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The Flow Characteristics of Fly Ash Slurry for Plugging Abandoned Wells Using Coiled Tubing

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ABSTRACT

The utilization of fly ash has been researched widely in recent years because of the environmental and economical concerns. The primary importance of plugging to abandon wells is to prevent contamination of groundwater aquifer by surface water, oil or gas seepage, or brine formation below the groundwater aquifers. Cement is the present plugging material. However, cement can be replaced by Class C fly ash which has more cementitious material than Class F fly ash due to its higher lime content.

In this paper, the fly ash slurry properties are investigated in the laboratory experiments. Thickening times are measured to estimate the needed pumping time for the fly ash slurry. The rheology of fly ash slurry is also investigated to check the fly ash slurry properties. Finally, the frictional pressure loss test is performed through coiled and straight tubing and the friction pressure loss data are reported.

1. INTRODUCTION

Number of wells has been drilled as water wells and oil wells since nineteenth century. These are eventually abandoned and have to be plugged with cement slurry after some time. However, there are many abandoned wells and improperly plugged wells in the state of Oklahoma. The primary environmental concern is that groundwater aquifer can be contaminated by surface water, oil or gas seepage, or brine in formations below the groundwater aquifers through these wells[1].

The fly ash has been used as a mineral admixture in Portland cement concrete in the oil field since 1950. The fly ash is known to have very similar properties to cement. Class C fly ash, especially, has high lime content, which is a cementitious component. This class C fly ash can replace cement that is primarily used in plugging abandoned wells. Presently, only about half of the fly ash produced by the various coal-fired power plants in the state of Oklahoma is used in cementing application. The rest must be treated as a waste product and disposed of in landfills. This means there is a ready supply of fly ash to use in plugging application. It is much cheaper than cement[2].

When the well is abandoned, most of the drilling equipment is removed from the well site. Pumping cement slurry at the appropriate place in abandoned wells requires rig that is very expensive. An alternative to the rig is the coiled tubing which has, over the years, proven to be a very quick and efficient way of pumping fluids in the oil field. Because of absence of connection (joints), it is safe and time saving operation. The equipment is very mobile since it is mounted on the truck. The coiled tubing becomes straight tubing when it is deployed in the well.

Shah and Cho[2] performed laboratory tests to develop an optimum fly ash slurry formulation and positively concluded that fly ash could be a replacement cement material for plugging abandoned wells. They designed different formulations for fly ash slurry and then tested these to determine compressive strength, fluid loss, free water, and thickening time. Based on compressive strength data (500 psi after one week of curing time), they developed an optimum formulation for fly ash slurry. By this optimum formulation, fly ash can be retarded like cement slurry and it can be pumped through coiled tubing. When designing cement job, adequate working time is seriously required. Therefore, the thickening time of the fly ash slurry is necessary. A premature curing of the fly ash slurry is obviously undesirable.

The conveyance of fly ash slurry into wells through coiled tubing requires knowledge of frictional pressure loss characteristics of fly ash slurry. Knowledge of frictional pressure loss at the target pump rate allows us to relate the coiled tubing head pressure to the displacement pressure (bottomhole pressure). The determination of the rheological behavior of fly ash slurries is essential for the proper evaluation of displacement pressures and flow rates for optimum fly ash placement. Fly ash slurries in this study are examined using concentric cylinder viscometer and the flow loop system.

2. EXPERIMENTAL

2.1. Material

Fly ash samples used in this study were collected from five major coal fired power plants located in Oklahoma. They are: Hugo (Hugo City), Muskogee (Muskogee City), Oologah (North of Tulsa), Red Rock (Ponca City), and Oklaunion (Oklaunion, west of Wichita Falls). These power plants commonly use the Wyoming coal as a fuel. These are normally producing Class C fly ash. The specific gravity range of fly ashes was from 2.65 to 2.78. The surface area was 261.4 to 274.3 ft^2/lb_m. Fly ash samples composed of: SiO_2 (30.76-35.63 %), Al_2O_3 (15.28-23.56), Fe_2O_3 (5.92-7.44), CaO (25.42-31.32), SO_3 (1.33-2.70), CaO (24.53-31.32), MgO (5.39-7.97), Na_2O (0.70-2.23). Physical characteristics were: Fineness (+325 mesh) (13.30-19.90), moisture content (0.0-0.14), loss on ignition (0.20-0.42). All fly ash samples met the standard specifications of ASTM C 618 for Class C fly ash[3].

2.2. Slurry Preparation

The optimum fly ash slurry formulation developed by Shah and Cho was fly ash with water (30 % by weight of fly ash) and retarder (0.5 % by weight of fly ash). Thirty percent of water by weight of fly ash was determined by free water tests[4]. All fly ash samples with 30 % water were within the acceptance criterion for class G and H cement. The retarder is a chemical that extends the setting time of the cement slurry. A half percent of retarder by weight of fly ash gave adequate thickening time for fly ash slurries[2].

Eight hundred grams of fly ash sample was weighed by using the electronic scale having 0.01 gram accuracy. Water was measured by graduated glass cylinder (30% of the fly ash sample). Fly ash and retarder (0.5%) were added in water while agitating the mixture in mixer. The procedure followed was according to Section 5 of API Recommended Practice 10B[4].

2.3. Thickening Time Tests

The objective of these tests was to determine the duration a given cement slurry remains as a pumpable fluid under the given laboratory conditions, and thus, serve as a means of comparing it with the cementing materials. Following is a description of the tests.

The slurry was poured into the inverted slurry container. Entrapped air was then removed by tapping the outside of the container. The slurry container was placed on the drive table in the pressure vessel. The potentiometer then placed so as to engage the shaft bar rotation. This preparation was finished within the time limitation (5 min. ± 15 sec) specified in Sect. 9 of API Spec 10A[5].

The pumpability or consistency of the slurry is measured in Bearden units (B_c), a dimensionless quantity with no direct conversion factor to more common units of viscosity such as the poise. The end of a thickening time test is defined when the slurry reaches a consistency of 100 B_c; however, 70 B_c is generally considered to be the maximum pumpable consistency.

2.4. Rheology Tests

Rheology tests were performed by the Bohlin Controlled Stress rheometer[6] (Model CS-50) available at the Well Construction Technology Center, University of Oklahoma. The Bohlin rheometer is a controlled stress instrument in which a shear stress is applied and resultant shear rate is measured. The Bohlin rheometer is capable of utilizing different measuring geometries and measures viscosity as well as viscoelastic characteristics of the fluid. The Bohlin rheometer is equipped with three measuring geometries: concentric cylinder, parallel plate, and cone and plate. The concentric cylinder geometry was used in the tests. The concentric cylinder measuring system consists of a rotating bob (25 mm) located in a fixed cup (27.5 mm) with the sample contained in the annular gap. The concentric cylinder geometry is ideal for testing particulate materials like suspensions.

Rheological properties of the cement slurry can be influenced significantly by temperature. An average depth of wells drilled in Oklahoma from 1980 to 1991 was 5,501 ft [1]. The bottomhole circulating temperature (BHCT) is estimated as 120 °F based on this depth[2]. The effect of temperature was examined for fly ash slurries with different temperatures (80, 100, and 120 ^{o}F). These temperatures represent the ambient, median, and maximum bottom hole circulation temperature, respectively. The experiments were limited to an ambient pressure because rheological properties are not too sensitive to pressure.

2.5. Frictional Pressure Loss Tests in Field-scale Equipment

Pumping slurry into the well through coiled tubing requires knowledge of frictional loss characteristics of the slurry. Knowledge of frictional pressure at the target slurry pump rate allows us to relate the tubing head pressure to the bottomhole pressure. The objectives of these experiments were: (1) to confirm the pumpability of fly ash slurry through coiled tubing, and (2) to obtain the frictional pressure loss data for fly ash slurry.

The optimum fly ash slurry formulation was pumped through a 2,000 ft of 1 ½-in. coiled tubing and a 20 ft section of straight 1 ½-in. tubing and its frictional pressure characteristics were determined. Figure 1 shows the experimental apparatus used in this test. One of the field blenders consisting of two-50 bbl mixing tanks was used to prepare the fluid. The fluid from these tanks was delivered to the triplex plunger pump via a Galigher centrifugal pump. The triplex pump can deliver up to about 80 gpm through 2,000 ft and 20 ft of 1 ½-in. coiled and straight tubing. The flow rate was measured with a Micromotion flowmeter with a density and temperature readout. The differential pressures were measured with Honeywell pressure transducers. The data were gathered via a Hydra data acquisition system and sent to PC for storage by the Hydra software.

Before flowing slurries into a test loop, the system was flushed with water. The slurry was pumped (through 2000 ft coiled tubing and 20 ft straight tubing) at 60 gpm for about 5 min. in order to ensure the complete displacement of water from the test loop. Water was first tested at various flow rates to evaluate the test loop system. The slurry was then pumped at various flow rates allowing 3 – 4 minutes at each flow rates to obtain stable data. Flow rate was changed in a 10 gpm increment with the highest being 80 gpm. Before and after the flow test, slurry samples were collected from a sample port in the loop. The measured data were closely monitored and judged during the test. If any abnormal reading occurred, the relevant part of the system were checked and corrected, such as purging the pressure lines for DP transducers.

3. RESULTS AND DISCUSSION

3.1. Thickening Time of the Optimum Fly Ash Slurry

The thickening time results at 70 B_c consistency (except Red Rock) and test temperature of 80 ^{o}F are summarized in Table 1.

The thickening time recommendations depend on the type of job, the well conditions, and the volume of fly ash slurry being pumped. In the field, the thickening time to perform the job generally varies from about one hour up to 50 % in excess of the working time[7]. The thickening time acceptance criterion for Class H or Class A cement is 1.5 to 2.0 hrs in order to have adequate working time as specified in Table 11 of API Spec. 10A[5]. It can be seen from the data on thickening times in Table 1 that all five samples were over 3 hours. In other words, there will be enough pumping time before the fly ash slurry will set up.

3.2. Rheological Properties of Fly Ash Slurries

Test samples of the fly ash slurry were measured by the Bohlin Controlled Stress rheometer for the rheological properties at three different temperatures. Figure 2 shows rheology of fly ash slurries and class H cement slurry at three different temperatures. The all rheology of fly ash slurries were influenced by temperature. Comparing to the cement slurry, fly ash slurries showed higher shear stress values, except the Oologah slurry. The shear stress is the force required to sustain a particular rate of fluid flow. It means that fly ash slurries require higher force to sustain a given flow rate than the cement slurry. The viscosity is defined as the ratio of shear stress to shear rate[9]. The viscous slurry thus requires more pumping power. At the higher temperature, the viscosity of each slurry decreases. The Oologah slurry showes less effect of temperature than others. The pressure effect on rheologocal properties of cement slurry could be neglected because it is not predominant[8].

Characterization of the flow properties were determined by the relationship between the shear rate and shear stress required for fluid movement. Extensive studies have resulted in the development of several mathematical models, which describe the relationship between shear stress and shear rate. The three most commonly used models are the Newtonian, Bingham Plastic and Power Law models. The Power law model $[\tau_w = K_v(\dot{\gamma}_w)^n]$ was used here since it best described fly ash slurry behavior. Its fluid parameters, flow behavior index, n, and consistency index, K_v were determined.[4] These parameters are presented in Table 2. The Oklaunion was the most viscous slurry, the Muskogee was the second and the Oologah and Red Rock were less viscous slurries.

3.3. Analysis of Frictional Pressure Loss Data

The Muskogee fly ash sample was selected for the test because it showed the least thickening time (3 hours) and was the second viscous slurry. If this slurry is pumped without problems, the others can be pumped.

3.3.1. Rheological Properties of Fly Ash Slurry During Frictional Pressure Loss Test

Test samples were for the rheological measurements taken from the sampling point before, and after the frictional pressure loss test run. The first sample (before test) was collected after recirculating the fly ash slurry. The second sample (after test) was collected after gathering frictional pressure loss data at the highest flow rate (80 gpm).

The rheological properties of the test fluid were determined by Bohlin rheometer at ambient conditions. The rheometer data were used for quality control as well as providing the rheological parameters for friction loss calculations.

The measurements of the fly ash slurry using Bohlin rheometer are shown in Fig. 3. The recommended maximum shear stress is at a shear rate of about 511 sec^{-1}. Exposing cement slurry to shear rate above 511 sec^{-1} has been reported to generate inconsistent results[4]. In this study, shear rate range was from 78 to 366 sec^{-1}. The rheometer data were used to calculate the Power law parameters (flow behavior index, n, and consistency index, K_v). The K_v was converted to K_p for pipe flow calculation. The rheology values are: $n = 0.953$, $K_v = 1.99\times10^{-4}$ $lb_f\text{-}s^n/ft^2$, and $K_p = 2.01\times10^{-4}$ $lb_f\text{-}s^n/ft^2$. The n and K_p values were used in the flow data analysis.

The above rheology measurements of Muskogee slurry sample gathered during frictional pressure loss test, however, showed differences with the rheological properties from the rheology test of the fly ash in Table 2. This could be because of improper mixing in 50 bbl mixing tank. The density of a properly blended mix should be about 16 lb_m/gal but instead, it was only 14.26 lb_m/gal.

3.3.2. Flow Loop Data Analysis

The primary data gathered from a 2000 ft of 1 ½ in. coiled and 20 ft of 1 ½ in. straight tubing included: flow rate, Q and pressure drop, △p. Other collected data during the friction pressure loss test include density and fluid temperature.

<u>Analysis Method</u>

The slurry data were analyzed using the Power law model. The equations used are as follows:

The pipe wall shear rate is given by:

$$\dot{\gamma}_w = 39.206\frac{Q}{d^3} \qquad (1)$$

where, Q = flow rate, gal/min
d = internal pipe diameter, inch
$\dot{\gamma}_w$ = wall shear rate, sec^{-1}

The pipe wall shear stress is given by:

$$\tau_w = \frac{3d\,\Delta p}{L} \qquad (2)$$

where, τ_w = wall shear stress, lb_f/ft^2
△p = pressure drop, psi
L = length between pressure ports, ft

Generalized Reynolds number, N_{Reg}, a dimensionless variable, for non-Newtonian fluid in pipe can be described as:

$$N_{\mathrm{Re}\,g} = \frac{928\rho\overline{V}d}{\mu_a} \quad \text{.......... (3)}$$

where, ρ = fluid density, lb_m/gal
$\overline{V}$ = average fluid velocity, ft/s

Apparent fluid viscosity, cp and can be calculated from

$$\mu_a = 47880 K_p (\dot{\gamma}_w)^{n-1} \quad \text{.......... (4)}$$

The Fanning friction factor for pipe flow is defined by the following expression:

$$f = 25.8 \frac{d\Delta p}{L\rho\overline{V}^2} \quad \text{.......... (5)}$$

where, the units of d, ΔP, L, ρ, $\overline{V}$ are as shown earlier.

Flow Loop System Evaluation – Water

Numerous empirical and experimental correlations are used for prediction of friction losses of Newtonian fluid flows, water used in this study, through straight and coiled tubing.

The Drew correlation[9] was used to compare turbulent flow water data in smooth straight tubing.

$$f = 0.0014 + 0.125(N_{\mathrm{Re}})^{-0.32} \quad \text{.......... (6)}$$

The Srinivasan correlation[10] was used for the similar water data in coiled tubing.

$$f = \frac{0.084}{N_{\mathrm{Re}}^{0.2}} \left(\frac{r}{R} \right)^{0.1} \quad \text{.......... (7)}$$

The Reynolds number (N_{Re}) is given by

$$N_{\mathrm{Re}} = \frac{928\rho\overline{V}d}{\mu} \quad \text{.......... (8)}$$

where, μ = viscosity of water, cp

The pressure drop versus flow rate data of water were converted to Fanning friction factor and Reynolds number[11]. Figure 4 depicts a logarithmic plot of Fanning friction factor versus Reynolds number for water data in 1 ½ in. coiled and straight tubing. The straight tubing water data are compared with the Drew correlation, valid for the turbulent flow data of Newtonian fluids (such as water) in smooth pipes. It can be seen in Fig. 4 that the straight tubing experimental friction factors are significantly greater than the prediction from the Drew correlation. This is an indication of the presence of internal pipe wall roughness. The coiled tubing water data exhibit reasonably good agreement with the Srinivasan correlation for the turbulent flow of Newtonian fluids in smooth pipes.

Analysis of Fly Ash Slurry

The pressure drop and flow rate data of the Muskogee fly ash slurry in coiled tubing and straight tubing were converted in terms of wall shear rate and wall shear stress and are presented in Fig. 3. The relationship of shear rate and shear stress obtained from friction pressure loss data analyses of both coiled and straight tubing is quite different from that of Bohlin data analysis. It is because rheology measurements obtained from Bohlin rheometer are in laminar flow regime but the measurements from the flow loop system are in turbulent flow regime.

The experimental Fanning friction factor versus generalized Reynolds number data of the Muskogee fly ash slurry in 1 ½ in. coiled and straight tubing are shown in Fig. 5. The coiled tubing friction factors are in general 18 % greater than the straight tubing friction factors. It can be seen from this figure that both the straight as well as coiled tubing data sets are below the Drew and Srinivasan correlation, respectively. The fly ash slurry data from the straight tubing were corrected for the pipe roughness effects. The correction of approximately 13 % was necessary for the data in the generalized Reynolds number range shown in Fig. 5. The fly ash slurry exhibits some degree of drag (friction) reduction[12] in both the straight and coiled tubing. The drag reduction is approximately 6 %. Thus, the fly ash slurry is easier to pump than its base fluid, i.e. water. The Muskogee fly ash slurry exhibited drag reduction because it contained 0.5 % retarder which is a polymer base. Generally, the fly ash slurry itself will not have drag reduction characteristic.

3. CONCLUSIONS

Class C fly ash samples from five different power plants in Oklahoma were investigated for their thickening times, rheological characteristics, and frictional pressure losses.

- Thickening times of the all fly ash slurries showed more than adequate pumping time (over 3 hours) before the fly ash slurry will set up.

- The rheological behavior of fly ash slurries can be described by a pseudoplastic non-Newtonian Power law fluid model. Rheological properties of fly ash slurries were influenced by temperature. The shear stress values decreased as the temperature increased. As compared to the cement slurry, fly ash slurries showed much higher shear stress values.

- The fly ash slurry was successfully pumped through 2000 ft of 1 ½ in. coiled and 20 ft of 1 ½ in. straight tubing. It exhibited approximately 6 % drag reduction in both coiled tubing and straight tubing. A plot of Fanning friction factor versus generalized Reynolds number for the Muskogee fly ash slurry is presented for the prediction of frictional pressure losses in coiled and straight tubing.

NOMENCLATURE

B_c = Bearden units of slurry consistency, (API 10)

d = tubing internal diameter, (*in.*)

f = Fanning friction factor, (dimensionless)

K_v = rheometric consistency index, ($lb_f\ s^n/ft^2$)

K_p = consistency index for pipe flow, ($lb_f\ s^n/ft^2$)

L = tubing length, (*ft*)

n = fluid behavior index (dimensionless)

N_{Re} = Reynolds number, (*dimensionless*)

N_{Reg} = generalized Reynolds number, (*dimensionless*)

Q = slurry flow rate, (*gal/min*)

r = radius of tubing, (*in.*)

R = radius of coiled tubing drum, (*in.*)

$\overline{V}$ = average slurry velocity, (*ft/s*)

Greek Symbols

Δp = frictional pressure drop, (*psi*)

$\dot{\gamma}_w$ = wall shear rate, (s^{-1})

ρ = slurry density, (*lbm/gal*)

τ_w = wall shear stress, (lb_f/ft^2)

μ_a = apparent viscosity, (cp)

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Table 1 – Thickening times of five fly ash slurries (unit: hr:min).

Fly Ash Source	Oologah	Muskogee	Hugo	Oklaunion	Redrock
Fly Ash + 0.5 % Retarder	3:50	3:00	4:45	4:15	7:34 to 55 B_c

Table 2 – The Power law model $[\tau_w = K_v(\dot{\gamma}_w)^n]$ parameters at 80 °F of fly ash slurries calculated from Bohlin rheometer data.

Fly Ash Source	Oologah	Muskogee	Hugo	Oklaunion	Red Rock	Cement
n	0.812	0.778	0.859	0.703	0.886	0.983
$K_v \times 10^{-3}$, (lb_f-s^n/ft^2)	1.50	2.87	2.12	4.83	1.79	0.51
Viscosity at 170 sec^{-1} (cp)	189	430	209	1064	154	27

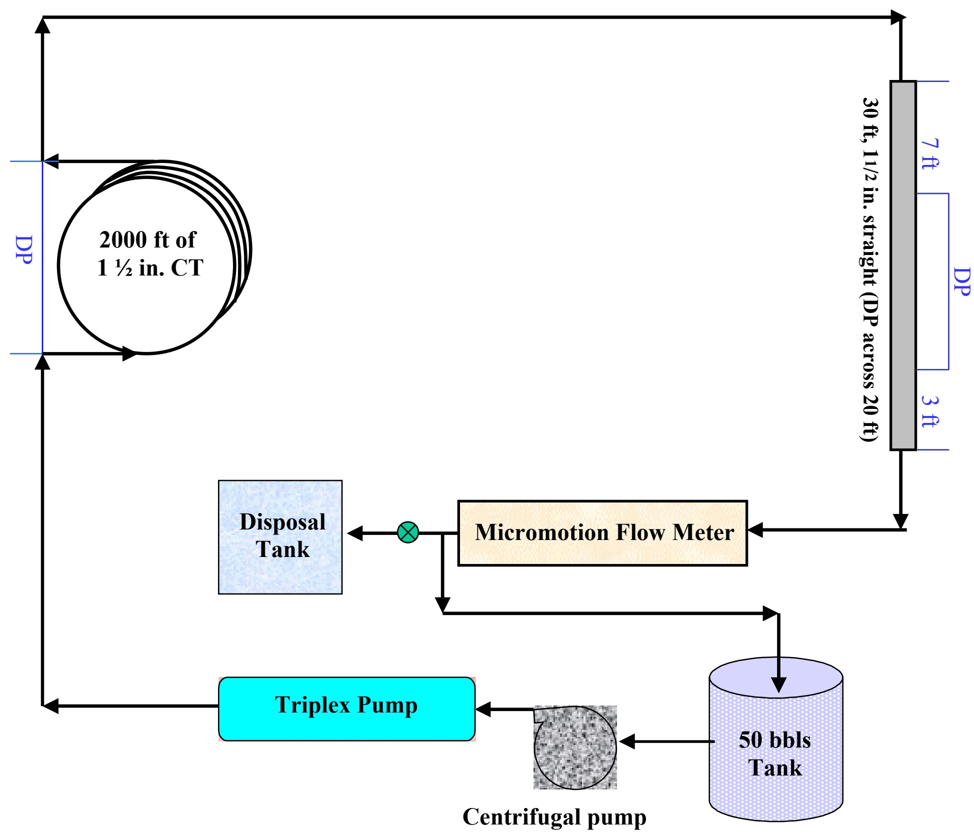

Fig. 1 – Schematic of experimental setup of flow loop at WCTC, Norman.

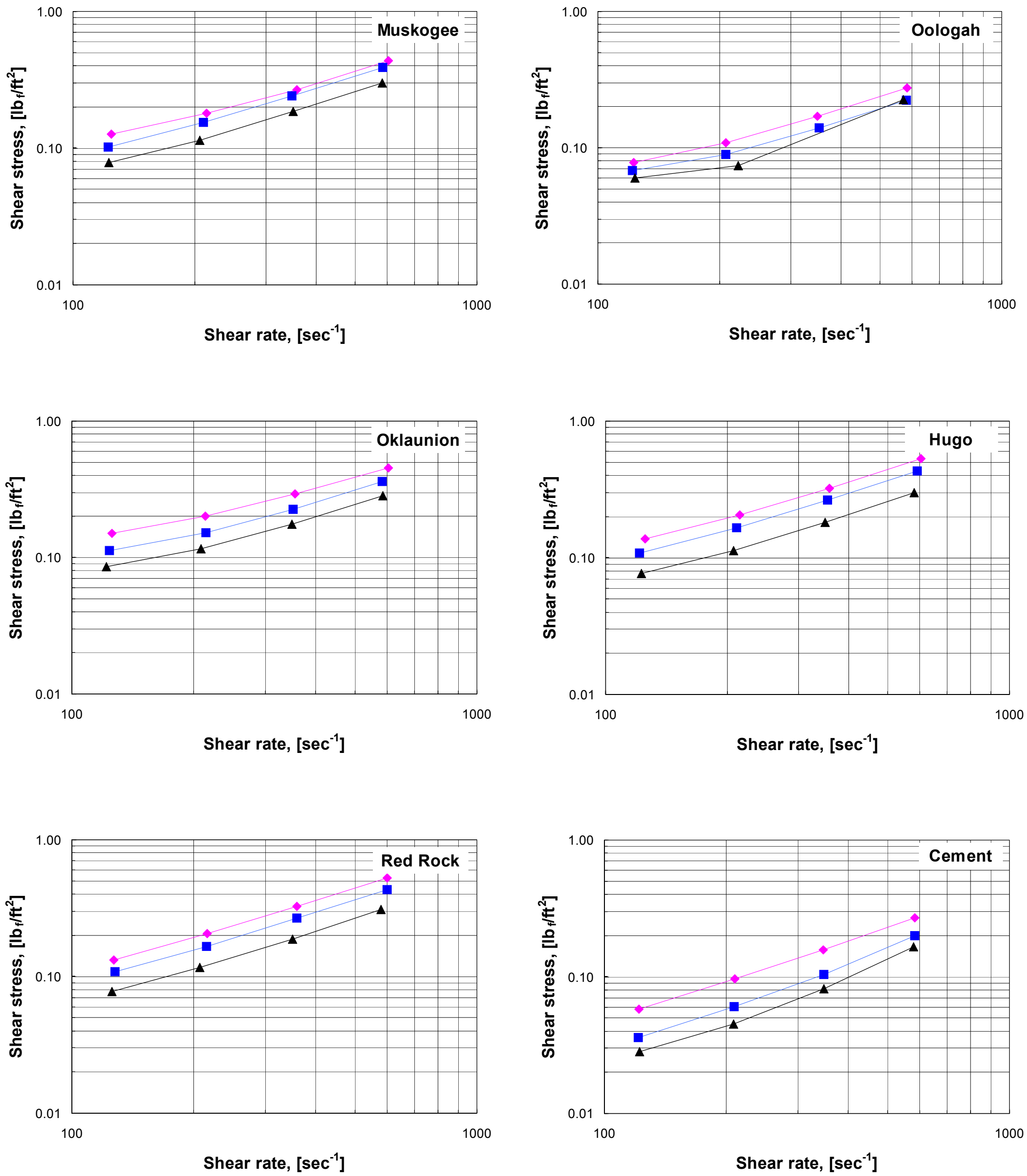

Fig. 2 – Rheology of fly ash slurries and class H cement slurry at three different temperatures (◊: 80 °F, □: 100 °F, △: 120 °F).

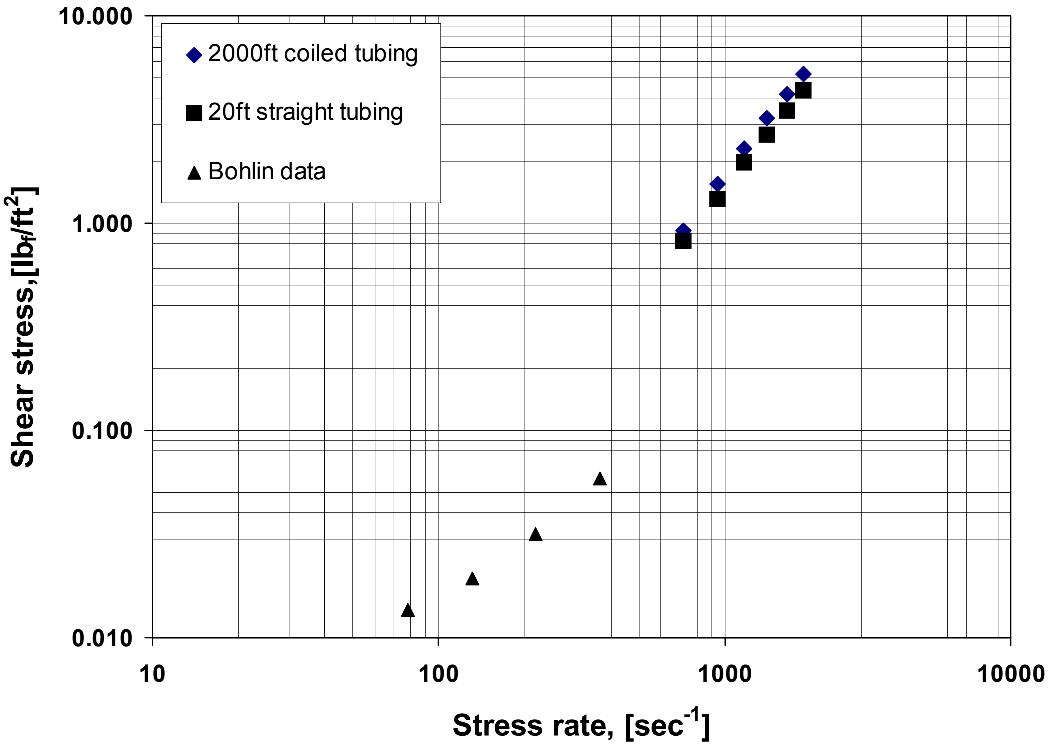

Fig. 3 – Rheogram of the Muskogee fly ash slurry measured by Bohlin rheometer and flow loop system.

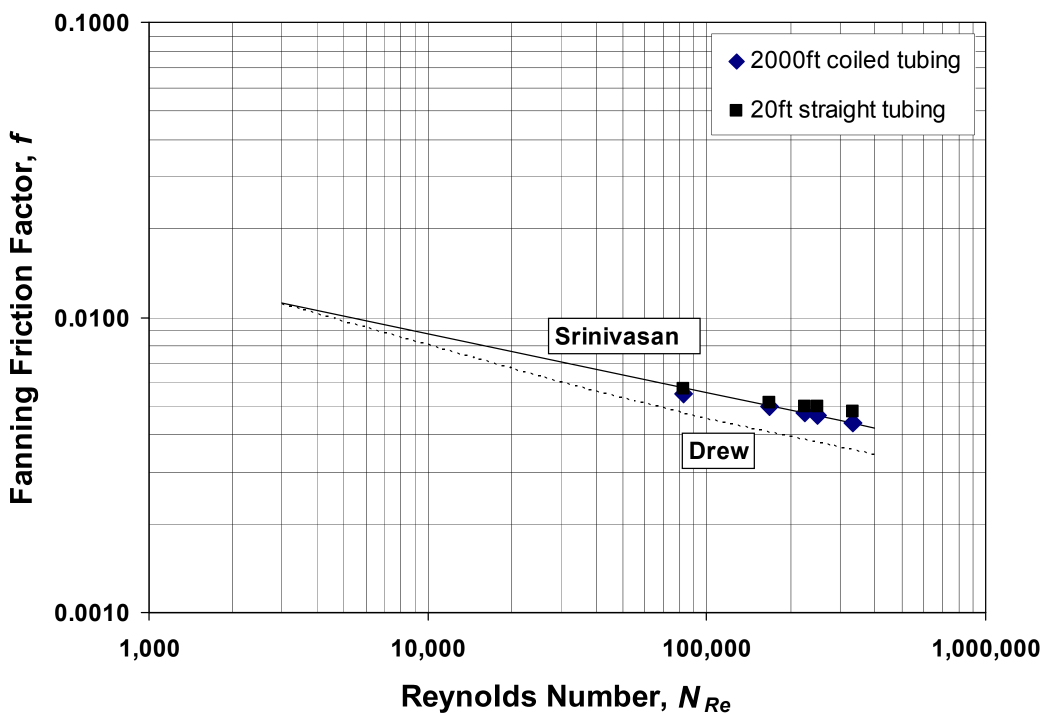

Fig. 4 – Evaluation of water data from coiled and straight 1 ½ in. tubing (pipe ID: 1.188 in., curvature ratio: 0.0165).

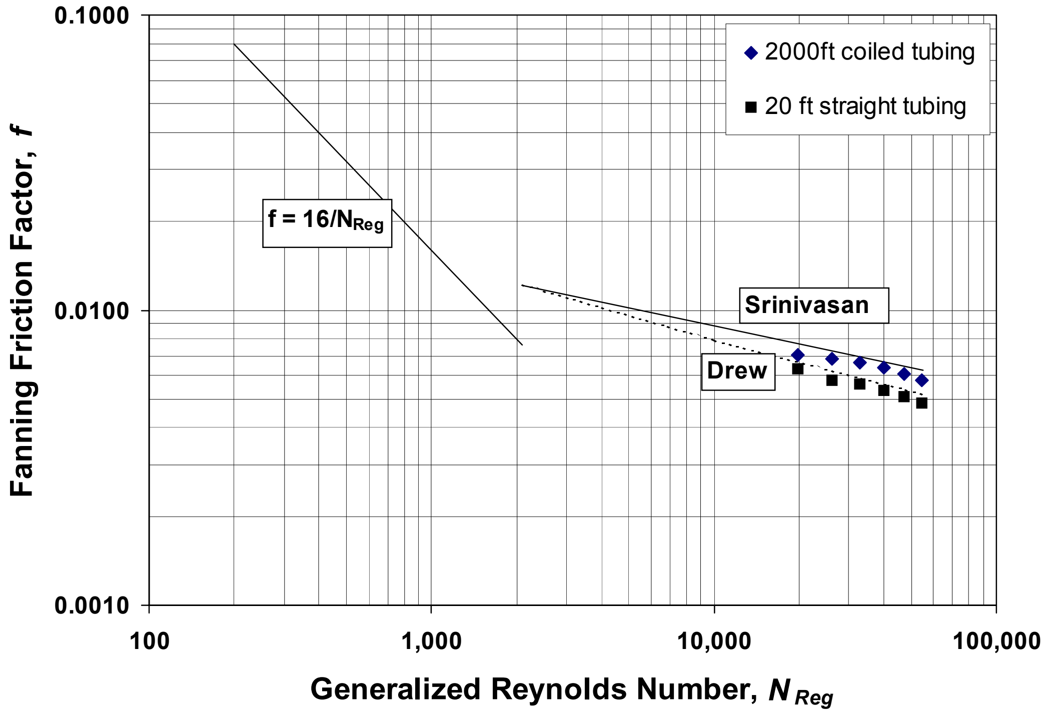

Fig. 5 – Fanning friction factor versus generalized Reynolds number of the Muskogee fly ash slurry.