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Evolution of Resilient Cements to Prevent Sustained Casing Pressures in Al-Shaheen Oil Field Qatar

Muhammad Faraz-Khan, Vincent Jean Pradet and Zahid Mohammed Karajagi, North Oil Company Qatar

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Abstract

Discovered in 1982, Al Shaheen (ALS) is one of the world's largest oil-producing carbonate fields situated offshore in Qatar. With over 500 ERD wells drilled over a span of 25 years, Sustained Casing Pressure (SCP) remains one of the biggest challenges especially in a brown field.

Extensive studies were conducted to determine wellbore stress environment surrounding the production casing over the life of well. Multiple failure mode analyses were performed to derive the required mechanical properties for cement to sustain stresses during production / injection cycles.

This paper discusses evolution of resilient cement designs from complex elastomer blends to innovative blend-free system, field practices and equipment optimizations that resulted in significant reduction in SCP. Cement slurries were designed to meet stringent gas tight and post-set mechanical properties. State-of-the-art STCA^{TM} (Slurry-To-Cement Analyzer) was used to evaluate cement pore pressure behaviour and mechanical properties development during transition from liquid to solid state under downhole conditions.

With advent of 3D Displacement Modelling, cement slurry placement was optimized periodically by redesigning fluid hierarchies (density and rheology), annular velocities, centralization, scavenger, and spacer systems to achieve minimum 95% displacement efficiency in highly deviated section with no casing movement.

Recent applications of new Liquid Flexible slurry and cementing practices show complete elimination of SCP, while reducing the cementing costs. This paper further summarizes design criteria and extraordinary mechanical properties of simple Latex-based flexible cement along with enhancement to cementing practices for deviated wells.

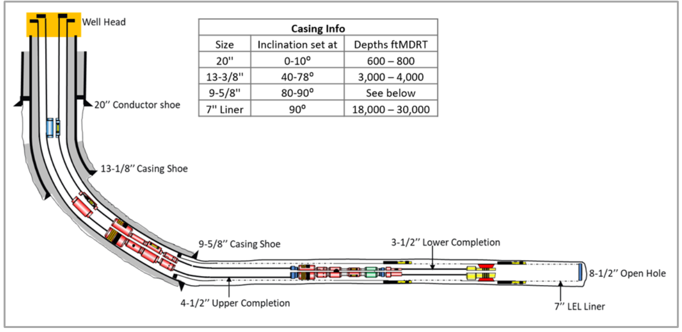
Introduction

With increasingly stringent environmental regulations, sustained casing pressures in maturing oil and gas field has become a major concern for oil industry. SCP is the result of fluid migrating through failed well barriers manifesting at the wellhead as annular pressures that rebuilds upon bleed-off. Production and abandonment of such wells is often associated with increased risks, environmental impact, and high operating costs. No effective remediation techniques exist today for treating sustained casing pressures, especially if it originates due to presence of micro-annulus. Prevention of SCP, therefore, remains the only practical way-forward while developing mature fields.

Cement systems, placement techniques and modeling softwares have evolved drastically over the past two decades. This allows to design fit-for-purpose cement systems and placement techniques to achieve zonal isolation. Adoption of such tools and practices has been seen to provide excellent results in primary cementing of 9-5/8" production casing in ALS field. A drop in wells with SCP was observed from 40% in first 15 years of field development to approximately 7% in next decade and further down to 0% in most recent years of field development.

As of December 2023, over 500 ultra-ERD wells have been drilled and completed in ALS Field, consisting of Oil Producers and Water Injectors. Most of these oil producers are gas lifted with pre-heated gas flowing from annulus to tubing while most of injectors are providing reservoir pressure support with water injected at 3000psi surface pressure. Some injector wells are operated with alternating cycles of water and gas (Water Alternating Gas - WAG Injectors) with injection pressure up to 3000psi and surface temperature up to 200 °F.

A typical ALS well is completed with 3 Casing policy as shown in Figure 1.



Casing Info

Size	Inclination set at	Depths ftMDRT
20"	0-10°	600 – 800
13-3/8"	40-78°	3,000 – 4,000
9-5/8"	80-90°	See below
7" Liner	90°	18,000 – 30,000

Fig.1 Typical Al Shaheen ERD Well Architecture

The 20" conductor pipe is typically driven/hammered from seabed until refusal. The 16" surface section is drilled across total loss zones with no returns using PHB Sweeps at an inclination up to 70º. This section is secured with a 13-3/8" casing that is cemented in place in two stages to provide structural support and isolation across loss zones. Subsequently, the 12-1/4" highly deviated section is drilled across multiple hydrocarbons bearing formations and enters into the reservoir pay zones with an inclination up to 90º. This section is cased-off with 9-5/8" production casing landing horizontally and cemented to surface. The 9-5/8" casing cementing is intended to achieve zonal isolation across all flow zones to surface and provide an additional barrier across the uncemented 13-3/8" casing section that is exposed to H_2S bearing formations. The 8-1/2" reservoir section is drilled horizontally (geo-steered) to target depth and completed either with 7" LEL multi-zone completions or barefoot completions.

This paper provides a detailed insight to the evolution of 9-5/8" production casing cementing practices adopted since 1995 to current times and their impact on eliminating SCP.

Presently, all 9-5/8" casings are cemented with blend-free liquid flexible cement systems. These are designed to be pumped with liquid additive system offshore. High flexibility of set cement with Young's Modulus lower than 0.75Mpsi and tensile strength above 260psi are achieved primarily with liquid Latex without any solid elastomers and/or fibers. The design is unique and simplistic to execute large volume cement jobs on the fly with small offshore jack-up rigs having limited storage capacities.

Over the years, placement techniques have been optimized using 3D displacement modeling softwares and application of recommended cementing practices such as pump rates, centralization, fluid designs, additional wiper plugs, use of scavenger cement etc. This has helped to achieve 100% cement coverage around the casing.

Background & Evolution

In the earlier years of field development, 1995 to 2007, 9-5/8" casings were cemented with conventional 12.5ppg filler lead slurry (no fluid loss control) and 15.8ppg tail slurry (minimal fluid loss control) with an objective of having a well-supported casing shoe and adequate cement coverage inside casing-casing section. Although the cementing practices met the basic objective to drill ahead and complete the well, it failed to provide long term zonal isolation on many wells. Up to 40% of the wells still experience sustained casing pressures above 200psi that requires regular bleeding off. Wireline logging of some of the wells indicated cement failure due to debonding / Microannulus as major reason for SCP. Fig.2 shows the effect of cementing evolution on SCP trends across all Field Development Programs (FDPs) from 1995 to 2021.

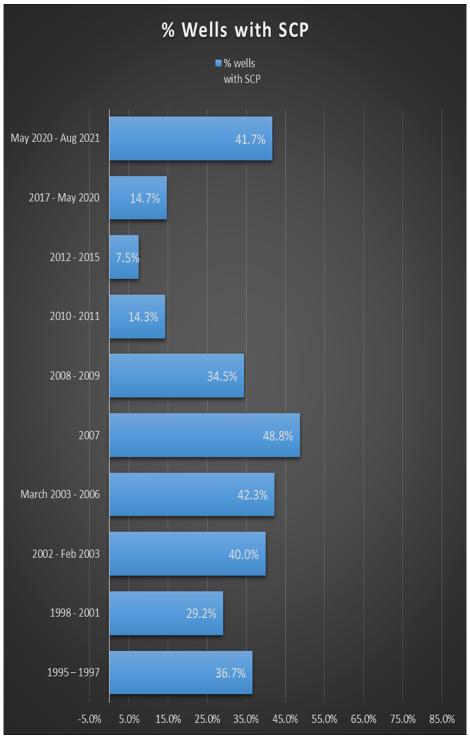


Fig 2. %Wells with SCP

In 2007, a multiple cement stress simulation studies were launched to evaluate the longevity of cement systems to provide zonal isolation. As a result, a 13.7ppg conventional cement slurry and weighted spacer were introduced. However, there was very minimal reduction observed in wells with SCP dropping from 40% to 34%.

In 2010 and 2011, two injector wells were subjected to trials with resilient (flexible) blend-based cement systems. Slurry design was based on service providers global experience with cement blend heavily loaded with elastomers and fibers ranging up to 22% bwoc cumulatively.

Multiple job execution / operational issues were observed during these trials pertaining to handling of complex blends -

- Maintaining the quality of blend delivered to cement unit due to complex blend composition (additives with wide variation in specific gravity)
- Inability to maintain slurry density on the fly.
- Segregation of blend components in cement slurry

Around the same time in 2010, advent of 3D displacement efficiency modeling provided ability to evaluate the effect of various job parameters viz. flow rates, annular fluid velocity, fluid density and rheology, hole geometry, centralization etc.) the cement placement and coverage around the casing (360deg coverage at each depth). With no changes in cement designs, job parameters viz. cement flow rate, centralizer frequency, spacer volumes, density and rheological hierarchies were optimized to achieve a minimum of 90% displacement efficiency across the open hole. A drastic reduction in wells with SCP from >30% to around 14% was achieved by improvement in placement techniques alone.

In 2012, a study with a holistic approach was performed to improve every aspect of 9-5/8” casing cementing practices. Study methodology and recommendations/results are as summarized below -

- Defining the wellbore stress regime in injector wells during Water and WAG injection cycles with accurate estimation of geo-mechanical properties for each formation drilled in 12-1/4” section.
- Simulating set of cement mechanical properties on finite element-based wellbore cement stress modeling software that can provide zonal isolation throughout the life for injector wells. Minimum mechanical properties required to be met were as outlined below –

Property	
Young’s Modulus	<0.6 Mpsi
Tensile Strength	>300 psi
Unconfined compressive strength	>1000psi
Expansion / Shrinkage	>0.2%

Table-1: Minimum required mechanical properties of flexible cement in FDP2012

- Designing of robust flexible cement slurry for injector wells with optimized (less complicated) blend composition including. The drop in elastomer and fiber content in comparison to designs pumped in 2010 were compensated with addition of liquid latex and liquid Silicalite to enhance the mechanical properties of set cement and to get away from blend handling issues observed in previous trial jobs. Synthetic retarders were introduced to ensure no adverse effect on compressive strength development typically observed with lignosulfonate-based cement retarders. Below is the 13.5ppg flexible cement design used for all injector wells.

Chemical	Concentration
Class G Cement	
Elastomer (in Blend)	6% bwoc
Tensile fibers (in Blend)	2% bwoc
Expansion Additive (in Blend)	5% bwoc
Blend flow enhancers (in Blend)	0.25% bwoc
Liquid Fluid Loss Additive	0.3 to 0.8 gps
Liquid Micro Latex	2.0 to 3 gps
Liquid Silicalite	1.5 gps
Liquid Synthetic Retarder	As required

Table-2: Typical Flexible slurry design used in FDP-2012

- Designing of cement slurries (13.7ppg Lead and 15.8ppg Tail) used for cementing producer wells and 13.5ppg flexible cement for injector wells and wells in gas cap areas with robust gas tight properties meeting much stringent requirements for fluid loss < 50cc/30min, static gel strength transition time (SGS 100lb/100ft^2 to 500 lb/100ft^2) < 30min, and a positive control of gas flow in gas flow tests / fluid migration analyzers (as shown in Fig3).

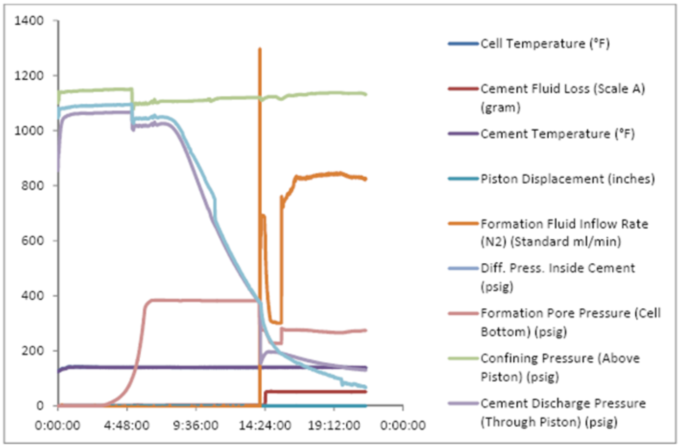


Fig 3. Fluid Migration Analyzer Test Chart for Flexible Cement

- Optimizations to cement placement techniques to improve achieve 100% cement coverage across open hole and a minimum of 90% cement coverage up to top of cement i.e. up to surface (as shown in Fig 4 & 5).

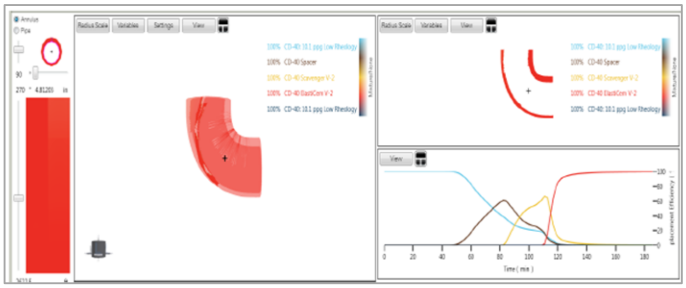


Fig 4. 3D Displacement Efficiency across open hole: 100%

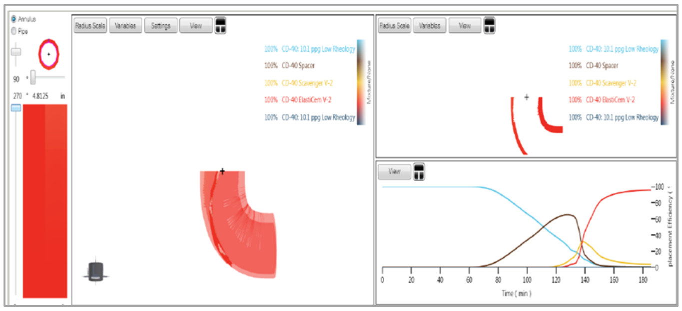


Fig 5. 3D Displacement Efficiency at top of cement: >90%

The optimizations included -

- Circulating low viscosity mud (Yield Point <15 lb/100ft^2) at high annular velocities prior to cement job to displace the drilling mud for effective mud removal during cementing.
- Maintaining rheological & density hierarchy: Optimizing the Low vis mud, spacer, and cement slurry/slurries rheologies to maintain rheological train (Low Vis Mud <

Spacer < Cement Lead < Cement Tail). Objective was to design a fluid density and hierarchy that can generate a higher-pressure drop-in annulus that preceding fluid system at as low rates as possible to ensure effective displacement at all rates. It also determines the minimum displacement rate required to be in the higher end of rheological hierarchy regime. As shown in in Fig6, a minimum flow rate of 3.5bpm is required to maintain the rheological hierarchy.

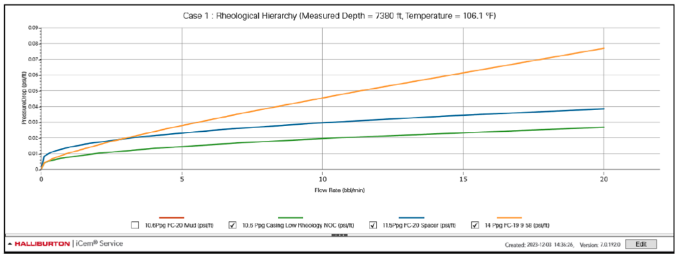


Fig 6. Rheological Hierarchy Trend – >90%

- Optimized Centralization: Since the casing was run in a highly deviated section and landed horizontally, a robust centralizer with ability to provide optimum standoff while being able to run the casing with sufficiently available surface hook load at TD was required. Casing was centralized with 9-5/8” x 12-1/4” (made to gauge) non-welded, semi-rigid, slip-on, bow spring centralizer (100% heat treated, no weak points), with a 3centralizer / 2joints placement frequency (as shown in Fig7). Centralization is aimed to achieve a minimum of 70% stand-off in open hole and higher in cased hole section as shown in Fig8.

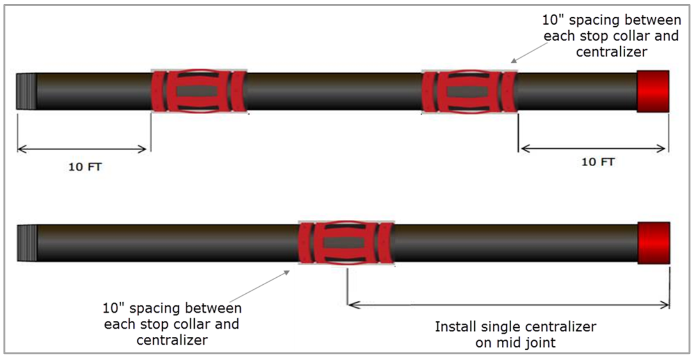


Fig7. Centralizer Placement Methodology (3Cent/2Joints)

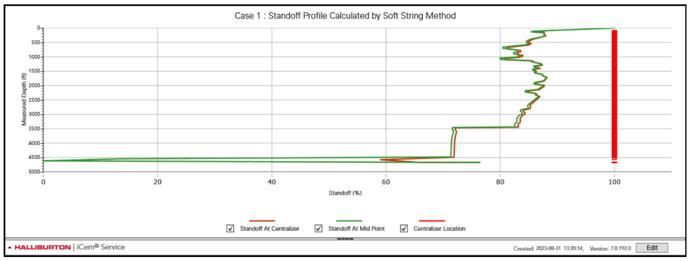


Fig8. Centralizer Stand-off (Min. 70%)

- Scavenger Slurries: In cases where 3D displacement modeling shows increased contamination between spacer and cement, gas tight scavenger slurries from 25bbl to 125bbl were pumped behind spacer to ensure complete cement coverage.
- Three wiper-plug system: 2 Bottom plugs and 1 Top plug were used to eliminate contamination of mud and spacer, spacer and cement, inside casing and to deliver uncontaminated fluid in annulus. 3D simulation shows that an absence of wiper plug between mud and spacer leads to heavy coning of spacer into mud, so much so that the spacer delivered in annulus is 75% contaminated with mud.

Approximately 50 wells were completed between 2012 to 2015 with all the recommendations from the study. The sustained casing pressures reduced to 7%. Although the results were promising for SCP, the complex flexible systems had a huge financial impact and proved to be operationally very challenging to handle multiple blends in field coupled with up to 20% blend losses during transfers from shore to boat and boat to offshore rigs to cement unit.

In 2017, a change in cement service provider brought about changes in the cement slurry systems (conventional gas tight and flexible), 3D modeling software capabilities and cementing equipment systems (semi-automatic Liquid additive systems) which had an impact on the SCP results of the cement jobs. Although the cement slurry properties and practices were largely the same as for FDP2012, wells with SCP increased from 7% to 14% between 2017 to 2020. This could be attributed to the lack of expansion additive in new flexible cement blend and relatively less robust 3D displacement modeling software.

In May 2020, multiple jobs experienced sharp pressure increases during displacement leading to an abrupt end to cement job leaving large volume of cement in the casing and high% of annulus uncemented. This was attributed to annular pack-offs during displacement possibly due to high solid content of blend in the cement slurry. Usage of flexible blend-based slurry systems was halted, and all wells were cemented with conventional 13.7ppg lead and 15.8ppg tail gas tight slurry systems. The conventional slurries did not have any expansion additive in system. A sharp increase in wells with SCP was observed over next one year from May 2020 to Aug 2021.

Meanwhile, the operating parameters of injection wells were also optimized across the field. The effect of gas lift operations on cement sheath (drastic temperature and pressure changes in tubing-casing annulus) was not evaluated for producer wells.

In 2021, an extensive study was launched to –

- Re-evaluate the need for flexible cement systems in ALS Field
- Assess the mechanical properties of cement required to provide a long-lasting zonal isolation in Injector and Producer wells considering the revised Injection parameters and Gas lift operations.
- Design a blend-free liquid flexible cement system (with Class G cement and Liquid additives only) that meets the flexible cement property requirements and can be pumped on fly using LAS systems.

Study methodology involved –

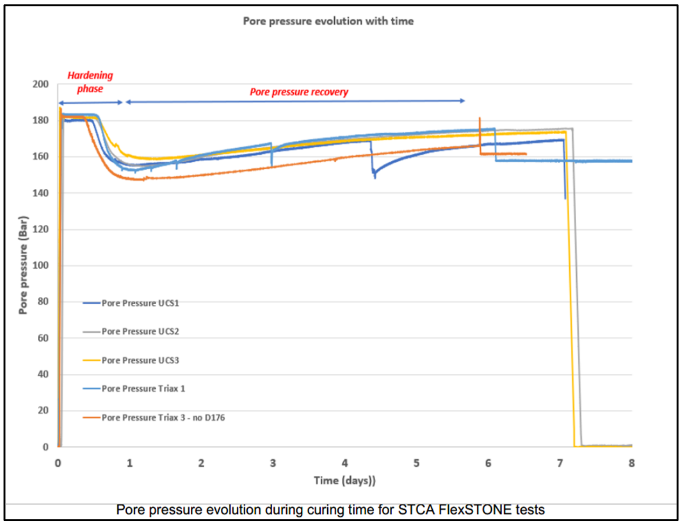
- STCA Lab Testing: Study the setting and mechanical property development behaviour of conventional and flexible cement slurries under downhole conditions using TotalEnergies' STCA technology.
- Mechanical property testing of flexible cement slurry to understand the post-set mechanical behaviour of cement when subjected to tensile and compressive loads and their respective failure limits.
- Evaluation of the effect of expansion additive in cement slurry with and without the presence of external source of water (formation water).
- Wellbore Stress Simulations: Multi-faceted wellbore stress modeling using both mathematical models based (TotalEnergies T-CemInt and SLB's Cemstress) and Finite element-based model based (Halliburton's WellLife) software.
- Slurry Designing: Data base review and pilot testing of liquid additives based flexible cement systems with major service providers.
- Lab Verification: Verification testing of qualified slurry designs for stability and mechanical properties with TotalEnergies lab using conventional triaxial cell test equipment.

STCA Testing

Slurry to Cement Analyzer (STCA) is state of art triaxial equipment, which allows testing samples that evolve within a pressure vessel from slurry to hard cement with continuous monitoring of strains and pore pressure under varying or fixed stress and temperature conditions (A. Onaisi et.al, 2017). STCA testing provides a more realistic simulation of slurry behaviour and mechanical properties development at downhole conditions, as it allows to keep the cement slurry at downhole pressure and temperature with no exposure to atmospheric conditions throughout the phase changes from liquid to gel to solid state during a 7-day cuing test.

Typically, for conventional cement systems, the pore pressure within cement tends to drop continuously throughout the setting and curing phase as it changes phase from liquid to solid. On the contrary, flexible cements show a regain of pore pressure overtime (Fig9) after the initial drop. This can be attributed to cumulative effect of below –

- High water to cement ratio (less amount of cementitious material)
- Low shrinkage rate and fast initial bulk volume recovery due to presence of expansion additive
- Composition of flexible cement (lightweight materials, elastomers, latex)



Pore pressure evolution during curing time for STCA FlexSTONE tests

Fig.9 Evolution of pore pressure in flexible cements during STCA

STCA test results highlight the inherent nature of lightweight flexible cements to prevent volume shrinkage and ability to build and/or confine pore pressure to resist cement mechanical failure. This can also be interpreted as an indication of better bonding ability with casing and formation demonstrated by cement sheath in annulus.

Mechanical Property Testing for Flexible Cement

Cement compositions in resilient cement with post set expansion additives, are designed to obtain elastic and strength properties as well as pre-stresses in the cement sheath that allow the cement sheath to resist tensile or shear stresses induced by pressure and thermal loads emanating from well during its full life cycle. (A. Onaisi 2017).

The laboratory measured values of mechanical properties become the input variable for wellbore stress engineering analysis to evaluate the cement sheath integrity. It is a common practice to cure cement formulations under downhole conditions, particularly at downhole temperatures, either under pressure or at atmospheric pressure, and at the end of the cure period, allow the samples to come to ambient conditions prior to testing for mechanical properties. (B.R. Reddy et.al. 2005).

The cement slurries were cured under downhole conditions for a minimum of 7 days up to 21 days with the tests performed under confined (Tri-axial tests) and unconfined (Uni-axial Compressive Strength) conditions to measure the set cement's young's modulus, Poisson's ratio, Friction angle and Cohesion Pressure using Stress Strain curves (while loading and unloading). Uni-axial and Triaxial stress-strain tests were performed on cylindrical samples as per ASTM D 3148 – 02 (Standard Test Method for Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression, Dec 2017) in view of API 10TR7 (Mechanical Behaviour of Cement). Testing was performed under controlled constant stress loading with displacement controlled at rate of 0.0001 inch/sec (0.0006 inch/min). In addition, the values for mechanical properties (Young's Modulus, Poisson's Ratio) were measured at three intervals across the curve in elastic region (10-25% range, 30-45% range and 35-50% range). Young's Modulus in the mid-range (35-50% range – tangent region) where a linear regression of curve is >0.995 was taken as representative for all engineering simulations and analysis.

Uniaxial Compressive tests allow the evaluation of the Unconfined Compressive Strength (UCS) value and estimate from unloading-reloading cycle the elastic properties (Young's modulus and Poisson's ratio) of the Cement. The triaxial test consists in loading the cylindrical sample in axial direction while maintaining confining stress constant. Triaxial tests allow to calculate Young's modulus, Poisson's ratio. Furthermore, cohesion and friction angle are calculated with maximum failure under different effective pressure. The cohesion and friction angle represents the linear envelope that is obtained from Mohr's plot of the shear strength of a material versus the applied normal stress. The interception between the tangent of all circles and the Y axis is the cohesion and the angle with X axis is the friction angle.

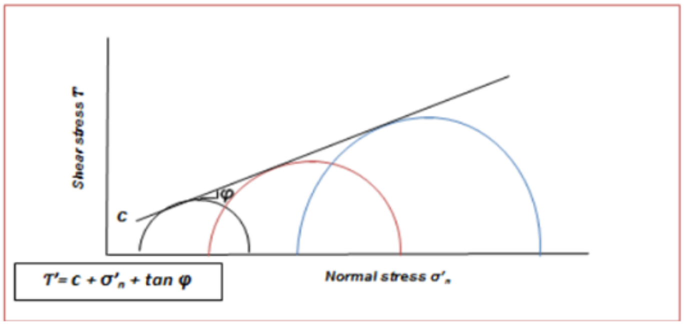


Fig.10 Mohr's Circle Plot – Material Failure Envelope

Three triaxial and two uniaxial tests were run on 13.5ppg flexible cement (blend based) indicating a very peculiar rock behaviour under compression loads –

- Low elastic failure envelope followed by a prolonged plastic behaviour. However, no visual cracks were observed until the max limit of sensor scales were reached due to high deformation.
- Low Young's Modulus
- High Tensile to Compressive Strength ratio (>300psi Tensile strength and 1000 to 1200psi compressive strength).

Below are the Uniaxial and Triaxial tests performed for Class G Cement and Flexible Cement.

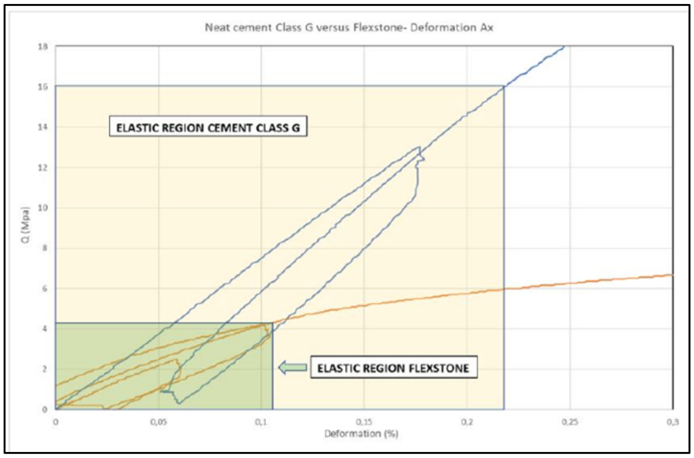


Fig.11 Uniaxial Tests - Elastic limit for Flexible cement v/s Neat Class G Cement

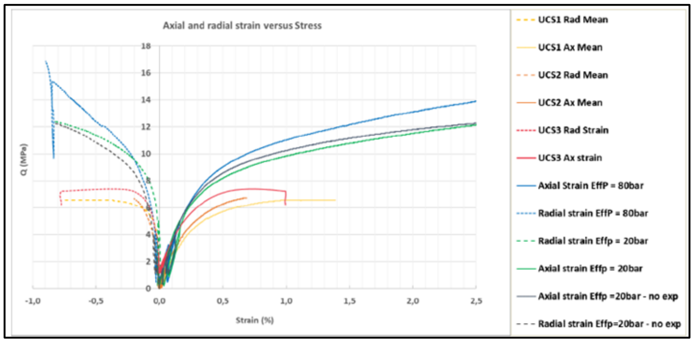


Fig.12 Triaxial Tests with Flexible Cement

Below are observations from the mechanical property testing.

- Non-brittle rupture of the UCS samples (within the testing envelope due to the low failure regime), the failure behavior can be defined as ductile with an elasto-plastic deformation mode during the loading. A maximum load is reached but the material still maintained his integrity. Post-mortem analysis of the sample does not allow to define the cracking comparison since the UCS performed on classical cement will typically exhibit a typical 45° crack and the sample is broken in two parts.
- The three triaxial tests on the other hand are in a ductile failure mode and it was impossible to reach the failure of the sample after 5% of axial strain deformation, test had to be stopped due to sensors limits. A high plasticity is observed for this slurry. The absence of difference between the two triaxial at 20bar of effective pressure with and without expansion additive seems to indicate a low impact on the mechanical properties of this additive. Small amplitude of the elastic part for each test coupled to a compacting behavior switching to a more dilating one after the transition from elastic to plastic deformation.

Evaluation on effect of expansion additive with and without the presence of external source of water

The cement slurry was tested for linear expansion with expansion rings as per API 10B5 testing procedures which requires the samples to be exposed to external source of water (in a water bath) throughout the test duration of 14 days. The cement samples showed positive expansion in range of 0.2% to 1%. However, the repeat of the same tests placed in oven without the presence of external water source shows no expansion.

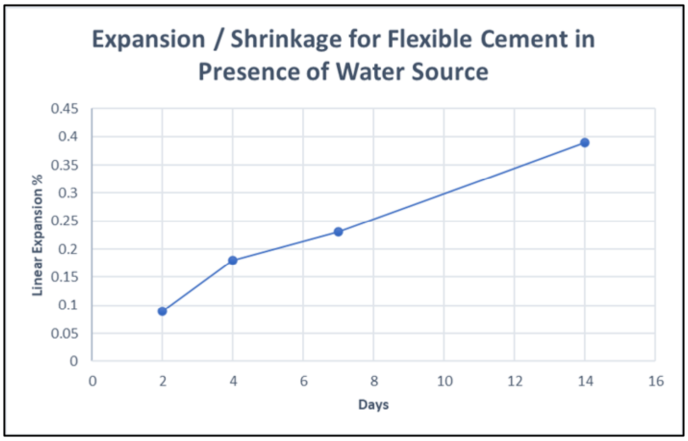


Fig.13 Expansion Tests in presence of external water source for Flexible Cement with 5%bwoc expansion additive

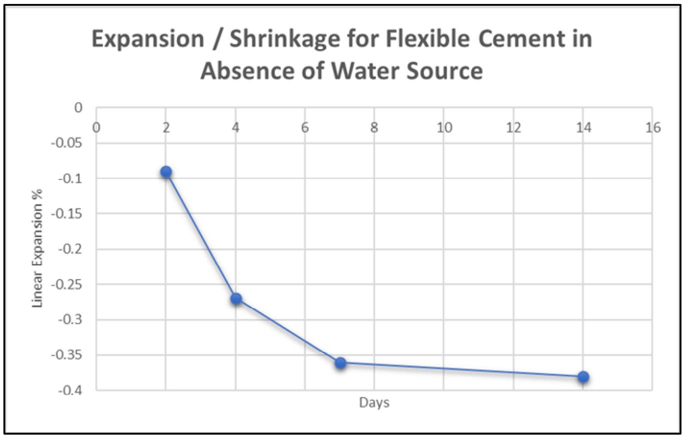


Fig.14 Expansion Tests in absence of external water source for Flexible Cement with 5%bwoc expansion additive

It was observed that the cement samples (expansion rings) placed in water bath saw a positive expansion up to 0.4%, however the cement samples placed in oven with no contact of external water shrunk up to -0.4% over a period of 14 days. This indicates that for the expansion additive to work, it would need a continuous supply of external water source and the innate water in pores of set cement would not be enough to cause expansion.

The tests confirm the findings of multiple studies performed on effect of expansion additives in post-set cement under downhole conditions (A. Onaisi et.al 2017; A. Shafqat et.al 2018, A. Onaisi et.al 2018). Expansion generated by hydration reaction of common expansion additives requires several conditions to be activated under downhole conditions. The more important conditions are effective stresses lower than expansion force, access to fluid to maintain 100% saturation of cement porosity. (A. Onaisi et.al. 2018)

Annular ring test provides a measurement of the maximum possible expansion, but it is not representative of the downhole conditions where the cement might be undrained, and the effective pressures are rather high. The STCA setup provides a more valuable alternative as it allows to study the shrinkage and expansion behavior of cement under complex downhole conditions. (A. Onaisi et.al. 2018)

There is a positive relationship between the amount of cementitious material and the probability of micro fissure formation. When exposed to the same temperature and treatment, a slurry system that has more cementitious material for a given volume unit shows signs of micro fissure formation, while the system that has less cementitious material does not show any sign of micro fissure (Shafqat et.al 2018).

This explains why the STCA results show a regain in pore-pressure with 13.5ppg flexible cement owing to the reduced cementitious material, continuous contact of water. Additionally, too much of expansion caused due to excessive concentration of expansion additive could lead to development of stresses within the cement sheath causing it to crack as reported in (Al Hammad and Altameimi,2002).

Inference of all the tests for STCA and Expansion Ring:

- Slurry to be designed with a density equal to or below 14ppg to have reduced cementitious material.
- Expansion additive concentration to be optimized to limit the expansion to 1% (ideally between 0.2% to 1%) to avoid development of internal stresses.
- Cement sheath in the casing-casing section is most likely to have no expansion due to lack of external water contact.
- 15.8ppg conventional slurry is known to be worst in shrinkage after the complete hydration due to high content of cementitious material and addition of expansion additive at moderate concentrations will not yield the expansion required to compensate for shrinkage. On the contrary, adding more expansion additive can be detrimental and create an internal stress leading to cement sheath failure.

Wellbore Stress Simulations

The stresses exerted on the cement sheath from wellbore operations in Injector and Producer wells respectively could be severe enough to damage the cement sheath leading to loss of zonal isolation. These stresses are often generated due to change in pressure and temperature across the cement column during wellbore construction, production, injection, or artificial lift operations.

The effect of these stresses on cement sheath were modelled using Total's TCemint and Halliburton's WellLife Cement Stress modeling softwares to simulate the optimal mechanical properties required for the cement sheath to prevent mechanical failure or debonding.

T-CemInt simulations were run for defined wellbore stresses up to a maximum of 3 injection/shut-in cycles with 15.8ppg conventional Class G system and 14.5ppg liquid flexible (blend free) slurry system. Sensitivity analyses were performed to account for variation in cement mechanical properties (YM, Tensile Strength, UCS) and heterogeneity in formation properties. T-CemInt simulations cannot simulate the effect of shrinkage or expansion in cement. Hence, WellLife (finite element-based model) was used in conjunction to understand the failure mechanisms related to shrinkage along with wellbore stresses related failures. STCA test results were studied to understand the behaviour of both the cement systems and impact shrinkage / expansion can have on cement failure.

Below are the operating parameters simulated for Injector and Producer wells respectively –

Injector Well:

- Displacement of well lower density 8-1/2" drilling mud.
- Drilling of 8-1/2" section" and running liners
- Displacement to same density completion fluid (brine)
- Pressure test of 9-5/8" casing to 3000 psi
- Produce well for 30 to 90 days.
- Shut-in for 30 days
- Inject Water at 80°F and 3000 psi surface temperature and pressure for 100 days.
- Inject gas at 140°F and 3000 psi surface temperature and pressure for 100 days.
- Shut in well for 100 days.
- Repeat the Injection cycle for minimum 2 times for simulation purpose.

Producer Well on Gas Lift Operations:

- Displacement of well lower density 8-1/2" drilling mud.
- Drilling of 8-1/2" section" and running liners
- Displacement to same density completion fluid (brine)
- Pressure test of 9-5/8" casing to 3000 psi
- Gas Lift Operations for 90 days at 45Bar and 55°F surface injection pressure and temperature
- 12 hours shut in (decompression effect)
- Gas Lift Operations for 90 days at 45Bar and 55°F surface injection pressure and temperature.

The cement sheath integrity was assessed across all flow zones in open hole viz. Kharaib (limestone), Shuaiba (limestone), Upper Mauddud (limestone), Nahr Umr (Sandstone), Nahr Umr (Shale), Khatiyah (Limestone – just below previous casing shoe) and 3 critical depths inside the casing – casing section viz. 500ft inside previous casing, across Umr Er Redhuma @ 1500ft MD and across 20" casing shoe (@ 600ft MD).

Below were the results of simulation exercises –

- 15.8ppg Tail and 13.7ppg lead conventional cements fail under tensile forces and debonding.
- Liquid flexible cements can sustain the wellbore stresses within the expansion limits of 0% to 0.9%. An expansion in liquid flexible cements above 0.9% increases the risk of failure due to development of internal stresses.
- The mechanical properties for a liquid flexible cement slurry to prevent cement failure shall be within the below envelope –
    - Youngs Modulus < 0.7 Mpsi
    - Tensile Strength > 260 psi
    - Expansion: 0.2% to 0.9%
    - Density: 13.5 to 14.0ppg
    - Compressive Strength > 1500psi

Slurry Designing and Lab Verification

The new flexible cement is designed with due consideration to meeting the slurry technical requirements and operational optimization to eliminate handling of multiple complex blends in offshore environment.

- Blend free system to allow use of a single simplified cement blend to be used in field for all cementing applications including expansion additive.
- Stable cement slurry with lower rheological profile.
- Exhibit gas tight properties
    - Fluid Loss < 50cc/30min
    - Static Gel strength transition time < 30 min
    - Passed the Gas Flow test.
- Mechanical properties in line with the requirements defined by Wellbore stress simulations.
- Slurry to be prepared with liquid additives only with concentrations compatible with the standard liquid additive systems.
- Not to exceed the liquid chemical storage / requirement beyond 6500gal for a 600 bbl cement job to comply with the Jack-up rigs storage capacity including Tote Tanks and LAS Tanks.
- Design to be replicable across cementing service providers to be able to pump a similar cement system irrespective of service provider on respective rigs.
- Manage the cost per bbl of cement slurry to be lower that standard blend based flexible cement designs.

Extensive lab testings were done with multiple service providers to come up with a novel cement slurry design with Latex and Fluid Loss Additive to meet all the above criteria.

14.0ppg cement slurry design with universal field blend

(Class G Cement + 4%bwoc Expansion Additive), 2.4gps Latex, 0.3 to 0.8gps Fluid Loss Additive and synthetic retarder met all the design criteria. The philosophy behind design was to –

- Lower the density to reduce the cementitious material and increase the water content to minimize the shrinkage effect and enhance the flexibility of cement. However, have enough cement to be able to provide compressive and tensile strength-
- High concentration of latex to provide slurry stability, control free water and fluid loss, reduction in modulus of elasticity. Latex also imparts a lower rheological profile and reduced friction due in cement slurry due to its lubricating effect.
- Synthetic retarder to provide a stable linear response without hampering the compressive strength development that is significant with lignosulfonate-based retarders. The concentrations needed are considerably low due to lower downhole temperatures (125°F to 140°F BHCT).

The overall cost per bbl for the cement slurry is comparable if not lower to a standard gas tight 15.8ppg cement slurry which is a huge achievement. Roughly 150% lower than the blend-based flexible cement slurries pumped in ALS field.

The finalized cement slurry designs were tested at Total HQ laboratory to verify and confirm the slurry properties including post set mechanical properties. Below were the slurry properties attained.

Properties	Design-1	Design-2
Settling / Sedimentation	None	None
Young's Modulus (Mpsi)	0.55	0.615
Tensile Strength (psi)	425	374
UCS (psi)	2453	1992
Poisson's Ratio	0.194	0.224

Table-3: Mechanical Properties of Liquid Flexible Cement Designs

Field Application Results

Between Q2 2022 to Q2 2023, multiple injector wells were cemented with new14.0ppg Liquid flexible slurry system with no wells showing any signs of sustained casing pressures. Consequently, from Q3 2023, all the wells have been cemented with 14.0ppg liquid flexible slurries with 0% SCP issues.

Conclusions

- With almost a decade and half of optimization since the first use of Wellbore Stress modeling and 3D displacement improvement techniques in 2010, the SCP issue in ALS Field has been mitigated to a large extent from 40% to 7% with promising signs of going down to 0% for all new wells.
- Expansion additives only work in presence of external water source and hence ineffective in casing-casing section when cemented up to surface.
- Conventional 15.8ppg cements are brittle and exhibit high volume shrinkage post setting. These cement slurries mostly fail under tensile mode and prove debonding. Small amounts of expansion additive do not compensate for shrinkage and large amounts of expansion additive can lead to internal stresses causing cement cracking.
- Lower density Flexible cements with expansion additive show an ability to regain pore pressure post hydration and some degree of positive expansion with lower concentration of expansion additive. This makes it less susceptible to debonding failure.
- STCA equipment is a more robust and accurate test equipment to measure cement mechanical properties, pore pressure variations and expansion/shrinkage under downhole conditions. Cements volume expansion/shrinkage is affected by the confining pressures which is missing in the expansion ring tests.
- Defining the wellbore stress environment and formation characteristics is paramount for an accurate simulation of cement integrity with Wellbore stress modeling softwares. Cement placed across soft and/or fluid bearing formations is more at risk of mechanical failure. Finite element-based model with ability to account for cement volume changes and the stresses developed due to it are more suitable for any stress modeling assessments.
- Thorough simulation studies with sensitivity analysis shall be performed to define the minimum mechanical property requirements for resilient cement systems to avoid overdesigning and complicating the cement designs.
- Resilient cements to the point of achieving Young's modulus as low as 0.6Mpsi can be achieved using Latex alone with no need of elastomers and complex blend components.
- Contrary to popular belief, high compressive strengths are not required to provide a robust cement system to eliminate sustained casing pressures.
- Operating in an offshore environment with 5 offshore rigs and multiple supply vessels, using one simplified cement blend across the field for all cement jobs helps optimize the rig storage capacity and logistics movements.
- Liquid flexible cements provide Operators to work with advanced / modified liquid additive systems to pump large volume jobs on the fly without delivery, chemical storage, or quality concerns.
- Simplifying and standardizing the cement systems across the field for all wells feeds into Factory Mode of

operation with a cheaper solution resulting in net savings in product cost, rig time, logistics and service personnel support.

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References

1. Onaisi, A et al, 2017. Impact Of Poro-Chemo-Mechanical Parameters On Pre-Stress And Cement Sheath Integrity Under Well Pressure And Thermal Loadings, SPE 188761-MS
2. Cement Mechanical Property Measurements Under Wellbore Conditions, B.R. Reddy, SPE, A. Santra, SPE, D. McMechan, SPE, D. Gray, SPE, C. Brenneis, and R. Dunn, Halliburton, SPE 9592, 2005
3. Study to Evaluate the Effect of Using Expansion Materials with Cement slurry for High-Pressure/High-Temperature Well, A. U. Shafqat, S. Taoutaou, R. Abdurrahman, A. A. Maksoud, and L. Otaremwa, Schlumberger, IADC/SPE-191062-MS, 2018
4. Is Post Expansion Measured by Standard Ring Experiment Meaningful for Cement Sheath Integrity? Atef Onaisi, Louis Zinsmeister, Modis, Christophe Urbanczyk, Andre Garnier and Jean-Yves Lansot, Total, SPE-192718-MS, 2018
5. Cement matrix evaluation, Al Hammad, M.A. and Altameimi, Y.M., SPE-77213, presented at IADC/SPE Asia Pacific Drilling Technology, Jakarta Indonesia, 2002

Nomenclature

LEL = Limited Entry Liner
BHCT = Bottomhole circulating temperature
Psi = pounds per square inch
Mpsi = Mega pounds per square inch
°F = degree Fahrenheit
ALS = Al Shaheen
ERD = Extended Reach Drilling
PHB = Pre-Hydrated Bentonite