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Cement Compressive Strength Development Drastically Affected by Testing Procedure

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Abstract

Horizontal drilling has become the most common wellbore design in the majority of unconventional plays in the United States. As laterals increase in length, the bottom hole circulating temperature (BHCT) approaches the bottom hole static temperature (BHST.) Consequently, cement slurries' retarder concentrations are designed around essentially the bottom hole static temperature of the well to ensure safe and effective placement. While increased cement retarder loadings allow for safe placement, these slurries often exhibit delayed short term (0 – 12 hour) compressive strength development if the slurry is not dynamically conditioned properly prior to the initiation of compressive strength testing. The delayed compressive strength development is often a cause of concern about overall cement quality and effective wellbore isolation. This paper empirically explores the relationship between the use of dynamic conditioning and compressive strength development. A cement control is tested using heat up schedules outlined in API Recommended Practice 10B-2 and again with a modified schedule that includes dynamic conditioning in a cement consistometer. Results indicate that cement slurries that are dynamically conditioned show drastically improved short term compressive strength results over slurries that are not dynamically conditioned. Past the short term time frame, the variance between the compressive strength development of slurries that are dynamically conditioned and those that are not narrows significantly.

Introduction

Cement slurries are often characterized by their fluid properties. Properties such as rheological behavior, thickening time, fluid loss and dynamic settling describe how the slurry will perform while being placed in the well. Once the placement is complete, properties such as free fluid, settling and compressive strength development are often used to describe the slurry. All of these physical properties can be adjusted through sound engineering practices and competent lab work. Of the physical properties most often measured, compressive strength development is most critical to ensure a safe and productive well. The cement sheath is responsible for isolating various zones, supporting the casing, and preventing casing erosion. Without a cement with sufficient compressive strength, casing failures are more likely and the life span of the well can be dramatically reduced.

As cement hydration reactions occur, the slurry transitions from a fluid to a gel and then finally to a solid mass. Once the cement has set into a solid, compressive strength development occurs rapidly in the short term (0 – 48 hours) and then continues to increase, albeit at a slower rate. In this short time frame, many other tasks are being performed on the well. The casings slips may be set, the casing may be tested, drilling may resume, or in the case of a production string, the blowout preventers (BOPs) may be removed and rig demobilization may begin. Because there are many critical operations that are undertaken in the short term, it is critical to understand when a particular slurry begins compressive strength development, and when the cement is competent to provide the necessary support and isolation.

The compressive strength development of a cement is most drastically affected by temperature. Temperature also influences the dynamic properties of the slurry such as thickening time, fluid loss, etc. In order to understand how a slurry will behave both as it is being pumped and once in a static state, it is critical to understand both the bottom hole static temperature and the bottom hole circulating temperature. The BHST is normally obtained from area temperature gradient maps and correlated electrical logging measurements. As more wells are drilled in an area, the knowledge of the BHST becomes more accurate and refined. The BHST is one component used to approximate the bottom hole circulating temperature. The BHCT can be estimated either from API correlations or computer modeling.[1] Computer modeling has proven to provide a more accurate approximation of the BHCT. Regardless of the determination method the trends remain the same. As a well transitions from vertical to horizontal, the BHCT approaches the BHST. This is intuitively understandable; the longer a fluid moves through a constant temperature zone (the lateral) the more it will heat up. As longer laterals become more common in unconventional reservoirs, BHCT's often come very close to matching BHST's.

Horizontal wells often require large volumes of cement to isolate productive zones and provide the support necessary for completion and production operations. Due to these larger volumes, cement jobs often require extended job placement times. The job placement time is multiplied by safety factors to determine the total thickening time (TTT) required. The TTT is a slurry property that is easily adjusted with the addition of cement retarders. Retarders are chemical additives added to a cement blend to increase the amount of time a slurry remains pumpable. Both the larger volume of cement required in a horizontal well and the elevated BHCT encountered mean that a horizontal well will require a significantly higher retarder concentration than a vertical well with the same BHST.

There are two common methods for determining the compressive strength of a cement slurry; destructive and non-destructive. The destructive method involves preparing a slurry in a mold and allowing the cement to cure under temperature and pressure for a specified amount of time. After this time has elapsed, the sample is put in a press and crushed. The force required to crush the sample is divided by the area over which it acted and a pressure is calculated. The main advantage of this method is that an exact value of compressive strength can be determined. Disadvantages of this method are that the compressive strength development is difficult to ascertain. A cube must be prepared and then crushed at every point of investigation. This is acceptable when determining the compressive strength at 12 hours or 24 hours, but becomes difficult when trying to determine the time to 50 or 500 psi. The non-destructive method involves using an ultrasonic cement analyzer (UCA.) The UCA passes ultrasonic signals through a cement sample and measures the transit time. As a cement begins to build compressive strength, the transit time decreases. Through the use of mathematical algorithms, the transit time is then converted into an approximate value for the compressive strength. The main advantage of the non-destructive method is that the compressive strength development is easily observed and recorded. The compressive strength can be approximated at any point from test initiation to completion.

Cement slurries are normally tested according to the American Petroleum Institute (API) Specification Recommended Practice 10b-2. According to the specification, cement slurries are to be mixed and then placed immediately into the UCA's curing chamber.[2] The temperature is then increased either according to a series of schedules listed, or according to specific well conditions. Normally, the temperature is increased from ambient to the BHCT at the same rate used during thickening time testing and to BHST in a total of four hours. All of this is done under static conditions.

An alternate method for increasing the temperature of the cement slurry has been developed which better simulates downhole conditions. With the alternate method, the slurry is dynamically conditioned in a high pressure / high temperature (HPHT) consistometer for the job placement time at various temperatures prior to being placed in the curing chamber. The results indicate that slurries which are dynamically conditioned prior to compressive strength testing exhibit substantial increases in initial set and early time compressive strength development.

Testing Methodology

A cement slurry designed for long laterals with BHSTs up to 330 ^{o}F was selected. The slurry was dynamically stable and contained cement additives to control free fluid and achieve a low fluid loss value. Furthermore, the slurry was designed to minimize the effects of strength retrogression, which commonly occurs at sustained temperatures above 230 ^{o}F. The designed slurry is typical in both properties and densities of a "tail" slurry placed along the length of the lateral.

Three test bottom hole static temperatures were selected for evaluation, 240 ^{o}F, 280 ^{o}F and 330 ^{o}F. The retarder concentration was tailored to the specific requirements according to the corresponding circulating temperature. Table 1 lists the thickening time for the selected temperatures.

Table 1: Thickening Time for Selected BHCTs

Test Temperature (^{o}F)	Total Thickening Time
230 ^{o}F	3:31
270 ^{o}F	3:04
320 ^{o}F	4:19

Once the retarder concentration had been determined for a specific temperature, compressive strength testing was performed. For each temperature, the compressive was tested three times. For the first test, the slurry was not dynamically conditioned prior to pouring in the UCA. The slurry was tested according to API specification 10b-2. For the second compressive strength test, the slurry was conditioned for job placement time at 180 °F prior to being poured into the UCA. The reason 180 °F was chosen is because most cementing labs are equipped with atmospheric consistometers for slurry conditioning that have a maximum temperature of 180 °F or 190 °F. Finally, for the third test the slurry was dynamically conditioned at BHCT in an HPHT consistometer prior to being poured into the UCA.

Results

Initial Compressive Strength Development

The results have been categorized first by the initial compressive strength development of the cement (< 8 hours), and then by the compressive strength development of the slurry to 48 hours. Figure 1 shows the initial compressive strength development of the slurry tested at a BHST of 240 °F. The time to 50 psi is known as the initial set of the cement and is normally regarded as the minimum compressive strength required to support casing. The time to 500 psi is also significant, as this is commonly known as the minimum compressive strength before drilling out or perforating the casing.

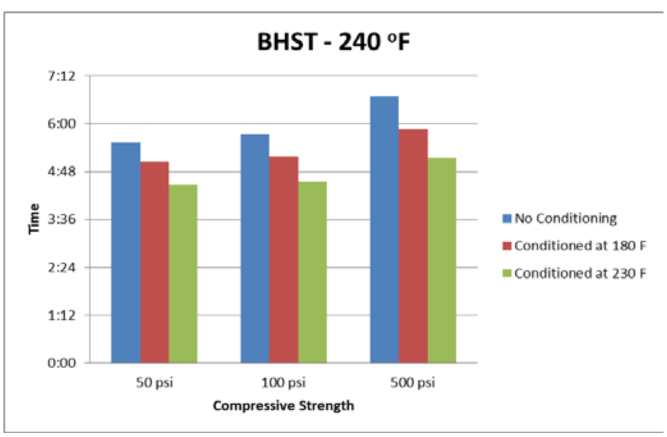
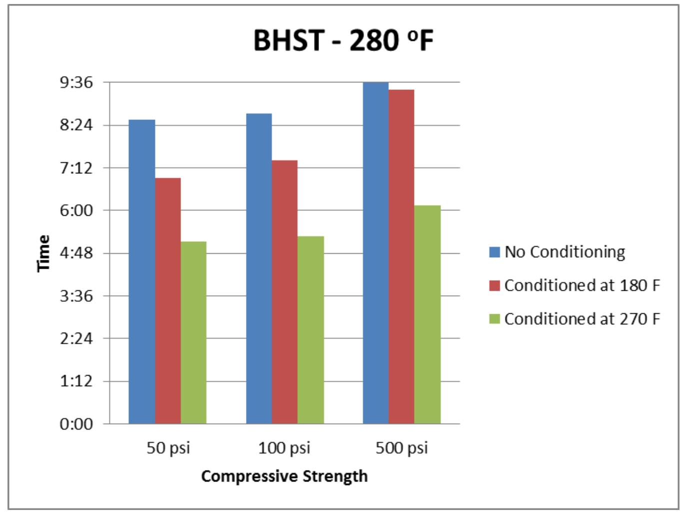


Figure 1 – Initial compressive strength at 240 °F

The difference between the control slurry and dynamically condition slurries is apparent. The slurry conditioned at 180 °F averaged 10% shorter times than the control slurry, and the slurry conditioned at 230 °F averaged 21% shorter times.

The trend continues as the BHST increases. Figure 2 shows the initial compressive strength at 280 °F.



. Figure 2 – Initial compressive strength at 280 °F

At this temperature, the slurries dynamically conditioned at 180 °F averaged a 12% shorter time, while the slurries dynamically conditioned at 270 °F averaged 38% shorter times.

Figure 3 shows the initial compressive strength of the slurries tested at a BHST of 330 °F.

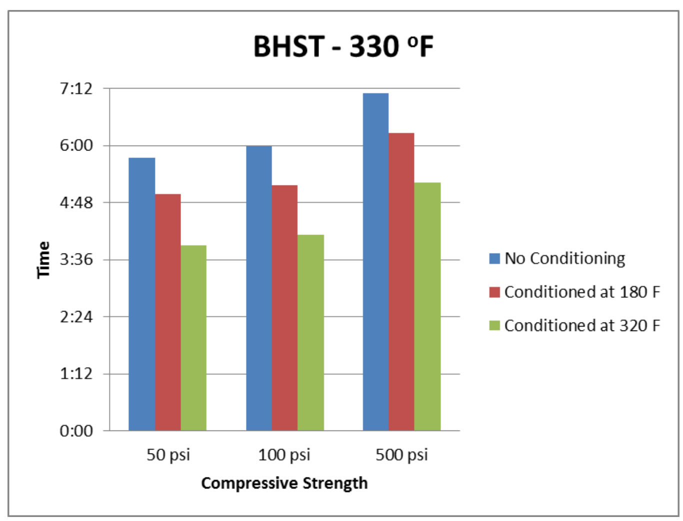


Figure 3 – Initial compressive strength at 330 °F

At this temperature, the slurries dynamically conditioned at 180 °F averaged a 13% shorter time, while the slurries dynamically conditioned at 320 °F averaged 30% shorter times.

48 Hour Compressive Strength Development

Once compressive strength development has begun, it rapidly increases as the cement hydration reactions continue. Each slurry was tested for 48 hours, and the results are shown in the following figures.

Figure 4 shows the relationship between the control slurry and conditioned slurries tested at 240 °F. At this temperature while there was little variance between the control slurry and the conditioned slurries at 48 hours, in the early time there was. At eight hours, there was a 12% difference between the control and the slurry conditioned at 180 °F, and a 44% difference between the control and the slurry conditioned at 230 °F. As time elapses, the variance diminishes and at 48 hours, all slurries have achieved strengths within 10% of each other.

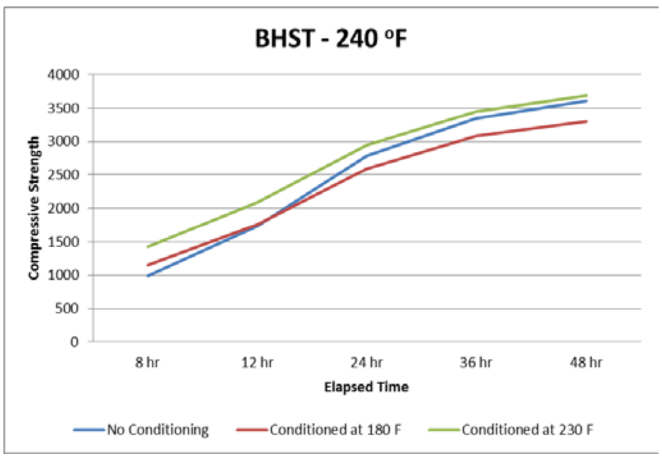


Figure 4 – 48 hour Strength Development at 240 °F

As temperatures increase, so does the early time variance between the controls and the slurries that are dynamically conditioned. Figures 5 and 6 show the development trend at 280 °F and 330 °F respectively. At 280 °F, similar trends are seen as at 240 °F. At eight hours, there was a 17% difference between the control and the slurry conditioned at 180 °F, and a 70% difference between the control and the slurry conditioned at 270 °F. As with the slurry tested at 240 °F, at 48 hours all slurries have achieved strengths within 10% of each other.

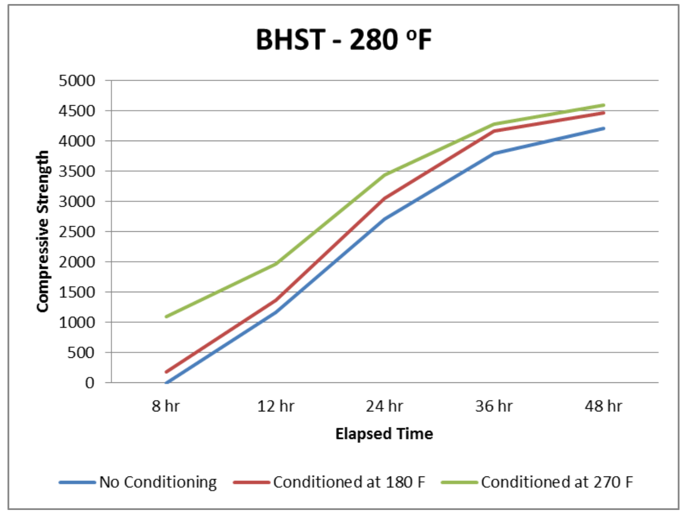


Figure 5 – 48 hour Strength Development at 280 °F

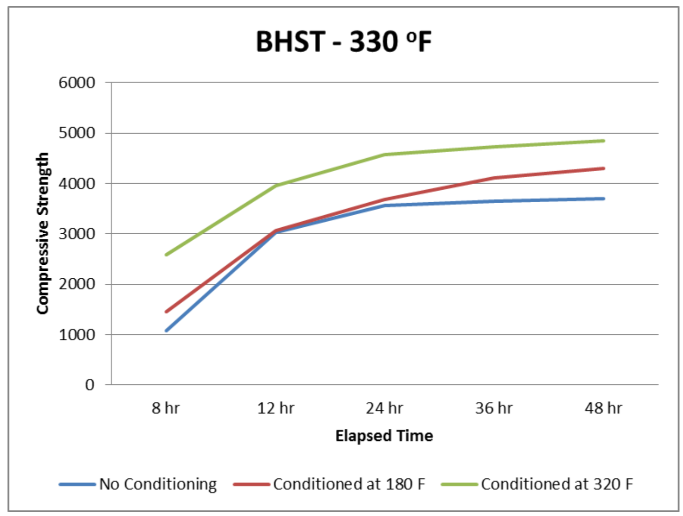


Figure 6 – 48 hour Strength Development at 330 °F

At the highest test temperature, the development trend varies from the other two temperatures tested. Dynamically conditioning at the BHCT has a measurable effect on the compressive strength. At eight hours, the slurry that was conditioned at BHCT was 139% stronger than the control. The slurry conditioned at 180 °F was 30% stronger at the same time. This trend continued throughout the test period. At 48 hours, the slurry conditioned at 180 °F was 16% stonger than the control, while the slurry conditioned at 320 °F was 31% stronger than the control slurry.

Conclusions

Dynamically conditioning cement sluries prior to initiating a compressive strength test effects the short term results. As the length of the test increases, and the compressive strength continues to develop, the effects of conditioning diminish. In the conducted testing, all slurries achieved sufficient compressive strength (>1000 psi) in less than 12 hours. At 48 hours, all slurries regardless of conditioning achieved greater than 3,000 psi. Dynamic conditioning has the greatest effect on the extreme short term, or initiation of compressive strenght development. As temperatures and retarder loadings increase, the effects on the compressive strength are more apparent. As with many chemical reacations, dynamically conditioning affects the rate of reaction. Dynamic conditioning is essentially stirring at temperature, and stirring has a well documented effect on the rate of reaction.[4] Dynamically conditioned slurries better simulate actual well conditions, as all cements are pumped for job placement time prior to allowing to set. The test results show that compressive strength development occurs measurably earlier when slurries are dynamically conditioned than if poured immediately into a UCA and heated without conditioning. If early development of compressive strength is critical to well operations or operator requirements, dynamic conditioning may aid in achieving these goals.

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Nomenclature

BHCT = *Bottom hole circulating temperature*
BHST = *Bottom hole static temperature*
BOP = *Blowout Preventer*
TTT = *Total Thickening Time*
UCA =*Ultrasonic Cement Analyzer*
HPHT = *High Pressure / High Temperature*

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