Testing methods to assess improved well cementing and remediation

Pierre Cerasi, Amir Ghaderi, Ali Taghipour, Jelena Todorovic, Kamila Gawel, Rémi Coquard, Laura Edvardsen, Nicolaine Agofack, Hossain Bhuiyan

SINTEF Industry, Trondheim, Norway

Keywords

Cement; well; fracture; stiffness; remediation; stress; shear; sandstone; shale.

ABSTRACT

Different innovative experimental and numerical methods are presented to assess strategies and materials susceptible of significantly improving well cementing, remediation of fractured cement sheaths and permanent well plugging. The methodology developed has two aims: the first is to test and model most realistic and relevant conditions, to probe and prioritize the issues in cementing and remediation; the second aim is to thereafter propose the best and most cost-effective solutions and test them for worst-case situations. Experimental techniques involve testing the cement to formation interface tensile strength, cement sheath integrity under casing cyclic pressure, remediation fluid sealing testing on controlled fractures and numerical simulations of improved well plugging. Care is taken to include as relevant as possible stress and pore pressure conditions in these tests, both when preparing the cement sheath and when testing integrity and remediation scenarios. The interface strength tests revealed the weakest link in the system and thus suggested a strategy of combining different stiffness of cement as a way to improve the sealing efficiency around the well. This strategy was explored numerically in the case of a cement well plug, suggesting an efficient but cost-effective method to abandon oil and gas or CO_2 injection wells.

1. Introduction

The well's cement sheath is a thin and long material structure that has to serve the important role of sealing and isolating the well interior from the formations around it (Randhol and Carlsen 2008). Wells are man-made conduits connecting the underground with the surface, bypassing the natural sealing ability of the sequence of rock formations in place. Therefore, the risk of leakage of subsurface fluids to the surface, or unwanted spread of well fluids and additivies to porous layers underground is highest in and around wells (Dusseault and Jackson 2014). Several barriers to fluid migration from deeper to shallower layers have thus to be implemented in order to secure the wells, during their active life and after abandonment. These come in the form of cement sheaths around steel casings and, after abandonment, of cylindrical plugs straddling the wellbore (Vrålstad et al. 2019). Traditionally, Portland cement has been and continues to be used for this purpose in oil and gas, CO_2 storage and geothermal wells (as primary cement sheath), although new materials are being suggested recently (Khalifeh et al. 2018); this is due to several concerns over the performance of Portland cement, notably its tendency to shrink upon curing (Backe et al. 1998) and embrittlement with age (De la Roij, Egyed, and Lips 2012). Alternative materials have also received much attention in the framework of remediation operations, where leakage paths in well barriers need to be plugged (Todorovic et al. 2016).

In addition to research on new materials capable of replacing altogether Portland cement as well construction material, considerable efforts are put into keeping cement as the base material, however with additives to try to achieve the desired properties for the cement. This has resulted in a flourish of specialized cement products on the market, mainly commercialized by oil and gas service companies (Broni-Bediako, Joel, and Ofori-Sarpong 2016). These include additives for high-temperature cements (Jupe et al. 2008), low density or foam cements (Harms and Febus 1985), CO_2-resistant cements (Barlet-Gouedard et al. 2007), and flexible or expanding cements (Williams et al. 2011).

In the framework of the "Mitigating Risks to Hydrocarbon Release through Integrative Advanced Materials for Wellbore Plugging and Remediation" project supported by NASEM (National Academies of Sciences, Engineering, and Medicine), division of Gulf Research Program, investigations have been launched into probing cement-based strategies for improving both cement sheath and cement plug performance, including as remediation material. In particular, improved methodologies are proposed in terms of scenario testing of materials and gathering of needed input parameters for subsequent modeling purposes. Finite Element models also point to a simple method to combine two cement formulations in order to fulfill the desired characteristics of an improved well plug, building on the sacrificial zone idea already implemented in train passenger wagons (end car crumple zones) (Milho, Ambrósio, and Pereira 2003) and automobiles (crush zone) (Wågström, Thomson, and Pipkorn 2004).

2. Experimental

In this section, we will present several experimental techniques developed or improved to assess some bulk and interface properties of well cement formulations, as well as fracturing modes relevant to subsurface wells. These techniques include testing the interface tensile strength between cement and different formations, testing intact and fracture permeability as well as pressure buildup after remediation with different materials, and fracturing of cement and formation under applied wellbore pressure.

2.1 Interface tensile strength

The cement bonding strength, or interface strength between cement and formation or cement and steel casing, is an important parameter for assessing the stability of cement sheaths or plugs under different solicitation scenarios. The interface is characterized by its shear and tensile strengths, where it was hypothesized that the two relate as in the bulk properties of the geomaterials on each side, namely with an order of magnitude ratio between the two. This was verified by conducting direct tensile strength tests on cement plugs cured onto sandstone and shale specimens (Figure 1).

The composite samples were created by pouring Portland class G cement slurry into a sleeve, at the bottom of which a sandstone or shale plug was placed. The assembly was then placed into an odometer cell, where applied pressure on the cement was set at 20 MPa to simulate cementing at 1 km depth, with controlled pore pressure in the rock specimen at 5 MPa. The cement paste was under controlled humidity (closed volume) but free to interact with the pore fluid in the rock it was in contact with. A constant temperature of 60 °C was maintained throughout curing time (up to one week).

The results of these tests are shown in Table 1. It is noticeable that cement bond to sandstone is stronger than bonding to shale; this last can be seen as the weakest link in cement integrity in the well.

Figure 1. From left to right: composite shale-cement plug, the same plug glued to the load-frame metal cups, fracture between sandstone and cement after testing, and chain rig for tensile testing in load frame.

Table 1. Interface tensile strength values comparing cement bonding to shale vs. sandstone.

Sample Shale	Tensile strength [kPa]	Sample Sandstone	Tensile strength [kPa]
Sh1	533	Sst1	1830
Sh2	321	Sst2	710
Sh3	282	Sst3	1300
Sh4	179		

2.2 Evaluation of remediation materials

Two simple existing modified Portland G cement formulations were analyzed, to see how they would perform as fracture-filling remediation material, compared to remediation not based on cement. Low density and flexible cement were chosen and compared to silicate gel. The flexible cement was prepared by adding bentonite and sodium metasilicate (Nelson and Guillot 2006), both at 1 % BWOC (by weight of cement) and a W/C (water to cement) ratio of 0.6. The low-density formulation was prepared by simply increasing the W/C ratio from 0.44 to 0.5.

Preliminary testing of the two cement formulations included UCS tests (Table 2), showing that the flexible cement is weaker than the low-density formulation. This may be correlated to the W/C ratio. The method adopted to evaluate the materials in their remediation role was to prepare a normal Portland G cement plug with a slit of given dimensions, and glue it with epoxy to a sandstone plug which acted as filter (Figure 2). In this manner, it was possible to circulate brine with the remediation fluid inside the cement slit and measure the pressure differential necessary to maintain flow (Figure 3).

Table 2. UCS tests of low-density and flexible cement.

Sample	Length [mm]	Diameter [mm]	Peak axial stress [MPa]	Young's Modulus [GPa]
Flexible Portland G 1	52.41	25.15	11.18	3.60
Flexible Portland G 2	53.43	25.08	10.88	3.49
Low-density Portland G 1	51.58	25.26	19.13	6.49
Low-density Portland G 2	51.89	25.30	18.84	6.11

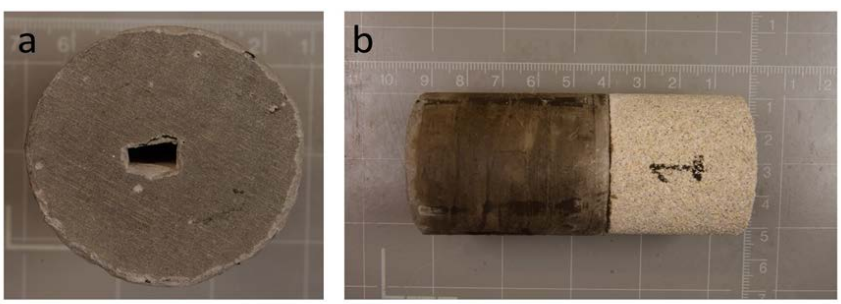

Figure 2. a) Slit made in cement plug, by positioning a silicon mold and pouring the cement slurry around it. b) Cement plug glued to Castlegate outcrop sandstone, serving as filter for hydraulic integrity testing.

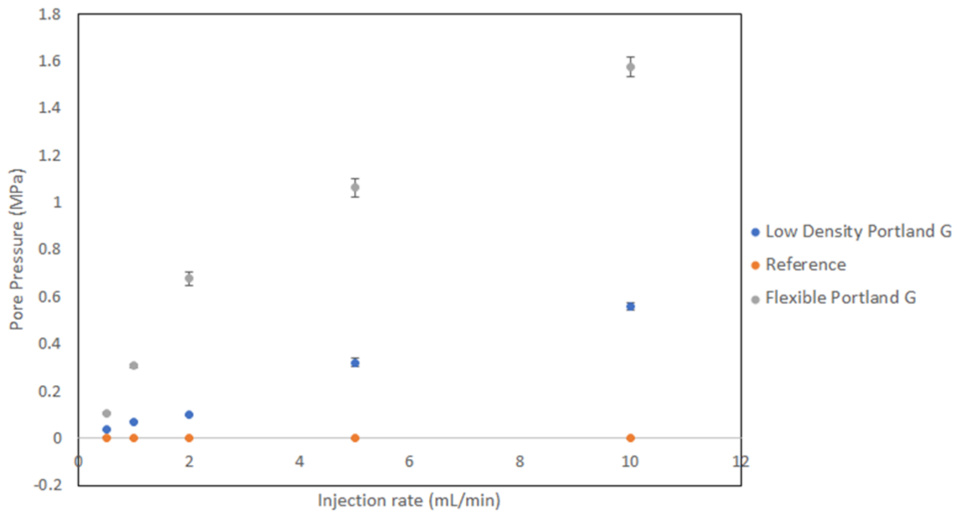

Figure 3. Remediation efficiency as measured by injection pressure with increasing flow rate (after curing of cement formulations in the fracture).

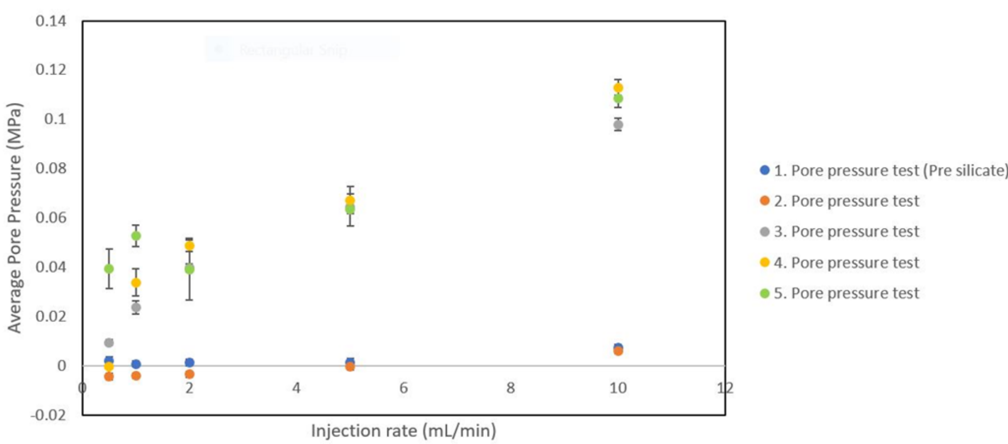

Figure 4. Remediation efficiency as measured by injection pressure with increasing flow for silicate gel.

2.3 Fracturing of cement sheath

Evaluation of cement fracturing risk in realistic conditions was performed under CT scanning using a new pressure vessel, developed as part of the ECCSEL research infrastructure partnership (Czernichowski-Lauriol et al. 2018). This cell allows for concentric steel casing, cement sheath and surrounding rock pressurizing and is an upgrade of previous cells used for thermal and pressure cyclic tests (Skorpa, Werner, and Vrålstad 2019). A casing of 40 mm outer diameter was cemented to a Castlegate outcrop sandstone of 90 mm outer diameter and 290 mm length and placed in the cell. The casing was pressurized up to 45 MPa, while a confining stress of 8.5 MPa was maintained on the rock, with pore pressure at 5 MPa. Inflating the casing led to the development of radial fractures, through the cement sheath and the surrounding rock, as shown in Figure 5.

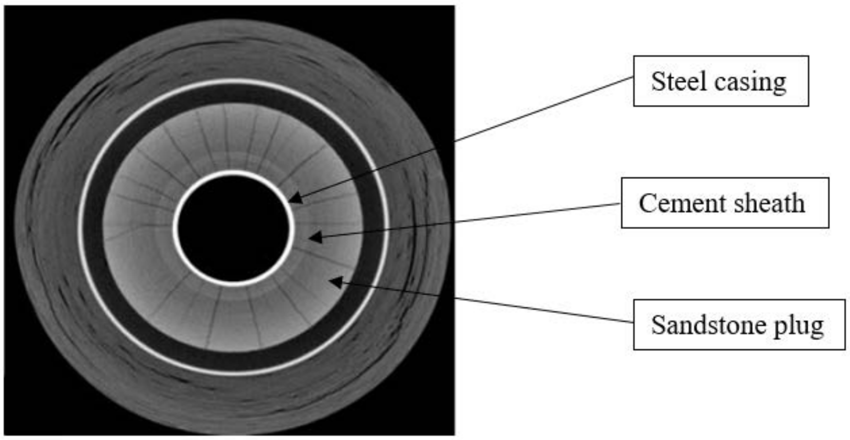

Figure 5. Apparition of fractures in cement sheath and surrounding sandstone, after pressurizing steel casing to 45 MPa.

3. Numerical modelling

The commercially available DIANA FEA (finite element analysis) software (DIANA 2018) was used to investigate the effect of implementing a dual cement composition scheme to well plugging. The studied case looked at a cement plug placed in a steel casing, itself cemented to an outside rock formation (not explicitly modelled). The cement plug incorporated a softer and more flexible part at its front exposed to well pressure (higher than the well pressure on the other side of the plug). A comparison was made to a single component plug in terms of resistance to differential pressure and friction against the steel casing.

The simulation's boundary conditions applied to the casing were seen to influence the yield stress of the cement interface deformation. Several degrees of debonding of the cement sheath from the surrounding formation were simulated, also including perfect bonding. Varying the radial stress applied on the casing was simulated by the amount of radial deformation allowed.

Three composite plug simulations were run, with one quarter, one half or three quarters of the plug being made of softer cement, with the soft part exposed to the highest well pressure (Figure 6). The shear yield strength increases the larger the proportion of soft to stiffer cement in the plug; however, the soft cement section leads to larger deformation of the entire plug. Further optimization can perhaps be achieved by varying the placement and alternance of the soft and rigid cement sections. For instance, the soft cement may be placed in the middle of the plug, in order to shield it from potentially aggressive well chemicals.

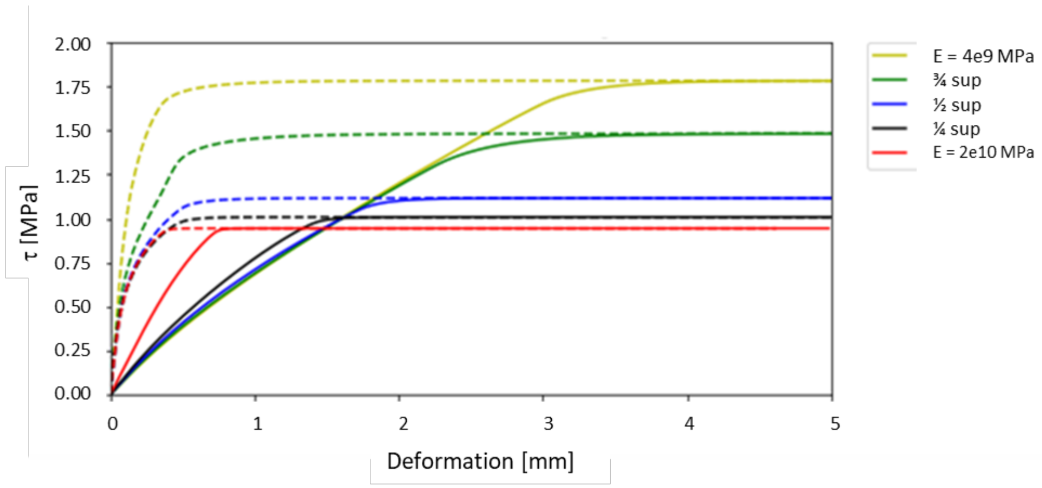

Figure 6. Shear stress plotted as a function of deformation, sampled on the end surfaces of the modeled cement plug. Increasing Young's modulus (E) is plotted, 4 GPa to 20 GPa. The black, blue and green curves correspond to ¼, ½ and ¾ of the plug made of lower stiffness cement, respectively. Solid curves: cement plug surface exposed to higher well pressure; dashed lines: plug surface at lower pressure.

3. Conclusion

Several experimental and numerical techniques have been developed to enable the investigation of well cement and other well sealing materials. These techniques seek to recreate as closely as possible the field conditions both for curing of the cement and for the expected solicitations on cured cement. One aspect is a thorough testing of the basic mechanical parameters needed for modelling purpose, addressing both bulk and interface mechanical properties as well as post-peak frictional properties. Two interfaces are important to consider: cement to casing and cement to rock. This last interface should include all lithologies the well will be drilled through. A second aspect is considering both geometrical factors and physico-chemical conditions: well cement is placed in particular spaces, either as a cylindrical plug inside the casing or in place of the casing (for P&A purposes), or as a thin and long sheath stuck between casing and rock. Therefore, testing is carried out in our method inside an advanced cell, in the presence of a scaled-down steel tube and inside a confining rock plug. Representative conditions are ensured by placing cement under stress and in contact with rocks under confining stress and with relevant pore pressure and pore fluid. This has a large influence on the performance of the hardened cement, as it interacts under hydration with the surrounding fluids.

Two tiers of validation of remediation or plugging fluids is introduced by a first qualification series using one fracture or slit in a cement plug under controlled injection conditions. This can then be further tested in the larger cell, with concentric casing, cement, and rock assembly and its more intricate fracture network. Finally, the experimental findings are strengthened by the numerical simulations, showing that a simple approach using different stiffnesses of the same basic cement type can already lead to much improved material behavior. This can evidently be even further improved by adding small amounts of new (geo)materials, enhancing self-healing where fractures appear.

Acknowledgments

Research reported in this report was supported by the Gulf Research Program of the National Academies of Sciences, Engineering, and Medicine under the Grant Agreement number 200008863. It also received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 764531.

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