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Rheology of Sludge-Slurry Grouts

Earl W. McDaniel

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Earl W. McDaniel

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RHEOLOGY OF SLUDGE-SLURRY GROUTS

Earl W. McDaniel

ABSTRACT

A series of rheograms was developed that relates the critical velocity (velocity where flow changes from laminar to turbulent) of a cementitious grout that incorporates a suspended sludge-slurry to the critical velocity of a reference grout made with a simulated waste solution.

The sludge that is now in the Gunite waste tanks at the Oak Ridge National Laboratory (ORNL) will be suspended and pumped to the new waste storage tanks in Melton Valley. The sludge will then be blended with a cement mix base to form a grout which will be injected underground by the shale fracturing process. This report describes the materials, equipment, and techniques used in the laboratory studies to suspend sludges and mix sludge-slurry grouts that have flow properties similar to those of current shale fracturing grouts.

Bentonite clay is an effective suspender in dilute $NaNO_3$ solutions: 15 wt % solids can be suspended with 2.0 wt % bentonite in a 0.1 $\underline{M}$ $NaNO_3$ solution. Other suspending materials were evaluated, but bentonite gave the best results.

If a slurry grout becomes too viscous to pump, methods must be available to "thin" the mixture. A number of thinners, friction reducers, and plasticizers were examined. Q-Broxin,* a thinner supplied by Baroid, reduced the velocity of a grout required for turbulent flow in a 5.0-cm (2-in.)-diam tube from 1.76 to 1.20 m/s (5.79 to 3.95 ft/s); FX-32C,** a plasticizer supplied by Fox Industries, Inc., reduced the velocity from 1.76 to 0.75 m/s (5.6 to 2.45 ft/s).

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*Manufactured by Baroid Petroleum Services, Houston, Tex.

**Manufactured by Fox Industries, Inc., Baltimore, Md.

1. INTRODUCTION

The sludge that is now in the Gunite waste tanks at ORNL will be suspended and pumped to the new intermediate-level waste (ILW) storage tanks in Melton Valley. Subsequently, this suspended sludge will be pumped to the new shale fracturing facility and combined with a cement mix base to form a grout. This grout will then be injected underground by the shale fracturing technique (Fig. 1). The grout containing the slurry must have properties similar to those of the current shale fracturing grouts.[1] It must be fluid and remain fluid for at least 24 h, exhibit phase separation of <5%, and have an acceptable compressive strength and leach rate.

Experiments were conducted to determine the critical velocity (the velocity at which flow changes from laminar to turbulent) for a standard dry-solids blend and a simulated waste solution.[1,2] This point was used as a reference for the flow characteristics of more viscous sludge-slurries, which would require less dry-solids addition to yield the same critical velocity as that of the reference mix.

Various materials were evaluated as suspending agents for the sludge. Data are presented on the use of chemical additives to control the flow properties of sludge-slurries and cementitious grouts. Methods have been developed to estimate and control the flow properties of sludge-slurry grout during a shale-fracturing waste disposal operation.

This report describes the development of a series of rheograms that relates the flow characteristics of a grout in which past pumping experience is available to a grout made with a sludge-slurry for which no pumping data is available. This was accomplished by establishing rheological reference points.

2. BASIC CONCEPTS

The flow characteristics of fluids are conventionally classified as Newtonian or non-Newtonian. Newtonian fluids such as oil or water exhibit a direct and constant proportionality between shear rate and shear stress. In a fluid of this type, viscosity is independent of the shear rate at

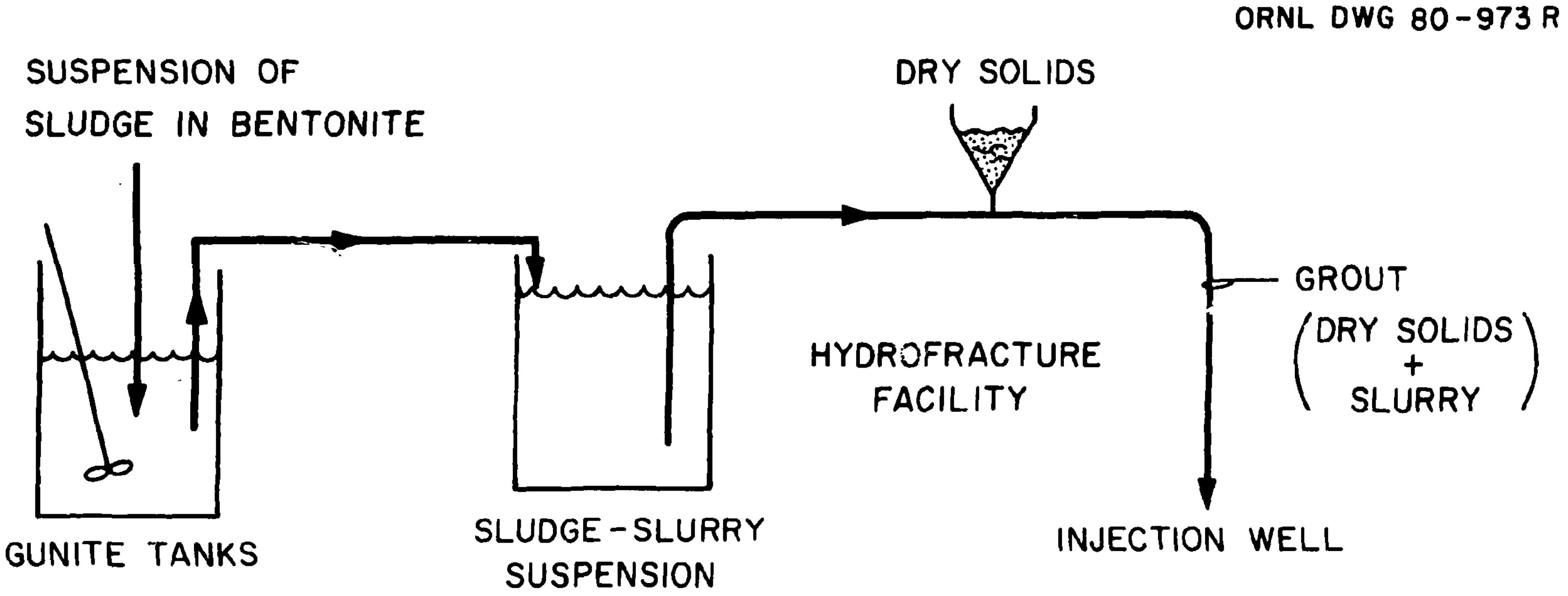

Fig. 1. Flow diagram of sludge-slurry grout hydrofacture process.

constant temperature and pressure. A Newtonian fluid will begin to flow immediately when pressure is applied.

The term non-Newtonian describes all fluids whose behavior is different from that of a Newtonian fluid.[3] These are rheologically complex, frequently particle-bearing fluids. Non-Newtonian fluids do not exhibit a direct proportionality between pressure loss and flow rate at constant temperature and pressure. Some non-Newtonian fluids do not start to flow immediately after a force is applied, but will go through stages of flow (i.e., plug, laminar, and turbulent).[4]

A complex type of non-Newtonian fluid is pseudoplastic, which includes the majority of industrial fluids. The apparent viscosities of these fluids decrease as shear rates increase. An empirical relationship known as the power law (Sect. 2.1) is most often used to characterize fluids of this type. Other non-Newtonian fluids are thixotropic. These fluids possess structure, and the breakdown of this structure is a function of time and shear rate. As the structure breaks down, the shear stress decreases with constant shear rate. This structure can rebuild itself if it is not prevented from doing so by externally applied forces. Other classifications exist, and their descriptions may be found in the literature.[3,4]

The literature indicates that the flow behavior of cement slurries is non-Newtonian and is described best by the power law method of analysis.[4] All flow characteristics described in this report are interpreted using this model.

Dry-solids slurry-mixing experiments were conducted in the laboratory using only those physical properties that can be readily determined in the field on the actual sludge-grout mix. These include, for example, the slurry viscosity and density. The underlying assumption that formed the basis of the measurements was that a sludge-slurry suspension of a given viscosity may be mixed with a dry-solids cement blend until the power required to mix the grout at a predetermined speed was equal to that of a reference mix. The resulting grout should then exhibit rheological properties similar to those of the reference grout. A series of grouts was made with sludge-slurries of increasing viscosities. The data derived from the mixes were used to establish a series of rheograms. The rheograms relate the power required to mix the slurry-grout to that required to mix a reference grout. These curves are then used to calculate the quantity of dry solids to be added to a sludge-slurry of known viscosity.

2.1 Power Law Model

The power law model is based on the assumption that a fluid exhibits a proportionality between the logarithm of the pressure loss and the logarithm of the flow rate in the region of laminar flow.[4] A log-log plot of shear stress vs shear rate is constructed to obtain the two parameters required to define the power law model. The intercept of this line at unit shear rate is called the fluid consistency index. This index is denoted by K'. The slope of the line, n', is referred to as the flow behavior index and is a measure of the non-Newtonian behavior of the fluid; for pseudoplastics, $0 < n' < 1$. Newtonian fluids have a flow behavior index of unity, and, in addition to K' and n', flow calculations are usually based on a Reynolds number correlation. The following equation is used to calculate the velocity (flow rate) at a specific Reynolds number.[4]

$$V = \left[\frac{N_{re} K' (96/d_i)^{n'}}{1.86D} \right]^{\frac{1}{2-n'}} ,$$

where

V = velocity, ft/s;*

N_{re} = Reynolds number, dimensionless;

K' = consistency index, lbf · $s^{n'}/ft^2$;

d_i = ratio of four times the area of the flow to the wetted perimeter, in.;

D = fluid density, lb/gal;

n' = flow behavior index, dimensionless.

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*To convert from ft/s to m/s, multiply by 0.3048.

A Reynolds number of 2100 is the accepted value for the start of turbulence in cement slurry—flow calculations. This N_{re} is used in all calculations presented in this report.

3. EXPERIMENT AND RESULTS

3.1 Determination of Flow Property Reference Points

A series of duplicate grout mixes was made to determine the average flow properties (Tables 1 and 2) for grouts that have routinely been pumped during the hydrofracture disposal of waste solutions. These mixes were assumed to have acceptable phase separation and viscosity. The average critical velocity for these mixtures was used as a reference for all flow characteristic measurement of grouts made with more viscous sludge-slurries. The sludge-slurries require the addition of less dry solids to yield an equal critical velocity. The experimental objective was to establish a rheogram relating the apparent viscosity of a slurry of simulated radioactive sludge to the dry mix-to-slurry ratio required to maintain a grout that can be pumped.

Table 1. Flow properties[a] of 719.0-g/ℓ (6.0-lb/gal) reference grout

Flow parameters		Phase separation (vol %)	Density		Viscosity	
Fluid consistency index (K')	Flow behavior index (n')		g/cm^3	lb/gal	Pa·s	cP
3.55×10^{-3}	0.61	4.92	1.40	11.65	0.016	16
7.75×10^{-3}	0.50	4.10	1.40	11.65	0.018	18
3.97×10^{-3}	0.58	4.90	1.40	11.65	0.014	14
6.43×10^{-3}	0.53	4.17	1.40	11.65	0.018	18
1.95×10^{-3}	0.68	4.07	1.40	11.65	0.013	13
2.92×10^{-3}	0.61	4.96	1.40	11.65	0.013	13
$\overline{X}$ 4.43×10^{-3}[b]	0.59	4.52	1.40	11.65	0.015	15.3
S 0.022	0.06	0.45	0.00	0.0	0.002	2.3

[a] The velocity in a 5-cm (2-in.)-ID pipe is equal to 0.8 m/s (27.2 gal/min).

[b] $\overline{X}$ = arithmetic average; S = standard deviation.

Table 2. Flow properties[a] of 958.0-g/ℓ (8.0-lb/gal) reference grout

Flow parameters		Phase Separation (vol %)	Density		Viscosity	
Fluid consistency index (K')	Flow behavior index (n')		g/cm^3	lb/gal	Pa·s	cP
3.16×10^{-2}	0.43	0.83	1.46	12.2	0.045	45
4.59×10^{-2}	0.38	0.56	1.47	12.3	0.050	50
4.81×10^{-2}	0.38	0.72	1.46	12.2	0.051	51
6.10×10^{-2}	0.32	0.30	1.49	12.4	0.042	42
5.70×10^{-2}	0.32	0.0	1.49	12.4	0.040	40
9.0×10^{-2}	0.26	0.0	1.49	12.4	0.044	44
$\bar{X}$ 5.56×10^{-2}[b]	0.35	0.40	1.48	12.3	0.045	45.3
S 0.02[b]	0.06	0.36	0.02	0.10	0.004	4.4

[a] The velocity in a 5-cm(2-in.)-ID pipe is equal to 1.90 m/s (60.5 gal/min).

[b] $\bar{X}$ = arithmetic average; S = standard deviation.

The apparent viscosity is the viscosity a fluid appears to have at a stated shear rate. It is a function of the plastic viscosity, which is the resistance to flow caused by friction between suspended particles and by the viscosity of the liquid phase, and the yield point, which is a measure of the forces which cause a gel structure to develop when the slurry is at rest.

The grout made at the hydrofracture facility to dispose of the waste supernate used a solids/liquid ratio predetermined in a series of laboratory tests. This procedure was modeled in the laboratory by preparing simulated waste solutions based on chemical analyses of actual waste solutions in the ORNL waste storage tanks.[2] Mixing was performed by adding dry solids slowly to the waste solution over a 15-s period while stirring followed by continued stirring for an additional 15 s at the same mix speed. A speed of 2000 rpm was used to simulate grout mixed in the plant mixer tub.

The grout resulting from mixing dry solids with a sludge-slurry suspension should have properties fairly similar to those used in the disposal of ILW waste solutions. Previous work has shown that even though other characteristics of grouts may vary greatly, they could exhibit similar pumping properties and phase separation. [4-7]

3.2 Equipment and Mixing

A laboratory mixer with an electronic speed control was used for all mixes. A sensitive ampmeter was used to detect changes in the current required to maintain a constant mixing speed. The power required to maintain a constant speed should be proportional to the viscosity of the mix. The current required as dry mix was added to a simulated waste solution was compared with the current required for mixing more viscous sludge-slurries. It is assumed that although the individual flow parameters of the grouts may vary, grouts that require equal current for mixing would display similar flow (pumping) characteristics. Multiple measurements were made for the reference grouts. The compositions of the dry solids are shown in Table 3. The standard mixing procedure at 2000 rpm was followed.

Table 3. Composition of dry solids used in reference grouts

Material	wt %
Type I Portland cement	38.5
Kingston fly ash	38.5
Attapulgite drilling clay	15.3
Indian Red pottery clay	7.7

Reference mixes were made in the ratio of 719.0 g/ℓ (6.0 lb/gal) and 958.0 g/ℓ (8.0 lb/gal). Reference mix data are listed in Tables 2 and 3. A Fann viscometer* was used to measure the shear stress at various shear rates. The grout density was determined with a Baroid mud balance.

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*Manufactured by Fann Instrument Company, Houston, Tex.

3.3 Slurries

The properties of the sludge-slurry suspension must be controlled within limits that will permit blending with sufficient dry solids to produce an acceptable grout. The properties of the suspension are a complex function of not only the components of the solids but also the particle size and number and forces between the particles, as well as the viscosity of the base liquid. A measurement that takes into account all of these factors at a single stage of flow is extremely complicated and requires a variable-speed direct-indicating viscometer. Such a measurement would be difficult and impractical to make at the waste transfer site. Even though such measurements are necessary for laboratory experiments, flow property changes in this report are related to parameters such as the density and the viscosity that can be either measured or estimated at the waste disposal site.

Various metal and/or metal oxides suspended with 2.0 wt % commercial-grade bentonite clay* in a 0.1 $\underline{M}$ $NaNO_3$ solution were used as simulated sludge-slurries (Table 4).

Table 4. Surface area, particle size, and density of suspended solids

Material	Surface area (m^2/g)	Particle size[a] (μm)	Density (g/cm^3)
Bentonite	35.96	7.22	2.32
Iron metal	0.20	24.99	7.59
Fe_2O_3	9.21	3.47	5.15
Fe_3O_4	1.81	29.41	4.78
Al_2O_3	0.75	54.00	3.96
Ottawa sand	0.029	370.00	2.64

[a] Maximum size of 50% of the particles.

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*The bentonite used was commercial-grade Wyoming bentonite that is listed in Table 5 as Thixogel # 2.

An area of interest in the compatibility testing of sludge-slurry grout is the effect of surface area and particle size on the viscosity and settling rate. Many investigations into the significance of particle size are reported in the literature.[8] Although no detailed study was made here, the trend was for the smaller particles to produce more viscous suspensions. This characteristic was used to its fullest advantage when slurries having equal solids contents but different viscosities were needed. Sand was too coarse to be suspended in a 2.0 wt % bentonite slurry. Other materials (Table 5) were tested as possible suspenders, but none were found to perform as well as bentonite.

Table 5. Materials evaluated as possible suspending agents

Trade name	Supplier	Type
Aquagel	Baroid Petroleum Services	Selected fine-ground bentonite
Zeagel	Baroid Petroleum Services	Attapulgite
XC Polymer	Baroid Petroleum Services	Organic
Cellex	Baroid Petroleum Services	Sodium carboxmethylcellulose
Thixogel # 1	Georgia Kaolin	Wyoming bentonite
Thixogel # 2	Georgia Kaolin	Wyoming bentonite
Mineral Colloid BP	Georgia Kaolin	Pure montmorillonite
Gelwhite L	Georgia Kaolin	Montmorillonite (white)
Quikgel	Baroid Petroleum Services	High-yield bentonite
Lo Loss	Baroid Petroleum Services	Oganic colloid

3.4 Sludge-Slurry Grouts

Slurries of different viscosities were made using 15.0 wt % metal oxides and/or metal particles suspended with 2.0 wt % bentonite clay in a 0.1 M $NaNO_3$ solution. To these was added a dry-solids blend composed of 46.0 wt % Type I Portland cement, 46.0 wt % Kingston fly ash, and 8.0 wt % Indian Red Pottery clay until the mixing current equaled that of a reference grout. The resulting data are listed in Tables 6 and 7.

Table 6. Flow properties of grouts extrapolated from 719.0-g/ℓ (6.0-lb/gal dry solids in a simulated waste solution—reference velocity of 0.8 m/s (2.8 ft/s)

Slurry viscosity[a]		Grout viscosity		Dry solids added		Grout density		Critical velocity[b]		Phase sep. vol.	Flow parameters	
Pa•s	cP	Pa•s	cP	g/cm^3	lb/gal	g/cm^3	lb/gal	m/s	ft/s	(%)	Fluid consistency index (K')	Flow behavior index (n')
0.0035	3.5	0.0270	27.0	0.66	5.5	1.43	11.96	1.33	4.40	3.64	4.81×10^{-2}	0.27
0.0045	4.5	0.0270	27.0	0.66	5.5	1.40	11.65	1.43	4.72	2.01	6.60×10^{-2}	0.23
0.0075	7.5	0.0375	37.5	0.60	5.0	1.39	11.60	1.74	5.71	1.82	1.22×10^{-1}	0.18
0.0085	8.5	0.0335	33.5	0.54	4.5	1.37	11.40	1.57	5.16	1.42	1.19×10^{-1}	0.16
0.0090	9.0	0.0330	33.0	0.54	4.5	1.36	11.35	1.60	5.26	2.10	1.03×10^{-1}	0.18
0.0120	12.0	0.0260	26.0	0.30	2.5	1.28	10.65	1.45	4.75	4.96	5.48×10^{-2}	0.25
0.0130	13.0	0.0270	27.0	0.24	2.0	1.27	10.60	1.50	4.91	4.10	5.48×10^{-2}	0.25
							$\bar{X}$ = 11.31[c]	1.52	4.98		8.11×10^{-2}	0.22
							S = 0.51[c]	0.13	0.43		0.03	0.04

[a] Slurry composed of 15.0 wt % Fe_3O_4 suspended with 2.0 wt % bentonite clay in 0.1 N $NaNO_3$ solution. Viscosity was varied by stabilizing at slightly different shear rates and slight variations in pH.

[b] Critical velocity for flow in a 5-cm (2-in.)-ID tube. Flow rate would be ∿3.2 ℓ/s (50 gal/min). A hydrofracture injection is normally made at a flow rate of 16 to 17 ℓ/s (250 to 275 gal/min).

[c] $\bar{X}$ = arithmetic average; S = standard deviation.

Table 7. Flow properties of grouts extrapolated from 959.0-g/ℓ (8.0-lb/gal) dry solids in a simulated waste solution—reference velocity of 1.9 m/s (6.2 ft/s)

Slurry[a] viscosity		Grout viscosity		Dry solids added		Grout density		Critical velocity[b]		Phase sep. vol. (%)	Flow parameters	
Pa•s	cP	Pa•s	cP	g/cm^3	lb/gal	g/cm^3	lb/gal	m/s	ft/s		Fluid consistency index (K')	Flow behavior index (n')
0.0030	3.0	0.0505	50.5	1.32	11.0	1.62	13.5	1.89	6.21	0.84	1.28×10^{-1}	0.23
0.0060	6.0	0.0660	66.0	1.17	9.8	1.60	13.35	2.16	7.10	1.10	1.40×10^{-1}	0.25
0.0095	9.5	0.0365	36.5	0.96	8.0	1.57	12.60	1.76	5.79	1.10	9.07×10^{-2}	0.24
0.0120	12.0	0.0465	46.5	0.9	7.5	1.51	12.65	1.85	6.09	0.48	1.25×10^{-1}	0.21
0.0160	16.0	0.0480	48.0	0.63	5.25	1.42	11.85	1.97	6.47	3.30	1.56×10^{-1}	0.18
0.017	17.0	0.0550	55.0	0.60	5.0	1.41	11.80	2.17	7.12	2.0	1.92×10^{-1}	0.17
0.019	19.0	0.0580	58.0	0.48	4.0	1.37	11.40	2.07	6.79	2.70	1.85×10^{-1}	0.16
						$\bar{X}$	12.45	1.98	6.51		1.45×10^{-1}	0.21
						S	0.80	0.16	0.51		0.04	0.04

[a] Slurry composed of 15.0 wt % Fe_3O_4 suspended with 2.0 wt % bentonite clay in 0.1 *M* $NaNO_3$ solution. Viscosity was varied by stabilizing at slightly different shear rates and slight variations in pH.

[b] Critical velocity for flow in 5-cm (2-in.)-ID tube. Flow rate would be ~4.0 ℓ/s (64 gal/min).

Data from Tables 6 and 7 are plotted in Fig. 2. The lower curve pertains to the flow parameters of 719-g/ℓ supernate grouts (Table 1). The upper curve represents grouts referenced to 958 g/ℓ (Table 2). The sludge-slurry grouts were found to have a much higher critical velocity for turbulent flow than the 719-g/ℓ reference grout. However, the velocities were essentially the same as the higher solids/liquid reference grout. Thus, for field application, one would use the upper line representing the higher reference grout.

3.5 Effect of pH on Sludge-Slurry Viscosity

In the neutralization of ILW, a pH $\geq$ 9.5 is necessary to ensure the complete precipitation of $^{90}Sr(OH)_2$. Slight variations in the pH in this region (9 to 12) were found to have a major effect on the viscosity of a sludge-slurry suspended with bentonite. The viscosities were determined for a 15.0 wt % Fe_3O_4 slurry suspended with 2.0 wt % bentonite in a 0.1 $\underline{M}$ $NaNO_3$ solution as a function of pH. At each point, the slurry was sheared by stirring until maximum viscosity was reached. The pH was then increased, and stirring was repeated (Fig. 3). Extreme shearing conditions were used in this experiment and are ~200 times greater than that expected in the actual injections. Maximum viscosity was reached at a pH of 11.2 and then decreased as the pH increased.

3.6 The Use of Chemical Additives to Control Flow Properties of Sludge-Slurries and Cementitious Grouts

There are several types of chemical compounds that may be used to change the flow properties of non-Newtonian liquid. For example, tannins, lignites, polyphosphates, and lignosulfonates are the compounds which the oil industry has found to be the most effective "thinners." Each of these material has its optimum effectiveness under certain conditions and within a definite pH range. Polyphosphates are rarely used if the pH exceeds 10. Tannins are effective if the pH is ≥ 8, and lignites work best between a pH of 8.5 and 9.5. The action of these compounds when added to

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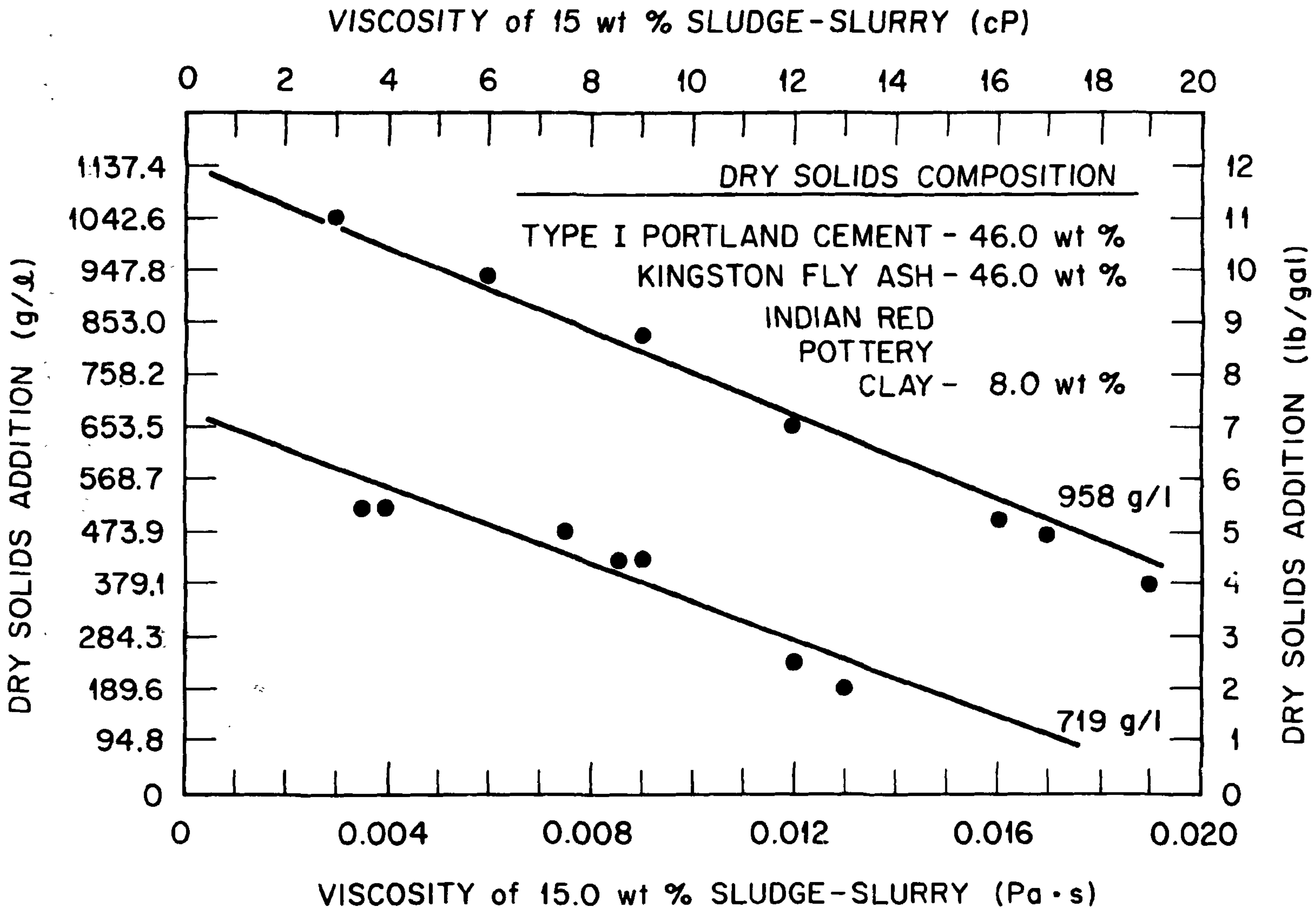

Fig. 2. Rheogram that relates the flow properties of a sludge-slurry grout to one made with waste solution.

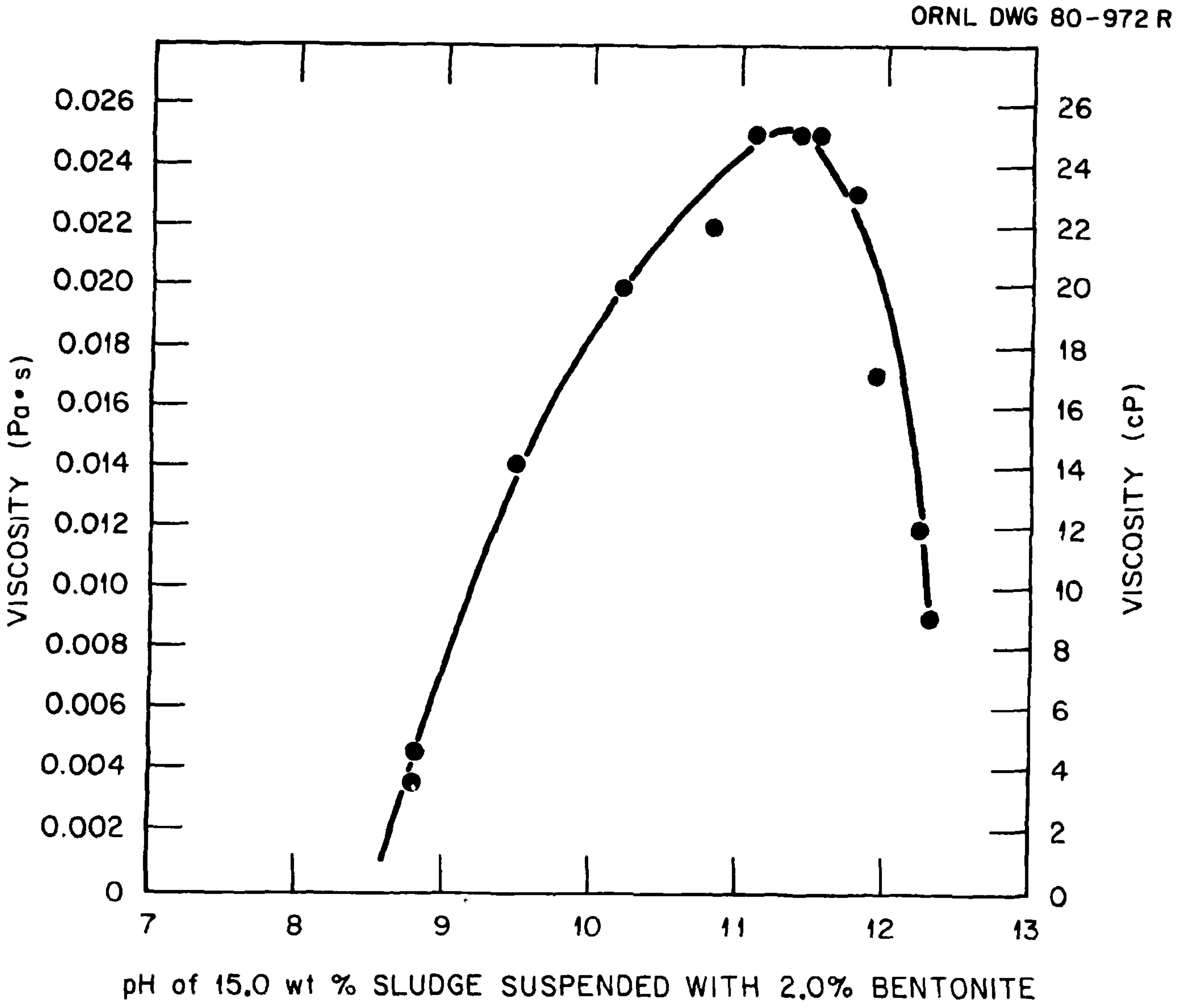

Fig. 3. Viscosity of a sludge-slurry as a function of pH.

a fluid to lower the velocity required for turbulent flow is thought to be that they complete broken valence bonds, thus reducing interparticle forces.[9]

Additives more closely related to cementing are the friction reducers and plasticizers. Friction reducers are essentially dispersing agents which reduce the apparent viscosity of the slurry with no change in flow rate. A lower apparent viscosity gives a higher Reynolds number and therefore a lower Fanning friction factor and a lower critical velocity.[4] Plasticizers increase the fluidity of a cement slurry for a given water-to-solids ratio. Friction reducers and plasticizers may be conveniently added to a dry solids blend. Data related to those chemicals are well covered in the literature.[4,7,8,10] Caution must be exercised in using chemicals to control flow properties of radioactive sludge-slurries and grouts because of the uncertainity of slurry composition. Chemical additives evaluated in this study along with comments are listed in Tables 8 to 10.

Table 8. Chemical additivies evaluated to alter flow properties of sludge-slurries and cementitious grouts

Trade name	Supplier	Type	Comments
Barafos	Baroid	Sodium pyrophosphate	Effective
Q-Broxin	Baroid	Heavy-metal lignosulfonate	Effective over wide pH range and in the presence of various electrolites
Carbonox	Baroid	Lignite	Calcium acts as a contaminant in the presence of lignites
CC-16	Baroid	Treated lignite	Increases pH; calcium decreases effectiveness

Extending the mixing time of 15.0 wt % sludge slurries changes the flow behavior index (i.e., the slurry becomes less Newtonian). The velocity required for turbulent flow is reduced by the addition of FX-32C and is not adversely affected by increasing mix time. (Table 11).

The effects of several of the potential additives on the flow properties of a grout are listed in Table 12. The FX-32C drastically

Table 9. Friction reducers

Trade name	Supplier	Type	Comments
CFR-1	Halliburton	Delta gluconol-acetone	Added to dry solids; reduces critical velocity of cement slurries necessary for turbulent flow; uses up to 0.3 wt %; most effective in slurries not containing bentonite
CFR-2	Halliburton	Proprietary compound	Reduces velocity required for turbulent flow; up to 2.0% may be used; effective in high gel-cement
HR-7	Halliburton	Proprietary compound	Effective in high gel-cement
Halad-9	Halliburton	Proprietary compound	Effective in high gel-cement

Table 10. Plasticizers

Trade name	Supplier	Type	Comments
FX-32C FX-32D	Fox Industries	Sulfonated naphthalene formaldehyde condensate	Produces very fluid grouts
Plastiment	Sika	Metallic salt of hydroxylated carboxylic acid	Water-reducing retarder
Melment	American Admixtures	Sulfonated melamine formaldehyde condensate	Liquid or dry solid effective water reducer
D-65	Dowell	Sodium salt of organic phosphate	Effective dry-solid fluidizer

Table 11. Effect of adding 0.2 wt % FX-32[a] on the flow properties of a 15 wt % sludge-slurry

Flow parameter	Mixing time (s)					
	60		600		3600	
	0 wt %	0.2 wt %	0 wt %	0.2 wt %	0 wt %	0.2 wt %
K'	1.6×10^{-2}	2.7×10^{-3}	3.5×10^{-2}	3.3×10^{-3}	4.1×10^{-2}	6.4×10^{-3}
n'	0.32	0.48	0.24	0.46	0.19	0.34
V, m/s	0.94	0.49	1.16	0.52	1.10	0.57
f/s	3.08	1.61	3.81	1.71	3.61	1.87
Density, g/cm	1.138	1.138	1.138	1.138	1.138	1.138
lb/gal	9.47	9.47	9.47	9.47	9.47	9.47

[a] 15.0 wt % Fe_2O_3 suspended with 2.0 wt % bentonite clay in 0.1 M solution (pH 9.5). Mixed at 2000 rpm.

Table 12. Effect of additives on sludge-slurry grouts

Flow parameter	Additive to 959.0-g/ℓ (8.0-lb/gal) dry solids[a]			
	0 wt %	1.0 wt % FX-32C	1.0 wt % Q Broxin	1.0 wt % CC-16
Viscosity of sludge, Pa·s[b]	0.095 (9.5 cP)	0.095 (9.5 cP)	0.095 (9.5 cP)	0.09 (9.5 cP)
Viscosity of grouts, Pa·s	0.041 (41 cP)	0.019 (19 cP)	0.031 (31 cP)	0.051 (51 cP)
Density, g/cm^3	1.51 (12.60 lb/gal)	1.55 (12.95 lb/gal)	1.55 (12.05 lb/gal)	1.50 (12.50 lb/gal)
Phase separation, vol %	1.0	6.0	0.9	1.6
K'	9.07×10^{-2}	2.45×10^{-3}	9.99×10^{-3}	1.23×10^{-1}
n'	0.24	0.70	0.55	0.23
Critical velocity, m/s	1.76 (5.79 ft/s)	0.75 (2.45 ft/s)	1.20 (3.95 ft/s)	1.92 (6.34 ft/s)
Flow rate, ℓ/s	3.57 (56.7 gal/min)	1.51 (24.0 gal/min)	1.39 (38.7 gal/min)	3.91 (62.0 gal/min)

[a] Dry solids consist of 46.0 wt % Type I Portland cement, 46.0 wt % Kingston TVA fly ash, and 8.0 wt % Indian Red Pottery clay.

[b] Slurry composed of 15.0 wt % Fe_3O_4 suspended with 2.0 wt % bentonite clay in 0.1 M $NaNO_3$ solution.

reduces the critical velocity and increases the density and flow behavior index (n') but increases the phase separation. The inference here is that the grout becomes more Newtonian. However, the objectionable effect is that there is increased phase separation. The Q-Broxin, however, decreases the critical velocity and increases the density and flow behavior index without increasing the phase separation. Even though the grout containing CC-16 demonstrated an increase in viscosity, the pumping properties are essentially identical to the grout without the additive.

4. CONCLUSIONS AND RECOMMENDATIONS

The rheograms presented in this report were designed for field personnel to be used in determining the dry solids/slurry ratio for making suitable grouts from sludge-slurries of various viscosities. The grouts referenced to 719.0 g/ℓ exhibit critical velocities twice that of the reference grout when the calculations are based on a 5.08-cm-ID tube but are quite accurate when referenced to a 958-g/ℓ reference grout. Addition of dry solids in the field can be based solely on the viscosity of the slurry.

Bentonite is an effective suspender for mixed oxide particle slurries in 0.1 $\underline{M}$ $NaNO_3$ solutions; 15 wt % solids can be suspended with 2.0 wt % bentonite at a settling rate $\leq$5.0 vol % in 24 h.

Under controlled conditions, the viscosity of a bentonite slurry is a function of pH. The slurry will thicken to a maximum viscosity at a pH of 11.2, but the actual viscosity achieved depends on shear rate and time. The viscosity decreases for pH $<$ 11.2, even with increased shear rate and time.

Chemical additives can be used to control the flow properties of sludge-slurries and grouts. These chemicals should not be used unless necessary since they would add to the complexity of the grout and increase operating costs.

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