

Emulsifier Powders for Oil-Based Muds

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Abstract

Based on the beneficial properties and performance of recently developed primary emulsifier powder (Maghrabi, et al. 2022), solid secondary emulsifiers were developed. Secondary emulsifiers are often desired in oil-based drilling fluids for their solids wetting and improved emulsion characteristics. Powdered secondary emulsifiers were developed as standalone materials or as a part of a dry all-in-one emulsifier.

The sustainability of powdered emulsifiers is improved compared to liquid emulsifiers: the powders are 100% active, highly efficient at both emulsification and fluid loss, and present without added adsorbent, diluent or other inactive ingredients. Clumping has not been observed for these emulsifier powders. Self-heating and oxidation were not observed and are not expected due to the chemical properties of the emulsifiers. The improved handling properties improve the sustainability profile of the emulsifier by removing drum usage, thus improving logistics and disposal costs.

The emulsifier powders were tested in oil-based mud (OBM) formulations, aged at 250°F or 300°F and 150 psi for 16 hours, followed by rheology and emulsion stability (ES) measurements at 120°F and high temperature high pressure (HTHP) fluid loss measurements at 250°F or 300°F. Plastic viscosity and yield point were between 7 – 20 cP, and gel strengths were between 7 – 15 lb/100ft² at 250°F. HTHP fluid loss was < 10 mL with no water in the filtrate, and ES measurements exceeded 600 V for all emulsifier powders at 250°F. Performance was comparable to current commercially available liquid emulsifiers with low gravity solids (LGS) and in mineral oil-based fluids at 250°F, while improved performance was observed at 300°F in diesel-based fluids.

Introduction

Solid emulsifiers are advantageous at rig site due to decreased footprint, improved dosage control, and ease of handling when compared to liquid emulsifiers because of the change in packaging, e.g. 50 lb bags versus 400 lb drums. Additionally, powdered products have lower associated transport costs due to lighter packaging and the removal of extraneous solvents. Packaging and disposal costs are also reduced for powders due to easy disposal of bags and the lack of drum transport, cleaning, and disposal.

It is important that powdered additives remain flowable

after manufacture, transport, and storage under a variety of conditions. To accomplish this, absorbents and solid supports are often added to emulsifier powders to maintain the desired flow properties (Albrighton, et al. 2019, Gupta, et al. 2019, Lifton, et al. 2017). Described herein are free flowing, 100% active all-in-one and secondary emulsifier powders that are storage stable without need of solid supports.

Fluid performance, powder flow properties, and sustainability characteristics are compared for all-in-one and secondary liquid emulsifiers and powders. Oil-based drilling fluids are described for the comparison of liquid and solid emulsifiers, and performance characteristics are highlighted. Powder flowability tests are described and highlight the flow and compaction characteristics of the emulsifier powders versus common oilfield powder additives.

The emulsifier powders have the following benefits:

- 100% active formulation
- No hazardous solvents
- Controlled HTHP fluid loss
- Good low gravity solids tolerance
- Acceptable powder flowability
- Improved dosage control
- Lower transportation costs and emissions

Experimental

Emulsifier Powder Development and Testing

Secondary emulsifier powders were developed and tested as standalone emulsifiers or in all-in-one formulations. When the secondary emulsifier was blended with a primary emulsifier, it was necessary to react the mixture with caustic solution and spray dry the resultant salt to form a 100% active, flowable powder (SAn1). It was not necessary to spray dry the standalone secondary emulsifier powder, because it formed a solid from the melt which could then be pulverized to form an emulsifier powder. A series of emulsifier powders, including SAn1 and five secondary emulsifiers (SSA-E), were produced for comparison against commercially available liquid all-in-one (LAn1) and liquid secondary (LS) emulsifiers. The secondary emulsifier powders were paired with a primary emulsifier powder (SDA) (Henry, et al. 2020), while the liquid secondary emulsifier was paired with a commercial liquid primary emulsifier (LP). Emulsifiers were tested in three separate oil-based mud formulations, using diesel or mineral oil at 250°F or 300°F [Table 1].

Materials Used

Diesel-based and synthetic systems were selected to mimic land-based drilling operations utilizing the following components:

- Base oil
- Lime
- Emulsifiers (liquid or solid)
 - Primary
 - Secondary
 - All-in-one
- Wetting agent
- Organophilic clay
- Salinity agent
- Weighting agent
- Fluid loss additive
- Low gravity solids

Test Procedures

Oil-based drilling fluids were mixed and analyzed according to American Petroleum Institute Recommended Practices (API RP 13B-2, API RP 13D, API RP 13I 2023). Muds were mixed for approximately 40 minutes in a stainless steel 48070 malt cup using the medium setting on a Hamilton Beach mixer, then dynamically aged for 16 hours using pressurized stainless steel rolling cells in a 5-roller oven (OFITE Model 173-00-RC). Once the aging was completed, the muds were cooled to room temperature and remixed for 5 minutes. Rheology was performed at 120°F using a OFITE Model 900 Viscometer, by measuring shear stress at 600, 300, 200, 100, 6, and 3 RPM as well as the 10-second and 10-minute gel strengths. Plastic viscosity (PV) [Equation 1] and yield point (YP) [Equation 2] were calculated by the equations below. Rheology was only measured after hot rolling in this

study.

Equation 1

$$\text{Plastic Viscosity (cP)} = 600 \text{ rpm SS} - 300 \text{ rpm SS}$$

Equation 2

$$\text{Yield Point (lb/100 ft}^2\text{)} = 2 \times 300 \text{ rpm SS} - 600 \text{ rpm SS}$$

ES of each mud was measured at 120°F using a FANN Model 23E Electrical Stability Tester. HTHP fluid loss measurements were carried out at either 250°F or 300°F with a 500-psi differential using a 175 mL, 4-unit filter press with regulators and temperature controllers (OFITE Model 170-00-4S). Fluid loss and cake thickness were recorded, and any water present in the filtrate was noted.

Powder flowability parameters of the dried emulsifiers were investigated using angle of repose, Hausner ratio, and Carr's index (EU Pharmacopoeia 6.0 2.9.36 2008). The angle of repose was obtained via direct measurement of piled material photographs. Compressibility/Carr's Index (CI) and Hausner ratio (HR) were determined from the initial bulk density and tapped density (after 5000 taps) of the powdered emulsifiers using an Autotap instrument (European Pharmacopoeia 6.0 2008). CI [Equation 3] and HR [Equation 4] were calculated using bulk and tapped densities.

Equation 3

$$CI = 100 \times \frac{(\rho_{\text{tapped}} - \rho_{\text{bulk}})}{\rho_{\text{tapped}}}$$

Equation 4

$$HR = \frac{\rho_{\text{tapped}}}{\rho_{\text{bulk}}}$$

Table 1 – Mud formulations and testing conditions for three oil-based drilling fluids examined in this study

Component	Diesel 1 (ppb)	Diesel 2 (ppb)	Mineral Oil (ppb)
Base Oil	As Required	As Required	As Required
Organophilic Clay	8.0	6.0	4.0
Lime	2.0	2.0	4.0
Emulsifiers	5.0	5.0	5.0
Wetting Agent	None	None	1.0
25% CaCl ₂ Brine	As Required	As Required	As Required
Barite	As Required	As Required	As Required
Gilsonite	None	None	5.0
Synthetic Drill Solids	As Required	None	None
OWR	80/20	80/20	70/30
Actual Mud Weight	13.0	13.0	13.0
Aging Temperature	250°F	250-300°F	250°F
Aging Pressure	150 psi	150 psi	150 psi
Rheology & ES Temperature	120°F	120°F	120°F
HTHP Fluid Loss Temperature	250°F	250-300°F	250°F

Degree of caking was established by placing small sample quantities in an oven to equilibrate to a constant weight then sieving samples through a US #10 (2 mm sieve opening) (Aguilera, et al. 1995). The degree of caking was calculated using the masses of the test sample and powder retained on the sieve [Equation 5].

Equation 5

Degree of caking

$$= 100 \times \frac{\text{weight of powder left on sieve}}{\text{weight of powder used}}$$

Results and Discussion

Mud Testing in Diesel-based Mud System 1

Solid emulsifiers were tested at equivalent concentrations versus liquid emulsifiers in a diesel-based mud system after aging at 250°F with and without LGS per the diesel 1 system [Table 1]. HTHP fluid loss testing was conducted at 250°F and rheology and ES were measured at 120°F. The rheology and fluid loss measurements were comparable for standalone primary and secondary emulsifiers without LGS [Table 2].

With the addition of LGS, the shear stresses increased significantly across all shear rates, but shear stress increase was significantly less when using emulsifier powders versus liquids. This increase in rheology also resulted in increased plastic viscosity (PV) and yield point (YP) [Figure 1]; liquid emulsifiers increased the PV and YP by 50% and 300%, respectively, while the emulsifier powders increased PV and YP by 15% and 50%, respectively. Fluid loss increases were equivalent for both emulsifier sets, with about a 100% increase in fluid loss with the addition of solids.

All-in-one emulsifiers were tested and compared in the same manner as the individual primary and secondary emulsifiers at 250°F in the diesel-based mud system [Table 3]. Each emulsifier was dosed at 5 ppb in the test mud with or without 6% LGS. Shear stresses and fluid loss were significantly higher when using the emulsifier powder, but the addition of LGS had a much smaller effect on the mud compared with the liquid all-in-one emulsifier, the latter having

higher shear stresses, PV, and YP with the addition of low gravity solids.

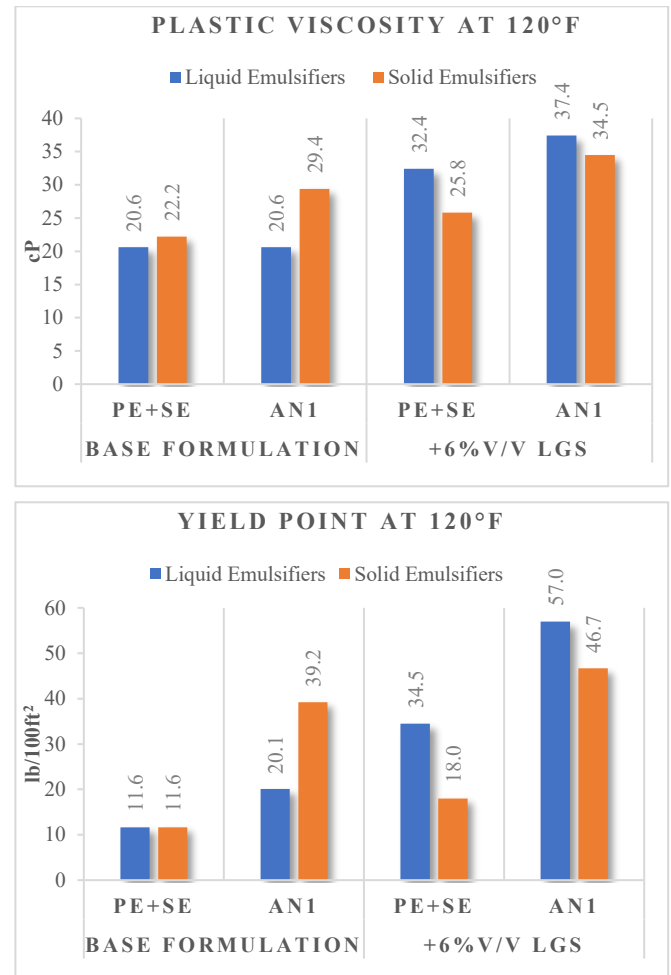


Figure 1 – Plastic viscosity (top) and yield point (bottom) calculated from rheological measurements for liquid and solid emulsifiers at 120°F using diesel-based mud system 1

Table 2 – Mud testing results for liquid and solid emulsifiers with and without 6% LGS in diesel-based mud system 1

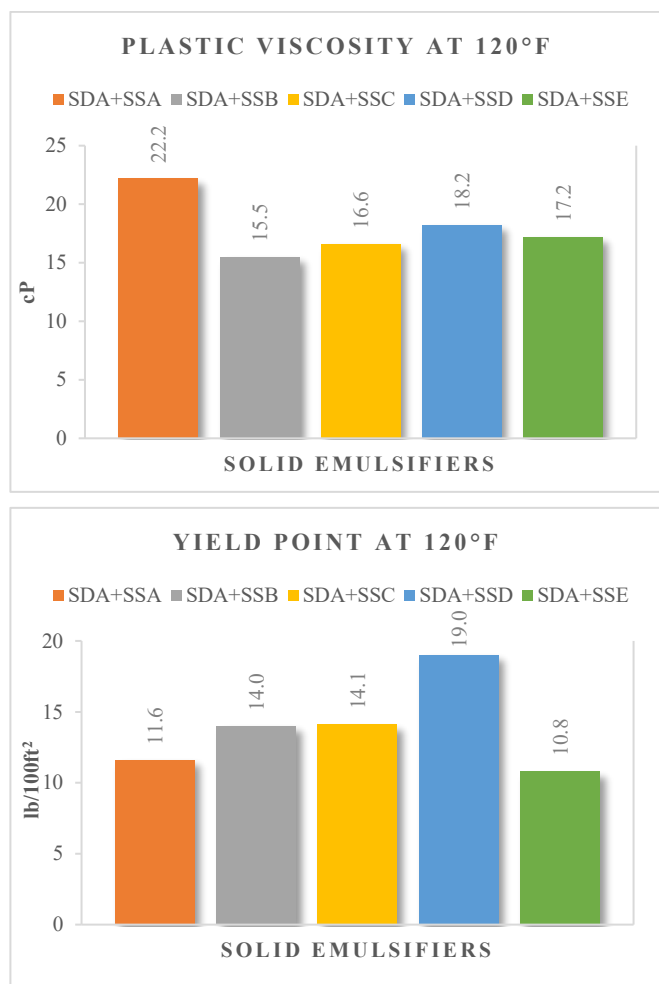
	3 ppb LP		3 ppb SDA	
	0	6%	0	6%
Primary Emulsifier	2 ppb LS		1.5 ppb SSA	
Secondary Emulsifier				
LGS	0	6%	0	6%
600 RPM (SS)	52.8	99.3	56.0	69.6
300 RPM (SS)	32.2	66.9	33.8	43.8
200 RPM (SS)	24.2	55.1	25.9	35.5
100 RPM (SS)	16.1	41.0	18.2	26.6
6 RPM (SS)	7.8	23.0	8.9	14.1
3 RPM (SS)	7.5	22.5	8.4	13.4
PV (cP)	20.6	32.4	22.2	25.8
YP (lb/100ft ²)	11.6	34.5	11.6	18.0
10s Gel (SS)	7	22	8	13
10m Gel (SS)	12	29	10	15
ES (V)	945	663	552	165
HTHP Fluid Loss (mL)	4.6	10.0	6.0	11.0
HTHP Filtrate Water (mL)	0	0	0	0
Filter Cake (32")	8	10	10	9

Table 3 – Mud testing for liquid and solid all-in-one emulsifiers with and without 6% LGS in diesel-based mud system 1

Emulsifier	5ppb LAN1		5ppb SAN1	
	0	6%	0	6%
LGS	0	6%	0	6%
600 RPM (SS)	61.3	131.8	98.0	115.7
300 RPM (SS)	40.7	94.4	68.6	81.2
200 RPM (SS)	32.9	78.4	57.5	67.7
100 RPM (SS)	24.2	60.1	44.8	52.0
6 RPM (SS)	12.8	34.7	28.6	30.0
3 RPM (SS)	12.1	33.5	27.5	28.0
PV (cP)	20.6	37.4	29.4	34.5
YP (lb/100ft ²)	20.1	57.0	39.2	46.7
10s Gel (SS)	11	30	26	28
10m Gel (SS)	12	32	24	33
ES (V)	1065	612	866	371
HTHP Fluid Loss (mL)	4.8	10.6	10.6	14.4
HTHP Filtrate Water (mL)	0	0.1	0	0
Filter Cake (32")	7	10	16	11

Table 4 – Mud testing results for secondary emulsifier powders SSA-E without LGS in diesel-based mud system 1

Primary Emulsifier	3 ppb SDA	3 ppb SDA	3 ppb SDA	3 ppb SDA	3 ppb SDA
Secondary Emulsifier	1.5 ppb SSA	2 ppb SSB	2 ppb SSC	2 ppb SSD	2 ppb SSE
600 RPM (SS)	56.0	45.0	47.3	55.4	45.2
300 RPM (SS)	33.8	29.5	30.7	37.2	28.0
200 RPM (SS)	25.9	21.8	23.3	28.7	19.8
100 RPM (SS)	18.2	14.4	16.2	20.3	13.5
6 RPM (SS)	8.9	7.8	8.8	11.3	6.9
3 RPM (SS)	8.4	7.3	8.4	10.7	6.7
PV (cP)	22.2	15.5	16.6	18.2	17.2
YP (lb/100ft ²)	11.6	14.0	14.1	19.0	10.8
10s Gel (SS)	8	8	8	11	7
10m Gel (SS)	10	10	11	13	8
ES (V)	552	718	752	674	652
HTHP Fluid Loss (mL)	6.0	4.8	4.4	4.4	5.0
HTHP Filtrate Water (mL)	0	0	0	0	0
Filter Cake (/32")	10	11	7	6	11

**Figure 2 – Plastic viscosity (top) and yield point (bottom) calculated from rheological measurements for solid emulsifiers at 120°F using diesel mud system 1**

By adjusting the composition of the solid secondary, a range of secondary emulsifier powders were developed and tested at 250°F in the diesel-based mud system [Table 4]. The shear stresses, ES and gel strengths varied some, but fluid loss remained relatively steady around 5mL with no water in the filtrate. Plastic viscosity ranged from 15-22 cP and YP ranged from 12-19 lb/100ft², showing the possibility for rheological property tuning [Figure 2].

Mud Testing in Diesel-based Mud System 2

Emulsifiers powders were compared with liquid emulsifiers after aging at 250°F or 300°F in a diesel-based mud system without LGS per the diesel 2 system [Table 1]. HTHP fluid loss tests were conducted at 250°F or 300°F and rheology and ES were measured at 120°F. Rheology and fluid loss measurements were comparable for the liquid and solid emulsifiers [Table 5]. Three different comparisons were made; combined primary and secondary emulsifier liquids versus powders, secondary emulsifier only liquid versus powder, and primary emulsifier powder with liquid secondary emulsifier versus liquid primary emulsifier with secondary emulsifier powder.

A comparison was made between 250°F and 300°F for this mud system. Increasing the aging and testing temperature resulted in a decrease in shear stress profile, yield point, gel strengths, and ES and an increase in fluid loss with liquid emulsifiers [Table 5]. Shear stress and YP were unchanged for emulsifier powders when increasing test temperatures to 300°F, but small decreases in gel strengths and ES and an increase in fluid loss were observed.

Small shear stress increases were observed when using emulsifier powders versus liquids in all cases, with the largest increases observed when using only emulsifier powders. Plastic viscosities were within 1-2 cP when comparing liquid and powder emulsifiers, but YP increased significantly when using emulsifier powders [Figure 3], with primary emulsifier powder as the biggest driver [Table 5]. Gel strengths also increased with

the use of emulsifier powders primarily contributed by the secondary emulsifier powder.

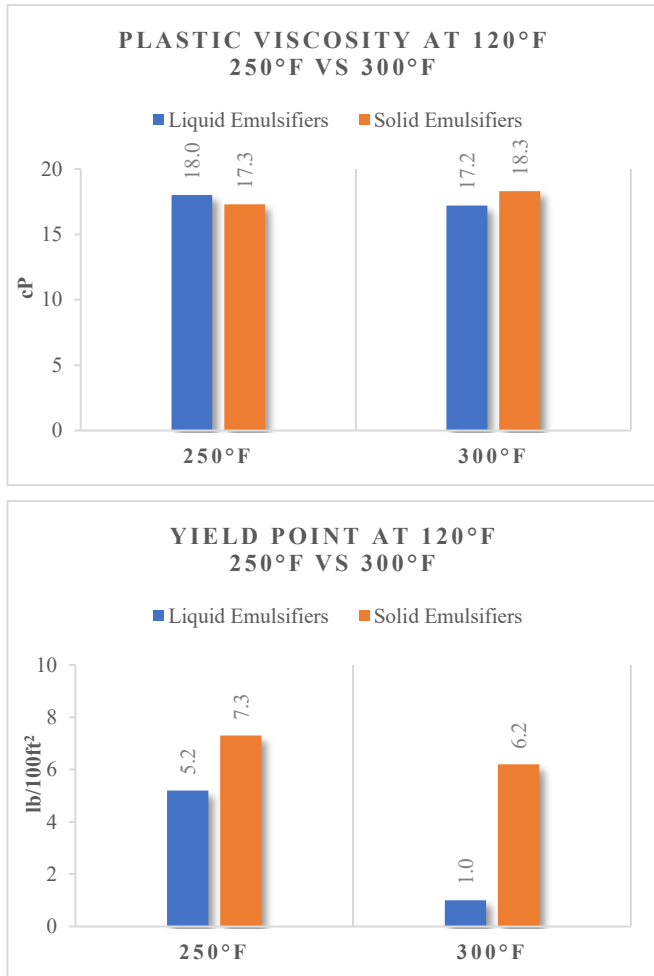


Figure 3 – Plastic viscosity (top) and yield point (bottom) calculated from rheological measurements for liquid and solid emulsifiers at 120°F using diesel-based mud system 2

Electrical stability of the test muds was improved with the use of emulsifier powders in all test cases [Table 5], and improvements were measured between 100-300 V. Fluid loss improved when using solid emulsifiers, though the effect was driven by the secondary emulsifier powder. This was especially noteworthy when using a liquid primary emulsifier or no primary emulsifier, where 3 mL of water was observed in the filtrate with the liquid emulsifier, but no water was observed when using the emulsifier powder [Table 5].

Mud Testing in Mineral Oil-based Mud System

Liquid and solid emulsifiers were tested after aging at 250°F in a mineral oil-based mud system as [Table 1]. HTHP fluid loss testing was conducted at 250°F and rheology and ES were measured at 120°F. Shear stresses, plastic viscosity, and gel strengths were higher with emulsifier powders versus liquid emulsifiers, while ES and fluid loss were comparable [Table 6].

Table 6 – Mud testing results for liquid and solid emulsifiers at 250°F in a mineral oil-based mud system

Primary Emulsifier	3 ppb LP	3 ppb SDA
Secondary Emulsifier	2 ppb LS	2 ppb SSA
600 RPM (SS)	42.7	51.7
300 RPM (SS)	23.7	28.5
200 RPM (SS)	15.8	20.8
100 RPM (SS)	9.2	12.9
6 RPM (SS)	2.4	4.3
3 RPM (SS)	2.0	3.9
PV (cP)	19.0	23.2
YP (lb/100ft ²)	4.7	5.3
10s Gel (SS)	3	5
10m Gel (SS)	6	14
ES (V)	313	370
HTHP Fluid Loss (mL)	2.0	1.0
HTHP Filtrate Water (mL)	0	0
Filter Cake (/32")	12	14

Table 5 – Mud testing results for liquid and solid emulsifiers at 250°F and 300°F in diesel-based mud system 2

Primary Emulsifier	3 ppb LP		3 ppb SDA		0	0	3 ppb SDA		3 ppb LP				
	2 ppb LS		1.5 ppb SSA				5 ppb LS		5 ppb SSA		2 ppb LS		1.5 ppb SSA
Aging/HTHP Temperature	250°F	300°F	250°F	300°F	300°F	300°F	300°F	300°F	300°F	300°F	300°F	300°F	300°F
600 RPM (SS)	41.2	35.4	41.9	42.8	37.5	44.4	39.4	39.6					
300 RPM (SS)	23.2	18.2	24.6	24.5	21.7	28.9	21.3	20.2					
200 RPM (SS)	15.2	10.9	16.1	15.9	15.9	22.0	13.0	12.7					
100 RPM (SS)	8.9	5.6	10.1	9.3	10.2	15.6	6.4	6.9					
6 RPM (SS)	2.6	0.2	4.2	2.5	3.0	7.4	0.9	1.0					
3 RPM (SS)	2.4	0.1	3.9	2.2	2.6	7.0	0.6	0.9					
PV (cP)	18.0	17.2	17.3	18.3	15.8	15.5	18.1	19.4					
YP (lb/100ft ²)	5.2	1.0	7.3	6.2	5.9	13.4	3.2	0.8					
10s Gel (SS)	2	0	4	3	2	7	1	0					
10m Gel (SS)	5	1	6	4	3	9	2	3					
ES (V)	504	333	543	480	554	663	672	638					
HTHP Fluid Loss (mL)	4.0	9.0	3.2	8.2	22.0	15.0	9.4	6.0					
HTHP Filtrate Water (mL)	0	0	0	0	3	0	0	0					
Filter Cake (/32")	8	16	7	18	16	16	6	*					

Powder Flow and Comparison to Industry Standards

The emulsifier powders were evaluated for their flow and compaction properties, e.g. angle of repose, Hausner ratio, Carr's index, and clumping after compaction, and were compared with several powdered materials commonly used in oil-based drilling fluid formulations. Angle of repose is a method of describing the flowability of a loose, unconsolidated material, where lower angles correspond to better flowability [Table 7]. The Hausner ratio and Carr's index describe the compressibility of a powder which correlates to the flowability of the material, where lower values correspond to better flowability [Table 7].

Table 7 – Relation of flow characteristics and angle of repose, Hausner ratio, and Carr's index

Flow Description		Angle of Repose (°)	Hausner Ratio	Carr's Index
Excellent	Free flowing	25-30	1.00-1.11	≤10
Good	Free flowing	31-35	1.12-1.18	11-15
Fair	Aid not needed	36-40	1.19-1.25	16-20
Passable	Easily fluidisable	41-45	1.26-1.34	21-25
Poor	Must agitate/vibrate	46-55	1.35-1.45	26-31
Very Poor	Cohesive	56-65	1.46-1.59	32-37
Very, Very Poor	Cohesive	≥66	≥1.60	≥38

Free-flowing, non-cohesive powders are desired for powdered materials for ease of handling and dispersal in fluids. Angle of repose was measured on unconsolidated powders, and samples were ordered by increasing angle of repose [Table 8]. While it is possible to calculate the angle of repose of a powder by calculating \tan^{-1} using the ratio of pile height/radius, in practice this led to a significant under estimation when compared against direct measurement of the angle using test images [Figure 4]. The powders fell within the good to fair and poor flowability ranges, with SSA and organophilic lignite having good and fair flowability, respectively and all other materials having poor flowability. SSA was a granular material which formed a neat, symmetrical pile, while most other test samples were cohesive powders that formed uneven, clumped piles like SAn1 [Figure 4].

Table 8 – Collected powder flowability test results for emulsifier powders and common oilfield materials

	Angle of Repose (°)	Hausner Ratio	Carr's Index	Degree of Caking 16 hr @ 50°C
SSA	35	1.19	16	0.9
Organophilic Lignite	42	1.30	23	2.7
Comm. Dry All-in-one	50	1.33	25	4.2
Organophilic Clay	50	1.43	30	8.6
Lime	52	1.59	37	4.5
CaCO ₃ - 5 μm	53	1.65	39	6.7
SAn1	54	1.41	29	2.8
SDA	55	1.31	24	3.1

Hausner ratio and Carr's index are measured by change in bulk density via 5000 taps on the test cylinder and relates to the compressibility and flow characteristics of a powder. Greater

change in volume corresponds to higher HR and CI, thus worse flowability. HR and CI moderately agreed with angle of repose measurements in determining flowability characteristics [Table 8]. Two notable exceptions were lime and 5 μm calcium carbonate which are characterized by angle of repose to have poor flow, but by Hausner ratio and CI are characterized as very poor or worse and cohesive. The all-in-one powder emulsifiers had flowability characteristics like organophilic clay and lime, while the secondary emulsifier powder had fair flowability, which was better than organophilic lignite.



Figure 4 – Angle of repose test images for SSA (top) and SAn1 (bottom)

Compaction testing demonstrated all samples had low degrees of caking [Table 8Error! Reference source not found.], with no clear trend between flowability measures and clumping tendency. The secondary emulsifier powder had the lowest degree of caking, 0.9, under the compression conditions of 6.5 psi for 24 hours at 50°C. The 6.5 psi compaction pressure corresponds to the pressure at the bottom of a stack of 4 supersacks, which is significantly higher than what is experienced at the bottom of a stack of pallets. The primary

(SDA) and all-in-one emulsifier (SAn1) powders had low degree of caking, in line with a commercial all-in-one emulsifier powder and lime in the range of 3-5. Organophilic clay and 5 μm calcium carbonate had the highest degrees of caking at 8.6 and 6.7, respectively.

Sustainability Comparison between Liquid and Solid Emulsifiers

Sustainability was evaluated based on carbon dioxide emissions via fuel consumption from shipping of formulated emulsifiers. Carbon lifecycle analysis is a more holistic sustainability comparison, but much of the information required was unavailable. Though the current evaluation only focuses on carbon dioxide emissions from shipment, additional sustainability benefits may be found during a more detailed study.

Carbon dioxide emissions were calculated for a truck travelling 100 miles. Truck fuel efficiency ranges from 4.51-6.53 mpg on the highway in North America (Geotab 2018), and a fuel efficiency of 5.94 mpg was used for emissions calculations, resulting in 16.8-gallons of diesel consumed over a 100-mile span [Equation 6]. Combustion of 1 gallon of diesel fuel produces 22.43 pounds of CO_2 (EPA-420-F-18-008 2018), or 379 pounds of CO_2 per 100 miles traveled [Equation 7].

Equation 6

$$\text{Diesel (gal/100 mi)} = \frac{100 \text{ mi}}{5.94 \text{ mpg}} = 16.8 \text{ gal}$$

Equation 7

$$\begin{aligned} \text{Emissions (lbs CO}_2\text{/100 mi)} &= \frac{16.8 \text{ gal}}{100 \text{ mi}} \times 10,180 \frac{\text{g CO}_2}{\text{gal}} \times \frac{2.203 \text{ lbs}}{1000 \text{ g}} \\ &= 379 \frac{\text{lbs CO}_2}{100 \text{ mi}} \end{aligned}$$

The CO_2 emissions per 100 miles was used to determine the difference in drummed liquid versus sacked powder emulsifier transport emissions. To accomplish this, the weight of emulsifier on a flatbed truck loaded by pallets was used for direct comparison. Drums and sacks are both transported on pallets and a pallet of liquid emulsifier has 1,745 lbs/pallet [Equation 8], while powders are assumed to be 2,000 lbs/pallet (40 x 50 lb sacks). The weight of emulsifier was then multiplied by the number of pallets typically loaded onto a truck, 22 for drums and 18 for sacks, to estimate 38,390 pounds of liquid emulsifier [Equation 9] and 36,000 pounds of emulsifier powder [Equation 10] on a flatbed truck.

Equation 8

$$\begin{aligned} \text{Liquid Emulsifier (lbs/pallet)} &= 220 \text{ gal} \times 7.93 \text{ ppg} \\ &= 1,745 \text{ lbs/pallet} \end{aligned}$$

Equation 9

$$\begin{aligned} \text{Liquid Emulsifier on Truck (lbs)} &= 22 \text{ pallets} \times 1,745 \text{ lbs/pallet} \\ &= 38,390 \text{ lbs} \end{aligned}$$

There are 2,390 additional pounds of drummed liquid emulsifiers versus solid emulsifiers on a truck due to the 4

additional pallets present. Liquid emulsifiers contain significant volumes of solvent to reduce the product viscosities and make the materials flowable. The solvent volume is up to 35% (v/v) of the liquid emulsifier, or 13,437 lbs [Equation 11].

Equation 10

$$\begin{aligned} \text{Dry Emulsifier on Truck (lbs)} &= 18 \text{ pallets} \times 2,000 \text{ lbs/pallet} \\ &= 36,000 \text{ lbs} \end{aligned}$$

Equation 11

$$\begin{aligned} \text{Solvent (lbs/truck)} &= 38,390 \text{ lbs} \times 0.35 \\ &= 13,437 \text{ lbs/truck} \end{aligned}$$

Thus, the weight of the liquid emulsifier active components is 24,953 lbs/truck. The emulsifier weight/truck was used to calculate the CO_2 emissions per pound of emulsifier per 100 miles traveled. The liquid emulsifiers [Equation 12] had increased CO_2 emissions versus emulsifier powder [Equation 13], with the solid emulsifier having 30% lower CO_2 emissions compared to liquid emulsifiers [Table 9].

Equation 12

$$\begin{aligned} \text{Emissions per lb of Liquid Emulsifier Actives} &= \frac{379 \text{ lbs CO}_2\text{/100 mi}}{24,953 \text{ lbs em}} \\ &= 0.0152 \text{ lbs CO}_2\text{/100 mi/lb em} \end{aligned}$$

Equation 13

$$\begin{aligned} \text{Emissions per lb of Dry Emulsifiers} &= \frac{379 \text{ lbs CO}_2\text{/100 mi}}{36,000 \text{ lbs em}} \\ &= 0.0105 \text{ lbs CO}_2\text{/100 mi/lb em} \end{aligned}$$

Additional sustainability benefits can be realized beyond emission reduction via transportation. Frequently used solvents are produced from petroleum sources and inherently reduce the amount of bioderived carbon in an emulsifier formulation. The solvent has associated flammability and environmental health and safety (EHS) profiles that must be considered during transport and usage as well. Removing the solvent can, potentially, increase the proportion of biogenic carbon and improve handling of the emulsifier, thus improving the sustainability profile.

Table 9 – Emissions calculation summary for liquid and solid emulsifiers

	Liquid	Solid	% Δ
Emulsifier per Pallet (lbs)	1,745	2,000	14.6%
Emulsifier per Truck (lbs)	38,390	36,000	-6.2%
Solvent per Truck (lbs)	13,437	0	
Active Emulsifier per Truck (lbs)	24,953	36,000	44.3%
Emissions per Emulsifier lb (lbs CO_2 /100 mi)	0.0152	0.0105	
Normalized Emissions per Emulsifier	1.45	1.00	-30.9%

Liquid emulsifiers are frequently packaged in drums or totes for transport to rig sites for ease of use. Drums are manufactured and shipped empty to the emulsifier manufacturer, and once empty, the drum needs to be shipped to a disposal site where it is washed and crushed, adding to the emission profile. Totes are similarly transported without contents to be filled, cleaned, and disposed. While sacks are sent to the emulsifier producer for

filling, they are shipped without void space and may have a lower associated emissions profile. When sacks are empty, they may be put into the standard rig site trash disposal, again incurring a lower associated emissions profile.

Conclusions

Emulsifier powders were very effective emulsifying agents in both diesel and mineral oil formulations at 250°F and 300°F. These emulsifiers were comparable to their liquid emulsifier counterparts in these fluid systems, especially in the case of standalone primary and secondary emulsifiers. The emulsifiers and fluid systems were not optimized for improved compatibility or performance.

In several cases, solid secondary emulsifiers outperformed the liquid secondary emulsifier in relation to rheology and HTHP fluid loss. Low gravity solid contamination was also well tolerated at 250°F in a diesel-based drilling fluid with powder emulsifiers showing much lower shear stress, PV, and YP increases on addition of LGS. A series of secondary emulsifier powders were synthesized and tested in at 250°F in a diesel-based system and showed consistent fluid loss performance, though variability was observed in the rheological properties across the series which could be used for customization for specific fluid systems.

Rheological and HTHP fluid loss properties were better maintained by emulsifier powders when test temperatures were increased to 300°F. The emulsifier powders maintained the shear stress profile, YP and gel strengths of the drilling fluid at higher temperature, while these values fell when using liquid emulsifiers. The removal of primary emulsifier at 300°F resulted in significantly higher HTHP fluid loss for both liquid and solid emulsifiers, but water in the filtrate only with liquid secondary emulsifier.

Powder characteristics were evaluated for the emulsifier powders and compared against powder materials currently used in drilling fluids. Flowability, compaction, and consolidation were similar across all tested materials with no significant difference between emulsifier powders and commercial drilling fluid additives. There was no expectation that emulsifier powder would pose any handling issues worse than current additives do in the field.

Sustainability benefits were estimated based on shipping related carbon emissions for active emulsifier components. The addition of solvent to liquid all-in-one and secondary emulsifiers reduces the proportion of active components by 28% and 35%, respectively, increasing the transportation emissions per pound of active emulsifier. The presence of solvent increases the relative carbon dioxide emissions by 30% and 45% per pound of active emulsifier for all-in-one and secondary emulsifiers, respectively. Further emission reductions could be realized by including the need for shipping empty containers when using liquid emulsifiers versus bags for solid emulsifiers.

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Nomenclature

°	= Degrees of angle
°C	= Degrees Celsius
°F	= Degrees Fahrenheit
/32"	= Thirty-seconds of an inch
API	= American Petroleum Institute
CI	= Carr's index
CO ₂	= Carbon dioxide
cP	= Centipoise
EHS	= Environmental health and safety
ES	= Electrical stability
g	= Grams
gal	= Gallons
hr	= Hour
HR	= Hausner ratio
HTHP	= High temperature, high pressure
LAn1	= Liquid all-in-one emulsifier
lb(s)	= Pound(s)
lb em	= Pounds of emulsifier
lb/100ft ²	= Pounds per 100 square feet
LGS	= Low gravity solids
LP	= Liquid primary emulsifier
LS	= Liquid secondary emulsifier
µm	= Micrometers
mi	= Miles
mL	= Milliliter
mpg	= Miles per gallon
OBM	= Oil-based mud
OWR	= Oil-water ratio
ppb	= Pounds per barrel
ppg	= Pounds per gallon
psi	= Pounds per square inch
PV	= Plastic viscosity
RP	= Recommended practices
RPM	= Revolutions per minute
SAn1	= Solid all-in-one emulsifier
SDA	= Spray-dried additive – solid primary emulsifier
SS	= Shear stress
SSA	= Solid secondary emulsifier A
SSB	= Solid secondary emulsifier B
SSC	= Solid secondary emulsifier C
SSD	= Solid secondary emulsifier D
SSE	= Solid secondary emulsifier E
tan ⁻¹	= Arctangent
V	= Volts
(v/v)	= Volume per volume
YP	= Yield point

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