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Aspects of Establishing the Mixing Formulae for Primary Cementing

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Abstract

After a period of 10-15 years more than 50% of the wells have serious problems with the cement sheaths, in many oil fields. It is necessary to enforce a new approach in the design activity for these operations. The way to establish the mixing formulae must take into account the whole life period of the wells which lasts for several decades.

Key words: effort, cement sheath, Ultrasonic Cement Analyzer, pressure waves, shearing waves.

Introduction

Keeping the cement sheet integrity through the lifetime of the well is the essential condition for its good functioning. That is why, the modality of programming the primary cementing operations is of highly importance. A big part of programming refers to the establishing and checking of cementing compositions in laboratory. Starting from the type and destination of the well, of the three categories of factors – geological, technical, technological – factors that influence the cementing operation and the physical and chemical processes of changing the cement paste into rock, experience has contoured the solution of the problem in three aspects:

- Analyzing the activities that will take place in the well later on;
- Establishing the recipes and the lab checking;
- Placing the paste and then the well functioning monitoring.

Since we take into account the building program, we will refer to the first two aspects further on, in order to underline the most appropriate solutions for the success of primary cementing operations.

The Analysis of the Activities that will Take Place Subsequently in the Well

The cementing of the annular space between the column and the wall of the well serves two purposes. On the one hand, it has as purpose the sealing of this space in order to isolate the geological formations that are crossed by the well, so that any fluid exchange between these and the surface should be prevented for as long as the well functions. On the other hand, it assures a mechanical backing for the column to increase its resistance to the pressures it will undergo during its creation and exploitation (variations of internal and external pressure, tracking, perforation etc.). The industrial experience has shown that even in the case of wells for which the tests showed a perfect state of functioning, there occured problems with the sealing of spaces between the columns or between the columns and the ground. Most of the sealing problems appeared in places like gas migration or like fissures in another zone than the predetermined zone. Most researchers think that the main reason for these unpleasant situations is the modification of the state of efforts in the cement sheet, modification that is induced by the variation of conditions in the well i. e. variations of pressure, variations of temperature, mechanical impacts that are produced in the well during certain specific operations. We intend to look over these specific operations and we notice that they may take place all through the lifetime of the well as follows:

The drilling continuation

It refers to the modification of the fluid qualities and properties (especilly of its density). This thing, together with the complementary procedures will produce more changes of pressure in the column. First the pressure is modified because of the change in the fluid density.The pressure state in the operations of checking the integrity of this interval of the well is modified and we refer to the test of internal pressure for the column and then to the build-up of pressure necessary for the leak-off test. There appears an increase of the temperature during the fluid circulation as the well goes deeper and deeper and the fluid takes up the heat from the crossed rocks. There may also be builds-up of pressure in the case of preventing some manifestations.

The perforation of the well

In this operation there is an aproximate 400 bar built –up of the local pressure when the jets are released. Even if the cement stone is more resistant when load dynamic is applied, like in this case, the column behaviour, the vibrations and the pressure that manifest in the perforations are important for the cement sheath integrity. If the operation takes place in a close system, there will be a sudden decrease of the pressure in the well and this has consequences on the cement sheath.

Hydraulic Fracture

The important increase of pressure during this operation can have negative consequences on the cement sheath, especially when it lasts for hours. In certain cases the pressure can manifest outside the cement sheath as well.

Commencement of Production

Commencement of production induces an important decrease of the pressure in the well for a long time. This situation may favour the loss of the cement stone adeherence to the wall.

Exploitation

In the beginning phase of the production, the pressure from the extraction casing may grow up to the reservoir pressure value. The greatest tension will be near the surface where the external pressure is very low. In addition to this state there is also the increase of the temperature induced by the exploited fluids. The cement sheath can be also subjected to external pressure when crossing plastic rocks and rocks subjected to creep phenomena. In the final phases of production the pressure in the inferior part of the well becomes very low and this induces the cement sheath to fall apart from the wall of the well. Moreover, since the reservoir pressure is very low, the great pressure gradients between the upper strata and the reservoir may induce the flow of fluids through the annular space to the reservoir. These gradients may also induce the pores collapse and even the caving of the superior wall.

Making the Windows for Deviation

During the exploitation of the well there can appear the necessity to modify the building program such as the making of horizontal interval of the well. This means making a window through the casing string for the kick off point. The activity for breaking the casing, the making of a rezonable opening and its gauging with mechanical mill bits generates cyclic loads, even vibrations that have a desastruous effect on the cement sheath and on its bonds with the casing and the well wall.

The Change of Efforts State in the Cement Sheath

In order to see the way in which the various operations in the well influence the value of the efforts in the cement sheath, we start from the moment the cementing operation is finished.
This means that the heat of the hydration reactions dissipated in the surrounding rocks and the cement hydration with the internal efforts is mostly consumed. We will consider the axis of the well (along the Oz axis) as the symmetry axis, so that we can use the cylindrical coordinates r, θ and z. We will reduce the boarder and initial conditions to a simple situation in which internally we have the pressure and the temperature in the well and externally, the efforts and temperature state at the distance in the rock-mass, without depending on the direction (on the θ angle).
A successful cementing operation means that in a section from the cemented area the cement ring is continuous, almost uniform as dimension along the ray, with perfect hydraulic bonds both to the casing string and to the rock well. The variables that we consider are *radial displacement,* σ_r *radial effort,* σ_θ *tangential effort,* σ_z *axial effort,* τ_{rz} *shear effort and the temperature T.* Conventionally, the compression efforts are positive. The thermoelasticity theory uses the following linear relations between the efforts, the temperature and the distortion:

$$\varepsilon_r - \alpha T = \frac{\sigma_r}{E} - \frac{\mu}{E}(\sigma_\theta + \sigma_z) \tag{1}$$

$$\varepsilon_\theta - \alpha T = \frac{\sigma_\vartheta}{E} - \frac{\mu}{E}(\sigma_r + \sigma_z) \tag{2}$$

$$\varepsilon_z - \alpha T = \frac{\sigma_z}{E} - \frac{\mu}{E}(\sigma_r + \sigma_\vartheta) \tag{3}$$

$$\gamma_{rz} = \frac{1}{G}\tau_{rz} \tag{4}$$

and the distribution of the temperature in time is obtained from the equation of the heat diffusion conditioned like in the preceding relations (1-4) and has the following form (5):

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}=\frac{\rho C}{K}\frac{\partial T}{\partial t} \tag{5}$$

Where the terms are known, except for α which here represents the linear coefficient of expansion, K thermical conductivity, C specific heat and ρ density.
In order to estimate the efforts variation in the cement sheath, because of the change in the well temperature and pressure conditions, we take into account the features of a successful cementing namely the fact that the hydraulic bonds of the sheath with both the casing and the wall are perfect. Therefore, we will have a tube with a very thick wall, which is made up of three materials (steel, cement, rock) with different mechanical characteristics. Considering a cross section in this tube, the way in which the efforts vary, because of the pressure variation, can be established with Lame's relations:

$$\sigma_\theta=\frac{P_i\cdot D^2{}_i-P_e\cdot D^2{}_e}{D^2{}_e-D^2{}_i}+\frac{(P_i-P_e)\cdot D^2{}_i\cdot D^2{}_e}{(D^2{}_e-D^2{}_i)\cdot D^2} \tag{6}$$

$$\sigma_r=\frac{P_i\cdot D^2{}_i-P_e\cdot D^2{}_e}{D^2{}_e-D^2{}_i}-\frac{(P_i-P_e)\cdot D^2{}_i\cdot D^2{}_e}{(D^2{}_e-D^2{}_i)\cdot D^2} \tag{7}$$

where: p_i – internal pressure;
p_e - external pressure;
D_i – internal diameter of the tube ;
D_e –external diameter of the tube;
D - current diameter of the tube ($D_i<D<D_e$) .

For example, in the case of a build-up of pressure in the well, the tangential effort absolute value decreases from the cement-casing interface towards the cement-rock interface in a hyperbolic curve and the radial effort has the same direction of an absolute value decrease in a logarithmic curve. Therefore the critical area is at the cement-casing interface and the tangential effort value is used to establish the resistance to traction that the cement stone must develop so that it does not crack. From the analysis of the two efforts expressions, one notices that their value at the interface with the casing is mostly given by the value of the pressure build-up and only to a limited extent by the geometry of the cement ring.
In reality (in fact) the situation is much more complicated. Even if we do not take into account the variation of the pressures values along the depth of the well, the tensions to which the cement sheath is submitted are strongly influenced by the mechanical characteristics of the cement that are different from those of the casing and of the surrounding rock. We refer especially to the elastic constant. We will make some commentary about some frequently met situations during the exploitation of wells that serve underground gas deposits.

The Pressure build-up in the Well

The phases of deposits loading bring the wells in this situation. The pressure inside the casing determines it to put pressure on the interior of the cement sheath with which it is one. In the section, a compression radial effort will be developed with an absolute maximum value at the casing-cement interface and a traction tangential effort with the highest value at the same interface. As it has been shown, this has a higher absolute value and will be used to establish the value of the resistance to traction that the cement stone must develop in order to resist to the effect of the pressure build-up. The cement stone can crack to traction under the form of some radial fissures that appear at the interface with the casing and that propagate towards the exterior of the cement sheath in vertical planes, therefore perpendicular to the direction of the tangential effort.

In order to establish the mechanical characteristics that the cement stone must have in this case – and we refer especially to the resistance at traction (draught) and to the elasticity module – we must know not only the geometry of the casing, but also the value of the pressure build-up and the elastic characteristics of the rocks that form the well wall. Some researchers [Tierce...] established that the traction resistance that the cement stone must have in order to resist to the tensions caused by the pressure build-up must be the bigger, the bigger the Young module for the cement stone and the lesser the Young module for the rock. That can be explained by the fact that a big module for the cement stone imposes a big effort for the deformation created by the expansion of the casing while a low module for the surrounding rock determines it to fail to be a firm backing for the cement sheath, permitting it to deform itself more and more and this leads to an even bigger tangential effort. The following idea results from that: the cement stone from the sheath must have the elasticity module as low as possible in order to permit it to deform itself without having dangerous efforts produced in its mass. In the same way, the surrounding rock must be a firm backing, so it must have an elasticity module as big as possible.

The Pressure Build-up in the Exterior of the Cement Sheath

This is the situation encountered in the unloading of the deposit. This state will produce a compression tension from the exterior to the interior on the cement sheath. Both efforts in the section will be of compression. In this situation the casing will play the part of a very firm backing for the cement stone. The deformation will be more important along the ray, so the radial effort value will be the landmark for establishing the resistance to compression that the cement sheath must develop. The tangential compression tension will play the role of a confining pressure, in other words it will increase the cement stone resistance to compression. The cement stone generally resists to such pressures, especially if it has a low elasticity module. But, if it is in areas above the deposit, next to rocks in which there is the creep phenomenon, the stone should have big resistance to compression, so that the resistance of the casing to these tensions should increase.

The Decrease of Pressure in the Well

This situation is met in the advanced stages of unloading or in the final stages of exploiting for the petroleum and gas wells. The effect is produced on the interior of the casing which reduces its diameter thus creating a tension of traction towards the interior on the cement sheath. This traction will determine in the cement rock a radial effort of traction with the highest value at the interface with the casing and a tangential effort of compression. The maximum effort is the radial one and can determine the crack of the traction stone. In most cases the crack may be produced by losing the hydraulic bond, namely the detachment of the cement stone at the interface with the casing or with the rock wall. Even if the value of the radial effort is bigger at the interface with the casing, the detachment can happen at either of the two interfaces. The detachment takes place where the value of the radial effort is bigger than the value of the link forces cement-casing or cement-rock. Theoretically, the cement-rock bond should be stronger as it has a larger surface and a greater degree of roughness. But, because the replacing of the fluid mud and of the filter cake by the cement paste leaves much to be desired, in most cases the detachment of the cement stone is produced at the well wall, permitting the fluids to flow towards upper formations with lower pressure or at the surface.

The Increase of Pressure in the Well

The state of efforts induced by the increase of temperature varies in time and it overlaps the state of efforts already existent in the cement sheath. For its evaluation one needs to know other characteristics of the involved materials (steel and stone) as well, namely: density, specific heat, thermal conductivity and the thermal dilatation coefficient.
Average values for these three materials are written in the table 1.

Table 1

	cement	rock	steel
Density, kg/m^3	1800	2300	7850
Specific heat, J/kg K	2000	1000	500
Termical conductivity, W/m K	1	1	15
Expantion coeficient, m/m K	$1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$

As it has been said, the increase of temperature is made with time. At first, the areas next to the well get warm. A ditatation, an expansion of the casing will be produced. Its effects will be similar to those of the pressure build-up in the well. Then, the cement stone around the casing will dilate. In this situation, the compression radial effort will grow. The tangential effort is compression effort near the casing because the dilated cement stone is boardered by the unexpanded rock around it. This unexpanded rock has an effect of constraint over the cement stone near the casing, equivalent to a pressure which limits dilatation and mentains a state of compression. Because the areas near the rock wall of the cement stone are pushed towards the exterior, they are tensioned by a radial effort of compression and by a tangential effort of streching. The critical effort is the tangential effort of streching, which has the highest value at the interface with the rock wall. As the heat front advances, enterring the rock wall, the heat becames uniform in the cement sheath. This leads to a decrease in the tangential effort value which can reach the state of compression. In the same way, if the well gets warm, the effort state induced by the temperature rise is ameliorated in the cement stone provided this has the low values elasticity module.

Establishing the Recipes and Testing in the Laboratory

In this stage, taking into account the geologically-thermal conditions of the cased and the cemented interval, and also the program in which the well will function, one establishes those recipes of cementing mixtures with features that make them appropriate for the cementing operation (density, flow properties, filtering properties, pumping time etc.). These mixtures must also prevent that the resulted cement stone be influenced by the tensions induced by the operations from the well exploitation program (resistance to compression, to traction, elasticity module etc.). In this stage one also runs laboratory tests of the suggseted recipes, to check whether the paste corresponds to the cementing operation and whether the resulted stone can face the tensions to which it will be submitted during the functioning of the well. For the paste, one usually measures the density, the stability, the setting time, the pumping time and the filtering capacity. For the stone, one measures the resistance to compression, the permeability, maybe the volume change and the resitance to bending. For the wells for which one expects problems because of the complex programs that they will have, the measurements are more thorough and are made on cement test tubes that are held for certain periods of time in the conditions of temperature, pressure, contact with various solutions that will be met in the well and the variation of volume is tested for long periods of time, in certain temperature conditions. With the obtained results other mechanical characteristics are calculated, such as the elasticity modules, those of volume (the matrix module), Poisson's coefficient that will help to make a better estimation of the stone behavior in the well. From the treatment of results of these measurements one can estimate the future behavior of the stone in the conditions corresponding to the well. Because the measurements are made in lab conditions, for instance, in order to establish the resistance to compression in steps, to measure the deformation, the result does not tell us much about the resistance to compression in the conditions present in the well and another kind of loding. In fact, the mere change of temperature and pressure conditions corresponding to the well alone, certainly induces some changes in the inimate structure of the stone and of its mechanical properties. For economic reasons this type of measurement can be used, but only using certain correlations that can be made between these results and those obtained under dynamical conditions on samples kept in temperature and pressure conditions of the well, during the whole time of the measurements.

With a well established set of correlations, a few results obtained in the conditions of the well are enough. In order to establish accurately enough the behavior of the cement stone in the well, the rest of the measurements could be made in conditions that are cheaper from the point of view of the necessary technology and of the time needed.

The measurement of the mechanical properties in temperature and pressure conditions similar to those in the well are made in devises such as the consistometer, that can assure and allow the monitoring of these conditions. These consistometers are of the UCA type (ultrasonic cement analyzer). They are additionally tooled with investigation devises that do not destroy the resulted paste and stone. The devises are in fact electronic transducers that use piestic/ piezometric materials, with the function of accoustic ultrashort waves transmision and reception, like in the devises of accoustic logging. Basically, they measure the time needed for the pressure and shearing accoustic waves to cross the sample and they establish the speed of these waves. The speeds established in various moments of the evolution of the paste or of the stone are used to establish certain properties values – that is why they are considered dynamic properties – with the help of some relations like the ones below, that were established on the grounds that the cement stone is homogeneous, izotropic, and that it has an elastic behaviour. For a better correlation, some measurements for the resistance to compression are made in tandem, namely, by placing the transducers on the turntable of the press. At the same time and nondistructively this mechanic property is measured. By means of the classical measurement of the resistance, the plastic characteristics of the stone are also obtained. These characteristics are the flow limit and the inner friction angle.

$$\mu = \frac{1}{2}\left[\frac{\left(V_p / V_s\right)^2 - 2}{\left(V_p / V_s\right)^2 - 1}\right] \tag{8}$$

$$E = 2V_s^2 \rho \left(1 + \mu\right) \tag{9}$$

$$G = V_s{}^2 \cdot \rho \tag{10}$$

$$B = V_p^2 \rho - 1{,}33G \tag{11}$$

where: G= the shearing module

B= the volume module
V_s= the shearing waves speed
V_p= the pressure waves speed
E= Young' s module
μ= Poisson' s coefficient
ρ= the density of the sample

Generally, the dynamic mechanical properties have higher values than their corresponding ones that are obtained by means of classical measurements. Their values decrease with the reduction of the paste density or with the increase of the gas content at foamed cementing.

The dynamic measurement of mechanic properties of the paste and of the stone that is made out of it, allows the operator to know exactly the paste behavior during its placement in the well and the evolution of the stone properties during several hours after the setting and this fact makes him more confident in his actions.

Conclusions

- In order to design a long life cement stone, we need to know all about the future program of the well, to establish the main conditions in which the cement sheath will be working;
- The mechanical properties of the cement stone must be strongly ameliorated in order to assure a longer life of the well;
- We must pay special attention to the elastic and plastic properties like the Young`s module, the Poisson`s coefficient, the plastic deformation;
- The measurements can be made especially by means of complex apparatus which canensure conditions at site, like pressure and temperature, and use nondestructive methods by using sonic and pressure waves devices.

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Aspecte ale stabilirii retetelor pentru prima cimentare

Rezumat

După o perioadă de 10-15 ani mai mult de 50% din sonde au probleme cu cimentările, pe foarte multe structuri petrolifere. Se impune o nouă abordare a proiectării acestor operaţii. Modul de stabilire a reţetelor trebuie sa aibe in vedere intreaga perioadă de viată a sondei, care este de cateva zeci de ani