Theory-Based Review of Limitations With Static Gel Strength in Cement/Matrix Characterization

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Summary

Gases can migrate into the cemented annulus of a wellbore during early gelation when hydrostatic pressure within the cement slurry drops. Different means to describe hydrostatic-pressure reduction have been proposed and reported in the literature. Among them, static gel strength (SGS) is the most widely accepted concept in describing the strength development of hydrating cement. The classic shear-stress theory uses SGS to quantify the hydrostatic-pressure reduction in the cement column. Approaches derived from the concept of SGS have contributed to understanding mechanisms of gas migration and methods of minimizing it. Unfortunately, these approaches do not accurately predict gas migration. Although SGS was originally adopted to describe the shear stress at interfaces, it has also been used to estimate the shear resistance required to deform slurry during the hydration period. Before early gelation, the hydrostatic pressure will overcome the formation gas pressure and prevent gas migrations. During gelation, the cement develops enough rigidity to withstand the gas invasion. This critical hydration period is defined as the transition time. *API STD 65-2* (API 2010a) provides standards for determining the transition time by use of the concept of SGS. Current industry practice is to reduce the transition time, thereby lowering the potential for invading gas introducing migration pathways in the cemented annulus. This approach, although certainly helpful in reducing the risk for gas migration, does not eliminate its occurrence. Experimental results presented in this study demonstrate that the relationship between SGS and hydrostatic-pressure reduction is not linear. Characteristics of the transition-time endpoints depend on slurry properties and downhole conditions. Moreover, SGS is not able to characterize the gas-tight property of a cement slurry. When slurry gels, the mechanical properties are governed by its growing solid fraction. The gel can deform under shear loading, but gases and other fluids will need to break or fracture the bond between solids and push them aside for pathways to form within the cement/matrix domain at this point. To fully understand this process, the bond strength between solid particles and the compressibility of the cement matrix are needed. The bond strength and compressibility are mechanical properties dependent on the changing rigidity of the gelling cement. However, SGS does not address these important properties and, therefore, SGS is limited in its ability to predict gas-migration potential. A better means to characterize the cement/matrix strength by use of fundamental concepts and variables for replacing SGS is desired.

Introduction

Casing support and zonal isolation are the two principal objectives of primary cementing (Bonett and Pafitis 1996). However, achieving zonal isolation usually poses the greatest challenge because it is difficult to predict when the potential for formation gas to migrate into the cement sheath exists. In this study, "gas migration" is defined as "short-term" gas migration (Nelson 1990), where gases from gas-bearing formations invade the cemented annulus and migrate to a lower-pressure zone or possibly to the surface during well-completion procedures. "Gas migration," "gas invasion," "annular gas flow," "gas leakage," and "gas channeling" are synonymous terms used to describe gas entry into cemented annular spaces. Historical practice strongly suggests that gas migration and vent flows before, during, or after cementing (Goodwin and Crook 1992; Jackson and Murphey 1993; Wojtanowicz et al. 2001; Bellabarba et al. 2008; Kutchko 2008) may have serious consequences, such as severe injuries and environmental pollution (Harrison 1985). Recently, gas-migration occurrences have attracted more public attention because of the rapid onshore exploitation of shale gas. In addition, incidents continue to occur even with significant improvements in well-construction practices. Examples include the freshwater contamination in Wyoming (EPA 2011), and stray gas migration in Pennsylvania (PA DEP 2009; Reese et al. 2014). Statistical data show that 25% of failures of primary-cement jobs are the result of gas migration (Gonzalo et al. 2005).

Typically, "primary" gas migration occurs within a few hours, or at most some days, after cement placement. The mechanisms of gas migration and the means to prevent it have been a topic of interest since the 1960s. Although gas migration was first believed to occur exclusively through the weakness of the casing/cement and cement/formation interfaces, Carter and Slagle (1972) documented that gases can also penetrate the cement matrix during cement gelation. Since then, more research has been focused on the early gelation stage of cement hydration. **Fig. 1** shows cement sheaths from laboratory tests exhibiting the effects of gas invasion during cement gelation (Crook and Heathman 1998). As seen in Fig. 1, significant irregularly shaped gas channels formed within the cement. Several scenarios have been studied regarding the means by which gases invade the cement annulus during setting and hardening. These studies attribute the cause of gas migration to ineffective hydrostatic head, fluid loss during cementing, and differential-pressure occurrence between the cement and formation, which precede the cement setting. The pressure difference between effective hydrostatic pressure and formation gas pressure allows gases to migrate into the gel pores of the cement matrix. During cement gelling and before complete hydration, the conventional cement slurry loses its ability to transmit hydrostatic pressure to the formation. It has been observed that the slurry pore pressure actually declines soon after cement placement (Cooke et al. 1983).

Different theories to explain the mechanisms of hydrostatic-pressure reduction have been proposed, including localized bridging caused by fluid loss (Bannister and Lawson 1985); sedimentation of cement suspensions caused by slurry instability (Hartog et al. 1983; Bannister and Lawson 1985); volume reduction caused by fluid loss and chemical shrinkage (Sykes and Logan 1987; Jones and Carpenter 1991; Zhou and Wojtanowicz 2000); and supporting of cement because of the bond at interfaces (Sutton et al. 1984a, b). The classic gas-migration theory is the most widely accepted theory, which accounts for both self-support and volume reduction of the cement. After slurry placement, the initial hydrostatic pressure in the cement column is designed to be higher than the formation gas pressure. Although fluid loss and chemical shrinkage occur, the slurry can move downward and

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Fig. 1—Test cores of cement subjected to gas migration (Crook and Heathman 1998).

compensate for the volume reduction. When the slurry can still flow (move downward), the hydrostatic pressure will not drop significantly. As gelation progresses, the interactions between the cement column and the annular surfaces develop and chemical shrinkage and/or fluid loss continues. Because of the supporting effect of the borehole wall on the cement column, the tendency to move downward gradually decreases. Therefore, the effective hydrostatic pressure starts to drop. The hydrostatic pressure continues to drop until some critical time when the hydrostatic pressure is less than the formation gas pressure. If the cement has not developed sufficient strength to withstand the gas pressure, pressurized formation gases will invade the hydrating cement and create gas channels. Gas invasion may not cease until final time when the cement develops enough cohesive strength to prevent the entry and flow of gases and other fluids through the cement column. The period between critical time and final time is defined as the transition time. Experimental work has verified that gases do not penetrate the cement matrix as long as the slurry pore pressure remains greater than the formation gas pressure (Cheung and Beirute 1985). This process is illustrated in **Fig. 2.**

To quantify the hydrostatic-pressure reduction, SGS was introduced in classic shear-stress theory to describe the shear stress at the casing/cement and cement/formation interfaces. In this way, the hydrostatic-pressure reduction can be expressed as a function of SGS. In *API STD 65-2* (API 2010a), SGS is specified for determining the transition time. Currently, the petroleum industry attempts to minimize the risk of gas migration by ensuring that the SGS-based transition time is as short as possible through the use of chemical additives in the slurry design.

The concept of controlling transition time and other approaches developed to evaluate the potential for gas migration can only provide a qualitative estimate. They help improve the slurry design and cementing practice, but cannot eliminate gas migration. In addition, SGS is not sufficient to predict when a cement slurry becomes gas-tight. In this study, research activities associated with SGS are summarized and its application for evaluating the potential for gas migration is evaluated. These evaluations show that SGS fails to adequately describe the observed hydrostatic-pressure reduction. A discussion is also provided regarding the limitations of SGS for characterizing slurry properties with respect to preventing gas migration.

SGS Theory

The first publication attempting to explain the gas communication by means other than leakage at interfaces was presented by Carter and Slagle (1972). Since then, a great amount of effort has been invested in this topic and can be divided into three categories: mechanisms of hydrostatic-pressure reduction; methods to calculate effective hydrostatic pressure; and ways to prevent hydrostatic-pressure reduction. It is recognized that the main factor preventing gas from entering the cement is the hydrostatic pressure generated by the cement column and the drilling mud above it. Hydrostatic pressure must be greater than formation pore pressure to prevent gas invasion and be less than the fracturing pressure (gradient) of the formation to avoid lost circulation and/or fluid losses. Different mechanisms of hydrostatic-pressure reduction have been proposed. Among them, the most widely used model, derived from the classic shear-stress theory, was proposed by Sutton et al. (Sutton et al. 1984a, b).

Determination of Hydrostatic-Pressure Reduction. ***Classical Shear-Stress Theory.*** A physical model of the classical shear-stress theory is shown in **Fig. 3.** In this model, the cement column is assumed to be a single-phase homogeneous material, which is loaded by gravity, wall shear stress, pressure applied from the cement column above, and pressure from the cement column below. The entire cement column will move after shear failure occurs at interfaces. The force-balanced equation for an increment of cement section (ΔL) can be written as (Sutton et al. 1984a, b)

$$\tau\pi(OD+ID)\cdot\Delta L=\frac{\pi(OD^2-ID^2)(P_1-P_2+\Delta L\cdot\rho_c\cdot g)}{4}, \quad (1)$$

where τ = shear stress or SGS; P_1 = pressure applied on the cement section from the top; P_2 = pressure applied on the cement section from the bottom; ρ_c = density of cement slurry; OD = borehole diameter; ID = casing outside diameter (OD); ΔL = cement-section length; and g = gravitational acceleration.

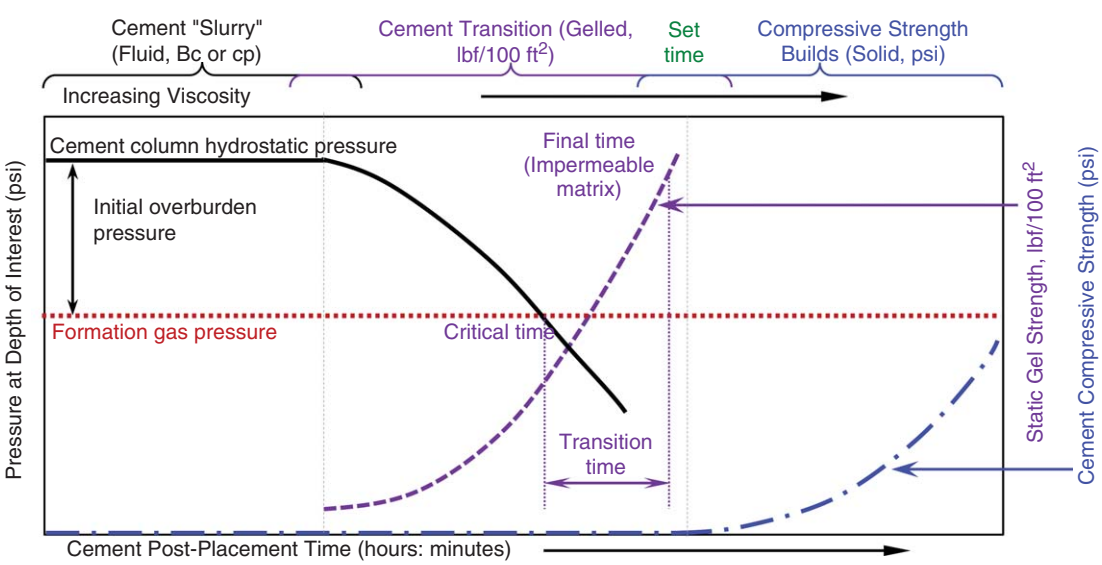


Fig. 2—Pressure and strength evolution. Bc = Bearden units of consistency.

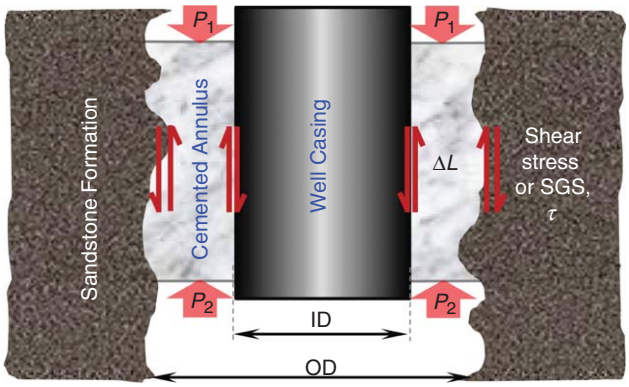


Fig. 3—Sketch of pressure reduction in hydrating-cement column.

By integrating from the top of the cement to the depth of interest, Eq. 1 can be written as

$$\int_0^L \tau \cdot \mathrm{d}L = \left(\frac{OD - ID}{4}\right) \cdot \left\{ [P_0 - P(L,t)] + g \int_0^L \rho_c \cdot \mathrm{d}L \right\}, \quad \cdots (2)$$

where P_0 = hydrostatic pressure applied on top surface of cement column, typically generated from drilling mud (P_m), washer (P_{wa}), spacer columns (P_{sp}), and surface pressure (SP). That is, $P_0 = (P_m + P_{wa} + P_{sp} + SP)$. In addition, $P(L,t)$ = effective pore pressure at depth L and time t, and L = cement-column length, considered from the top of cement to the depth of interest.

Assuming that the properties of the entire cement column are identical, Eq. 2 can be simplified as

$$\tau = \frac{(OD - ID) \cdot [\rho_c \cdot gL + P_0 - P(L,t)]}{4L}. \quad \cdots (3a)$$

Therefore, the effective hydrostatic pressure at depth H and time t can be rewritten as

$$P(L,t) = P_0 + \rho_c \cdot gL - \frac{4L}{OD - ID}.\tau. \quad \cdots (3b)$$

The original intention of Eq. 3 was to explain the hydrostatic-pressure reduction during cement gelation. It captures the essential mechanism of hydrostatic-pressure reduction and serves as a tool to quantify the hydrostatic pressure during cement gelation. The industry has assumed that SGS can be used to quantify shear stress. In reality, SGS is not a fundamental parameter. The limitations in assuming that SGS can be used to characterize the shear stress are discussed in this study.

After the aforementioned model was developed, researchers tried to predict the hydrostatic-pressure reduction by use of this model but were unsuccessful. According to Eq. 3b, the relationship between the pressure reduction and the SGS is linear, as shown in **Fig. 4.** Experimental results contradict this assumption. As seen in **Fig. 5,** the hydrostatic-pressure reduction is not necessarily proportional to the SGS development. Although the classic shear-stress theory reflects the interaction between cement and borehole, it is not sufficient to predict the hydrostatic-pressure reduction accurately.

When the model dependent on the classical shear-stress theory was developed, the physical meaning of shear stress and factors causing pressure reduction were not fully understood, thereby affecting the accuracy of the developed relationship. First, the cement slurry is a solid/fluid-coupled media, particularly in the early-gelation stage. It is inappropriate to assume that the cement slurry is a single-phase homogeneous material. Second, the mechanism of hydrostatic-pressure reduction may change with the development of cement hydration. The microstructure of the cement matrix and its evolution are not considered in this model. The cement composition and additives will significantly influence the slurry mechanical properties and its hydration. In addition, the model does not consider the effect of slurry instability and inclined annuli.

Revised Model. Volume reduction was identified as another critical factor affecting hydrostatic-pressure reduction. The internal volume of cement slurry decreases because of chemical shrinkage and fluid loss (Tinsley et al. 1980). By assuming no volume change during the early-gelation stage, the existence of a linear relationship in Eq. 3 is contradicted. Later, it was recognized that the borehole and the casing will deform because of the pressure change (Jones and Carpenter 1991; Zhou and Wojtanowicz 2000). According to Boyle-Mariotte's law (Draper 1861), the effective hydrostatic pressure will decrease because of volume reduction. The basic relationship between pressure change and volume changes is presented as (Zhou and Wojtanowicz 2000)

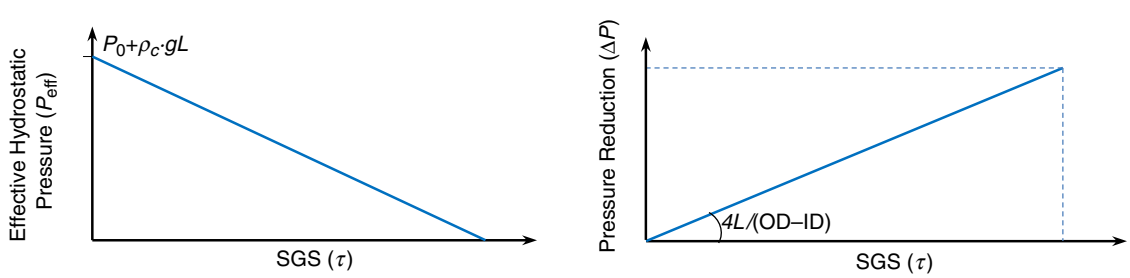
$$\Delta p = (\Delta v_{\mathrm{loss}} + \Delta v_{sh} - \Delta v_T - \Delta v_{wh} - \Delta v_{csg})/(V_0 \cdot c), \quad \cdots (4)$$

where $\Delta v_{\mathrm{loss}}, \Delta v_{sh}, \Delta v_T, \Delta v_{wh}$, and Δv_{csg} denote volume changes caused by fluid loss, chemical shrinkage, temperature change, wellbore deformation, and casing deformation, respectively.

The volume-reduction method captures the physical changes in the borehole. Nevertheless, in-situ conditions are so complicated that the pressure reduction is difficult to accurately predict. Many of the influential factors are difficult to quantify and have to be assumed. Moreover, the theory assumes a static state for the cement slurry. This would overlook the deformation of the cement column and the volume change in the cement matrix. As a result, this theory is more applicable to the later-hydration stage rather than the early-gelation stage.

To consider both slurry rheological properties and volume reduction, Chenevert and Jin (1989) studied the effects of time-dependent variables on SGS, including temperature and pressure in the cement column and slurry composition and set time of the cement. By integrating from the top to the depth of interest, a revised expression of effective hydrostatic pressure can be written as (Chenevert and Jin 1989; Prohaska et al. 1993)

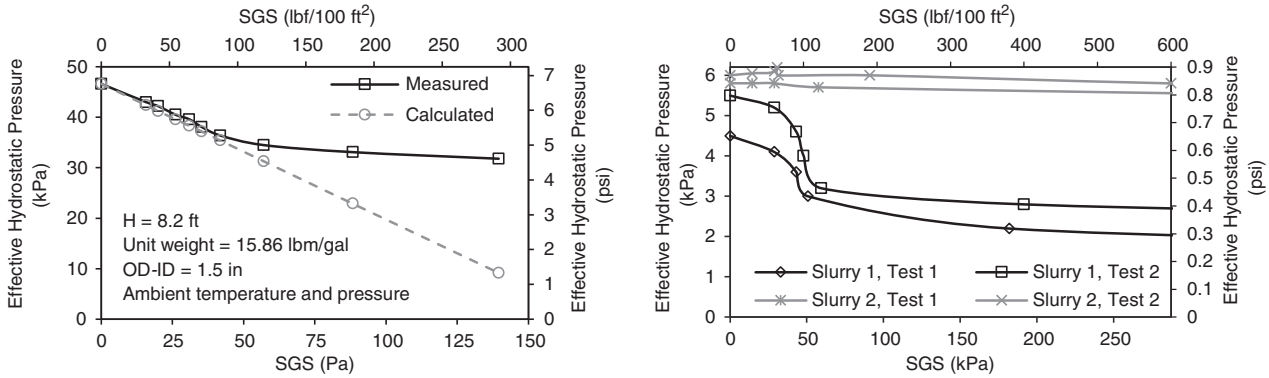
$$P(L,t) = P_0 + g \cdot \int_0^L \frac{\rho_c}{1 - S(L,t)} \cdot \mathrm{d}L - \frac{4}{OD - ID} \int_0^L \tau(\gamma, t) \cdot \mathrm{d}L, \quad \cdots (5)$$



(a) Effective hydrostatic pressure vs. SGS

(b) Pressure reduction vs. SGS

Fig. 4—Relationship between hydrostatic pressure and SGS.



(a) Measured vs. calculated results (adapted from Zhang 2002)

(b) Results of two different slurry designs (adapted from Zhu et al. 2012)

Fig. 5—Effective hydrostatic pressure with respect to SGS.

where γ = shear strain and $S(L,t)$ = shrinkage of cement slurry at depth L and time t.

Eq. 5 is more comprehensive and theoretically accurate than Eq. 3b. Not only is the variation of SGS in the wellbore considered, but so are volume changes with respect to the time and depth. However, this model is fundamentally derived from the classical shear-stress theory, which shares the same limitations previously discussed. After the cement is placed, the hydrostatic pressure is constant while the cement deforms to some extent to compensate for the volume reduction caused by fluid loss and chemical shrinkage. The friction, or bond, at the interface tries to support the cement matrix. When the slurry at or near the interfaces is not able to deform, it is inappropriate to determine the static friction by use of the force-balanced equation, because the actual shear stress at the interface will be less than the backcalculated SGS from Eq. 3. The reason is that the friction component is determined by other variables in the statically indeterminate system. In addition, enhanced additives are typically blended in the slurry design to control gas migration, which makes it inappropriate to predict the hydrostatic-pressure reduction by use of Eq. 3. For instance, an expanding agent helps maintain a high hydrostatic pressure even in the presence of the SGS development, as shown in Fig. 5b. Therefore, the theoretical relationship by use of the concept of SGS is not capable of evaluating the potential for gas migration.

Practical Approaches. A desire for design criteria to be applied in the field triggered the petroleum industry to develop approaches to assist operators in predicting the potential for gas migration. Several of the more common approaches are presented in the following subsections.

Flow-Potential Factor (FPF). Because Eq. 3 captures the phenomena of hydrostatic-pressure reduction in the early gelation, researchers tried to evaluate the feasibility of using this model for predicting gas migration. By use of the classical shear-stress theory, Sutton et al. (1984b) developed a gas FPF to predict the potential for gas migration. FPF, sometimes called gas-flow potential, is defined as

$$FPF = MPR/OBP, \quad (6)$$

where OBP = initial overbalance pressure, defined as

$$OBP = \rho_c \cdot gL + P_0 - P_f, \quad (7)$$

where P_f = formation gas pressure and MPR = maximum pressure reduction at a given SGS value. The MPR can be obtained by substituting Eq. 3 (for English units),

$$\begin{aligned} MPR &= \rho_c \cdot gL + P_0 - P(L,t) = \tau \cdot 4L/(OD - ID) \\ &= SGS/300 \times L/D, \quad (8) \end{aligned}$$

where D = difference between hole diameter and casing diameter ($OD - ID$) in inches; 300 = conversion factor, lbf/in.; SGS = static gel strength, lbf/100 ft^2.

The assumption of the FPF theory is that gases will not penetrate the cement slurry if effective hydrostatic pressure is higher than formation gas pressure. Eq. 6 is in fact a modification of the standard shear-stress equation presented in Eq. 3b. According to Eqs. 3 and 6, FPF should equal unity when effective hydrostatic pressure equals formation gas pressure. The SGS at the time when the effective hydrostatic pressure is zero can also be determined by use of Eq. 3a for a typical slurry design:

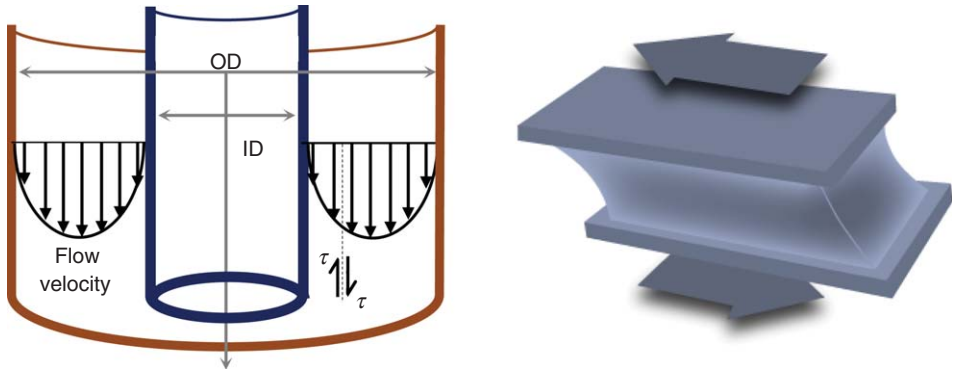
$$\begin{aligned} SGS &= [\rho_c \cdot gL + P_0 - P(L,t)] \cdot \frac{OD - ID}{4L} \\ &= (\rho_c \cdot gL + 0 - 0) \cdot \frac{OD - ID}{4L} = (\rho_c \cdot g) \cdot \frac{OD - ID}{4} \\ &= \left[(15.6\,\text{lbm/gal} \times 0.052) \times \left(\frac{2.5\,\text{in.}}{4} \times \frac{1.0\,\text{ft}}{12\,\text{in.}}\right)\right] \text{ psi} \\ &= 0.0423 \text{ psi} = 608 \text{ lbf}/100\text{ft}^2. \quad (9) \end{aligned}$$

However, Eq. 3b may overestimate the hydrostatic-pressure reduction. Experiments indicate that residual effective hydrostatic pressure exists even after final set of the cement, as shown in Fig. 5. This can be explained by use of boundary-flow theory, as shown in **Fig. 6.** With the development of cement hydration, chemical shrinkage occurs and cement slurry is capable of moving downward because of gravitational forces. As the interface bond increases, slurry particles near the borehole wall will adhere onto the surface. The central portion of the slurry is still able to move downward relatively freely, maintaining the effective hydrostatic pressure. The movement of cement slurry is governed by the principles of laminar flow, and the shear deformation described in Eq. 3 occurs between cement interlayers.

Because of the lack of effective methods to accurately predict gas migration, criteria for defining gas-migration potential have been established by use of empirical field observations. SGS at the end of transition time was experimentally determined to be 250 Pa (522 lbf/100 ft^2) by Sabins et al. (1982). An SGS of 500 lbf/100 ft^2 is commonly used to calculate the FPF. On the basis of field experience, the results of FPF are divided into three categories: severe, moderate, and minor. Unfortunately, the development of these rules remains unpublished (Nelson 1990).

Generally, FPF is a unit-less value used to predict the severity for encountering gas migration. FPF lacks a physical meaning and its use is a qualitative approach, with the empirical criteria for this approach established by use of relatively limited field experience.

Critical Wall-Shear Stress (CWSS). To provide a meaningful variable in evaluating the potential for gas migration (Bonett and Pafitis 1996). Wall-shear stress is defined as static friction that



(a) Boundary layer flow (b) Resistance to shear deformation

Fig. 6—Boundary-flow theory and shear bond strength.

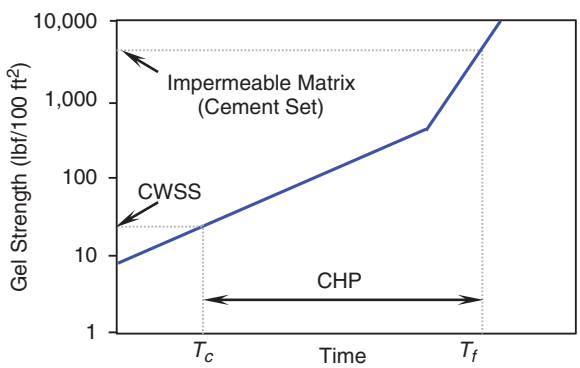


Fig. 7—CHP in the CWSS approach (Brandt et al. 1998).

occurs at the interfaces between the cement and the casing or formation. Therefore, the CWSS represents the shear stress at the interfaces when the effective hydrostatic pressure is equal to the formation gas pressure (Bonett and Pafitis 1996; Stiles 1997). The original formula is shown as

$$CWSS = 0.25(P_m + P_{wa} + P_{sp} + P_{sl} + SP - P_f) \times (OD - ID)/L, \quad (10a)$$

which can be simplified as

$$CWSS = OBP \times D/4L. \quad (10b)$$

Critical hydration period (CHP) is another term for the transition time, which is described as the time period between the CWSS and the development of an impermeable cement matrix that gases can no longer enter or migrate through. In the CWSS approach, the risk of gas migration can be reduced by shortening the CHP, as shown in **Fig. 7.** A means to reduce the CHP is to increase the CWSS. A relatively high CWSS will result in a relatively lower risk for gas migration.

In essence, the theoretical foundation of the CWSS is similar to that of the FPF. Although the FPF method is used to calculate the effective pressure by use of SGS, the CWSS method is used to determine the shear stress by use of the maximum-allowable pressure reduction. The relationship between FPF and CWSS can be derived from Eqs. 3, 6, and 10, and shown as

$$FPF = SGS/CWSS. \quad (11)$$

A comparison between FPF and CWSS is presented in **Table 1.** Although the CWSS provides more levels of classification, both of them can only provide a qualitative severity level for encountering gas migration. Similar to the FPF, the empirical criteria for the CWSS method were established on the basis of limited field experience. In addition, the CWSS denotes the mechanical properties at the interfaces, but it is not a slurry property.

Slurry-Response Number (SRN). Two necessary conditions are required for gas invasion into settable slurry (Bonett and Pafitis 1996): a driving force (differential pressure) to start the gas flow, and space within the cemented annulus for gas to occupy. The stability of the cement slurry is critical to maintaining the effective hydrostatic pressure during cement hydration. Fluid loss will dramatically decrease the hydrostatic pressure, which will also provide space for gas to occupy. To consider the fluid loss during cement hydration in predicting the potential for gas migration, the SRN method was proposed. SRN is defined as a ratio of the SGS development rate to the rate of fluid loss at the time when SGS develops at a maximum rate of change (Sutton and Ravi 1989; Harris et al. 1990), and can be written as

$$SRN = \frac{\frac{d(SGS)}{dt}/SGS_{\text{maxrate}}}{\frac{dl}{dt}/(V/A)}, \quad (12)$$

where $d(SGS)/dt =$ maximum rate of change of static gel strength; $SGS_{\text{max rate}} =$ SGS at time of maximum rate of change; $dl/dt =$ rate of fluid loss at time of $SGS_{\max}$; $V =$ volume of

Approach	Severity Rating				
FPF	Severe	Moderate	Minor		
	>8 (8)	4–8 (4)	<4		
CWSS	Very critical	Critical	Moderate	Low	Very low
	25 Pa (50 lbf/100 ft²)	75 Pa (150 lbf/100 ft²)	150 Pa (300 lbf/100 ft²)	250 Pa (500 lbf/100 ft²)	

Table 1—Comparison between FPF and CWSS values. FPF and CWSS values are orders of magnitude, which are derived from limited experience.

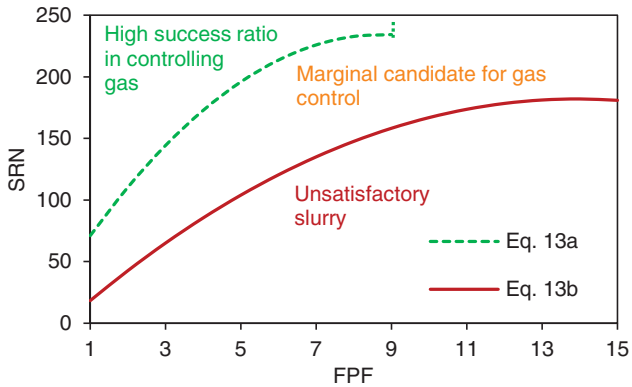


Fig. 8—SRN ranges.

annular space per unit length; and A = area of formation face per unit length.

The SRN is a significant improvement over the slurry-performance factor developed by Schlumberger (Wilkins and Free 1989). The critical time determined by the SRN method corresponds to the onset of a rapid increase in SGS. Fluid loss represents volumetric reduction of the slurry, and the rate of fluid loss declines over time. At the critical time, the rate of fluid loss should be very small (high values of SRN). Otherwise, pressure at the bottom of cement slurry could rapidly decline, causing gas migration.

The SRN method was correlated with the conventional measure of gas-migration potential, the FPF. This constitutes the first "quantitative" model for the annular-wellbore-seal integrity (Harris et al. 1990). **Fig. 8** and Eq. 13 show the criteria for slurry design by use of the SRN/FPF approach.

$$SRN = 26.3 + (47.4 \times FPF) - \left(2.7 \times FPF^2\right), \quad \text{for } 1 < FPF < 9, \qquad (13a)$$

$$SRN = -8.1 + (27.3 \times FPF) - \left(0.98 \times FPF^2\right), \quad \text{for } 1 < FPF < 15. \qquad (13b)$$

The SRN method intends to determine the critical time when the maximum rate of pressure reduction will occur. Volume reduction and self-support are both taken into account. However, typical values of SGS_{maxrate} take place when the SGS is approximately 100–200 lbf/100 ft^2. Because the slurry is still flowable, the rate of pressure reduction at the critical time determined by the SRN may not be the maximum. Also, because the FPF is used to quantify the failure criteria, the SRN method is also dependent on empirical criteria established by use of relatively limited field experience.

Discussions. The aforementioned approaches capture the essential factors affecting hydrostatic-pressure reduction. They provide guidelines on improving slurry design and construction practice (Levine et al. 1979). For example, new cement designs, such as right-angle-set cement, surfactant agents, expansive cement, impermeable agents, and latex particles, have been developed and implemented on the basis of their performance. Casing-design optimization, multistage cementing (Shiflet et al. 2005; Labibzadeh et al. 2010), and cement-pulsation treatment (Wojtanowicz et al. 2002) have been used in practice. The industry has also long understood the advantages of reciprocating and rotating casings during cementing operations.

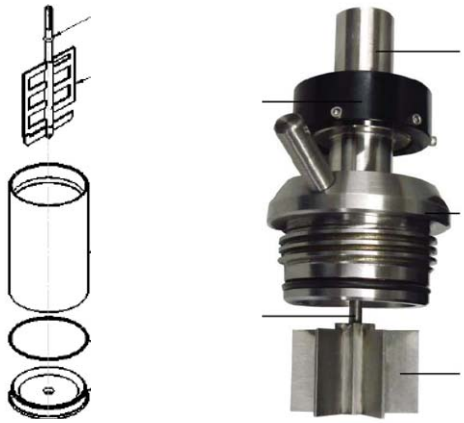
However, the accuracy of these approaches remains a concern because it is very difficult to quantify the efficiency of cement displacement. Moreover, the approaches are derived from the classical shear-stress theory, and therefore share the same limitations discussed previously. As seen in Table 1 and Fig. 8, the aforementioned approaches are fundamentally of the same philosophy. The criteria are not slurry properties but calculated values (Stiles 1997; Gonzalo et al. 2005), which only provide a qualitative estimation of the potential for gas migration. Currently, these approaches are mainly used for designing slurries with favorable properties, such as optimal density, minimal fluid loss, and short transition time. They also provide guidance for casing-string design. Calibrated by use of field experience, the approaches have been able to assist operators in mitigating bottomhole gas migration. However, recent gas-migration occurrences from onshore unconventional shale-gas plays have caused the petroleum industry to re-evaluate them. Although the approaches indicate a "minor" potential for gas migration, shallow stray-gas migration and interzonal communication are underestimated by all these approaches (PA DEP 2009; EPA 2011; Dusseault et al. 2014).

Measuring Transition Time. Because of the absence of an effective means to determine gas-migration occurrence, the petroleum industry tries to reduce the risk of gas migration by shortening the transition time, the critical hydration period during the gelation stage (Rogers et al. 2004). After the relationship between SGS and hydrostatic pressure was established through the application of classical shear-stress theory, the petroleum industry tried to use this model by focusing research efforts on methods to determine SGS and criteria for its application.

In *API STD 65-2* (API 2010a), the concept of SGS is referenced to determine the transition time, which is defined as the period between the time when critical SGS (CSGS) and optimal SGS (OSGS) are achieved. When cement achieves CSGS, the slurry is no longer capable of transmitting hydrostatic pressure that overbalances the formation pore pressure. CSGS can be calculated when the formation pore pressure is known by use of Eq. 3a. When sufficient information is not available to confidently calculate CSGS, a value of 100 lbf/100 ft^2 (48 Pa) may be used (API 2010b). In addition, 500 lbf/100 ft^2 (API 2010a) is specified as the OSGS, at which the slurry has developed enough cohesive strength to prevent the entry and flow of gas and reservoir fluids through the cement (Kolstad et al. 2004). The faster the OSGS is achieved, the less likely it is that gases will percolate through the cement slurry. The OSGS is specified as 500 lbf/100 ft^2(240 Pa). It should be noted that the study published by Sabins et al. (1982) is the only available peer-reviewed document in which 100 and 500 lbf/100 ft^2 were justified as acceptable criteria, regardless of different slurry designs and application conditions. Moreover, Stewart and Schouten (1988) showed that gel strength considerably less than 500 lbf/100 ft^2 could inhibit gas percolation, but most gas migration was conclusively shown to occur after the initial set of cement.

The International Organization for Standardization (ISO) has been evaluating different types of SGS test devices to develop standard measurement methods. In *ISO 10426-6 (ISO 2008)*, three different testing apparatuses for determining SGS are recommended, including: (1) rotating-type; (2) intermittent rotation-type, and (3) ultrasonic-type SGS devices.

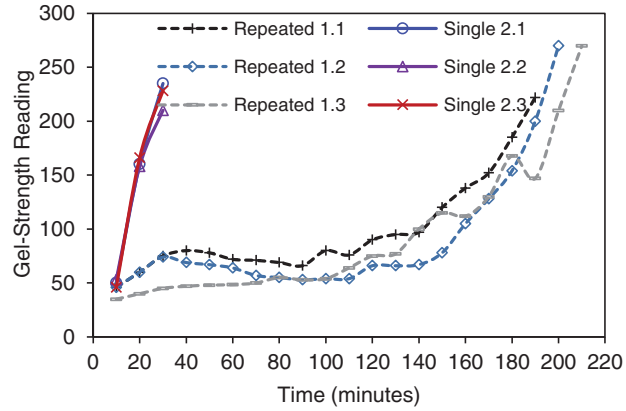
Mechanical Measurement. Even though the equipment designs for measuring SGS attempt to maintain a quasistatic state for cement slurries, results vary from different rotating speeds, measurement time intervals, and device types. **Fig. 9** shows the paddle and the vane used to shear the slurry in the mechanical SGS devices (Fann Instrument Company 2011; OFI Testing Equipment 2014). It should be noted that 100 and 500 lbf/100 ft^2 were developed by use of the paddle design shown in Fig. 9a. Although an extremely low shear rate is used, the slurry is repeatedly destructed along the shearing front. For the rotating-type SGS device in Fig. 9a, standard rotating speed of 0.2 degrees/min indicates a 3.0 μm/s shearing speed at the edge of the paddle, which is the same scale as the cement-particle size (an average cement-particle size is approximate 20 μm). Therefore, the rotating-type SGS device is a continuously destructive test. The rotating speed of the paddle will significantly affect the measured results. By reducing the rotating speed of the paddle, the measured SGS will continuously get closer to the true SGS of the slurry. When it comes to the intermittent-rotation-type SGS device, the shearing front is created once the shearing movement occurs. The



(a) Paddle in rotating-type device (Fann Instrument Co. 2011)

(b) Six-blade vane in intermittent rotation-type device (OFITE 2014)

Fig. 9—Paddle design and typical SGS measurements.



Note: Repeated Destruction (Three repetitions: 1.1, 1.2, 1.3) vs. Single Destruction (Three repetitions: 2.1, 2.2, 2.3)

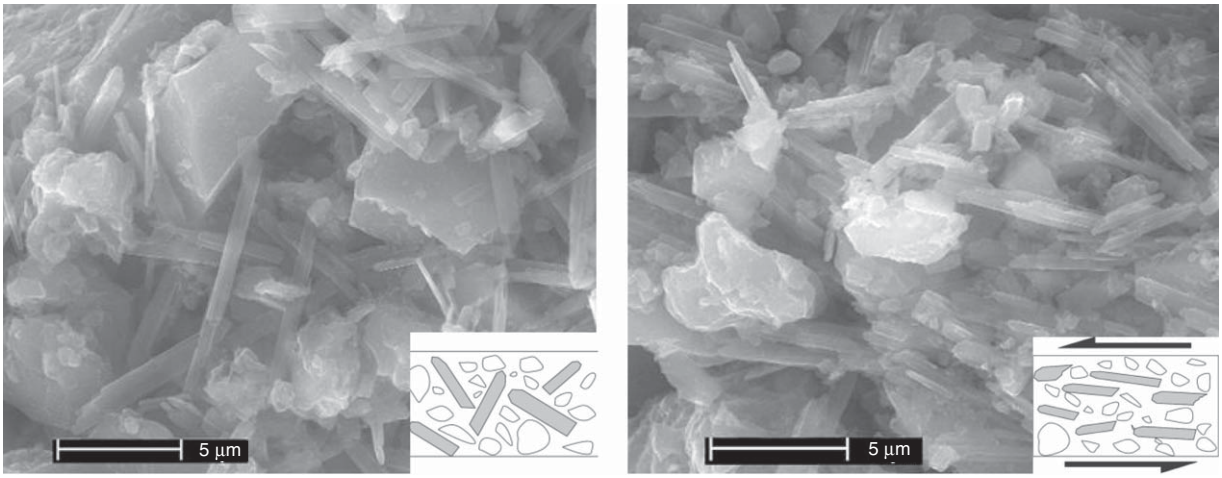
Fig. 10—Gel-strength-development comparison (Zhang 2002).

measured SGS mainly depends on the static time period for cement flocculating. The later the test starts, the higher the SGS. The shearing front is the cylindrical surface generated by the vane, which is the area used to calculate the SGS. The rotating-type device creates a shearing front similar to that created by the intermittent-rotation-type device, even though the shape of the stirring paddle is different, as shown in Fig. 9b. The flocculation of hydration products at the shearing front suffers the cycles of construction, damage, and reconstruction. Therefore, neither the rotating-type nor the intermittent-rotation-type device qualifies for nondestructive testing, because a weak shearing front is created from the repeated microstructural destruction.

An example of destructive testing is shown in **Fig. 10,** where the degradation of gel strength is related to the number of destructive measurement points. The repeatedly destructed tests were conducted by shearing the same slurry sample every 10 minutes, whereas the single destructed tests were performed on the slurries that set quiescently from the beginning until the testing time. As seen in Fig. 10, the repeated destruction dramatically decreases the gel strength of the slurry. **Fig. 11** shows the morphology of hydration products. After 2 hours of stirring in the viscometer, the typical morphology of hydration products does not change but crystals align in the shear direction (indicated by arrows) to develop a preferred orientation.

Nondestructive Measurement. Because of the copyright of patents, the method by use of ultrasonic technology to determine SGS is not described in *API RP 10B-6* (API 2010b). Details of an acoustic device for determining the SGS of a cement slurry can be found in Patent Application No. US5992223A (Sabins and Maki 1999). According to Patent Application No. US599223A, ultrasonic devices do not always provide accurate SGS measurements, as shown in **Fig. 12.** Cement properties are inferred by measuring the change in the energy level of an ultrasonic signal transmitted through the cement specimen as it gels and are labeled as "computed gel strength" in Fig. 12. Clearly, the relationship has to be accurately calibrated between SGS development and longitudinal-ultrasonic-wave properties (i.e., velocity and attenuation). As seen in Fig. 12b, although the predictions of SGS development are relatively accurate with the ultrasonic testing, the results for the transition time (from 100 to 500 lbf/100 ft^2) are not applicable, which may be caused by the presence of latexes. Air bubbles also significantly affect the ultrasonic velocity. Therefore, slurries containing additives, such as increased levels of latexes or air bubbles, may require an adjustment of the coefficients in the computational models.

The literature indicates that the ultrasonic testing can be used to determine the initial set of cement. Zhang et al. (2010) studied the effect of the water/cement ratio, temperature, and chemical additives on early hydration of API Class H cement. As shown in **Fig. 13,** the ultrasonic-wave velocity remains constant (approximately 1500 m/s, which is equivalent to the wave velocity through



(a) Cement hydrated without agitation: random orientation

(b) Cement paste after 2 hours of shearing in the viscometer: preferred orientation

Fig. 11—Environmental scanning electron microscope image of cement after 2 hours of hydration (Rößler et al. 2008).

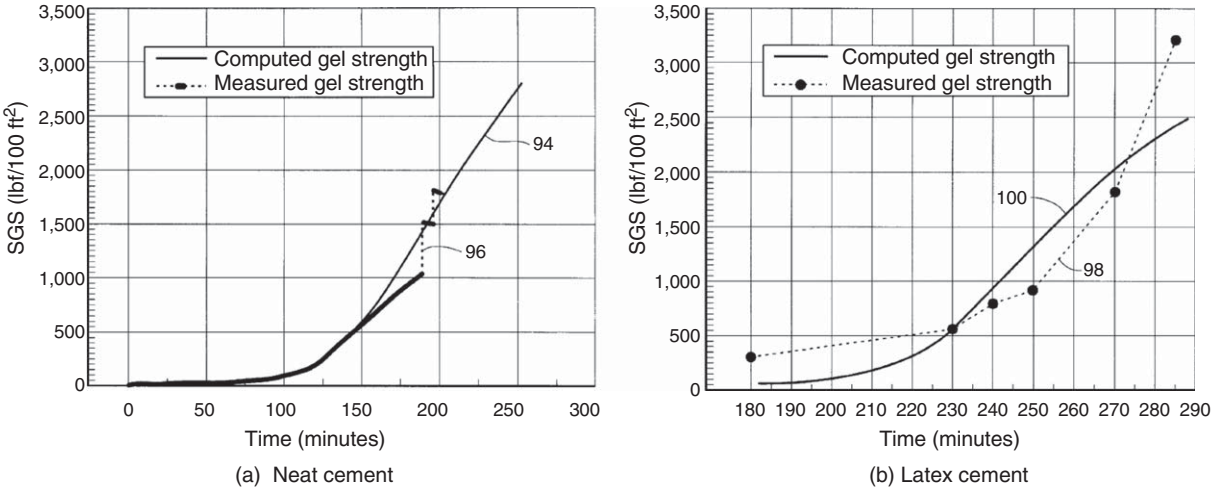


Fig. 12—Evaluation of SGS measurement by use of ultrasonic device (Sabins and Maki 1999).

water) until cement slurries gain the initial setting strength defined in *ASTM C191* (ASTM International 2013).

Other nondestructive methods to monitor cement hydration include nonelectrode resistivity measurement and dielectric constant measurement. Similar to ultrasonic measurement devices, these nondestructive methods can capture the slurry-phase changes. The amplitude of the measurement depends on the components and their quantities. Therefore, it is difficult to develop a general relationship between the SGS and the electrical resistivity or the dielectric permittivity during the early gelation stage.

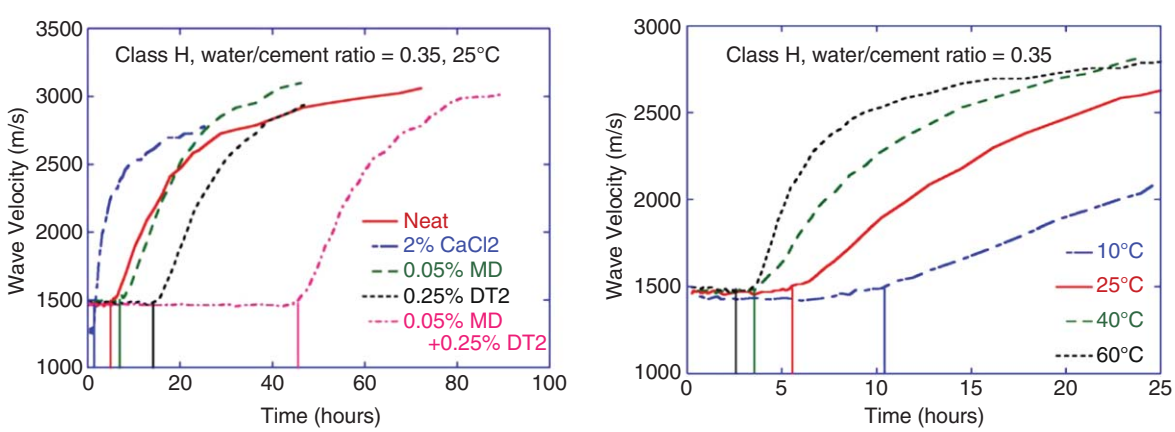
Cement/Matrix Characterization

Use of SGS To Quantify Cement Rigidity. The term "gel," which is commonly used within the petroleum industry, differs significantly from the definition applied in polymer science. It is used to describe cement thixotropic properties. SGS is defined as the shear stress derived from force required to start flow of a fluid. The concepts and methods for cement characterization are actually adopted from the viscosity concept for liquid materials. However, the cement slurry is not a liquid, but a phase-changing solid/fluid-coupled media.

As discussed previously, the concept of SGS was originally used to describe the static shear stress at interfaces. After cement placement, a very-thin cement layer will adhere to the rough surface of the casing and the formation. As cement continues gelling, shear deformation occurs within cement slurry and should follow the boundary-layer-flow theory, as shown in Fig. 6. Therefore, SGS describes cement resistance to deformation by shear stress. Adopted from fluid dynamics, SGS does reflect the cement strength as it increases with rigidity development of the cement matrix. However, the interaction between the formation gas and the cement matrix is not purely shearing. Gases and other fluids have to break through the cement matrix and generate a path by pushing bonded solids apart. This requires that the normal bond strength be overcome and the cement matrix be compressed, as shown in **Fig. 14.**

Neither the compressibility of the cement matrix, nor the normal bond strength between the particles, has a direct relationship with the shear bond friction. Being a bulk mechanical property, SGS includes the interface bond or cohesion between particles; however, it is impossible to distinguish the normal strength between particles from the shear strength within the cement layers by use of SGS solely. In addition, SGS cannot describe the compressibility of the cement matrix because SGS alone is not sufficient to reflect either shear thinning or shear thickening. Therefore, SGS is an "apparent" parameter describing the bulk mechanical character of the cement matrix. Neither the normal bond strength between solids nor the compressibility of the cement matrix can be distinguished from shear bond strength by use of only SGS. The next subsection will demonstrate the limitations of SGS through a discussion of its inability to isolate the gas-tight properties associated with the use of slurry additives.

Slurry-Performance Enhancements. Different additives are commonly blended to adjust slurry properties and achieve desirable results. For example, it has been demonstrated that latexes and



Note: solid straight lines indicating the initial setting time determined by Vicat test (ASTM C191-13 2013)

Fig. 13—Ultrasonic wave velocity vs. time curves (Zhang et al. 2010).

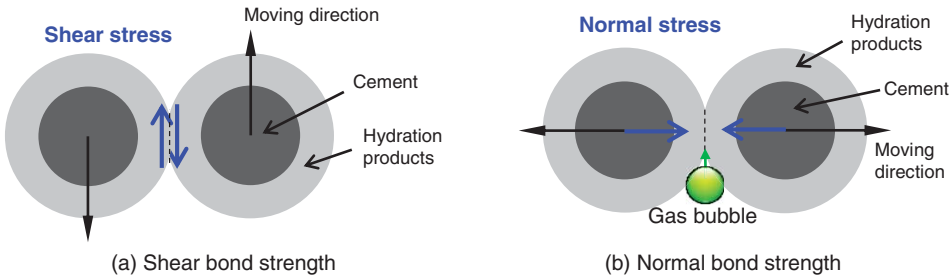


Fig. 14—Shear bond strength and normal bond strength.

particle-size distributions (PSDs) can improve the gas-tight properties of cement slurry. However, neither the SGS nor the model for hydrostatic-pressure reduction is able to capture the effectiveness of these additives in preventing gas migration.

Latexes. The mechanisms of latexes in helping with resistance to gas migration have been discussed for a considerable length of time (Jones and Carpenter 1991). A sensitivity study was carried out to evaluate the effects of latex, dispersant, and water/cement ratio (Tavares et al. 2013).

Table 2 shows the results of SGS development and gas-migration occurrences. Slurries with adequate concentrations of latex were resistant to gas migration, despite their shrinkage and SGS history. Early in the hydration process, latex particles are suspended separately in the cement slurry. They will flocculate and coalesce as films or membranes within the cement matrix during early gelation. Because the latex is a deformable polymer, the SGS does not significantly increase. The latex films serve as the crystallization nucleus for hydration products promoting growth. Therefore, CSGS is achieved more rapidly when latex is added. **Fig. 15a** shows that hydration products coagulate on latex flocculants. However, embedded latex flocculants decrease the "permeability" of cement matrix when cement starts to gel. In more-basic slurry designs, such as groups with 0.09% of dispersant, the latex can extend the transition time. The adhesive and cohesive properties of latex help to resist the cement from being torn apart. Fig. 15b shows the adhesion effect of latex in the cement matrix (Plank 2014).

Compared with the micrometer (10^{-6} m) magnitude of the size of cement particles, nanometer-scale (10^{-9} m) latexes can form a colloid-dispersion system between cement particles, which reduces the permeability of cement matrix. When latex flocculates, it performs like a barrier, which can also bridge hydration products. The adhesive and cohesive properties of latex improve the bond between solids and the elasticity of the cement matrix (Bonett and Pafitis 1996). Unfortunately, SGS is unable to capture the dramatic enhancement of the ductility because of the bridging effect of latexes. Because the shearing movement is extremely low in the mechanical SGS-measurement devices discussed previously, the latex film is not expanded and reinforcement cannot be shown. Therefore, SGS is not able to distinguish the normal interaction from the shearing property. Neither the barrier effect nor the lower permeability can be captured by SGS.

PSD. Another means to enhance slurry performance with respect to gas-migration prevention is optimization of the PSD (Boisnault et al. 1999). When the PSD is optimized, solid particles can be well-compacted. Therefore, less water is needed and the fluid loss can be reduced. Another advantage is that a well-graded slurry is less compressible than a poorly graded slurry. As shown in Fig. 14, gases have to push solids apart to form a channel. By filling space between bigger solids with smaller particles, the solid fraction is larger and gaps are smaller, as shown in **Fig. 16.** In a well-graded slurry sample, solid particles are compacted and in close contact with surrounding particles. This will also decrease the permeability of the cement matrix.

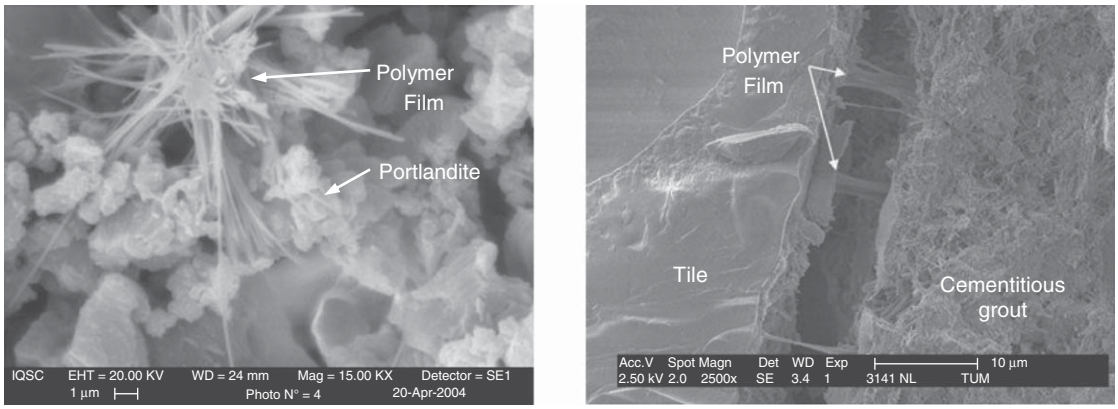
It is notable that SGS may not necessarily be high in a well-graded slurry. To demonstrate the effect of cement-particle size on the cement/matrix-strength development, coarse cement particles are assumed to be twice as large as fine cement particles. With an identical water/cement ratio, the contact area will be the same for the same hydration stage, as shown in **Fig. 17.** The SGS may be equal because the contract area is the same. However, the finer matrix provides much-smaller voids and, therefore, a less-permeable matrix.

Microstructural Development. As discussed previously, SGS is an "apparent" property reflective of the strength development of cement slurry. Compressibility, permeability, and normal bond strength of a cement matrix cannot be distinguished from shear bond strength by use of only SGS. To predict the gas-tight properties of cement, a better approach is to characterize cement-microstructural development.

Solid/Fluid-Coupled Media. The microstructural development of cement is illustrated in **Fig. 18.** When cement is mixed with water, the cement particles disperse in the water, forming a suspension. Because cement particles are small and the interaction between particles is weak, the mixture maintains a high fluidity. However, when the water/cement ratio is lowered or the interaction between cement solids increases because of hydration, a network is generated by the particles interacting with each other. Cohesive strength develops between solids as the volumetric fraction of solids increases. The bond and friction between particles strengthen when the hydration products on solids start to overlap with each other. An initial load is required to overcome the resistance to deform the cement matrix, which is commonly referred to as the "yield point" of the slurry. When the slurry starts deforming, the measured plastic viscosity indicates the effect of the cohesion and the friction between solids. The bond will be reconstructed when the slurry is left undisturbed.

Dispersant, BWOC	0.09%				0.46%			
Water/cement ratio, BWOC	0.4		0.44		0.4		0.44	
Latex, BWOC	0%	8.14%	0%	8.14%	0%	8.14%	0%	8.14%
Time, CSGS (minutes)	203	91	217	137	252	220	288	241
Time, OSGS (minutes)	286	319	296	399	347	262	359	319
Transition time (minutes)	83	228	79	262	95	42	71	78
Gas-tight	No	Yes	No	Yes	No	Yes	No	Yes

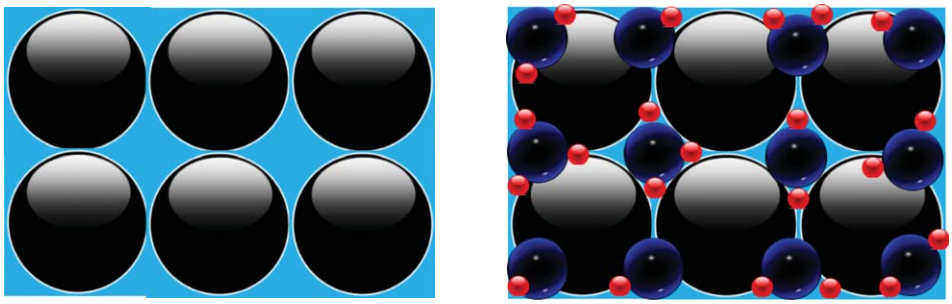
Table 2—Effect of latex on SGS development and gas-tight property (adapted from Tavares et al. 2013). BWOC = by weight of cement.



(a) Adherence between polymer film and Portlandite (Gomes et al. 2005).

(b) Adhesion of a sintered tile on cement mortar by latex film bridging (28 days hardening) (Plank 2014).

Fig. 15—Scanning-electron-microscope graphs of latex in cement matrix.



(a) Conventional cement slurries

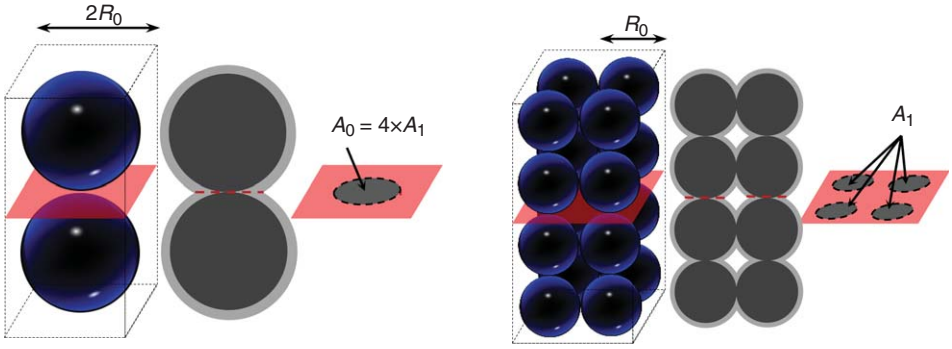
(b) Particle size optimization slurries

Fig. 16—Compressibility of cement matrix.

Although fluid and solid mechanisms can be used to analyze the behavior of the slurry when it is either entirely liquid or solid, the transition-gelation state is more complicated to assess. As mentioned previously, the cement slurry is actually a solid/fluid-coupled media. By assuming a mixture of cement particles suspended in water, the effects of different additives can be easily demonstrated. For example, a dispersant agent can be added to the slurry design to increase the fluidity of the cement slurry. **Fig. 19** presents the viscosity results for a neat slurry as well as the same mix blended with a dispersant agent. As seen in Fig. 19, a dispersant agent decreases the yield stress of the slurry and has little effect on the plastic viscosity. This decrease in yield stress occurs because the dispersant agent reduces the solid interaction and weakens the apparent network within the cement matrix. After the cement slurry begins to deform, the shearing occurs within the cement. The particle friction of cement slurry is similar and will, therefore, govern the plastic viscosity. The opposite is true when a thixotropic agent is used.

Principal Properties. The microstructure of the cement slurry determines its properties. To capture the development of cement physical properties, fundamental concepts and variables should be used to characterize the chemical evolution of cement hydration and the micromorphology of the cement matrix.

Cement hydration is a chemical reaction in which the major compounds in cement form chemical bonds with water molecules and become hydrates or hydration products. Compositions of a slurry vary in components and their quantities. Curing conditions can affect strength development and hydration products. Nevertheless, the fraction of Portland cement clinker (including interground gypsum) that has fully reacted with water can always be used to describe the hydration stage for a slurry design. Hydration kinetics were previously discussed from the view of



(a) Coarse cement particles

(b) Fine cement particles

Fig. 17—The same contact area at the same hydration stage.

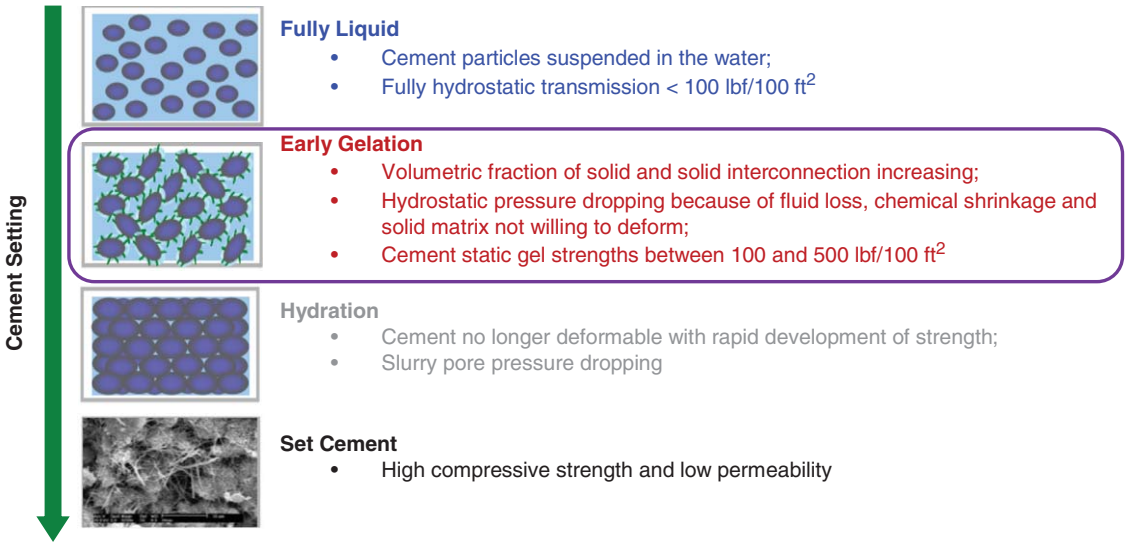
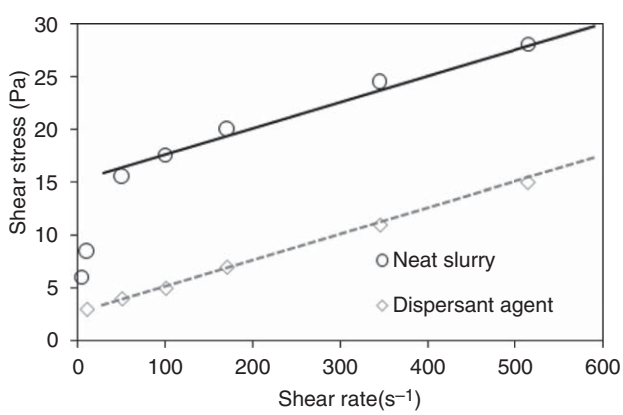


Fig. 18—Microstructural development of cement (Kellingray 2007).

microstructural development. The cement-microstructural development may be identical for cement when the fraction of cement clinker reacted with water is the same. This can be the case according to the findings by Zhang et al. (2010). As shown in Fig. 13, although the initial set time is different for the same slurry designs blended with different chemical additives, the percentage of cement clinker fully reacted with water is identical at the initial set. By use of the percentage of cement clinker reacted with water to describe the cement hydration, the effects of other variables can be distinguished. For instance, the water/cement ratio affects the physical properties of cement slurry significantly. **Fig. 20** presents a random distribution of cement particles. By comparing Figs. 20a and 20b, the effect of the water/cement ratio is illustrated by use of the microstructural development of the cement matrix. When the water/cement ratio is high, the cement particles are suspended in the water with little contact with other particles. As the distance between particles increases, the interactions are lower, and therefore a high fluidity is observed. More hydration products must form to fill the space between particles. Therefore, a high-water/cement-ratio design needs to achieve a higher reaction stage to develop the same cement/matrix strength compared with that of a low-water/cement-ratio design.

The interaction between solids can be described by use of the shear and normal bond strengths, as shown in Fig. 14. The cement particles have a variety of angular shapes, and the particle sizes are typically from 1 to 100 μm. Nevertheless, the rigidity of the cement slurry depends on the strength of the flocculated structure of cement matrix, more specifically the bridging strength of solids. In a stabilized slurry design, cement particles are suspended in the solution in a homogeneous state. The distance between particles can be determined when the water/cement ratio is known. As cement hydrates, the volumetric fraction of solids increases and a flocculated structure is generated by the solid matrix connected by the hydration products, as shown in Fig. 18. The shear bond strength and the normal bond strength between solids develop and continue to increase when more hydration products between different solid particles overlap each other. The compressibility of the cement matrix can be estimated when the volumetric fraction of solids and the strength between solids are known.

By knowing cement components and other additives and their physical properties, the volumetric fraction of solids and the percolation of cement matrix can be predicted with respect to the stage of cement hydration. The rigidity of the cement matrix can be characterized by use of the shear and normal bond strengths between solids. Finally, cement/matrix properties can be reliably characterized at the microstructural scale instead of by use of laboratory tests designed to quantify an "apparent" mechanical property. Quantifying these cement properties instead of use of apparent mechanical properties would lead to a more-reliable and adaptable prediction of the ability of a cement to mechanically prevent gas migration.

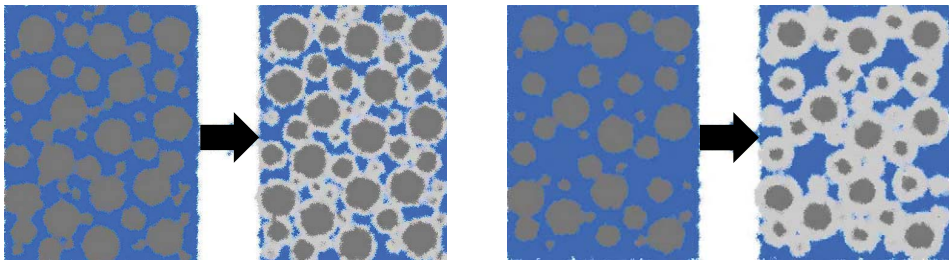


Note: Neat slurry – neat Class H slurry mixed at 15.8 ppg; Dispersant agent – same formulation mixed with 0.1 gal/sk of lignosulfonate dispersant.

Fig. 19—Effect of dispersant agent on slurry viscosity (Nelson 1990).

Conclusions

Although SGS was originally adopted to describe the shear stress at interfaces, it is now defined as the slurry resistance to deformation under shear load. Experimental results indicate that gases can only invade the cement slurry from the time when the hydrostatic pressure is lower than the gas pressure to the time when cement develops enough rigidity to withstand the gas pressure (Cheung and Beirute 1985). This critical hydration period is defined as the transition time. Because no effective approach to evaluating the potential for gas migration is available, the petroleum industry now tries to minimize, if not prevent, the risk of gas migration by shortening the transition time. *API STD 65-2* (API 2010a) provides the standards for determining the transition time by use of the concept of SGS for practical application by use of commercial SGS-measurement devices. On the basis of limited experimental results (Sabins et al. 1982; Stewart and Schouten 1988), 100 and 500 lbf/100 ft^2 are standardized for all slurries and applied conditions (API 2010a). However, a sensitivity study has shown that no relationship was observed between the transition time and the occurrence of gas migration (Rogers et al. 2004; Tavares et al. 2013), although a slurry with a short transition time potentially



(a) Low water/cement ratio (b) High water/cement ratio

Fig. 20—Effect of water/cement ratio on cement matrix development (Zhang et al. 2010).

reduces the time available for gas to infiltrate a cemented annulus. Experimental results (Zhang 2002; Zhu et al. 2012) also contradicted the linear relationship between the SGS and the hydrostatic-pressure reduction in the classical shear-stress theory. Although fluid loss and chemical shrinkage are recognized to be additional critical factors causing the hydrostatic-pressure reduction, gas migration is a multiphase problem (Beirute and Cheung 1990). Neither SGS nor fluid loss is able to predict the onset of gas-tight conditions in a cement slurry.

The limitations of SGS in evaluating the potential for gas migration drive the demand for improved cement/matrix characterization. SGS may be applicable to describe the fluidity of the slurry in the beginning of early hydration. When a gel fluid forms, solids in the slurry primarily govern the mechanical properties. Although the gel will deform under a shear mode, gases and other fluids actually need to break the bonding strength between solids and push solids aside in cement matrix, which requires characterizing the cement/matrix strength and matrix compressibility. SGS is an "apparent" mechanical property and reflects resistance development within cement slurry. Nevertheless, SGS is not sufficient to characterize the compressibility and permeability of the cement matrix. It is also impossible to distinguish normal bond strength from the shear strength by use of SGS solely. All these drawbacks during use of SGS in predicting gas migration indicate the need for replacing SGS as the metric to predict gas-tight conditions. A more-accurate approach for replacing SGS is desirable for cement/matrix characterization, in which fundamental concepts and variables are used to characterize the solid/fluid-coupled matrix.

Nomenclature

A = area of formation face per unit length
Bc = Bearden units of consistency
CWSS = critical wall shear stress
$\frac{dl}{dt}$ = rate of fluid loss at time of SGS_{max}
$\frac{d(SGS)}{dt}$ = maximum rate of change of static gel strength
D = difference between hole diameter and casing diameter
g = gravitational acceleration
ID = casing outside diameter
L = cement column length, considered from the top of cement to the depth of interest
MPR = maximum pressure reduction at a given SGS value
OBP = initial overbalance pressure
OD = borehole diameter
p_f = formation gas pressure
$P(L,t)_c$ = effective pore pressure at depth L and time t
P_m = hydrostatic pressure generated from drilling mud
P_{sp} = hydrostatic pressure generated from spacer columns
P_{wa} = hydrostatic pressure generated from washer
P_0 = hydrostatic pressure applied on top surface of cement column
P_1 = pressure applied on the cement section from the top
P_2 = pressure applied on the cement section from the bottom
SGS = static gel strength, lbf/100ft^2
$SGS_{max\ rate}$ = static gel strength at time of maximum rate of change
SP = hydrostatic pressure generated from surface pressure
$S(L,t)$ = shrinkage of cement slurry at depth L and time t
t = time
v = volume of annular space per unit length
γ = shear strain
ΔL = cement section length
Δv_{csg} = volume changes caused by casing deformation
Δv_{loss} = volume changes caused by fluid loss
Δv_{sh} = volume changes caused by chemical shrinkage
Δv_T = volume changes caused by temperature change
Δv_{wh} = volume changes caused by wellbore deformation
ρ_c = density of cement slurry
τ = shear stress

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SI Metric-Conversion Factors

ft	3.048*	E-01	=	m
miles	1.609 344*	E+03	=	m
psi	6.894757	E+00	=	kPa
lbf/ft^2	4.788 026	E+01	=	Pa
in.	2.54*	E+00	=	cm
gallon	3.785 412	E–03	=	m^3

*Conversion factor is exact.

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