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Modelling Suspension of Lost Circulation Materials in a Drilling Fluid

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Abstract

Loss of drilling fluids into formations (i.e., lost circulation [LC] through natural/induced fractures) is a recurring and costly issue within the industry. Numerous solutions/practices are applied to prevent or resolve LC. Among these, the addition of lost circulation materials (LCMs) into drilling fluids to plug the fractures has been a widely accepted practice. Well-known LCMs include ground marble, graphitic carbon, cellulosic particulates, and fibres.

For an LC control operation to be effective and successful, it is necessary to avoid or minimize settling of LCM in the treatment or drilling fluid. Uniform suspension of LCM is required during pill preparation and wellbore applications such as during a hesitation squeeze operation.

This paper presents semi-empirical models useful for predicting the *suspend-ability* (resistance to settling) of a LCM in a treatment or drilling fluid. The design parameters used in these models—which can significantly influence the LCM suspend-ability response—consist of density, shape, and particle size distribution of the LCM, in addition to density, rheology, and composition of the carrier fluid. The modelling work in this paper also provides methods for tailoring LCM and/or drilling fluid properties to achieve effective LCM suspension.

Determination and control of the suspension characteristics of LCM-carrying drilling fluids can help ensure efficient use of LCMs for LC control. This method is especially important in severe loss zones where large-size LCMs are used as well as in high-pressure/high-temperature (HP/HT) or inclined wells where the fluid's ability to suspend the LCM is most critical.

Introduction

Several methods for lost circulation control have been reported in the literature, and mostly take the form of adding lost circulation materials (LCM) to the treatment fluids or carrier drilling fluids. Different types of LCM, ranging from particles, flakes, and cement gunk to chemical sealants, are used, depending on the availability of the materials and loss rates. In addition, the specific LCM can be selected based on the nature of the losses, type of drilling fluid being used (e.g., water-based vs. oil-based), type of formation being drilled and economic constraints. A more accurate selection of the LCMs is possible when there is detailed understanding of LCM properties and functions; and such selection can lead to efficient lost circulation control. For instance, LCM properties like crush strength and resiliency were demonstrated to have significant impact on both lost circulation control and wellbore strengthening.[1] Recently, LCM particles were also studied from shear degradation perspective. Various studies[2,3,4] showed that different materials behaved differently under the types of tests performed. This again validates the point that 'all LCMs are not equal'. Most of the comparison was performed between three widely used LCM that include ground marble, resilient graphitic carbon and nut shells. Resilient graphitic carbon and nut shells reported to have high mechanical and shear degradation resistance, i.e., they can withstand high pressures without any significant PSD change. On the other hand, the ground marble always showed high PSD changes when subjected to the same pressure levels. In addition to the above studies, the selection of the appropriate LCM can also be based on its impact on the rheology of drilling fluids and equivalent circulating density (ECD).[5]

LCM selection also depends on the fracture dimensions. The fractures are simulated in the drilling fluid lab, using Particle Plugging Apparatus (PPA) with either aloxite discs or metallic constant area slots. More recently tapered slots[3] were used to assess the performance of LCM combinations on the PPA. The application of fibers with high aspect ratios along with particulate LCM to improve the plugging ability of fractures in aqueous and non-aqueous drilling fluids has also been investigated.[6,7,8]

This paper presents another novel aspect of LCM and fluid interaction which may be crucial for efficient lost circulation control. The paper provides a comprehensive method to design an LCM-carrier drilling fluid combination that provides efficient suspension for the LCM in the fluid.

In this context, "suspend-ability" represents ability of the particles to resist settling in a fluid. The suspend-ability of a LCM in the carrier drilling fluid is important to help ensure the following:

1. Uniform suspension of LCM in the pill-preparation

tank.

2. Proper suspension of LCM in a wellbore annulus during a lost circulation control operation.

Handy prediction and management of LCM suspension properties and the resulting effective lost circulation control can provide a significant improvement in LCM technology. The model could serve as a tool mud engineers use to evaluate the suspend-ability of a LCM in a given fluid, allowing them to make speedy decisions at the rig site to optimize the LCM and fluid combinations. This can help minimize the corresponding down-time and prevent wellbore stability related issues. This work may also be a part of a drilling fluid design and reduce costly, time consuming trial and error attempts to design LCM treatments.

Theory: Suspend-ability Modeling

Based on the literature[9], a suspend-ability index S_i has been defined for measuring the degree of suspension of an LCM particle in an *un-sheared* (or weakly sheared) visco-plastic drilling fluid as shown below:

$$S_i = f(\text{LCM properties, fluid properties}) \quad \text{……..}\textbf{Eq. 1}$$

$$\text{LCM properties} = \rho_\text{p}, d_\text{p}, sf_p$$
$$\text{Fluid properties} = \rho, \tau_0$$

LCM properties: 'd_p' is particle diameter and ρ_p is the density of the particle. The shape factor 'sf_p' of the LCM particle accounts for the typical non-spherical shapes of the lost circulation material. It was assumed that the particle concentration is low enough to have no collective influence on the fluid properties.

Drilling fluid properties: τ_0 is the yield stress of the fluid**.** The τ_0 value in the Eq. 1 may be interpreted for the LCM carrying drilling fluids in various ways as noted below:

- LSYP (low shear yield point) obtained by applying Bingham plastic model to low shear data from a viscometer/rheometer, It is measured in lb/100 ft^2.
- Herschel-Bulkley yield stress obtained by modeling the shear stress vs. shear rate data from viscometer/rheometer.
- The 10 sec or 10 min gel strength, obtained from a viscometer/rheometer (e.g., conventional Fann® 35).

Note that the τ_0 values depend on the temperature and pressure of the carrier drilling fluid. Therefore, this parameter was measured at or adjusted to desired temperature and pressure conditions. The drilling fluid density is denoted by ρ and it was also measured at or adjusted to desired temperature and pressure conditions.

Suspend-ability index S_i **:** S_i defines the ability of the drilling fluid to effectively suspend the LCM particulates. By incorporating experimental data in Eq. 1, semi-empirical models were developed to predict the suspend-ability of the LCM in the drilling fluids**.** The models describes that the S_i parameter, obtained based on LCM and fluid properties, is indicative of particle suspend-ability. If $S_i > S_{i-crit}$ where S_{i-crit} is the critical value of the determined S_i value based on experimental study, the particle will not settle in the suspending visco-plastic fluid. However, if $S_i < S_{i-crit}$, particle settling would initiate. The value of $S_{i\ -crit}$ is expected to vary with the method of determining yield stress.

Experimental Study: Materials

LCM materials: The LCM particles of specific size ranges were obtained by sieving the ground walnut shells. Three samples of different sizes were obtained by the sieving process using VWR USA mesh standard test sieves as shown below in **Table 1**.

Table 1: LCM particles (ground walnut shells) of different sizes retained between corresponding sieving meshes (-* = passed, +* = retained).

	Sieving Mesh	LCM size d_p (microns)
Size 1	-30 mesh +35 mesh	500-600 µm
Size 2	-18 mesh +20 mesh	850-1000 µm
Size 3	-14 mesh +16 mesh	1180-1400 µm

The density of the walnut shells was ρ_p = 1.43 g/cc as obtained from a helium ultra-pycnometer.

Drilling Fluids: As shown in **Appendix 1**, four different clay-free water-based drilling fluids were formulated to exhibit variations in yield stress (τ_0) and mud weights. After formulation, the drilling fluids were hot-rolled at 150°F for 16 hours before performing the suspend-ability tests with the LCM particulates.

Experimental Methodology

FANN® 35 viscometer rheology and mud weight: The rheology of the hot-rolled drilling fluid was measured at 150°F (**Appendix 2**). The LSYP was measured as [2*(dial reading at 3 RPM) – (dial reading at 6 RPM)]. The `10 s' and `10 min' gel strengths (GS) were also measured after leaving the pre-sheared sample under static condition for 10 seconds and 10 minutes respectively, and then obtaining the maximum dial reading at 3 RPM condition. The mud weight of the fluid was measured on a standard mud balance.

LCM-fluid uniform mixing: The given size of LCM at a specific concentration (4-5 volume %) and the drilling fluid (of given density and rheology) were mixed thoroughly with spatula. The *uniform* mixture was then poured in a glass liner which was kept in a stainless steel aging cell.

***Suspend-ability test*:** The stainless steel aging cell containing the LCM fluid mixture in a glass liner was placed in the static oven at 150°F and aged for 4 hours. After aging, the system was allowed to cool down in a water bath for 10 minutes.

The distribution of the LCM in the static-aged mixture was investigated by separating the mixture in the glass liner in two equal sections: the top half section and bottom half section. The LCM quantities in each section were separated from mixture by filtering it through a 50-mesh USA standard test sieve and washing the LCM on the sieve with water to remove any adhered mud. Separated LCM particles were dried in oven at 105°C and then cooled and weighed.

The same tests were repeated for different LCM and drilling fluid combinations.

Results and Discussion

The experiments were conducted to investigate dependence on LCM and fluid properties on suspend-ability as described by Eq. 1. In addition, the experimental data was analyzed using Eq. 1 to obtain the critical value of the suspend-ability index S_{i-crit} which could be used to predict suspend-ability of a LCM of given size/shape and density in the drilling fluid of given rheology and mud weight.

Effect of LCM particle size on suspend-ability: The suspend-ability of the LCM particles (ground walnut shells) of the three selected sizes was measured in the drilling fluid *B* (mud weight = 9.0 *ppg* and LSYP = 4 lb/100 ft^2). **Figure 1** shows the distribution of different size LCM particles in the glass liner *after* static aging for the period of 4 hours at 150°F. The figure shows that, after aging, the large size 1180-1400 µm particles have settled almost completely towards the bottom section of the liner, whereas the medium size 850-1000 µm particles showed some degree of suspension in the fluid while the small size 500-600 µm particles appeared to stay suspended uniformly in the fluid. Thus, the suspend-ability decreases with increase in particle size which is qualitatively in agreement with Eq. 1. It is quantified as shown below.

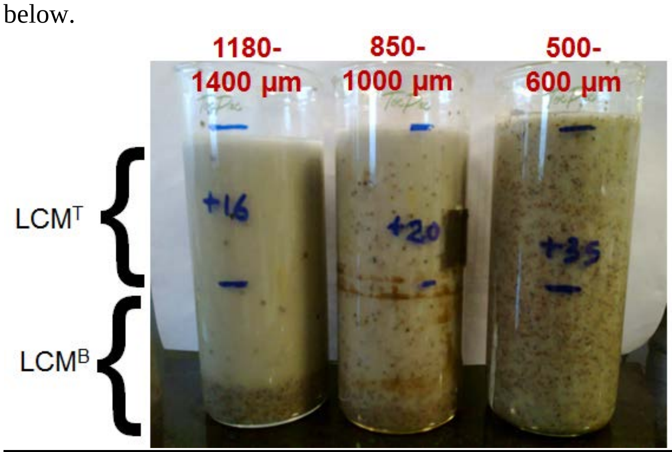

Figure 1: Suspension of different sizes of LCM particles (ground walnut shells) in water-based Fluid B (9.0 ppg, LSYP = 4).

The quantities of LCM in the top half section and bottom half section of the glass liner were indicated as LCM^T and LCM^B respectively. The degree of LCM suspend-ability is quantified in the below equation in terms of percentage of LCM retention in top half section of glass liner *(% LCM^T)* obtained after the aging of the sample as:

$$\%LCM^T = \frac{LCM^T}{LCM^T + LCM^B} * 100 \qquad \text{....Eq. 2.}$$

In a situation where there is no (zero) settling of LCM particles during aging, the suspension in the glass liner would stay completely uniform (i.e., '$LCM^T \approx LCM^B$' or '% $LCM^T \approx 50\%$'). On the other hand, when all the LCM particles sink to the bottom during aging, '$LCM^T \approx 0$' *or* '% $LCM^T \approx 0\%$'. If some partial settling occurs during the aging process, then '0% < % LCM^T < 50%' (considering no upward motion of LCM in the fluid as LCM is generally assumed to be heavier than the fluid).

For the LCM distribution after aging, we considered that a condition of '*40% ≤ % LCM^T ≤ 50%*' stands for <u>good</u> suspend-ability condition. On the other hand, '5% < % LCM^T < 40%' was accounted as <u>weak</u> suspend-ability condition and '% LCM^T < 5%' was denoted as <u>no</u> suspend-ability condition.

Table 2 shows % LCM^T for the above mentioned experiments with the three different sized particles in the drilling fluid *B*. Consistent with the qualitative observations, the large size 1180-1400 µm particles showed almost <u>no</u> suspend-ability ('% LCM^T < 5%), the medium size 850-1000 µm particles showed <u>weak</u> suspend-ability (5% < % LCM^T < 40%) while the small size 500-600 µm particles demonstrated <u>good</u> suspend-ability (*40% ≤ % LCM^T ≤ 50%).*

Table 2 also shows values of the suspend-ability index S_i using Eq. 1 based on the properties of the ground walnut shells (density and size/shape) and the drilling fluid *B* (yield stress and mud weight) used for above experiments. It was evident that the suspend-ability of LCM (indicated by ***% LCM^T***) increases with increase in the respective suspend-ability index S_i parameter (Table 2**)**.

Table 2: Percentage of LCM retention in top half section of glass liner (% LCM^T) and suspend-ability index S_i for suspension of different sizes of LCM particles in a drilling fluid (9.0 ppg, LSYP = 4).

LCM size (ground walnut shells)	% LCM^T (after aging)	S_i
1180-1400 µm	1.3%	0.46
850-1000 µm	17.2%	0.64
500-600 µm	40.3%	1.1

Effect of yield stress of carrier fluid on LCM suspend-ability: The suspend-ability of LCM particles (ground walnut shales) of size 850-1000 µm is measured in two different drilling fluids (fluid *B* and fluid *C*). Both of these fluids have the same mud weight of 9.0 ppg but different rheological properties: fluid *B* has LSYP = 4 while fluid *C* has LSYP = 6 lb/100 ft^2. **Figure 2** shows the distribution of the selected size LCM particles in the glass liner after static aging for the period of 4 hours at 150°F. The figure shows that, after aging, the selected LCM particles exhibit significant settling in the first fluid (LSYP = 4) whereas the same size of LCM particles show a good degree of suspension in the second fluid (LSYP = 6). Thus, the suspend-ability increases with increase in LSYP or GS which is qualitatively in agreement with Eq. 1. This observation is quantified as described below.

Table 3 shows % LCM^T for the above mentioned experiments with LCM (ground walnut shales) of 850-1000 µm size particles in the two drilling fluids. Consistent with the qualitative observations, the selected LCM particles showed weak suspend-ability (% $LCM^T \approx 17.2\%$) in the fluid *B* with lower yield stress (LSYP = 4) while they showed good suspend-ability (% $LCM^T \approx 48.6\%$) in the fluid *C* with higher yield stress (LSYP = 6).

Table 3 also shows values of the suspend-ability index S_i using Eq. 1 based on the properties of the LCM particles (density and size/shape) and the drilling fluids (rheology and mud weight) that were used for the experiments shown in Figure 2. It was again evident that the suspend-ability of LCM (indicated by % LCM^T) increases with increase in the suspend-ability index S_i (Table 3**)**.

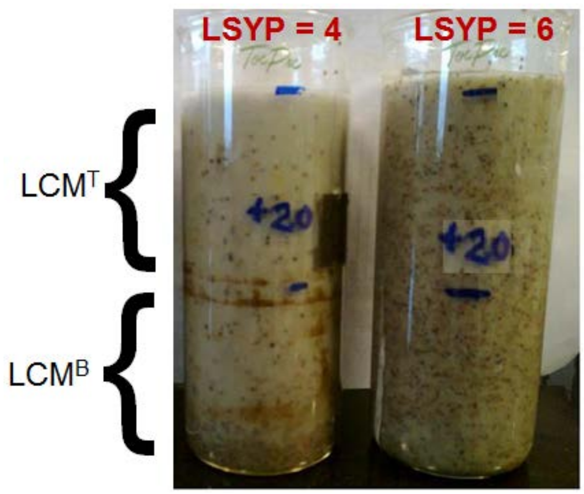

Figure 2: Suspension of 850-1000 µm LCM particles (ground walnut particles) in two drilling fluids (fluid *B* and fluid *C*) with variation in LSYP (mud weight= 9.0 ppg).

Table 3: Percentage of LCM retention in top half section of glass liner (% LCM^T) and suspend-ability index S_i for 850-1000 µm size LCM particles in two different fluids with a variation in LSYP (corresponding to Figure 2).

Drilling fluids	% LCM^T (after aging)	S_i
Fluid B (LSYP = 4, 9ppg)	17.2%	0.64
Fluid C (LSYP = 6, 9 ppg)	48.8%	0.98

Comprehensive experimental data to determine critical value of the suspend-ability index S_{i-crit} for LCM suspend-ability: **Table 4** shows % LCM^T for a set of experiments with variation in LCM and fluid properties. Qualitatively, it could be seen that the experimental data agrees with Eq. 1 (i.e., the suspend-ability increases with increase in fluid rheology); in addition, it increases with a decrease in LCM particle size as well as a decrease in density difference between LCM particles and the fluid.

Table 4: Experimental data on percentage of LCM retention in top half section of glass liner (% LCM^T) for the three different sized LCM particles (density = 1.43 g/cc) in four drilling fluids with variation in LSYP and mud weights.

Particle size → / Fluid ↓	1180-1400 µm	850-1000 µm	500-600 µm
Fluid *A* (LSYP = 3, 9.0 ppg)	0% (NO)	0% (NO)	4% (NO)
Fluid *B* (LSYP = 4, 9.0 ppg)	1.3% (NO)	17.2% (WEAK)	40.3% (GOOD)
Fluid *C* (LSYP = 6, 9.0 ppg)	31.3% (WEAK)	45.6% (GOOD)	48 % (GOOD)
Fluid *D* (LSYP = 8, 10.0 ppg)	47.6 (GOOD)	50.8% (GOOD)	51 % (GOOD)

Table 5 shows values of the suspend-ability index S_i based on Eq. 1 using the properties of the LCM particles (density and size) and the drilling fluids (yield stress and mud weight) that were used for the experiments shown in Table 4. The experimentally obtained values of % LCM^T (Table 4) show strong *correlation* with the respective suspend-ability index S_i values (Table 5**)**; this correlation is summarized in **Table 6**.

Table 5: The suspend-ability index S_i using Eq. 1 for the three different sizes of LCM particles in the 4 fluids with variation in LSYP and mud weight (corresponding to Table 4).

Particle size → / Fluid ↓	1180-1400 µm	850-1000 µm	500-600 µm
Fluid *A* (LSYP = 3, 9.0 ppg)	0.34	0.48	0.81
Fluid *B* (LSYP = 4, 9.0 ppg)	0.45	0.64	1.1
Fluid *C* (LSYP = 6, 9.0 ppg)	0.68	0.98	1.6
Fluid *D* (LSYP = 8, 10.0 ppg)	1.2	1.7	2.9

As shown in Table 6, the suspend-ability index S_i obtained based on material properties of given LCM and the fluid could be used as indicative of LCM suspend-ability. The LCM or fluid properties may be adjusted to obtain the desired suspend-ability index S_i values to assure effective suspend-ability of LCM.

Similar correlations were developed using gel strength as a measure of the yield stress rather than LSYP.

Table 6: Correlations between the suspend-ability index S_i and experimental suspend-ability (LCMT) using the information from Table 4 and Table 5.

S_i < 0.5 ↔ No suspend-ability (% LCM^T < 5%)
0.5 < S_i < 1 ↔ Weak suspend-ability (5%< LCM^T < 40%)
S_i > 1 ↔ Good suspend-ability (40% < LCM^T < 50%)

Conclusions

- The experimental work shows that, in some cases, LCM particles can settle severely in the typical drilling fluids. Therefore, determination and control of LCM suspend-ability is important.
- The LCM suspend-ability increases with increase in the fluid's rheology; in addition, it increases with decrease in LCM particle size as well as decrease in density difference between LCM particles and the fluid.
- The semi-empirical models can be used for predicting the suspend-ability of a LCM in the treatment or drilling fluid.
- The models may be used to adjust the carrier fluid properties (rheology and mud-weight) or to select LCM particle of appropriate size and density to enable adequate suspension of the LCM.
- Handy prediction and management of LCM suspension properties may ensure effective lost circulation control especially for high-pressure/high-temperature (HP/HT) and inclined wells.

Acknowledgments

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Nomenclature

LCM = *Lost Circulation Material*
LSYP = *Low Shear Rate Yield Point*
S_i = *Suspend-ability index*
ppg = *pounds per gallon*

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Appendix 1: Fluid Formulations

Fluid-*A* (9 ppg)

Component	Concentration, ppb
Brine (100,000 ppm)	As required
Viscosifier	1
Fluid loss additive I	1
Fluid loss additive II	2
Shale stabilizer I	3.5
Shale stabilizer II	7.5
Barite	As required (**9 ppg**)
pH control additive	0.3

Fluid-*B* (9 ppg)

Component	Concentration, ppb
Brine (100,000 ppm)	As required
Viscosifier	1.2
Fluid loss additive I	1.25
Fluid loss additive II	2
Shale stabilizer I	3.5
Shale stabilizer II	7.5
Barite	As required (**9 ppg**)
pH control additive	0.3

Fluid-*C* (9 ppg)

Component	Concentration, ppb
Brine (100,000 ppm)	As required
Viscosifier	1.5
Fluid loss additive I	1.25
Fluid loss additive II	2
Shale stabilizer I	3.5
Shale stabilizer II	7.5
Barite	As required (**9 ppg**)
pH control additive	0.3

Fluid-*D* (10 ppg)

Component	Concentration, ppb
Brine (100,000 ppm)	As required
Viscosifier	1.5
Fluid loss additive I	1.25
Fluid loss additive II	2
Shale stabilizer I	3.5
Shale stabilizer II	7.5
Barite	As required (**9 ppg**)
pH control additive	0.3

Appendix 2: FANN® 35 viscometer Data @150°F

RPM	Fluid-*A*	Fluid-*B*	Fluid-*C*	Fluid-*D*
600	49	64	67	77
300	31	45	51	58
200	26	37	43	50
100	18	27	33	38
6	5	8	10	10
3	4	6	8	9
PV (cp)	18	19	16	19
LSYP (lb/100 ft^2)	3	4	6	8
10 Sec/10 Min Gel Strength (lb/100 ft^2)	4/5	8/9	10,13	11,14