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Abstract.

The objective of this experimental study is to investigate the impact of physical and chemical mud contaminations on cement-formation shear bond strength for sandstone and shale formations. Physical contamination occurs when drilling fluids (mud) dehydrates on the surface of the formation, while chemical contamination on the other hand occurs when the drilling fluid (still in the liquid state) is mixed with cement slurry and reacts chemically with the cement during a cementing job. We investigated the impact of the contamination on the shear bond strength and the changes in the mineralogy of the cement at the cement-formation interface to quantify the impact of the contamination on the cement-formation shear bond strength. Wellbore cement has been used to provide well integrity through zonal isolation in oil & gas wells as well as geothermal wells. Cement failures could result from poor cementing, failure to completely displace the drilling fluids to failure on the path of the casing. A failed cement job could result in creation of cracks and micro annulus through which produced fluids could migrate to the surface leading to sustained casing pressure, contamination of fresh water aquifer and blow out in some cases. In addition, cement failures could risk the release of chemical substances from hydraulic fracturing into fresh water aquifer during the injection process. To achieve proper cementing, the drilling fluid should be completely displaced by the cement slurry. However, this is hard to achieve in practice, some mud is usually left on the wellbore which ends up contaminating the cement afterwards. For this experimental study, Berea sandstone and clay rich rock discs/cores had cement bonded with them to simulate cement-formation interfaces. These interface were contaminated either physically (dehydrated clays deposited on the surface) or chemically (by intermixing drilling fluids with cement slurry). Shear bond tests were performed on the composite cores after complete hydration of cement occurred (after 28days) in order to determine the shear bond strength. Preliminary results suggested that the detrimental impact of the contamination is higher when the cores are physically contaminated i.e. when we have mud cake present at the surface of the wellbore before a cement job is performed. Also, the results showed that shear bond strength is higher for sandstone formations when compared to shale formations, implying that the low permeability formations form much weaker bond with cement. This is of particular interest to wellbore integrity issues in hydraulic fracturing where high injection pressures of fracking fluids can easily cause de-bonding of weak rock-cement interface. Material characterization analysis was carried out to determine the micro structural changes at the cement-formation interface. Electron microscopy provided coupling of chemical/mineralogical composition with geomechanics of the interface. The phase compositions were characterized using a Jeol 8530F EPMA (with 5 wavelength dispersive spectrometers and a SDD energy dispersive spectrometer). Line transects were used to assess variations in the bulk composition. Abundances of phases were estimated using the Thermo NSS and Compass software on a Hitachi S3500N SEM with a energy dispersive spectrometer.

Keywords: **Cement-formation interface, shear bond strength, mud contamination, zonal isolation and material characterization**

INTRODUCTION

Gas migration still remains a major problem for the oil and gas industry over the past decades. The increased cost of remediation, environmental damage, 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 issue [1]. Cement is place in a wellbore to support and protect the casing and also to provide zonal isolation of the well [2]. The presence of flow paths which could be situated at the casing cement interface, within the cement matrix and at the cement formation interface could lead to failure in zonal isolation [3] .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 fails [4]. 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. Theses bond depends 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 and then extends through the weakest paths (transition zone) [5, 6]

The bonding of cement to the casing and to the formation is normally reported as the shear bond or hydraulic bond strength. The force required to initiate the movement of the casing in the cement sheath or the movement of the cement from the formation is defined as the shear bond strength. The hydraulic bond strength on the other hand is the bond between the casing and the cement or the cement and the formation that prevents fluids flow [7]. 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 5-60µm while sand grain size is in the range of 70-200µm [5, 6] .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 grains [3]. 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 [8, 9]. Poor primary cementing resulting from inadequate drilling mud displacement is mainly the course poor rock-formation bond; however, there are many other factors that affects cement quality such as casing centralization, borehole status, drilling fluids, washers, spacers and the operating technique[10]. 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 [4, 11, 12]. 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 has been found to be anywhere between 37% and 99% [13-17]. Becker et al. (1963) evaluated the effect of mud cake and mud contamination on cement formation bond [12]. Ladva et al. (2004) 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[11,18].

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..

METHODOLOGY

Sample Preparation

Sandstone-cement and Shale-cement composite cores were used for this study. The composite cores were made by bonding 300mD Berea sandstone and Catoosa shale were bonded to the cement 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 cements was used for this study and the cement slurry was prepared following the API Recommended Practice for Testing Oil-well Cements, API RP-10B. 2868 g of class H cement was mixed with 1090g of $H2O$ in a Waring® commercial blender at 20,800 revolutions per minute for 45 minutes resulting in 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 distilled 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 interface	

The rock cores were cut into 1-in. long smaller cores to create the composite 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 1-in. 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 a 24 hours wait on cement (WOC) period at room temperature to cure for 28 days to achieve over 70% hydration 16. NaOH with a PH level of 12 was added to the water to maintain the PH level of the cement between 12 and 13

Shear Strength Test

The Chandler Engineering 4207D compressive strength tester shown in figure 1 was used for the shearing test. The model 4207D compressive strength 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 as shown in figure 1 to accommodate our sample design has a maximum load of 50,000 lb. and a maximum loading rate of 40,000 lb. /min

The composite cores were mounted on the compressive strength tester and the rock section of the composite core was placed in the mount and the 1-in. cement section of the composite core was left outside the mount as an overhand. The equipment was then used to apply force on the cement section of the composite core until failure occurs. The final force applied at the point of failure per unit contact area was used in the determination of the shear bond strength

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

FIGURE 1. Picture of a post shear strength test showing the fractured surface of the composite core

RESULTS AND DISCUSSIONS

Shear Bond Test

The Chandler Engineering 4207D digital compressive strength tester was used for this experiment. The samples were mounted on the compressive strength tester as shown in figure1. 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.

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 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
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 were 34 psi for the physically contaminated samples and 230 psi for the chemically contaminated samples.

These results suggest that physical contamination impacts more negatively on the shear bond strength that chemical contamination. When we compared the results obtained for physical contamination in sandstone and shale, the impact was less in shale because of the compatibility between shale and mud

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	

Material Characterization Experiments

The FEI Quanta 3D FEG. FIB/SEM dual beam system interfaced with EDAX EDS/EBSD was used for the SEM imaging. The results confirmed that the presence of mud within the interfacial transition zone negatively impacts the bond between the cement and the formation.

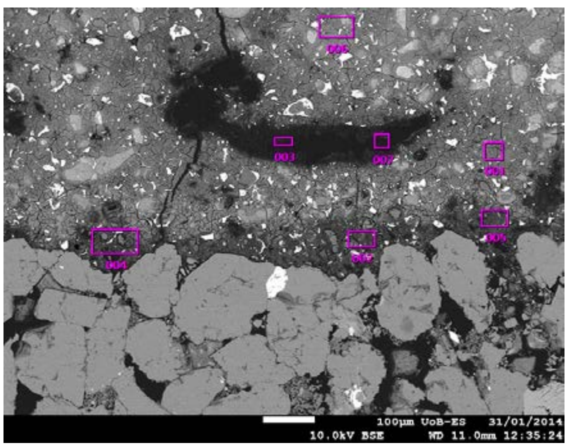

FIGURE 2. Backscattered secondary electron microscope image showing the presence of mud at the cement-rock interface (cement top, rock bottom)

The Backscattered secondary electron image (Figure 2) shows the bonding interface between the cement and the rock. The dark sections represent pore spaces while the bright sections are the grains. The presence of the mud at this inteface resulted in a reduction of the effective surface area for bonding. Further material characterization were performed using the the BSE michrograph technique. The images were obtained after continous flow through experiments were perfomed on the samples for 30 days using formation brine. The results obtained (Figures 4 and 5) sheds more light on the interaction at the interface between sandstone and the cement for the 0% and 10% mud contaminated samples.

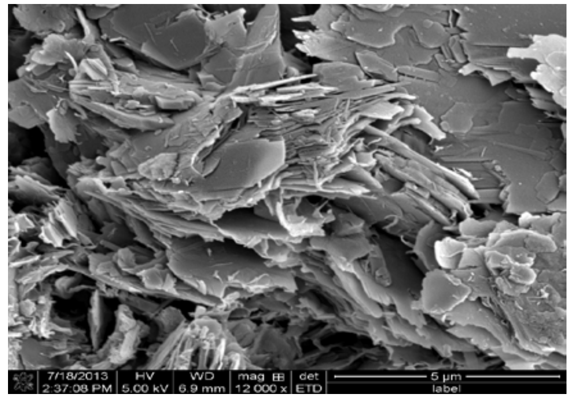

FIGURE 3. SEM image showing clay plates lying on the surface of the rock at the bond interface

The images revealed the increase in hydraulic conductivity at the interface due to leaching of the cement surrounding the pores at the interface between the cement and the formation. The sample with 10% mud contamination was suceptible to faster deterioration than thawithout contamination.

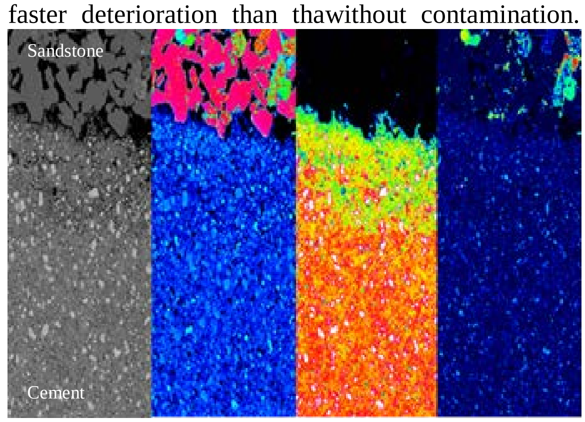

FIGURE 4. BSE micrograph for sandstone at the interface with corresponding elemental maps of Si, Ca and Al, (left to right) for 0% mud contamination

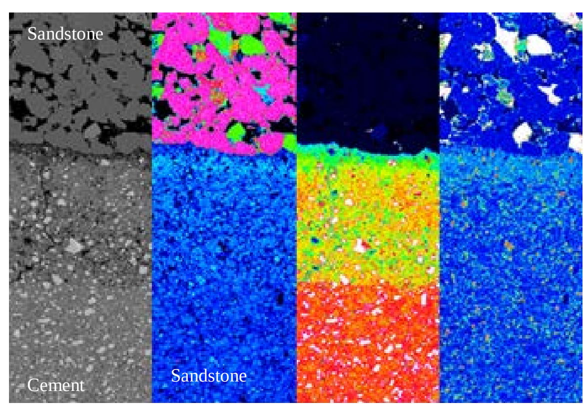

FIGURE 5. BSE micrograph for cement at the interface with corresponding elemental maps of Si, Ca and Al, (left to right) for 10% mud contamination

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 mud contamination in sandstone and shale formations has been investigated. Physical mud contamination impacts more negatively on the cement-formation bond strength. Therefore, the presence of mud cake at the interface is detrimental to cement-formation bond
3. The calculated bond strength was maximum (250 psi) for sandstone-cement composite cores and minimum (69 psi) for the shale-cement composite core
4. Failure of the bond occurs at the interface between the cement and the formation when applied load exceeds the tensile strength at that interface.
5. The nature of the bond between cement and formation is strongly dependent on the characteristics if the interface

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REFERENCES

1. Annular Casing Pressure Management for Offshore Wells (Final Rule), Federal Register.p. 23582, May 4, 2010.
2. Parcevaux, P. A., and P. H. Sault. "Cement shrinkage and elasticity: a new approach for a good zonal isolation." SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 1984.
3. Celia, Michael A., et al. "Quantitative estimation of CO2 leakage from geological storage: Analytical models, numerical models and data needs." Proceedings of 7th International Conference on Greenhouse Gas Control Technologies.(GHGT-7). 2004.
4. Evans, George W., and L. Gregory Carter. "Bounding Studies of Cementing Compositions to Pipe and Formations." Drilling and production Practice (1962)
5. Hewlett, Peter. Lea's chemistry of cement and concrete. Butterworth-Heinemann, 2003
6. Agbasimalo, N., and M. Radonjic. "Experimental study of portland cement/rock interface in relation to wellbore stability for carbon capture and storage (ccs)."46th US Rock Mechanics/Geomechanics Symposium. American Rock Mechanics Association, 2012
7. Todorovic, Jelena, et al. "Experimental Study on the Cement-Formation Bonding." SPE International Symposium and Exhibition on Formation Damage Control. Society of Petroleum Engineers, 2014.
8. Rao, G. Appa, and BK Raghu Prasad. "Influence of interface properties on fracture behaviour of concrete." Sadhana 36.2 (2011): 193-208
9. Newman, John, and Ban Seng Choo, eds. Advanced concrete technology set. Butterworth-Heinemann, 2003, 314
10. Xiao-hua, Xiaohua Che, J.L.et al:“Simulated Experimental InvestigationAbout Effects of Different Bondings on Cement Bond Quality”,Well Logging Technology(Jun.2005)185-187
11. Yong, Ma, et al. "How to Evaluate the Effect of Mud Cake on Cement Bond Quality of Second Interface?." SPE/IADC Middle East Drilling and Technology Conference. Society of Petroleum Engineers, 2007
12. Peterson, Becker. "Bond of cement compositions for cementing wells." 6th World Petroleum Congress. World Petroleum Congress, 1963
13. Clark, Charles R., and Greg L. Carter. "Mud displacement with cement slurries." Journal of Petroleum Technology 25.07 (1973): 775-783
14. Zuiderwijk, J. J. M. "Mud displacement in primary cementation." SPE European Spring Meeting. Society of Petroleum Engineers, 1974
15. Hart, W. A., and T. R. Smith. "Improved Cementing Practices Reduce Cementing Failures." Journal of Canadian Petroleum Technology 29.06 (1990)
16. Ross, W. M. and Wahl, W. W.: "Slow Flow Cementing. A Primary Cementing Technique Using Low Displacement Rates," paper SPE 1234, presented at SPE-AIME 40th Annual Fall Meeting, Denver, Colo., Oct. 3-6, 1965
17. Teplitz, A. J., and W. E. Hassenbroek. "An Investigation of Oil-Well Cementing." Drilling and Production Practice 1946
18. Ladva, Hemant KJ, et al. "The cement-to-formation interface in zonal isolation."IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition. Society of Petroleum Engineers, 2004
19. Nelson, Erik B., ed. Well cementing. Newnes, 1990.