

Msc Drilling Engineering

HPHT Cementing Coursework

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References

NPD guidelines.
BJ (Norway cementing services.)
Well Cementing (Eric B Nelson.)
Handout from BJ services (Norway)

1 Summary

High temperature wells present special cement system challenges. The physical and chemical behaviour of well cements changes significantly at elevated pressures and temperatures.

1.) The challenges in high temperature, high pressure cementing are therefore connected to the

- Temperature regimes
- Pressure regimes
- Narrow margin between fracture and pore pressures
- Wellbore geometry. (i.e. often 5 ½" or 7" liners in high pressure zones.)
- Control of flow (gas migration) after cementing
- Chemical behaviour of mud, cement, and its additives

that exist in the well and their individual and combined effects of the mud, cement and the formation characteristics..

2.) The results of failed cement job are:

- Kick & well control problems
- Remedial work
- Time and high costs involved

3.) It is vitally important to evaluate and predict accurately the correct temperatures, pressure and formation regimes in order to best simulate and test the cement slurries before executing the cement operation to be able to achieve best results.

4.) Because both the cement and the cement additives are very sensitive to changes in temperature. Sensitivity tests should always be performed before cementing in a high temperature well. In addition a stability test is recommended.

6.) A uniform cement slurry with the correct density is best obtained by using a batch mixer. However, utilising batch mixing requires close monitoring of the mixing energy to be able to simulate the same conditions in the laboratory. Recommended test procedures for sensitivity , stability of slurries and laboratory simulation of batch mixing is included in the report.

7.) In view of the narrow operating envelope between fracture and pore pressures in HPHT wells. Hydrostatic, dynamic and circulating effects must be accounted for at every stage of the cement operation. *(e.g. 24hrs conditioning a mud in a properly centralised liner, is much cheaper alternative than, large volumes of gas at surface due to cement channelling, gas migration and weeks of remedial treatment.)*
The efficiency of cement displacements at very low pump rates are recommended to be evaluated.

8.) Simulation of cement job before and after can only assist in the learning and development to ensure higher efficiency and effectiveness for all future HPHT cementation and to assist in the development of the models run.

9.) For the future, new cement systems are needed that are less sensitive to temperatures. This may lead to the development of synthetic retarders and alternative cement materials, like plastics or thermal setting resins etc.

Introduction

Definition of HPHT

HPHT wells are defined by the Norwegian Petroleum Directorate, (i.e. NPD) as wells deeper than 4000m TVD and/or those that have an expected shut in wellhead pressure greater than or equal to 690bar (10,000psi). Or that have temperatures in excess of 150 degrees C.

NPD rules and regulations

NPD rules and regulations suggest additional modelling to be undertaken in order to determine the exact circulation temperature.

Special considerations for cementing of HPHT wells are;

- Cementing of a liner in deep HPHT wells should be carried out so as to achieve a good mixing of additives and achieve uniform rheological properties of the cement mix. This can be achieved by using separate mixing tanks or corresponding methods.
- Consider using two cement systems with different setting times.
- Optimise cement properties with regards to
- Fluid loss, hydration, rheology, setting times, temperature,
- Short term & long term strength, gas density, free water.
- In particular the risk of migration should be given particular attention.
- Displacement of drilling mud with cement requires consideration to be attended to the following
- Optimum stand-off (centralisation) between well diameter and the casing
- Improved procedures for pumping of drilling mud prior to cementing (mud gel removal !)
- Use of compatible fluids, spacers and cement slurries and that they are properly tested
- Optimisation displacement velocities, the use of centralisers
- Rotation and reciprocation of casing & liners.
- Preparation of procedures / technologies for squeeze cementing of loss zones shall be emphasised.

Note: It is the general opinion of the NPD that primary cementing of casing is not carried out in a technologically satisfactory manner. Improved mixing procedures and process control should be developed in order that an adequate quality control of the mixing process can be implemented.

Guidelines into practise

Most of the factors stated by NPD in their goal setting standards are involved in the planning of most any cement job. HPHT cementing should therefore not be any more complicated than cementing a normal well, if all planning, testing, data collection, operational and execution aspects are duly considered and accounted for.

The problems exist because of the smaller margins of error that exist between the pore and fracture pressures. In a high pressure, high temperature regime therefore the consequences of not maintaining a proper and controlled process are much more serious for the operating company. *I.e. Expensive remedial treatments.*

2 Sensitivity of Cement Slurries

2.1 Temperature Sensitivity

Small changes in testing temperature can make substantial changes to the slurry properties, thickening time in particular. *E.g. Increased temperature escalates the hydration of the cement, and therefore decreases the thickening time.* Other factors such as rheology, fluid loss, stability and compressive strength also vary greatly with temperature.

It is important therefore to obtain the most accurate temperature data from the well. This data will normally be in the form of maximum logged temperature at a maximum log depth. Details of the circulation and static periods should be provided with the temperature data so that analyses can be performed to estimate the BHST from which the BHCT will be derived.

BHST prediction.

Is the natural temperature of the formation under static conditions. It is most commonly estimated from wire-line logs. It is however vital to know how it is measured.

If the well has been static for 36hrs or more, the temperature is considered static.

The temperature can also be logged at different time intervals after different circulation times and by extrapolation techniques calculated back to static BHST.

BHCT prediction

The BHCT is a qualified guess of temperature or can be determined approximately by API tables. The API tables are based solely on well depth and temperature gradient. However, the evolution of BHCT is also influenced by flow rate, formation properties, circulating time, inlet temperature, fluid rheology and well inclination.

Experience show that the HPHT wells are cooled down very rapidly with circulation, and much more compared to conventional wells. *i.e. the difference between BHST and BHCT is big i.e. up to 30 degrees C.* In general the design temperature has been estimated too high. With new improved API methods for deep wells, the maximum overestimation has been reduced to approx. 20 degrees C.

Underestimating may lead to flash cement and costly remedial work. Overestimating the temperature and testing of a cement slurry at a too high circulating temperature may be detrimental to the result of the cement job. *E.g. Over-retarded, too low compressive strength, poor rheology resulting in soft casing shoes, poor zonal isolation, and costly remedial job.*

Therefore in HPHT wells where the BHCT may be above the API BHCT. The engineer should use all available information, temperature simulation software and add a safety factor, to evaluate the temperatures.

Several new circulating temperature simulators are now available on the market. If modelled correctly, over estimation of BHCT can be further reduced to provide the following benefits.

- Minimised waiting on cement
- Increased job safety
- Allows design to follow well conditions
- Optimises circulating times and rates
- Eliminates risk of premature setting
- Aids in retarder selection

2.2 Retarder sensitivity.

“Small difference in retarder amounts can result in dramatic changes in thickening

Cement slurry properties are very thus sensitive to small changes in retarder concentration at high temperatures. The uncertainty in temperature prediction further influences the sensitivity of designs. Most importantly thickening time and compressive strength development can be significantly affected.

Sensitivity checks must therefore be carried out on the cement slurry to determine whether the proposed cement slurry is acceptable. The selection of correct retarder is very important to avoid over-retardation.

The best recommendation is to run thickening time and compressive strength tests both at TD and at TOC (in case of very high TOC) with the actual temperature, pressure and heat-up and cool-down times. Some cementing service companies have software that can generate these data.

Attachment 1 is Saga recommended sensitivity test. Attachment 2 is an example for a recommended procedure submitted by BP.

2.3 Cement Sensitivity

Batch control and the properties of the cement itself is very dependent on quality of slurry achieved. The cement can vary over time, in storage, transportation, with humidity etc. It is important therefore, that in laboratory tests, the same cement as being used offshore is tested.

All cements respond differently with additives. At high temperature these differences become more pronounced and some cements are better than others. It is also not uncommon for one batch or mill-run of a manufactures cement to behave quite differently from a separate batch or mill-run of the same manufacture.

A poor cement for use at high temperature may be characterised by one or more of the following

- Failure to obtain sufficient thickening time with common high temperature retarders
- Significant viscosity increases or “humps” in the consistency well before the end of the pumping time.
- Extreme sensitivity of common retarders such that the sensitivity checks cannot be achieved.

If these problems cannot be overcome with cementing additives, then an alternative batch, mill-run or manufacture of cement should be sought. Because of variations from one batch to another, the quantity of cement destined for the HPHT job must be identified and isolated.

2.4 Weight material

High density cement slurries up to 2.3sg are often required. Density can be increased to 2.05sg by reducing the amount of water by the use of dispersants but this is not a good option as the availability of water is important to the hydration process of the cement. The next step is then to go to weighted material, most commonly Haematite. This must be dry mixed with cement onshore prior to it being sent offshore. This creates problems as in the process of transporting and storing, the Haematite will partly settle out of the dry blend resulting in an inconsistent slurry during mixing.

Another drawback with mixed blends is that they are inflexible to last minute changes. *I.e. If density requirements change.*

Problems are however solved with newer products on the *market* (*e.g, A very fine Manganese Oxide*) that could be premixed with water, having no problems of segregation in the dry blend. Slurries could be re-designed until the last minutes with exact samples. (Ref. SPE 25976.)

To be acceptable as a weighting agent the following criteria must be met.

- Particle size distribution of material must be compatible with cement. *(larger particles will settle out of the slurry, smaller particles tend to increase slurry viscosity.)*
- Water requirement must be low.
- Material must be inert with respect to cement hydration, and compatible with other cement additives.

2.5 Composition of Slurry

Some slurry designs sometimes tend to be very complicated with up to 8 or 9 additives, both liquid and dry. This is of course undesired because there will be an uncertainty in the amounts added for each, which in turn adds up and may affect the properties significantly. A practical solution to better control the amounts added is to premix the additives with very accurate proportioning. If the premix is prepared in the mud tanks there is always a danger for contamination. Be aware that mix-water that is prepared a long time before the cement job (e.g. 6 hours) can experience ageing effects. A slurry mixed with an aged mix-water can have different properties from those designed. It is recommended either to mix the mix-water just before it is required for the cement job or to check the ageing sensitivity of the mix-water in the laboratory.

The high temperature and high cement density does not necessitate highly complicated slurries. The minimum required additives are as follows

- Cement (most likely API class G or H)
- Silica (sand or flour)
- Weighting agent (Hematite or Manganese Oxide)
- High temperate Fluid loss additive
- De-foamer
- Water

Possible additional additives are

- anti-settling additives
- and/or temperature stabilisers.

Weighting agents should not be required for cement slurries that are less than 2.05 SG.

If silica sand is used it should be added separately to the batch mixer and not pre-blended since it can settle out of the bulk cement. However. silica flour may be pre-blended with cement without problems.

In wells with temperature above 110 degrees Centigrade, Silica addition should be considered for the whole casing length, also at shallow depth. If the cement column is exposed to the well temperature and the integrity of the cement must be kept intact. **Note:** Silica prevents strength retrogression from occurring.

A very fine Manganese Oxide has successfully been used as weighting agent both in cement slurries and cement spacers. The fine Manganese Oxide can be slurrified, and therefore the slurry density can easily be adjusted after the cement blend has arrived on the rig. The fine Manganese Oxide improves the stability of the cement slurry and spacer.

2.6 Batch Mixing

The mixing of the cement slurry can be improved by using a batch mixer, premixed water, large averaging tanks when mixing direct, better density control etc. Mixing eqpt also varies from rig to rig and must be evaluated before executing a HPHT cement job.

Furthermore, experience has shown that retardation of HPHT slurries may be significantly influenced by the mixing energy put into the slurry while mixing. If the slurry is planned to be batch mixed, then this should be simulated in the laboratory to reveal impact on thickening time and other properties on the cement slurry.

The cement slurry should be batch mixed to guarantee correct cement density is pumped downhole. Normal API mixing and thickening time testing procedures do not simulate the time that the slurry spends on surface while being mixed in the batch mixer. Time spent in a batch mixer can reduce the downhole thickening time and can result in viscosity increases that may render the cement non-mixable in the field. These effects may not be seen if the slurry is simply mixed and tested for thickening time using just the API procedure. To simulate batch mixing, the following mixing and thickening time test is recommended

Mix additives into a Waring blender in the order to be added in the field
Add all the cement/silica/weighting agent at 4000 rpm as fast as possible but preventing dry cement building up at the top of the blender
Shear at 12000 rpm, or the maximum attainable speed if less than this, for 35 sec
Pour the slurry into consistometer cup and stir on consistometer without applying pressure or temperature for 90 minutes. Observe consistency
Apply pressure and temperature and proceed with the thickening time tester retarder

Any undesirable viscosity increases should be seen during the 90 minutes ambient stirring. The downhole thickening time is the time from application of temperature and pressure to the 70 Bc point.

2.7 Rheology and Stability

Normally, the rheology measurements are not performed at actual conditions for HPHT slurries, but at 90 degrees Centigrade and atmospheric pressure. However, the cement slurries undergo a thinning effect with increasing temperature and the slurry should be checked with some kind of a settling tester at actual bottom hole conditions to verify the stability.

Fluid loss control.

Some fluid in the cement slurry will always be lost to the formation as long as the hydrostatic head of the fluid exceeds that of the formation pressure. Fluid loss can be slowed by the use of fluid loss additives.

Any volume change within the cement will increase the chance of a pore pressure reduction in the cement. This may lead to gas intrusion from the formation.

If the cement has a poor fluid loss the chance of bridging off across a permeable zone increases. A bridge will prevent full hydrostatic pressure from being exerted on the formation, can lead to gas intrusion. (See also anti gas migration.)

2.8 Density

Density variance of the slurry mixed and pumped down hole is very critical in HPHT wells. Very often the density is the same as the mud weight and is therefore important for keeping well control. Slurry pumped downhole should be monitored and recorded continuously. Spot checks with pressurised mud balance should be taken at certain intervals. Density variations will also affect the retardation of the slurry.

2.9 H₂S & CO₂ corrosion resistance.

The cements used for HPHT wells must be high sulphate resistant, due to the chance of H₂S. The requirement for good isolation of the casing from possible sour environments are especially important in these wells.

3 Hydraulics

3.1 Wellbore Pressures/ECD

Hydrostatic pressure of the mud column is often very close to the minimum wellbore fracture pressure. This situation creates problems of lost circulation while drilling, running the casing/liner and cementing.

Also the tubulars required are thick walled and combined with usually long and deep well sections, This adds up to give high friction pressure losses and danger for lost circulation. Unless the lost circulation is controlled at all times it will reduce the hydrostatic head of the mud and induce a kick. The risk of losses during the cementing stage can be minimised by performing ECD calculations to determine displacement rates which keep the ECD below the fracture pressure. These calculations often show that low displacement rates are required. (in the region of 3 BPM or .5 m³/min.) In the planning phase. the cementing simulators should be used to determine the different actions to be taken to get the cement top at desired level

Actions normally considered are.

- mud density and rheology
- spacer density and rheology
- cement density and rheology
- run casing as liner for later tie-back
- limited cement top on liners where either a liner lap squeeze or a liner top packer is planned

The pressure to break circulation should be calculated. The risk of losses while running the casing or liner can be reduced by lowering the mud gels and rheology prior to pulling the drillstring. This reduces swab and surge pressures while running the casing or liner and also reduces the ECD during cementing. Swab-surge models should be run to determine safe running speeds and recommended mud properties. Continuous circulation (no breaks related to changing hoses and pumps etc.) should be planned to prevent gelation of mud.

A step wise circulation test up to planned circulation rate should be performed. The pressure should be plotted versus time/rate/mud properties while circulating and conditioning the mud before cementing.

Continue the circulation until no significant gain in lower pump pressure is observed on the plot. The pressure drop across rigid centralisers should be considered. Watch for any leak-off indications.

The hydrostatic pressure from the mud column is often very close to the formation pore pressure. This necessitates careful control of the spacer and cement density during the cement job. Both spacer and cement must be mixed to the correct density using a pressurised mud balance. A standard un-pressurised balance should not be used. The spacer must be continuously monitored while being agitated before pumping as barite settling can occur if the spacer does not have the appropriate viscosity. The cement should be displaced with the highest possible rate.

3.2 Displacement Issues

The low density difference between mud spacer and cement and the low displacement rates that are required to prevent losses will reduce the displacement efficiency significantly. Displacement efficiency can be optimised by taking the following steps:

Ensure that stand-off is the best possible. This is likely to be the only variable that can be used to maximum advantage under these conditions. In vertical hole, one centraliser per alternate joint is recommended from the shoe joint and across the sections where zonal isolation is required

Maximise the (small) density difference between mud, spacer and cement

At high densities, cements and spacers cannot be designed to be pumped in turbulent flow at low displacement rates without being unstable and settling out of solids. **The displacement will have to be a laminar flow displacement.**

Design the spacer and cement rheology such that the apparent viscosity, at the annular shear rate, are in the order $\text{mud} < \text{spacer} < \text{cement}$ with the difference between successive fluids being at least 20%

Ensure that the hole is properly cleaned of cuttings then reduce mud gels to the lowest acceptable value prior to pulling the drillstring for the final time before running casing/liner.

Circulate mud for at least 4 times the open hole annular volume prior to starting the cement operation. Check that 4 open hole annular volumes is sufficient to cool the hole to the BHCT used by the laboratory to design the slurry formulation. If possible, rotate the liner while circulating

Once the liner has been landed. try to **maintain circulation continuously until the cement has been displaced.** Minimise the length of any shut-down.

Displacement simulation

For all the factors discussed above and the realisation of the complexities that exist. It is not difficult to conclude the insurance and important to what a properly modelled simulation can provide and value it can add to displacement techniques and practices to be executed.

Simulation can be used to tailor fluid rheologies, mixing and displacement rates etc. so that the best parameters are used without exceeding the fracture pressures of the formations exposed.

4 Techniques and Equipment

4.1 *Mixing the Slurry*

It is very important to have available modern re-circulation mixer for HPHT cement mixing because the cement slurries are very sensitive to retarder response. For the same reason it is also recommended to premix the mix-water for better control. The batch mixer should be used for all liners and small volume jobs. The slurry design should take into consideration the batch mixing period. The shear and the mixing period for small volumes should be evaluated.

In cases where the slurry density is critical for well control it is recommended to batch mix the slurry and check the weight before pumping it down hole.

Monitoring equipment for rate, density and volume must be available. The parameters shall be displayed in real time and be recorded on chart or magnetic disc. Slurry density checks shall also be made manually with pressurised mud balance and recorded at the time the sample was taken.

For solid chemicals, a weighing scale should be used to weigh small quantities of retarders (less than 25 kg) and part quantities of sacked retarders. A calibrated bucket (10 - 20 l with 1 litre divisions) should be used to measure small quantities of retarders or part quantities of drums of retarders. To reduce the dusting problem from the weighting agents, these materials should preferably be provided in large containers or 1 MT big bags.

4.2 *Liner Overlap Packer*

Because of the unfavourable displacement conditions, it is recommended that a liner overlap packer is run to seal the top of the liner. This can be run integrated with the hanger or as a separate run after cementing and cleaning out the top of the liner. Weight-set packers are used.

When using integrated packers, circulate above liner until the cement is set as if the packer was not in place, in case of packer failure. If the packer leaks, consider to run another packer.

4.3 Gas Migration

An important development in HPHT wells was the control of flow after cementing. Without proper slurry design, natural gas can invade and flow through the cement matrix during the waiting on cement (WOC) time. This gas must be prevented from invading the cement. Failure to prevent gas migration can cause problems such as high annular pressure at surface, poor zonal isolation and loss of productivity. All are costly to correct.

As one of the primary objectives of cementing is to prevent fluid migration in the annulus and achieve zonal isolation. To achieve such objectives effort must then be taken to obtain a good cement job. This may require utilising a gas tight cement slurry.

During the settling phase of the cement, the cement builds up gel strength that will prevent the full hydrostatic head of the fluid column above. The mechanism that allows gas to invade the cement matrix is this gel strength development of the slurry as it changes from a liquid to a solid. The hydrostatic head of the cement column may thus be reduced down to that of the mix water. This may be too low to control the formation pore pressures and fluid or gas may enter into the cement, creating channels or contaminate the cement. Several additives and methods can be used to prevent gas migration.

e.g. A right angle set cement slurry is important in this respect. As a right angle set cement will have a short transient period from the gel strength build up until the cement is set

Proper mud displacement and conditioning prior to cementing. (this should not be rushed.)

Centralisation of the casing affording maximum stand-off, and pipe reciprocation or rotation, will assist in enhanced cementing efficiency.

Reducing the matrix permeability of the cement system during the critical liquid to solid transition time. (e.g. Latex additives and the other benefits that lattices provide. Impart lubricity and excellent rheological properties.)

Gas migration may thus occur in HPHT wells in the same way as in wells of more moderate depth and temperature. One of the main objective for the cementing is to prevent fluid migration in the annulus and achieve zonal isolation. To achieve such objectives effort should be taken to obtain a good cement job. This may require utilising a gas tight cement slurry.

Finally right angle set cement slurries (RAS), can be defined as well dispersed systems that show no progressively gel tendency yet set very rapidly because of rapid hydration kinetics. Such systems maintain a full hydrostatic load on the gas zone up to the commencement of set, and develop a very low permeability matrix with sufficient speed to prevent gas intrusion.

4.4 Cement design

The following steps are recommended when designing for cementing across a high pressure high temperature hydrocarbon zone are as follows.

- Concentrate on obtaining good displacement and conditioning of mud.
- Hole in excellent shape before cementing
- No gas in mud
- Mud in excellent condition, low gels
- Greater than 67% stand off (centralisation)
- Rotate / reciprocate casing, prior to and during cementation
- Minimal U tubing during job. (compatible fluids, use of appropriate spacer washers.)
- Engineered displacement regime (mud gel removal, best suited flow regime, no channelling)
- 10 minute spacer contact time as selected flow regime.
- Two or more bottom plugs.

Design the cement slurry with reasonable fluid loss control (< 150 ml/30 mm API) and minimum settlement (5 mm max settling according to fex. BP settlement test for a vertical hole)

Ensure densities of spacer and cement are as designed before pumping. Use a pressurised mud balance to verify this

The conditions in a HPHT well may be more susceptible for gas migration compared to conventional wells because of higher pore pressure and less margins between hydrostatic pressure of the cement and the pore pressure.

Also the need for silica and weight materials adds to complicate the situation.

The established practice to prevent gas migration in HPHT wells has been similar to conventional wells which is characterised by

Immobilisation of pore water in the cement by addition of micro silica or latex
0 % free water, < 50 ml fluid loss, right angle set

4.5. Supplementary notes.

In 1992 Statoil sponsored building of a special test rig for simulation and testing of gas migration at temperatures up to 250 °C. A series of 8 tests were conducted. All major service companies participated with their ~ own slurry proposals.

The conclusion were that both micro silica and latex are capable of preventing gas migration at high temperatures, provided that the design parameters are met.

However, one of the tests showed the importance of having a stable slurry with zero free water to be capable of preventing gas migration. The unstable slurries let gas through instantly.

The recommendation for preventing gas migration is to use established technique with addition of a settling test, like the BP settling tube test.

5 Future work

5.1 Further studies/research

The items listed below are recommendations on where further research work should be performed by the industry to improve the success and safety of HPHT cementing:

A cementing system (i.e. combination of cement plus chemicals) that is insensitive to the likely differences between actual and designed temperatures and also to the likely retarder concentration inaccuracy when mixing in the field. The rheology and stability behaviour at elevated temperatures should be investigated further.

- Development of alternative cement materials like plastics, thermal setting resins etc.
- Development of synthetic retarder
- More reliable integral liner packers for use in HPHT wells
- Displacement studies concentrating on the *constraints (low flow rate and density differential)* of typical HPHT liner cement jobs.
- Displacement studies of heavy fluids in narrow annuli at limited pump rates

Attachments

Attachment 1

Saga recommendation for retarder sensitivity testing.

"The laboratory testing procedures can be modified to compensate for the sensitive retarder response. First the necessary retarder concentration for the desired thickening time shall be determined using the API test schedules.

In case of very sensitive response the following test procedure should be considered:

Add an additional amount of retarder and start the test using the previous test schedule. When the required thickening time is reached, the test temperature shall be increased gradually towards static temperature until set. Use this slurry if satisfactory compressive strength at the liner lap is obtained."

Attachment 2

BP example of testing retarder sensitivity.

"The sensitivity check recommended is as follows:

*Verify what % accuracy of retarder addition can be obtained on the cement job. For this example the accuracy is called +X%.

*Test 1 : Design slurry to give required thickening time equal to : surface mixing time + placement time + time to pull running tool clear of the liner top + 2 hours safety.

*Test 2 : Test thickening time using above retarder concentration minus X%.

*Test 3 : Test strength development at liner top using retarder concentration plus X%.

-Test 2 : thickening time should be sufficient to pull liner running tool clear + 30 minutes safety.

-Test 3 : strength should still be satisfactory (>1500psi) to allow operations to continue without having to wait on cement.

If the results from test 2 or 3 are not acceptable then one or more of the following should be considered:

*Increase the retarder concentration to make test 2 acceptable (test 3 should then be repeated with the higher retarder concentration.)

*If the strength development from test 3 is unacceptable, consider repeating the test but applying the real downhole pressure from the mud at that depth (this assumes initial test was done at API test pressure of 3000 psi.) This is more realistic of the conditions to be expected and will show an improved rate of strength development.

*Improve accuracy of addition of retarder at the rig site to reduce the retarder quantity "X".

*Consider a different retarder or cement."