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Estimating Water-Based Mud Rheology from Marsh-Funnel Drainage Using Capillary-Flow Analysis

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Abstract

The Marsh funnel is widely used at the rig site as a rapid drilling-fluid quality-control tool, but its conventional output—a single drainage time—does not provide full rheological characterization. This study evaluates whether Marsh-funnel drainage data can be converted into rheological information for water-based drilling muds using capillary-flow analysis, funnel-geometry variation, and statistical modeling. Nine water-based mud samples, including gel mud, KCl-polymer mud, and KCl-silicate mud, were tested with a 6-speed rotational viscometer and six funnel geometries. Drain-volume/time data were collected for immediate drainage and after 1-, 5-, and 10-minute waiting periods. Wall shear stress and corrected wall shear rate were calculated using pressure-driven-flow concepts and Weissenberg-Rabinowitsch correction, and funnel-derived rheograms were compared with 6-speed viscometer behavior. Power-law behavior described the mud samples more consistently than the Bingham plastic model, with an average R^2 of 0.956 compared with 0.773 for Bingham fitting. Funnel geometry affected the reliability of funnel-derived rheograms; larger orifices reduced orifice resistance and improved fluid-behavior expression, whereas the smallest orifice produced poor or invalid responses for viscous samples. Multivariable regression linked the consistency index primarily to solid content and funnel drainage-time ratios, whereas the flow-behavior index required consistency-index information for reliable prediction. A gel-strength indicator based on the area change between apparent-viscosity/shear-rate curves after static waiting detected gel response in 94 of 145 valid attempts, or 64.8%. The results support Marsh-funnel use as a supplementary field rheometry tool when calibrated against conventional viscometer data, although standalone deployment requires further validation across temperature, oil-based muds, and broader field mud systems.

Keywords

Marsh Funnel, Water-Based Mud, Capillary-Flow Analysis, Rheology, Power-Law Model, Gel-Strength Indicator

1. Introduction

Drilling-fluid rheology controls hole cleaning, solids suspension, hydraulic calculations, equivalent circulating density, and the pressure required to restart circulation after static periods [1]-[9]. In field operations, the 6-speed rotational viscometer remains the standard instrument for estimating plastic viscosity, yield point, gel strength, and power-law parameters; however, the Marsh funnel remains the most common rapid rig-site viscosity check [1] [10].

Conventional Marsh-funnel practice reports the time required to drain a fixed volume. This single-point measurement is useful for quality control but is insufficient for describing non-Newtonian drilling-fluid behavior. Previous studies have examined Marsh-funnel viscosity, apparent viscosity correlations, and pressure-driven interpretations of funnel discharge [11]-[17]. This study addresses the limitation of conventional Marsh-funnel testing by evaluating whether drainage-volume/time data can be converted into rheological indicators for water-based drilling muds. The objective is to develop and assess a Marsh-funnel-based workflow for estimating power-law rheological parameters and indicating gel response using controlled mud formulations, modified funnel geometries, static waiting periods, capillary-flow analysis, and regression modeling. The method is evaluated against 6-speed rotational viscometer measurements for gel mud, KCl-polymer mud, and KCl-silicate mud systems.

2. Technical Background

Water-based muds are non-Newtonian suspensions whose apparent viscosity depends on shear rate, solid content, polymer content, clay interactions, and electrochemical structure [3] [6] [7] [9]. This study evaluated Bingham plastic and power-law descriptions using 6-speed viscometer data and used R^2 to determine which model better represented each sample. Yield-stress and non-Newtonian-flow interpretation can be sensitive to measurement geometry and operating shear range [18] [19].

The Marsh funnel resembles a pressure-driven capillary rheometer because flow is generated by hydrostatic pressure through an orifice. By recording drainage volume as a function of time, calculating instantaneous flow rate, estimating wall shear stress, and applying non-Newtonian shear-rate correction, a funnel rheogram can be constructed rather than relying only on a single funnel time [11]-[15].

3. Materials and Methods

3.1. Mud Systems and Measurements

Nine water-based muds were prepared: three gel muds, three KCl-polymer muds, and three KCl-silicate muds. The full formulations are reported in Table 1 to allow reproduction of the rheological differences among samples. Concentrations are expressed in pounds per barrel, except silicate, which is reported in gallons per barrel. The general preparation and field-testing procedures followed standard drilling-fluid measurement practice [1].

Table 1. Mud sample formulations used to prepare gel, KCl-polymer, and KCl-silicate water-based muds.

Sample	Soda Ash	Bentonite	Caustic Soda	FLC	Barite	PAC LV	PAL ZAN	Silicate	PAC RS	KCl
GEL-01	0.01	5.0	0.1	—	—	—	—	—	—	—
GEL-02	0.01	7.5	0.1	—	—	—	0.5	—	—	—
GEL-03	0.01	12.0	0.1	—	3.50	—	1.5	—	—	—
KCL-01	0.15	—	0.15	2.87	20.0	3.9	1.0	—	0.75	18
KCL-02	0.15	—	0.15	—	20.0	3.0	0.5	—	0.75	20
KCL-03	0.15	—	0.15	—	20.0	9.0	—	—	0.75	18
SILICA-01	0.15	—	0.15	—	20.0	3.0	—	6	0.50	15
SILICA-02	0.15	—	0.15	—	20.0	3.0	—	8	0.75	18
SILICA-03	0.15	—	0.15	—	20.0	3.0	1.0	10	0.75	18

Each mud was prepared at ambient laboratory temperature using fresh water as the continuous phase. Additives were weighed according to Table 1 and added sequentially under mechanical agitation in the following order: water conditioning additives, clay or polymer viscosifiers, shale inhibitors or silicate, fluid-loss-control additives, and weighting material where applicable. Each slurry was mixed until visually homogeneous, with a minimum mixing time of 1 h before testing. Density was measured using a calibrated mud balance, solid content was measured using a mud retort, and rheological measurements were collected using a calibrated 6-speed rotational viscometer.

3.2. Funnel Geometry, Calibration, and Drainage Procedure

Table 2. Geometric dimensions of the standard and modified Marsh funnels used in drainage analysis.

Funnel	Z1, cm	Ro, cm	Z2, cm	RL, cm	α, degrees	V0, cm^3	Remarks
1	27.94	6.985	5.08	0.238	13.611	1500	Standard Marsh Funnel
2	28.80	7.250	5.10	0.360	12.766	1680	Modified Funnel
3	28.80	7.250	6.08	0.230	12.766	1680	Modified Funnel
4	28.80	7.250	5.02	0.225	12.766	1680	Modified Funnel
5	28.80	7.250	4.10	0.225	12.766	1680	Modified Funnel
6	28.80	7.250	5.05	0.150	12.766	1680	Modified Funnel

Six funnel geometries were used: one standard Marsh funnel and five modified funnels with interchangeable orifices. The geometric parameters used in the calculations are listed in Table 2. Here, Z1 is the cone height, Ro is the upper cone radius, Z2 is the orifice length, RL is the orifice radius, α is the funnel-wall slope, and V0 is the initial filled volume.

The experimental workflow used to convert Marsh-funnel drainage measurements into rheological indicators is shown in Figure 1.

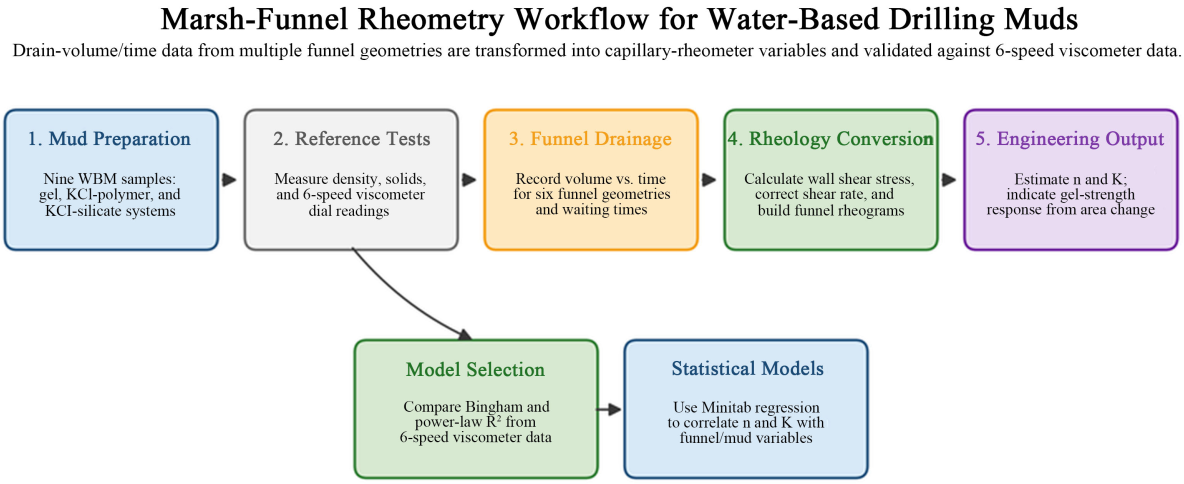

Figure 1. Workflow for converting Marsh-funnel drainage data into rheological indicators for water-based muds.

The geometric parameters of each funnel, including cone height, top radius, orifice radius, orifice length, and wall slope, are summarized in Table 2. These dimensions were used to convert drained volume into instantaneous fluid height.

Hydrostatic pressure driving the flow was calculated using $P = \rho g h$, where h is the instantaneous fluid height inside the funnel. The fluid head was updated with time from the measured volume-time data and funnel geometry, ensuring that the decreasing driving pressure during drainage was accounted for in the wall shear stress calculations.

Calibration requirement before rheological estimation. Before a funnel geometry is used as a rheological estimation tool, the orifice must be cleaned and visually inspected, the funnel must be leveled vertically, and freshwater drainage must be measured repeatedly at the test temperature. In this study, freshwater calibration was repeated 20 times for each modified funnel, and the mean drainage time and standard deviation were used as geometry-specific hydraulic reference values. For field use, the same funnel/orifice combination should be calibrated with fresh water and at least one reference mud previously characterized by a 6-speed rotational viscometer; the resulting calibration should be checked whenever the orifice is changed, cleaned, damaged, or used at a substantially different temperature.

3.3. Data Analysis

Marsh-funnel discharge was treated as capillary-type pressure-driven flow because the fluid is discharged through a confined outlet under a hydrostatic pressure difference, analogous to gravity-driven capillary rheometry. This treatment assumes incompressible flow, no wall slip, and a usable laminar-flow region in which wall shear stress and corrected wall shear rate can be estimated from the drainage record. The Weissenberg-Rabinowitsch correction was applied to account for non-Newtonian behavior [11] [12].

Data were screened before rheological fitting. Points were retained only when the instantaneous slope used in the Weissenberg-Rabinowitsch correction remained within the recommended range of approximately $0.2 < n' < 1.3$, and when the log-log shear-stress/nominal-shear-rate trend did not show abrupt slope changes associated with non-laminar, entrance-loss, or orifice-dominated behavior [12]. Small-orifice responses, especially for very viscous samples, were rejected when they failed to represent bulk fluid flow.

4. Results

4.1. Rheological Model Selection

Power-law behavior provided the more consistent description for the nine mud samples. The average power-law R^2 was 0.956, compared with 0.773 for the Bingham plastic model. Power-law R^2 exceeded Bingham R^2 for 8 of the 9 samples, and 6 of 9 power-law fits had R^2 values greater than 0.95.

Comparison with the 6-speed viscometer was used as the primary benchmark for evaluating funnel-derived rheograms. The funnel-derived curves reproduced the general shear-thinning tendency observed in the viscometer data, but the absolute values of shear stress and fitted parameters did not match perfectly because the Marsh funnel operates over a different shear-rate range and is affected by entrance and/or orifice losses. Therefore, agreement was interpreted in terms of rheological trend and model discrimination rather than direct replacement of standard viscometer measurements.

Figure 2 compares Bingham plastic and power-law model fits obtained from the rotational viscometer data.

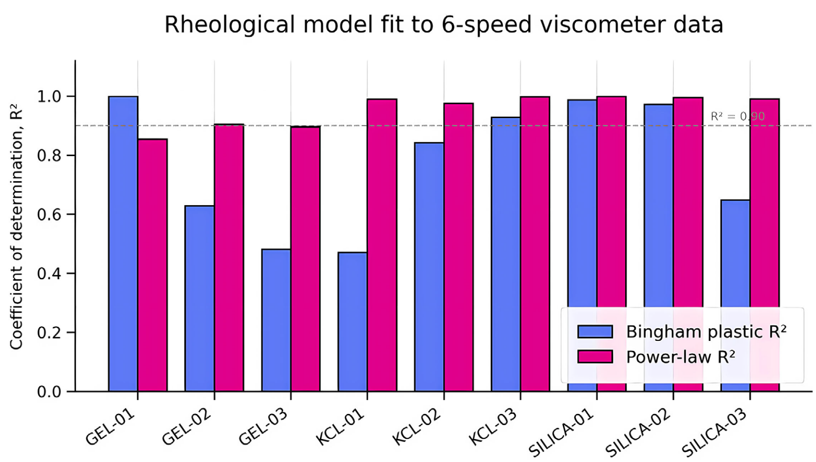

Figure 2. Comparison of Bingham plastic and power-law model fit to 6-speed viscometer data.

4.2. Effect of Funnel Geometry

Freshwater drain time varied strongly with funnel geometry, from 12.5 seconds for funnel #2 to 78.2 seconds for funnel #6. This confirms that orifice geometry materially changes hydraulic response and must be included when interpreting funnel drainage data.

Funnel #2 provided the most reliable rheological response among the tested geometries. Its larger orifice radius (0.360 cm) and short freshwater drainage time (12.463 s) reduced orifice resistance and allowed the drainage curve to reflect bulk fluid behavior more clearly than smaller-orifice funnels. By contrast, Funnel #6, with the smallest orifice radius (0.150 cm), produced long drainage times and invalid or poor responses for viscous samples, indicating that entrance/orifice losses can dominate the measured response when the outlet is too restrictive.

Accordingly, field application should be restricted to calibrated funnels that produce complete, monotonic drainage curves within the tested fluid-property range. The present correlations should not be extrapolated to oil-based muds, high-temperature fluids, highly weighted systems, or muds that do not drain smoothly through the selected orifice without additional calibration.

Figure 3 summarizes the freshwater drainage-time response for each funnel geometry.

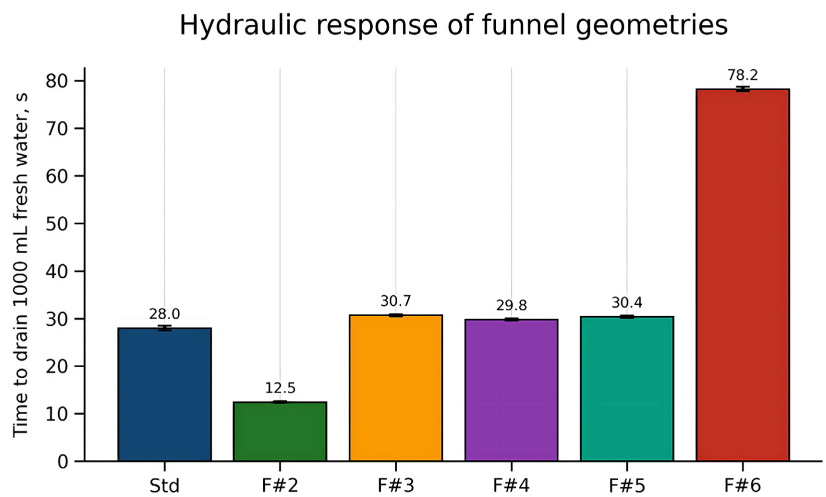

Figure 3. Freshwater drainage time for each funnel geometry.

4.3. Statistical Estimation of Power-Law Parameters

The final multivariable regression model for the consistency index K retained solid content, drainage-time ratio, freshwater drainage time, the square of freshwater drainage time, initial funnel volume, and the square of solid content as predictors:

$$K = 7.65S - 72.65(DivT) - 1.66T\_w + 0.01266T\_w^2 - 0.0492V_0 - 3.145S^2 + 169.2$$

where S is solid content (%), DivT is the mud/water drainage-time ratio, T_w is the time required to drain 1000 mL of fresh water, and V_0 is the initial funnel volume. The K model produced $R^2 = 74.77\%$ and $p = 0.024$.

The final regression model for the flow-behavior index n retained K, drainage-time ratio, drainage-time difference, and K^2 as predictors:

$$n = 0.698 - 0.04502K + 0.0947\,(\mathrm{DivT}) - 0.000931(\Delta T) + 0.000611K^2$$

The n model produced $R^2 = 87.26\%$ and $p = 0.029$. Because only nine mud systems were available, overfitting was addressed by retaining only statistically useful predictors, rejecting funnel-geometry dimensions when they did not improve the model, and interpreting the regressions as screening correlations rather than universal predictive equations. Additional validation with independent mud systems is required before field deployment.

Because the dataset contains only nine mud systems, the regression models and gel-response indicator should be interpreted as preliminary calibrated relationships for the tested water-based muds. The Marsh funnel should therefore be considered a supplementary field rheometry tool, not a standalone replacement for a rotational viscometer, until the method is validated using a larger independent dataset covering broader mud chemistries, temperatures, densities, and solids contents.

Figure 4 shows the consistency-index relationship with solid content and mud density.

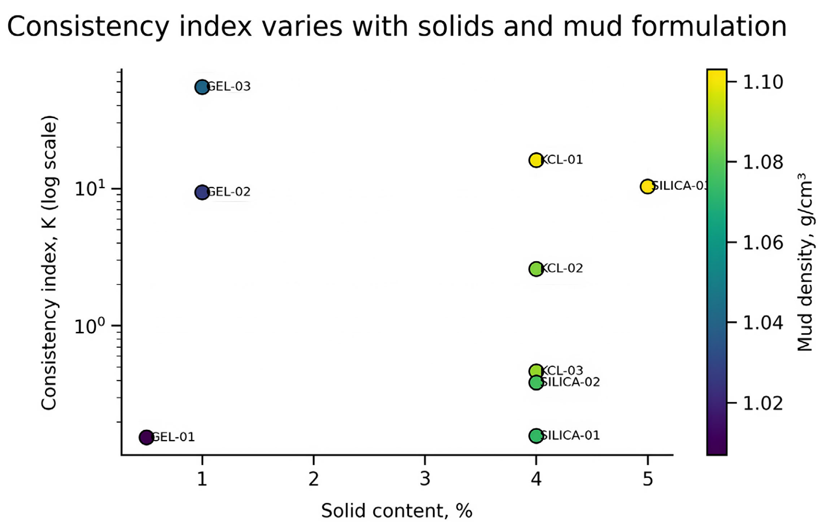

Figure 4. Power-law consistency index as a function of solid content and mud density.

4.4. Gel-Strength Indication

Freshwater calibration runs were repeated 20 times for each modified funnel geometry; mean drainage time and standard deviation were reported. Mud drainage tests were performed in duplicate, and the average drainage-volume/time response was used to reduce operator timing error. For gel-response testing, each valid sample-funnel combination could generate three waiting-period comparisons: immediate versus 1 min, immediate versus 5 min, and immediate versus 10 min.

A "valid attempt" was defined as a drainage comparison in which the mud passed through the funnel without blockage, produced a complete and monotonic volume/time record, allowed calculation of flow rate, shear stress, corrected shear rate, and apparent viscosity, and remained within the accepted capillary-flow screening range. Runs were rejected when the sample was too viscous to pass through the nozzle properly, when no complete drainage curve was obtained, when the response was dominated by orifice resistance rather than fluid-flow behavior, or when slope changes indicated departure from the usable laminar-flow range. The denominator of 145, therefore, represents only valid waiting-period comparisons, not all physically attempted combinations.

The gel-response method detected a positive response in 94 of 145 valid attempts, giving a success rate of 64.8%. Using a binomial proportion treatment, the approximate 95% Wilson confidence interval is 56.8% - 72.1%. This uncertainty should be reported with the success value to avoid overstatement of the gel-indicator reliability.

Figure 5 reports the gel-strength indication success by mud sample and funnel geometry.

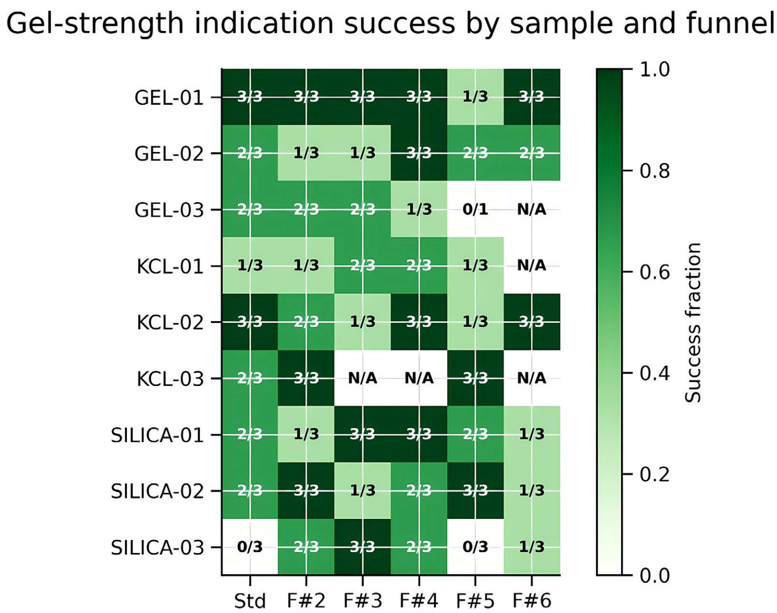

Figure 5. Gel-strength indication success by mud sample and funnel geometry.

5. Discussion

The results show that the Marsh funnel contains more rheological information than conventional funnel time suggests. When drainage volume is recorded as a function of time and converted using capillary-flow theory, the funnel can generate rheograms and provide estimates of power-law behavior.

A key limitation is the restricted experimental matrix. Only nine water-based mud systems were evaluated, and the fluids were prepared and tested at ambient laboratory conditions. Although the samples included gel, KCl-polymer, and KCl-silicate muds, they do not represent the full range of field drilling fluids, especially high-temperature muds, oil-based muds, highly weighted systems, contaminated muds, or fluids containing drilled solids. The regression equations and gel-response indicator should therefore be interpreted as preliminary calibrated relationships for the tested mud systems rather than universal predictive models.

The method is most defensible as a supplementary field rheometry workflow rather than a full replacement for rotational viscometry. The funnel-derived parameters can overestimate shear stress relative to the 6-speed viscometer, likely because the funnel operates at different shear-rate ranges and because small-orifice resistance can dominate the flow response.

The practical implication is that the Marsh funnel can support trend monitoring and rapid screening, but it should not replace rotational viscometry when quantitative values of plastic viscosity, yield point, gel strength, or full rheological model parameters are required. A field workflow should therefore use the funnel method as a calibrated supplement to standard 6-speed viscometer testing, especially when rapid rig-site decisions are needed between full rheometer measurements.

Funnel #2 showed the most favorable hydraulic response because its larger outlet reduced orifice resistance and allowed the measured drainage curve to reflect fluid rheology more than nozzle restriction. Funnel #6 and very viscous samples produced invalid or poor responses because the small orifice increased the likelihood of blockage, entrance losses, and non-representative pressure-drop behavior. This indicates that any field implementation should specify an acceptable funnel geometry, shear-rate range, laminar-flow screening criterion, and fluid viscosity range.

The gel-strength indicator is a relative thixotropic-response metric based on the change in area under apparent-viscosity/shear-rate curves after static waiting. A positive response indicates that the delayed-drainage curve has a larger area than the immediate-drainage curve, which is consistent with structure build-up during static aging. However, this indicator is not equivalent to API 10-second or 10-minute gel strength and does not directly report gel strength in lbf/100 ft^2. Instead, the 1-, 5-, and 10-minute waiting-period comparisons provide a qualitative-to-semiquantitative indication of gel development that must be calibrated against standard viscometer gel measurements before field use.

6. Conclusions

1) The nine water-based mud samples were better represented by the power-law model than by the Bingham plastic model, based on average R^2 and sample-by-sample comparison.

2) Marsh-funnel drainage data can be transformed into rheograms when volume/time measurements, funnel geometry, wall shear-stress estimation, and non-Newtonian shear-rate correction are applied.

3) Funnel geometry materially affects rheological interpretation; very small orifices can shift the response from fluid-flow behavior toward orifice-resistance behavior.

4) Multivariable regression predicted K with an R^2 of 74.77% and n with an R^2 of 87.26%, indicating that funnel variables and mud properties can support approximate rheological-parameter estimation.

5) The proposed area-based gel-strength indicator detected gel response in 64.8% of valid attempts and showed statistical evidence that Marsh-funnel data can indicate thixotropic behavior.

6) The Marsh funnel should be considered a calibrated supplementary rheometry tool for water-based muds, not a standalone replacement for a rotational viscometer. Reliable field use requires freshwater calibration, reference-mud calibration against a 6-speed viscometer, an acceptable funnel geometry such as Funnel #2, and rejection of drainage responses affected by blockage, excessive viscosity, or orifice-dominated flow.

7) The present findings are limited by the small number of mud systems and ambient-temperature testing. Additional validation is required across broader mud chemistries, density ranges, solid contents, temperatures, and field-contaminated fluids before the regression models can be generalized.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Nomenclature

Symbol/Term	Definition	Units
AV	Apparent viscosity	cP
GSI	Gel-strength indicator	fraction or %
K	Power-law consistency index	model-dependent
n	Power-law flow-behavior index	dimensionless
OBM	Oil-based mud	—
PV	Plastic viscosity	cP
Q	Volumetric flow rate	cm^3/s
R^2	Coefficient of determination	dimensionless
S%	Solid content	%
WBM	Water-based mud	—
YP	Yield point	lbf/100 ft^2
$\dot{\gamma}$	Shear rate	s^{-1}
μapp	Apparent viscosity	cP
ρ	Mud density	g/cm^3
τ	Shear stress	Pa
DivT	Mud/water drainage-time ratio	dimensionless
ΔT	Drainage-time difference	s
T_w	Fresh-water drainage time for 1000 mL	s
V_0	Initial funnel volume	cm^3
n'	Instantaneous slope used in Weissenberg-Rabinowitsch correction	dimensionless