Development of an Environmental Friendly and Economical Process for Plugging Abandoned Wells

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This project is the continuation of the project titled "New Process for Plugging Abandoned Wells (EPA-R 82-7015-01-0)". The first three month objectives of this project are: (1) to collect samples of fly ash from five different power plants, (2) to determine chemical components and thickening times of fly ash samples, and (3) to measure rheological properties of fly ash slurry and friction pressure loss through straight and coiled tubing.

Sample Collection of Fly Ash

Fly ash samples used in phase II are from the same sources as in phase I. Class C fly ash samples were selected from the five coal fired power plants located in Oklahoma. The location of the power plants is shown in Fig. 1. They are Hugo (Hugo City), Muskogee (Muskogee City), Oologah (North of Tulsa), Red Rock (Ponca City), and Oklaunion (Oklaunion, west of Wichita Falls). These five plants are major power plants and use the same Wyoming coal as a fuel. They produce over 90 % of fly ash in Oklahoma. In order to maintain the test consistency and to conduct various tests with the same samples, enough volume of each sample was collected.

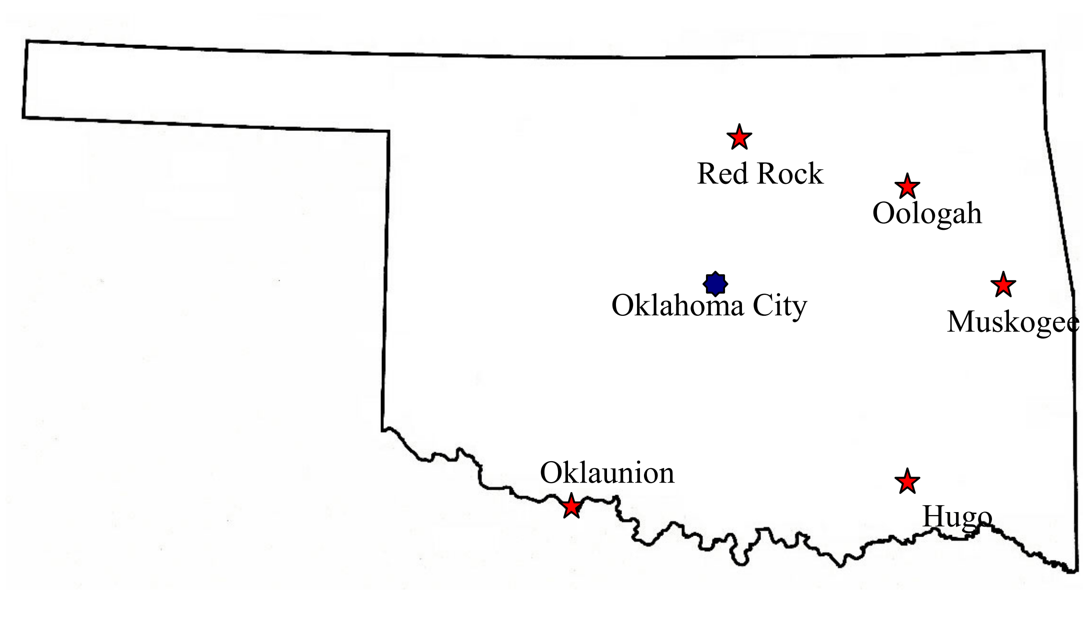

Fig. 1 – The location of fly ash collection

Physical and Chemical Analysis

The Wyoming coal is a bituminous or sub-bituminous which has high thermal energy. Class C fly ash is normally produced from lignite or sub-bituminous coal. Both physical and chemical analyses were performed and then the data obtained from analyses were compared to the standard specifications in ASTM C 618 "Fly Ash and Raw or Calcined Natural Pozzalan for Use as a Mineral Admixture in Portland Cement Concrete"[1]. Tables 1 and 2 show the averaged chemical and physical analysis, respectively. From these data, it can be concluded that all fly ash samples meet ASTM C 618 specifications for Class C fly ash.

Table 1. – Chemical analysis results of each fly ash source 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	61.26	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: * are optional items, min: minimum, max: maximum

Table 2. – Physical analysis results of each fly ash 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.

Thickening Time Tests

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. Tests were performed according to Section 9 of API Spec 10A[2].

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[3].

Table 3. – Thickening times of five fly ash samples (unit: hrs: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

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[4]. The study in phase I of the project decided that adequate working time is 1.5 to 2 hours. It can be seen from the data on thickening times in Table 3 that all five samples were over the criteria[5]. In other words, there will be enough pumping time before the fly ash slurry will set up.

Rheology Tests

Test samples of the fly ash slurry were measured for their rheological properties. A model 35 Fann viscometer available at WCTC was used. Eighty grams of fly ash sample was weighed by using an electronic scale having 0.01 gram accuracy. Water was measured by graduated glass cylinder (30 % by the weight of fly ash sample). Fly ash and retarder (0.5 % by the weight of fly ash) were added in water while agitating the mixture in mixer.

These measurements were obtained under ambient condition. The Fann 35 data for different fly ashes are shown in Table 4. The Power law model [$\tau = k_v(\dot{\gamma})^n$] was used and its fluid parameters, flow behavior index, *n*, and consistency index, K_v were determined.[2] These parameters are also presented in Table 4.

The fly ash slurry is a non-Newtonian fluid. The viscosity of non-Newtonian fluid is changing with shear rate. Therefore, apparent viscosities of fly ash at 300 rpm were calculated for each sample and then compared. The Oologah sample was least viscous the Hugo sample was found to be the most viscous. Furthermore, observing the Power law parameter, n, it is obvious that all slurries deviate slightly from the Newtonian behavior.

Table. 4. – Fann 35 data for the fly ashes studied (#1 spring)

RPM	Dial Reading				
	Oologah	Muskogee	Hugo	Oklaunion	Red Rock
600	59	78	112	69	96
300	28	39	55	35	48
200	18	25	37	24	32
100	9	13	19	13	16
6	1	2	2	2	2
3	1	1	1	1	1
Calculated Fluid Properties for Power law model					
n	1.048	1.021	0.993	0.930	0.994
k_v, $lb_f sec^n/ft^2$	0.00043	0.00071	0.00114	0.00122	0.00104
k_p, $lb_f sec^n/ft^2$	0.00043	0.00070	0.00116	0.00122	0.00104
Apparent viscosity at 511 sec^{-1}, cp	27.81	38.39	55.79	35.75	48.18

Frictional Pressure Loss Tests

Friction pressure loss test was performed to confirm the pumpability of fly ash slurry through coiled tubing, and to obtain a correlation for industry. Twenty barrels of fly ash slurry was made in 50 bbl mixing tank. The fly ash slurry was pumped through a 2,000 ft of 1 ½-in. coiled tubing and a 20 ft (between pressure ports) section of straightened 1 ½-in. tubing and its frictional pressure characteristics were determined. Figure 2 shows the experimental flow loop used in this test. Before flowing the slurry into a test loop, water was pumped to flush the system. Then the slurry was pumped at 20 gpm for about 5 min. in order to ensure the complete displacement of water from the test loop. The slurry was then pumped a maximum flow rate possible for 3 to 4 min. to obtain stable flow. Flow rate was changed in a 10 gpm decrement with the lowest being 30 gpm. 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.

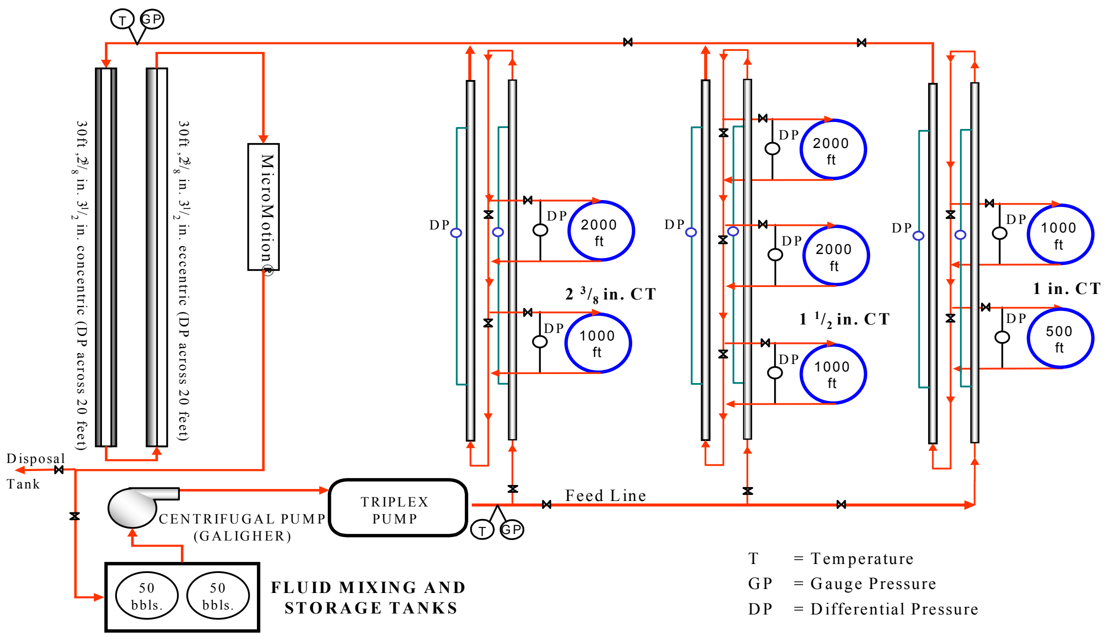

Fig. 2. – Schematic of Experimental Setup of Flow Loop at WCTC, Norman

Before and after the flow test, slurry samples were collected from a sample port in the loop. Rheology of slurry samples was measured by Fann 35 viscometer, then rheological parameters were calculated with Power law model.

Table. 5. – Fann 35 data for the fly ashes during frictional pressure loss test (#1/5 spring)

RPM	Dial Reading	
	Sample #1 (before)	Sample #2 (after)
600	105	106
300	46	44
200	29	28
100	14	14
Calculated fluid Properties for Power law model		
Temperature, °F	92	98

n	1.125	1.129
$k_{v,}$ (lb_f-s^n/ft^2)	8.987×10^{-5}	8.625×10^{-5}
$k_{p,}$ (lb_f-s^n/ft^2)	8.776×10^{-5}	8.416×10^{-5}
$k_{a,}$ (lb_f-s^n/ft^2)	8.682×10^{-5}	8.323×10^{-5}

The chart of generalized Reynolds vs. Fanning friction factor is commonly used to predict frictional pressure loss of fluid in pipe. Generalized Reynolds number, N_{Reg}, a dimensionless variable, for non-Newtonian fluid in pipe can be described as:

$$N_{\mathrm{Re}\,g} = \left(\frac{1}{12}\right)^n \frac{7.48052}{32.17\times 8^{n-1}} \frac{d_i^n V^{2-n} \rho}{k_p} \quad \text{.......} (1)$$

where, n = flow behavior index (dimensionless)
k_p = flow consistency index for pipe, lb_f-s^n/ft^2

Generalized Reynolds number is calculated with rheological parameters which are calculated from Fann 35 data during the test.

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

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

where, ρ = fluid density, lb_m/gal
V = fluid velocity, ft/sec
τ_w = wall shear stress, lb_f/ft^2

Fanning friction factor is calculated from pressure loss data through 2000 ft coiled tubing and 20 ft straight tubing. Table 6 shows the average experimental pressure loss data of coiled tubing and straight tubing.

Table 6 - Average experimental data of pressure loss

Flow rate (gpm)	DP (psi) of 1 ½-in. 2000 ft coiled tubing	DP (psi) of 1 ½-in. 20 ft straight tubing
31	516.48	5.19
40	869.82	8.50
50	1292.22	12.63
60	1806.10	17.63
70	2337.94	23.11

81	2935.04	29.17

Figure 3 shows the log-log plot of Fanning friction factor vs. generalized Reynolds number for the fly ash slurry in 1-1/2 in. 20 ft straight and 2000 ft coiled tubing. The Drew correlation[6] (1932) was developed for Newtonian turbulent flow in straight smooth pipe. The Srinivasan correlation[7] (1970) was developed for Newtonian turbulent flow in coiled smooth pipe. The Fanning friction factors from the fly ash slurry experimental data of straight tubing are very close to Drew correlation. The Fanning friction factors of the fly ash slurry in coiled tubing are lower than Srinivasan correlation and much close to the Drew correlation.

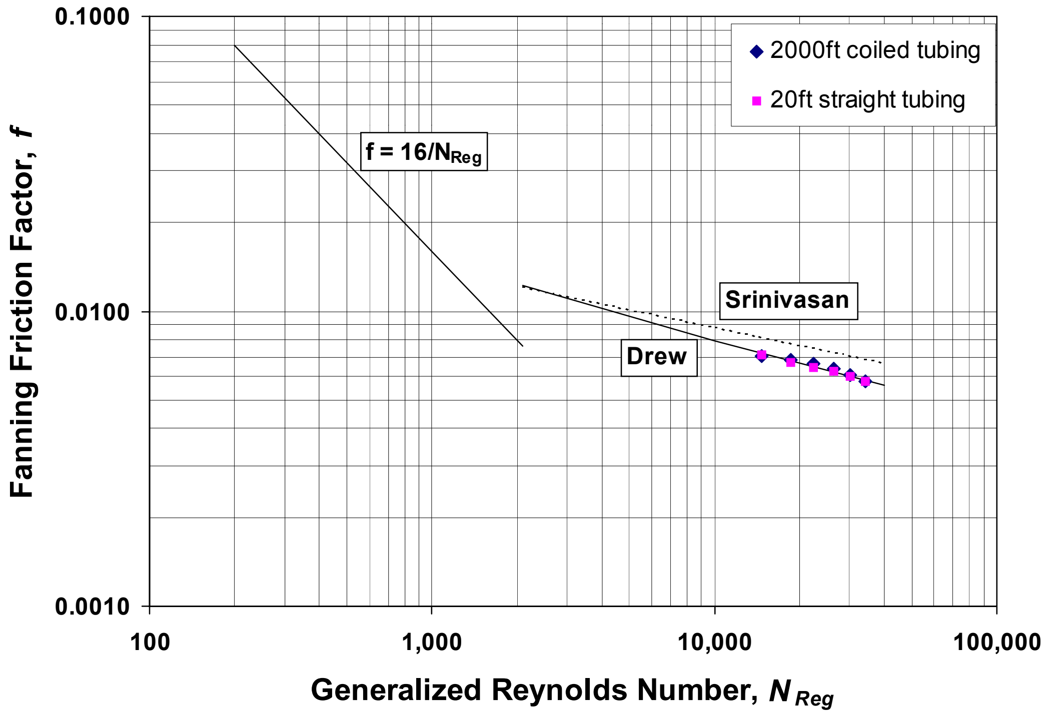

Fig. 3. – Fanning friction factor vs. Generalized Reynolds number for the fly ash slurry

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1. Standard Specification for Fly Ash and Raw Calcined Natural Pozzolan for Use as a mineral Admixture in Portland Cement Concrete, ASTM C 618-94a, American Society for Testing and Materials, Philadelphia, 1995.
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4. Smith, D.K., Cementing, SPE Monograph, vol. 4, Society of Petroleum Engineers, Dallas, 1976.

5. Shah, S.N. and Cho, H.: “Development of an Environmentally Friendly and Economical Material for Plugging Abandoned Wells”, presented at the 8th International Petroleum Environmental Conference, Houston, Texas, November 2001.
6. Drew, T.B., Koo, E.C., and McAdams, W.H.: “The Friction Factors for Clean Round Pipes”, Trans. AIChE, Vol. 28, 56, 1932.
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Publications/Presentations

1. Shah, S.N., and Jeong, Y.T., “The Pumpability of Fly Ash Slurry for Plugging Abandoned Wells Using Coiled Tubing”, 2003 International Ash Utilization Symposium, Lexington, KY, Oct. 20-22, 2003 (accepted).
2. Shah, S.N., and Jeong, Y.T., “Development of an Environmentally Friendly and Economical Process for Plugging Abandoned Wells”, 10th International Petroleum Environmental Conference, Houston, TX, Nov. 11-14, 2003 (accepted).

Future Activities

The placement method for fly ash using coiled tubing will be determined. The effect of contamination between wellbore fluids and fly ash slurry will be investigated, and then the effective removal technique for wellbore fluids will be determined.