A Brief Review of Gas Migration in Oilwell Cement Slurries

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Abstract: Gas migration in oil and gas wells is defined as gases and/or fluids from adjacent formations invading a freshly cemented annulus. During well completions, gas and/or fluids can migrate to zones with lower pressure or even to the surface. Static gel strength (SGS), related to the yield stress of the cement, is a widely accepted measurement used to predict and minimize gas migration. In this review article, we look at the mechanisms and some possible solutions to gas migration during oil and gas well cementing. The use of static gel strength (SGS) and experimental measurements for SGS and wellbore pressure reduction are discussed. Rheological properties, including the yield stress and the viscosity of cement slurries, are also briefly discussed. Understanding the rheological properties of cement is complex since its material properties depend on cement type, as well as the shape and size distribution of cement particles. From this brief review, it is evident that in order to reduce free water and settling of the cement particles, to lower fluid loss, and to develop compressive strength in the early stages of cementing, an optimal cement slurry design is needed. The SGS test is a standard method used in estimating the free water in the well and could be a reference for gas migration reduction for oilwell cement slurries.

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1. Introduction

Cement is, in general, a non-linear complex fluid that sometimes behaves as a viscoelastic material and sometimes as a viscoplastic material. Gas migration and leakage within the cemented annulus were recognized in the 1960s. Research investigations and possible solutions to prevent and control gas migration are ongoing. In the oil and gas industry, it has become the standard and the recommended practice (API RP 10B-6) [1] to use the static gel strength (SGS) to measure the developing yield stress and gelling of the cement slurry as it hydrates and hardens. SGS is used in determining the transition time, traditionally defined as the time it takes a slurry to change from a fluid-like material to a solid-like one and no longer transmitting the hydrostatic pressure to where the slurry has developed a gel strength that resists gas percolation through the cement column [2]. SGS will be defined further in Section 2.3.

Gas migration, also referred to as gas leakage, annular gas flow, gas channeling, or gas invasion [3,4], is considered a serious problem worldwide in oil and gas wells. Gas migration issues are estimated to represent about 25–30% of the primary cement job failures during well completion [5,6]. More recent and comprehensive studies that look more globally at barrier and integrity failure of both onshore and offshore wells of varying ages show barrier and integrity failure rates ranging from 1.9–75% [7], with reported gas-migration-specific barrier failure at 22% [7]. The highest estimate includes all well integrity failures, which include gas migration through primary cement jobs, though the estimated number has not been specified.

Early researchers have indicated that gas flow through wellbore cement slurry is caused by the reduction of the wellbore pressure of the cement column, which is related to

low density, inadequate bonding and displacement, excessive settling of the particles, gelation, filtration, bridging, water separation, and chemical shrinkage [4,8,9]. Surveys or field data rely on predictive techniques such as the use of special cements; mud displacement; and casing condition [10]. Researchers have offered some solutions to the problem of gas migration: using special seals, using cement containing filtration control, high slurry compressibility, high fluid density, having a shorter cement column (stage cementing), applying an annulus pressure against the pressure drop in the formation, ways to lower the free water which is a layer of water on top of the cement, using cement with thixotropic agent for customized jobs, modifying the viscosity of gelation both chemically and mechanically, using chemicals to reduce the gas flow, and using salt cements [2,11–16].

It is a challenge for the petroleum industry to (1) prevent the gas migrating into the cement slurry during the hydration process and (2) maintain the annular cement seal and well isolation for the long term applications [17–22]. Well integrity issues during the production can lead to loss of product (i.e., oil and gas) and are expensive to remediate. In the past few decades, a great deal of research has been performed to study and solve this issue, although the exact failure mechanisms of the problem are complicated and gas migration problems continue to occur [23–32].

2. Gas Migration in a Cement Column

This Section is a summary review of the research conducted to understand the mechanisms that control gas migration and leakage through the cement column.

2.1. Mechanisms of Gas Migration in Well Cement Slurry

Carter and Slagle [12] seem to have been the first researchers who explained the problem of gas migration, at the cement–casing–formation interfaces. They considered the fluid column density and the filtration control as the most important factors in preventing gas migration. The fluid column density (hydrostatic head) must exceed the formation gas pressure to prevent gas invasion and migration through the cement annulus. When cement is in its fluid-like state, gas migration can occur if the gas pressure is greater than the hydrostatic pressure of the cement slurry. After the initial setting of the cement, gas migration can continue due to the formation of a few or many channels as the gas pressure decreases. During the cement hydration process, the gas can migrate, which can cause channeling through the permeable zone(s) where the filter cake is built. Additionally, the bridging of particles in cementing operations and gelation in the cement slurry can cause loss of hydrostatic pressure. During the gelation process, viscosity increases significantly. The duration of the gel state depends on temperature, composition, pressure, and water-to-cement ratio [33–36]. Cheung and Beirute [37] proposed, through conducting several tests, that the pore pressure inside the cement becomes independent of the hydrostatic load when the cement starts to bear the load due to the hydration process. Gas migration occurs primarily when the pore pressure inside the cement drops below the formation gas pressure, and as a result the gas can invade and penetrate the cement. Figure 1, based on [38], indicates how the gas enters the annulus. According to Bol et al. [38], as the cement begins to set, its ability to transmit the hydrostatic pressure decreases; this can cause a lower water content and a lower pore pressure resulting in gas migration into the cement.

Bonett and Pafitis [17] provided some predictions and solutions to gas migration issues in cementing operations. They considered density control, mud removal, and slurry design to be the important factors to be considered in cementing operations. According to the authors, the annular cement column progresses with time and behaves differently in different stages: (1) initially the slurry is a granular suspension which can transmit hydrostatic pressure fully; (2) next, the slurry becomes like a two-phase material with a solid component (cement reaction products) and a fluid component, namely, the pore fluid forming a gel; (3) finally, the cement becomes an impermeable solid after setting. In their approach, Bonett and Pafitis [17] assumed that the wall shear stress (WSS) is equal to the static gel strength (SGS). The authors also reviewed software (GASRULE and CemCADE),

which can be used to study problems related to gas migration. The software considered four design factors: formation, the removal of mud, postplacement, and the performance of the slurry. In addition, Bonett and Pafitis [17] calculated the WSS, which is capable of supporting the annular column during the gelation process and describing the reduction in the pressure. Figure 2, based on [17], depicts gas migration in oilwell cement slurries.

Figure 1. A diagram describing how gas enters the annulus. Developed from Bol et al., 1991 [38].

Figure 2. Gas migration in oilwell cement slurries. Developed from Bonett and Pafitis, 1996 [17].

Talabani et al. [39] defined three different mechanisms of gas migration in the cement annulus: (1) gas migration between the casing and cement (influenced mostly by the temperature effects on the slurry hydration but also by pressure and temperature on the bond between the metal and the cement); (2) gas migration between the cement and the borehole wall (due to water losses in some formations followed by an incomplete hydration reaction); (3) pressure changes in the cement during the setting (creating fractures in the microstructure of the cement).

Ahmady et al. [32] found that gas migration issues in wells in the Montney Formation area of British Columbia, Canada were caused by loss of filtrate and the reduction in volume due to hydration, leading to the surface casing vent flow (SCVF). The authors indicated that the gas migration could be caused by (1) the failure to properly and sufficiently remove the drilling fluid from the system; (2) poor cement bonding, which can include poor initial bonding and debonding of the cement; and (3) cement practices with high gas-flow potential factor (GFP).

2.2. Possible Mechanisms to Reduce or Eliminate Gas Migration

Levine and Thomas [40] indicated that if there is a gas flowing through cement, then the effective hydrostatic head is decreased during the initial curing period. They proposed a graphical technique to predict the gas flow during the cementing process. They plotted their results by showing the relationship between the depth of the gas zone versus the hydrostatic pressure versus the pore pressure. Levine and Thomas [40] proposed several preventive techniques, including (1) minimizing the height of the cement column, increasing the surface pressure on the annulus; (2) increasing the mud density and the density of the cement mixed with water; and (3) adjusting the cement slurry thickening times to decrease the gas flow. Tinsley et al. [41] summarized the different types of annular gas flow with different terrains by conducting high-pressure tests on various cement slurries. The authors suggested that it is most effective to reduce the gas migration by increasing the compressibility of the cement slurry or by counterbalancing the cement volume decrease. Tinsley et al. [41] recommended fluid-loss controlled slurries with Fluid Loss Additives (FLAs) for less fluid transmissibility, which allows a lower pore pressure. Cooke et al. [42] reported the results of field measurements for pressure and temperature in cement columns. They observed that the annular pressure in the cement column started to decrease shortly after the pumping process had begun; this was likely caused by the volume reduction combined with adequate gel strength of the cement. The authors also suggested applying additional surface pressure to prevent the hydrostatic pressure drop by compensating the volume reduction and breaking the gel strength in the cement column. Hartog et al. [43] developed a theoretical model to illustrate the mechanics of hydrostatic pressure loss, which causes annular gas flow. The theoretical model could help define specific cement designs by considering the cement-formulation variables such as the high-temperature high-pressure (HTHP) fluid loss, time to place the cement, and cement displacement velocities. The authors provided some recommendations for the drilling fluid (avoid gelled and thick mud cakes in the hole), water spacers (150 m), cement slurry design (highly thinned scavenger cement slurry), drilling fluid loss (12.2 inch³), displacement velocities (393.7 ft/min), well, and casing conditions (pipe reciprocation for well and efficiently centralized casing). Bannister and Lawson [44] studied the behavior of cement when there is fluid-loss in the wellbore, which could affect the loss of hydrostatic pressure, resulting in gas migration. The authors suggested increasing the overbalance pressure and the annular gap, applying a high water-to-solid ratio cement slurry design and considering appropriate cement fluid loss, mud fluid loss, and cement compressibility. Cheung and Beirute [37] suggested reducing the mobility of the cement filtrate (fluid) in the pore spaces during early hydration by increasing the filtrate viscosity and mechanical bridging of the pore spaces by adding a fluid-loss-control polymer. They also indicate that the conventional fluid-loss control at the cement interface alone is not enough to prevent the gas migration. They also [45] evaluated the performance of the impermeable cement system in controlling gas migration, and the success rate of the cement system was over 90%.

The transition time of the cement slurries has been defined in various ways, including right-angle-set related to the transfer from pumpable to a non-pumpable state, wait on cement (WOC) time, and SGS to 500 lbf/100 ft². Sabin et al. [2] defined cement transition time as the period during which the slurry changes from a basic fluid to a highly viscous one showing some solid-like characteristics. The authors indicated that the main cause of gas flow in the cement is the incompressibility of the cement slurry during the setting process. The authors suggested that the gas flow in the annular region can be prevented if the pressure in the cement near the high-pressure gas zone can be maintained at a value greater or equal than the pressure of the gas until the end of the transition time. The end of the transition time was established by Sabins and Tinsley [2], where the cement slurry developed a SGS value of 522 lbf/100 ft². Sabins and Sutton [23] studied the relationship among the thickening time, the gel strength, and the compressive strength of the oilwell cements and indicated that the thickening-time and the compressive-strength tests are

not adequate to evaluate the gas migration potential in oilwell cement field laboratories. According to these authors, the SGS development under HTHP conditions could be used for predicting the behavior of the cement slurry in the downhole. The authors also indicated that the time for the development of the SGS is related to the type of cement slurry and not to the thickening time. It was also pointed out that the 12- and the 24-hour compressive strengths do not decrease with the increase of the thickening time. Sykes and Logan [46] mentioned that the causes of the pressure loss resulting in the annular gas migration are cement gelation and volume reduction. From the SGS tests, they suggested ways of preventing gas flow by delaying the development of the gel strength and by rapidly setting the cement, which allows full hydrostatic pressure transmission and prevents gas invasion. Figure 3, based on [46], shows the effect of delayed gel strength development.

Figure 3. Gel strength development for normal cement slurry vs. delayed gel strength slurry. Developed from Sykes and Logan, 1987 [46].

Stewart and Schouten [47] indicated that the traditional zonal isolation techniques such as good drilling fluid-displacement with stable, low-fluid-loss, and fast-setting cement are not enough to prevent gas presence in the cement slurry. To prevent gas migration, the authors suggested some additional and secondary measures, for example, using a surfactant cement system and mechanical seal-ring devices for the casing contraction. Fery and Romieu [24] suggested the use of two products for controlling the gas migration: (1) a composite cement made of Class G cement and blast furnace slag, and (2) a polymer additive providing gummy substance. Wilkins and Free [3] indicated that the gas channeling is significantly affected by the SGS development rate and the downhole volume losses. The fluid loss rate could be controlled by application of proper drilling fluid filter cake, fluid loss control additives, proper American Petroleum Institute (API) fluid loss control techniques, and reactive silicate washes. They predicted the gas flow after the cement placement; this was based on four key factors including formation and annular configuration, fluid hydrostatics, drilling fluid displacement, and slurry performance. Beirute and Cheung [48] proposed a scaled-down method from the well environment to laboratory conditions to select cement recipes for the prevention of gas migration.

The laboratory gas flow test recommended some simple cement recipes for the control of gas migration in wellbores. Jones and Carpenter [25] developed a new cementing system called latex, expanding, and thixotropic cement (LXT). Thixotropic cement slurries have been shown to remain fluid while being sheared and immediately begin to gel when the shearing stops. This LXT system increases the cement slurry performance and reduces the

costs by reducing the weakness of cement filtrate, gas migration prevention in the hydrating cement, a more rapid gel strength and compressive strength development, a shorter transition-to-set time, and a better cement bonding. Skalle and Sveen [49] proposed adding an emulsion (3–15% vol.) to the cement slurry to reduce the friction and prevent the gas migration. The emulsion cement contained a double emulsion and water-in-oil-in-cement.

Sutton and Ravi [50] suggested the use of the low-rate pipe movement (rotation or reciprocation) technique during the cement gelation to control the gas migration by delaying the hydrostatic pressure loss and by improving the strength of the cement bond. Goodwin and Crook [26] noticed that the cement failure could occur due to the high temperature changes or large pressure in the internal casing. The cement failure causes higher annular pressure in the wells and in the radial cracks of the cement in the annulus. The authors suggested using a low-density, low-compressive-strength cement slurry to prevent cracks and to reduce the loss of the annular fluid. Coker et al. [51] reviewed the lightweight cement slurries in gas migration control cementing system with additives and found that the silica fume cement and various other additives, including colloidal silica and cement with smaller particle sizes, are effective in controlling the shallow gas migration in offshore wells. Jackson and Murphey [52] studied the effect of casing pressure on gas flow by performing two casing-cement-loading laboratory tests under increasing and decreasing casing pressures. They reported that the gas flow increased in the annulus after the cyclic loading application for both tests. Calloni et al. [27] developed a novel additive—carbon black additive—to control gas migration in cement slurries. The carbon black additive has comparable performance in reducing gas migration with other commercial additives including silica fume and polymer latexes, but the cost is much lower.

Stiles [53] suggested three approaches for effective cementing in areas with shallow flow: (1) to obtain enough hydraulic seal from the gas migration, (2) to provide structural support for the casing, and (3) to increase the durability of the well. In order to reduce the gas migration in the cement annulus, Talabani et al. [39] suggested conducting experiments in the laboratory before performing the cement job in the field; they provided guidelines for calculating the elastomer volume (a polymer with viscoelasticity and weak intermolecular forces) to improve the cementing operations. The authors also suggested adding various materials such as the anchorage clay and the rubber powders with appropriate cement design.

Brandt et al. [54] investigated deepwater operations for drilling fluids and well cementing. Fluid properties at low-temperatures and high-pressures should be taken into consideration. The primary challenge for well cementing under deepwater operations lies in the shallow saltwater flow. The authors suggested (1) minimizing the critical hydration period (CHP) of the cement slurry and setting the cement rapidly once the critical wall shear stress (CWSS) is reached and (2) applying “right-angle” set slurries that prohibit flow and ensure that fracture pressures (the pressure required to fracture the formation) are not exceeded.

Al-Buraik et al. [28] discussed different techniques to prevent surface gas migration through cement. These techniques included the use of light weight latex slurry with additives such as silica microspheres in cement, quick-setting cement systems, right angle set latex slurry with calcium sulfate hemihydrate in Portland cement, and a Sandwich Technique with the lead and tail cement slurry systems. The authors suggested the use of a novel low-temperature product (gasblok) containing submicron particles coupled with some modifications in the drilling practices, including controlling washouts, conditioning of the drilling fluid, casing centralization, the use of inner string cementer (ISC), and the fluid train.

Boisnault et al. [29] pointed to the limitations of conventional cementing technology: the performance of slurry and set conditions are opposing each other, water-to-cement ratio dominates the cement system performance, and remediation of unsatisfactory cement is difficult. The authors proposed a new concrete-based slurry system (CemCRETE technology) to optimize for both slurry performance and set-cement properties during cement

placement. A particle-size distribution (PSD) optimization technique, with three or more different particle sizes, was selected to develop a high-performance slurry arrangement (Figure 4, based on [29]). The advantage of this system is that it provides a trade-off between the fluid viscosity and density, which offers constant viscosities for water-reduced slurries at high densities and low gel strengths. It was also noticed that a low water content reduced the sedimentation, while giving higher compressive strengths and lowering the permeability. According to Mueller [30], conventional design for cement includes (a) a “zero gel strength” in the pressure range 0–100 lbf/100 ft², where the cement slurry is considered to be a fluid with a hydrostatic pressure and is able to control the shallow water flow (SWF); (b) attempts to reduce the transition time of SGS in the range of 100 to 500 lbf/100 ft² from hours to minutes or less to mitigate the SWF; and (c) attempts to reduce the fluid loss to 6.1 inch³/30 min. It was also suggested that a tail cement should build up the compressive strength to 500 psi at the bottomhole static temperature (BHST) in 24 h and a lightweight lead cement build up 50–200 psi in 24 h. It has been noticed that the control of the transition time has some limitations due to the assumptions above [30]. The accepted SGS values for the transition time are now 100 to 500 lbf/100 ft². In addition, the “zero gel strength” does not result in any decay in hydrostatic pressure because gelation is taken into consideration with the value of SGS less than 100 lbf/100 ft².

Figure 4. Particle-size optimization. (a): slurry with single-size particles, containing larger water-filled spaces; (b): slurry with optimized blend of several particle sizes, where the smallest particles act as lubricating ball bearings. Developed from Boisnault et al., 1999 [29].

Dusterhoft et al. [55] discussed the cement pulsation techniques by applying 700 kPa pulses to the cement annulus after its placement to control the gas migration. The pulsation technique reduced the cement gel strength while allowing the hydrostatic pressure to be transmitted through the gas zone, which blocked the gas flow to the cement annulus.

Rogers et al. [56] showed and discussed the limitations of using only SGS and transition time for preventing the gas migration; they suggested a new definition for the cement transition time. They discussed some of the misconceptions surrounding “right angle set” and initial compressive strength determination from the Ultrasonic Cement Analyzer (UCA). Rogers et al. [56] showed through testing that slurries with short transition times can fail in gas migration tests and those with long transitions may be able to prevent the gas intrusion successfully. They also suggested a fit-for-purpose cement, which requires the following conditions: a stabilized slurry, low fluid-loss, short transition time, minimized volume reduction, and reduced internal slurry permeability. A cement slurry is considered gas tight slurry when it has a gradual decline of slurry pore pressure as it sets and does not transmit hydrostatic pressure of fluid above the cement top. Gas migration is usually indicated when the pore pressure usually stops decreasing and starts to rise as higher-pressure formation gas pushes its way into the setting cement. According to Rogers et al., neither SGS nor the ultra-low fluid loss control can be considered the main factor

in preventing gas migration, although they are important to prevent shallow water flows. Bellabarba et al. [57] reviewed some ultrasonic tools detecting the casing eccentricity and evaluated the material such as the cements and drilling fluids in the annulus; they also suggested the application of long-life self-healing cement for zonal isolation. Zhu et al. [58] proposed a new method to evaluate the performance of cement slurry for gas migration from the decline of the upper annular column hydrostatic pressure.

Zhang and Bachu [59] reviewed the various mechanisms of well integrity failure using laboratory experiments, field tests, and simulations. They suggested that the slurry density is a key factor and should be kept high enough to generate hydrostatic pressure to prevent gas migration. Abbas et al. [60,61] introduced a multifunctional additive—hydroxypropylmethylcellulose (HPHC)—for oil well cementing under high temperature conditions to reduce gas migration by controlling the fluid loss and by providing an impermeable barrier. Al-Yami et al. [62,63] developed an innovative cement to reduce gas migration in deep wells by adding a set of solid particles with different sizes, such as silica sand (100 microns), hematite, silica flour, expansion additives, and manganese tetroxide (Mn_3O_4). This new cement formula decreased the cement porosity and the particles settling and had a better performance in controlling fluid loss and gas migration. To prevent gas migration, Isgenderov et al. [64] analyzed the impact of various liquid and solid additives to cement slurry and concluded that solid polymers were the most effective additives under extreme cold conditions for the oil and gas industry. Velayati et al. [65] applied the fluid migration analyzer (FMA) test to optimize and to assess the impact of additives in the cement slurries; they suggested the use of thixotropic agents to reduce gas migration. The addition of latex in newer cement designs, used by You et al. [66], showed an improved capability to reduce gas migration caused by the use of fluid loss additives. Okoli [67] conducted a case study on the abandoned well (Well XRT) to evaluate the cement slurry design and to study methods to prevent the gas migration in wells. Ahmady et al. [32] applied foam cement in the wells for a better and more compressible cement system. This approach decreases the risk of SCVF by compensating for the cement slurry hydrate volume reduction and by reducing the potential of cement debonding and cracks in operations due to the relatively improved ductility, which is related to the gas phase of foam cement. According to this study, with only about 20% of foam added to the cement, the success rate for controlling SCVF increases from 24% to 74%.

2.3. The Static Gel Strength Approach

The oil and gas industries have widely accepted the use of SGS as a method to characterize cement slurries and assess their use for a specific well (API RP 10B-6). The API recommended practice is to minimize the time where the cement slurry is susceptible to pressure losses during the cement hydration and the gel strength development, where an underbalanced condition for the pressure exists in the wellbore. Once the cement has developed enough gel strength, it should be able to resist gas migration from the surrounding formation. In practice, this means reducing the transition time as much as possible to reduce the potential of gas migration through the cement.

2.3.1. Background

Cement must keep its fluid-like characteristics long enough while being pumped to the anticipated location, and it needs to develop sound compressive strength within a specific time after its placement. Gel strength, SGS, is related to the resisting shear stress before the onset of the cement flow; this is considered as the major factor for hydrostatic pressure loss and gas migration [68].

During the first stage of cement hydration, cement slurries transition from a viscous fluid to a material with gelling properties while they begin to develop compressive strength. During the last stages of hydration, cement becomes a solid-like material with compressive strength able to resist the flow of gas or other fluids. Among different methods to indicate hydrostatic pressure reduction as the cement hydrates, SGS is the most widely used

criterion for strength development of hydrating cement [69]. Hydrostatic pressure drops until the critical time, where gas can invade, because the cement pore pressure is below the formation gas pressure. The gas will penetrate the cement if the slurry has not developed enough strength to resist the formation gas pressure. It is proposed that the gas would stop invading at the end of the transition time, which is bound by the SGS values of 100 lbf/100 ft² (critical) and 500 lbf/100 ft² (final). The SGS is related to the hydrostatic pressure reduction and is used to determine the transition time between the critical time and the final time. The SGS transition time is then minimized by adding chemical additives to the slurry.

The SGS is essentially (related to) the yield stress and is used to show when the phase change from a fluid to a gel begins to occur during the hydration process; this is related to the safety factor (the ratio between the strength of the material and the maximum stress) and the gas migration. The gas migration/channeling happens when the value of the SGS is between 48 Pa (100 lbf/100 ft²) and 240 Pa (501 lbf/100 ft²) [70]. It is thought that a shorter transition time could decrease the possibility of gas migration (<20 min).

The reduction in the annular pressure in the wellbore is the key factor resulting in the gas flow; this is related to the shear stress opposing the downward motion of the slurry [71]. Researchers have come up with various equations for the wellbore pressure reduction considering different effects including gel strength, geometry, and time. We discuss some of these concepts in this section.

2.3.2. Some Basic Calculations and Definitions

In this Section, we will provide a brief discussion of some simple engineering calculations relating various concepts such as the pressures, SGS, shear stress, etc. Moore [72] showed that the pressure required to initiate the flow at a given SGS in the cement column is given by

$$\Delta p = \text{SGS} \times 4L/d \quad (1)$$

where Δp is the pressure needed to overcome the SGS, SGS is the static gel strength, L is the length of the column, and d is the (effective) diameter: $d = d_h$ (hole diameter) d_p (pipe diameter).

For oil fields in USA, usually the following units are used: pressure (psi), the SGS with units of (lbf/100 ft²), length (ft), and diameter (in), then Equation (1) is re-written as

$$\Delta p = \text{SGS}/300 \times L/d \quad (2)$$

Researchers tend to agree that the wellbore pressure is reduced by the thixotropy of cement and the cement downward movement caused by the filtrate migration during the setting [4,41,43]. Figure 5, based on [73], shows a typical oil and gas well configuration.

Figure 5. A typical oil and gas well configuration. Reprinted with permission, Elsevier, 2021 [73].

Sabins et al. [2] related the pressure reduction to the gel strength development:

$$\left(\frac{\partial p}{\partial h}\right)_{GS} = \frac{4\tau_y}{d_w - d_{cas}} \quad (3)$$

where h is the depth of the cement column, $\frac{\partial p}{\partial h}$ is the pressure gradient, τ_y is the gel strength, and d_w and d_{cas} are the diameters of the well and the casing.

By applying the force balance equation on the element of the annulus, the pressure gradient is written as

$$\frac{\partial p_c}{\partial h} = \left(\frac{\partial p}{\partial h}\right)_{Gravity} - \left(\frac{\partial p}{\partial h}\right)_{GS} = \rho_c g - \frac{4\tau_y}{d_w - d_{cas}} \quad (4)$$

where p_c is the pore pressure of the cement slurry and ρ_c is the slurry density. For a uniform gel strength over the entire depth of the well, by integrating Equation (3), the pressure becomes

$$p = p_{h,i} - \frac{4\tau_y L}{d_w - d_{cas}} \quad (5)$$

where $p_{h,i}$ is the initial hydrostatic pressure and L is the length of the cemented column.

Chenevert and Jin [8] suggested a different formulation for calculating the wellbore pressure as a function of time. In their approach, the wellbore pressure declined faster with higher chemical shrinkage, filtration, or gelation. The total pressure at any given depth h in a cement column after a given time t was given as

$$P(h, t) = \int_0^h \frac{\rho_0}{1 - S(t)} dh - \frac{2}{R_o - R_i} \int_0^h \tau(\dot{\gamma}, t) dh + P_0 \quad (6)$$

where the first term on the right hand side indicates the gravitational term, the second term is related to the shear stress, P_0 is the pressure applied on the top of the cement column, ρ_0 is the initial density of cement, $S(t)$ is the chemical shrinkage volume fraction with time, τ is the shear stress, $\dot{\gamma}$ is the shear rate, R_o is the outside radius of the cement column, and R_i is the radius of casing.

This equation considers the variation of SGS in the wellbore and the changes in the volume with time and depth. However, there are some limitations in this formulation: (1) the actual shear stress at the interface is less than the SGS calculated because of the friction component and (2) the enhanced additives blended in the slurry make the calculation of hydrostatic-pressure reduction inaccurate [69].

Sutton and Ravi [74] showed that controlling the gas migration is related to the rate of fluid loss in the transition period; they indicated that the performance of cement slurry to resist gas migration can be related to a dimensionless number called the slurry response number (SRN). This relates the SGS development rate, the downhole fluid loss rate, and the well geometry:

$$SRN = \frac{N_{SG}}{N_{FL}} N_{SG} = (dSGS/dt)/SGSN_{FL} = (dp/dt)/(V/A) \quad (7)$$

where N_{SG} is the usefulness of the static gel rate, N_{FL} is the fluid loss rate (cc/30 min), V/A is the ratio of the volume of the annulus to the borehole area (in³/in²), and dp/dt is rate of velocity of fluid loss at the time of SGS (lbf/100 ft²). The SRN provides a mechanism to evaluate the trade-off between the thixotropic development and the fluid loss.

Harris et al. [75] suggested that the slurry response number (SRN) and the gas flow potential (GFP) are related; this is an indication of the probability of gas flow under some specific given cement job conditions for the oil well. Harris et al. [75] applied the SRN approach to control the gas migration for different cement slurries.

Prohaska et al. [68] suggested a few factors which can cause a pressure drop in the cement annulus. They stated that the development of the gel strength could be delayed

by higher shear rates, lower temperatures, and pressures; these can cause a delay in the gel strength development at the top of the slurry column which is subjected to lower temperatures and pressures. Prohaska et al. [68] presented an improved wellbore pressure drop equation by using the force balance and the mass balance equations in the cement slurry column and showed that the depth-dependent behavior of gel strength had a large effect on wellbore pressure loss:

$$\frac{\partial p_c}{\partial h} = \rho_c(h, t)g - \frac{4\tau_w(h, t)}{d_w - d_{cas}} \quad (8)$$

where p_c is the pore pressure of the cement slurry; τ_w is the wall shear stress; d_w and d_{cas} are the diameters of the well and the casing; and ρ_c is the slurry density, which is a function of time and depth. The equation for the balance of mass is then used:

$$\frac{\partial \rho_c}{\partial t} = \frac{\partial(\rho_c v_c)}{\partial h} + \frac{4\rho_{fl} d_w}{d_w^2 - d_{cas}^2} v_{fl} \quad (9)$$

where v_c is the slurry velocity, ρ_{fl} is the filtrate (where water tends to filter through the medium leaving particles behind) density, and v_{fl} is the filtrate velocity.

Calloni et al. [76] proposed an approach to formulate gas impermeable cement slurries, where gas is not transmitted to the pore. They used small amplitude oscillatory measurements and introduced a modified SRN based on Equation (7) in order to rank the cement slurries in terms of its capability of stopping the gas migration:

$$\text{mSRN} = \frac{m/G'}{(dv/dt)/(V/A)} \quad (10)$$

where m is the maximum rate of change of gelation during the transition time (Pa/min), G' is the storage modulus at the maximum rate of gelation change (Pa), dv/dt is the rate of velocity of fluid loss during the transition period/API area (cm/min), and V/A is the ratio of the volume of the annulus to the borehole cross sectional area. Furthermore, m and G' are obtained from the experimental data in the oscillatory regime. Cement slurries with higher mSRN values are more effective in preventing gas migration than those with lower values.

Stiles [53] investigated the mechanism for gas migration during cementing in deep water with overpressured shallow sediments. Two items were discussed: (1) a critical hydration period (CHP) of cement slurries, defined as the period of time from when the cement slurry becomes incapable of transmitting hydrostatic pressure to when the cement slurry develops enough strength to prevent gas entry and flow; (2) a critical wall shear stress (CWSS) at the wellbore, defined as the lower limit of CHP:

$$\text{CWSS} = 0.25 \left[P_t + 0.052\rho \left(\frac{l}{12} \right) \cos\Theta - P_f \right] [D_h - D_c]/l \quad (11)$$

where ρ is the cement density (lb/gal), l is the length of the column (in), Θ is the angle of inclination of the cemented annulus (degree), P_t is the pressure at top of the cement column (psi), P_f is the pore pressure of the flow zone (psi), D_h is the diameter of the cemented portion of the hole (in), and D_c is the outer diameter of the casing (in). A shorter CHP indicates a better controlled gas migration, which could be achieved by increasing the CWSS, decreasing the gel strength needed to stop the migration, and increasing the slope of gel strength vs. time. The CWSS could be increased by increasing the cement density, increasing the top pressure of the cement column, increasing the size of the annular gap, and decreasing the length of the cement column. Stiles [53] also showed that certain properties such as the friction pressure related to the viscosity of the cement slurry are related to proper fluid displacement in the annulus. The frictional pressure of the lead cement slurry should be greater than that of the spacer and less than that of the tail slurry.

It was also suggested that the viscosity of the cement slurry should not be too high to be mixed in the field.

Crook and Heathman [77] stated that short-term migration occurs before the cement sets and long-term migration happens after the cement has set. Short-term gas migration occurs when the cement column is incapable of bearing the overbalance pressure, which is related to (1) the development of SGS, (2) the transition time, and (3) the volume reduction due to hydration. Long-term gas migration is caused by lack of drilling fluid displacement and cement debonding. The amount of gas flow was estimated by the gas-flow potential factor (GFP), which is shown in Figure 6, based on [77]. GFP is a function of cement slurry, formation properties, and well design conditions [32].

Figure 6. Gas flow potential factor. Developed from Crook and Heathman, 1998 [77].

The GFP is given by

$$\text{GFP} = \text{MPR}/\text{OBP} \quad (12)$$

where MPR is the theoretical maximum pressure restriction (psi), $\text{MPR} = 1.67LD$ (maximum pressure loss possible when the SGS is 500 lbf/100 ft²) (psi), L is the length of the cement column (ft), D is the effective diameter of the cement column (hole diameter minus pipe diameter) (in), and OBP is the overbalance pressure (difference between the hydrostatic pressure and the formation pressure) (psi). When the GFP is less than 1.0, there is no gas leakage problem. The GFP could be decreased by changing the mud and the cement densities, column length, and the back pressure. Increasing the slurry compressibility or adjusting its thixotropic properties are also suggested as possible mechanisms to prevent gas migration for cases with GFP larger than 1.0. For severe gas-flow potential conditions, Crook and Heathman [77] suggested either utilizing a cement system that consistently produces gas bubbles through the cement column or inserting gas into the system during the placement of cement to get a highly compressible cement system. The effect of increasing compressibility was given as

$$\text{DP} = \text{DV}/\text{CF} \quad (13)$$

where DP is the pressure loss due to volume reduction, DV is the volume reduction from the fluid loss and cement hydration, and CF is the compressibility factor.

Zhou and Wojtanowicz [71] proposed an equation for the reduction in the annular pressure during cementing:

$$\Delta p = \frac{\Delta v_{fil} + \Delta v_{sh} - \Delta v_T - \Delta v_w - \Delta v_{cas}}{v(c_{cem} + c_{ww} + c_{cas})} \quad (14)$$

where Δv_{fil} is the volume change caused by the filtration loss, Δv_{sh} is the volume change caused by the chemical shrinkage, Δv_T is the volume change caused by temperature change, Δv_w is the wellbore deformation, Δv_{cas} is the volume change caused by the deformation in the casing string, and $c_{cem} + c_{ww} + c_{cas}$ represents the total compressibility of the system. The disadvantages of this approach are (1) the prediction of the pressure reduction is not accurate and needs many assumptions because of the complications of the chemical reactions in the cement annulus; and (2) it assures that the cement slurry is in a static state, where the deformation of the cement column and the volume change in the cement matrix are not considered [69].

Mueller [30] measured the SGS variation with time and calculated the annular pressure loss as a function of the SGS, and using Equation (2) he was able to predict the time when the pore pressure exceeds the annular hydrostatic pressure of the gelled cement and the sea water. Shallow water flow (SWF) has a negative effect on the construction of wells. Mueller [30] suggested a critical static gel strength (CSGS) to represent the starting point of the transition time, which represents the value of the gel strength when the overall hydrostatic pressure of the annulus is less than the pore pressure of the SWF zone:

$$CSGS = (\Delta p) (300) \div (L/D) \quad (15)$$

The transition time is then determined as the elapsed time from CSGS to 500 lbf/100 ft² gel strength. L is the length of the cement column (ft), and D is the effective diameter of the cement column (in).

Vazquez et al. [5] proposed a different methodology to evaluate the gas migration in cement slurries; their approach included three steps: (1) calculate the gas-flow potential factor, Equation (12), for the severity of the problem; (2) measure the SGS as a function of time and get the transition time of the cement slurry; and (3) calculate the pressure reduction from the SGS data by utilizing the FMA. Tavares et al. [78] studied the relationship between gas migration and the composition of the cement slurry and found that slurries with a higher concentration of latex and dispersant could increase the resistance to gas migration.

Li et al. [69] reviewed the SGS formulations and indicated the limitations of the SGS method. Their sensitivity study shows that the transition time is unrelated to the gas migration. According to the authors, the SGS approach can predict the fluidity of the slurry at an early stage of hydration but not sufficiently to evaluate the compressibility and the permeability for the cement matrix. Instead of using the SGS approach to evaluate the potential for gas migration, cement/matrix characterization is suggested with fundamental concepts, such as microstructural development of cement and cement hydration process and variables to characterize the cement solid/fluid-coupled matrix.

2.3.3. Experimental Measurements

Different experimental measurements on gels can provide material properties related to rigidity, elasticity, plastic viscosity, or the resistance of gels to applied forces. Researchers have developed various methods to measure the gel strength for materials that gel.

In one of the earliest studies, Hamer [79] proposed an improved method to determine the strength and deformability of all types of gels, including the reversible (gelatin) or irreversible (starch) type materials. This method improved the Saare-Martens disk method [80] by applying an adjustable platform instead of a stationary one and using mercury instead of lead shot to measure the deformability and rigidity of the gels under a steady and under a consistent rate. In this experiment, the brass disk is suspended in the gel and connected by a brass wire.

The gel strength is then calculated by the equation

$$\text{Gel strength} = \frac{\text{load}}{\pi r^2 \left(1 - e^{-0.24(\frac{h}{r})^{1.1}}\right)} \text{ g/cm}^2 \quad (16)$$

where h is the depth of immersion (cm), r is the radius of the disk (cm), and the load is in grams.

Moon and Wang [81] used acoustic methods along with the SGS Analyzer (SGSA) to measure the SGS. During the gelation process, the cement shows the characteristics of a polymer, behaving as a non-Newtonian fluid. The different approaches to measure the SGS include differential pressure measurements across a cement column and torque measurement on the paddle due to gel structure. However, these approaches lack sensitivity due to the friction in the system. To study the potential for gas migration in a cement slurry, comprehensive physical models and/or measurement of the SGS are needed. Moon and Wang [81] developed a new instrument to measure the SGS of cement slurries under HTHP conditions. The relationship between the signal attenuation and the SGS value is determined, and their studies show that this method is independent of the effects of temperature (T) and pressure (P). From the acoustic measurements, a correlation between the signal attenuation and the SGS is obtained based on experiment and curve fitting the data; this is suitable for most slurries since the SGS-time method was developed for cement slurries. Sabins and Maki [82] also developed an acoustic method to measure the static gel strength for cement slurries at different wellbore temperatures and pressures. They inserted two transducers to generate and accept the acoustic signals through cement slurries and obtained the value of SGS based on the relation between the signal amplitude and the SGS.

Zhu et al. [83] used two different methods to evaluate the hydrostatic pressure of cement slurries and found that the SGSA is more accurate than the cement pressure drop test method (PDTM). The reduction in the hydrostatic pressure for the entire annulus using the SGSA method is given by

$$P_r = \sum_{i=1}^n \frac{4 \times \text{SGS}_i \times L_i}{D - d} \quad (17)$$

where P_r is the pressure reduction from the cement gel strength (Pa), SGS_i is the SGS of the i^{th} cement column (Pa), L_i is the measured length of i^{th} cement column (m), D and d are the diameters of the hole and the casing (m), and n is the total number of the cement columns ($n \geq 1$).

In this section, we have provided a brief review of some basic calculations, definitions, and experimental measurements related to SGS and how these are used to assess cement quality and response. These calculations and measurements could be used to evaluate and reduce the potential for gas migration in the oilwell cement slurries. It is noticed that all the correlations and equations are given in their one-dimensional forms; there does not seem to be too many fundamental studies, using mathematics and physical principles, to provide a better understanding of gas migration and how it can be eliminated or remedied. There is a clear need for more fundamental fluid mechanics (of non-Newtonian fluids) and multiphase flow approaches using computational fluid dynamics (CFD) to model and study gas migration. In the next section, we will briefly discuss the yield stress and the viscosity of cement slurries including.

3. Rheology of Cement Slurries

Tao et al. [36,84–89] reviewed the various models for cement slurries with applications in oil well industries. It was noticed that yield stress, thixotropy, and viscosity are among the important parameters in the constitutive models. Tao et al. [36,84–89] also discussed the effect of cement particle concentration, water-to-cement ratio, shear rate, temperature, pressure, and the mixing method.

3.1. Yield Stress Measurements

SGS is essentially the cement yield stress, measured during hydration. Cement exhibits a growing yield stress during the cement hydration process and can be determined with yield stress measurement techniques [90]. Under typical conditions, a cement slurry transitions from a viscous fluid to a viscoelastic fluid [17]. The yield stress is one of the most important parts of constitutive modeling of many complex fluids and concentrated suspensions [91].

Dzuy and Boger [91,92] proposed a single-point measurement using the vane device to measure the yield stress for highly concentrated solid–liquid suspensions with applications in soil mechanics. The yield stress for these suspensions was shown to increase rapidly with the particle concentration. The authors indicated that the vane method is an attractive method since it is simple, and with its low-cost, it could be operated under static conditions without too much disturbance before and during the measurement.

Most viscoplastic (yield-stress) fluids including cement slurries are, in general, multi-phase mixtures, which are more difficult to characterize. In most applications, however, it is assumed that the cement can be a single component non-homogeneous fluid. In general, it is possible to distinguish between two types of yield stresses: (1) the low yield stress type is related to the end of the elastic behavior and the beginning of the plastic deformation and (2) the higher yield stress is related to the transition between plastic and the viscous behavior [93]. There are at least two methods to measure the yield stress: the indirect method and the direct method. For the indirect method, researchers perform a torque vs. rotation experiment and obtain the shear stress (related to the applied torque) vs. the shear rate (related to the angular or the rotational velocity) plot; in this approach, correlations for various viscoplastic models such as the Bingham model, the nonlinear Casson model, the Herschel–Bulkley model, etc., are obtained. For the direct method, the yield stress is measured directly from experiments such as a creep/recovery experiment, the stress growth experiment, the vane method, the cone penetration, etc. In a recent NETL technical report [90], we have reviewed the application of the vane method to various cement slurries and for different vane configurations using the direct shear test.

One of the most popular yield stress models for cement slurries is the Herschel–Bulkley model [94]:

$$\tau = \tau_y + \kappa \dot{\gamma}^n \quad (18)$$

where $\dot{\gamma}$ is shear rate and τ_y , κ and n are constants. This is the generalization of the popular Bingham model. According to Banfill [95], κ could be chosen as 2.5 or 0.25 and n as 0.75 or 1.25 for cement. The above equation is based on the Power law model, also known as the Ostwald de Waele model [96], which is one of the most popular models in describing the behavior of the pseudoplastic (non-Newtonian) fluids without yield stress:

$$\tau = K \dot{\gamma}^n \quad (19)$$

where K is the consistency factor and n is the flow behavior index (the power-law exponent); when $n = 1$, the fluid is a Newtonian fluid; when $n < 1$, the fluid behaves as a shear-thinning fluid; and when $n > 1$, it is shear-thickening, and $\dot{\gamma}$ is the shear rate (see Macosko [97]). The above equations are applicable to one-dimensional situations; for more complicated cases and for a thorough review of the various constitutive models for cement slurries with or without yield stress, we refer the reader to Tao et al. [36]. Table 1 shows a summary for the 1D and 3D yield stress models and the dependence of the yield stress on concentration, the water-to-cement ratio, etc.

Table 1. Summary of the Yield Stress Model. Reprinted from Tao et al., MDPI, 2021 [36].

Effect of Concentration	$\tau_y = A_0 a^{(\phi-0.5)}$
	$\tau_y = P_1 \cdot e^{P_2 \cdot \phi}$
	$\tau_y = \left(\sum \phi_{vi} \tau_{yi}^{1/2} \right)^2$
	$\tau_{y,max} = K \left(\frac{\phi}{1-\phi} \right)^c \frac{1}{d^2}$
	$\tau_y = m_1 \frac{\phi^2 (\phi - \phi_{perc})}{\phi_{max} (\phi_{max} - \phi)}$
	$\tau_y = m_1 \frac{(\phi_0 (1 + \chi \alpha(t)))^2 (\phi_0 (1 + \chi \alpha(t)) - \phi_{perc})}{\phi_{max} (\phi_{max} - \phi_0 (1 + \chi \alpha(t)))}$
	$\frac{\tau_y(\phi)}{\tau_y(0)} = \sqrt{\frac{1-\phi}{(1-\phi/\phi_m)^{2.5\phi_m}}}$
	$\tau_y^{dyn} = \frac{F}{a^2} \left(\frac{\phi}{\phi_{max}} \right)^{\frac{1}{m(3-f)}}$
Effect of Water-to-Cement Ratio	$\tau_y = 2.1 \times 10^{-3} e^{19.2 \cdot \phi} \cdot S_{vB}^{2.5}$
	$\tau = (-175w/c + 137) \left(\frac{\dot{\gamma}}{\dot{\gamma}_0} \right)^{0.6}$
Effect of Additives/Admixtures	$\tau_y = K(w/c)(SSB - 2000)$
	$\begin{aligned} \tau_y = & -118.5 - 72.3X_1 - 104.8X_2 + 103.6X_3 - 46.1X_4 - 48.7X_5 \\ & + 75.4X_1X_2 - 77.4X_1X_3 + 38X_1X_4 + 42.4X_1X_5 \\ & - 107X_2X_3 + 39.9X_2X_4 + 41.6X_2X_5 - 54.5X_3X_4 \\ & - 50.7X_3X_5 + 21.5X_1^2 + 19.3X_2^2 + 158.7X_3^2 + 38.9X_4^2 \\ & + 37.1X_5^2 \end{aligned}$
	$\tau_y = P_1 \cdot e^{P_2 \cdot \phi} \cdot (1 - \phi_f) + P_3 \cdot e^{P_4 \cdot \phi} \cdot \phi_f$
Effect of Damage	$\tau = \left[1 - \left(D_1 + D_0 \dot{\gamma}_d^\xi \right) \gamma \right] \cdot \left[A_0 + A_1 \left(\frac{\dot{\gamma}_d}{\dot{\gamma}_s} \right)^B \right] \gamma$
3D Yield Stress Tensor	$T = 2\eta_p D$ for $\Pi_{2D}^{1/2} \leq \dot{\gamma}_c$
	$T_y = 2 \left[\frac{m_1 \frac{\phi^2 (\phi - \phi_{perc})}{\phi_m (\phi_m - \phi)} \times (-175w/c + 137)}{ \Pi_{2D} ^{1/2}} + K \Pi_{2D} ^{\frac{n-1}{2}} \right] D$ for $\Pi_{2D}^{1/2} > \dot{\gamma}_c$

3.2. Viscosity of Cement Slurries

According to Tao et al. [36], the shear viscosity of cement slurries could be a function of various factors such as shear rate, volume fraction, temperature, pressure, water-to-cement ratio, additives, and mixing methods.

Some researchers [98] indicate that the viscosity of cement is a function of the concentration of cement particles. Krieger–Dougherty's Equation is one of the most widely used correlations depicting the dependence of the viscosity on the concentration [99]:

$$\eta_r = \frac{\eta}{\eta_0} = \left(1 - \frac{\phi}{\phi_m} \right)^{-\alpha \phi_m} \quad (20)$$

where η_r is the relative viscosity, η is the apparent viscosity, η_0 is the apparent viscosity of the fluid without any particles, ϕ is the volume fraction of the cement particles, ϕ_m is the maximum packing volume fraction, and α is a parameter which depends on the particle shape. According to Struble and Sun [98], for dispersed cement pastes, $\phi_m \cong 0.7$, $\alpha \cong 5$. Cement pastes that are not dispersed have higher viscosities and lower ϕ_m . Cement pastes at lower concentrations (higher w/c) exhibit Newtonian behavior, while at higher concentrations (lower w/c) they exhibit pseudo-plastic or plastic behavior.

More relationships for the viscosity with various effects are shown in Table 2.

Table 2. Summary of viscosity relationships of cement. Reprinted from Tao et al., MDPI, 2021 [36].

Effect of Shear Rate	$\eta = \frac{\tau}{\dot{\gamma}} = K\dot{\gamma}^{n-1}$
	$\eta_{eff} = \frac{A(\dot{\gamma}_R + C)^B}{\dot{\gamma}_R}$
	$\eta = \frac{1}{\dot{\gamma}} \left[k_0 + k_1 \sqrt{\dot{\gamma}} \right]^2$
	$\eta = \eta_\infty + (\eta_0 - \eta_\infty) \frac{1 + \ln(1 + k\dot{\gamma})}{1 + k\dot{\gamma}}$
Effect of Volume Fraction	$\eta_r = \frac{\eta}{\eta_0} = 1 + \alpha\phi$
	$\eta_r = \frac{\eta}{\eta_0} = (1 - \phi)^{-2.5}$
	$\eta_r = \frac{\eta}{\eta_0} = e^{\left[\frac{\alpha\phi}{(1 - \phi_m)} \right]}$
	$\eta_r = \frac{\eta}{\eta_0} = (1 - 1.35\phi)^{-2.5}$
	$\eta_r = \frac{\eta}{\eta_0} = \left(1 - \frac{\phi}{\phi_m} \right)^{-\alpha\phi_m}$
	$\eta_r = \left(1 - \frac{\phi}{\phi_m} \right)^{-2.78} e^{0.073t}$
	$\eta_r = \frac{\eta}{\eta_0} = B_0 e^{(K_1\phi + K_2)}$
	$\eta_0 = Q_1 \cdot e^{Q_2 \cdot \phi}$
	$\eta_r = \frac{\eta}{\eta_0} = \frac{(1 - \phi)}{\left(1 - \frac{\phi}{\phi_m} \right)^z}$
	$\eta_r = \frac{\eta}{\eta_0} = [a(\phi - \phi_m)]^{-n}$
Effects of Temperature and Pressure	$\eta_r = \frac{\eta}{\eta_0} = \left(1 + \frac{0.75 \frac{\phi}{\phi_m}}{1 - \frac{\phi}{\phi_m}} \right)^2$
	$\frac{1}{\eta_\theta} = \frac{1}{\eta_{\theta,0}} e^{\left[-\frac{U}{R} \left(\frac{1}{\theta} - \frac{1}{\theta_0} \right) \right]}$
	$\tilde{A}(\xi) = \dot{\xi} e^{\left(\frac{E_a}{R\theta} \right)}$
	$X \approx \frac{\pi}{3} O_v^B I_B G^3 t^4$
	$G(T, p) \approx G_0 e^{\left(-\frac{\Delta E_G + p\Delta V_G}{R\theta} \right)}$
	$I_B(T, p) \approx I_0 e^{\left(-\frac{\Delta E_I + p\Delta V_I}{R\theta} \right)}$
	$\dot{\xi}(t) = \dot{\xi}_r(C(\theta, P), t)$
	$C = e^{\left[\frac{E_a}{R \left(\frac{1}{\theta_r} - \frac{1}{\theta} \right)} + \frac{\Delta H^\ddagger}{R} \left(\frac{P_r}{\theta} - \frac{P}{\theta} \right) \right]}$
	$\eta_c = \eta_r \cdot e^{\left[\frac{E}{R\theta_c} \right]}$
	$\eta_c = \eta_{c0} + (1000 - \eta_{c0}) \cdot (t/t_v)^n$
Effect of Additives/Admixtures	$\eta_c = \eta_r \cdot e^{\left[\frac{E}{R\theta_{c0}} \right]} + \left(1000 - \eta_r \cdot e^{\left[\frac{E}{R\theta_{c0}} \right]} \right) \Delta(t/t_v)^n$
	$\eta = -300.8 - 357.6X_1 - 553.4X_2 + 575.4X_3 - 80.8X_4 - 22.4X_5 + 293.7X_1X_2 - 329.4X_1X_3 + 14.7X_1X_4 + 57X_1X_5 - 528.4X_2X_3 + 48.9X_2X_4 + 21.2X_2X_5 - 151.1X_3X_4 - 29.3X_3X_5 + 175.2X_4X_5 + 114.4X_1^2 + 152.8X_2^2 + 664.6X_3^2 + 159.2X_4^2 + 213X_5^2$
	$\eta_0 = Q_1 \cdot e^{Q_2 \cdot \phi} \cdot (1 - \phi_f) + Q_3 \cdot e^{Q_4 \cdot \phi} \cdot \phi_f$
Effect of Measurements (slip)	$\eta_s = C_S \frac{\tau}{\dot{\gamma}}$
3D Viscous Stress Tensor	$T_v = -pI + \mu_0 \left(1 - \frac{\phi}{\phi_m} \right)^{-\beta} (1 + \lambda^n) [1 + \alpha \text{tr} A_1^2]^m A_1 + \alpha_1 A_2 + \alpha_2 A_1^2$
	$\frac{d\lambda}{dt} = \frac{1}{t_0} - \kappa \lambda \dot{\gamma}$

4. Conclusions

Gas migration issues in wellbore cement applications are important to understand to prevent costly remediation. Most sources identify the main reason that gas migration occurs is due to the reduction in hydrostatic head as the cement slurry begins to hydrate,

where the formation gas pressure exceeds the hydrostatic pressure in the cement slurry pores. For this reason, the use of the SGS method to calculate and minimize the transition time is the standard industry practice. Other practices include special cement designs, filtration control, minimizing the height of the cement column, increasing surface pressure on the annulus, and reducing fluid loss [2,11,14,15]. The suggestions for minimizing gas migration focus mostly on cement slurry design in order to reduce the flow of free water within the pores and settling of the cement particles, to lower fluid loss, and to develop compressive strength in the early stages of cementing [23,25,26,29,30]. Specialized cements have been designed [24,25,27,28,31,32,100] as attempts to address one or several of the issues that lead to gas tight cement. To characterize these cement slurries, SGS remains the recommended method in determining the potential for formation gas and fluid to invade and migrate through the annulus.

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Nomenclature

$c_{cem} + c_{ww} + c_{cas}$	Total compressibility of the system
d	Diameter, $d = d_h$ (hole diameter) $- d_p$ (pipe diameter)
d_{cas}	Diameter of the casing
d_w	Diameter of the well
dv/dt	Rate of fluid loss during the transition period/API area
$d\rho/dt$	Rate of fluid loss at the time of SGS
G'	Storage modulus at the maximum rate of gelation change
h	Depth of cement column
L	Length of the column
m	Maximum rate of change of gelation during the transition time
N_{FL}	Fluid loss rate
N_{SG}	Usefulness of static gel rate
P_f	Pore pressure of the flow zone
P_r	Pressure reduction from the cement gel strength
P_t	Pressure at top of the cement column
P_0	Pressure applied on the top of the cement column
p_c	Pore pressure of the cement slurry

$p_{h,i}$	Initial hydrostatic pressure
R_i	Radius of casing
R_o	Outside radius of the cement column
r	Radius of the disk
$S(t)$	Chemical shrinkage volume fraction with time
V/A	Ratio of the volume of the annulus to the borehole area
w/c	Water to cement ratio
$\dot{\gamma}$	Shear rate
Δp	Pressure to overcome the static gel strength
Δv_{fil}	Volume change caused by the filtration loss
Δv_{sh}	Volume change caused by the chemical shrinkage
Δv_T	Volume change caused by temperature change
Δv_w	Wellbore deformation
Δv_{cas}	Volume change caused by the deformation in the casing string
Θ	Angle of inclination of the cemented annulus
ρ_c	Slurry density
ρ_0	Initial density of cement
τ	Shear stress
τ_w	Wall shear stress
ϕ	Volume fraction of cement particles
ϕ_m	Maximum packing volume fraction
$\frac{\partial p}{\partial h}$	Pressure gradient
CF	Compressibility factor
CSGS	Critical static gel strength
CWSS	Critical wall shear stress
DP	Pressure loss due to volume reduction
DV	Volume reduction from the fluid loss and cement hydration
GFP	Gas-flow potential factor
MPR	Theoretical maximum pressure restriction
OBP	Overbalance pressure (the hydrostatic pressure – the formation pressure)
SGS	Static gel strength
SRN	Slurry response number

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