

Impact of physical and chemical mud contamination on wellbore cement-formation shear bond strength

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Abstract

The purpose of this experimental study was to investigate the impact of physical and chemical mud contaminations on cement-formation bond strength for different types of formation. Physical contamination occurs when drilling fluids (mud) dry on the surface of the formation forming a mud cake, while chemical contamination on the other hand occurs when drilling fluids which is still in the liquid form interacts chemically with the cement during a cementing job. Wellbore cement has been used to provide well integrity through zonal isolation in oil, gas and geothermal wells. It has also been used to provide mechanical support for the casing and protect the casing from corrosive fluids. Failure of cement could be caused by several factors ranging from poor cementing, failure to completely displace the drilling fluid to failure due to casing centralization. A failed cement job could result in creation of cracks/microannulus through which formation fluids could migrate to the surface which could lead to sustained casing pressure, contamination of fresh water aquifers and even blowout in some cases. To achieve proper cementing, the drilling fluid should be completely displaced by the cement slurry. However, this is hard to achieve in practice since some mud is usually left on the wellbore wall which ends up contaminating the cement. This study focuses on the impact of contamination on the shear bond strength and the changes in the mineralogy of the cement at the cement-formation interface.

Introduction

Gas migration still remains a major problem for the oil and gas industry over the past decades. The high cost of remediation, effect on the environment, production impact and abandonment cost are some of the numerous impacts of gas migration. Over 8,000 wells in the Gulf of Mexico currently exhibit sustained casing pressure and over 18, 000 of the wells in Alberta, Canada have leak related issue¹. Understanding the nature of the bond at the cement-formation interface is a prerequisite to solving the issues of gas migration. The nature of the bond between the cement and the formation can be used to determine the amount of load set cement can support before

it fails². The bonding mechanism at the cement-formation interface is a combination of the mechanical interlocking of the cement matrix to the formation surface by the hydration products and the chemical reaction between the rock grains and the cement paste. These bonds depend largely on the characteristics of the interface and documented evidence suggest that the first cracks are initiated in the cement matrix parallel to the direction of the applied force, extending through the weakest paths (transition zone)^{3, 4}.

At the cement-formation interface, a zone of increased porosity which is known as the interfacial transition zone (ITZ) exists. The ITZ is created by wall effect due to the differences in size between cement and formation grains. Typical cement grain size is in the range of 5-60 μm while sand grain size is in the range of 70-200 μm ^{3,4}. The huge disparity in size makes the sand grains appear as walls when placed beside cement grains and this interferes with the packing of the cement grains near the sand grains. The resultant packing at the interface causes accumulation of water and increased porosity at the interface. The wall effect is most pronounced within 15-20 μm of the sand grains³. The mechanism of the load transfer between the cement and the formation depends on the type of cement paste, the surface characteristics and the bond developed at the interface^{5, 6}. Poor primary cementing resulting from inadequate drilling mud displacement is mainly the course of poor rock-formation bond; however, there are many other factors which affect cement quality such as casing centralization, borehole status, drilling fluids, washers, spacers and the operating technique⁷. Most studies over the years have been focused on the improvement of cementing fluid system, but experience has shown that the performance and type of drilling fluid have significant effect on cement quality. The mud used for drilling forms a layer of mud cake (physical contamination) on the walls of the borehole rock as a result of the reaction between the mud and the rock at elevated temperatures and pressures. Some of the residual mud contaminates the cement (chemical contamination) altering its properties such as its bond strength^{2, 8, 9}.

Several reports have been published on the proper techniques for maximum mud displacement and the results show that depending on several factors such as casing

centralization, mud conditioning, density difference between the cement and the mud and flow regime, different levels of displacement efficiencies could be achieved. The displacement efficiency could be anywhere between 37% and 99%¹⁰⁻¹⁴. Becker et al. (1963) evaluated the effect of mud cake and mud contamination on cement formation bond. Ladva et al. (2005) investigated the effect of different mud system on cement formation bond and Yong et al. (2007) evaluated the effect of mudcake produced by different drilling fluids on the shear bond strength of the cement-formation interface.

Our study was conducted to extend our current understanding of the nature of the bond at the cement-formation interface and to determine the bonding ability of sandstones to cement versus shale and cement using shear bond strength.

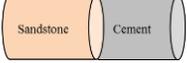
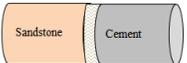
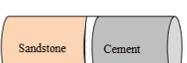
Experimental Methodology

Sample preparation

Sandstone-cement and Shale-cement composite cores were used for this study. The composite cores were made by bonding 300 mD Berea sandstone and Catoosa shale to the cement surface respectively to form a composite core. The composite cores were 2 in. long and 2 in. in diameter for both the chemical and physical contamination experiments. Class H cement was used for this study and the cement slurry was prepared following the API Recommended Practice for Testing Oil-well Cements, API RP-10B. 2,868 g of class H cement was mixed with 1,090 g of deionized water in a Waring® commercial blender at 20,800 revolutions per minute for 45 seconds resulting in a 16.4 lb/gal cement slurry. A vacuum pump was then used to degas the cement slurry before it was poured into the mold for curing.

The mud was prepared by mixing 350 mL of deionized water and 15 g of bentonite for 5 minutes. 0.5 g of carboxyl-methyl cellulose (CNL) and 0.2 g of NaOH were then added and was stirred continuously for 3 minutes to obtain 8.5 lb/gal mud. The mud was poured on the surface of the rock and then sucked into the rock using a vacuum pump.

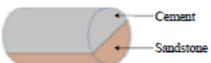
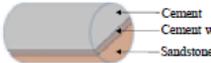
Table 1: Sample designs for physical mud contamination

Physical contamination	
Composite core with no drilling fluid contamination at the surface	
Composite cores (sandstone/cement & shale/cement) scraped of the mud leaving a slight residue of mud at the interface	
composite cores (sandstone/cement & shale/cement) washed of the mud leaving some mud particles at the	

In order to create the composite cores, the rock cores were cut into 1-in. long smaller cores. The cores were then wrapped

with duct tape leaving a 1-in. overhang on top of the cores to act as mold for the cement. The cement slurry was then poured into the overhang and then cured for 28 days after a wait on cement (WOC) time of 24 hours. Three different scenarios of mud contamination were demonstrated in this study as summarized in tables 1 and 2.

Table 2: Sample designs for chemical mud contamination

Chemical contamination	
Composite core with no drilling fluid contamination at the surface	
Composite core with 5% drilling fluid contamination at the surface	
Composite core with 10% drilling fluid contamination at the surface	

For chemical contamination, we had three levels of contamination, 0%, 5% and 10% mud contamination. The 0% mud contamination which is the control had no mud present at the interface between the cement and the formation. The 5% and the 10% mud contaminated samples had the interface between the cement and the formation contaminated with 5% mud and 10% mud respectively.

Similarly, for the physically contaminated samples, there were three levels of contamination. The surface of the rock was first contaminated with mud and left to dry and form mud cake at the interface. For the control, there was no mud present at the interface between the rock and the cement. For the second scenario, the mud cake was scrapped off the surface of the rock leaving a slight residue of mud cake at the interface between the cement and the rock. For the last scenario, the mud was washed off the surface of the rock using sodium silicate as the preflush leaving some mud particles at the interface. The cement slurry was then poured on the surface of the pre-contaminated rocks. The composite cores were then placed in a water bath after 24 hours of WOC period at room temperature to cure for 28 days to achieve over 70% hydration¹⁶. NaOH was added to the water to maintain the pH level of the water bath between 12 and 13.

Shear Strength Test

The Chandler Engineering 4207D compressive strength tester shown in Fig. 1 was used for the shearing test. This tester is an automatically digitally controlled hydraulic press designed to test the compressive strength of standard 2-in. cement cubes. The equipment which was modified (shown in Figure 1) to accommodate our sample design, has a maximum load of 50,000 lbf and a maximum loading rate of 40,000 lbf/min.

The composite cores were mounted on the compressive strength tester and the rock section of the composite core was placed in the mount. The 1in. cement section of the composite core was left outside the mount as an overhang. The equipment was then used to apply force on the cement section

of the composite core until failure. The final force applied at the point of failure per unit contact area was used in the determination of the shear bond strength.



Figure 1: Picture of a post shear strength test showing the fractured surface of the composite core

Material Characterization Experiments

Scanning electron microscopy (SEM) and backscattered electron micrograph were the material characterization techniques used for this study. The techniques enabled us to evaluate the composite core at the interface in order to visualize and corroborate observations with measured parameters. Fractured fragments taken from the composite cores were coated with platinum coating before the experiments were performed. The FEI Quanta 3D FEG FIB/SEM dual beam system interfaced with EDAX EDS/EBSD system located at the Material Characterization Center in the Department of Mechanical Engineering at Louisiana State University was used in this study.

Results and Discussions

Shear Strength Test

The samples were mounted on the compressive strength tester as shown in Figure 1. Incremental load was then applied on the samples to shear the bond between the cement and the formation. The composite core absorbed the applied load continuously until it reached the point of failure where the bond between the cement and the formation was destroyed. The failure point occurred when the maximum effective strength at the interface equaled the applied stress and the weakest point within the cement-formation composite core is usually the point where failure begins. The final load (lbf.) applied to debond the composite cores was used in the determination of the shear bond strength

Table 3: Shear strength test data for sandstone-cement composite core for physical mud contamination

Core Identification	Core Length (in)	Core Diameter (in)	Maximum Load (lbf)	Shear Strength (psi)	Avg. Shear Strength (psi)
Clean S11	1.87	2.45	1080	229.09	250.62
Clean S12	1.88	2.45	1283	172.15	
Scraped S5	1.74	1.98	224	72.75	75.83
Scraped S6	1.95	1.98	243	78.92	
Washed S1	1.8	1.97	108	35.43	34.12
Washed S2	1.82	1.97	100	32.81	

Two sets of experiments, physical and chemical mud were carried out in this study to quantify the effect of mud contamination on shear bond strength. Table 3 shows the shear bond strength measurements for sandstone-cement formation for the case of physical contamination. The results for the shear bond test for the chemically contaminated sandstone-cement composite cores are shown in Table 4.

Table 4: Shear strength test data for sandstone-cement composite core for chemical mud contamination

Core Identification	Core Length (in)	Core Diameter (in)	Maximum Load (lbf)	Shear Strength (psi)	Avg. Shear Strength (psi)
0% Contamination					
Sample 1	1.88	2.45	1123	238.18	241.82
Sample 2	1.82	2.44	1148	245.46	
5% Contamination					
Sample 1	1.95	2.46	997	209.76	202.8
Sample 2	1.95	2.46	931	195.84	
10% Contamination					
Sample 1	1.82	2.46	998	209.88	229.27
Sample 2	1.87	2.44	1163	248.66	

Similar experiments were performed using shale-cement composite cores and the results are tabulated in Table 5. The maximum shear bond strength obtained was 250 psi and 242 psi for chemical and physical contamination respectively. The minimum shear bond strength obtained was 34 psi for the physically contaminated samples and 230 psi for the chemically contaminated samples.

Table 5: Shear strength test data for shale-cement composite core for physical mud contamination

Core Identification	Core Length (in)	Core Diameter (in)	Maximum Load (lbf)	Shear Strength (psi)	Avg. Shear Strength (psi)
Clean SH11	2.03	1.98	116	37.67	68.03
Clean SH12	2.21	1.98	303	98.4	
Scraped SH4	1.83	1.98	123	39.94	34.1
Scraped SH6	1.81	1.98	87	28.25	
Washed SH1	2	1.97	110	36.08	55.06
Washed SH2	2.03	1.98	228	74.04	

These results suggest that physical contamination impacts more negatively on the shear bond strength than chemical contamination and the impact was less in shale because of the compatibility between shale and mud.

Material Characterization Experiments

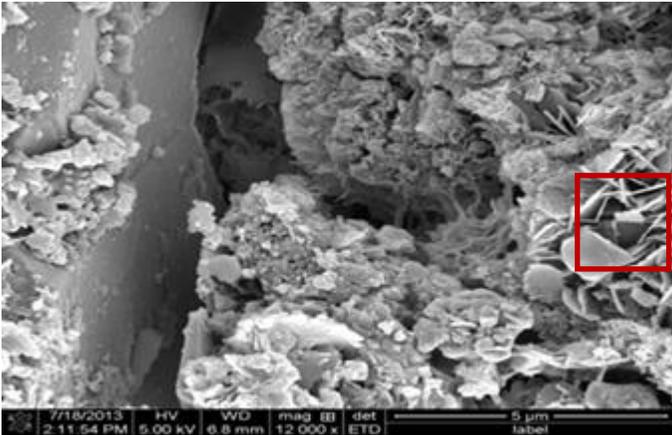


Figure 2: SEM image showing the presence of mud at the cement-rock interface

The results from the material characterization experiments confirmed that the presence of clay in the mud which was present at the interfacial transition zone negatively impacts the bond between the cement and the formation.

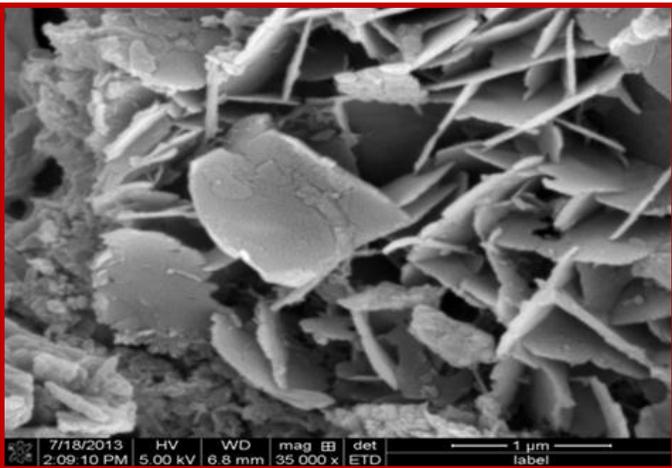


Figure 3: Clay plates lying on the surface of the rock at the bond interface

The SEM image (Figure 2) shows the reduction in the effective surface area for bonding by the presence of the clay minerals (Figure 3) at the interface between the cement and the formation. The plate-like structures are clays which generally have very weak bonding properties. The hydraulic conductivity of the contaminated rock interface (Figure 2) is much higher and susceptible to faster deterioration than that of an uncontaminated interface.

Conclusions

1. The nature of the bond between the cement and the formation was simulated. The method used is a foundation for further investigation into the effect of drilling fluid contamination on cement formation shear bond strength.
2. The effect of both physical and chemical contamination in sandstone and shale formations has been investigated. Physical contamination has been found to have the most negative impact on cement-formation shear bond strength. The shear bond strength for chemically contaminated samples was significantly higher than those for the physically contaminated samples. The presence of mud cake at the interface is detrimental to the cement-formation shear bond strength.
3. The estimated shear bond strength falls in the range 34 psi to 250 psi for the sandstone–cement composite cores and between 34 psi and 69 psi for the shale-cement composite cores.
4. Failure occurs at the interface between the cement and the formation when the applied stress exceeds the tensile strength. The material characterization results confirm the weakest point is at the interfacial transition zone.
5. The nature of the bond between the cement and the formation strongly depends on the characteristics of the interface.

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Nomenclature

lb./gal. = Pounds per Gallon

lbf./min = Pound Force per Minutes

mD = Milli-Darcy

WOC = Wait On Cement

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