IMPROVED COMPRESSIVE STRENGTH EVALUATIONS IN FOAMED CEMENTS USING THE PULSE ECHO TOOL

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ABSTRACT

Experimental and theoretical methods to determine the compressive strength of cements using wireline interpretation techniques are the subject of several papers. Reasonable values of cement compressive strength result from the use of the techniques described when evaluating cements of "standard composition." Standard composition implies cement slurries not incorporating foaming additives for density reductions.

The introduction of foaming agents, notably air and nitrogen, complicates the relationship for compressive strength determinations based on wireline techniques. Bruckdorfer and Masson modeled the response of 20 kHz cement bond tools to derive an interpretation routine based upon attenuation rates of sonic signals propagating in foam cemented casings. Catala, et. al., related acoustic impedance and compressive strength for the case of ultrasonic cement bond evaluation tools, reporting linear relationships for "normal" and "lightweight" cements. The routine use of ultrasonic cement bond evaluation tools such as the Pulse Echo Tool* and the Cement Evaluation Tool+ creates the requirement for more precise knowledge of the tools' responses in foamed cements.

This work focuses on the testing of foamed cements which resulted in the determination of the relationship between compressive strength and acoustic impedance for foamed cements. Tests conducted on API standard cubes of varying composition and density indicated a significantly different trend for foamed cement as compared to standard cement slurries. Measurements of acoustic impedance and compressive strength led to the development of an improved algorithm for predicting compressive strength in foamed cements using PET logs. A point representing the acoustic impedance of water may be used as a calibration point to define compressive strength when cement composition changes. Experimental results and log examples show improved accuracy resulting from the use of the presented algorithm for compressive strength evaluations of foamed cements.

* Mark of Gearhart
\+ Mark of Schlumberger

INTRODUCTION

Over the years, various studies have demonstrated relationships between acoustic attenuation effects, compressive strength and shear modulus for different types of cement. The goal of these investigations was to quantify interpretive techniques used to evaluate cement jobs, and therefore determine if the hydraulic seal between casing and the formation will prevent migration of undesirable fluids.[2,8] Originally these investigations applied to Cement Bond logging, but have also been applied to the special cases of attenuation bond logs,[4] and ultrasonic cement bond logging tools.[3,5,6]

Experience with the ultrasonic Pulse Echo Tool (PET) and other tools of this type which present cement compressive strength values on the log raised questions regarding the applicability of the "average curves" used to relate acoustic impedance and compressive strength in varying cement types. A major objective of this experimental work was to obtain data on the response of the PET for the special case of foamed cements. Once obtained, the experimental data was used to correlate the acoustic response of the PET tool to measured compressive strengths of foamed cements. A discussion of the PET, the testing process, and the results of the experimentation are presented in the paragraphs which follow.

THE PULSE ECHO LOGGING TOOL

The PET was first described by Sheives, et al.[10] in 1986. It uses a double-helix arrangement of 8 transducers, each of which act as both transmitters and receivers of high frequency acoustic energy to investigate the circumferential casing response. The amount of attenuation of the returned acoustic energy pulse can be related to the certain characteristics of the cement/casing interface opposite the transducer. From sophisticated analysis of the normalized energy of the returned acoustic signal, values of acoustic impedance (the product of density and acoustic velocity) may be determined, which when plotted for a particular casing wall thickness may then be related to compressive strength for the portion of the casing opposite the transducers (Figure 1). Thus a representation of the bonding around the circumference of the casing is presented on the log in a graphical form, along with values of compressive strength. A circumferential bond presentation is particularly important in defining channels in the cement sheath, as related by Albert, et al.[1]

Additional analysis using an adaptive filtering technique allows direct determination of casing wall thickness from the returned signal, without assumptions of nominal wall thickness added to an acoustic caliper reading. Auxiliary measurements include hole deviation, relative bearing of a reference transducer, average internal diameter, average wall thickness, and other quality control curves.

Other authors have described the benefits of ultrasonic bond evaluation in situations which confuse CBL interpretation, such as fast formation conditions, or the presence of a microannulus. Additional work combined ultrasonic bond evaluation with standard CBL measurements to distinguish between gas and fluid behind casing.[3,6]

CEMENT COMPOSITION VARIABILITY AND INTERPRETIVE PROBLEMS

In many oil producing areas, primary cementing operations are plagued by serious problems with low fracture gradients, lost circulation, and gas migration. The use of foaming agents, principally nitrogen and air, instead of additional mix water to achieve reductions in slurry density without sacrificing compressive strength, ideally suits foamed cement to a variety of applications. While these foamed cement systems have improved cement integrity and completion efficiency, they have complicated cement bond log interpretation. Masson and Bruckdorfer[7] discussed standard CBL evaluation for foam cemented casings, and presented updated CBL evaluation nomograph to determine cement compressive strength. Published work regarding ultrasonic bond evaluation tools, like the PET, has heretofore ignored foamed cements.

Since the primary determinant of compressive strength from the PET is the measured acoustic impedance, which depends upon the ultrasonic velocity and density of material behind casing, it became apparent that the "averaged" relationships available were not applicable to the case of foamed cements. Indeed, PET compressive strength evaluations were recognized to be overly optimistic in foamed cemented casings, when compared to expected values of compressive strength based upon published cementing tables, and values determined from the CBL using charts proposed by Masson and Bruckdorfer.

LABORATORY ANALYSIS OF FOAMED CEMENTS

Class C and Class G foam cement samples from slurry densities of 8, 9, and 10 pounds per gallon were obtained. API standard 2 inch cubes were prepared, cured, and tested under identical conditions. Measurements of the specimens determined density, acoustic velocity, and compressive strength. The experimental apparatus to determine acoustic velocity was similar to that described by Rao, et al.[9]

Each sample cube was cured for over 72 hours, then placed between two PET transducers to measure transit time (reciprocal of velocity). The center frequency of the ultrasonic transducers used in the testing was 450 kHz. Immediately after the transit time measurements were completed, the sample cubes were crushed to determine compressive strength. Figure 2 shows the compressive strengths and acoustic impedance values of the tested samples.

EXPERIMENTAL RESULTS

Laboratory measurements of ultrasonic velocity, density, and compressive strength performed on the foam cement samples led to the derivation of an empirical, linear relationship between acoustic impedance and compressive strength. The compressive strength value corresponding to the intersection of the best-fit line through the test sample data points, and the acoustic impedance of water represents a calibration point for identifying free casing in a cement bond evaluation. In other words, for the water-casing-water model, each defined relationship assigns a value of compressive strength for the water behind the casing. Since water has no compressive strength, the calibration value is physically meaningless--except to serve as the basis for log interpretation.

Evaluating the integrity of the cement sheath would be difficult without assigning a value of compressive strength for some standard condition, in this case, the water-casing-water model, or free pipe condition. All cement bond interpretation schemes depend upon knowledge of the free pipe reference in order calculate cement integrity. If one can accurately identify free casing, then the determination of bonding throughout the cemented section with a great degree of confidence.

For comparison, Figure 3 shows the relationships between acoustic impedance and compressive strength for several cement types commonly used in oilfield operations. Obviously, the type and amount of additives, curing time and temperature, and many other factors influence the development of compressive strength of a cement system. Acoustic impedance measurements depend upon sample density and acoustic velocity, both affected greatly by variability in cement composition. No single relationship will precisely define the compressive strengths of all cement systems. Accordingly, relationships for common oilfield cements whose acoustic and mechanical properties have been studied are now available for use in the field logging units. The logging engineer selects the proper cement type for the interval being logged, and the appropriate compressive strength relationship is applied to the tool response to yield values of compressive strength much closer to the expected strengths than has been possible using some average response line.

EXAMPLES OF LOG RESPONSES

The first log example (Figure 4.a) and the accompanying chart (Figure 4.b) show the familiar CBL interpretation in a foam cemented interval using the method outlined by Masson and Bruckdorfer. Compressive strengths calculated for the interval correspond well to the ideal values listed from cementing tables for the encountered well conditions. Based upon the average relationship, the PET yields compressive strengths higher than those determined from CBL response, (Figure 5.a).

The curves depicted in track 2 of Figure 5.a include the maximum compressive strength MAXCS, the minimum compressive strength MINCS, and a mean value CS-A, for a particular depth. The cement map in track 3 is shaded to correspond to the calculated compressive strengths for each of the 8 transducers. Deviation and relative bearing traces identify hole inclination, and the position of transducer number 1 with respect to the high side of the hole, respectively.

The next log section (Figure 5.b) shows the PET data recomputed using the foam cement relationship developed in this study. Presented values of compressive strength are much closer to the expected values, and are reasonable considering the composition of the cement system. Both minimum and maximum values fall into the expected range of compressive strengths, indicating that the new relationship improves interpretations in foam cemented intervals. The cement map in track 3 differs from Figure 5.a because compressive strengths have changed according to the new relationship derived for foam cement.

Figure 3 indicates the water point (acoustic impedance of 1.5 x 10**6 MKS) which determines the free casing response. For the foam cement line, the corresponding compressive strength for free casing is approximately -100 psi. The higher slopes of the other lines define free pipe responses at much lower values of compressive strength. This difference in the resulting compressive strength of free pipe intervals, and the depiction of those strengths on the cement map may lead to overestimation of the radial extent of a cement channel when the wrong cement relationship is used. The existence of a channel is confirmed by the PET in either case.

Table I summarizes the calculated compressive strengths from the different logs displayed. For the table, mean compressive strength values are listed for the PET results. The relatively lower compressive strengths determined using the standard cement bond method reveal that in this interval, the CBL is primarily responding to the channel apparent on the PET log.

CONCLUSIONS

Laboratory testing of foamed cements of varying density and composition allowed determination of an empirical formula relating acoustic impedance and compressive strength. This relationship has been included in the software of the Pulse Echo Tool (PET) to improve cement bond evaluations of cased wells. A point representing the acoustic impedance of water may be used as a calibration point for distinguishing between water, cement, and gas behind casing. Interpretations from PET logs presented demonstrate the advantages of the technique.

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Table 1
Calculated Compressive Strength Comparisons

Depth ft.	CBL psi	PET(avg.) psi	PET(foam) psi
5774	800	2750	1450
5871	1700	3650	1750
5887	700	2000	1150
5906	680	3100	1600
5916	900	3500	1750

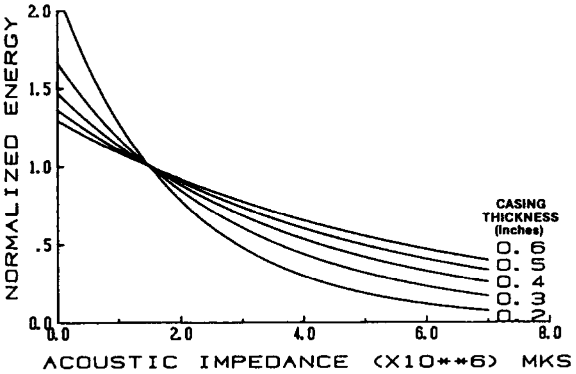

Figure 1

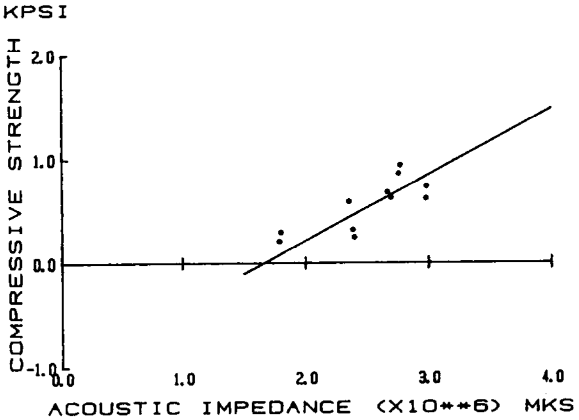

Figure 2 - Sample points

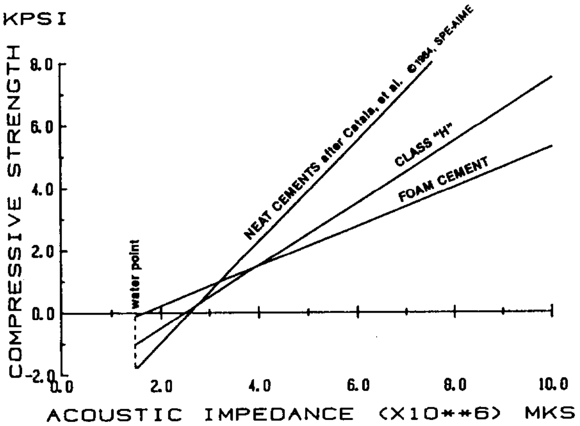

Figure 3 - Cement relationships

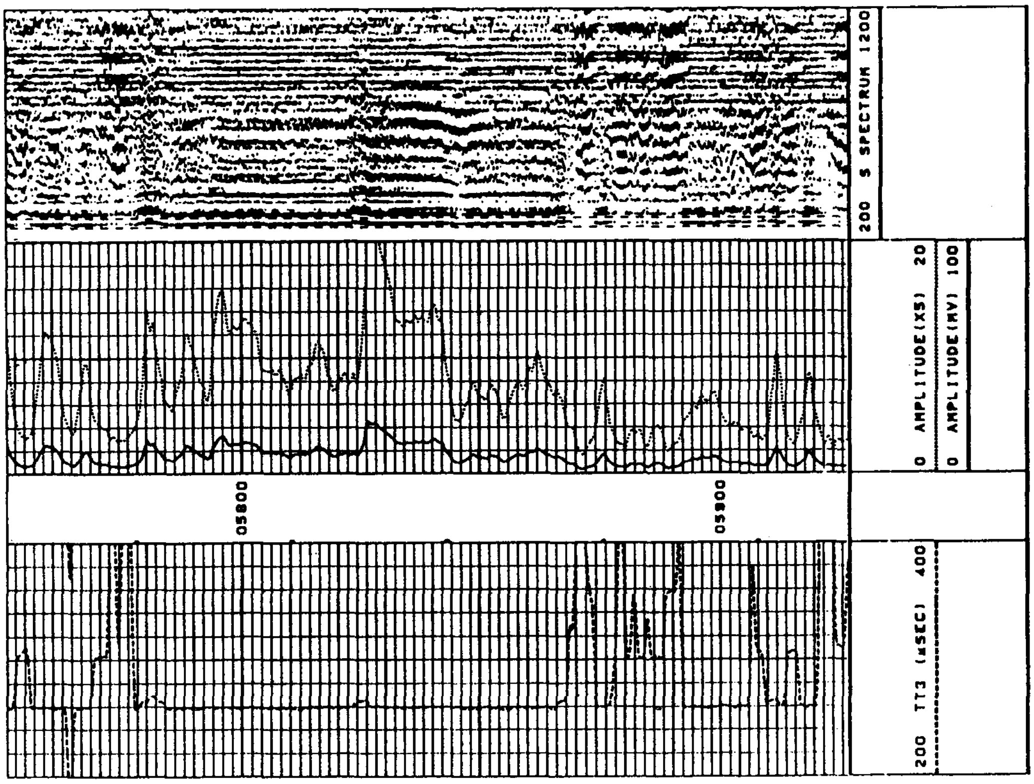

Figure 4a

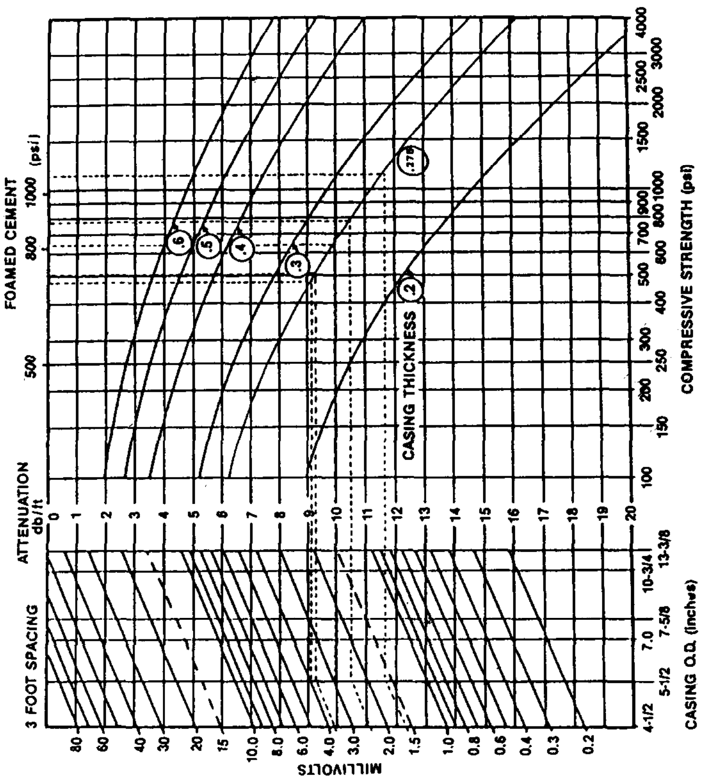

Figure 4b - Cement bond log interpretation chart

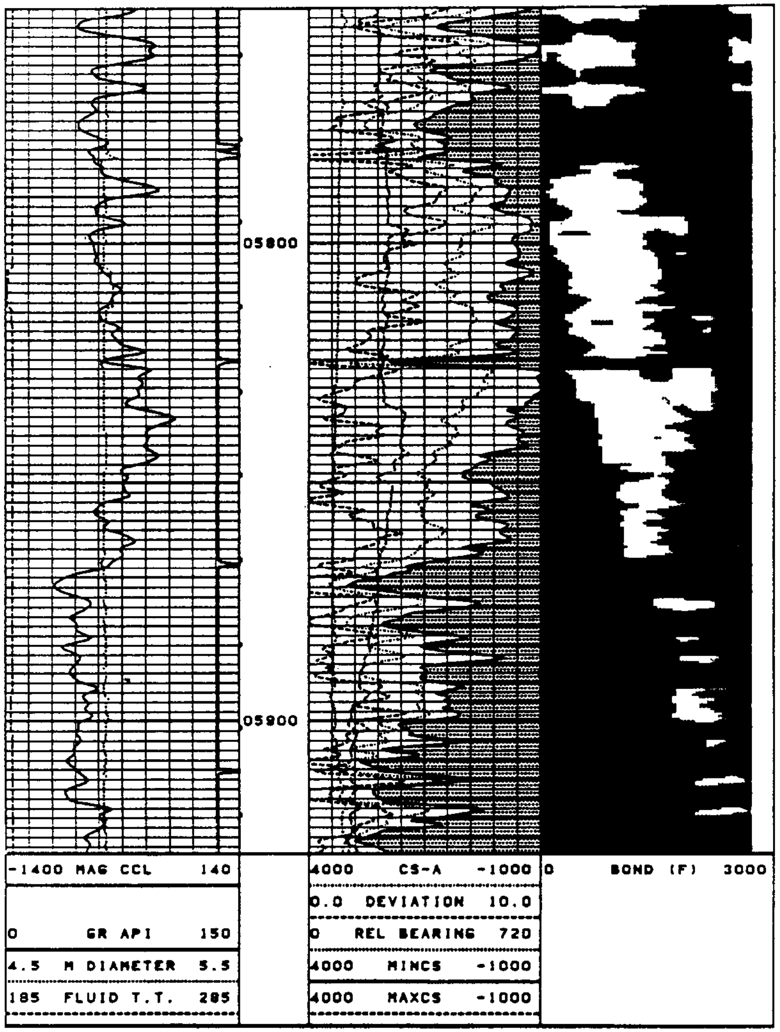

Figure 5a

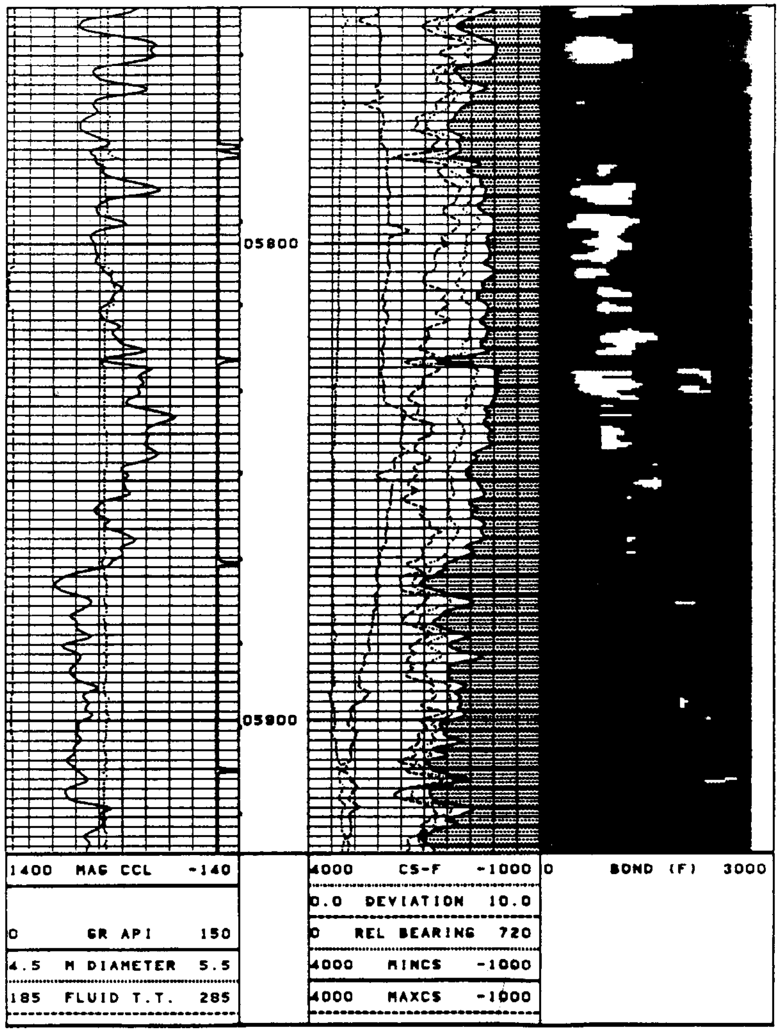

Figure 5b