Advancing Cement Paste Shrinkage Modeling: Investigating The Normalized Ultrasonic Pulse Transit Time Evolution And Its Impact On Stress Analysis In Oil Wells

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Abstract. This study presents a new modeling approach for predicting cement paste shrinkage evolution, with a specific focus on its relationship with transit time, and consequently with the hydration of the cement paste. Cement plays a crucial role in well integrity, and therefore, cement shrinkage is a critical factor in stress analysis within oil wells. By developing a proper modeling technique, it becomes possible to numerically calculate the residual capacity of the cement sheath, accounting for thermal and pressure loads throughout the well's lifespan. In this research, a new modeling approach is proposed for the evolution of shrinkage based on cement slurry cured under temperature 60 °C and pressure of 1.0 kpsi. The development of the cement was analyzed using ultrasonic pulse velocity and volumetric shrinkage tests over a period of 90 hours. The newly developed shrinkage evolution model is compared to the traditional linear adjustment method, considering the degree of hydration.

Keywords: cement shrinkage, finite element method, transit time, degree of hydration, remaining capacity.

1 Introduction

Numerical analysis techniques are employed to assess the impacts of cement paste shrinkage on stress distribution and evaluate the integrity of the cement sheath under various loads encountered during well construction and operation, such as pressure testing, fluid exchange, and production. The findings presented in this paper introduce a novel modeling approach that enhances the accuracy of numerical simulations for cement sheath integrity [1]. As a result, it offers the potential for more reliable cementing designs for offshore scenarios. Moreover, this refined modeling approach contributes to a more comprehensive understanding of the behavior of cement paste shrinkage in oil wells and enables more reliable stress analysis predictions. These insights can aid in the optimization of cementing practices and enhance the long-term stability and performance of oil wells.

For sensitivity analysis of the results, a numerical solver based on finite elements was used, which calculates displacements and stresses in the cement sheath [2]. This method is employed to numerically solve differential equations in various physics domains. Its approach aims to model the studied system with a finite number of simpler elements and obtain an approximation of the response by grouping these elements. As showed in Figure 1, this model is one-dimensional, considering axial symmetry (r, θ) for the well circumference and plane strain deformation at depth (z).

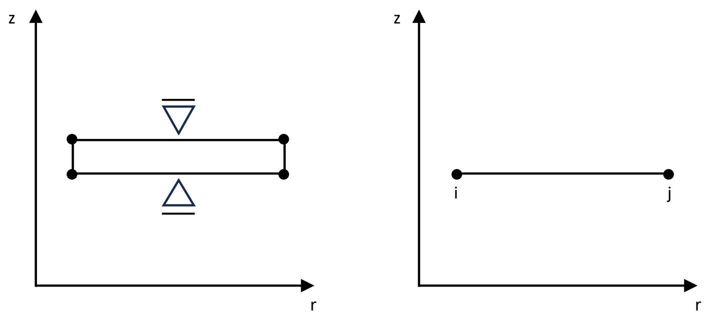


Figure 1. Model Simplification.

2 Experimental Results

The employed cement paste formulation is outlined in Table *1*. The cement curing process occurred under conditions of 60°C and a pressure of 1.0 kpsi.

Table 1. Cement paste formulation.

Formulation	Water/Cement = 0.36
Material	Concentration
Class G Cement	72.18 %
Industrial Water	4.06 gps
Defoamer	0.01 gps
Fluid Loss	0.12 gps
Dispersant	0.06 gps
Retarder	0.04 gps
Free Fluid Control	0.043 gps

2.1 Transit Time and Displacement

Figure 2 illustrates the findings obtained through measurements of ultrasonic pulse transit time and piston displacement. Involving a cylindrical cell, the pressurized shrinkage equipment is designed for replicating downhole conditions on a predetermined volume of cement paste. This equipment employs a diaphragm, a displacement piston, and a Linear Variable Differential Transducer (LVDT) to continuously gauge the apparent volumetric alteration [3]. At around 22 hours of testing, a noticeable decrease in transit time emerges, marking the onset of the phase transition from the paste's liquid to solid state. This period of transit time reduction aligns with a simultaneous decline in displacement.

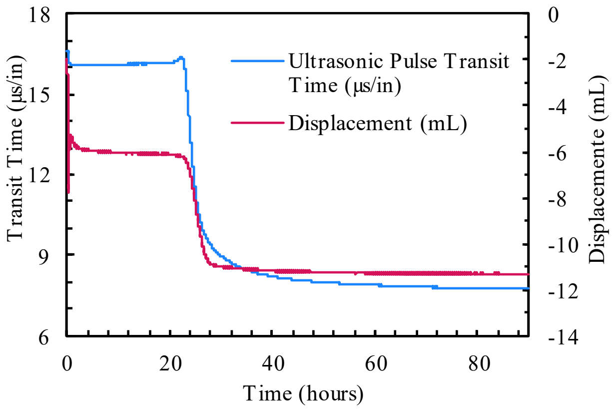


Figure 2. Ultrasonic Pulse Transit Time (µs/in) and Displacement (mL) x Time (h).

2.2 Normalized Ultrasonic Pulse Transit Time and Bulk Shrinkage

Figure 3 presents the treated curves of bulk shrinkage and ultrasonic pulse transit time, both shown over time. The overall shrinkage of the cement paste reached 2.6%. Moving to Figure 4, it illustrates the temporal progression of the normalized bulk shrinkage and ultrasonic pulse transit time curves, identifying the moment when the curves reached the value of 0.1. This juncture served as the basis for correlating the two curves. Transitioning to Figure 5, it reveals a direct relationship between normalized bulk shrinkage and transit time. A noticeable distinction is evident, characterized by two linear segments. The point that connects the two lines is designated as the inflection point.

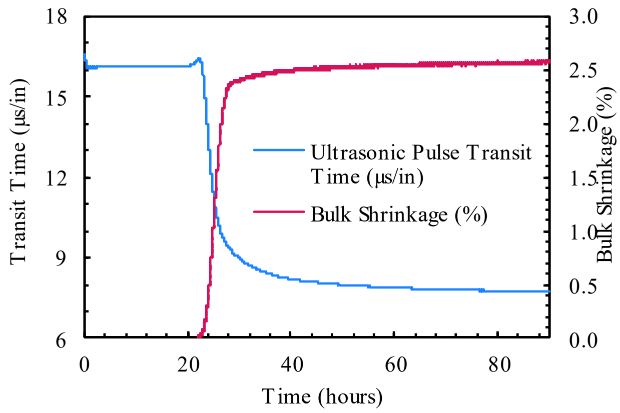


Figure 3. Ultrasonic Pulse Transit Time (μs/in) and Bulk Shrinkage (%) x Time (h).

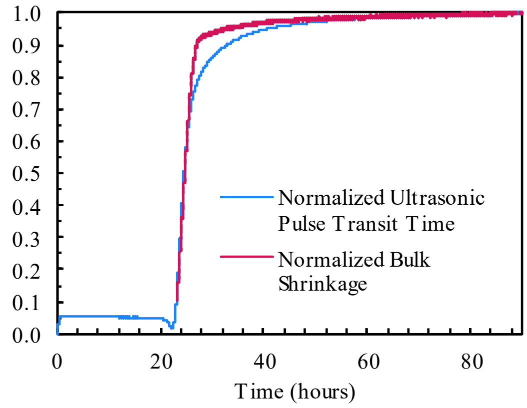


Figure 4. Normalized Ultrasonic Pulse Transit Time and Bulk Shrinkage x Time (h).

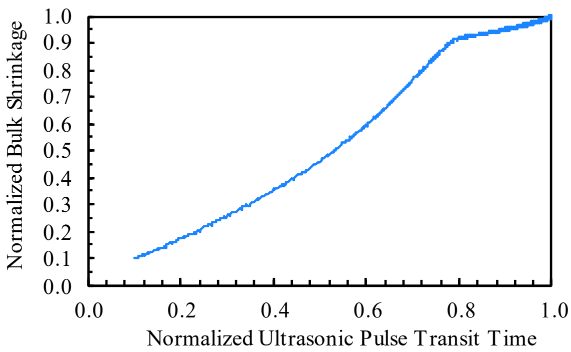


Figure 5. Normalized Bulk Shrinkage x Normalized Ultrasonic Pulse Transit Time.

3 Modelling

In this model, the equations governing the problem are deduced within the thermodynamic theoretical framework, considering the interplay between hydration reaction, temperature evolution, deformations, and alterations in concrete properties. As key considerations, the following are highlighted:

- It treats the paste as a chemically reactive substance.
- In the initial phase, it behaves as a fluid containing water as the continuous medium, transitioning into a solid only after reaching its percolation threshold.
- The heat released by the hydration reaction is considered in the thermal simulation.
- The cement temperature impacts the hydration rate following an Arrhenius law.

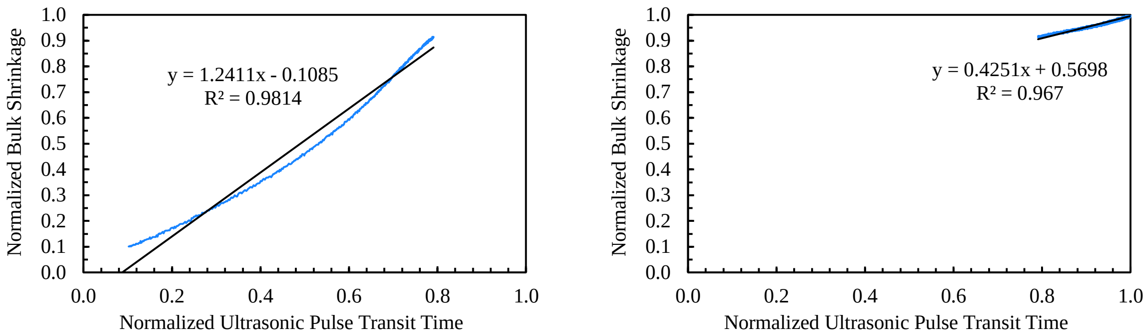
Bentz [4] reviewed the effect of hydration degree on cement paste properties. The specific heat of water is 4180 J/(kg·K), while that of cement is 750 J/(kg·K). The higher the water content in the cement paste, the greater its thermal capacity. Consequently, specific heat decreases with hydration. The thermal conductivity of the fluid paste is a combination of the conductivity of the base fluid (water and additives) and the solids. Water has a conductivity of 0.604 W/(m·K), while pure cement has a conductivity of 1.55 W/(m·K). Bentz [4] obtained an approximately constant value of 1.0 W/(m·K) ± 10% for the tested pastes. The coefficient of thermal expansion is affected by the hydration degree [5], an effect that seems to be correlated with free water content, which decreases during shrinkage. Despite its significant impact, this effect is mainly concentrated at low hydration degrees and does not appear to follow a general rule.

Variations in the elasticity modulus and Poisson's coefficient reflect the transition from a fluid to a solid state. The percolation threshold depends on the water-cement ratio (w/c) since cement grains need to come into contact, which depends on the water quantity in the paste. [6] found a strong correlation between the w/c and degree of hydration (ξ). The threshold linearly varies from $\xi = 0.028$ to 0.042 for w/c from 0.25 to 0.40. After percolation, the Poisson's coefficient reduces to the value measured in the solid state, and the elasticity modulus increases to its final value. De Schutter & Taerwe [7] reviewed the evolution curves of the elasticity modulus and reported that most authors consider the modulus grows with the square root of the hydration degree, starting from percolation. De Schutter & Taerwe [7] reported that uniaxial compressive strength linearly increases with the hydration degree from percolation (which they determined as 0.3). The same applies to tensile strength.

Given that the model used for the numerical simulations considers the variation of properties with hydration degree, it's important to emphasize that, for the specific purpose of analyzing the shrinkage phenomenon, all the previously mentioned cement properties were held constant. This approach allows for an isolated analysis of the modeling based on the experiment in comparison with the traditional linear fit.

3.1 Shrinkage Evolution Modeling

In Figure 6a, the inflection point occurs at a normalized ultrasonic pulse transit time about 0.8, while the bulk shrinkage reaches a value of 0.9. In Figure 6b, these two segments are visualized separately, and each of them has a straight-line equation with an R^2 greater than 0.9.



(a) Before inflection point (b) After inflection point

Figure 6. Normalized Bulk Shrinkage x Normalized Ultrasonic Pulse Transit Time.

In the numerical simulation, the normalization of ultrasonic pulse transit time was employed to represent the progression of hydration degree. Consequently, it becomes possible to utilize the correlation between the variation in shrinkage and the degree of hydration.

3.2 Case

To conduct the sensitivity analysis using the experimental shrinkage modeling, a well configuration (Figure 7) was designed, where the key information of the utilized scenario and the fictional properties of the paste are listed in Table 2 and Table 3.

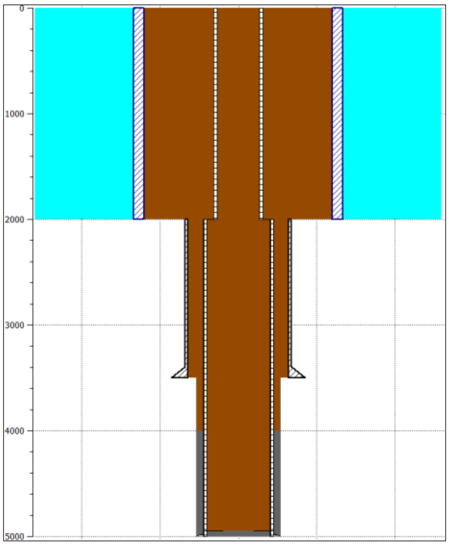


Figure 7. Case Study.

Table 2. Scenario.

Mud Line	2000 m
Previous Casing	10 3/4”
Current Casing	7”
Open Wellbore	8,5”
Cement Density	16.5 ppg
Top of Cement	4000 m
Botton of Cement	5000 m
Analysis Depth[1]	5000 m

[1] Excluding the Shoe Track.

Table 3. Cement Slurry Properties.

Young's Modulus	10 GPa
Poisson's Ratio	0.16
Thermal Expansion	5.6e-06
Thermal Conductivity	1.6 W/m.°C
Specific Heat	1034 J/Kg.°C
Tensile Strength	1500 psi
Friction Angle	20°
Cohesion	35 GPa
Bulk Shrinkage	2.6%

4 Results and Discussion

The simulation for analyzing the integrity of the cement sheath was exclusively focused on the cement paste curing process over a period of 5 days. The analysis of results was performed at a depth of 5000 meters. Figure 8 depicts the temperature of the cement sheath, demonstrating the observable temperature increase over the course of days due to the exothermic hydration reaction and the influence of the higher formation temperature, which consequently imparts heat to the cement.

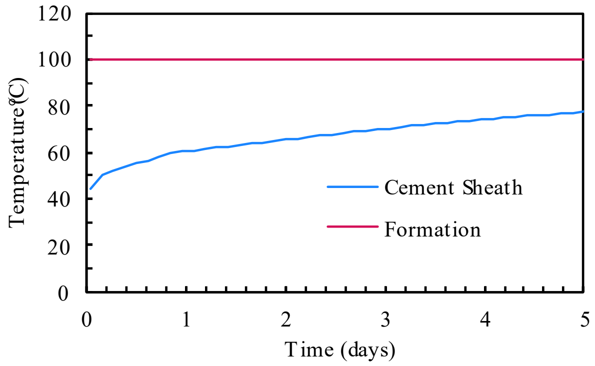


Figure 8. Temperature (°C) x Time (days).

Figure 9 presents the evolution of the cement's degree of hydration over time, indicating that within 5 days, for the specific scenario created, the cement paste's hydration reaches 100%.

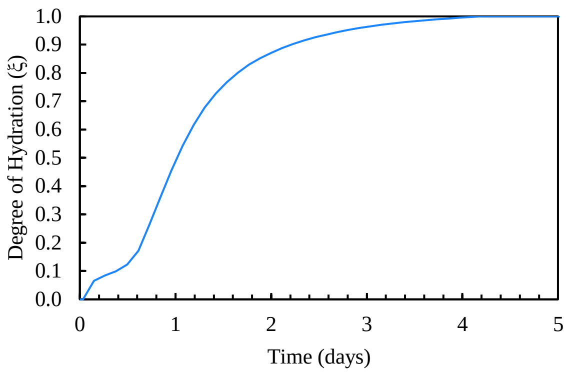


Figure 9. Degree of Hydration x Time (days).

Comparing the linear cement shrinkage model with the experimentally adjusted model from the previous chapter, as shown in Figure 10, it is evident that the curves largely coincide during the latter stages of hydration. Thus, a difference in the simulation outcome of cement integrity is expected.

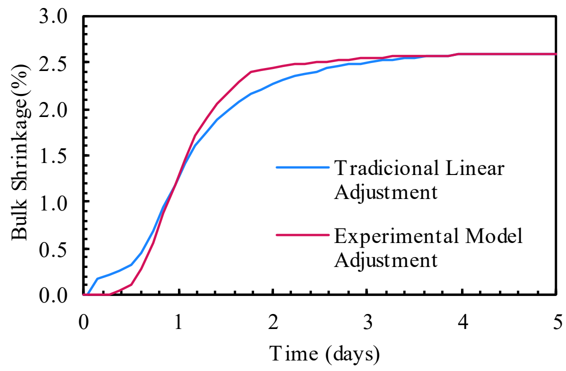


Figure 10. Bulk Shrinkage x Time (days).

The result of remaining capacity (RC) for both adjustments is illustrated in Figure 11. The RC reflects the ratio between the stress exerted on the cement sheath and its ability to withstand it. It can range between 0% and 100%, where 0% signifies the cement entering the plastic regime, and 100% denotes a state of neutral stress. As per the results displayed in Figure 11, during the cement curing process, the new model yields lower RC values. What's being observed is that the new model anticipates shrinkage related to hydration, which could potentially lead to advantageous outcomes due to the lower modulus of elasticity and reduced stress accumulation. In other words, for greater maturities, a smaller amount of shrinkage is expected, resulting in reduced stress on the cement sheath due to this phenomenon.

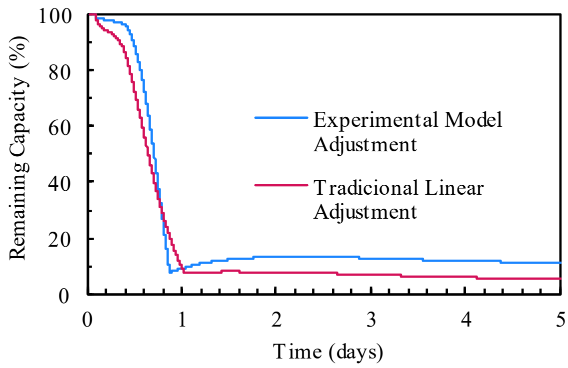


Figure 11. Remaining Capacity (Mohr-Coulomb) x Time (days).

5 Conclusions

This study highlights the significance of accurately modeling cement paste shrinkage in well integrity analysis. The proposed evolution model, which considers the correlation between shrinkage and ultrasonic pulse transit time, offers a more comprehensive understanding of the complex interactions within the cement sheath. The comparison between the newly developed model and the traditional linear adjustment highlights the importance of a nuanced approach in predicting cement behavior. While the linear model provides a simplified approximation, the experimentally adjusted model better captures the evolving nature of shrinkage. This finding reinforces the need for advanced modeling techniques in addressing the challenges associated with cement shrinkage in oil well operations.

Moreover, the exploration of remaining capacity (RC) via both modeling methodologies illuminates the possibility of enhancing stress analysis in oil wells. The results highlight the importance of customized modeling techniques in addressing the distinct challenges posed by cement behavior in well integrity assessment.

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