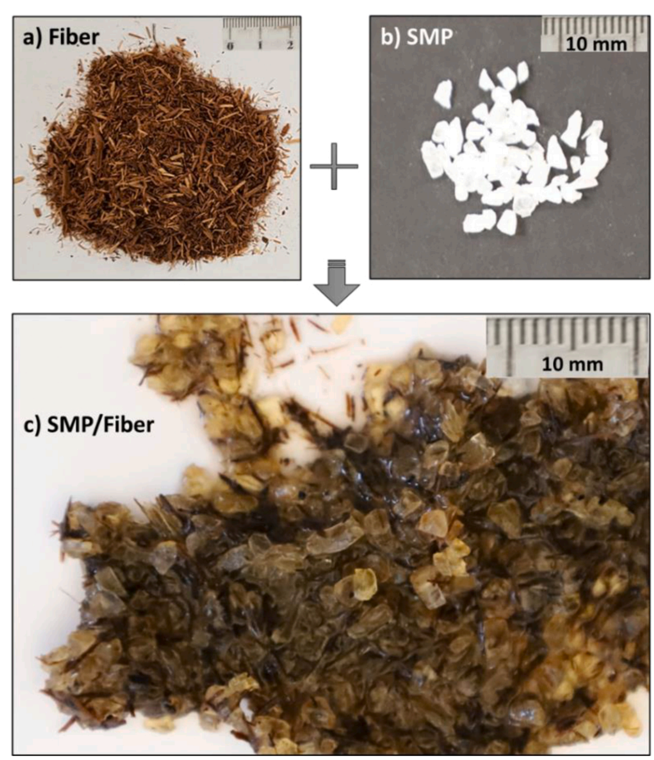

Fig. 3. Photos of a) Cedar fiber, b) SMP, and c) SMP/Fiber mixture after a fracture sealing test.

2.2. Inter-lock mechanism between fiber and SMP

Different particle bridging and fracture sealing theories are available in the literature as well as different WS models. Magzoub reviewed the common WS models and LCM selection methods, often, different types of LCM are mixed to form a better pill for loss circulation treatment (Magzoub et al., 2020b). Alsaba et al. (2017) concluded from a statistical investigation on experimental data of different LCM types that mixing LCM of different sizes has the same effect on sealing efficiency as increasing concentration of LCM and usually results in better seal integrity (Alsaba et al., 2017). The LCM can be granular, flake or fiber, and when mixed into a drilling fluid will seal the formation that is taking mud from the system. One of the main selection criteria is the particle size distribution (PSD), since it enhances bridging capabilities of LCMs. Generally, the solids in drilling fluids should be large enough to bridge over the fracture mouth. Smaller size particles may also be needed to form the matrix of the seal with the larger ones and to form a low permeable filter cake. The fracture aperture usually used to select the proper LCM blends. The common principle of size selection relies on Abraham's one-third rule that governs the size of the LCM with respect to the fracture aperture, ideal packing theory, or numerical model (Dick et al., 2000; Vickers et al., 2006).

Adequate concentration of LCM as well as proper sized fine and coarse particles is vital for effective fracture sealing (Razavi et al., 2016b). Therefore, in this paper, we proposed SMP/fiber blend shown in Fig. 3, which shows that the SMP is believed to give good performance when mixed with cedar fiber. The thermoset shape memory polymer can overcome the limitation of larger particle size that is required to seal large opening fractures since it expands only on the desired depth that is programed to be activated at certain temperature.

In this paper, cedar fiber was used for two purposes, one as a base case for comparison, and the second is to be mixed with the SMP to form a better plug by bridging. Both fiber and SMP are not soluble, inert and do not react with the mud, hence, at high temperature the SMP will expand and form the larger particles required to seal the tip of the fracture and the fiber will form the network of the bridge to completely seal off the fracture. Particle size, rheology, and permeability plugging test are included in this study in addition to the dynamic LCM testing at high temperature.

2.3. Rheology and particle size analysis (PSD)

Rheology and PSD of drilling fluids are the most important factors affecting drilling fluid performance and fluid loss control (Iscan and Kok, 2007; Magzoub et al., 2017; Razavi et al., 2016a; Whitfill, 2008). A speed dial viscometer was used for rheology measurements and apparent viscosity, plastic viscosity and yield point were obtained. For PSD, two methods are often used to analyze the PSD of an LCM, the mechanical sieve analysis, and the laser diffraction method. PSD analysis was conducted for cedar fiber using mechanical sieving. Mechanical sieving can generate a PSD with a range of sizes (63 −1200 μm). A known weight of the cedar fiber was loaded into the top tray of a sieve shaker, then run at max speed for 20 min. During sieving the particles were fractionated based on their sizes. For the SMP, the PSD was conducted using laser scattering with the dry method. The Malvern particle size analyzer gave the full PSD for particles in the range from 0.2–3000 μm.

2.4. Fractures and cores preparation

For the SMP performance evaluation as a preventive method for lost circulation, both aluminum discs and rock cores were used in the permeability plugging tester (PPT), and the new developed high temperature dynamic LCM testing unit (HT/Dyn). In the dynamic LCM testing unit, granite cores were used as an example of a rock type in geothermal drilling. The granite rock samples were collected from Oklahoma. A 2 × 13.5 in. core is prepared and split into two halves and then welded again with aluminum sheet as spacer in order to make the fracture shown in Fig. 4, the fracture width is 1000 μm and has a height of 1 inch and a length of 13.5 in.. For the PPT, a slotted aluminum discs were fabricated to be used as artificial fractures. The disc diameter is 2.5 in. and the thickness is 0.25 in.. The fracture is cut through the disc to make 1 inch long with 1000 μm fracture width.

2.5. Fracture sealing experiments

Two methods were adopted for evaluation of the fracture sealing efficiency; permeability plugging tester equipped with slotted disc and a novel high temperature dynamic fracture testing simulator (Fig. 5 Fig. 6). The permeability plugging test is valuable in predicting an LCM ability to form plug that will seal off an artificially fractured disc. The differential pressure is maintained by applying pressure from the bottom of the PPT cell while the back pressure is applied from the top. The filtrates are collected from the top.

The novel high temperature dynamic fracture testing unit was built specifically for this study. The simulator unit allows a method for evaluating the performance of LCM in larger scale dynamically with a circulated drilling fluid. Fig. 6 shows the sketch of the testing unit that consist of a 13.3′ feet long circulation loop, high temperature circulating pump, confining cell that can accommodate a 2 × 13.5″ core, filtrates collection cell, and a set of hydraulic pumps, heating belts, thermocouples and gauges.

The method of testing is based on applying a differential pressure across the 13.5″ long core by circulating the pressurized flow-loop with a mud containing LCM. The circulation rate is kept constant while increasing the temperature to 400 °F, then pressure is increased step wise from 100 to 500 psi. The testing unit allows collecting of filtrates every minute while monitoring sealing pressure. The objective of this experiment was to test the efficiency of LCM for plugging the fracture. This was assessed dynamically through circulation system meant to provide a continuous fluid circulation across the core to simulate drilling fluid circulation inside the well. A case of fully open fracture is identified by the full communication of pressure before and after the core. The LCM in the circulated drilling fluid will form the bridge to seal the fracture mouth, and during this process, any filtrate that escapes the entire core length will be accumulated inside the collection pressure vessel mounted after the fracture. The pressure difference between the differential pressure and the pressure after the fracture will be considered as the sealing pressure. For data reproducibility and error estimation, and since experiments with the dynamic high temperature setup are difficult, expensive and time consuming, a test with WBM was repeated once. The measurements error on the cumulative filtrates and sealing pressure were within 5–10%, and sealing pressure was less than 5%.

Fig. 4. Core with 2″ OD x13.5″ length core split into two halves (left), welded core with fracture length: 13.5″ (middle), and top view of fracture width 1000 μm (right).

Fig. 5. Photo of the high temperature dynamic LCM testing setup.

3. Results and discussion

3.1. Rheology

The high temperatures in geothermal wells raise concerns about the stability of drilling fluids under these extreme conditions. Assuming that the rheology profile is independent of pressure and temperature is only valid in shallow wells where changes in temperature are insignificant, therefore prior to drilling, the rheological properties of proposed mud should be assessed at HPHT conditions. The rheological properties must be maintained under compression and expansion caused by temperature changes, along with the degradation of drilling fluids additives. Maintaining a good rheology is a crucial issue in order for drilling fluids to function properly at various reservoir conditions.

In addition to the fact that it directly affects fluid invasion into a permeable rocks and fractures, the carrying capacity of solids content as well as suspension of LCM with large particle size also depend on the rheological properties of drilling fluids. Since the viscosity of additives and rheology modifiers can hold up to a certain operation conditions, drilling fluid should be designed to overcome these limitations to ensure good temperature dependent profile.

The SMP and fiber mud were tested for rheology at 200 °F as shown in Fig. 7. The results show that fiber and SMP/fiber mixture have viscosities and yield point around typical values of drilling fluids, thus it should be easily handled by the mud pumps at the site of drilling rig and is not expected to increase the equivalent circulation density (ECD). Although the SMP is activated at 300 °F, due to limitation of equipment, the test at 200 °F is assumed to give a fair comparison since the SMP is inert and expected to have larger particles size after activation. Given this, no degradation is occurring and the increased particles size after the SMP activation will prevent the rheology from deteriorating.

3.2. Particle size distribution (PSD)

Fracture sealing efficiency and seal integrity depend highly on PSD of the LCM. Numerous experimental studies have proven the theory of increasing sealing pressure as particle size distribution becomes coarser, particularly when different sizes are mixed (Alsaba et al., 2017; Whitfill, 2008). Generally, in designing of drilling fluids for loss circulation treatment and wellbore strengthening, a wider PSD is recommended. A rule of thumb for size of bridging materials that is validated by many previous fracture sealing studies is to have the median of particle size to be equal or slightly greater than one-third of the fracture size (Dick et al., 2000; Mansour et al., 2019; Salehi et al., 2014).

The PSD analysis for the SMP and the cedar fiber are shown in Fig. 8 shows. Overall, the SMP has larger particles than the fiber with D50 of 1637 µm. The fiber on the other hand although it is showing less D50 (600 µm), however, it has wider range of particle size, which is good for bridging of LCM plug. This tow different and varied PSD means that the combination of SMP and fiber will result in a good LCM mixture for fracture sealing. The mixture will have enough large particles to form a bridge at or near the fracture mouth, along with enough small and wider range of particles to form a matrix of the seal with better sealing

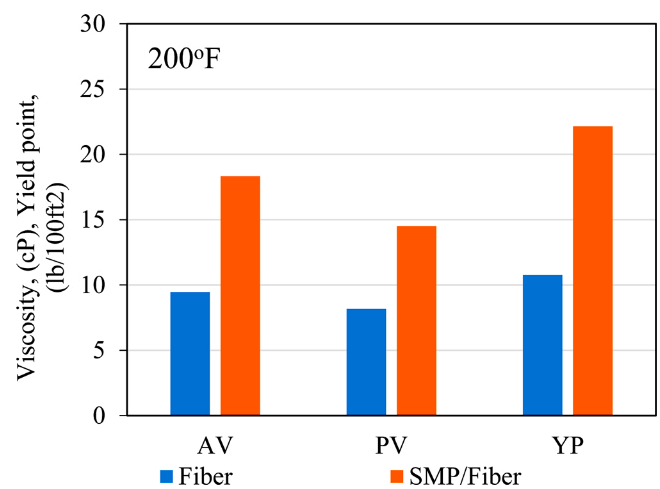

Fig. 7. Rheology result for the 5 lb/bbl fiber and 3 wt.% SMP plus 5 lb/bbl Fiber.

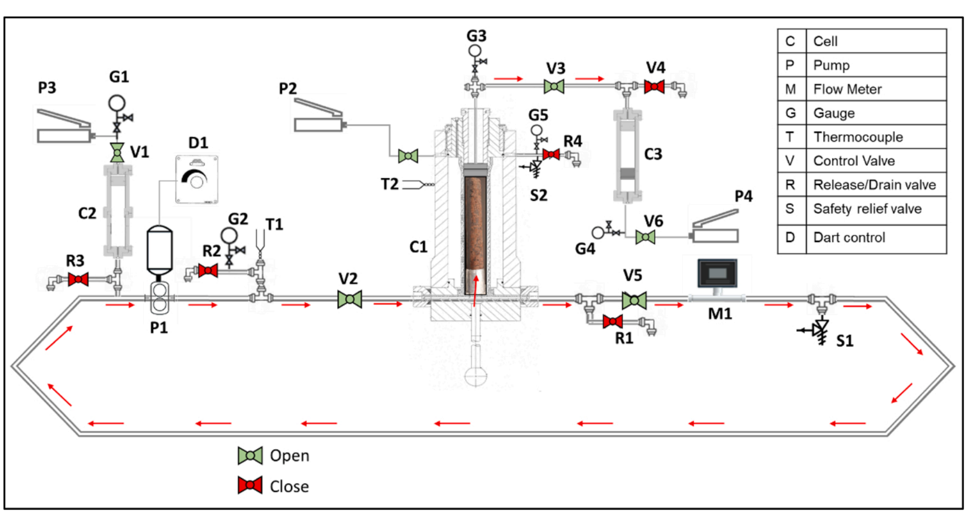

Fig. 6. Sketch of the high temperature dynamic LCM testing unite, and a 2 × 13.5″ core inserted in the confined cell.

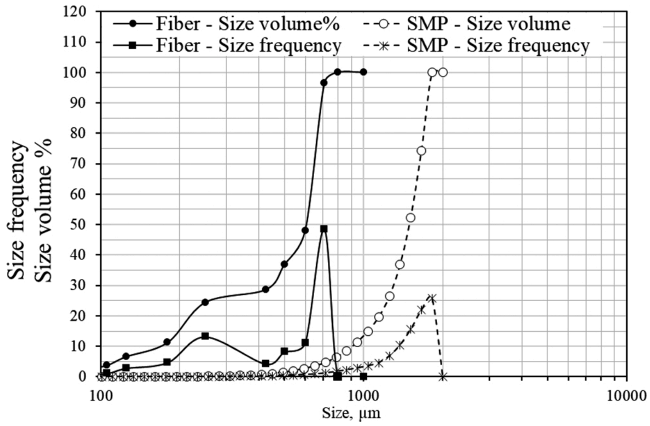

Fig. 8. Size volume % and frequency of the fiber and SMP from the particle size analysis.

efficiency.

3.3. Permeability plugging tester (PPT)

The differential pressure across the slotted disc was recorded and the highest stable pressure after filtration stops is considered as the maximum sealing pressure. Fig. 9 shows the sealing pressure obtained with the two different LCM. Both fiber and fiber plus SMP formed a plug inside the fracture that can hold up to 500 psi differential pressure. These values were stable for at least 30 min during the test period. In case of increasing the pressure above 500 psi, neither LCM mixture could not handle the pressure and a sudden drop in the pressure across the slotted disc was observed. Although the pressure was built up again in a few seconds, the maximum pressure obtained afterwards was not the same as the initial sealing pressure, and the values fluctuated around 200 psi or less for both fiber and fiber plus SMP.

Accordingly, the filtrates volume was collected through the 30 min of the test period while the differential pressure was kept constant at 500 psi. Fig. 9 also shows the cumulative volume of the collected filtrates. With 5 wt.% fiber, the slotted disc allowed spurt loss of about 1.5 cm^3 in the first 15 s, and then ceased to flow in about 2.5 min. At the end of the 30 min the cumulative filtrate volume was 2 cm^3. The SMP and fiber blend outperformed fiber. The spurt loss was almost zero and the fracture was sealed instantly. The filtrates after differential pressure was increased above the sealing pressure was not considered in this figure since the fracture was no longer sealed. After the test, the slotted disc was retrieved and examined, and the fracture was sealed as shown in Fig. 10. The mud cake formed by the fiber was a thin layer, about 1 mm, while the SMP and fiber blend formed a layer of plaster on the aluminum disc. This could be due to the smooth surface of the aluminum and/or simply due to the different fluid's structures. Another noticeable difference is that after the disc was washed with tap water the plug formed with the fiber was completely washed out while the plug formed with the SMP and fiber blend held in place firmly.

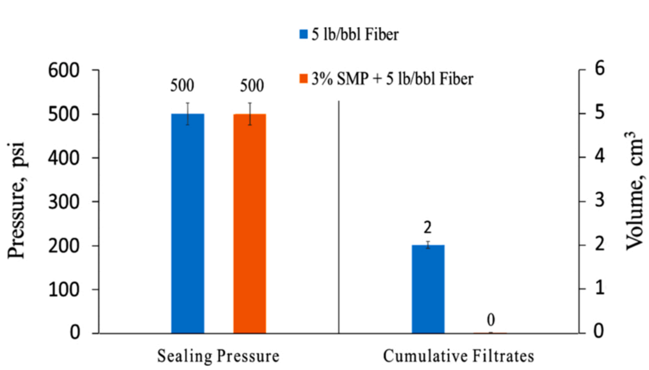

Fig. 9. Sealing pressure and cumulative 30 min filtrates volume of the PPT for SMP and fiber.

3.4. High temperature dynamic LCM testing unit

The results of the dynamic fracture sealing test using the high temperature dynamic LCM testing unit are described in the following section. One-inch length fracture with a thousand microns opening along the full length of the granite core (13.5 in.) was used for both tests with fiber and with SMP/fiber mixture.

The results illustrate the differential pressure across the fracture length which reflect the sealing status of the fracture dynamically at every time step. During the dynamic test, the flow rate was kept constant at 2 gpm and the temperature was raised to 300 °F. Fig. 11 shows the results of the dynamic experiment with fiber. The circulating pressure applied in the circulation is represented by differential pressure applied against the tip of the fracture during the circulation and differential pressure across the fracture which is represented in the figure as the sealing pressure. From the result of fiber performance, the sealing pressure is found to be less than 300 psi. As the circulating pressure is increased, the differential pressure increased gradually and so did the recorded sealing pressure since at the beginning there were no communications between the fracture tip and the fracture end. When the circulating pressure reached 300 psi the pressure wave hit the upper gauge after the fracture, which indicates that the fracture opening pressure is 300 psi. After about seven minutes, the sealing was rebuilt again, and the sealing pressure of 300 psi was regained for only four minutes before the fracture reopen. This concludes that at 300 °F the maximum sealing pressure with fiber is impossible to be higher than 300 psi. This is considered as the opening pressure of the fracture, and if the circulating pressure exceeded this value, the fracture will fully open and drilling fluid will be lost. The filtrates volume was also recorded every minute and it was also reflecting the plug status which is indicated by the sealing pressure. First, a spurt loss of 5 cm^3 was collected in 15 s as soon as the pressure hit 300 psi. Then, filtrates were accumulating and about 50 cm^3 collected at the second reopen at 300 psi after 23 min of the test.

A better result was obtained with the mixture of 3 wt.% SMP and 5 lb/bbl fiber as shown in Fig. 12. The sealing was formed immediately, and the sealing integrity was maintained as circulating pressure was gradually increased. A spurt loss was observed at 200 psi differential pressure and filtrates accumulated up to 10 cm^3 before the fracture completely sealed again in less than two minutes. The total fluid escaping from the fracture was 10 cm^3 till the end of the test, and the integrity of the seal was able to be maintained up to 500 psi. This result clearly shows the improvement in the performance with the introduction of the SMP. At high temperature, when most LCM fails, the SMP expands and recovers to its permeant shape with larger particle size to form an efficient plug to seal the fracture. The sealing pressure was noticeably increased with SMP of 3 wt% and the integrity of the plug at the tip of the fracture was maintained at differential pressure up to 500 psi at 300 °F, and the total filtrates volume was also reduced by more than 95 %.

Fig. 13 shows a comparison between the maximum sealing pressure and the cumulative filtrates volume collected through 30 min of the high temperature dynamic fracture sealing tests. The fiber showed sealing pressure of less than 300 psi while the test with SMP and fiber blend showed stable sealing pressure up to 500 psi. These values were noticeably different than those obtained from the PPT results. The PPT showed that both fiber and SMP/fiber blend have the same sealing efficiency with matching results, while with the dynamic LCM testing unit the outperformance of the SMP/fiber blend is obvious. The reason is that in the PPT test, the SMP was not triggered for shape recovery because the temperature of 200 °F is lower than the glass transition temperature of the SMP, which is 300 °F.

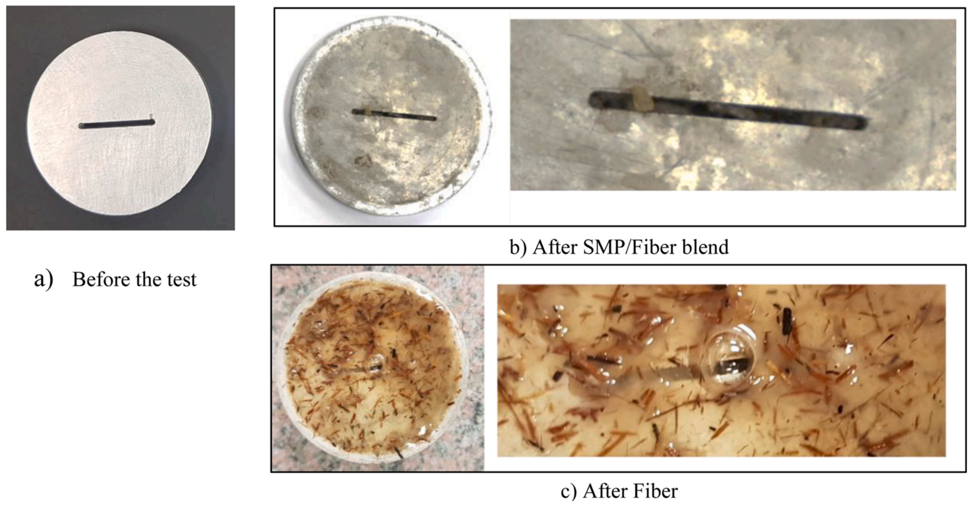

Fig. 10. Aluminum disc, a) before and after PPT, tested with b) SMP/Fiber blend and with c) Fiber.

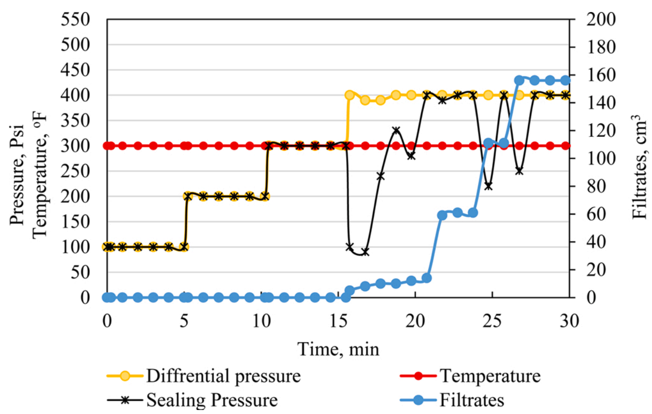

Fig. 11. Dynamic LCM testing with 5 lb/bbl fiber at 300oF.

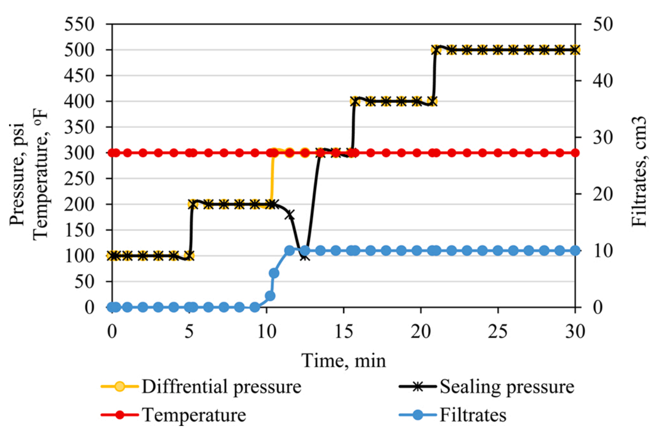

Fig. 12. Dynamic LCM testing with 3 wt.% SMP mixed with 5 lb/bbl fiber at 300oF.

In addition to sealing test, a physical observation after the test was conducted. The core was split again into two halves, and by examining the split it was clear that the plug of the SMP/fiber is well established on fracture tip as shown in Fig. 14; on the other hand, no traces on fracture tip were shown after the dynamic fracture sealing test with fiber.

4. Conclusion

Wellbore strengthening by a drilling fluid containing proper LCM can decrease the cost of geothermal wells. Solving drilling problems associated with loss circulation can greatly reduce the NPT of geothermal drilling and assist in making geothermal energy a more competitive alternative energy source. In quest of developing of smarter technologies and methods to remedy problem lost circulation problem, in this paper we used a novel method of dynamic LCM performance analysis to help design the proper drilling fluid for fracture sealing and wellbore strengthening under high temperature. The following are the key findings:

- Shape memory polymers have great potential for sealing large fractures by using formation temperature to trigger the thermoset polymer at a preprogrammed point. The recovered shape and size will work as a bridging material.
- SMP and fiber blend offered appropriate PSD with wide range of small and large particles and enhanced the sealing integrity.
- The PPT is a useful analysis method for fracture sealing test; however due to the small fracture length and height ratio provided by the disc (0.25:1) the test is not a good representation to the fracture sealing screening tests.
- The dynamics LCM testing unit provided a better tool for LCM performance evaluation at high temperature. And with sealing pressure and filtration volume as the key indicator for sealing efficiency, a better drilling fluid design can be validated.
- The concentration of SMP is expected to play a major role in sealing fractures with larger openings; more investigation on the relation between fracture size and SMP concentration is needed.

Authors note

I am pleased to submit the revision to our article entitled “Loss Circulation Prevention in Geothermal Drilling by Shape Memory Polymer”. for publication in Geothermics.

We would like to thank the editor and the reviewers for their time and efforts, and for the valuable comments and suggestions. We have revised the manuscript and addressed the comments made by the reviewers. Following are our specific responses to the reviewers’ comments (highlighted in blue) and our revisions to the manuscript.

Please note that all changes are marked blue in the revised manuscript. The following section explains how and where each point of the reviewer’s comments has been incorporated. Thank you again for the time and effort you will take to review our work.

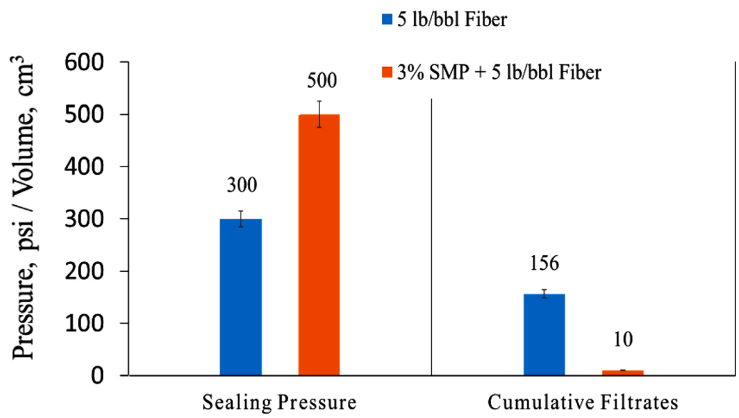

Fig. 13. Sealing pressure and filtrates volume from dynamic LCM testing for fiber and SMP/fiber blend.

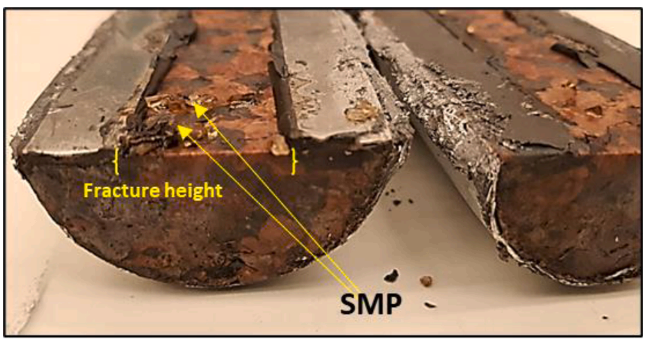

Fig. 14. Split core after the dynamic LCM testing with SMP/fiber blend.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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