# Development of an Environmentally Friendly and Economical Process for Plugging Abandoned Wells

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# ABSTRACT

Fly ash has long been known for its cementitious properties. Presently, however, cement grout is used for plugging the abandoned wells. It has been reported in our previous research that the use of Class C fly ash as plugging material for the abandoned wells is an economically viable option. In that work the optimum fly ash slurry formulation was developed, tested, and compared with Class H cement. The results were very encouraging and now it appears that the fly ash plug could be an economical substitute for cement.

The objective of this paper is to report the progress on continuation of the previous work using fly ash grout. In this study, results of the additional laboratory tests with fly ash slurry as plugging material are reported. The chemical and physical compositions, and the thickening times are first investigated in order to verify the representation and consistency of fly ash samples from different sources and to use them as slurry for plugging abandoned wells. Then, frictional pressure loss data are determined by pumping the fly ash slurry through 2000 ft of 1 ½-in. coiled tubing as well as 20 ft of the same size straight tubing. Bonding properties of fly ash plug are also investigated by a specially designed apparatus. The future plans for performing the field tests with the optimum fly ash formulation and placement technique are also addressed.

# INTRODUCTION

Many wells have been drilled for oil and gas as well as water, seismic, mine drainage and other applications. A 12 % of the total US oil and gas wells are drilled in the State of Oklahoma. Oil and gas wells plugged and abandoned in 2002 in Oklahoma was 1691 and total 102,331 from 1971 to 2002[1]. In 1999, the State of Oklahoma spent $341,426 to plug 95 abandoned wells. Not only the State of Oklahoma but also other States such as Kansas, Texas, and Pennsylvania are spending significant funds from their budgets on plugging abandoned wells.

Abandoned well plugging is a hot issue in the oil and gas industry because of contamination of freshwater aquifer. Groundwater gets contaminated by wellbore fluids such as drilling fluids and oil, contaminated surface water, and formation brine. Therefore, many States' law requires that abandoned wells be plugged. However, enforcement has been limited and in many areas it is nonexistent[2].

Cement grout is the material presently used in plugging. However, a few States are using materials such as cuttings, crushed bentonite, etc with cement for plugging abandoned wells[3]. Fly ash is known to have properties very similar to cement and can produce sufficient strength for well plugging. Especially, Class C fly ash is more cementitious than other fly ashes because of high lime content. As per the available estimate the production of coal fly ash in US was over 68 million tons in 2001. Presently, huge amount of fly ash is disposed of in landfills as a waste material. Its use provides many environmental and financial benefits. Utilization of fly ash helps reduce greenhouse gas emissions, creates revenue for utilities, and reduces the need for land for disposal and, in turn, corresponding disposal costs. Further, these factors reduce the cost of electricity to the public, commerce and industry, which leads to greater economic growth. Finally, utilization of fly ash reduces the volume of solid waste disposed and the volume of natural materials needs to be mined or otherwise obtained for construction purposes. In this regard, utilization of coal by-products has a strong environmental benefit.

The feasibility of using fly ash has been investigated but by a limited studies. Most of these were using fly ash with cement. Since early 1980s, several studies have dealt with the mineralogy and other properties of fly ash[4,5,6]. Kenneth and Arman[7] studied the Class C fly ash as full or partial replacement for Portland cement or lime as stabilizer for road construction. They concluded that fly ash could be substituted for cement with some sand. In the study of Mirza et al.[8], the basic rheological and mechanical properties of high-volume fly ash grouts were studied but it was also for partial replacement of cement for grouting.

Recently, Shah and Cho[9] developed the optimum fly ash slurry containing 30 % water and 0.5 % retarder by weight of fly ash. Their investigation was phase I of this present study and funded by IPEC. To ensure a comprehensive understanding of fly ash grout characteristics as a plugging material, extensive experiments were performed. They measured compressive strengths of the fly ash plugs and reported that they were over 500 psi (generally accepted as a minimum strength for abandonment plug by oil and gas industry). The chemical composition and particle size distribution of five fly ash sources in Oklahoma were analyzed. Thickening time, durability and rheology of fly ash slurry were also investigated. From these tests, it was concluded that the Class C fly ash could be retarded like cement when the proper concentration of the additive was mixed, and it could be pumped and placed like cement using coiled tubing instead of employing a rig.

This paper is a continuation of the earlier project titled "New Process for Plugging Abandoned Wells, phase I". Five fly ash samples are collected from the same sources as before. Then chemical / physical analysis and thickening time tests are performed to verify the quality of fly ash samples. Shear bond strength between pipe and fly ash plug is measured. Frictional pressure losses are determined through 2000 ft of 1 ½ in. coiled tubing and 20 ft straight tubing. The pumping of the new formulation through coiled tubing, which is a newly emerged technique in the oil and gas industry, can replace the conventional rig, which is very expensive.

# VERIFICATION OF FLY ASH

Fly ash is a very fine powder material that is carried with the stack gases and is collected by electrostatic precipitators or a baghouse prior to exiting the stack. It is not the main product but the by-product. The composition of fly ash can be widely distributed depending on the type of coal burned and the type of burner used. In this study, fly ash is obtained from five coal-fired power plants in Oklahoma. These power plants commonly use the Wyoming coal as a fuel. Fly ash produced is generally very homogeneous. However, contamination may occur from using other fuels to start the plant, and inconsistencies in carbon content can occur until the plant reaches its full operating efficiency. The ash produced from the start-up and shut-down must be separated from what is produced from the plant when it is operating efficiently. In order to verify the representation and consistency of samples from different fly ash sources and to use them as slurry for plugging abandoned wells, the chemical and physical compositions, and the thickening times of slurry must be investigated.

Tables 1 and 2 show the results of chemical and physical analysis of fly ash samples, respectively. From these data, it can be concluded that all fly ash samples meet ASTM C 618[10] specifications for Class C fly ash. The most important chemical component of Class C fly ash is the lime content which is a cementitious material. The average value of lime content in Table 1 is approximately 27 %. The magnesium oxide (MgO) provides good swelling characteristics in cement. Rubiandini[11] concluded that MgO helped increase the shear bond strength of cement. The average value of MgO in fly ash samples (Table 1) is 6.2 %, which is higher than in Class H cement (1.14 %). The carbon content, which is indicated by the loss on ignition, will affect water demand since the carbon absorbs water. All fly ash samples show very low values (< 0.42 %). Thus, it cannot adversely affect the water content of fly ash. The fineness (+325 mesh) of all five fly ash samples is lower than 19.9 %. ASTM C-618 Class C fly ash requirement is 34 % maximum. It shows that fly ash is very uniform in size and will make a good homogeneous mix.

Determining the time the slurry remains in a pumpable fluid state is very important in cement job design. The thickening time, therefore, is investigated for evaluating the pumpability or consistency of the slurry, which 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 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 cement job generally varies from about one hour up to 50 % in excess of the working time[12]. 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. Tests were performed according to Section 9 of API Spec 10A[13]. The elapsed time between the initial application of temperature to the atmospheric consistometer and the time at which a consistency of 70 $B_c$ is reached was recorded as the thickening time for the test[14]. The phase I of the project[9] concluded that working time of 1.5 to 2 hours is adequate. It can be seen from the thickening time data in Table 3 that all

five samples were over the criteria. In other words, there is enough pumping time before the fly ash slurry will set up.

The chemical / physical properties and thickening time of fly ash samples varied with the fly ash source. However, the general properties were consistent for all.

# FLOW CHARACTERISTICS

Pumping slurry into the well through coiled tubing requires knowledge of frictional loss characteristics of the slurry. The knowledge of frictional pressure loss at the target slurry pump rate allows us to relate the tubing head pressure to the bottomhole pressure. The objectives, therefore, 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 of fly ash slurry.

The Muskogee fly ash slurry which showed the least thickening time (3 hours) was selected and pumped through a 2,000 ft of 1 ½-in. coiled tubing and a 20 ft straight 1 ½-in. tubing and its frictional pressure characteristics were determined. Figure 1 shows the schematic of the experimental set up used for 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 via the Hydra software.

Before flowing slurry 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 rate to obtain steady state. 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 parts of the system were checked and corrected, such as purging the pressure lines for DP transducers.

## Rheological Properties of Fly Ash Slurry During Frictional Pressure Loss Test

Test samples for the rheological measurements were taken from the sampling point, before and after the frictional pressure loss test. The initial sample (before test) was collected after recirculating the fly ash slurry. The final 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 the Bohlin Controlled Stress rheometer (Model CS-50) at ambient condition. The rheometer data were used for quality control as well as providing the rheological parameters for friction loss calculations. The rheometer data of the fly ash slurry are plotted in Fig. 2. 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[12]. In this study, the shear rate range was from 78 to 366 $sec^{-1}$. The rheometer data were used to

calculate the Power law $[\tau_w = K_v(\dot{\gamma}_w)^n]$ parameters (flow behavior index, $n$, and consistency index, $K_v$) of both samples. The $K_v$ was converted to $K_p$ for pipe flow calculation. The rheology values are: $n$ = 0.953, $K_v = 1.99\times10^{-4}$ $lb_f$-$s^n/ft^2$, and $K_p = 2.01\times10^{-4}$ $lb_f$-$s^n/ft^2$. The $n$ and $K_p$ values were used in the flow loop data analysis.

## 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.

The slurry data were analyzed using the Power law model. The equations used are as follows:
The pipe wall shear rate is given by:

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

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:

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

where, $\tau_w$ = 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:

$$N_{Reg} = \frac{928\rho\bar{V}d}{\mu_a} \quad \text{..... (3)}$$

where, $\rho$ = fluid density, $lb_m$/gal
$\bar{V}$ = 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:

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

where, the units of $d$, $\Delta P$, $L$, $\rho$, $\bar{V}$ are as shown earlier.

Before testing fly ash slurry, water was tested through flow loop system to evaluate the quality of data collected. 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[15] was used to compare turbulent flow water data in smooth straight tubing.

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

The Srinivasan correlation[16] was used for the similar water data in coiled tubing.

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

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

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

where, $\mu$ = viscosity of water, cp

Above correlations very well represent the Newtonian fluid flow through coiled and straight tubing. The pressure drop versus flow rate data of water was converted to Fanning friction factor and Reynolds number[17]. Comparing the experimental values with the values from above correlations showed a validity of the test results. Figure 3 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 Figure 3 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.

Once the flow loop system was evaluated with water test, the Muskogee fly ash slurry was pumped through the system to gather the data of the 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. 2. 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. 4. 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. 4. The fly ash

slurry exhibits some degree of drag (friction) reduction[18] 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 that is a polymer base. Generally, the fly ash slurry itself would not have drag reduction characteristic.

# BONDING OF THE PLUG

Five fly ash samples showed over 500 psi of compressive strength that is generally accepted as a minimum strength for both production and abandonment plug by the oil and gas industry[9]. Sealing recommendations are often made on the basis of compressive or tensile strength of set material on the assumption that a material satisfying strength requirements will also provide an adequate bond. However, this assumption cannot be always valid[3]. For field application, bonding properties of oil well cementing can be investigated as shear and hydraulic bond. Shear and hydraulic bond strengths are two extremely important parameters in well plugging and abandonment. Improper strength for the plugging situation can cause failure of the plug and, therefore, invasion of undesired fluid into the wellbore or the surface. The shear bond strength of the set slurry is a measure of the force required to initiate movement of the plug in the hole. The hydraulic bond strength is a measure of the hydraulic pressure required to initiate leakage of fluid between the plug and the wall of the wellbore. Initially, these bond strengths will be determined or tested with a "clean" wellbore wall (a wall devoid of any mud cake buildup).

An apparatus is constructed to hydraulically push the plug out of a piece of pipe. The core holder (see Fig. 5) is used to set a plug in. The internal surface condition of the pipe prior to running tests affects the bond of fly ash plug to pipe. A loss in bond strength is readily noticeable when a thin sheath of mud is present at the pipe and cement interface[19]. However, this mud cake can be removed effectively by the various removal techniques available. This test, however, used a rusty steel pipe without any contamination on the wall of the pipe. Results of this test will indicate bond strength between fly ash plug and rusty pipe. The shear bond strength is unaffected by the pipe diameter but is dependent upon the length to diameter ratio because of the stress distribution along the interface. It has also been shown[20] that the influence of length is negligible provided the length to diameter ratio is below 1.5. To remain within this specification, the dimension of core holder is 2 3/8 in. of diameter and 3.23 in. of length. The bond length for the test is 2.84 in. One side of the core holder is covered by a plastic lid (I.D.: 1.94 in., height: 0.394 in.), which will give a space to move the plug in pipe. Also a couple of core holders of dimensions 2 3/8 in. diameter and 5.89 in. length are designed to ascertain the length effect of bond strength.

Eight hundred grams of fly ash sample is weighed by using the electronic scale having 0.01 gram accuracy. Water is measured by graduated glass cylinder (30% of the fly ash sample). Fly ash and retarder (0.5%) are added in water while agitating the mixture in mixer. The procedure followed is according to Section 5 of API Recommended Practice 10B[21]. Each of fly ash slurries is poured in the core holder and cured in water bath maintained at 80 $^{o}$F for a week (see Fig. 6). There are the temperatures and time effects on shear bond strength development. However, tests were performed at ambient temperature (80 °F) with one week of curing because the compressive strength of fly ash sample was over 500 psi after one week of curing time, regardless of water bath temperature[9]. Then one side of fly ash plug in core holder is loaded by a steel cylinder, which is capable of significant force application. This steel cylinder is placed between fly ash plug and loading plate. Hydraulic force is loaded from the loading plate to the steel cylinder by hydraulic testing machine (Carver Lab Press), whose hydraulic capacity is 0 –

20,000 $lb_f$ (see Fig. 7). The axial load is transferred from the steel cylinder to the fly ash plug in form of shear stresses along the interface. Loads are incremented stepwise at intervals of 10 second until failure occurs. A dial gauge that measures the vertical force on the plug is connected to the loading rod. The force required divided by the contact area of the plug with the pipe determines the strength on a force per unit area basis.

Each fly ash was tested with three replicates. The test results showed good repeatability within 15 %. As it can be seen from Table 4, the Hugo fly ash showed the highest shear bond strength of 1132 psi, the Muskogee fly ash was second at 1070 psi, and the Oologah fly ash showed the lowest strength of 97 psi. Evans and Carter[19] tested the bond strength of Class A cement to rusty steel pipe. They reported 141 psi for one day curing at 80 °F, and 422 psi for 2 days of curing at the same temperature. Parcevaux et al.[20] tested the bond strength of Class G cement which was 1150 psi for one week curing at 68 °F. These are not the same conditions as our shear bond strength test of fly ash but comparing the results of cement with the results of fly ash indicate that the shear bond strength of fly ash is reasonable as shown in Table 4. When fly ash is added to cement, it develops the strength slowly but the long-term strength is remarkably enhanced[22]. Elapsing curing time will develop higher shear bond strength.

To investigate the effect of length of core holder on bond strength, the Muskogee fly ash sample was tested in both short core holder (3.23 in.) and long core holder (5.89 in.) at the same condition. Results of the test from short and long core holder were very close at 1070 psi and 1103 psi, respectively. Thus, it confirms that the length effect can be neglected for bond strength test.

In case of cement, the relationship between compressive strength and shear bond strength was determined based on experimental data[19]. This information gives a guideline in determining the approximately supporting ability of cement if the compressive strength is known. The shear bond of cement to pipe is even influenced by brands of cement in a same API class. For example, the compressive strength of API Class A cement varies as much as 1,500 psi between different brands of cement. Unfortunately, in this study, the relationship between compressive strength and shear bond strength of fly ash samples could not be determined because of limited data. However, it can be generally concluded that fly ash which has low compressive strength will generate lower bond strength than fly ash which has high compressive strength (see Table 5).

To investigate the relationship between chemical/physical properties results and shear bond strength of fly ash samples, correlation coefficients were calculated by a statistical tool (SPSS version 10). Any of the chemical component and physical property was not correlated significantly with the bond strength of fly ash samples except silicon dioxide ($SiO_2$). Figure 8 shows the relationship between shear bond strength and silicon dioxide with 0.83 of correlation coefficient. The reason for poor correlation may be because of small number of fly ash samples used in the study. Microsilica is often used to achieve high compressive and tensile strength, durability, low permeability and improved properties of fresh concrete. Silicon dioxide can affect the bond strength of fly ash samples because fly ash is very fine.

# CONCLUSIONS

1. Fly ash samples from five coal-fired power plants in Oklahoma were verified for sample consistency. The chemical/physical properties and thickening times of these samples varied somewhat with the fly ash source, in general, the properties of all fly ash samples were consistent.

2. A 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 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.

3. The shear bond strength of fly ash plug to pipe was determined by the bond strength tester. The shear bond strengths were in reasonable agreement with the similar values reported for cement plug.

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# FUTURE WORK

Hydraulic bond strength that is significant for zonal isolation will be tested in the future study. Slurry placement techniques and mud removal techniques will be also evaluated. Then, the field tests will be performed based on these developed techniques.

# 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

$\Delta p$ = frictional pressure drop, (*psi*)

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

$\rho$ = slurry density, ($lb_m/gal$)

$\tau_w$ = wall shear stress, ($lb_f/ft^2$)

$\mu_a$ = apparent viscosity, (cp)

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**Table 1.** Chemical analysis results of each fly ash sample in percentage.

| Items | ASTM C-618 Class C Requirements | Oologah | Muskogee | Hugo | Oklaunion | Red rock |
|---|---|---|---|---|---|---|
| Silicon dioxide ($SiO_2$) | - | 30.76 | 35.63 | 34.16 | 31.33 | 33.89 |
| Aluminum oxide ($Al_2O_3$) | - | 23.56 | 21.97 | 17.01 | 15.28 | 22.31 |
| Iron oxide ($Fe_2O_3$) | - | 7.44 | 5.97 | 6.23 | 5.92 | 5.97 |
| Sum of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ | 50.0 min | 61.76 | 63.57 | 57.50 | 52.53 | 62.16 |
| Sulfur trioxide ($SO_3$) | 5.0 max | 1.81 | 1.33 | 2.70 | 2.51 | 1.51 |
| Calcium oxide (CaO) | - | 25.63 | 24.53 | 26.5 | 31.32 | 25.42 |
| Magnesium oxide* (MgO) | - | 5.39 | 5.60 | 6.05 | 7.97 | 5.93 |
| Available alkalies as $Na_2O$* | 1.5 max | 1.47 | 1.45 | 2.23 | 0.70 | 1.46 |

Note: * optional items, min: minimum, max: maximum.

**Table 2.** Physical analysis results of each fly ash sample in percentage.

| Items | ASTM C-618 Class C Requirements | Oologah | Muskogee | Hugo | Oklaunion | Redrock |
|---|---|---|---|---|---|---|
| Fineness (+325 mesh) | 34.0 max | 13.30 | 13.55 | 19.90 | 13.40 | 14.10 |
| Fineness variable | 5.0 max | 0.10 | 0.18 | 0.73 | - | 0.70 |
| Moisture content | 3.0 max | 0.09 | 0.08 | 0.10 | 0.00 | 0.14 |
| Specific gravity | - | 2.71 | 2.67 | 2.68 | 2.78 | 2.65 |
| Specific gravity variable | 5.0 max | 0.59 | 0.23 | 0.96 | - | 0.26 |
| Loss on ignition | 6.0 max | 0.20 | 0.20 | 0.40 | 0.42 | 0.23 |
| Autoclave expansion (*1) | 0.8 max | 0.01 | 0.03 | 0.10 | 0.13 | 0.03 |
| Water require % control | 105.0 max | 93.40 | 93.40 | 95.00 | 92.60 | 94.63 |
| SAI 28 days (*2) | 75.0 min | 92.35 | 98.88 | 90.00 | 111.10 | 96.83 |

Note) *1: Autoclave expansion or contraction (soundness).
*2: Strength Activity Index with fly ash at 28 days % of control in accordance with ASTM C-618.

**Table 3.** 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 4.** The bond strengths of each fly ash samples.

| Items | Oologah | Muskogee | Hugo | Oklaunion | Red Rock |
|---|---|---|---|---|---|
| Bond Strength, psi | 97 | 1070 | 1132 | 763 | 866 |
| Compressive Strength, psi | 536 | 711 | * | * | 1544 |

Note: * not measured.

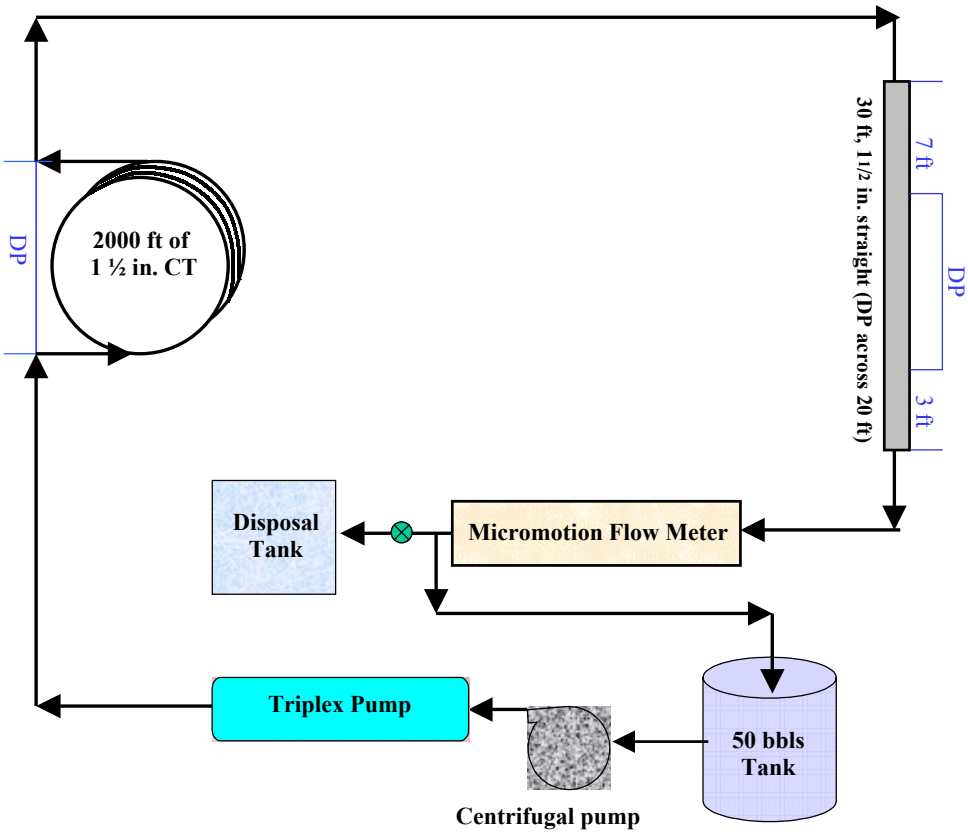


**Fig. 1.** Schematic of experimental setup of flow loop at WCTC, Norman.

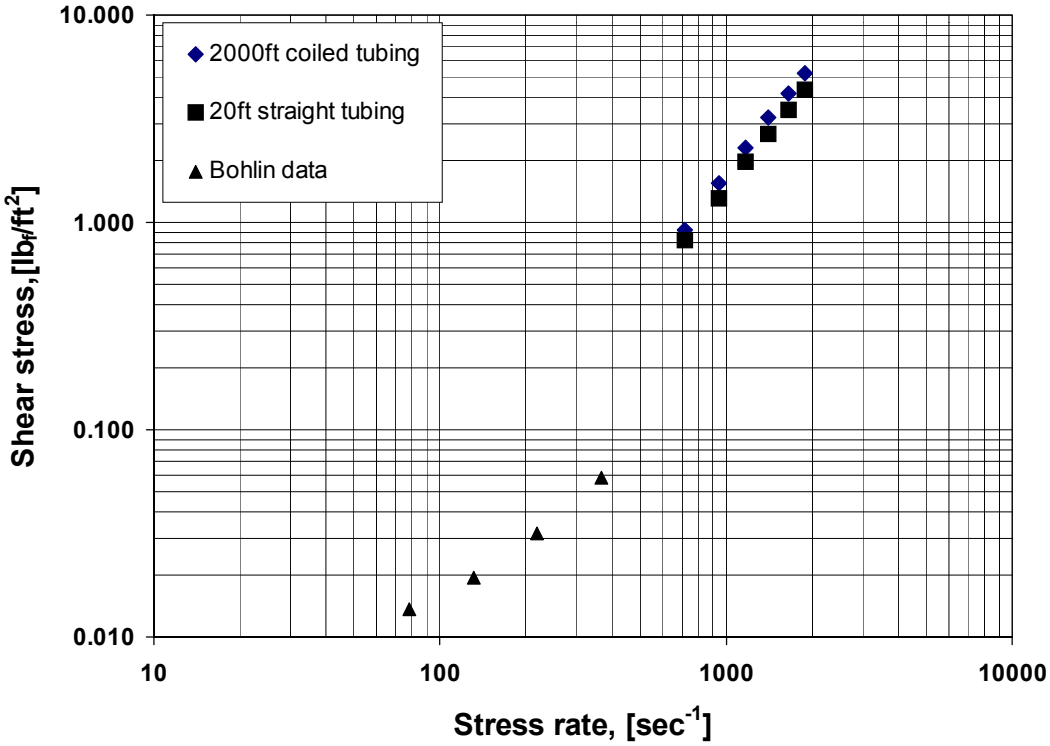


**Fig. 2.** Rheogram of the Muskogee fly ash slurry measured by Bohlin rheometer and flow loop system.

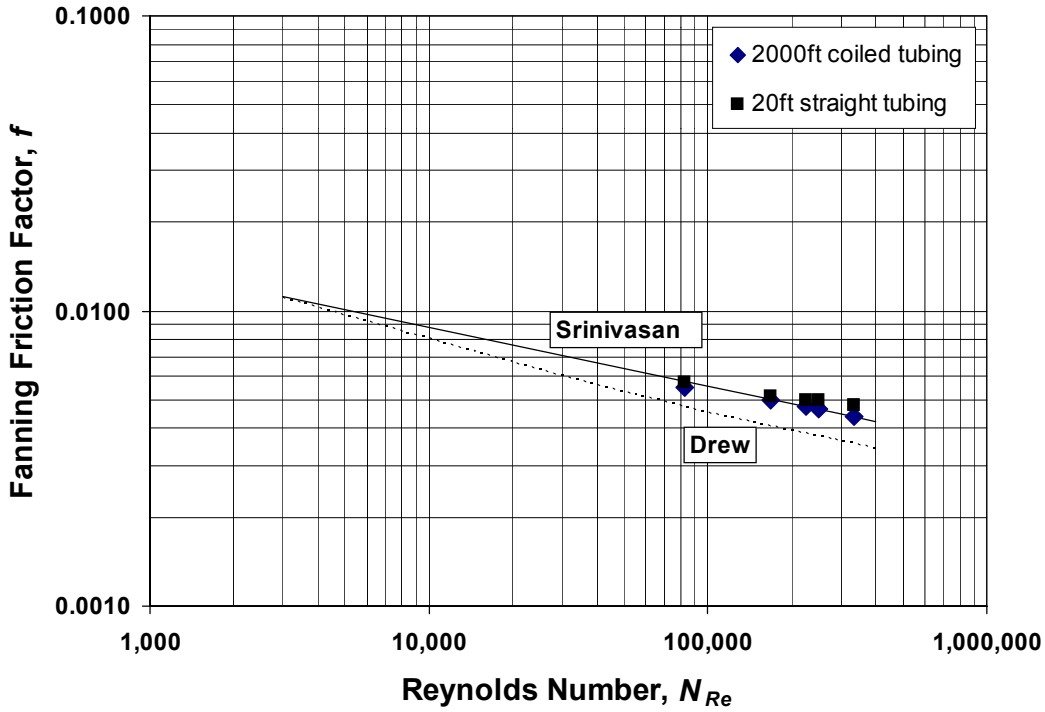


**Fig. 3.** Evaluation of water data from coiled and straight 1 ½ in. tubing (pipe ID: 1.188 in., curvature ratio: 0.0165).

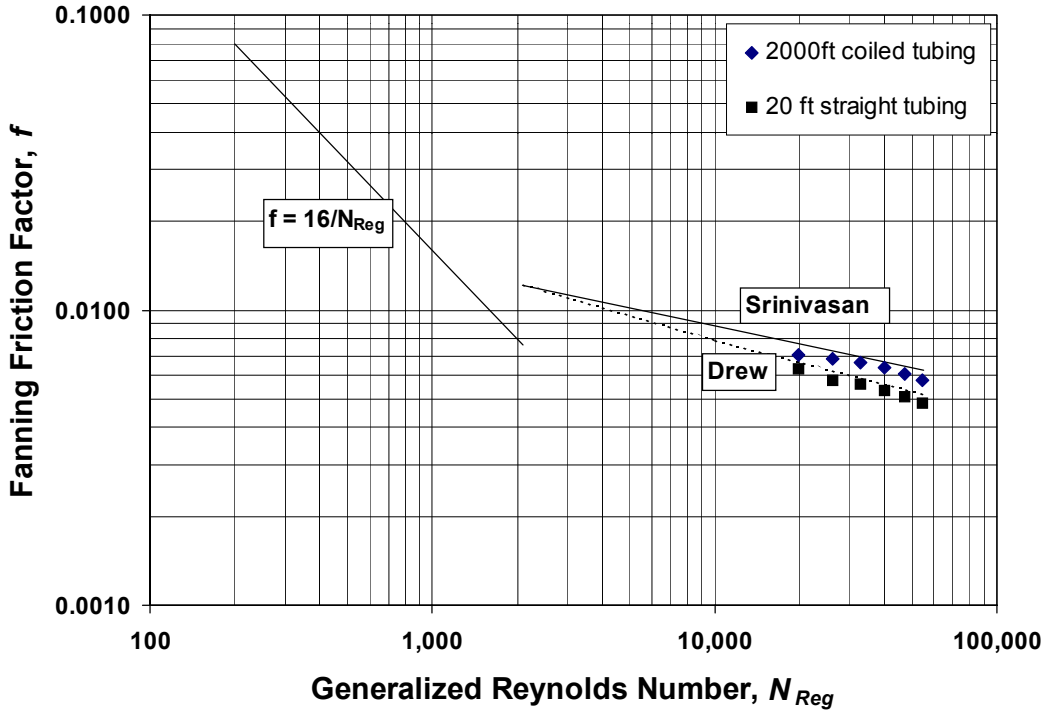


**Fig. 4.** Fanning friction factor versus generalized Reynolds number of the Muskogee fly ash slurry.

**Fig. 5.** Core holder for testing the bond strength of fly ash samples (diameter: 2 3/8 in., length: 3.23 in. and 5.89 in.).

**Fig. 6.** Fly ash plugs in core holder after one week of curing in water bath for testing the shear bond strength.

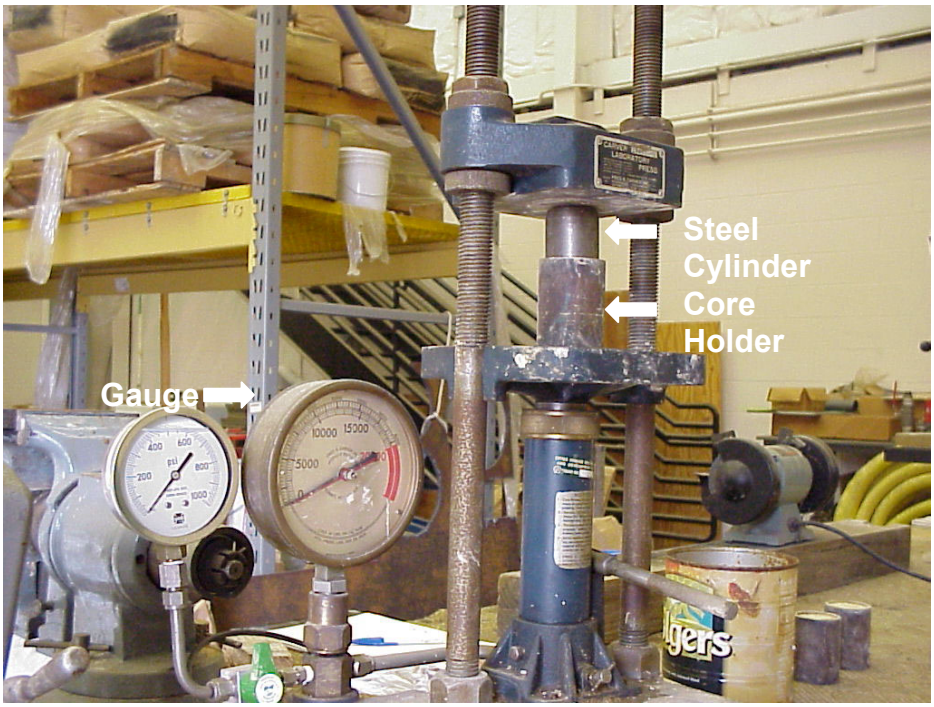


**Fig. 7.** Shear bond strength tester designed by Well Construction Technology Center, Norman.

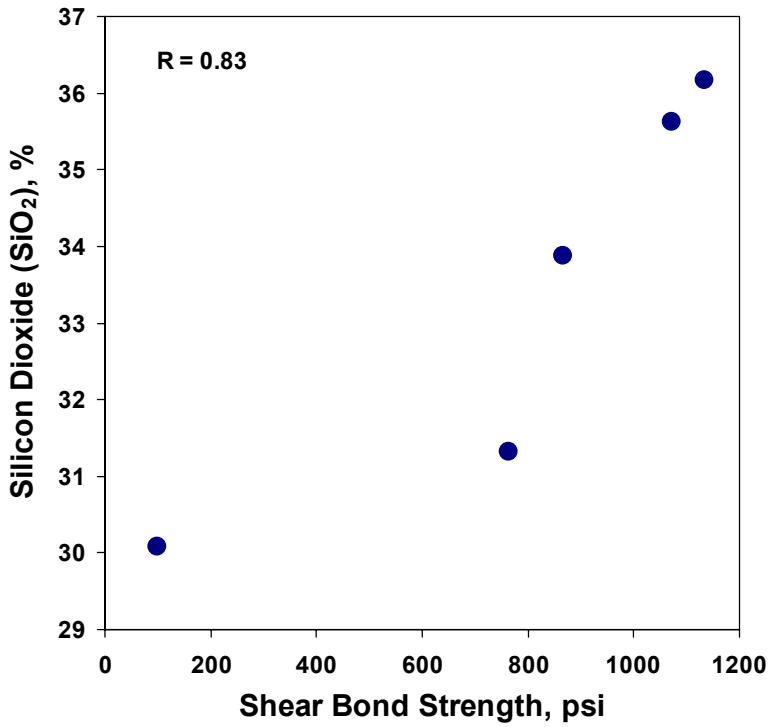


**Fig. 8.** Scatter diagram between abundances of silicon dioxide and shear bond strength of fly ash.