Article “German Geothermal Congress DGK 2018” Essen, Germany, 27. – 29. November 2018

GeoWell- Development, testing and modelling of cements for high temperature geothermal wells

Jan ter Heege[1], Frank Vercauteren[2], Marcel Naumann[3], Penny Pipilikaki[4] and Jens Wollenweber[1]

[1] TNO Applied Geosciences, [2] TNO Material Solutions, [3] Equinor ASA, [4] TNO Structural Reliability

Keywords: well cement, formulation, mineralogy, mechanical properties, discrete element models

Abstract

The development, testing and modelling of cements for high temperature geothermal wells was studied in order to improve existing cementing practices. A three step approach was taken that includes (1) evaluation of the most promising options for new cement formulations, (2) analysis of mineralogical and mechanical changes in synthetic samples of Portland-type cement that were subjected to different exposure times, temperatures and pressures, and in cement samples obtained from the excavated top section of the IDDP-1 well that experienced temperatures up to 450°C for several months, (3) determination of critical stress conditions for cement failure, initiation and development of damage in the cements using discrete element modelling of a well section at conditions occurring during operation of the geothermal wells. The studies showed that new cement formulations should focus on reducing the amount of water as well as the supplementary pressure due to the presence of excess water. Mineralogical changes in Portland cement with 40% added silica flour at exposure temperatures above 120°C affect the mechanical properties when exposure times exceed 7-14 days. Failure strength and friction angle increase, static and dynamic Young’s modulus increase with increasing exposure times while Poisson’s ratio remains fairly constant. Mechanical behavior is more brittle at low confining pressures and more ductile at higher mean stresses. Discrete element model simulations show that damage in well cement occurs already at relatively low temperatures during thermal recovery at temperatures above ~120°C for perfectly cemented central casings and above ~95°C for imperfectly cemented eccentric casings. Cement damage due to thermal stresses or mineralogical changes likely promotes fluid migration along and through the cement sheath, thereby reducing thermal isolation of the casing by the cement sheath and enhancing thermal stresses and corrosion. Improved cement formulations need to counteract these well integrity issues to increase the lifetime of high temperature geothermal wells.

1. Introduction

Geothermal drilling environments are often hostile to well materials, especially in magmatic settings where properties of well casing and cements may rapidly change as a result of high temperatures and chemically reactive formation fluids. Maintaining long term wellbore integrity in high temperature environments is one of the key challenges for the commercial success of geothermal projects.

Recent wells target super-hot reservoirs containing supercritical fluids, such as the IDDP-1 and IDDP-2 well (Iceland Deep Drilling Project) with envisaged reservoir temperatures and pressures reaching up to above 400°C and 300 bars (Friðleifsson et al., 2015). Long term wellbore integrity at these conditions is critically affected by changing mechanical properties of well materials that may ultimately lead to casing rupture or collapse (Kaldal et al. 2016). Moreover, properties of interfaces between different casing components, cement sheaths and rock formation play a crucial role. To withstand such conditions, tailored high-temperature cements need to be developed and tested that ensure the plugging of loss zones during drilling, proper anchoring, corrosion protection of casing strings, zonal isolation and well integrity at these elevated temperatures and pressures (HPHT conditions).

Prevention and mitigation of well integrity problems under these conditions is also aided by detailed knowledge of critical conditions for wellbore failure and by analysis of special requirements for well materials. The integrity of wellbore cement is particularly important in high temperature geothermal wells as cement damage promotes migration of reactive fluids along and through the cement sheath, and reduces thermal isolation of the casing by the cement sheath. The resulting reduction in zonal isolation, enhanced casing corrosion, and elevated thermo-mechanical stresses may significantly reduce the lifetime of geothermal wells.

2. Approach

This study aims to improve existing cementing practices for high-temperature geothermal wells by the means of:

- Development of new cement formulations by cross-linking geothermal knowledge with lessons-learned from current cementing practices used in HPHT oil & gas wells (e.g. wells used for steam-assisted gravity drainage)
- Experimental testing of the performance of Portland-type cements subject to different exposure times, temperatures and pressures, including investigation of mineralogical and mechanical properties of cement samples obtained from the excavated top section of the IDDP-1 well that experienced temperatures up to 450°C for several months
- Discrete element modelling of cement performance during operation of the geothermal wells to determine critical stress conditions for cement failure, initiation and development of damage in the cements, and implications for well integrity

2. Results

2.1 Development of new cement formulations

One of the main risks in high temperature geothermal wells is the pressure generated by the water in the cement sheath both in water pockets, because of incomplete placement, and in the cement itself. At high temperature water that remains in the cement sheath can generate a high pressure, that can cause indentations or buckling of the casing. This compromises the production and the integrity of the casing. Water in the cement paste is needed for the curing reaction of cement and to make the cement paste pumpable to allow a good placement. A lot of the water in the cement paste needs to be replaced without affecting cement rheology which is technically challenging. Not only water pockets but also the residual water in the cement will contribute to the generated pressure and to radial stress on the casing. It is not clear to what extend cement can immobilise water in the internal structure and therefore to what extend this contributes to the pressure generation.

Accordingly, the demand of water as well as the supplementary pressure need to be reduced. An inventory was made of most promising option to reduce the pressure generated by water in the cement. Calculations were made to provide boundary conditions and evaluate the options. The calculations showed that the water in the cement paste needed for the good flowability, is much higher than the amount of water that can be consumed by the curing reaction. This means even after complete curing a large amount of water remains in the cement. It is estimated that almost 80% of water that is present in a Portland cement with w/c ratio of 0,4 and 40% of silica flower needs to be replaced, given the water is present as free water.

It was also estimated what pressures can in principle be expected at different temperatures based on known data on pure water properties and an estimation was made of the space available for the water. In the ideal case the supplementary pressure due to excess water would be reduced to around 30 bars. The main two options to reduce the supplementary pressure that were evaluated are:

1. Increasing the pore space available for thermal expansion of water, by means of hollow glass beads with dedicated burst pressure
2. Replacing the water in the cement paste without compromising the rheology of the cement paste, for example by adding materials that are soluble in water or by adding particulate material with specific grain size.

It was concluded that the different options need to be explored simultaneously to reach a viable solution.

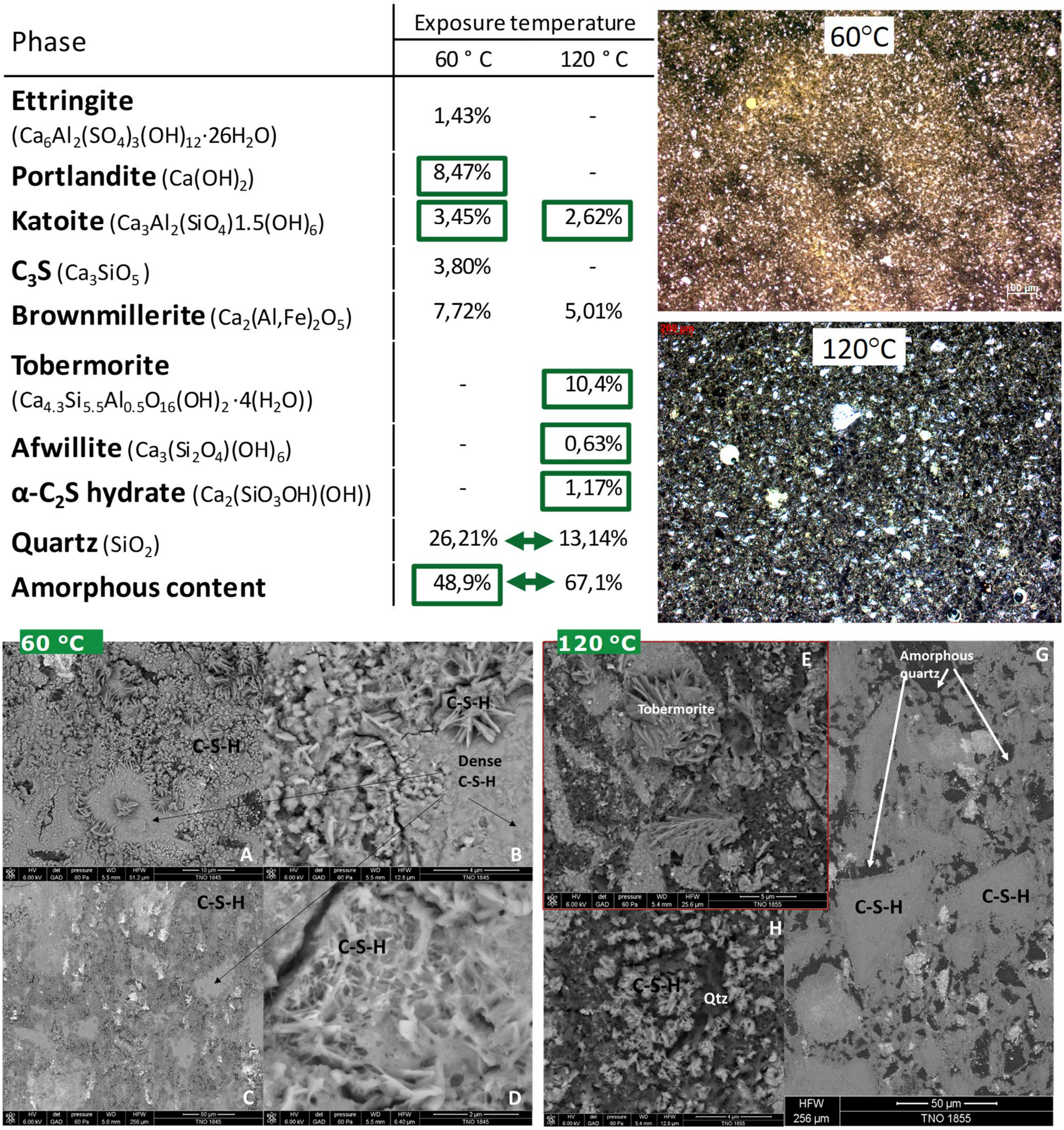
2.2 Experimental testing of the performance of Portland-type cements

Portland-type cements are often selected for high temperature geothermal or oil & gas wells. Its cement properties are expected to change during the operation of high temperature geothermal wells as a result of pressure and temperature fluctuations during drilling, cementation, thermal recovery, discharge, quenching and decommissioning of the wells (Friðleifsson et al. 2015, Kaldal et al. 2015, 2016). The relation between changes in mineralogy and mechanical properties of Portland-type cements was studied by a combination of (1) chemical analysis using X-ray diffraction (XRD), (2) microstructural analysis using scanning electron microscopy (SEM) and optical microscopy, (3) mechanical properties (failure stress, Young's modulus Poisson's ratio) using unconfined compressive strength (UCS) and triaxial strength tests.

For the experiments on synthetic cement samples, Dyckerhoff HT Basic Blend of cement clinker (API class G cement) with 40 % silica flour was used as a starting material (Papaioannou 2018). Samples were cured in molds for 3 days at 60°C and subsequently exposed for 2-371 days at atmospheric pressure and 60°C or at 2 bar and 120°C. Exposure temperatures were chosen well below and above 110°C where mineralogical and mechanical changes in ordinary Portland cement (OPC) are expected to occur (Patchen 1960, Taylor 1990, Kyritsis et al. 2009). Addition of 40% silica flour is expected to decrease the ratio of calcium oxide to silicon oxide below 3.1 for OPC, thereby favoring formation of high strength and low permeability monocalcium forms of silicate hydrate over dicalcium forms (Patchen 1960, Papaioannou 2018). In addition, mineralogical and mechanical properties were analyzed for cement samples obtained from the excavated top section of the IDDP-1 well that experienced different temperatures up to 450°C for several months.

XRD analysis of samples exposed for 28 days at 60 and 120°C suggest that 28 days of exposure is sufficient to induce temperature-dependent changes in mineralogy of the cement (Fig. 1, Papaioannou 2018). Temperature-induced changes in mineralogy are mainly (1) formation of Tobermorite, Afwillite and α-C_2S hydrate, (2) reduction of Ettringite, Portlandite, Katoite, C_3S and Brownmillerite phases, (3) a reduction in crystalline quartz content due to formation of the new minerals and dissolution of quartz in the amorphous phase, and (4) change in composition of the amorphous phase from C-S-H gel formed during cement hydration to C-S-H gel with dissolved quartz.

Optical microscopy indicates that 60°C samples have darker zones with dense (low capillary porosity) C-S-H cement phases and brighter zones (due to better penetration of fluorescent epoxy) where water separation ("microbleeding") has led to C-S-H phases with higher capillary porosity (Fig. 1). In the 120°C samples, capillary porosity is more evenly distributed. SEM shows the specific texture of the different mineral phases with evidence for microbleeding at 60°C (Fig. 1B, D) and Si-rich dark outer rims at 120°C indicating a reaction front between the C-S-H gel and amorphous silica (Fig. 1G, H).



Phase	Exposure temperature 60 ° C	Exposure temperature 120 ° C
Ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$)	1,43%	-
Portlandite ($Ca(OH)_2$)	8,47%	-
Katoite ($Ca_3Al_2(SiO_4)1.5(OH)_6$)	3,45%	2,62%
C_3S (Ca_3SiO_5)	3,80%	-
Brownmillerite ($Ca_2(Al,Fe)_2O_5$)	7,72%	5,01%
Tobermorite ($Ca_{4.3}Si_{5.5}Al_{0.5}O_{16}(OH)_2\cdot 4(H_2O)$)	-	10,4%
Afwillite ($Ca_3(Si_2O_4)(OH)_6$)	-	0,63%
α-C_2S hydrate ($Ca_2(SiO_3OH)(OH)$)	-	1,17%
Quartz (SiO_2)	26,21%	13,14%
Amorphous content	48,9%	67,1%

Fig. 1: XRD analysis, optical microscope images (*top right*) and SEM images (*A-G*) of hardened cement paste exposed for 28 days at 60°C and 120°C (Papaioannou 2018).

Samples from different cement sheaths in the excavated top section of the IDDP-1 well indicated different mineralogy and degree of microbleeding associated with different temperature histories experienced by the sheaths depending on their locations relative to the circulating fluids (Fig. 2).

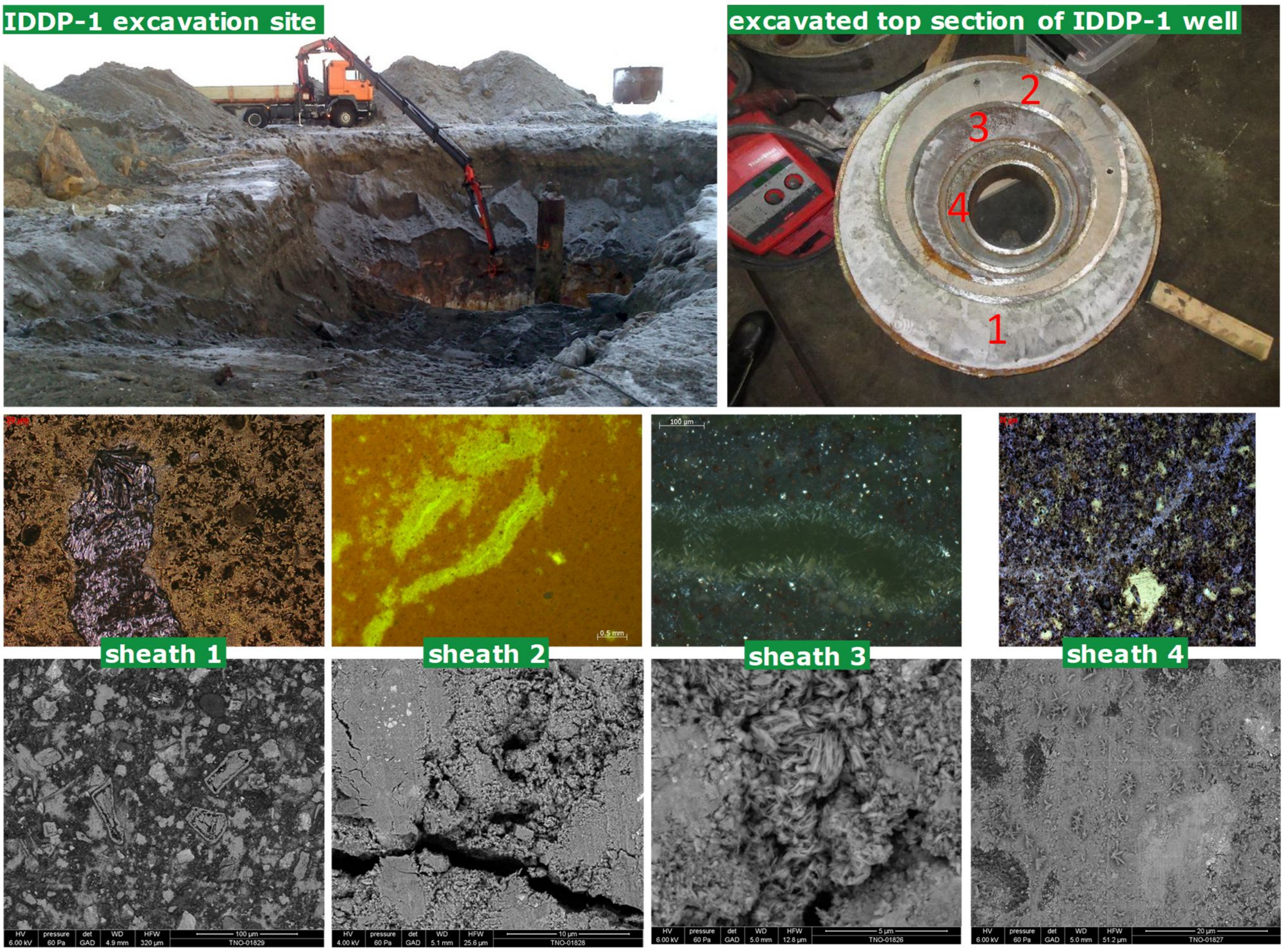


Fig. 2: Optical microscopy and SEM images of samples from different cement sheaths in the excavated top section of the IDDP-1 well showing (1) zones with fine crystals and reaction rims indicating reacted quartz, (2) bleeding structures in dense cement matrix indicating inhomogeneous water separation and distribution, (3) bleeding structures overgrown by Xonotlite crystals, and (4) Xonotlite/Wollastonite crystals grown in microbleeding channels (*left to right, middle and bottom rows*, Pipilikaki et al. 2017; Vercauteren et al. 2018). IDDP-1 samples, images (*top row*) and information courtesy of ISOR.

UCS tests were performed on cylindrical samples exposed for 2-42 days at 60 and 120°C (Fig. 1). It can be observed that (1) differences in mechanical properties between samples exposed at 60 and 120°C occur after exposure times above ~7-14 days, probably due to changes in mineralogy

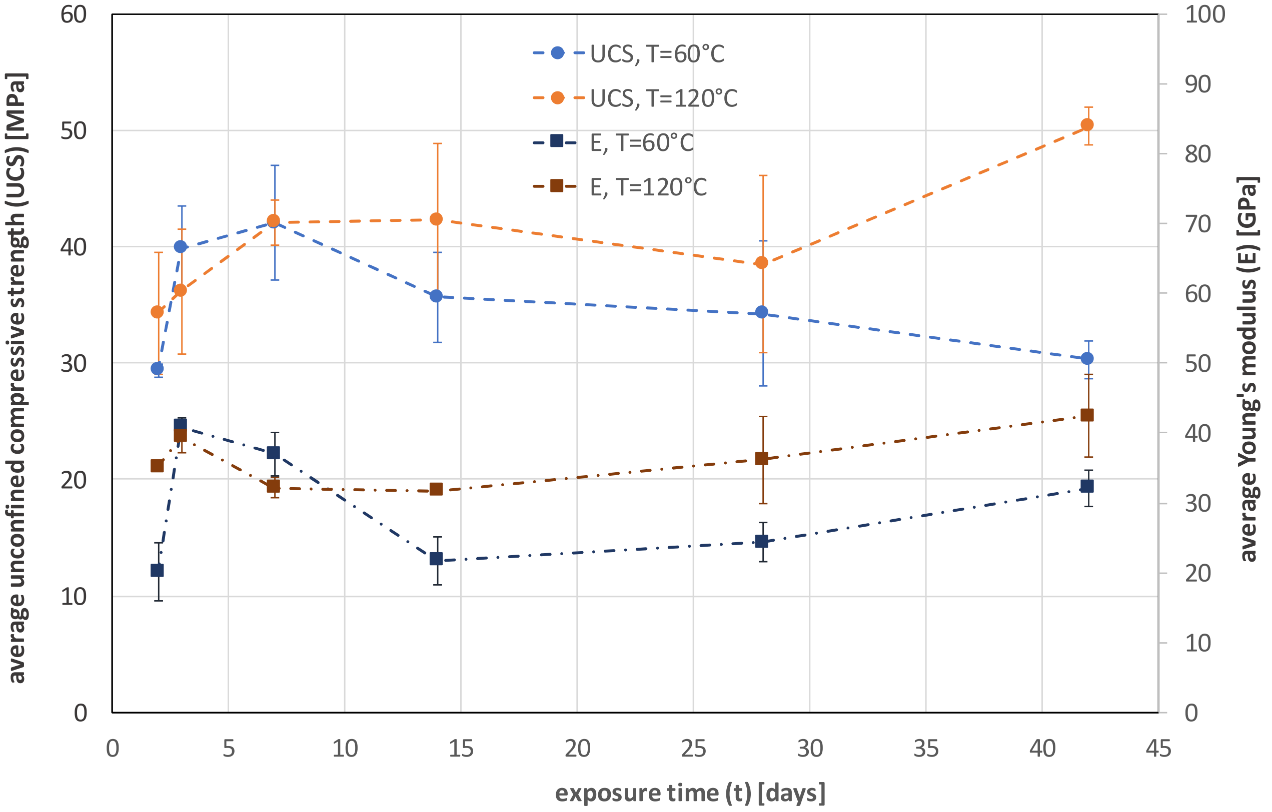


Fig. 3: Average unconfined compressive strength and Young's modulus with standard deviations for samples exposed for 2-42 days at 60°C and 120°C (data from Papaioannou 2018).

Triaxial tests were performed on cylindrical samples exposed for 1-53 weeks at 60 and 120°C with confining pressures of 2-15 MPa, room temperature and pore pressures at ambient conditions. First results indicate that mineralogical changes in samples exposed to 60 and 120°C result in (1) increasing failure strength and friction angle of cement samples, (2) increasing static and dynamic Young's modulus with increasing exposure times and decreasing confining pressures, (3) fairly constant Poisson's ratio, and (4) significant residual stresses after failure with more brittle (strain softening) behavior at low confining pressures and more ductile behavior at higher mean stresses.

2.3 Discrete element modelling of cement performance

Critical failure conditions and damage in wellbore cement during operation of geothermal wells were studied using a combination of analytical and discrete element models (TerHeege et al. 2017). Discrete element models are particularly suitable to investigate these aspects because they can be used as a "virtual laboratory" that allow (1) modelling of the evolution of material and interface properties with changing pressure and temperature conditions, (2) introduction of damage or imperfections in casing, cement or rock materials for more realistic models, (3) extending the number of tests and range of conditions of experimental data, (4) bridging the scale between experiments and wellbore systems to test new materials and well designs.

The analytical models are used to determine wellbore stresses for open and completed wellbores including thermo- and poro-elastic effects. The calculated wellbore stresses are applied to 3D discrete element models (DEM) of typical well sections to explore possibilities of analyzing damage in wellbore cement (Fig. 1).

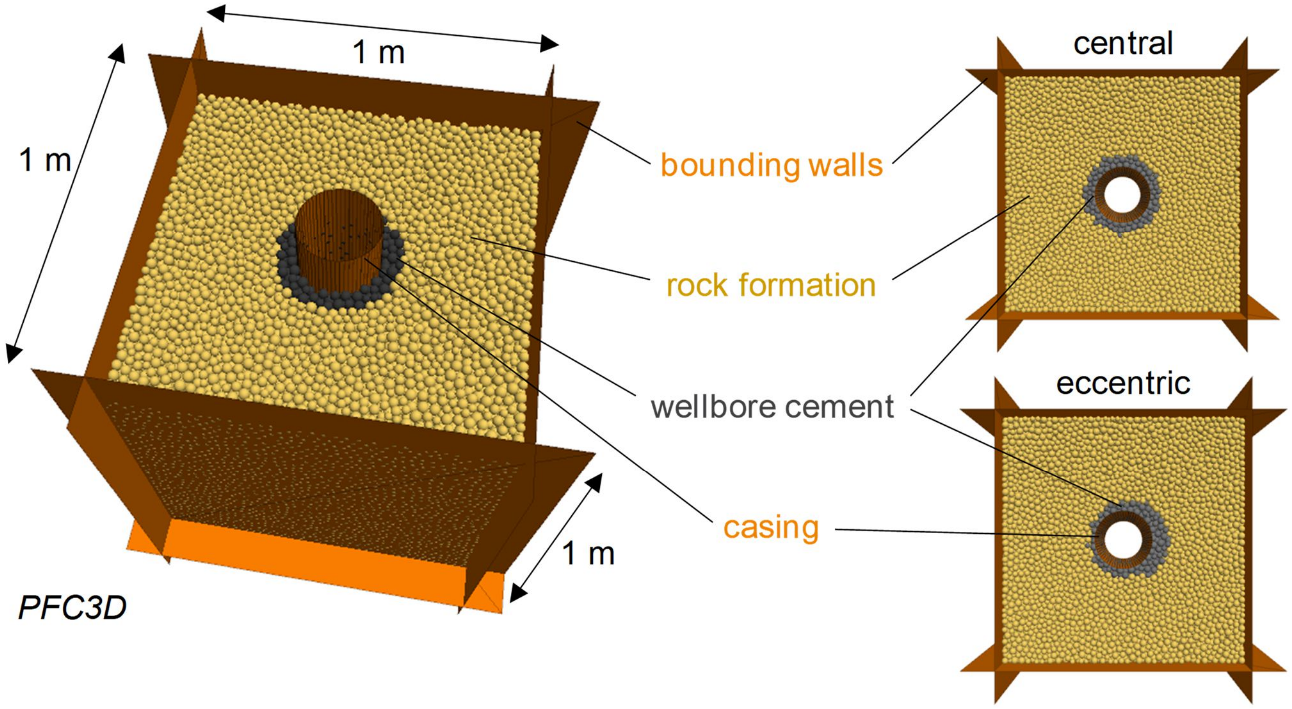


Fig. 4: Different discrete element models (PFC3D) of a wellbore section including rock formation and wellbore cement. Cubical wellbore models are used with servo-controlled bounding walls to apply far field stresses, either with a perfectly cemented central wellbore or a partially cemented eccentric wellbore (*right*).

The mechanical properties of model wellbore materials are tuned to typical properties determined in laboratory experiments (Kaldal et al. 2015). Model simulations specifically focused on (1) combining both geological and operational conditions in analyzing the evolution of stresses in the vicinity of geothermal wells, (2) analyzing the effect of different wellbore geometries including both central and eccentric wellbores, and (3) determining critical stress conditions for the initiation of cement failure during thermal recovery of geothermal wells (Fig. 2).

Wellbore models and boundary conditions are based on subsurface conditions encountered in well IDDP-1 of the Iceland Deep Drilling Project, located within the caldera structure of the Krafla central volcano in the Northeast of Iceland (Mortensen et al., 2014). This well was drilled to 2096 m depth reaching pressures of 151 bar, and produced superheated steam at 452°C and 141 bar at the wellhead (Friðleifsson et al., 2015; Kaldal et al., 2016). The model simulations are used to map out critical downhole conditions at 1700 meter depth around the anchor casing in the IDDP-1 well where cement bond log indicated the bottom of the cement (Friðleifsson et al., 2015).

Model simulations show that damage occurs already at relatively low temperatures during thermal recovery. For the central wellbore, the cement sheath shows widespread damage with interconnected fractures extending into the rock formation at temperatures above ~120°C. For the eccentric wellbore, widespread damage and interconnected fractures extending into the rock formation already occur at ~95°C. This type of damage promotes fluid migration along and through the cement sheath, and reduces thermal isolation of the casing by the cement sheath.

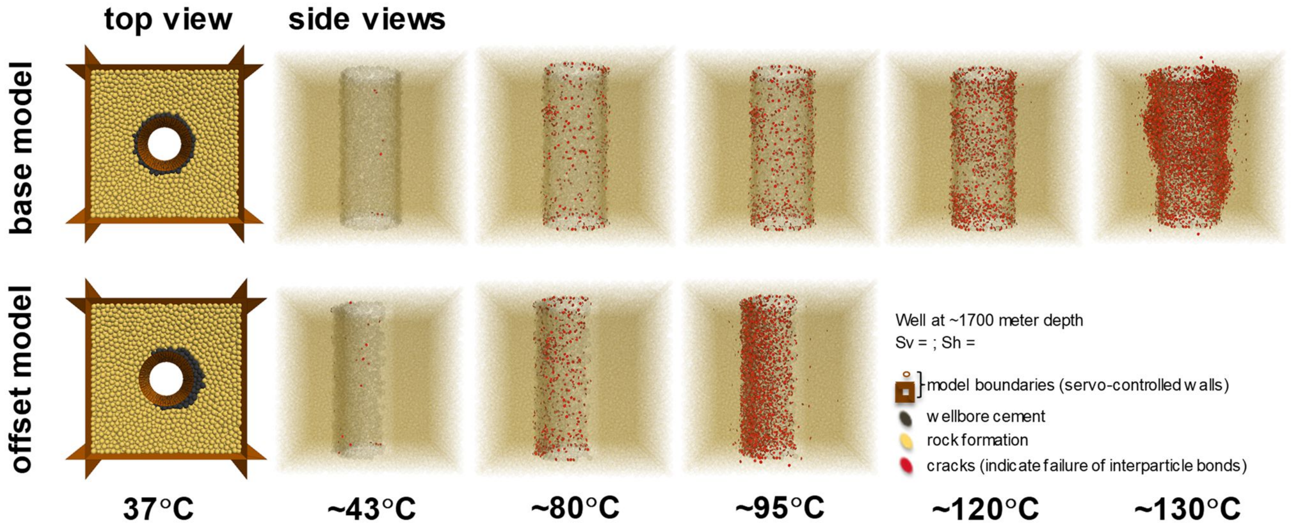


Fig. 5: Damage (cracks) in the cement sheath at ~1700 meter depth in the modelled IDDP-1 well for different temperatures during thermal recovery. Simulations are for a perfectly cemented central wellbore with complete cement sheath (*top*) and for a partially cemented eccentric wellbore (*bottom*). The cubical wellbore model is shown in the background.

Therefore, the casing may be subject to enhanced thermal stress and corrosion at the early stages of thermal recovery. The lifetime of high temperature geothermal wells may be extended if this type of widespread damage can be prevented, for example by improving the design of wellbore systems and materials. Options may include better (thermal resistant) cement or coated casings. The current approach of combined analytical and discrete element modelling of rock-cement-casing interactions can be used in follow-up studies to test different types of cement, and outline what cement and casing properties are less prone to damage and rupture.

3. Summary & conclusions

The development, testing and modelling of cements for high temperature geothermal wells was studied in order to improve existing cementing practices. A three step approach was taken that includes (1) evaluation of the most promising options for new cement formulations, (2) analysis of mineralogical and mechanical changes in synthetic samples of Portland-type cement that were subjected to different exposure times, temperatures and pressures, and in cement samples obtained from the excavated top section of the IDDP-1 well that experienced temperatures up to 450°C for several months, (3) determination of critical stress conditions for cement failure, initiation and development of damage in the cements using discrete element modelling of a well section at conditions occurring during operation of the geothermal wells.

The studies showed that:

- Main options for new cement formulations should focus on reducing the amount of water as well as the supplementary pressure due to the presence of excess water. Reduction of water content could be achieved by replacing water in the cement paste using soluble materials or particulate material that does not compromise the rheology of the cement paste required for successful cementation. Reduction of supplementary pressure could be achieved by increasing available pore space for thermal expansion of water using hollow glass beads with dedicated burst pressure.
- Mineralogical changes in Portland cement with 40% added silica flour at exposure temperatures above 120°C affect the mechanical properties when exposure times exceed 7-14 days. Changes in mechanical behavior include generally increasing failure strength and

friction angle, increasing static and dynamic Young's modulus with increasing exposure times (Poisson's ratio remains fairly constant). Post failure behavior is brittle at low confining pressures and transits into more ductile behavior at higher mean stresses.

- Discrete element model simulations show that damage occurs already at relatively low temperatures during thermal recovery. Widespread damage of well cement is observed at temperatures above ~120°C for perfectly cemented central casings and above ~95°C for imperfectly cemented eccentric casings, regardless of changes in mechanical properties. The damage likely promotes fluid migration along and through the cement sheath, thereby reducing thermal isolation of the casing by the cement sheath and enhancing thermal stresses and corrosion at the early stages of thermal recovery.
- Improved cement formulations need to counteract changes in mechanical behaviour of cements in high temperature geothermal wells and well integrity issues associated with such damage to increase the lifetime of high temperature geothermal wells.

Acknowledgements

This research was performed within the EC Horizon 2020 project GeoWell "Innovative materials and designs for long-life high-temperature geothermal wells" under the grant agreement No. 654497.

Sources

Friðleifsson, G. Ó., B. Pálsson, A.L. Albertsson, B. Stefánsson, E. Gunnlaugsson, J. Ketilsson & Þ. Gíslason: IDDP-1 Drilled Into Magma – World's First Magma-EGS System Created. In *Proceedings World Geothermal Congress, Melbourne, Australia, 19-25 April 2015.*

Kaldal, G.S. M.T. Jonsson, H. Palsson & S.N. Karlsdottir: Structural modeling of the casings in high temperature geothermal wells, *Geothermics*, 55, (2015), 126-137.

Kaldal, G.S. M.T. Jonsson, H. Palsson & S.N. Karlsdottir: Structural modeling of the casings in the IDDP-1 well: Load history analysis, *Geothermics*, 62, (2016), 1-11.

Kyritsis, K., Hall, C., Bentz, D.P., Meller, N., Wilson, M.A.: Relationship between engineering properties, mineralogy, and microstructure in cement-based hydroceramic materials cured at 200 - 350 C, *Journal of the American Ceramic Society*, 92, (2009), 694–701.

Mortensen, A.K., Egilson, Þ., Gautason, B., Árnadóttir, S., Guðmundsson, Á.: Stratigraphy, alteration mineralogy, permeability & temperature conditions of well IDDP-1, Krafla, NE-Iceland, *Geothermics*, 49, (2014), 31-41.

Papaioannou, A.: Impact of in-situ ageing on the mineralogy and mechanical properties of Portland-based cement in geothermal applications, *M.Sc. thesis Utrecht University* (2018), 44 p.

Patchen, F. D.: Reaction and Properties of Silica-Portland Cement Mixtures Cured at Elevated Temperatures, *Journal of the Society of Petroleum Engineers*, 219, (1960), 281–287.

Pipilikaki, P., Vercauteren, F., & Wollenweber, J.: Chemical and microstructural alterations of annular cements of a high-temperature geothermal well, *Celle Drilling 2017, 11-12 September 2017.*

Taylor, H. F. W.: Cement chemistry, *Academic Press* (1990).

TerHeege, J.H., Orlic, B., & Wollenweber, J. Discrete element modelling of wellbore integrity in high temperature geothermal reservoirs. In *51st US Rock Mechanics / Geomechanics Symposium held in San Francisco, California, USA, 25-28 June 2017*.

Vercauteren, F., Naumann, M., Pipilikaki, P., Ter Heege, J., Wollenweber, J., & Kampfer, G.: Testing and development of cements for high-temperature geothermal wells, *AAPG "Geothermal Cross Over Technologies Workshop" April 18/19th 2018, Utrecht, Netherlands*.

Princetonlaan 6, 3584 CB, Utrecht, the Netherlands
Jan.terHeege@tno.nl