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INVESTIGATION OF THE MECHANICAL PROPERTIES OF CLASS G CEMENT AND THEIR EFFECT ON WELL INTEGRITY

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ABSTRACT

The new quest for unconventional resources is the achievement of well integrity which is highlighted by the inadequacy of conventional cementing procedures to provide zonal isolation. High temperatures and pressures or even post-cementing stresses imposed on the cement sheath as a result of casing pressure testing and formation integrity tests set in motion events which could compromise the long term integrity of the cement sheath due to fatigue.

Knowledge of the mechanism of fatigue in cement and factors that affect it such as the magnitude of the load, strength and composition of the cement, mechanical properties of the cement and pattern of load cycles are important to achieve a realistic design of a cement system that will be subjected to fatigue loading. Such a design will go a long way to ensure the long term integrity of a well operating under downhole conditions. Finite element investigations help engineers to assess the stress magnitude and evolution for a given well configuration, but when structural calculations for casing-cement system are required, missing input parameters reduce the quality of the results.

In order to have reliable data we performed an extensive experimental work using Class G cement in order to measure the principal parameters for mechanical structural calculations: compressive and tensile strength, Young's modulus, and Poison Ratio. The data was measured under room conditions as well as at elevated temperatures and pressures. The results were also extrapolated for a time period for more than 300 days. This paper will provide an excellent data inventory for Class G Cement that can be used when mechanical studies on cement, like finite element studies, are required.

Keywords: well integrity, mechanical properties, Class G cement.

1. Introduction

Providing zonal isolation for the life of a well to allow the safe and economic production of oil and gas is the main purpose of the annular cement. To maintain the integrity of an oil well and to produce it effectively and economically, it is pertinent that a complete zonal isolation is achieved during the life of the well. This complete zonal isolation, however, can be compromised due to factors that come into play during the operative life of the completed well. Such factors may come in the form of thermal or pressure loads generally regarded as HTHP (High Temperature-High Pressure) loads which can manifest themselves as static/cyclic loads or both depending on how it is exerted.

Oilwell cement is subjected to failure mainly by the process of:

- Debonding
- Radial Cracking
- Cement Plastic Deformation

These are not new failure modes but just a petroleum engineer's term for the usual failure modes in mechanics of materials. Debonding can also be regarded as shear failure and can exist in two forms; debonding from casing and debonding from formation. It is important to note that debonding can also occur as a result of cement shrinkage and in this case cannot be regarded as a failure due to shear. Radial cracking is a failure mode by fracture which is the result of the gradual growth of cracks when the cement is subjected to fatigue loading. Usually, the surface exhibits no sign of deformation and will finally fail under a gradually increasing load perpendicular to the loading axis in tension and inclined to the loading axis in compression. Plastic deformation is the result of yielding failure. It usually results in the change of shape of the material involved.

Cook and Young (1999) discussed different classical theories of failure for brittle materials like the maximum normal stress and Mohr-Coulomb's criteria which may partly define some of the failure modes described above. These failure criteria are used to predict if a given material, in this case cement, will fail under a given stress condition. Concrete under triaxial stresses fail in a unique manner and the Mohr-Coulomb's criterion can be used to approximately predict failure when concrete is under compressive and tensile stresses. Neither this criterion nor the

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International Journal of Engineering and Applied Sciences

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maximum normal stress criterion will suffice in the case of triaxial compressive state.

The research methods on well cements can be divided into two categories, lab test and finite element methods. For the field of lab test, Goodwin built a test model for the test as it was taken to cement sheath failure. This model simulates the field condition. In 2006, D. Stiles build another model for testing the long term HPHT condition on the properties of cements. For geothermal well studies, A.J. Philippacopoulos and M.L. Berndt experimented on the mechanical properties of geothermal well cements. Many other researchers have also investigated on the cement failure. For FEM analysis, FEM models are easy to carry out. It doesn't require any special test equipment. What is important is the input data and choosing the right FEM model. The best way to study the HPHT well cement failure is combining the lab test and FEM methods. Using the lab data to improve and verify the FEM model. Problems associated with conventional cement in petroleum industry are shear failures and debonding between the cement and casing.

In 2010, Teodoriu, Ugwu and Schubert came up with a new analytical model capable to determine the cement-casing-rock interaction. It has been also shown that the results are strongly influenced by the quality of cement properties, because steel and rock properties are well documented in the literature.

Analytical methods as well as numerical methods require precise input data in order to lead to good results. Therefore it is more than important to generate accurate properties for well cements, if possible under in situ conditions. In this paper we present our efforts to characterize Class G Cement, hence to measure the principal parameters for mechanical structural calculations: compressive and tensile strength, Young's modulus, Poison Ratio.

2. Fatigue – General description and application to wellbore cements

The idea behind the principle of fatigue is that cyclic loading on any material causes a special form of damage called fatigue. This damage accumulates over the course of several cycles and can lead to failure. A load on a sample does not necessarily cause damage if it is rather low, but intermediate loads can cause accumulating damage. Over time this can lead to the formation of fissures starting at molecular dimensions. The fissure may widen up to cracks and result in a total material failure. For cement and concrete there are only few studies on the fatigue behavior, but a lot of research has been performed on the fatigue of metals. According to Ugwu (2008) the fatigue process passes the following stages: *"Crack initiation which occurs as a result of cumulative damage in a localized region under successive cycles of loading; Crack accumulation resulting in crack growth as a result of continued loading; Crack propagation where the specimen fractures and fails."*

One model for fatigue description for metals is the Stress/Number of Cycles (S/N) curve, where the stress amplitude is plotted over a number of cycles. There are three regions in the plot: K, S and Z. One example how this curve looks like is shown in Figure 1. The K-region represents the behavior for a small number of cycles (10^0-10^3); for this case, there is a limit in the amplitude where a sample is going to fail. In the region Z the integrity of a sample depends on the number of cycles. For specific amplitude, the system is stable, as long as the point of stress amplitude and repetitions remains below the curve. With increasing number of cycles the amplitude the range for this region is between 10^3 to 10^8 or 10^9cycles. Region D shows the long-life fatigue strength of the specimen. If a body was able to withstand at least 10^8 or 10^9 cycles it is estimated to withstand significantly more cycles and be stable for long terms under these conditions.

Fatigue analysis with S/N-curves is purely empirical; it represents the results from a series of experiments. It has been found to be very complicated to apply this method to new materials (alloys, non-metallic materials) in order to make predictions without a new series of experimental testing.

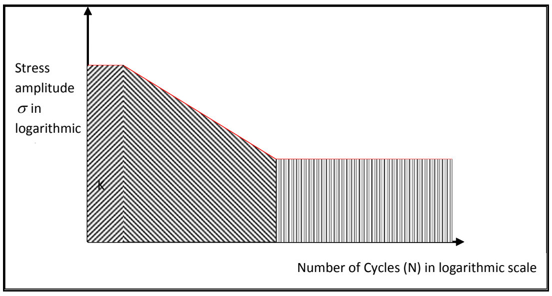

Figure 1: Standardized S/N-curve after Hoffmann (2007)

Based on the fact that concrete is one of the most common building materials of the 20th and 21st century and this even for buildings under cyclic loadings, there are some investigations on the fatigue behavior of this nutrient. The results of these investigations by Ugwu (2008), Hoffmann (2007) and Munz (1971) reveal that increasing strength decreases the resistance to fatigue, because a more ductile material is able to withstand cyclic forces in a better way. Furthermore, it was found that the water/cement factor influences concrete's behavior concerning fatigue, as a lower

International Journal of Engineering and Applied Sciences

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value for this variable causes higher shrinkage of the material during hydration. If shrinkage is higher, the capillary pore system builds up intensively and shrinkage stresses weaken the molecular compound formed during the hydration. An additional result of the research is that the damage in concrete mainly depends on the evolution of fatigue strain and not only on the number of cycles. Another factor influencing the fatigue behavior is given by the solid particle properties in the concrete. They will cause difference in the behavior because the used material is not uniform. Gravel or sand, which is typically used as the solid additive for concrete, has different compositions for various sandpits. By using sieves and monitoring of the materials and their fractions it is possible to norm this resource, but there will always be heterogeneity. This is a difference compared to metal and also to Portland cement-water mixtures, which appear as homogenous bodies. It has been found that concrete could be to a certain extend described with S/N-curves, but the limits of this application could not be identified clearly.

3. Effect of HPHT condition on Cement properties

A.J. Philippacopoulos and M.L. Berndt did experiment on the mechanical property of geothermal well cements. Plain and fiber reinforced cements were tested for mechanical properties. The plain cements have been subjected to uniaxial and triaxial compression, tensile, flexural and thermal property tests. Standard Class G Cement/40% silica flour mix (40SF), a latex-modified mix (40SFL), and a perlite-modified mix (40SFP) are presented.

Selected plain cement formulations were tested in uniaxial and triaxial compression at elevated temperature (200^0C, 392^0F). Ambient temperature tests under uniaxial conditions were also conducted for comparison. The specimens have a diameter of 38mm and length of 76 mm. for the elevated temperature tests it was necessary to use a low confining pressure of 100 psi.

Static elastic modulus and Poisson's ration in compression were determined under the same conditions. Triaxial compression tests were conducted on the standard and latex-modified cements with pore pressure of 300 psi and confining pressures of 1000, 2000 and 3000 psi.

Two specimens per confining pressure were tested for each mix. All specimens subjected to elevated temperature tests were vacuum saturated with NaCl solution to simulate geothermal brine. Test results were shown in Fig.2, Fig.3 and Fig.4.

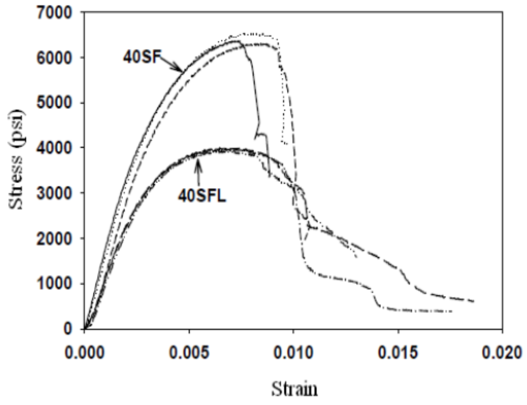

Figure 2. Uniaxial compression stress-strain curve at ambient temperature (Philippacopoulos and Berndt, 2001)

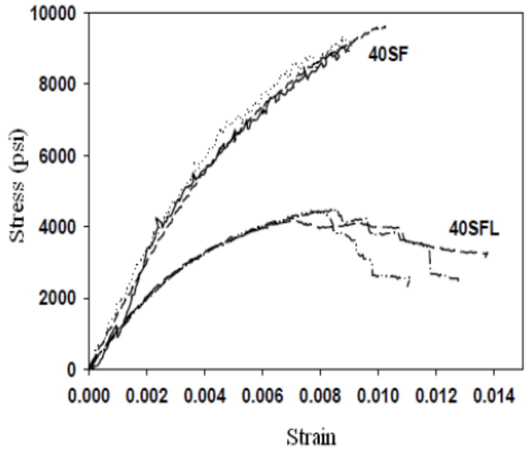

Figure 3. Uniaxial compression stress-strain curve at elevated temperature, (Philippacopoulos and Berndt, 2001)

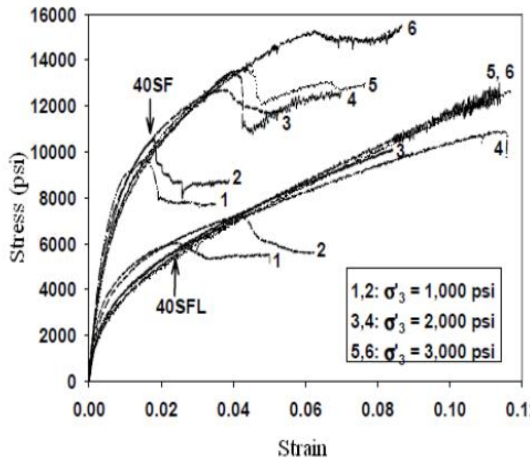

Figure 4. Triaxial compression stress-strain curve at elevated temperature, (Philippacopoulos and Berndt, 2001)

International Journal of Engineering and Applied Sciences

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Ugwu (2008) pointed out how important are the cement mechanical parameters when stress-strain calculations are performed on wellbore cements. Figure 5 shows a comparison of three cement systems with different Poisson's and Young's modulus values. The three cement formulations are as follows:

- Cement System 1 - Ductile cement system with compressive strength of 3000 psi, tensile strength of 1000 psi, a young's modulus of 0.69 x 106 psi and a Poisson ratio of 0.4.
- Cement System 2 - Brittle cement system with compressive strength of 9500 psi, tensile strength of 3000 psi, a young's modulus of 2.4 x 106 psi and a Poisson ratio of 0.1.
- Cement System 3- A low young's modulus and a low Poisson ratio cement system with compressive strength of 2500 psi, tensile strength of 1000 psi a young's modulus of 1 x 106 psi and a Poisson ratio of 0.25.

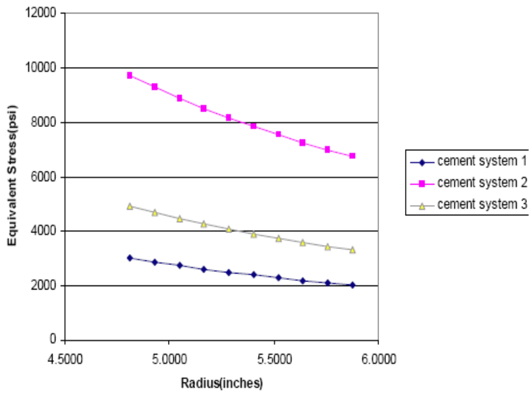

Figure 5. Equivalent stress in three cement systems, (Ugwu, 2008)

Based on the findings of the previous published work we decided to start an intensive experimental campaign to measure the Class G Cement's mechanical properties that can be later used to analyze and predict the HPHT behavior.

4. Experimental results

Class G cement is very commonly used, therefore our efforts focus on generating an accurate data package for this cement to be used as reference to other cement recipes.

The Class G Cement composition had a water cement factor of 0.45% and no other additives had been added. The density of the slurry was 1.89 g/cm3.

The methods used for measuring mechanical properties are described below:

Sample Preparation. Cement samples were cured in metal molds with 50.8 mm (2 in.) x 50.8 mm (2 in.) and a height of 127 mm (5 in.). The top of the samples were cut back to approximately 101.6 mm (4 in.), and surface grinding equipment was used to prepare the end surfaces once the samples cured and were removed from the molds. The cement was mixed according to API specifications. The samples are then immersed in autoclaves filled with same mixing water, after which the temperature and pressure are applied. Before measurements, the samples are cooled down and the pressure is released.

Young's Modulus, Poisson's Ratio, and Compressive Strength. Conventional unconfined and confined compressive strength tests were performed on cubic samples to determine the compressive strength. Samples tested were nominal 2-in. by 2-in. cubicals. Ultra-epoch 4 was used to measure Poisson Ratio and Young's Modulus of cements. It can measure the velocities of shear and compressive waves and thus Poisson Ratio and Young's Modulus can be calculated. The relationships between the velocities of shear and compressive waves and the material properties of a homogeneous, isotropic, elastic solid are shown below. Shear waves do not propagate in liquids and gases, and therefore shear wave velocities in a fluid medium are zero.

Cement Compression Strength Test. For the Class G Cement compressive strength, Figure 6 showed that one day strength is 6 MPa, and the compressive strength increased substantially from 1 day to 20 days. After 20 days, the compressive strength increase a little along with time. For the cement cured at 65^{0}C it can be shown that one day compressive strength of Class G Cement reaches 36 MPa. The compressive strength increased from 36 MPa at one day to 64 MPa at 14 days, after that, the compressive strength almost kept constant at 64 MPa. The compressive strength of Class G Cement cured under the condition of 100^{0}C and 18 MPa is 47MPa, after that the compressive strength almost kept constant. The compressive strength at 14 days is almost the same as the one at 3 days. Due the low amount of samples for high pressure high temperature test we can only extrapolate that at HPHT conditions the cement compressive strength will be fast developed and remain constant for a while. All HPHT test were done at a maximum of 20 days curing time, and these tests did not reflect the temperature degradation of cement which is observed in steam injection or geothermal wells.

At room conditions the Poisson Ratio almost keeps constant, around 0.3. For the Cement cured at 75^{0}C the

International Journal of Engineering and Applied Sciences

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Poisson Ratio is 0.3 at three days. Along with time, Poisson Ratio decreased to 0.2 at 12 days. After that, the Poisson Ratio kept constant at 0.2. After curing 14 days under the condition of 100^0C and 18MPa, Poisson ratio remain constant at 0.2 at 6 days and 14 days. However, after curing 21 days under the condition of 100^0C and 18MPa, Poisson ratio doesn't change too much, see Figure 7.

Young's Modulus slightly increases from 12,000MPa at 11 days to 16,000MPa at 43 days. After 20 days, Young's modulus keeps stable at 16,000MPa. For the cement cured at 65^0C the Young's Modulus also shows a clear trend. From 3 days to 16 days, Young's Modulus increased from 12,000MPa to 17,200MPa, see figure 8.

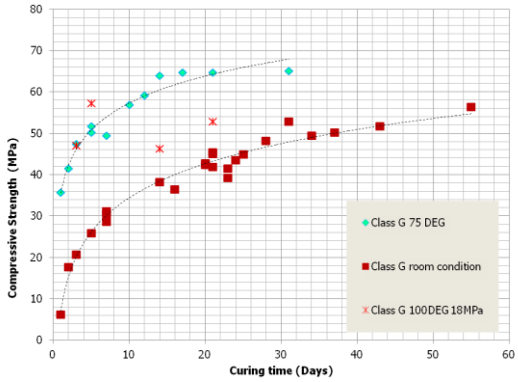

Figure. 6. Compressive strength of Class G cement as a function of curing time

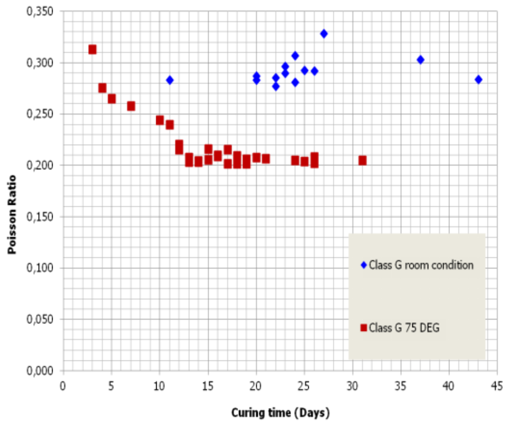

Figure 7. Poisson Ration evolution of Class G cements

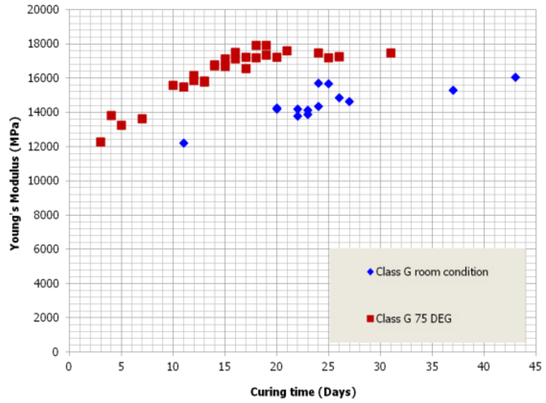

Figure 8. Young's Modulus evolution of Class G cements

5. Discussions

The compressive strength of class G cement at room Temperature reaches a stabilization value of about 67 MPa after more than 70 curing days. This value should be used for calculations of surface casing-cement interaction. At elevated temperatures the stabilized compressive strength reaches even higher values, around 70 to 75 MPa.

Both tests show that if we extrapolate the experimental points the Young's Modulus will stabilize at 17,000 MPa after a longer curing time. This value should be used for further numerical work where the cement is exposed at temperatures below 65^0C.

The Poisson Ratio showed different behavior between room temperature sample and those cured at 65^0C. Here, the curing temperature plays a very important role. The measured values vary between 0.3 at room temperature and 0.2 at 65^0C. The very few HPHT test on class G cement reveal that a Poisson ration of 0.2 is more than adequate when cement properties are considered.

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Table 1: Strength parameters of a class G cement according to various authors

	Wehling 2008	Morris 2003	LeRoy-Delange	This work after 72 h	This work after stabilization
Compressive strength [MPa]	49	40	37	48	60
Tensile strength [MPa]	2	2	n/a	n/a	3
Young's Modulus [MPa]	8700	5400	6600	12000	17000
Poisson ratio	0.15	n/a	n/a	0.2	0.2

The major problem in the comparability of these values is the curing time of the cement and the cement additives. It must be noted that our cement samples where class G cement and fresh water. The reference was cement cured at room conditions. The other investigations used the following curing conditions:

- The samples tested by Morris et. al. [18] were cured at 84°C and 27 MPa pressure and developed the strength within 48 hours.
- The samples tested by Le Roy-Delage cured at a temperature of 77°C and a pressure of 27 MPa for 72 hours.

Our samples were tested up to 60 days and the final values were also extrapolated so that the cement properties became independent of time.

Although tensile strength of the cement is very important for HPHT calculations, we could not find a reliable testing procedure to estimate this value. Several tests performed using the so called Brazilian test showed no good results for the investigated samples.

An extensive sensitivity analysis was performed by Yuan et al (2012) and focused on the casing-cement-formation interaction. The investigations showed that the Von Misses Stress in the cement is sensitive to cement and formation Young's Modulus. Figure 9 shows the sensitivity analysis for Maximum calculated Von Mises Stress for cement.

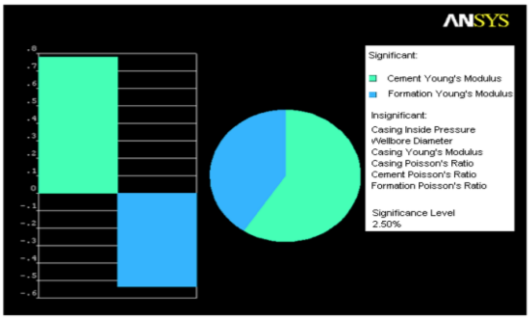

Figure 9. Cement maximum Von Mises stress sensitivity analysis, (Yuan et al, 2012)

Kosinowski (2012) and Ugwu (2008) showed in their Master Thesis that the cement compressive and tensile strength become critical when a failure criterion is selected. For example we estimated the low cycle fatigue for selected cements cured at different conditions and hence having different mechanical properties. The results shown in figure 10 show the sensitivity of the results as a function of the cement mechanical properties, especially when high strain loads exists. The cement cured under room condition with higher Poisson's ratio and lower Young's Modulus shows better low cycle fatigue behavior than the cement cured under the other two conditions. At the same strain, this type of cement has the highest available cycles. The cement properties with higher Poisson ration and lower Young's modulus are more desirable for reducing cement fatigue failure probability

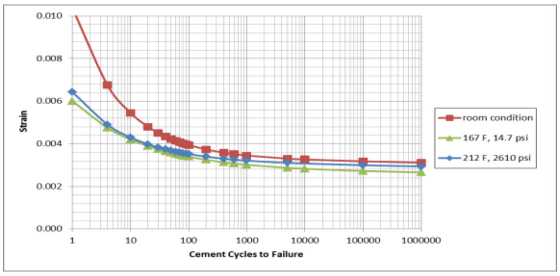

Figure 10. Cement Low Cycle Strain-N Semi Log Plots (the Confining Pressure of 4000 psi)

6. Conclusions

The paper provide an excellent data inventory for class G cement that can be used when mechanical studies on cement, like finite element studies, are required.

It had been observed that under low temperature conditions the mechanical properties of cement became independent of time, so that this values (stabilized values) can be easily used for integrity calculations.

We found out that the Compressive strength of the cement increases with curing temperature showing stabilization around 70 MPa. The stabilized Young's Modulus is double as reported by various authors, but the measured one at

International Journal of Engineering and Applied Sciences

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corresponding lower curing time is comparable. Finally the Poisson ratio was found to be around 0.2.

For better characterization of cement behavior under HPHT conditions a data base should created where mechanical properties of commonly used cements will be stored. This can allow the engineers to better simulate and calculate the well integrity for the life of the well.

Acknowledgment

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