Concrete Developments in Cementing Technology

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CemCADE, CemCRETE, DeepCRETE, DensCRETE, DESC (Design and Evaluation Services for Clients), FLAC (fluid-loss additives for cement), GASBLOK, LiteCRETE, SqueezeCRETE, USI (UltraSonic Imager) and Variable Density are marks of Schlumberger. Ping-Pong is a mark of Parker Brothers, Inc.

Perhaps the most difficult borehole fluid to handle, cement is critical to the performance and life of a well. Optimal slurry properties for placement of standard oilfield cements typically do not coincide with optimal mechanical properties of set cement necessary for long-term zonal isolation. New technology optimizes both slurry and set-cement properties simultaneously.

Since a flawlessly cemented wellbore protects the conduit that links reservoir fluids to the surface where they are used, high-quality oilfield cement is an essential ingredient in any successful well. The quality and integrity of a cement job can determine how long a well remains stable and productive without requiring repair. In addition to promoting ongoing operational safety and success, today’s cements must also be designed with cost savings and challenging operating environments in mind. Environmental protection is a greater concern than ever, especially protection of shallow aquifers during and after drilling. A good primary cement job is essential because remedial cementing (squeezing) is difficult to accomplish and provides only temporary, local zonal isolation— it is preferable to do the job correctly the first time. Overcoming the trade-off between cement slurry properties, including rheology, fluid loss, pumpability and thickening time, and mechanical properties of set cement, such as compressive strength, porosity and permeability, is a major challenge.

Traditional Cementing Approaches

There are several fundamental purposes for placing cement in oil and gas wells. Cement is used to support the casing. In addition, it hydraulically isolates the various formations the well penetrates, thereby protecting aquifers and preventing fluid flow from high-pressure to low-pressure formations, which might result in a loss of hydrocarbon production or excessive water production. Cement guards against fluid broaching to the surface, which could lead to a catastrophic blowout. Cement also protects the casing from corrosion by chemically aggressive brines.

In the past, the least expensive material and technology— typically displacing drilling fluids by pumping Portland cement behind casing— were acceptable in all but the most difficult cases. Portland cement mixes easily with water to produce a slurry that is readily pumpable and can be placed anywhere within hydrostatic pressure constraints of a wellbore. Prepared at the recommended water-to-cement ratio, Portland cement fulfills the most important objective, hydraulically isolating the formations. Furthermore, Portland cement is readily available worldwide and is inexpensive.
The usual method for placing a slurry in a well during primary cementing operations consists of pumping a series of fluids down the casing while the fluid already in the well—the drilling mud—flows out the casing-formation annulus to surface. The first fluid pumped is usually a preflush or spacer, or both, that separates the drilling fluid from the cement slurry. The spacer must be compatible with both the drilling fluid and the slurry, yet keep those fluids apart to preclude contamination of the slurry by drilling fluid. Such contamination degrades the quality of the set cement. This is followed by as many as four slurries. The preflush-spacer-cement series must displace from the annulus all fluids ahead of it to prevent development of mud channels within the cement sheath. Such channels allow formation fluid migration. The presence of mud can also negatively affect set-cement properties, for example by inducing shrinkage cracks, reducing compressive strength or increasing permeability. A mechanical plug is then launched into the casing and displaced to the bottom of the well by another fluid, typically the drilling fluid needed to drill the next section of hole. At the end of the operation, the cement occupies the annular space between the casing and the penetrated formation from the bottom of the hole up to the desired level.

During the cementing operation, the critical goal is to maintain the pressure in the annulus between the pore and fracture pressures of the penetrated formations at all times and all depths throughout the openhole interval. If the annular pressure becomes lower than the formation pore pressure, fluids can flow into the annulus and lead to a potentially catastrophic situation, a blowout. At the other extreme, if the annular pressure becomes higher than the formation fracture pressure, fluids can split the surrounding rock, damaging the borehole and escaping into the formation.

slurry must not lose excessive interstitial water to the formation when the pressure in the annulus is higher than in the formation. Excessive fluid loss from a slurry can increase the viscosity, which might result in incomplete placement of the slurry and bridging of the annulus, and can also lead to volume reduction in the cement, producing channels or other defects. Finally, the slurry should not thicken or set prematurely during placement.

Performance of conventional cement slurries ultimately is a function of many variables, including the amount and types of solids, water, chemical additives, temperature and pressure. Weighting agents increase density; extenders decrease it. Dispersants control rheology by breaking larger particles into smaller ones, which can reduce viscosity. Stability is either intrinsic to the design, or improved by using free water control or solid-suspending agents (antisettling agents). Fluid-loss control is achieved by adding FLAC fluid-loss additives for cement. Retarders or accelerators control thickening time. Clearly, chemical additives define the performance of Portland cement slurries.

Once in place, the cement slurry should set quickly and develop adequate strength to minimize the time spent waiting on cement (WOC) so that the operator can proceed with the next phase of well construction as soon as possible.

Limitations of Conventional Cementing Technology

Good slurry and set-cement properties are mutually exclusive in many conventional cementing situations. For example, standard high-density cements, while necessary for well control in high-pressure drilling, are difficult to pump and prone to sedimentation as weighting agents settle out of suspension. Low-density slurries with proportionately higher liquid volumes develop compressive strength slowly and attain low final compressive strengths, limiting their value when cementing production casing. Although chemical additives are crucial to successful cementing operations, the ultimate performance of conventional cement systems is dominated by the water-to-cement ratio.

The optimal water-to-cement ratio is about 44% by weight for a low-viscosity, stable slurry of API (American Petroleum Institute) Class G cement, one of the most commonly used Portland cements in the oil field. This gives a density of around 15.8 lbm/gal [1900 kg/m³]. Higher densities can be reached by either decreasing the water-to-solid ratio or increasing the density of the solid blend at a given water-to-solid ratio. When the water-to-cement ratio is close to the optimal value, the better choice is to reduce the amount of water; but this quickly leads to unpumpable or unmixable slurries. At that point, the only option is to add weighting materials to the cement, normally high-density minerals such as barite, hematite (the most common weighting agent) or ilmenite. The densities of these materials are 35 to 43 lbm/gal [4200 to 5200 kg/m³], whereas the density of Portland cement is about 27 lbm/gal [3200 kg/m³].

To achieve lower densities, the methods are reversed: either increase the water-to-solid ratio or add lightweight aggregates. Another possible option is foaming the slurry with gas—usually nitrogen or air. When the water-to-cement ratio approaches the optimal value, the simplest approach is to add more water to the slurry, but this jeopardizes its stability, reduces the strength of the set cement and increases porosity and permeability. To rectify stability problems, interstitial water can be viscosified using colloidal clays (bentonite or attapulgite), sodium silicates or hydrosoluble polymers. However, these cement systems exhibit higher porosity and permeability once set, which often precludes their use in critical casing strings. Another technique consists of blending Portland cement with lighter solid materials such as diatomaceous earth, perlite, fly ash, fumed silica, blast furnace slag or hollow microspheres. This method works only in relatively narrow density ranges where the water-to-solid ratio is maintained above a given threshold for the slurry to be mixable and pumpable.

A further problem with standard cement systems is that remediation of unsatisfactory primary cement jobs is difficult. Squeeze cementing, even when performed satisfactorily, merely provides a temporary patch. Conventional cements are difficult to place in small defects, such as partially plugged perforations and damaged casing, because of their relatively large particle sizes and poor injectability.

Operators seek cementing materials that not only are easier to place the first time, but also offer the best long-term performance. Cements that achieve compressive strength earlier reduce waiting time and increase efficiency. Because drilling a well is typically the culmination of months or even years of intensive effort, including the acquisition and interpretation of seismic data and planning well construction, it is critical to achieve 100% cementing success at the outset.

Concrete Improvement

Typically, cements are weighted without consideration for the particle sizes of the ingredients (primarily cement and weighting agents). As the required density increases, conventional additives alone quickly lead to either an unpumpable or unmixable slurry if the solid-to-liquid ratio is too high, or to a system that does not contain enough cement to develop a reasonable strength. A new system, CemCRETE technology, is concrete-based slurry technology to optimize slurry performance during placement while ensuring a high set-cement quality. By adjusting the particle-size distribution (PSD) of the different solids, this technique uses more solid particles in a given slurry volume while keeping slurry rheology reasonably low. This allows slurries with densities as high as 24 lbm/gal [2900 kg/m³] to be used to cement critical casing strings in wells with high pressure gradients.

Because many traditional cement slurries have single-size particles, they can be visualized as a box full of Ping-Pong balls (previous page). Between each ball, there are large air-filled voids. In a real slurry, the void space would be filled with water rather than air. In a high-performance slurry with engineered PSD optimization, particles of three or more different sizes are carefully selected. A box of Ping-Pong balls with green peas and grains of sand filling the voids is crudely analogous to a trimodal PSD CemCRETE system.

By adjusting the PSD of the solids in the blend, CemCRETE technology increases the solids per unit volume of slurry above that of Portland cement slurries. This increases compressive strength and reduces porosity and permeability by achieving a higher packing volume fraction (PVF) independent of slurry density. Packing volume fraction is defined as the ratio of the sum of the absolute volumes of all particles in the dry blend divided by the bulk volume of the dry-blend components. Higher PVF values generally indicate better set-cement properties. For example, hexagonal packing of identical spheres results in a PVF of 0.74, but random packing of the same spheres achieves a PVF of 0.64. The packing volume fraction of an optimized dry blend is increased by using a trimodal PSD, which in turn decreases set-cement permeability (below left).

Because the remaining fluid content is used more efficiently, CemCRETE technology usually requires lower concentrations of most chemical additives compared to traditional approaches. Gas-migration technology is more easily applied because of the lower water-to-solid ratio and because of the lower permeability and porosity of the cement slurry during the transition from liquid to solid as the cement sets. The 35 to 45% porosity, or water content, of the new high-performance slurries is significantly lower than the average 55 to 75% porosity for standard slurries (below right).

In contrast to conventional Portland cement, state-of-the-art cements contain a specific blend of particles engineered for each specific slurry density. The PVF of the optimized blends commonly exceeds 0.80. The high solids content results in stable systems that disconnect the slurry density from rheology, require few additives and are easy to mix and place in operations that are as simple as ordinary jobs yet require no specialized equipment. These systems exhibit low porosity and permeability once set, even for slurry densities as low as 10 lbm/gal [1200 kg/m³]. More simply stated, physics succeeds where chemistry often fails.
Sedimentation and segregation. In the BP settling test, a column of set cement cured under controlled pressure and temperature is cut into sections and the density of each cylindrical section is measured. High-density conventional cements tend to show greater vertical density variation because the weighting agent tends to settle out of suspension as the cement sets. DensCRETE cements, or high-density CemCRETE cements, show little variation in density from top to bottom because the network of particles and associated reduced water content inhibit sedimentation or segregation of the heaviest particles. Each column represents a different cement type and density, with density variation measured in the top, middle (where the designed density is most likely to be found) and bottom sections of the column.

Fluid-loss effects. As slurries lose fluids to permeable formations, plastic viscosity tends to increase. Compared with optimized slurries, conventional Portland cement slurries tend to suffer greater increases in plastic viscosity per unit of fluid loss. The bottom two curves show the difference in viscosity between an optimized blend and a standard blend. The top two curves show the increase in viscosity after both slurries have lost 20% of their fluid. Optimized blends suffer less viscosification per unit of fluid loss.

Plastic viscosity of silica suspensions. A dry blend consisting of a monomodal particle-size distribution produces a high-viscosity slurry even at a relatively low solids content. The blend with the trimodal particle-size distribution, typical of CemCRETE technology, achieves better slurry properties and contains more solids per unit volume.
The rheology of CemCRETE slurry is decoupled from its density (previous page, top left). These water-reduced slurries have constant viscosities even at high densities, low gel strengths and are easy to place. Low water content diminishes sedimentation (previous page, bottom), or separation of liquid and solids during cementing, yielding higher compressive strength and lower permeability (previous page, top right). The specially engineered particle sizes allow easy mixing and pumping because the smallest particles act like ball bearings to provide lubricity for the larger solids in the slurry. The compressive strength of set CemCRETE slurries, whether of high or low density, develops faster and reaches higher levels than conventional cements (right) because of the low water content.

CemCRETE technology benefits not only primary cementing applications, but also remediation. Particle-size optimization inhibits premature dehydration of the slurry and the associated friction-pressure increase that commonly prevents any remedial slurry from achieving deep penetration. Water-reduced primary cements have a lower incidence of costly remediation than Portland cements.

Additional benefits are that CemCRETE technology does not require specialized equipment or personnel, and while never desirable, mixing errors are better tolerated in the new slurries than in Portland cement. Optimized dry blends may be mixed with fresh water, seawater or salt water. Optimized slurries can include conventional defoamers, accelerators, dispersants, retarders, fluid-loss control additives, right-angle set (RAS) additives and GASBLOK gas migration control cement technology. In fact, the combination of specialized gas-migration control additives, low bulk shrinkage and rapid strength development of optimized cements is breaking new ground in gas-migration control. Clearly, as exemplified in the case histories that follow, advanced cementing technology can be tailored to specific needs by changing components of the dry blend.

Specialized Applications

There are four broad applications of CemCRETE technology, encompassing low-density, high-density, remedial and deep-water cementing situations. LiteCRETE slurry systems have low densities and are ideal for cementing weak formations or eliminating a casing string or a risky multiple-stage operation (below). LiteCRETE slurries of 9.7 to 13 lbm/gal [1166 to 1563 kg/m³] perform comparably to ordinary 15.8-lbm/gal [1900 kg/m³] slurries. Optimized lightweight cement develops compressive strength earlier and reaches higher levels than conventional cement slurries. Rapid compressive-strength development reduces waiting-on-cement time and speeds well construction.

^ New approaches to common problems. LiteCRETE cement (left) can replace stage-cementing operations, saving rig time and avoiding a complex, more expensive operation. Here, the two-stage cementing operation on the left has a weak zone that is eliminated in the single-stage LiteCRETE operation on the right. For cementing production liners (center) or casing across a weak or depleted zone, high-quality cement is placed across the primary pay zone as a tail slurry at the bottom of the well. Shallow formations, isolated with lower-quality filler slurry, cannot be completed without additional cementing work. LiteCRETE cement can be placed throughout the entire annulus so that any zone may be completed without additional cementing work, such as block squeezes. Placing a higher density cement plug in a lightweight fluid (right) can lead to instability as the fluids intermix. Cement placement is improved by matching low fluid densities with LiteCRETE slurries, which prevents fluid contamination and degradation of set-cement properties.
than conventional cement, reducing WOC time. In addition, this type of slurry is more stable than low-density Portland cement slurries because of its low water content. It is strong enough to be perforated cleanly and withstands fracturing and stimulation treatments (above left). DensCRETE technology offers better rheology at high density, adjustable density at the wellsite and improved well control during cementing (above right). High-density, water-reduced cement is useful for whipstock plugs and high-pressure cementing operations, for situations where the fracture and pore pressure margin is narrow, and for grouting (injection of cement to consolidate seabed sediments or injection of high-strength cement between pipes such as the legs of offshore platforms). A high-performance, high-density slurry of 17 to 24 lbm/gal [2040 to 2900 kg/m³] has a lower equivalent circulating density than that of a conventional high-density cement slurry, allowing placement even when the window between pore pressure and fracture pressure is tight and conventional high-density slurries are inadequate. Slurry density can be adjusted by as much as 1 lbm/gal at the last minute on location without perturbing other slurry properties. DensCRETE slurries usually develop compressive strengths well in excess of 5000 psi [34.5 MPa] and can reach 20,000 psi [138 MPa] in especially demanding applications.

For remediation of faulty cement jobs and for water control, SqueezeCRETE technology offers a new solution for wellbore repairs, such as casing leaks, liner top leaks, old partially plugged perforations, channels behind casing, leaking stage tools, fractures or even squeezing a gravel pack (below). A SqueezeCRETE slurry system applies the new technology at the microscale for injection into very small gaps or fractures in primary cements and casing. Optimized slurries with specially engineered particle-size distributions penetrate deeply not only because of the small particle sizes of the blend, but also because their improved resistance to dehydration reduces viscosification during placement. The improved injectability that results from fine-sized particles is key to success in remediation. In addition to high injectability, SqueezeCRETE cement has high compressive strength and low permeability. Strength makes cementing high-pressure formations. In high-pressure wells with narrow pore-fracture pressure windows, the friction pressure increase in a tight annulus during cementing can fracture the formation (left), leading to improper zonal isolation. DensCRETE slurries have lower viscosity, allowing slurry placement throughout the annulus. In deviated holes, standard high-density slurries are prone to sedimentation as hematite particles settle on the low side of the wellbore and do not contribute to the total hydrostatic pressure (right). This instability can lead to serious well control problems.

^Clean perforating. While conventional cements can shatter during perforating, CemCRETE cement remains intact after perforating. The perforation diameter is 0.4 in.

^ Remediation success. Perhaps the most versatile application of CemCRETE technology, SqueezeCRETE slurries penetrate more effectively than other cement slurries. SqueezeCRETE slurries repair small microannuli and leaks in casing, channels in cement and liner tops. They can also isolate old, partially plugged perforations and even be placed through gravel packs.
SqueezeCRETE cement an appropriate material to plug wells upon abandonment, although it is more commonly applied to remediate wellbore problems that cannot be repaired with typical cementing materials.

SqueezeCRETE technology succeeds where standard gels used for water-control applications might fail, including remediation of crossflow behind casing and as a tail behind conventional gel treatments. When water crossflow behind the casing is diagnosed, the path through the primary cement sheath might not yet be large enough to place ordinary squeeze slurries. On the other hand, the path may already be so large that a standard gel used for water-control applications cannot perform correctly or withstand the differential pressure once the well returns to production. The advanced slurry experiences a lower viscosity increase for the same volume of fluid loss than conventional squeeze cements. Its enhanced fluid-loss control properties, commonly better than those of drilling fluids, greatly improve slurry penetration properties: it can penetrate 120 micron slots more than 10 times farther than well-dispersed squeeze slurries (top right).

Engineered slurry for squeeze applications is placed after deep penetration through the channel and set like ordinary primary cement. In this manner, SqueezeCRETE technology restores the integrity of the cement sheath and provides competent zonal isolation.

An alternative to foamed cement, DeepCRETE technology, has been developed for deepwater wells. Foamed cement—cement plus nitrogen or air—requires specialized equipment and a cementing team trained in its use (as well as availability of nitrogen when air is not used), which might be logistically costly and costly on some offshore rigs and platforms. DeepCRETE cement develops strength faster, even at temperatures as low as 39°F [4°C], so WOC time is reduced when rig costs are calculated by the minute, such as in deepwater areas. No specialized equipment clutters up limited floor space. LiteCRETE slurry systems can also substitute for foamed cement.

Traditionally, cement jobs were planned by identifying the application of the cement and the total hydrostatic limitations on the placed cement column. The liquid slurry density was inferred from the physical properties necessary for the set cement. A major change precipitated by new cementing technology is that the initial planning step is to decide the slurry density first and then the slurry porosity. From that, the specific gravity of the dry blend is calculated and a blend designed according to the job parameters.6

CemCRETE technology results in cement properties that ensure long-lasting zonal isolation. Its strong resistance to corrosion from acid stimulations and formation fluids is enhanced by its low permeability (above left). Its mechanical integrity is high, even in workover, perforating and other specialized applications (above right).

Oilfield cement must withstand corrosion and CemCRETE cements provide good sulfate resistance when designed for that purpose.


Also, their low permeability inhibits water percolation into the cement, slowing corrosion (see bottom left figure, page 19). Destructive events, such as repeated freeze-thaw cycling, tectonic activity, production-induced subsidence and thermal expansion during production and tests prior to abandonment of wells, can impact cement integrity.

Protection of shallow aquifers is an ongoing concern, so regulatory requirements for cement performance, such as in well abandonments, are becoming stricter in many areas. Recently, prudent operators have recognized that surface casing should be cemented as carefully as production liners. New high-performance oilfield cements have greater reliability than traditional cements, even in extreme conditions, so using the best technology available might help operators meet stricter environmental protection standards.

During 1998, more than 250 CemCRETE jobs were carried out in 20 countries (left). LiteCRETE, DensCRETE and SqueezeCRETE technologies have been used in most cases, although DeepCRETE technology, introduced at the end of 1998, is also gaining popularity.

Elimination of Stage-Cementing Operations

In the Hassi Berkine field in the Ghadames basin of Algeria, Anadarko Algeria Company uses LiteCRETE cement to avoid stage-cementing operations and better protect the supply of fresh water coming from the overpressured Albian sandstone. The Albian aquifer overlies oil-producing Cambrian sandstones and underlies salty Senonian carbonate and evaporite rocks. Additional geologic complications include the weakness of certain formations below the Albian that are prone to lost circulation during drilling and the potential for flowing salt. The previous approach had been to set a stage tool below the Albian, cement the lower zones, and then isolate the Albian in the second stage of cementing operations.

Stage cementing resulted in higher costs than a single-stage operation and suboptimal zonal isolation that often required remedial cementing. After careful consideration of the risks and rewards of different approaches, Anadarko chose a solution proposed by Dowell engineers—single-stage cementing using a LiteCRETE slurry. Key factors that make this preferable to conventional cementing include rapid setting time, high compressive strength, low set-cement porosity and permeability that result in better zonal isolation and superior resistance to corrosive formation fluids (left).
The cost savings associated with the single-stage operation and decreased need for remedial cementing were also compelling. A typical single-stage operation in this area can save almost a full day of rig time and decrease costs of fluid contamination that might occur during the first stage of cementing. Additional savings stem from the low incidence of remedial work, which typically requires two days of rig time as well as additional cementing costs. The elimination of the stage tool removes a known weak point from the low incidence of remedial work, which typically requires two days of rig time as well as additional cementing costs.

In the United Arab Emirates, Abu Dhabi Company for Onshore Oil Operations (ADCO) has performed similar successful single-stage LiteCRETE cementing operations.

Ongoing collaboration between engineers from Dowell and Schlumberger Wireline & Testing has improved interpretation of bond logs of lightweight cementing systems. In the past, acoustic properties were incorrectly related to compressive strengths of cement, resulting in a false expectation of similar log responses between 15.8-lbm/gal Portland and LiteCRETE systems. The new systems have compressive strengths as high as 15.8-lbm/gal Portland cements, but their acoustic impedances are between 15.8-lbm/gal cements and ordinary lightweight cements. LiteCRETE systems display a lower acoustic impedance cement than for standard, heavier cements, which typically have greater attenuation. Finally, the Variable Density cement bond log (VDL) in track 5 provides information about the quality of the cement-formation bond by displaying a color-coded traveltime trace at every depth. The relatively low color contrast (low amplitudes) at early times indicates weak casing arrivals, which is to be expected for a good bond between the casing and a relatively low acoustic impedance cement. (A high acoustic impedance cement under the same circumstances would give lower amplitudes and weaker casing arrivals, if any.) The higher color contrast (high amplitudes) at later times represents arrivals from the formation, whose velocity varies with lithology, and correlates roughly with lithology indicated in the gamma ray log.
Optimized CemCRETE Plug for Sidetracking

- High-performance lightweight slurry. Optimized, low-density blends are used for whipstock plugs and liner cements in depleted reservoirs with low fracture gradients. In this example, PEMEX decided to sidetrack to reach a better part of the reservoir. By using CemCRETE technology, PEMEX has improved its success ratio for kickoff plugs and minimized WOC time.

Whipstock Plugs and Liner Cementing

In Mexico, Petróleos Mexicanos (PEMEX) has used LiteCRETE cement for whipstock plugs and liner cementing. PEMEX initially used the lightweight optimized blend for whipstock plugs to kick off deviated wells past irretrievable fish. The success ratio of kickoff plugs has been improved greatly by using the new technology in a low-density environment. The matched densities of the drilling fluids and cement slurries prevented swapping and mixing of fluids during placement and ensured development of the required compressive strength.

In a field with a low fracture gradient in the Villahermosa region, CemCRETE technology proved to be the best answer for cementing deep (4500- to 5000-m) [14,760- to 16,400-ft], depleted, fractured, dolomitic Mesozoic carbonate reservoirs. Lightweight cement is employed because the reservoirs have a low fracture gradient. In one deviated well, PEMEX elected to kick off in order to reach a better part of the reservoir (above left). A special 15-lbm/gal optimized whipstock plug material designed for PEMEX reached a compressive strength of 3750 psi (26 MPa) within eight hours and a final compressive strength of 4203 psi (29 MPa) in 12.5 hours, allowing the sidetrack to be completed successfully.

Cementing Shallow, Low-Pressure Zones

Hunt Petroleum Corporation has used LiteCRETE cement to complete five wells in the Olla field, LaSalle Parish, Louisiana, USA. Shallow Wilcox oil wells, with total depths of 3500 ft [1067 m] and bottomhole static temperatures of 129°F [54°C], have low bottomhole pressures and low fracture gradients, so getting a column of cement high enough in the annulus has proven difficult. In the past, as many as three block squeezes per well were performed to remediate poor primary cement jobs in 5⅝-in. casing (left).

The Wilcox reservoir in Olla field has a strong waterdrive. Productive zones are completed by perforating the top of the productive interval above the oil-water contact. Offset wells commonly produce high volumes of water at water cuts greater than 95%. The wells completed with LiteCRETE cement produce at water cuts less than 85% water, but, more importantly, the total volume of water produced is significantly reduced. Hunt Petroleum interprets the reduced water production as verification of proper isolation of the producing zone from nearby zones that contain 100% water. The additional water production in the offset wells has been attributed to water channeling from nearby water zones; radioactive tracer injection logs have verified this. None of the wells in which Hunt Petroleum used LiteCRETE cement has required remedial work.

Besides reducing the need for remedial work, Hunt Petroleum has lowered total well costs on Wilcox completions by avoiding the mechanical risks associated with squeezing operations. Such risks include the possibility of setting the cement retainer incorrectly, drilling a hole in the casing when drilling out the cement retainer, splitting casing during the squeeze, cementing the workstring if cement sets up early, or fracturing into a water zone. Because LiteCRETE cement columns extend higher in the annulus, upper zones of the Wilcox may be completed without additional cementing to cover these zones, which generally are not covered during conventional operations.


10. In the North Sea, a LiteCRETE blend remained on a supply boat for several days in bad weather. Nevertheless, the blend did not segregate during its rough journey to the wellsite.
Cementing High-Pressure Wells

High-pressure wells benefit from the use of reduced-water cements. Petroleum Development Oman (PDO) first adopted DensCRETE technology to address numerous challenges in fields such as the Al Noor and Sarmad fields of southern Oman. While adjustments to the mud system and casing program can reduce the cost and risk of drilling operations, the use of new cementing technology was the most important factor in improving operations for PDO.

In the southern Oman fields, PDO produces oil from stringers of tight Cambrian Athel silicilyte embedded in salt. The Athel reservoir, which is also a world-class hydrocarbon source rock, is up to 400 m [1312 ft] thick and contains 80 to 90% microcrystalline silica, with an average porosity of 22% and permeability below 0.05 mD. High drawdown pressures are applied to produce oil from such a tight reservoir, so it is crucial to mechanically isolate the individual stringers of reservoir rock.

Drilling and completing such wells successfully are challenging. At depths of 3500 to 4800 m [11,483 to 15,748 ft] and temperatures of 90°C [194°F], pressure control dictates a high-density slurry. Segregation of the weighting agent, hematite, from conventional dry blends during transport across graded roads led to difficulty mixing and pumping slurries and up to three hours of lost time to clean plugged cementing lines. Displacing heavy muds with 21.5-lbm/gal [2576-kg/m³] slurry and a 7-in. liner at 4100 m [13,451 ft] and 4300 m [14,108 ft] encountered a fault and fluid losses occurred just above the fault and then cement the liner using a 19.5-lbm/gal [2337-kg/m³] cement. There was little leeway to adjust densities and displacement rates.

Contamination of fluids by salt-saturated mud led to instability. Bulk shrinkage of set cement often resulted in microannuli. In at least one well, a microannulus was not detectable with a cement bond log, but was discovered when pressure in the annulus rose. Finally, when compared with conventional cements, CemCRETE slurries set faster at the top of the liner, which reduces the risk of fluid migration. In one well, a gas kick occurred 14 hours after conventionally cementing the liner and it took four days to control the well and avoid a blowout.

Before approval for the initial use of DensCRETE cement by PDO, numerous tests by PDO and by Dowell in Oman and at the Schlumberger-Riboud Product Center in France confirmed that the advanced technology would surpass critical performance requirements. In addition to exceeding the performance of traditional cements in 8-hour compressive strength, 24-hour compressive strength, stability and shrinkage, DensCRETE cement offered greater ability to optimize slurry rheology and density (below). A yard trial in early 1998 also demonstrated that the DensCRETE blend would not segregate during transport, remained mixable after transport and passed relevant API tests, such as rheology, compressive strength and fluid loss.10

The first DensCRETE operations in Oman were performed during the second quarter of 1996 on the Sarmad-1 well, placing cement plugs at 4100 m [13,451 ft] and 4300 m [14,108 ft] with 21.5-lbm/gal [2576-kg/m³] slurry and a 7-in. liner at 3850 m [12,631 ft] with 19.5-lbm/gal [2337-kg/m³] slurry (above). Because the well encountered a fault and fluid losses occurred just above total depth, PDO decided to set plugs above the fault and then cement the liner using DensCRETE cement for both operations. The plugged interval exceeded 200 m [656 ft] in thickness, so the plug was set in two stages.

To date, seven DensCRETE cement jobs have been performed in the area for PDO, including three liner jobs and four plugs for abandonment of high-pressure wells. The slurry is less sensitive to salt-saturated mud contamination than ordinary cement. As the optimized high-density cement sets, it is less prone to forming a microannulus because it suffers less bulk shrinkage. Even in long liners, no density gradient is observed in the set cement column in the annulus. The column is uniform and stable, even as the cement is setting, so the risk of a blowout is reduced. The top of DensCRETE plugs is closer to the theoretical top than that of conventional plugs because the rheology of optimized high-density slurries allows more efficient removal of drilling fluids.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Conventional slurry</th>
<th>DensCRETE slurry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength at 8 hr</td>
<td>0 kPa</td>
<td>18,616 kPa [2700 psi]</td>
</tr>
<tr>
<td>Initial set 50 psi</td>
<td>After 20 hours</td>
<td>After 4 hours</td>
</tr>
<tr>
<td>Compressive strength at 24 hr</td>
<td>18.275 kPa [2651 psi]</td>
<td>24.132 kPa [3500 psi]</td>
</tr>
<tr>
<td>Stability of set cement (BP settling test)</td>
<td>0.35 kPa/m [0.297 lbm/gal] top to bottom</td>
<td>0.20 kPa/m [0.169 lbm/gal] top to bottom</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>1.5% after 24 hours</td>
<td>0% after 24 hours</td>
</tr>
<tr>
<td>Separation of heavy particles from blend during transport</td>
<td>High risk</td>
<td>Very low risk</td>
</tr>
<tr>
<td>Tolerance to density variations</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>
The WOC time for conventional cements to develop adequate compressive strength under the conditions in the southern Oman fields is at least 28 hours. DensCRETE cement achieves high compressive strength in as few as 15 hours (the worst case to date has been 26 hours) and ultimately develops higher compressive strength than standard high-density cement (right). The decrease in WOC time has proven especially important in drilling exploration wells, and there has been a decreased need to repeat plugs or remediate liner cements. Thus, PDO plans to continue to use DensCRETE cement for high-pressure cementing operations.11

Water-Control Applications

SqueezeCRETE technology has been used in Alberta, Canada, for numerous squeeze jobs. In the Halkirk field northeast of Calgary, an oil well operated by PanCanadian Petroleum Ltd. produced 35 m$^3$ [220 bbl] of oil nearly water-free from the Upper Manville “I” Glauconitic formation upon its initial production in 1995. Within a year, however, water production increased from 1 m$^3$ [6 bbl] per day to more than 20 m$^3$ [126 bbl] per day. By late 1998, the well was completely watered out. From knowledge of reservoir geology and performance, the water influx was attributed to layer breakthrough.

The attractive economics for remedial work prompted action. On the basis of known wellbore integrity, a bridge plug was set above existing perforations at 1266.5 m [4154 ft] and the zone above it was reperforated, but water production continued. After reviewing geological, reservoir and completion data, the water influx was ascribed to poor cement behind the bridge plug. Because of a large drawdown and close water proximity, the Dowell DESC Design and Evaluation Services for Clients engineer was asked to verify that water coning was occurring.

Water-control diagnostic plots, which display raw historical production data versus time on a log-log scale, help identify water sources, such as differentiating bottomwater coning from multilayer channeling (below). Systematic flow model numerical simulations were performed to

Rapid development of compressive strength. High-density optimized slurries develop compressive strength sooner than their conventional counterparts. In this example from the Al Shomou-4 well, the 22-lbm/gal DensCRETE slurry achieved a strength of 5000 psi in only 17 hr.
produce characteristic curves for different types of water production. On the basis of the water-control analysis for the Halkirk well, the diagnosis was a high-permeability layer with water breakthrough (right). This problem was complicated by a microannulus that allowed water flow behind the casing.

Because of low oil prices and the fact that the mature Halkirk field is undergoing waterflooding, workover costs must be minimized to achieve acceptable economic results. Considerable effort is made to mitigate the risk and impact of unsuccessful treatments. Therefore, procedures with a high probability of success are favored. In this well, a conventional cement squeeze was deemed too risky. The SqueezeCRETE treatment was predicted to have a much higher probability of success, so the economics for that treatment were acceptable.

SqueezeCRETE slurry was placed across the perforations from 1263 to 1265.25 m [4144 to 4151 ft] as a balanced plug, and a hesitation squeeze was performed. After 24 hours, the cement was drilled out and successfully pressure- and swab-tested. Following reperforation, the zone is producing 28 m³ [176 bbl] of oil, 3100 m³ [1112 Mcf] of gas and 0.32 m³ [2 bbl] of water per day, reversing the water cut from 99.5% before to only 1.1% after the squeeze operation.

In another well in southern Alberta, PanCanadian wanted to shut off old perforations and complete a deeper interval. Because the slurry feed rate into the old perforations was less than 20 L/min [5.3 gal/min], ordinary slurries would not be effective. After acid was spotted across the perforations to increase the injection rate, only minor improvement occurred. SqueezeCRETE slurry was then batch mixed and 1.2 m³ [8 bbl] placed across the perforations, followed by a hesitation squeeze. After 48 hours, the cement was drilled out and the perforations were successfully pressure tested and swab tested. The lower interval was subsequently perforated and completed. Without a highly injectable remedial system like SqueezeCRETE slurry, the operator might have risked impairing the additional completion by using a casing patch to shut off the abandoned perforations.

SqueezeCRETE cement has the potential to address stringent well plugging requirements as some of the many shallow gas wells in western Canada are abandoned. Its high injectability and low permeability can repair gas leaks better than traditional cementing materials.

Successful water-shutoff jobs have been performed using engineered squeeze cements elsewhere. In one case in the North Sea, oil production increased from 2000 to 4000 bbl per day [317 to 635 m³/d] while water production decreased from 7000 to 1500 bbl per day [1112 to 238 m³/d]. This sharp reduction in water production made gas lift unnecessary after production resumed.

Also in the North Sea, BP Amoco plc successfully abandoned a reservoir section in a well from its Bruce platform using a single optimized cement plug. After remedial completion efforts and other attempts to isolate and abandon the reservoir failed, SqueezeCRETE slurry was pumped through coiled tubing across the perforations and then squeezed. BP Amoco plc was then able to sidetrack an adjacent wellbore to reach the reservoir.

Merely pumping a superior slurry does not always effect the desired repair. Sound completion engineering concepts, proper design and execution are critical ingredients for successful well remediation.

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12. In a hesitation squeeze, a portion of the slurry is pumped, then pumping stops to expose the slurry to differential pressure against the zone of interest in stages over a period from several minutes to several hours. This pressure, higher than necessary for fluid movement, is applied to force filtrate from the cement slurry, leaving only solid material in the area requiring repair. This procedure is repeated until all the slurry has been pumped. The dehydrated cement remaining in the zone forms a seal with a higher compressive strength and lower permeability than the original slurry design.