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Extensive Investigation of Whipstock Cement Plug Designs at 299^o F Yield Critical Developments

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Abstract

High temperature whipstock plug cementing has been inherently difficult and costly due to a number of factors including high pressure and temperature extremes, high slurry density and viscosity, detrimental effects of drilling fluids on slurry compressive strength and differential movement of cement, drilling mud and other wellbore fluids.

Extensive testing is often required of proposed slurries and, when possible, should be completed well in advance of the setting of the whipstock plug to determine the slurry formulation most conducive to placement and optimum compressive strength development. Issues impacting slurry design and performance include bottom hole temperatures, type and composition of the cement, slurry density, mix-water ratio, impact of silica and silica mesh size on compressive strength, the influence of chemical retarders on compressive strength development, and waiting time prior to “dress-off” and “kick-off”. In addition, the mechanical properties of the formation to be sidetracked and the compressive strength the slurry must achieve for a successful sidetrack are often unknown.

This paper addresses specific chemical and physical properties of an 18.0 pound per gallon Portland Class H whipstock plug slurry at a bottom hole static temperature of 299^o Fahrenheit (^{o} F), and discusses critical developments learned from the testing conducted. Specific recommendations are made for the slurry design of moderate to high temperature whipstock plugs to maximize compressive strength and prevent strength retrogression.

Introduction

While proper slurry design is important in achieving a competent whipstock plug, the cement slurry itself may be secondary to the placement method utilized. The best slurry designs have a high potential for failure if not placed in such as manner as to prevent the cement slurry from contamination by wellbore fluids.

Cement slurries are designed and tested under ideal conditions where cement slurry contamination is controlled. Testing yields the properties of a given cement system at downhole conditions at the same temperature and pressure as the slurry will encounter when placed in the wellbore. Laboratory conditions do not normally include contamination with incompatible well bore fluids that may include water based, oil based or inverted muds, and various mud additives.

The design of whipstock plugs at moderate or high temperatures is applied using a variety of cementing procedures and techniques that begin with the hydration of the cement slurry. One technique used to address high temperatures is to use the bottom hole static temperature (BHST) as the bottom hole circulating temperature (BHCT) in developing the total thickening time[1]. This conservative approach is due to the often, limited circulation volume and time, and the low corresponding cool-down of the fluid. This places a critical demand on the slurry to attain an adequate thickening time with high early compressive strength development. Once an appropriate thickening time is determined, compressive strength development may not be suitable for standard “dress-off” and “kick-off” times. The difficulty is that the BHCT and BHST are the same and the expected temperature increase from the BHCT to the BHST that normally aids the development of high early compressive strength does not exist. Under these conditions where “dressing off” is conducted at a “standard” 12-hours and “kicking off” at 24-hours, failure can occur if adequate compressive strength has not developed.

Previous experience has suggested that reducing the cement mix water requirement correspondingly increases the compressive strength (and density) of the final set cement. This concept has been prevalent over the years and has proven successful in general whipstock applications. A comprehensive study conducted at 299^o F indicated that decreasing the mix water did increase the compressive strength appreciably, up to a point. Interestingly, further decreases in the mix water from this point decreased the compressive strength.

Another common practice is to ignore compressive strength retrogression[2] at high temperatures when the plug is temporary or expendable and strength retrogression is thought to occur after the expected useful life of the plug. Testing at 299^{o} F has indicated that strength retrogression can occur within 72-hours where plugs are normally “dressed-off” and “kicked-off”, which can contribute to less than optimum plug performance.

Placement Procedures and Downhole Fluid Contamination

The subject matter of this paper deals specifically with the design of whipstock cement slurry systems. However, to ensure that the designed properties of a specific cement system do not change, it is important to ensure that proper placement techniques are practiced. The best slurry design has a high potential to fail if it is not placed in such a manner as to prevent plug movements due to fluid density differential and the contamination of the slurry with wellbore fluids.

A number of reasons for plug failure related to placement techniques have been identified. The first potential failure mechanism is improper mud displacement or hole conditioning[1]. Many Permian Basin mud systems are salt saturated sodium chloride brines (10.0 pounds per gallon (ppg)) or mixtures of brine and fresh waters commonly resulting in a density of 9.0 ppg or greater. Brine water contamination can retard cement slurries (or in some cases accelerate total thickening times) and in so doing, effect early compressive strength development by exposure to high concentrations of sodium chloride and by dilution. Cement contamination can also include mud additives, such as barite, bentonite, high pH buffers, emulsifiers, friction reducers, oils and any number of other mud system components. Whether through contamination or dilution, each can significantly change the properties of the slurry and/or the final set time and compressive strength.

Circulating the hole completely is highly recommended, and where possible a minimum of two annular volumes should be pumped. It is also recommended to “stop and break circulation” frequently when running in the hole with the plug placement tubulars. As a gauge to measure adequate circulation, little or no cuttings should be observed in the returns prior to the cementing operations.

Conditioning the mud prior to cementing should also be considered to ensure the mud can be displaced from the hole. This may be accomplished by reducing the plastic viscosity and the yield point of the drilling mud where hole conditions allow.

Downhole Fluid Density Differentials

The slurry tested at 299°F was a Portland Class H cement at a density of 18 ppg. When these high densities are used in whipstock plug applications it is important to ensure that fluid exchange (swapping) due to density differentials does not occur. Differences in the density of wellbore fluids and cement slurries are normal. These differences must be considered when placing a cement plug in a wellbore[1]. The density of the cement is normally greater than the wellbore fluids and when placed on top in a balanced plug scenario it will tend to displace or mix with the lighter fluid (mud) below. It is in balanced plug applications that precautions must be taken to ensure that fluid swapping does not occur which would result in a contaminated and diluted cement slurry[3]. Contamination or dilution will adversely alter the designed properties of the cement plug and may result in a plug failure.

In order to eliminate the affects of fluid density differentials and subsequent fluid in fluid movement and cement slurry contamination, it is recommended that the heavier whipstock plug be placed at the bottom of the hole. If it is impractical or not possible to place the plug at the bottom of the wellbore (i.e., a balanced plug) an artificial bottom may be placed in the hole just below the whipstock plug to prevent fluid movement. One method used is to place a viscous pill[4] below the cement slurry that may be composed of polymers, crosslinked fluids, or muds. In some cases, sand can be placed below the whipstock plug to provide a bottom.

Cement Slurry Volumes and Plug Performance

A potential for plug failure also exists in the length or volume of the cement plug that is placed. In a balanced plug, some percentage of the cement plug will be lost due to contamination regardless of the placement technique used. The success of the cement plug can be significantly increased if this loss is anticipated in the initial design. Numerous plug failures have been attributed to inadequate cement volumes. A minimum of 500 foot of plug is recommended, whenever the wellbore and hole conditions allow. Fluid calipers can be run when possible to more accurately determine the amount of cement needed. If it is not possible to run a fluid caliper, cement volume calculations should be made based on a gauged hole and an appropriate excess.

Balanced Plugs

Most whipstock plugs are placed in the annular space between the placement tubulars and casing, or tubulars and open hole. This technique requires placing (spotting) the slurry through the tubulars to the proper depth. The cement in the tubing (or drill pipe) is pumped until the annular space is filled with cement or balanced. The tubing, (partially filled with cement) is then withdrawn from the cement plug. It is important that the tubing be pulled slowly to allow the more dense cement to fall from the tubing and fill the void left by the tubing. If the tubing is pulled too quickly, wellbore fluid, mud or water can be pulled into the cement through a swabbing effect[3]. This will cause the contamination and or dilution of the cement slurry and will affect early compressive strength development and can contribute plug failure.

Tools & Plug Performance

There are a variety of hardware or downhole tools available to the industry that can aid in the placement and effectiveness of whipstock plug applications and have been include for reference:

- The use of small diameter stingers placed below the primary delivery tubulars, at a length the same or greater than the length of the whipstock plug.
- Plug catchers can assist by providing a positive surface indication and prevent flowback until reverse circulation is established.
- Diverter subs which allow cement to be diverted up the hole at a 45°angle during pumping as opposed to open ended tubing which directs the cement slurry downward during pumping and potentially forces the cement into the wellbore fluid (Fig 1).
- Plug isolation tools can eliminate the need for diverter tools or viscous pills by providing a mechanical means of separating fluids of different density and eliminate the potential for fluid mixing. Figure 2 illustrates an ideal balanced plug and how an isolation tool can provide fluid separation when it is not possible or practical to set a viscous pill below the whipstock plug.
- Mechanical plugs can be used if the formation to be sidetracked is known to be extremely hard or tough, or there is a need for short-radius “kick-off”[1], or if offset wells have been successfully sidetracked using mechanical plugs.

Whipstock Plug Design at 299^{o} F

Often little is known regarding the properties of the formation to be sidetracked (i.e., mechanical properties of the rock, fluid loss characteristics, water flows, etc.). In the study conducted, the formation to be sidetracked was described as a hard chert that would require a cement system with “high” compressive strength. An 18-ppg slurry was proposed with maximum compressive strength development.

Total Thickening Time, Chemical Retrarders and Additive Chemistry

A high temperature retarder and boron complex intensifier was utilized with the API Class H cement to retard the total thickening time to 5 hours and 25 minutes at 299^{o} F. Initially, it was thought that the use of the boron complex would have a detrimental effect on compressive strength. This was disproved with excellent strength being developed at 12, 24 and 72 hours of 989 psi, 6,896 psi and 7,312 psi respectively as measured with the Ultrasonic Compressive Strength Analyzer[5] (UCA). Similar results were observed by the destructive method of analysis (Fig. 3).

Other additives considered included hematite as the weighting agent to obtain an 18 ppg slurry density, silica to prevent strength retrogression, anti-settling agents for solids suspension and distribution and free water control agents.

Mix Water Ratios and Relative Compressive Strength

Lower mix water ratios and higher densities have long since been related to higher compressive strengths in whipstock plugs. The use of cement dispersants has made it possible to reduce the mix water ratios to as little as 25% by the weight of cement (BWOC) or 2.82 gallons per sack (gps) and less. Testing at 299^{o} F indicated that there exists a point at which lowering the mix water further actually decreases the compressive strength. An optimum mix water ratio exists that maximizes the compressive strength development of a slurry, with respect to the slurry density, additive chemistry and a specific test temperature. The optimum mix water ratio for Class H at 18.0 ppg at 299^{o} F proved to be 39.92% BWOC or 4.50 gps (Fig. 4). (The API water requirement for Class H is 38% BWOC)[6]. This discovery allowed the mix water ratio to be fixed while the other additives were varied for thickening time, rheological and solids suspension properties.

Strength Retrogression

Silica is known to prevent strength retrogression at temperatures of 230^{o} F or greater[7], but is not often included in the design of whipstock plugs at these elevated temperatures. Testing at 299^{o} F indicated that strength retrogression did occur within the first 72 hours and as much as 830-psi was lost between 24 hours and 72 hours (Fig. 3). Importantly, the peak compressive strength was not achieved within 24 hours (Fig. 3) where plugs are often “kicked-off”. The loss of compressive strength due to strength retrogression can be significant and may compromise the whipstock plug. Testing also indicated that silica flour (200-mesh) was more efficient in preventing strength retrogression than 100-mesh silica sand (Fig. 3). 30 pound per sack (pps) silica flour was included in the final slurry formulation. The identification of the type and concentration of silica that prevented strength retrogression proved significant and allowed the silica flour content to be fixed while the other additives were varied.

“Dress-Off” and “Kick-Off” Times

A very important consideration is the static time before “dressing off” or “kicking-off”. Testing has indicated that a cement slurry of nominal density (or higher) will normally attain the majority of its compressive strength at approximately 72-hours after placement. While a properly designed and placed whipstock plug may not require maximum compressive strength development before “kick-off”, it will, in most cases require a minimum of 24 hours to achieve adequate compressive strength for “kick-off”. Many competent whipstock plugs are “drilled up” (and referred to as “green”) because the plug was not given enough time to develop the necessary compressive strength. Often the time for “dress-off” and “kick-off” has been resolved well before the compressive strengths have been determined (if they are determined) i.e., 12 hour “dress-off” and 24 hour “kick-off”. The slurry should attain sufficient compressive strength to “dress-off” without damaging or moving the plug during the process. UCA charts can offer a more definite time frame for these processes.

At 17,700 feet and 299° F, a 24-hour “dress-off” time was recommended since the 12-hour strength was 989 psi (Fig. 3) and the 24-hour 6,896-psi. Given the extraordinary mechanical properties of the chert at 17,700 feet, it was recommended that the slurry achieve the majority if its total strength prior to “kick-off” or 72 hours where it developed 7,256-psi (Fig. 3)

Final Slurry Design at 299°F

The final slurry design included Class H + 30 pps Silica Flour + 20 pps Hematite + 1.75% Dispersant + 0.3% Free Water Control + 2% Boron Complex + 1.3% Retarder + 39.92% Mix Water at a density of 18.0 ppg.

The total thickening time at 299° F was 5 hours and 25 minutes. Compressive strength (UCA) development at 299° F included 500 psi at 11 hours 48 minutes, 989 psi at 12 hours, 6,896 psi at 24 hours and 7,312 psi at 72 hours. The destructive method of analysis indicated a 24-hour strength of 6,466 psi and a 72-hour strength of 7,256 psi.

Conclusions

1. Proper whipstock plug placement techniques must be employed in order to ensure that designed and tested cement slurry properties are maintained at down hole conditions.
2. High temperature retarders and boron complex intensifiers can be used effectively to retard thickening times and develop excellent compressive strength for whipstock applications.
3. Hematite can be used to obtain a desired slurry weight while maintaining the optimum water ratio and silica content.
4. Decreasing the mix water appreciably increases the compressive strength of a slurry to a point where further decreases in the mix water decreases the compressive strength. An optimum cement mix water exists that allows for the maximum development of compressive strength with respect to the slurry density, additive chemistry and bottom hole temperature. The optimum water ratio for an API Class H at 18 ppg at 299° F was 39.92% BWOC.
5. Laboratory testing concluded that strength retrogression does occur within 72 hours at 299° F and that silica should be included to prevent the loss of compressive strength.
6. Testing indicated silica flour (200-mesh silica sand) was more efficient than 100-mesh silica sand in preventing short-term compressive strength retrogression. 30 pps BWOC 200 mesh silica flour was used to prevent strength retrogression at 299° F.
7. “Dress-off” and “kick-off” times should be determined from UCA charts rather than from predetermined times. “Dress-off” at 299° F was recommended at 24 hours (6,896 psi) and “kick-off” was recommended at 72 hours (7,312 psi).
8. The final slurry design at 299° F included: Class H + 30 PPS Silica Flour + 20 PPS Hematite + 1.75% Dispersant + 0.3% Free Water Control + 2% Boron Complex + 1.3% Retarder + 39.92% Mix Water at a density of 18.0 ppg.

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References

1. LaPrade, D., Low, N.; “New Cement System Replaces Mechanical Whipstock Plug,” SPE 83466, SPE Western Regional/AAPG Pacific Section Joint Meeting, Long Beach, California, U.S.A. May 2003.
2. Eiders, L.H., Root, R.L.; “Long-Term Effects of High Temperature on Strength Retrogression of Cements,” SPE 5871, 46th Annual California Regional Meeting of the Society of Petroleum Engineers of AIME, Long Beach, California, April 8-9, 1976.
3. Crawshaw, J.P and Frigaard, I.; “Cement Plugs: Stability and Failure by Buoyancy-Driven Mechanism,” SPE 56959, Offshore Europe Conference, Aberdeen, Scotland, September 7-9, 1999.
4. Smith R.C., Beirute R.M. and Holman, G. B.; “Improved Method of Setting Successful Whipstock Cement Plugs”, IADC/SPE 11414, IADC/SPE Drilling Conference, New Orleans, Louisiana, February 20-23, 1983.
5. Ro, F.L., Sutton, D.L., Childs, J.D., Cunningham, WIC., “An Automatic Device of Nondestructive Testing of Oilwell Cements at Elevated Temperatures and pressures,” SPE 9283”, JPT, 1982
6 American Petroleum Institute (API),; *“Specifications for* Cements and Materials for Well Cementing, API *Specification 10A*” 23 Edition (April 2002) 22-36 and 7.
7. Smith, Dwight K., “Cementing” Society of Petroleum Engineers, Monograph Volume 4, Henry L. Doherty Series, Copyright 1976

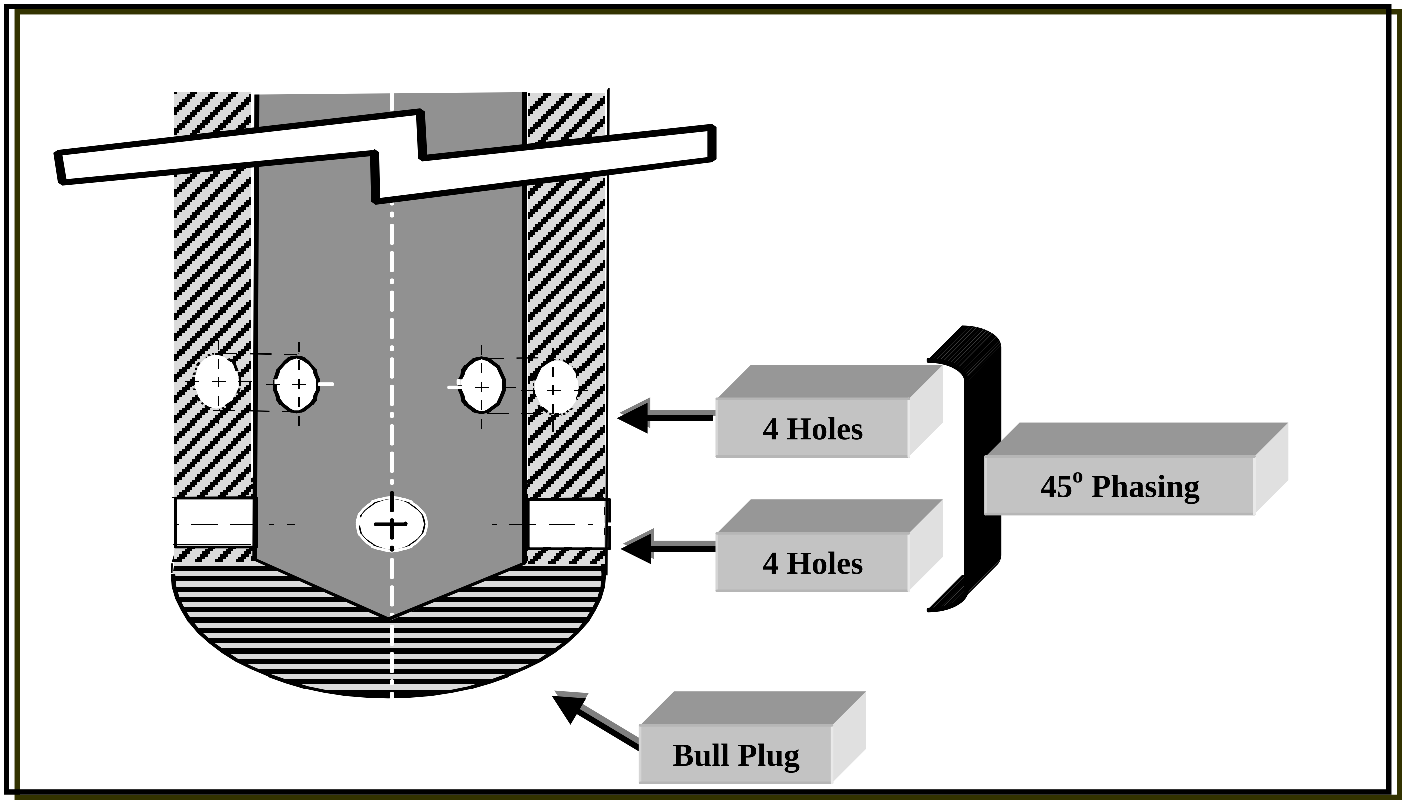

Fig. 1 – Diverter Sub

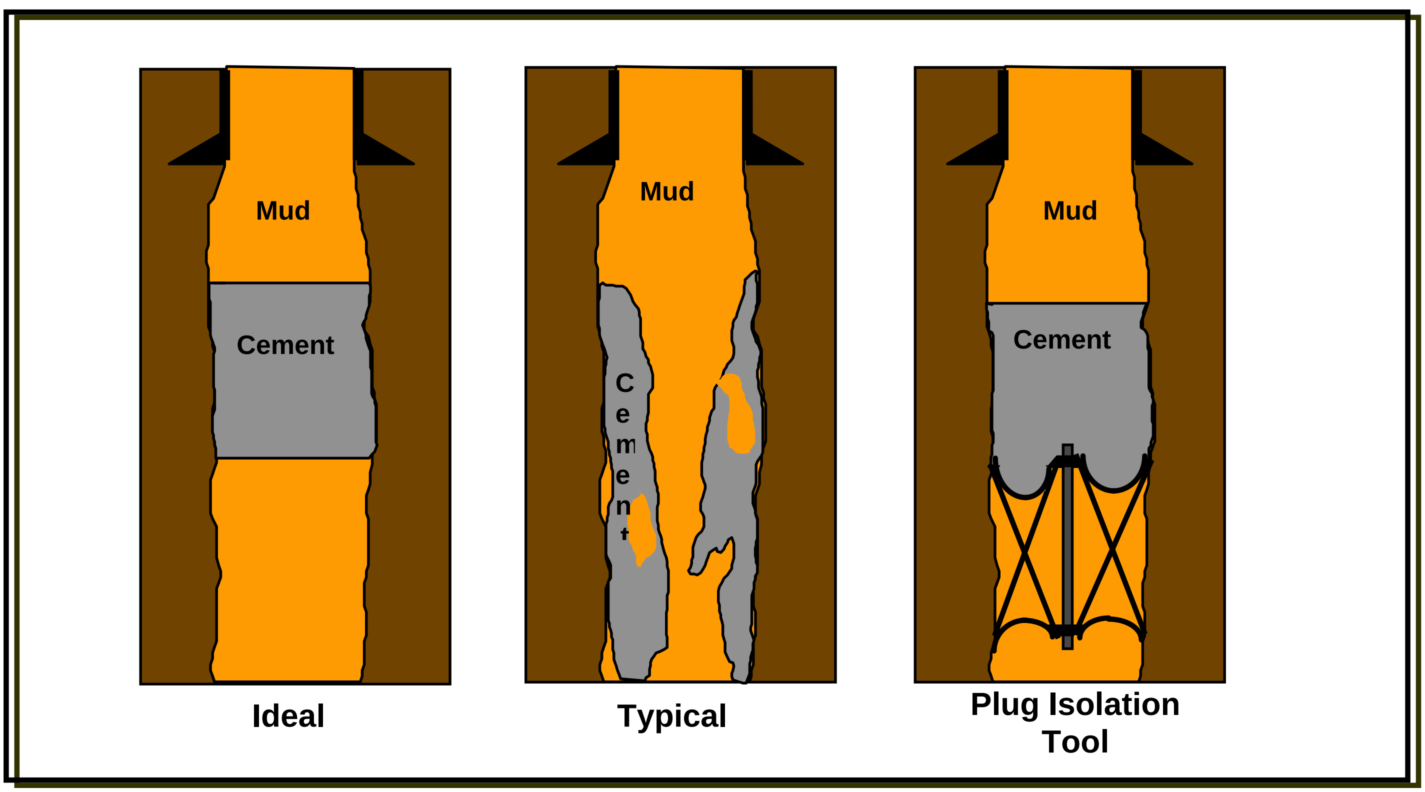

Fig. 2 – Ideal Plug Placement verses Typical Plug Placement

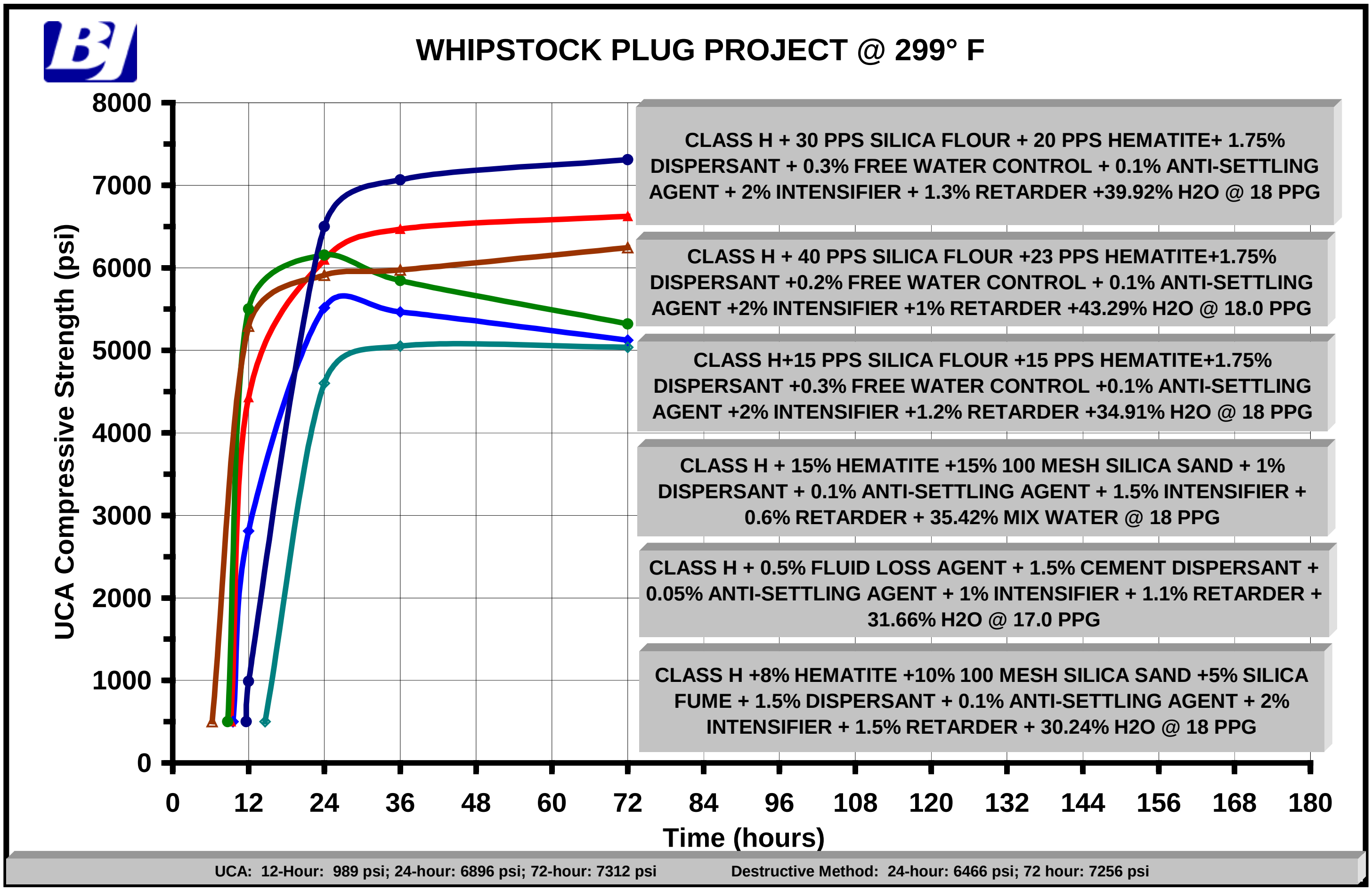

Fig. 3 – Compressive Strength as a Function of Time

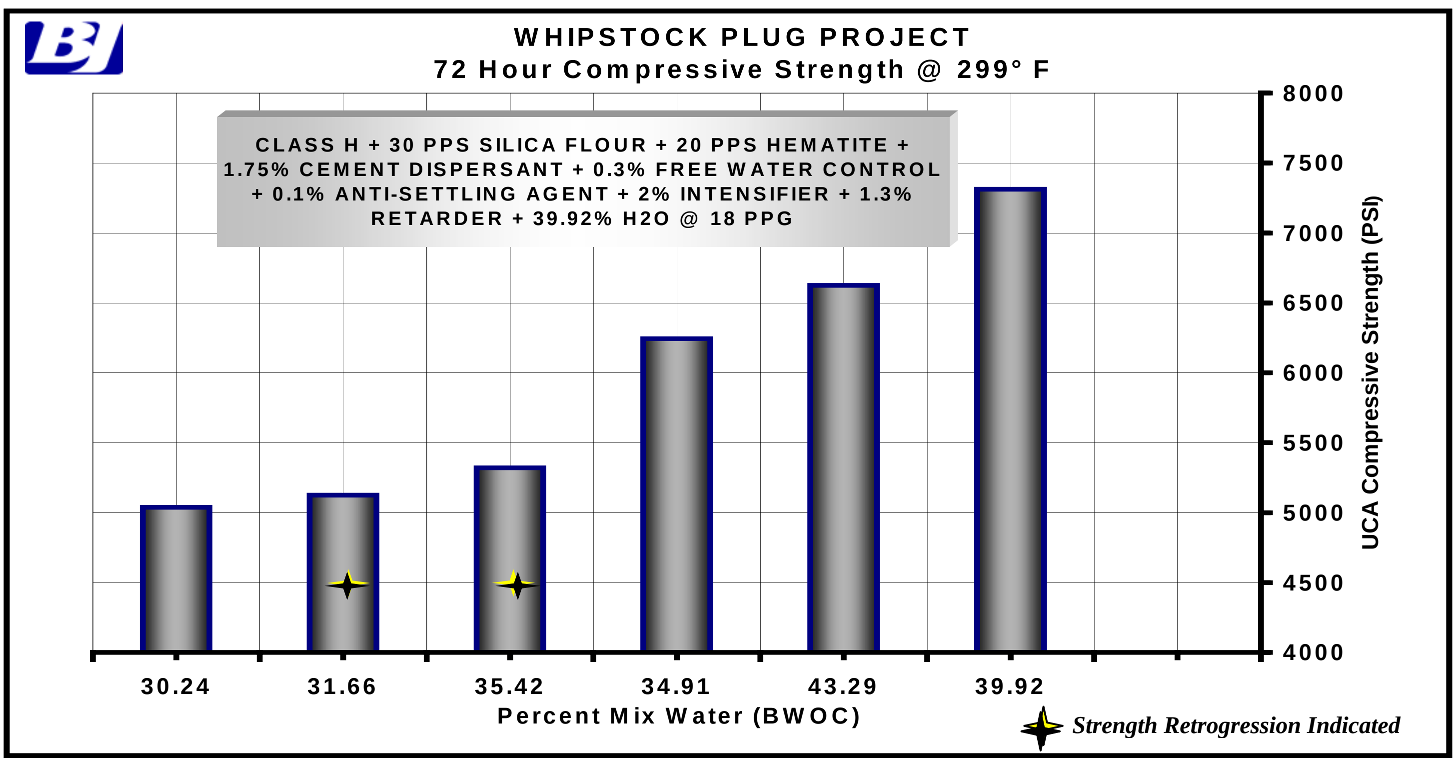

Fig. 3 – Compressive Strength as a Function of Percent Mix Water at 299° F