Cements for Water-, Gas Storage-, Waste Disposal- and Plug-and-Abandonment-Wells

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SUMMARY

Cement types used in these specialist wells are highlighted in the context of actual and likely downhole environments. ISO Classes of well cements, usually with appropriate additives, can be employed for numerous such cementations, provided the wells are not considered to be 'critical' ones. Speciality cements, like ARMC for example, can be utilised for particular cementing jobs. Also, ductile cement compositions may be necessary for successfully cementing some of these specialist wells, particularly in critical areas like high temperature-high pressure reservoir or disposal zones, where long term durability of hardened cement sheaths is increasingly becoming paramount. In these latter instances shrinkage of the hardened cement sheath, microannulus formation and gas migration from the formations need to be avoided.

1. INTRODUCTION

Within the oil and gas industry for the drilling and completion of wells, operations sometimes involve special consideration of the well types for seeking the most appropriate cements for successful well cementing (particularly where wells other than oil- and gas-wells are considered). This paper discusses how well cements can be appropriately utilised for securing a number of less commonly employed, but carefully defined well types, where the particular problems that can occur with the cements employed often need to be more commonly appreciated. The paper focuses upon the well cement or cementing composition that is suitable for use in water wells, gas storage wells, waste disposal wells and plug-and-abandonment wells. These well types are currently receiving increased attention during drilling operations, not least because of greater environmental considerations than before, which mean that long term cement sheath durability is very important. Cement slurry selection must be very carefully evaluated.

This article is not specifically about the details of the well cementing or indeed environmental legislation, because it addresses the scientific aspects of the well cement slurries from the cement perspective. Instead it looks briefly in a broadly scientific context at the well cements themselves and explains in straightforward terminology where they can be useful in successfully cementing these special wells. Such information is designed to assist materials scientists involved with well cements and the supply thereof in understanding the main basic problem areas associated with these special well types.

Water wells, gas storage wells, waste disposal wells and plug-and-abandonment wells are in the future likely to receive increased prominence in drilling and completion operations. At present oil- and gas-wells are much more commonly drilled and completed than these other wells, which still appear in some cases to be given a much lower prominence in drilling and completion activities downhole than the former. It is now beginning to become more increasingly recognised that cementations of these special well types need to be carried out ideally with better quality well cements, which will in the future more commonly include ductile cement compositions and non-Portland cements that may also be ductile. The hardened cement sheaths will of course increasingly require to possess long term durability, ideally for the lifetimes of these particular well types, many of which will be regarded as 'critical wells needing critical cementations'.

For these particular well types:

- There is increased awareness nowadays that in the future more water wells in particular will need to be cemented in arid areas. At present many water wells are shallow and not cemented at all.
- Also, with increased transportation, storage and usage of natural gas, there are greater requirements arising for safe storage of natural gas and for suitable well cementing in order to access this gas from gas storage wells especially drilled for the purpose.
- Waste disposal wells have been drilled and cemented for disposing of unwanted saltwater, waste effluents and other industrial waste by pumping into the formations. In the future such wells are likely to feature prominently in storing waste carbon dioxide in impermeable rock formations.
- Plug-and-abandonment wells are likely to be re-entered in many instances in the future to recover the untapped hydrocarbon residues when the oil price rises to a level that becomes economic for extracting hydrocarbons from.

2. WATER WELLS

Many current water wells are relatively small and based upon accessing water from natural artesian wells for drinking. Such wells are connected to natural and artificial water courses to feed into the water transport system and there is rarely any requirement to cement such wells. However, with increased shortages of drinking water likely to be prevalent in the future, it will be necessary, particularly in arid areas to drill deeper wells. These will increasingly need to be cemented, so that the cement sheath between the borehole walls and the metal casing (pipe) can protect the metal casing from corrosion during the metal lifetime.

Water wells are commonly dismissed as being easy wells to cement. In fact, as mentioned above, many water wells are not cemented at all, as such work has been effectively deemed unnecessary for the provision of drinking water in most places at the present time. This approach of not cementing water wells could be very short-sighted for the longer term situation, because of possible corrosion. Stainless steel for metal casings can be particularly prone to corrosion from sulphides that may be present in the water and from chlorides at the top of the casing where sufficient oxygen may be present (unlike at greater depths) to give normal iron corrosion. Special steels protected against such corrosion are better to employ for well durability in the longer term.

Here the term ‘water wells’ refers specifically to wells used to extract water for drinking purposes. Geothermal wells commonly produce steam or hot water, which is primarily used for conversion into heat energy or into electricity and not normally for drinking water. Geothermal cements are not covered in this paper.

For the cementing of water wells the most commonly used cements to date are ISO Classes A, C, G and H. Silica sand and bentonite clay are sometimes used as fillers to adjust the slurry weight for optimum cementing. Ready-mixed concrete has sometimes been used at shallow depths in the USA in place of normal cementing. Standard cementing practices for oil and gas wells are normally followed here with the more conventional wells, with small volumes of cement slurry normally being needed. Placement time is not usually critical unless industrial or irrigation wells are being drilled and completed. In the latter instances suitable cements and additives should be chosen to thicken and harden within the time constraints required. Casings should be centralised for uniform distribution of the cement slurry within the annular spaces [1].

Chloride corrosion does not normally arise at significant depths below the surface due to the lack of downhole oxygen that would be necessary for chloride corrosion to ensue. However, corrosion can arise from small quantities of sulphides percolating through the rock formations into the water deposits. Thereby, over the passage of time, the steel casings/liners within the wells become corroded by chemical reactions between the sulphides in solution and the metal casing/liner. The ensuing rusting of the metal casing/liner would allow at least some of the water gushing up the casing/liner to be lost into the rock formations and thus be unavailable for drinking purposes. Unless there is likely to be no corrosion from within the well, it is advisable to cement water wells, so as to preserve long term durability.

When the wells are cemented, sometimes, as has happened for example in water extraction from the Sahara Desert, the water can gush out of the formations at temperatures up to nearly 100^{o}C to be propelled up the well and into the pipelines for distribution and appropriate purification prior to consumption. This type of behaviour can take place in water wells where the bottom hole circulating temperatures (BHCTs) are around 40^{o}C or above.

There are sometimes problems of saltwater layers and salt beds in the rocks through or under which the water percolates. As a result good zonal isolation is essential, so as to thwart saltwater from contaminating the essential freshwater required for drinking purposes. Indeed, one of the problems of drilling water wells can be the necessity of drilling through weak rock formations containing salt (sodium chloride) beds. When drilling, there can be a serious problem of undesirable hole enlargement caused by the dissolution of some of the salt into the water used for the drilling muds being circulated. Such hole enlargement can be minimised by reducing the rate of salt dissolution into water as much as possible. This minimisation of hole enlargement can be suitably attained by having partial salt-saturation of the drilling muds, such as those containing magnesium chloride $MgCl_2$, and/or partial salt-saturation of the spacer fluid with *ca.* 18-24% salt (sodium chloride, NaCl).

HSR Class G cement is the most commonly used to cement the annuli of water wells, when these wells are actually cemented. Strength retrogression inhibition by using suitable additions of around 35-40% (by weight of cement) silica sand or silica flour may be needed in the well cementing formulation for preventing both losses in strength and increases in permeability from taking place. Good zonal isolation can be very important with such wells, so ideally it is important to avoid shrinkage, microannulus development and hence annular gas migration for long term well durability, where this is needed.

Therefore appropriate additives should be utilised in the water well cementing formulations where necessary to provide long term durability ideally for the well lifetime. It should be remembered, particularly in extracting water from large underground reservoirs, that appropriate ductile cementing compositions [2] based upon computed mechanical designs for the various well parameters may need to be considered for critical cementations of water wells in the future. This requires a good quality binder (often HSR Class G or H), increasingly contained within a ductile cementing formulation that has been pre-tested for suitability in thickening and hardening downhole.

Thus the drilling and cementing of water wells may turn out in the future to be much more complex operations than is commonly envisaged at present.

3. SOME FURTHER INFORMATION ON WATER WELLS

Smith [1] has discussed water well cementing and various regulatory matters associated with this in the USA. In most areas, the drilling and cementing of water wells must comply with the strictest of regulations. Therefore a freshwater aquifer must be drilled on the basis of the best surface and subsurface information and be completed for the maximum protection and isolation of all freshwater strata.

Most water wells have been completed at depths of less than 1500 ft (455 m) and without undue emphasis on casing equipment and cementing materials. This does not mean that water wells do not require maximum control to protect freshwater zones from contamination and surface pollution [3]

For water well casing programmes in the United States, the American Water Well Association Committee on Specifications has recommended that "*The casing should be new and composed of steel or other ferrous materials and shall be in accordance with the American Water Works Standards A100, ASTM or API*." Normally casing programmes employed by the oil industry for surface or conductor pipe will meet these specifications and satisfy most regulations. However, in planning any casing programme for water wells, the AWWA Standards should be referred to [1,4].

Water wells are normally completed in one of three ways [1]:

- The water zone is cased through and the casing is perforated as it would be in an oilwell.
- The casing is set on top of the water-bearing zone and cemented, then the zone is drilled into and sand- or gravel-packed.
- Casing is set at the top of the water-bearing zones and cemented and then a removable screen or liner is run through the water-bearing zone.

For the cementing materials it was reported [1] that the pumpability, strength and waiting-on-cement (WOC) time of cement are not so critical in water wells as in oil wells. Also, most water wells have been cemented using sack *(bagged)* cement and paying little attention to weight control *(sic)*. Simple Portland cement has been used – ASTM Type I or III cement, or API *(now ISO)* Class A or Class C cement, which have been water slurried to approximately 15 lb m/US gallon (s.g. 1.80). A mixture of equal proportions of sand and cement is not uncommon for utlilising in these slurries. It is often forgotten that water wells may be cemented using the same basic techniques as used with conventional oil- and gas-wells.

Water well abandonment is of course an important environmental issue. For unsealed abandoned wells constitute a hazard to public health and welfare and may not be regulated at all localities. The sealing of these wells presents a number of problems, the character of which depends upon the construction of the well, the geological formations encountered and the hydrological conditions [4]. Sealing an abandoned well properly requires the following:

- Eliminating physical hazard
- Preventing contamination of groundwater
- Conserving yield and hydrostatic head of aquifers
- Preventing intermingling of desirable and undesirable waters.

- The guiding principle in the sealing of abandoned water wells is the restoration as far as possible of the controlling geological conditions that existed before the well was drilled or constructed.
- The removal of pipe from some wells may be necessary to ensure placement of an effective seal. If the casing opposite water-bearing zones cannot be removed easily, it should be pulled or ripped with a casing ripper to ensure the proper sealing of water-bearing zones with the sealing material.
- At least the upper portion of the casing should be removed to prevent surface water from entering the water-bearing strata by flowing down the casing.

With current HSE (health, safety and environmental) requirements, it is important not to extract too much water from the wells and negatively affect the underground reservoirs. Ideally an equilibrium situation is required, so that the underground reservoirs are not completely dried out by over-extraction of water, so that no damage is done to the underground rock formations in which the water has naturally accumulated. The water wells should be shut down before the supplies of water begin to dry out until the reservoirs can refill, so that the supply of drinking water can become a renewable resource again. Increasingly in the future water wells are likely to require ductile cements for durable zonal isolation, which have been carefully checked during pre-testing under simulated downhole conditions for the given well. Careful checking is needed in order to overcome shrinkage cracking, microannulus development and gas migration within the annulus that impede long term well durability.

4. GAS STORAGE WELLS

Natural gas is one of the cleaner sources of energy. The extreme conditions that occur in gas storage and gas producing wells could cause the cement sheath to fail, resulting in fluid migration through the annulus. Designing cement sheaths that can withstand the stresses induced by the various operations and maintain integrity during the life of the well will help to minimise the risk of cement failure. Stresses encountered downhole can be induced by pressure, temperature, or both pressure and temperature. Well cement may be subjected to significant stress levels in gas storage wells [5,6], which are likely to require ductile cement compositions that overcome well events (see later).

Although there is much technical information available on how temperature alone or combined temperature and pressure variations affect thickening time, there is still a paucity of information available about the effects of pressure alone at constant temperature upon the thickening times of the hydrating well cements. This particular problem has been addressed. Experiments undertaken at constant temperature (67^{o}C) were carried out upon neat HSR (high sulphate resistant) Class G cement alone and with 0.2% BWOC sodium calcium lignosulphonate retarder, both cement slurries being at the standard water/cement ratio of 0.44 for HSR Class G well cement [7].

The effects of increasing the pressure at the aforementioned temperature were found to be considerable, but not as great as with temperature alone, and revealed interesting results. The effects of pressure alone were definitely significant in the experiments carried out with Rugby HSR Class G cement at 67^{o}C; the final pressures achieved were raised in stages from 26.7 MPa to 70.5 MPa. The concomitant thickening time decreased from 148 to 98 minutes for the Class G cement alone and from 171 to 111 minutes for the retarded cement under analogous respective conditions [8].

Underground gas storage in common usage is gas transferred from the reservoir of discovery to other areas, usually closer to market areas, where it is stored until needed to meet market demand. Natural gas is stored in underground reservoirs to help ensure the capability of the gas industry to meet seasonal fluctuations in demand. There are more than 400 underground storage sites in 27 states across the USA and Canada. Together these sites can hold 3 trillion cubic feet of natural gas ready to be withdrawn. In Western Europe the expansion of underground gas storage capacity has been an integral component of gas marketing policy in a number of countries. Norway in particular has considerable gas storage capacity. In the future the world gas storage capacity is expected to grow, mainly in parts of Europe.

More capacity for gas storage is coming with increased demand for liquid natural gas (LNG), which is liquefied and compressed under pressure for ease of transport and of storage. For the wells that service these reservoirs, their hardened cement linings need to be robust so as to withstand the effects of rapid temperature change when the gas is required for use. Good quality ductile cement compositions are to be preferred for long term durability here with the cement linings for optimum well lifetime.

The loss of cement integrity in the annulus can cause the following events to take place, potentially increasing operating costs and decreasing company assets [6]:

- Loss of gas reserves
- Unsafe operations
- Premature water or cap gas production
- Extra cost incurred because of unplanned remedial operations
- Well shutdown to comply with government regulations.

Analytical techniques like stress analysis methods [9,10] and finite element procedures [11] have been employed for designing cement slurries to help reduce the probability of cement sheath failure under the particular well conditions and the operating envelope of the well. Calculations of mechanical and physical properties of the wellbore, cement and casing/liner are carried out. Such measurements include Young's modulus (associated with compressive strength), Poisson's ratio (associated with tensile and bending strengths) and other useful mechanical properties. The effects of the wellbore rock(s), cement and casing/liner upon one another are considered, by analysing the problem in discrete sections as the well is constructed and as the hydrocarbons are being produced. These calculations allow evaluation of which candidate formulations are likely to be optimal and which are likely to fail. Success is judged in terms of which formulations actually avert shrinkage and microannulus developments to avoid gas migration and leakage of extraneous materials through the annulus [6].

Interest in cementing gas storage wells is likely to increase considerably in the future as more and more gas is exported from the major gas producers to other parts of the world where it is also needed.

6. WASTE DISPOSAL WELLS

Waste disposal wells to date have mainly been cemented with ISO Class G or H cement except in numerous instances across the disposal zones where a special completion job may be required. Sometimes ISO well cements of zero C_3A (aluminate phase) content or resins are employed rather than the conventional Class G or H cements across and through the disposal zones, where the testing of the material is critical. Uniform coverage of cement sheaths in the annuli are necessary for achieving total zonal isolation. Saltwater or waste effluents are often disposed of in a waste disposal well specially designed for the purpose, or else removed by injection into a permeable underground rock formation in an already depleted oilwell [1].

Before the cementing job is carried out, the materials for disposal must be checked out for alkalinity and acidity which, if significant, should be neutralised with water, so that there are no deleterious effects upon the cement slurries when they are thickening up and hardening in position downhole. Both the casing design and the cementing methods are dependent upon which effluents are being disposed of. Commonly special alloy casing and coiled tubing are required. The casing may be set either through or on top of the disposal zone – centralisation of the casing is critical for distribution of the cement slurry within the annulus [1].

Well depths can often range *ca.* 90-3660 m (300-12000 ft) [1]. Shallow waste disposal wells can be cemented with Class G or H cement in the normal manner. For deep waste disposal wells, which may be critical in terms of well cementing, there is often a need for protection of the hardened cement sheath against strength retrogression. With Portland-based well cements, *ca.* 30-50% (by weight of cement) silica sand or silica flour as strength retrogression inhibitors are likely to be utilised, when the bottom hole static temperatures (BHSTs) exceed 100^{o}C [12]. This allows more impermeable crystalline calcium silicate hydrates like tobermorite, gyrolite and xonotlite to be formed from such high temperature well cement compositions being able to react with water under hydrothermal conditions, which benefits longer term zonal isolation. Ductile cement compositions may also be needed here for the more difficult well cementing jobs, where critical cementations using good quality cements may be required for militating against shrinkage cracking, microannulus formation and gas migration through the annulus.

Like water wells, waste disposal wells are normally governed by statutory requirements, particularly in the disposal zones, and of course increasingly now there are mandatory HSE requirements that apply for such waste disposal. An impetus is now being given to waste disposal for injecting carbon dioxide into impermeable formations where there is no danger of leakage, for environmental reasons, which will increase the number of ‘disposal zones’ significantly. Hardened well cement sheaths for ‘capping’ these wells for giving good long term durability will increasingly be needed for securing the wells that service these designated disposal zones.

7. PLUG-AND-ABANDONMENT WELLS

There are many plug-and-abandonment wells around in oil- and gas-producing regions, which are no longer used, or waiting for the oil price to rise so that such wells become economic to produce from again. Normally plug-and-abandonment wells are plugged with ISO Class G or H cement, but sometimes special cements and cementing compositions are employed. An example of the latter is acid-resistant magnesia cement (ARMC) that has been successfully employed in the field up to at least 120^{o}C. This material is basically composed of a mixture of magnesium and calcium oxides, carbonates and sulphates, which react with water to produce complex polyhydrates that are unaffected by normal cement contaminants [13,14]. Such a cement is very different in its hydration behaviour from what is normally found with standard Portland well cements like those of Class G [15].

The ARMC functions as an *in situ* Sorel cement to a large degree by reacting with seawater and chloride brines. Complex calcium and magnesium carbonate chloride hydrates are formed, which are very stable to downhole water. This cement is used for correcting lost circulation problems, as a diverter, to provide temporary zonal isolation, or as a kick-off plug in weak formations, and can be pumped similarly to conventional well cements. Plug-and-abandonment wells are often sealed with this special type of cement, which is advantageous in having a negligible insoluble residue content, which does not interfere with subsequent completions operations in wells. Various other cement-based products that have proprietary formulations can be utilised in such downhole applications, along with appropriate ductile cement compositions that have been checked out for suitability in more critical well cementing environments.

ARMC would also have its uses in re-entering plug-and-abandonment wells in the early stages for the aforementioned reasons, where extensive workovers would be necessary to restore production.

Well re-entry will be very expensive and is likely to arise when the basic oil price becomes much higher than it is at present. However, there are still substantial amounts of oil and gas in abandoned reservoirs, because greater extraction has not been economic in the past. Up to the late 1980s the majority of wells were vertical wells, which were normally straightforward to cement, mainly with Class G or H cements. However, the oil recovery rates were considered good if 30-35% recovery was possible during the well lifetime. Also drilling wells could be very 'hit-and-miss', which added to the costs. Nowadays with modern developments, like extended reach and horizontal wells, slimhole wells and multilateral wells, oil recovery is much greater, with 60-65% recovery being more commonplace. So, there is still plenty of oil and gas left in many of these old reservoirs, but the costs and logistics of re-entry are generally too high for current economic conditions. Any produced water from such wells is likely to contain residual hydrocarbons, a common phenomenon in mature wells, and would need appropriate cleaning up treatment before being released into the environment.

Some wells still in production are now being 'converted' during special workovers into extended reach and horizontal wells in order to tap the reservoirs more efficiently from the viewpoint of recovery of the hydrocarbons. The cementing of these new deviated sections is more critical than the earlier cementing of the then vertical wells would have been. Thus cementing these 'converted wells' requires good quality well cements, such as those of ISO Classes G and H with zero free water and low fluid loss (below 50 ml/30 minutes ISO) to avoid bleeding or segregation [16].

8. DUCTILE CEMENT COMPOSITIONS

Cements for use in the well types discussed are likely to feature more ductile cement compositions in the future, because of the need to have total zonal isolation of the cement sheaths for the entire well lifetimes. Ductile cement compositions have much improved tensile, flexural and bending strengths compared with those given by conventional Class G or H well cements, can include the following [5]:

- Flexible cements having engineered particle size distributions that contain appropriate solid fillers (e.g. ground rubber tyres, metal fibres, polymer fibres etc.).
- Latex systems, which also impart high ductility and increased workability, and are commonly reinforced with organosilanes and epoxy compounds.
- Foamed cement systems, especially in deepwater situations and where there are unconsolidated or weak zones in the rock formations.

- Expanding systems containing an expanding agent to give slow expansion with time.
- Mud-to-cement conversion downhole involving cement extenders, like ground granulated blastfurnace slag, fly ash or metakaolin, can impart suitable ductility to the hardened slurries.
- Other ductile cementing systems can be based upon storage of retarded cement slurries with activation on demand, or high alumina-phosphate cement compositions etc.

Candidate cement compositions that appear to satisfy the well requirements chemically are also evaluated for their mechanical properties. The mechanical engineering properties of the casing/liner, cement and rock formation(s) are the underlying properties that must be borne in mind and need to be measured. The predicted outcome in terms of whether a given well cementing composition results in a hardened cement that gives rise to no cracking and does not develop microannuli within the annulus has to be predicted in advance of the cementing job being carried out. If the results are satisfactory, then the cementing composition can be used and, if not, it cannot be so used. Reaction kinetics of the cement hydration process should also be reliably evaluated. Free fluid (also known as free water) should be zero. Ductility is the key property of the cementing compositions, so that they can withstand well events like pressure testing, perforation, stimulation, production etc. Such resistance to the well events can prevent cracking and shrinkage, as already explained.

9. CONCLUSIONS

In the future there will be more demand for the drilling of water-, gas recovery- and waste disposal- wells and re-entering many plug-and-abandonment wells. Interestingly, although the cements have been discussed in this paper by starting on the basis of well type, the broad categories of well cement classes and cementing compositions required do have numerous points of commonality. This commonality arises for each type of well considered in terms of the principles of whether (a) normal' Class G, H or other types of well cements plus suitable additives, or (b) special ductile cementing compositions are to be used. Ductile cements and cementing practices have been extensively reviewed [5].

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