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Experimental Evaluation of the Impact of Oil-Based Mud Residuals on Cement-Formation Bonding Strength

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Abstract

Mud removal is a key operation to ensure successful well cementing and, consequently, zonal isolation through the lifetime of the well. If not properly removed, a thin layer of mud remains in place, contaminating the cement slurry and preventing it from developing a strong bond to the formation or to the casing. Without a strong bond, the annulus become susceptible to gas migration, especially under extreme conditions, such as hydraulic fracturing, where large pressure fluctuations are involved.

Oil based muds (OBMs), in comparison with water-based muds (WBMs), are improving drilling operations in term of lubricity, temperature and borehole stability, resistance to contamination, and greater penetration rates in certain formations. However, OBMs have countereffects on cement performance in wellbores by oil-wetting the formation. The objective of this work is to evaluate the impact of wettability alteration caused by mud residuals on cement bonding with three different formations, sandstone, limestone, and shale. A modified push-out setup containing steel pipe, cement and a rock core in the center was prepared and cured under high pressure and high temperature conditions. Then, the specimen was tested under a low displacement rate for shear-bond strength measurements. Additionally, the effects of OBM oil/water ratio (OWR) on the cement-formation interface were analyzed. It is notable that a proper removal of OBM by spacer increased the shear-bond strength of the cement significantly. However, the results are still 50% below the ones done in absence of mudcake. The proposed experimental setup can provide an effective tool to study the impact of mud removal by a spacer in a reliable and repeatable manner.

Introduction

OBMs have gained popularity over the years due to excellent drilling performance achieved when compared to WBMs. In many cases, they are less damaging to oil reservoirs and have better stability for clays and shales. Formation damage during drilling can substantially reduce well productivity, thus OBMs are preferred in drilling formations with sensitive clays and shales (Fjelde, 2017). In addition, drilling with OBMs in most times delivers better-quality boreholes than when using WBMs (Salazar *et al*., 2011).

OBM has various applications in drilling, providing multiple benefits as, for instance, lubricity, temperature and borehole stability, resistance to contamination, and greater penetration rates. Consequently, OBM can noticeably affect cement performance in wellbores, and that usually happens when OBM mix with cement at well cementing after casing (Harder *et al*., 1993)

It is important to understand the composition of OBMs, and the benefits obtained through its use. OBMs are a water-in-oil emulsion consisting of three phases, the internal phase, surfactants, also called emulsifiers, the drilled solids and commercial additives. The internal phase exists as water droplets emulsified within the external oil phase. The surfactants maintain the emulsion of the water droplets to keep it stable under downhole conditions and keep solids oil wet and in the external phase. The drilled solids and commercial additives are used to maintain required drilling properties (Harder *et al*., 1993).

OWR is a representation of the fraction of oil and water in oil-based muds. It represents the ratio of the percent volume of oil to the percent volume of water that can be determined through a retort analysis or could predetermined while designing a fluid mixture. The retort analysis is done when a sample of OBM is controlled burnt in a retort kit at specific temperature. Then, oil and water are extracted out from the OBM where solids are left in the retort kit to give a percentage by volume of each component and that is used to determine the OWR (Lyons et al, 2011). Furthermore, oil-in-water (O/W) emulsion is a type of emulsions where oil droplets are contained inside water, water being the external phase whereas oil being the internal phase. An example for O/W emulsion is WBMs containing oil. However, water-in-oil (W/O) emulsion is a type of emulsions where water droplets are contained inside oil, oil being the external phase and water being the internal phase. An example for W/O emulsion is OBMs (Patel and Growcock, 1999). As well, wettability is an important factor that may be influenced by the use of OBMs, it is an interfacial phenomenon of spreading and adhesion of fluids on a rock surface (Hirasaki, 1991).

If cementing job was not done properly, it would weaken cement bond strength between casing-cement and cement-formation interfaces that can be a great source of gas migration behind casing and sustained casing pressure build up (Michael *et al*., 2004). Cement is designed according to well's and reservoir's properties, such as depth and temperature, so the volume of cement and the rheological properties can be adjusted to attend the needs of the operation.

Prior to cementing operations, spacer fluids are typically used to pre-flush the wellbore annulus to displace the drilling fluid and prepare the well for cementing (Fig. 1). Cement slurries and drilling fluids are usually chemically incompatible; drilling fluids can contaminate cement slurries and cause various problems that will be discussed later in this work. Therefore, the drilling fluid has to be displaced from the annulus before the placement of cement slurry. This operation is generally done by pumping a spacer fluid between the drilling fluid and cement slurries to form a buffer and prevent the drilling fluid and the cement slurry from coming into contact. Since the spacer fluid is in direct contact with cement slurry and the drilling fluid in the wellbore annulus, the spacer fluid has to be chemically compatible with both of them (Atlantic Richfield Co, 1991). Additionally, the quality of the cement job in the annulus on the long run is mainly influenced by an effective drilling fluid removal (Shadravan *et al*., 2015). In order to accomplish a good drilling mud displacement, the downhole forces implemented by the circulating fluids in the borehole have to be enough to overcome the yield stress of any partially dehydrated drilling fluids left in the hole (Ravi and Weber, 1996).

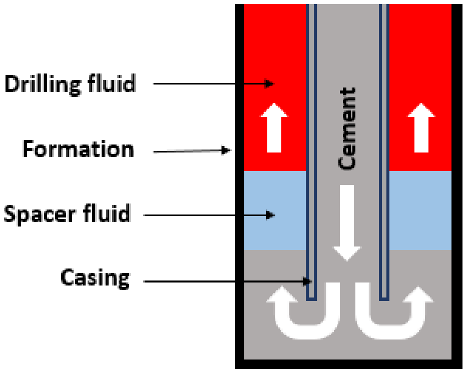

Figure 1. Schematic of drilling fluid displacement by spacer followed by cement injection

To ensure an effective cementing operation, two conditions have to be met: First, the drilling mud has to be effectively removed from the wellbore; wellbore surface and casing surfaces. Second, the formation surface has to be water-wet. Failing the first condition can cause cement contamination and affect the cement performance, where cement slurries do not bond properly with each other. Whereas failing the second condition may weaken bonding between the cement paste and the rock surface in the wellbore and casing. Spacer fluid is an aqueous water-based fluid, which comes into contact with an OBM and breaks its emulsion. The OBM has a water-in-oil emulsion, and when it comes into contact with the spacer, the mud's emulsified water droplets absorb water until the droplets become so big that the external oil layer cannot hold them any longer, breaking the emulsion and water-wetting the mixture. Formation wall wettability plays a critical role in cementing quality. Cement slurries do not bond effectively to oil-wet surfaces. Therefore, spacer is used to water-wet the formation right after an OBM was used (Patel *et al*., 1999).

The apparent-wettability testing can be used in the lab to evaluate the performance of spacer fluids (Osode *et al*., 2012). The evaluation can help choosing the right surfactants to water-wet the well. Apparent-wettability can be majored by measuring the electrical activity during the water-wetting process. Since oil-external fluids are bad electricity conductors, while water-external fluids are, so majoring electrical activity can provide a sense of wettability (Deshpande *et al*., 2016).

The objective of this paper is to evaluate the effect of OBM residuals on cement performance experimentally, and how effective spacer is in displacing those residuals and improving cement bonding.

MATERIALS AND METHODS

Sample Preparation

Three different oil-based muds were prepared in three different OWRs: 60/40, 75/25, and 90/10, and the components are listed in Table 1.

Table 1. Oil-based muds components

OWR	60/40	75/25	90/10
Diesel (ml)	364.25	448.96	531.34
Water (ml)	239.68	147.71	58.27
Barite (gr)	224.23	260.10	294.97
$CaCl_2$ (gr)	12.63	7.78	3.07
Bentonite (gr)	30	30	30
Emulsifiers (gr)	28.5	28.5	28.5

The rheology of the drilling fluids was measured in a rotational rheometer and the values obtained are listed on Table 2.

Table 2. Rheology of oil-based muds

OWR	60/40	75/25	90/10
Speed (RPM)	**Dial Reading (lbm/100 ft^2)**		
600	133	68	26
300	94	46	21.5
200	79	37	13
100	60	27.5	9

6	29	12	4
3	27	11	3.5

Spacer fluid was prepared according to manufacturer's standard specifications with 97.06% mass of deionized water to total mass of spacer and water. Then, a spacer-to-OBM compatibility test was done using the rheology meter to evaluate the performance of the spacer and decide if the addition of a polymer was essential. An initial mud displacement test showed negative spacer compatibility and an amount of spacer polymer equivalent to 5.04% of spacer fluid mass needed to be added to reach the desired mud displacement. Some rock samples were soaked in a dynamic spacer bath for 10 minutes to displace the OBM and water-wet the outside surface.

Push-Out Test

A modified push-out setup comprising a concentric configuration of rock core sample, cement, and casing-grade steel pipe was developed (Fig. 2). The rock cylindrical sample dimensions are 1 in. in diameter by 2 in. in height, and the pipe is 3.5 in. in OD, 2.6 in. in ID and 2 in. in height. Three different rocks were evaluated, sandstone, limestone and shale (Marcellus shale).

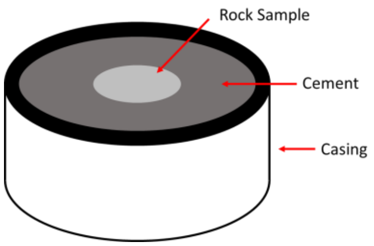

Figure 2. Schematic of a push out sample

Class G cement was prepared with 0.44 water ratio and poured in the annular space between the rock and steel pipe. The specimen was cured in a curing chamber under 200 °F and 3000 psi for 24 hours. The prepared specimen was then tested under 0.3 mm/min rate of axial platen for shear-bond strength measurements. The peak load achieved, divided by the contact area, is considered the bonding strength.

In the experiments, three distinct scenarios were evaluated. The first scenario is rock cores saturated in water. The second is rock cores preconditioned in OBM for 24 hours at 140 °F and 600 psi. In the last scenario, after being preconditioned in OBM, the rocks were washed with spacer fluid for 10 minutes using a magnetic stirrer at room pressure and temperature. Then, the specimen is tested using a load frame under constant displacement rate of 0.3 mm/min and stopped at a 12 mm displacement.

RESULTS AND DISCUSSION

A load vs. displacement curve for shale sample saturated in water is illustrated in Fig. 3. As it can be seen, the load quickly builds up until it reaches failure. Then, as the displacement proceeds, the force reduces to a residual value due to friction of the core to the cement. The peak value divided by the contact are of the rock is considered the shear bond strength.

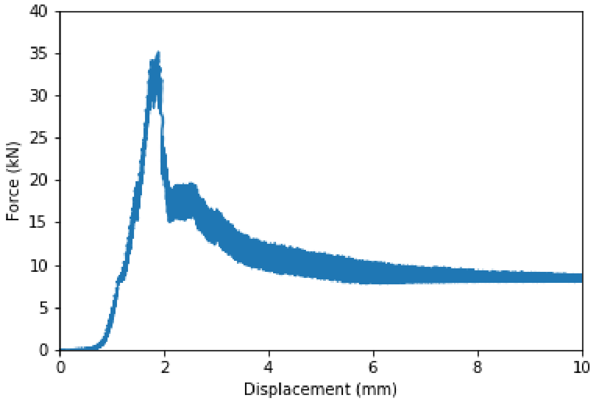

Figure 3. Load vs. displacement curve from a push-out test of a shale sample saturated in water

Two tests were run for the samples saturated in water and the results are shown in Fig. 4. The shear bond strength values for limestone and sandstone are very similar but they are substantially lower than shale. As mentioned by Zhang *et al.*, (2017), Marcellus shale tend to swell due to hydration of the clays. In their analysis using X-ray diffractometry the clay content was found to be 19%.

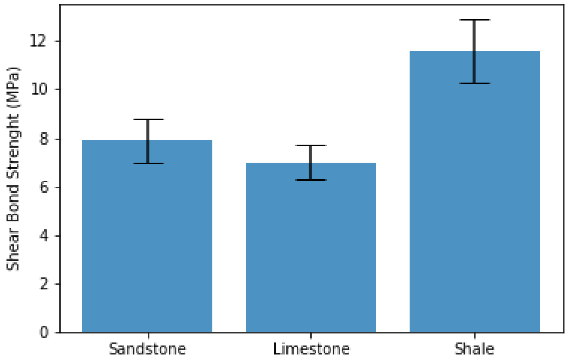

Figure 4. Shear bond strength of the samples saturated in water

The Effect of OBM's OWR in the shear bond is observed in Fig. 5. Overall, the values decreased in around 85%. It is notable that the higher the OWR, the smaller the bond between cement and formation. However, the difference between them is not significant. The difference between the three lithologies is also very small. Due to the inhibit nature of OBMs, no apparent swelling occurred in the clays, thus the values are not higher than the other samples.

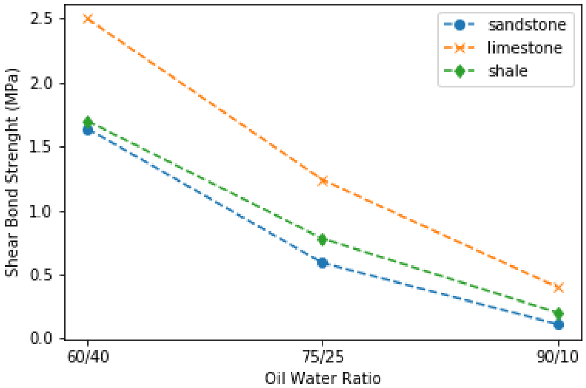

Figure 5. Shear bond strength for the samples pre-conditioned in OBM. The bond strength decreases with increase OWR

For the samples washed with spacer fluid, the bond strength increased, but did not return to the original values (Fig. 6). The spacer might not have removed all OBM, due to long exposure to the fluid. The results demonstrate that the shear bond doubled in relation to when no spacer was used. The mud residuals are responsible for the decrease in bond strength, when compared to water.

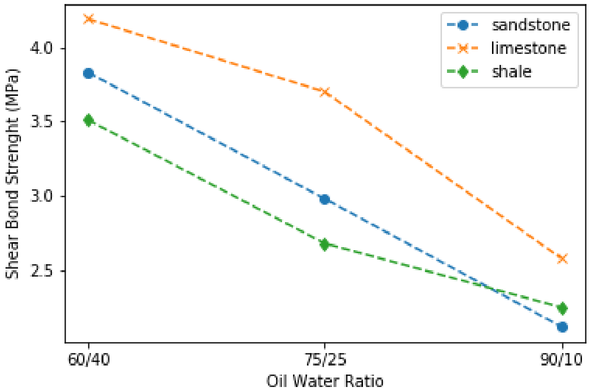

Figure 6. Shear bond strength for the samples washed with spacer fluid after being pre-conditioned in OBM

The results suggest that the use of spacer improved the bonding but not to the initial condition. The spacer did not completely remove the OBM and a filter cake might have been left at the interfaces. At the absence of mudcake the shear bond values are still around two times higher than the ones obtained with spacer. This is not valid for shale, that presented values unusually high in the absence of mudcake, as explained earlier in this work. Future works should include different spacer formulation and longer time exposure to dynamic bath as an attempt to improve the mud removal.

Conclusions

- Push out test is an effective tool to study the effect of mud removal on shear bond strength.
- Shale expansion due to clay swelling is responsible for higher shear bond strength when the core is saturated in water. Such phenomenon is not observed in OBM due to its inhibiting nature to clay.
- No significant difference in bond strength is observed in the results of the experiments with different lithologies
- Higher OWR have a larger impact of bond strength but the difference between the different values is not substantial.
- The exposure to spacer fluid was not enough to remove all OBM as verified by the lower shear bond strength in comparison with samples with no mudcake.

Acknowledgments

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Nomenclature

OBM =*Oil-based mud*
WBM =*Water-based mud*
OWR =*Oil/water ratio*
O/W =*Oil-in-water*
W/O =*Water-in-oil*
OD =*Outer diameter*
ID =*Inner diameter*

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