TECHNICAL ASSISTANCE REPORT TO:
THE APPALACHIAN REGION MANAGEMENT COUNCIL

The Flowability of Impounded Coal Refuse

A review of recent work and current ideas in the engineering profession

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3 Parkway Center
Pittsburgh, PA 15220

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THE FLOWABILITY OF IMPOUNDED COAL REFUSE

A review of recent work and current ideas in the engineering profession

By Peter Michael, Raul Murguia, and Lisa Kosareo

Summary

Following interviews and a literature review on the stability and potential flow characteristics of impounded coal refuse and tailings, we cannot assure that all (or even the majority of) existing refuse impoundments would avoid flows of fine refuse through breakthroughs into an underground mine. The main basis for our concern is the influence of pore water pressure in the fine refuse and potentiality of static liquefaction; and the sense that at least some impoundments are not constructed to adequately allow drainage of excess water from the fines.

Unfortunately, our review did not find any empirical data on the potential flow characteristics of coal-refuse. It is apparent that the flow behavior, or rheology, of viscous fluids is influenced by a complex interrelationship among a number of factors. There is some indication that one particular flow model, called "Bingham Plastic," may be applicable to coal-refuse flow, but this needs to be verified. Even if that or any other model is correct, it is only a relationship among constants and variables, i.e. it cannot tell us how refuse in a specific, existing impoundment might respond to an opening to an underground mine. Consequently, field and lab testing, and perhaps modeling, of coal refuse rheology may be warranted.

Purpose of Study

The purpose of this study was to review current knowledge on--or applicable to-- the potential flow characteristics of impounded coal refuse. The review explored two interrelated issues: (1) given the occurrence of a breakthrough event that would result in a potential flow conduit between an underground mine and an impoundment, should we expect coal refuse to flow into the mine? and (2) if the refuse would flow, what would be the nature (e.g. velocity and extent) of that flow?

Sources employed in the review include: (1) interviews with the OSM impoundment oversight team; (2) interviews with geotechnical experts in coal-refuse and tailings impoundment construction from academia, other federal agencies, and the industry; (3) geotechnical articles obtained through literature searches provided by Nerac, Inc.[1] and through direct contacts with the authors; and (4) various web sites on the Internet.

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[1] Nerac, Inc. provides customized information services for clients across all industrial sectors. The company combines a powerful internet search engine with a computing environment staffed with technical information specialists who use a wide variety of databases and professional contacts to provide

This report includes modifications in response to solicited comments on the first draft completed in August 31, 2004. Most of the comments were provided by geotechnical engineers and engineering geologists outside of OSM with expertise in mine waste impoundments or similar structures. Input was also provided by the technical staff of the OSM Charleston, WV Field Office. The reader can identify all comments by the referenced dates, 2004 or 2005.

Statement of Problem

Question 1: What is the flow potential of impounded fine refuse?

The answer to this question should vary site-specifically according to: the strength characteristics of the refuse; size of the impoundment (i.e. how much stress might bear on the material if a breakthrough occurs); and nature of a breakthrough into an underground mine (e.g. its position in the impoundment, and size, length, and inclination of the opening). Our search has not encountered any study that has scrutinized the interaction of all three of those variables, either empirically or through modeling. However, a considerable amount of work has been accomplished relating to the static, load-bearing strengths of coal refuse and tailings. We have distinguished three general properties of this material that is assessed in the literature. Most attention has been applied to consolidation strength, i.e. the development of shear strength in the fine refuse during the consolidation process. Two other properties covered in the papers we reviewed, matric suction and thixotropic strength, were applied to tailings deposits. We include these in this report, assuming they are potentially applicable to fine refuse[2]. Two additional aspects that may have bearing on refuse stability are the potential effect of chemical additives, and the design and construction of the impoundments.

Consolidation strength

One of the properties that impact design, stability, and drainage of an impoundment is consolidation. Consolidation of a soil is defined as a void-ratio reduction which takes place as a function of time. Consolidation is a gradual process which involves slow drainage, compression (density increase, volume reduction, reduction in void space between particles), and stress transfer or gradual pressure adjustment. The development of engineering strength in the soil during consolidation results from the effective-stress build up among the soil particles (by frictional contact and cohesion) and reduction of

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information on request. Nerac services are delivered to OSM under contract and are managed by the WRCC Librarian.

[2] We reviewed two references that compared the characteristics of sampled coal refuse and various tailings. For instance, Qui et al. (1998) reported that "coal wash" void ratio decreases relatively rapidly with consolidation. Coal wash is described as "plastic cohesive" (due to the abundance of constituent clay minerals). Composite tailings, in comparison are "low plastic cohesive;" and copper and gold tailings are "non-plastic non-cohesive." Qui et al. (2001) found that coal waste hydraulic conductivity was low relative to copper and gold tailings, even at much higher void ratios. Also, coal refuse had much higher moisture content than the tailings at any void ratio.

positive pore-water pressure. Consolidation is affected in part by particle size distribution and density or void ratio.

The rate and degree of consolidation depends on the induced load on the soil and the soil's "coefficient of consolidation" (Cc). The factors influencing Cc includes the soil's compressibility and its permeability (or hydraulic conductivity). Compressibility is a ratio of the strain of the material (specifically the rate of volume reduction) to induced stress and depends on particle shape, size distribution, and initial void ratio. (Figure 1) With higher compressibility, the Cc is lower, and more strain is necessary for the build-up of effective stress in the soil. Permeability is the facility with which water is able to travel through the pores of the soil and is a function of the size, number, and interconnection of voids between the soil particles. The higher the permeability, the higher is the Cc.

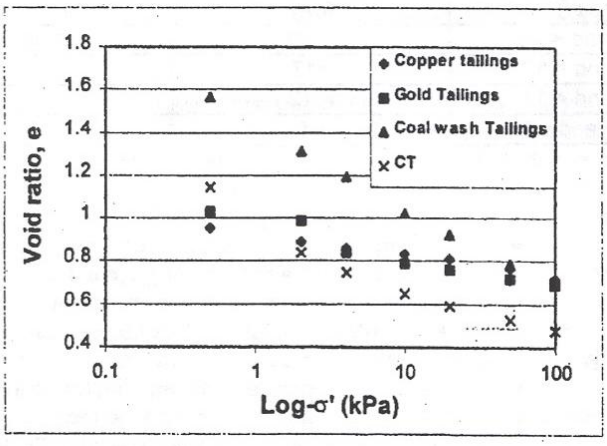

Figure 1: Compressibility of mine tailings as a function of void ratio.
(Qiu et al., 1998)

The stability of impounded fine refuse and tailings depends in large part on the development of consolidation strength in the material. Insufficient shear strength under static or dynamic load will result in deformation of the refuse. Of major concern is that insufficient drainage during the consolidation process may result in liquefaction, i.e. excessive pore pressures under load and consequent material flow.

The following comments from literature pertaining to coal-refuse consolidation strength are noted:

- **Permeability:** Consolidation in impounded coal refuse and tailings is more influenced by permeability than compressibility. The permeability of refuse is low and the length of the drainage path is long so that consolidation of the material can take a long time. One should expect high excess pore pressure to exist in fine refuse for years after the initial placement, which would significantly reduce the shear strength of the material. Even after the material is fully consolidated, the void ratio of fine refuse is still high (Zeng et al., 1998; Sweigard et al., 1997; Suthaker et al., 1994, 1996, 1997).

- **Moisture content:** Unless relatively dry, the undrained shear strength of even partially saturated fine coal refuse is very sensitive to moisture contents**.** A change in moisture content of only one percent may cause a large change in the undrained strength (Huang et al., 1987).

- **Slow rate of consolidation:** Suthaker et al. (1994, 1997) conducted large scale testing of oil sand fine tails, using a 2-meter and a 10-meter stand pipe. Whereas sedimentation occurred from the bottom-up and was rapid (2.5 days), self-weight consolidation occurred from the top-down and was long-term (300 days). Tang et al. (1997) examined mature fine tailings with scanning electron microscope and found that after a certain void ratio was reached (ratio of 6), the rate of consolidation slowed considerably. Suthaker et al. (1997) also found that a decrease in void ratio resulted in a decrease of hydraulic conductivity, resulting in slower consolidation.

- **Consolidation rate and rate of impoundment construction:** Huang et al. (1987) and Zeng et al. (1998) both recommended a rate of impoundment construction, particularly for upstream construction methods, slow enough to provide sufficient time for consolidation-strength development. For instance, Zeng (1998), conducted centrifuge modeling of the response of coal waste dams to seismic loading[3]: Models 1, 2, and 3 corresponded to the downstream method, upstream method, and upstream method with induced consolidation, respectively. Model 1 resulted in a small amount of deformation but remained stable. Model 2 resulted in catastrophic failure. Model 3 had more deformation than Model 1 but was still stable after the simulated earthquake. Zeng concluded that it is imperative that consolidation of in-place coal refuse should be monitored in the field during upstream impoundment construction.

- **Low shear strength of fine refuse and tailings in existing impoundments:** Concern over consolidation strength in impoundments has been expressed by Busch et al. (1975), Zeng et al. (1998), Sweigard et al. (1997), and Suthaker et al. (1994, 1996, 1997). Related observations include: high moisture contents (some that are above the liquid limit); increases in moisture content, void ratio, compressibility, and pore pressure with depth in the impoundment; and generally low shear strength even after years of consolidation. Suthaker et al., in their large-scale consolidation test, found that there was no effective stress build-up after 14.4 years in the oil-sand tailings except in the bottom part of the stand pipe.

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[3] Although this document is specifically concerned with the effect of an underground mine breakthrough, not an earthquake or other form of dynamic loading, we feel the referenced findings are pertinent. Just as seismic activity may cause liquefaction, "static liquefaction" from a load increase or loss of foundation support (e.g. from subsidence) can take place. The U.S. Mine Safety and Health Administration is also on record as identifying the potential influence of static liquefaction on the stability of coal refuse impoundments (Michalek, 2005).

- **Uncertainty whether the consolidation process results in the development of shear strength in the impounded refuse:** The foregoing points assume that shear strength in refuse will increase as a result of the consolidation process. That is not the case if consolidation occurs without sufficient dewatering of the material. Sweigard et al. (1997) attempted to address the long-term effect of consolidation of refuse at or above its liquid limit on its shear strength. Their results were inconclusive.

- **Susceptibility of refuse and tailings to liquefaction:** As previously stated, an important issue pertaining to development of consolidation strength in impounded fine refuse and tailings is the avoidance of liquefaction. Most soils continue to behave in a solid state after they fail in shear, i.e. shear strength is not completely lost and the amount of strain that occurs depends on the duration of sufficient ("residual" or "ultimate") shear stress. The exception is when liquefaction takes place. Liquefaction is a process by which soil structure collapses under shock or other type of loading and is associated with a sudden, temporary increase in pore water pressure. The material then temporarily transforms into a liquid. Liquefaction can occur in response to dynamic forces such as earthquakes and mine blasting. Static liquefaction can result from sudden shear stresses induced by mine-barrier breakthroughs, mine subsidence, or other kinds of single-cycle events.

  According to Terzaghi et al. (1996), soils most susceptible to liquefaction: (1) comprise clean sands and silty sands with minimal clay content; (2) are loose enough to be contractive; and (3) are of sufficiently low permeability to experience no significant drainage during static or dynamic loading. The literature indicates that at least some impounded refuse and tailings deposits may be prone to liquefaction (Figure 2).

  Fourie (2004) emphasized the important role of liquefaction, referencing his studies of a tailings-dam failure in South Africa (2001). He pointed out that the susceptibility of a material to liquefaction is governed by the relative values of the material in-situ density (or void ratio) and effective stress. Liquefaction potential relates to the conditions under which deposition of tailings occurred and the inter-grain 'fabric' that thus developed. For example, sub-aqueous deposition will result in a much lower density and effective stress than sub-aerial deposition, even when the deposit is fully consolidated. Such material then behaves in a contractive fashion when loaded undrained, i.e. the solid content of the material contracts and induces excess pore-water pressures. Recognition that fine coal refuse consolidated in up-stream impoundments is "usually highly contractive" is documented by Genes et al. (2000). Volpe (2004) cited conditions in fine refuse conducive to contractive behavior in reference to the tragic Buffalo Creek failure in 1972, i.e. very low density and a high void ratio.

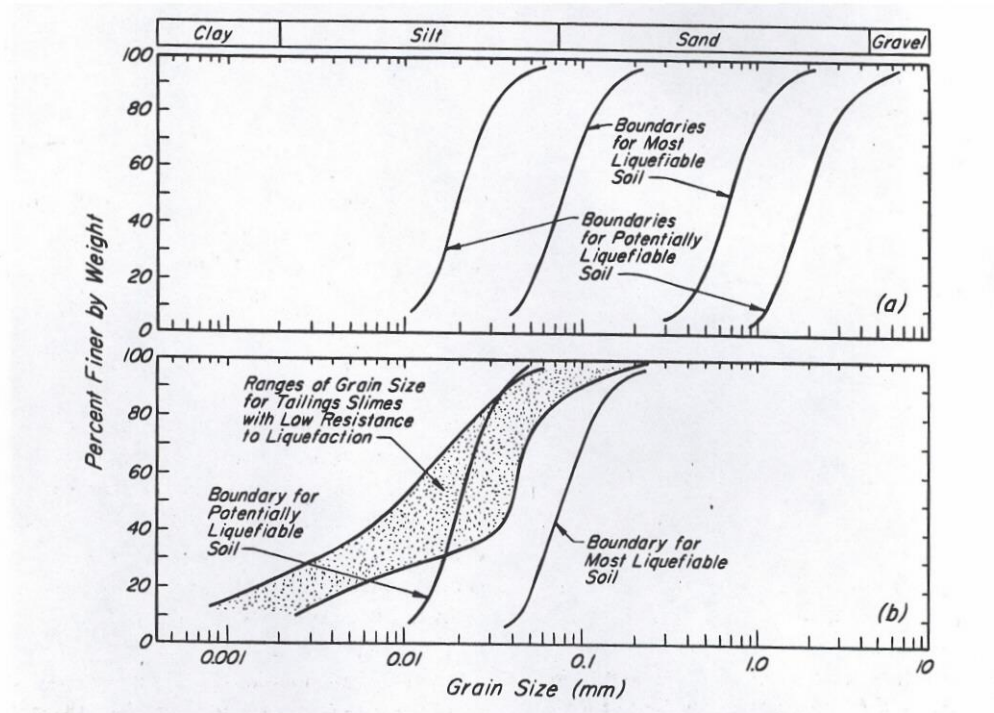

Figure 2: Gradation curves defining limits of liquefiable and non-liquefiable soils and range of grain sizes for tailings dams with low resistance to liquefaction. (Terzaghi et al., 1996)

Matric Suction

References concerning the process of matric suction in tailings and soils in general include Nishimura et al. (2001), Pease et al. (1996), and Rassam et al. (1999). The behavior of both unsaturated and saturated soils is affected by the pore-water pressure. Unsaturated soils have negative pore-water pressure (called matric or capillary suction). Matric suction results from surface tension across the boundary between air and water and also attraction between water molecules and soil minerals. It can have a major positive effect on the shear strength of unsaturated soils; and can be interpreted as additional apparent cohesion. Rassam et al. performed a numerical analysis of matric suction to predict the ultimate load bearing capacity of desiccated gold tailings. A few of his comments are as follows:

- Matric suction is a function of moisture content. If the soil is saturated, the matric suction is zero. As the moisture content decreases, the matric suction increases. The contribution of matric suction to the shear strength of tailings is more effective under evaporative vs. hydrostatic conditions.

- Depth of the water table is important when considering matric suction and its influence on shear strength. The lower the water table, the greater the overall effects of matric suction.

- Matric suction tends to be more effective in materials with lower hydraulic conductivity.

Thixotropic strength

Usui (1998) identified coal-water slurry as thixotropic in nature. Since coal refuse slurry may have some engineering properties similar to coal-water mixtures, we include thixotropy in this report as a potential factor affecting the shear strength of impounded refuse.

The term thixotropy was originally introduced to describe the well-known phenomenon of isothermal, reversible gel-sol (solid-liquid) transformation in colloidal suspensions due to mechanical agitation. Thixotropy is the property of some substances to behave like a fluid when worked or agitated and settle to a semisolid state when at rest. Thixotropy is also classified as a rheological process. From this perspective it is described as a continuous decrease in apparent viscosity with time under shear, and subsequent recovery of viscosity after cessation of flow. From a geotechnical point of view, thixotropy is a process of softening caused by remolding, followed by a time-dependent return to the original harder state at a constant water content and constant porosity (in contrast to consolidation). For remolded clays, the mechanism of the softening is thought to include destruction of orderly arrangement of water molecules and ions in the adsorbed layers of the soil, damage to the structure acquired during sedimentation and consolidation, and realignment of clay plates (Terzaghi et al, 1996). Thixotropic strength gain is measured as a ratio of the strength after an elapsed time to the strength immediately after remolding (or compaction) and is called thixotropic strength ratio. Generally, the ratio is determined in terms of undrained shear strength, not effective (i.e. drained) shear strength.[4]

We acquired information about thixotropy as it may pertain to the stability of coal refuse impoundments from the work of Suthaker et al., 1997 on oil-sand tailings. Several of his comments and findings are as follows:

- **Factors affecting thixotropy:** Several factors such as the mineralogy of the clay, water content, and rate of loading directly affect thixotropy of fine tailings. Some clays exhibit high thixotropy naturally. Kaolinite and illite of oil sands are not thixotropic. However, because of the addition of a dispersing agent, organic matter in the form of bitumen, and organic acids in the pore water, fine tailings are thixotropic in nature. Since thixotropic strength gain may affect consolidation, there is a need to understand the process for a comprehensive consolidation model.

[4] Greene (2004) suggested the April 1978 Rissa landslide in Norway as a dramatic example of thixotropic strength loss. Five to 6 million cubic meters "quick clay" flowed into a lake very quickly. Quick clays are extra-sensitive to disturbance because of very loose soil structure.

- **Duration of thixotropic strength gain:** Using cavity-expansion, vane-shear[5], and viscometer testing equipment, Suthaker et al. conducted three tests at different water contents up to 450 days. Thixotropic strength increased quadratically and was still increasing at 450 days.

- **Effect of moisture content on thixotropy:** The thixotropy of fine tailings is highly dependent on water content. Substantial thixotropic strength increases were seen for fine tailings with water contents less than 150 percent. (Figure 3) The lower the water content, the higher the thixotropic strength. The thixotropic strength ratio for fine tailings is at a minimum at 150 percent water content. Generally, the thixotropic strength ratio increased with an increase in water content.

- **Relationship between thixotropy and consolidation:** Long-term strength development in slurries can be either thixotropic or a combination of thixotropic and consolidation strengths. At low water content (<100 percent), there was no consolidation strength development, as the water content remained unchanged. At a higher water contents, water content changes were prominent, indicating the existence of consolidation effects.

- **Effect of self-weight consolidation on thixotropy.** Shearing strains resulting from consolidation impede the physicochemical bonding that produces thixotropic strength. The higher the rate of consolidation, that is, the shearing rate, the smaller the thixotropic strength gain.

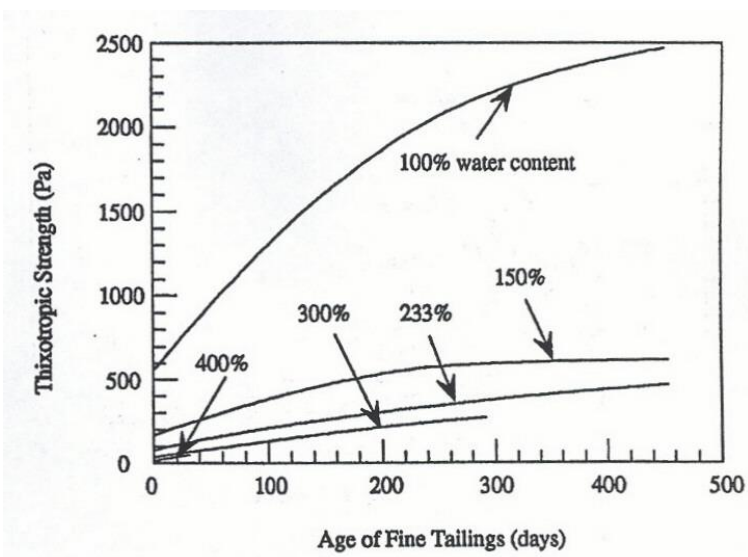

Figure 3: Thixotropic strength with time for a number of water contents. (Suthaker et al., 1997)

[5] The vane-shear test is an in situ field test that measures the undrained shear strength of a soil. The test consists of inserting a four-bladed vane into the soil and measuring the maximum torque required to rotate the vane and shear the soil. The undrained shear strength can then be calculated using a standard equation.

Effect of additives on impounded refuse and tailings

In our review, it became apparent that at least some of the existing impounded coal refuse may have been treated with additives for various purposes. At this time we do not know how frequently such treatment takes place or how much of it is strictly experimental vs. standard practice. Indications that additives are applied to coal-refuse slurry or tailings in some cases come from Puri et al. (1990), Tang et al. (1997), Suthaker et al. (1997), Liu (1999), and Heywood et al. (2003). Potential objectives of the additives include accelerating consolidation and increasing shear strength of impounded refuse, and reduction of slurry viscosity for pipeline transport to the impoundment. Michalek (2005) has stated that, in experience of the U.S. Mine Safety and Health Administration (MSHA), mining companies generally use additives to accelerate slurry particle sedimentation in order to decant clear water back into the mine operation. We believe that an accurate analysis of the strength and stability of fine coal refuse will have to account for the extent and variety of additive use, irregardless of its purpose, and identify its effect(s) on the material.

Design, construction, and performance of impoundments

It is apparent from the points listed above that one very important consideration in the design and construction of an impoundment should be the effective drainage of the impounded fine refuse or tailings. This appears to receive support from the following papers:

- **Comparison of failed and stable impoundments:** Mittal et al. (1977) compared the tailings dams of five large mines in Canada and listed the characteristics of failed and stable impoundments. Failed impoundments had high phreatic surfaces, in addition to overly steep downstream slopes and weak foundation soils. The qualities of stable impounding structures included pervious foundations, in addition to relatively course impounded fines and slow impoundment construction rates.

- **Wick drains:** The use of wick drains to solve the design problem of slow consolidation of fine refuse and tailings was reported by Liu et al. (1999) and Thacker et al. (1988). Wick drains are closely-spaced artificial drainage paths to which the pore water can flow, thus decreasing the consolidation time to "a matter of months." Wakeley et al. (2004) recommended that OSM further consider wick drains as an important tool for dewatering impoundments prone to liquefaction. Fourie (2004) also recognized their potential utility; but he also cautioned that their effectiveness requires excess pore pressures in the surrounding medium, which in turn necessitate an expensive surcharge (e.g. a sand fill). Further information on this technology can be found on the following web sites (Wakeley et al., 2004):

  www.americandrainagesystems.com
  www.american**wick**.com

www.geotechnics.com
www.terrasystems-inc.com/wick.htm
mceer.buffalo.edu/research/HighwayPrj/ 094/TaskStatements/Year3/E2-1.html

Findings concerning the strength and stability of fine coal refuse

Based on our review of published information on refuse and tailings shear strength, we are not confident that all or even the majority of existing impoundments (yet under construction or reclaimed) would avoid flows of the fine refuse through breakthroughs into underground mines. There is significant uncertainty regarding the effectiveness of strength development through consolidation in the fine refuse. Other reasons for our concern include the influence of pore water pressure in the refuse and potentiality of liquefaction--and the sense that at least some impoundments are not constructed to effectively drain water from the material. The potentially positive influence of matric suction is mute under these conditions, even where it may have some effect in the upper elevations of the impoundment (i.e. if an underground mine is below a phreatic surface). Further, whereas in one sense the effect of thixotropy may temporarily supplement what consolidation strength may occur under conditions of high moisture content, its reversibility may only induce a "false sense of security." That is, wet, thixotropic refuse may appear to be stable under static conditions before changing to a liquid state when agitated.

Question 2: If the refuse of at least some impoundments does have flow potential, what would be the nature of its flow into an underground mine, following failure of a barrier?

We were unable to find any documentation containing empirical data on the viscosity or any other flow properties of impounded fine coal refuse. What we have found are: (1) qualitative indicators of refuse and tailings viscosity from several case histories of impoundment failure; (2) empirical and modeling studies of coal-water slurry flow in pipelines; and (3) prediction modeling of refuse or tailings flow following a hypothetical dam or embankment failure. The results of our search only give us a subjective account of what the potential flow characteristics of impounded coal refuse may be, and an appreciation of the general principles and variables that should affect its flow, if in fact flow takes place.[6]

[6]Wakeley (2004) cautioned against applying specific flow models developed for coal-water slurries in pipelines or mineral mine tailings to coal refuse. In the former case coal-water slurry has extremely high water content. It is engineered to keep flowing, and keep solids in suspension by use flow-controlling admixtures. Standard models for pipeline flow should not be applied to more dense coal refuse; and cannot account for the high variability of conditions in a waste impoundment. In the latter case, Wakeley notes that the mineralogy, grain size, grain shape and other physical characteristics of mine waste are attributable to the geologic setting of the mined substance. Coal refuse, derived from cyclothem sedimentary rock, is relatively rich in clay minerals and clay-sized particles. In contrast, tailings from gold mining (for instance) in igneous and metamorphic rock are characterized by small but hard, angular particles. The chemicals used to process gold are also different from those used in coal processing.

Case histories of impoundment failures

Most documented impoundment failure events entail failures of the dams or embankments of the impoundments. Quite frequently these follow storm events that suddenly and drastically increase the load of the impounded material on the dam and, following the breach, lubricate the flow of the fine material. In such cases the potential flow properties, or rheology, of the slurry may become considerably different from what they were prior to the storm event. Such cases provide little information about the potential rheolology of impounded refuse that may flow into an underground mine. Two possible exceptions follow.

- **The Martin County Coal Company, Big Branch surface impoundment breakthrough in Martin County, KY:** Several studies of this breakthrough event concluded that it resulted from water seeping through a thin barrier to an underground coal mine and weakening the barrier to where it could no longer withstand the stress exerted by the coal slurry {MSHA, 2001; National Academies of Science and Engineering (NASE), 2003}. Under this scenario, it may be an open question as to whether the slurry itself flowed into the mine, or was piped into it by clear water. Short an answer, we know nothing of the refuse rheology prior to the breakthrough. However, two documents question the significance of the seepage effect (Thacker et al., 2002; Hagerty et al., 2004). Using finite-element seepage analyses, they attempt to demonstrate that the proposed sequence of seepage, barrier weakening, and breakthrough should not have occurred. Their alternative conclusion is that the hydrostatic pressure from the impounded slurry and rainwater surcharge was sufficient to push through the barrier (i.e. without the assistance of seepage). If that is correct, then the hydrodynamic pressures at the time of the breakthrough, size of the conduit to the mine, and initial slurry rheology were enough for the flow to begin.

- **Failure of the Los Frailes tailings dam:** An example of tailings flow without the assistance of clear-water piping is available from the web site: http://www.antenna.nl/wise/uranium/mdaflf.html. The failure of the Los Frailes tailings impoundment in Aznalcollar, Spain in 1998 involved a breach of the dam. However, the mechanism of the breach was a bearing failure in the dam foundation, composed of impervious Tertiary marl, in response to extra stress buildup from water above the fine tailings during a heavy rain. The tailings flow is depicted as initially following the slide of the foundation material from underneath impoundment.

Studies of coal refuse, tailings, and coal-water rheology

Rheology is the study of the deformation and flow of matter. Rheology of suspensions, such as coal-refuse, tailings, and coal-water slurries, depends upon several factors, such as solids content, grain-size distribution, temperature, mineralogy of the solids, and chemistry of the water. Some related publications that we have acquired report technological developments in pipeline transport of coal-water slurry and slurry in

general. The technological challenges in coal-water transport include: (1) a balance between greater slurry density (more coal solids per unit of slurry) and lower viscosity (for ease of pipeline flow); and (2) limiting sedimentation in the pipelines. The chemical additives used to achieve those objectives and other differences between coal-water and coal-refuse slurries limit the applicability of specific rheological models of the former to the latter (see footnote 7). However, the general principles and factors documented for coal-water flow behavior should be relevant to other viscous fluids, including coal refuse.

We were unable to find papers specifically related to the pipeline transport of coal refuse, nor any work that provided data on the potential flow behavior of impounded coal refuse. Collected work on the rheology of refuse and tailings is limited to a few papers on the modeling of downstream slurry flow following an embankment failure. The findings of our literature search follows:

- **Viscosity:** Viscosity is the ratio of shear stress and shear rate during flow. Informally, viscosity is described as the quantity that represents a fluid's resistance to flow. Generally, the viscosity of liquids decreases with increasing temperature and increases under very high pressures. Viscosity increases with solids percent and decreasing mean particle size (Atesok et al., 2002).

- **Newtonian vs. non-Newtonian fluids:** Viscosity is constant for all shear rates in a Newtonian fluid. Thus, its flow curve in a graph is a straight line passing through the origin (Figure 4). For non-Newtonian fluids, viscosity changes with shear rate and is called the apparent viscosity at any particular shear rate. The apparent viscosity increases with shear rate for a dilatant fluid, and decreases shear rate for a pseudoplastic fluid. Dilatant and pseudoplastic fluids are also called shear thickening and shear thinning fluids, respectively. Bingham-Plastic fluids exhibit a yield stress, that is, they do not begin to flow until a critical shear stress is reached (Figures 4 and 5). A yield stress can also be exhibited by a pseudoplastic fluid.

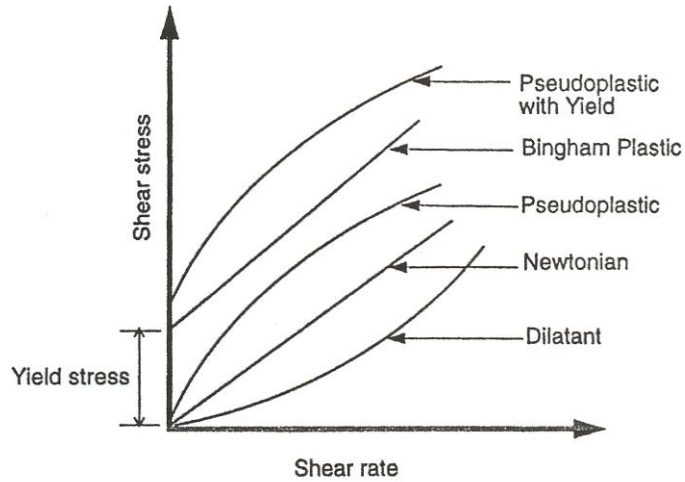

Figure 4: Basic types of rheological behavior.
(Kawatra et al., 1995)

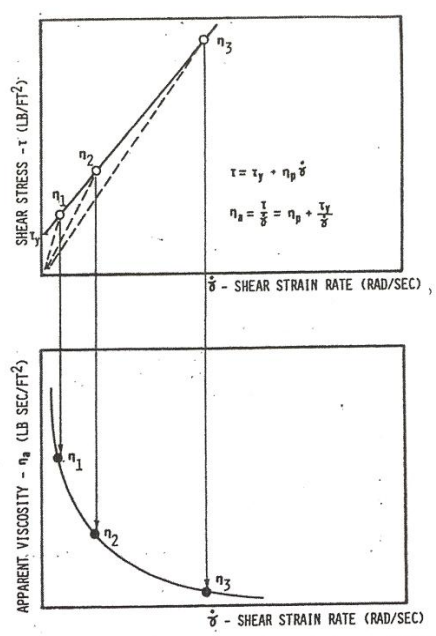

Figure 5: Apparent Viscosities for a Bingham-Plastic Fluid.
(Jayapalan et al., 1983)

The four most common flow models used in pipeline design for nonsettling slurries are: Newtonian, Power-Law, Bingham Plastic, and Generalized Bingham Plastic (or Herschel-Bulkley). Their underlying equations are shown in Table 1.

Flow Model Name	Equation	Parameter Symbols, Names and Units
Newtonian	$\tau = \eta\dot{\gamma}$	η = viscosity, Pa-s
Power Law	$\tau = K\dot{\gamma}^n$	K = consistency coefficient, Pa-s^n n = flow behavior index
Bingham Plastic	$\tau = \tau_{yB} + \eta_B\dot{\gamma}$	τ_{yB} = Bingham yield stress, Pa η_B = plastic viscosity, Pa-s
Generalized Bingham Plastic (Herschel-Bulkley)	$\tau = \tau_{yHB} + K\dot{\gamma}^n$	τ_{yHB} = Herschel-Bulkley yield stress, Pa K = Herschel-Bulkley consistency coefficient, Pa-s^n n = Herschel-Bulkley consistency coefficient

Table 1: Common rheological models used for slurry flows.
(Heywood et al., 1999)

An example study in the Newtonian vs. non-Newtonian behavior of coal-water slurries is that of Kawatra et al. (1995). They distinguished Newtonian vs. non-Newtonian samples of coal-water mixtures with various properties with two different lab instruments that measure viscosity at small and large shear rates. If the apparent viscosities from the two instruments were similar, the material was considered Newtonian, otherwise non-Newtonian. Among all the parameters affecting slurry rheology, they found percent solids to be the most important. At low percent solids (by weight) most samples exhibited Newtonian flow properties, but as solids content increased to greater than 20 percent, particle-to-particle interaction became important and the slurry changed to non-Newtonian.

Usui (1998) developed a thixotropic model for non-Newtonian flow of coal-water mixtures. The Model is based on a multi-breakup of inter-particle bonding, assuming a particle cluster chain breaks into two parts under simple shear during flow. The drag force exerted from shear is quantitatively compared with the bonding strength of the cluster, based on the estimated number of bonding-cluster chains crossing a break-up surface.

- **Laminar vs. turbulent flow:** It is known that the characteristics of flow vary with velocity. When the velocity is below a certain critical value, the flow is laminar, and when the velocity is above the critical value, the flow becomes turbulent. Laminar flow is relatively smooth, i.e. the streamlines or fluid elements of the flow follow paths that are somewhat straight and parallel to channel walls.

Under this condition, head loss or frictional resistance to flow is inversely proportional to flow velocity. By contrast the fluid elements in turbulent flow move randomly relative to the general direction of flow, and head loss is influenced by the roughness of the channel walls (Figure 6). A Reynolds number {a dimensionless parameter that is the ratio of the inertial forces (product of the flow velocity and dimensions of the channel walls) divided by the viscosity of the fluid} between 2,000 and 4,000 is accepted as the critical value, above which the flow becomes turbulent, in the case of Newtonian fluids.

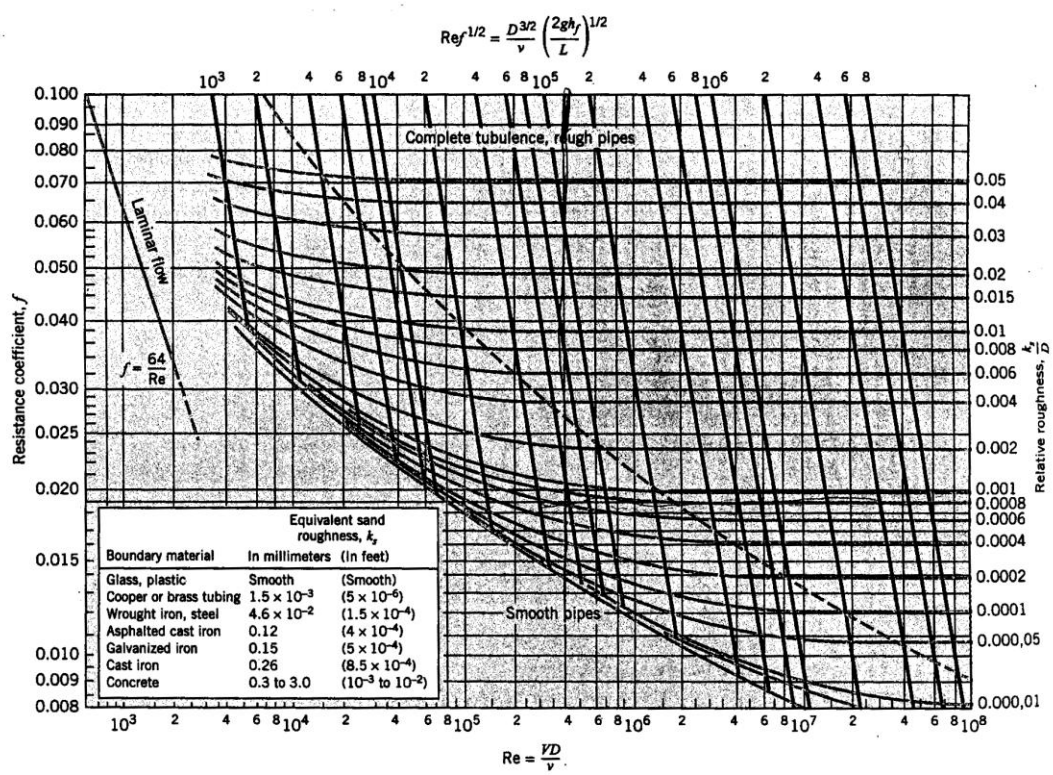

Figure 6: Moody's Diagram
(Robertson et al., 1997)

Vlasak et al. (1999), Turian et al. (1998), and Heywood (2003) have studied the transition between laminar and turbulent flow for coal-water slurry pipeline conveyance, and its effect on the relationship of either mean flow velocity or Reynolds number and frictional pressure loss in a pipe (Figure 7). Instrumentation used for measuring slurry flow characteristics have been described as: tube viscometers with three different pipe diameters (Vlasak et al.); and a capillary viscometer and Brookfield viscometer (Turian et al., 1998). The authors also utilized or tested a variety of models representing non-Newtonian flow behavior. Turian et al. and Vlasak et al. each applied separate models for laminar and turbulent flow.

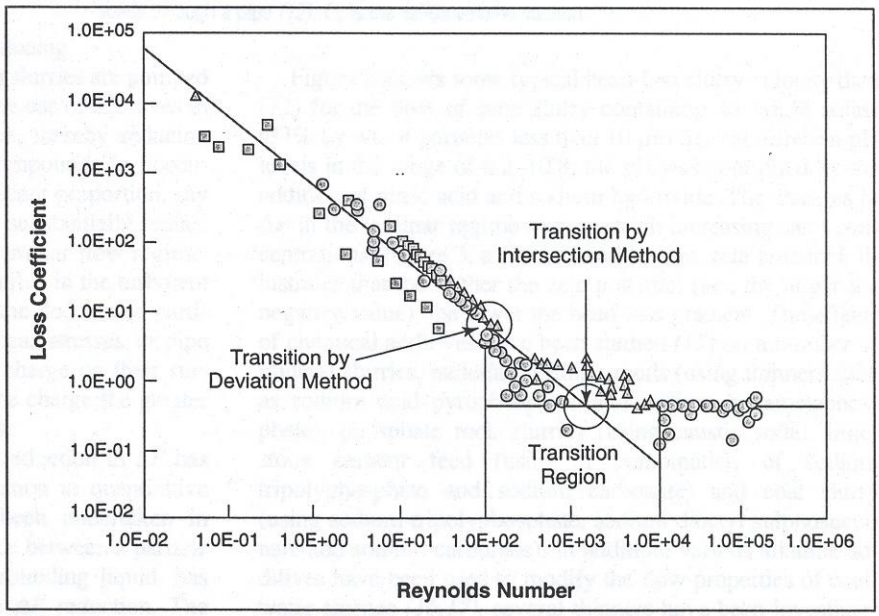

Figure 7: Head loss vs. Reynolds number showing the change from laminar to turbulent flow.
(Heywood et al., 2003)

Hanks and Pratt (1967) made a detailed analysis of a large amount of published experimental data on tailings and proposed the chart shown in Figure 8 for determining the laminar-turbulent transition conditions for Bingham-Plastic fluids. In this chart, the critical Reynolds number for transition from turbulent to laminar flow is expressed in terms of the "Hedstrom number" (a ratio among various standard flow variables and Bingham-Plastic parameters).

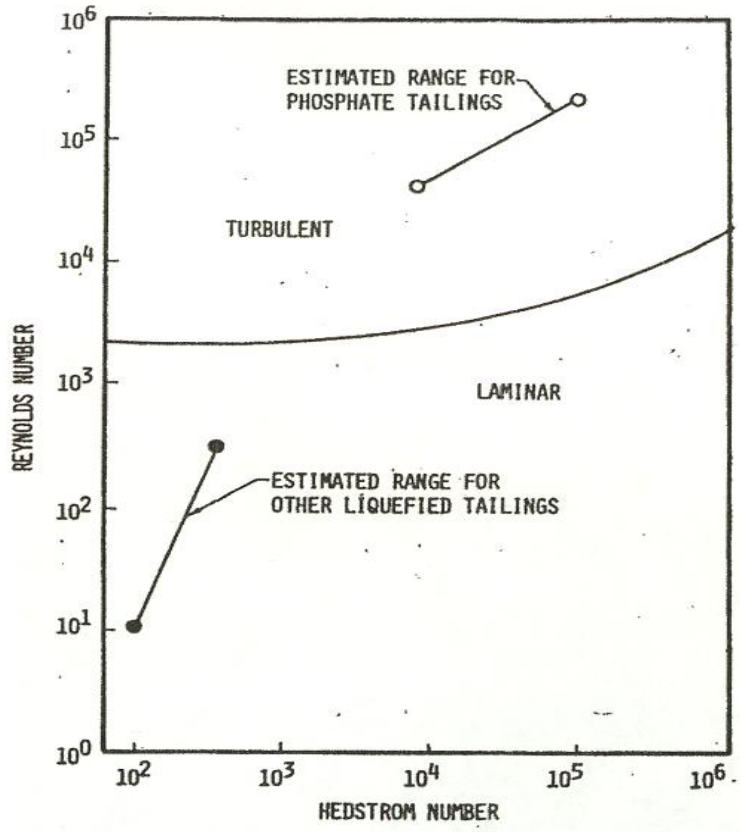

Figure 8: Variation of Critical Reynolds Number for Bingham-Plastic Fluids. (Jeyapalan et al., 1983).

- **Prediction of down-stream coal-refuse and tailings flow following an impoundment failure:** Noting the tendency of impounded mine refuse and tailings to liquefy and flow over substantial distances after a dam failure, Jeyapalan et al. (1983) cited the importance of predicting the velocity, depth, and extent of a hypothetical flow. They developed a prediction system based on the Bingham-Plastic flow model. Predictions based on the model were compared with flume experiments and field cases (including the 1972 Buffalo Creek disaster in West Virginia). A similar (if not identical) model is available at the web site: http://www.antenna.nl/wise/uranium/ctfs.html.

  It is noteworthy that the Bingham-Plastic flow model was also applied to mudflows by Johnson (1970) and Vallejo, et al. (2003). Techniques developed by Vallejo et al. for measuring yield stress (or undrained shear strength) and viscosity for mudflows were a cylinder-strength meter device and a transparent, plexiglass channel, respectively. Whether this use of the model is validation for

its application to fine coal refuse and tailings partly depends on certain property similarities between the two types of substances. Bush et al., Greene, Wakeley, and Zeng have opined that it probably does apply (2004). Wakeley noted coal waste mineralogy, grain properties (size, shape etc.), and even the water content in some cases, would resemble flowing mud. The only indication we found that some other fine-refuse flow behavior might occur are the references to contractive behavior leading to liquefaction (see discussion on p. 5). Conceivably, if significant contraction continued to operate during flow, Pseudoplastic (or "shear thinning") behavior might take place (Figure 8).

Findings concerning the rheological properties of impounded coal refuse

Our review did not find any empirical data on the rheology of impounded coal-refuse. A few papers indicate that the Bingham-Plastic flow model may be applicable to refuse flow. However, it is apparent that the rheology of viscous fluids is influenced by a complex interrelationship among a number of factors; it is possible that one model may not fit all impoundments--or even all locations within any one impoundment. Further, a model is only a relationship among constants and variables, i.e. it cannot tell us how the refuse of a specific, existing impoundment might respond to an opening to an underground mine.

Future Study

All of the commenters have stated that further work needs to be done on the strength and rheological properties of impounded fine coal refuse. Our description and assessment of their recommendations are organized into four categories, as follows:

1. **Review studies related to other materials:** Our review to-date has focused on coal refuse (the subject material of our report), mineral tailings, and coal-water pipeline slurries—with the exception of two works on mudflow. Greene recommended additional attention to studies on mudflow. Drumm indicated that rheology studies in ceramics, refractory clays and pharmaceuticals might provide applicable insight into the strength and flow properties of refuse. Finally Greene and Vallejo referenced books or papers on the properties of soils in general that they considered warranting our review. All of these can be easily done by OSM staff, of course, given adequate time and prioritization. However, we feel that little will be gained if the extra effort is not made in tandem with hands-on field and lab analyses of fine coal refuse. The applicability of a prima-facie promising model for mudflows or ceramics cannot be determined without testing them on refuse.

2. **Conduct empirical analyses on the strength and flow properties of fine coal refuse:** Most of the commenters have recommended lab and in situ testing of the consolidation, shear strength, liquefaction potential and rheology of fine coal refuse. They posited that the scope of the testing should cover variations in water

content, mineralogy, and grain properties; and account for variable conditions among different impoundments and within the same impoundment. Bush et al. indicated a need to assess some of the relevant testing techniques themselves by citing the pros and cons of using the in situ van shear test vs. the lab triaxial test for measuring refuse shear strength. Finally, Zeng suggested the use of centrifuge or other small-scale devices to simulate refuse reaction to a mine breakthrough.

We are aware of several other geotechnical techniques from the literature that would also be potentially useful to a follow-up study OSM might decide to undertake. Given the aforementioned uncertainties pertaining to the strength and flow properties of impounded coal refuse, we support the concept of cost-effective on-site and/or lab testing to determine the range of conditions of impounded fine refuse. However, given the numerous optional approaches and tools available, the project would have to be carefully developed to maximize the utility of the results. We suggest a Request for Proposals approach in order to procure the best expertise possible to carry out such a study.

3. **Model impounded fine coal refuse response to a breakthrough into an underground mine:** Drumm, Fourie, and Zeng recommended either a search for the most applicable model for coal refuse flow or development of a new one. They suggested that a model should account for differences in solid composition and water content. Drumm recommended construction of a comprehensive model that incorporated both pre-flow shear strength and flow behavior, and encompassed not only fine refuse rheology but also stress state in the impoundment and the geometric constraints of a breakthrough. He also suggested that probabilistic methods be employed to account for uncertainties such as the depth and configuration of the underground mine.

   We feel that the development or adaptation of a model to simulate coal refuse impoundment breakthrough scenarios would be useful as long as it ultimately provided: (1) a useful tool for ensuring impoundment stability; or (2) assisted in developing an effective emergency action plan in the case of a breakthrough. We cannot be sure, at present, if those conditions would be satisfied. Undertaking such a project would necessitate the first two recommended actions above, i.e. more extensive literature review and empirical data gathering. We recommend that future work that may include modeling involve a phased approach in which the value of model development would be assessed from the results of test data analysis.

4. **Review refuse impoundment construction practices:** Superfesky et al. (2005) have identified several issues with respect to current impoundment construction practices as they potentially affect structural stability. Two of them, (1) upstream construction of the impoundment and (2) slow drainage of the fine refuse, have been identified in this report and have our endorsement. Another concern is the building of excess spoil fills on top of old refuse impoundments. This practice potentially jeopardizes the stability of both the impoundment and valley fill from

surcharge effects and potentially weak foundation conditions, respectively. We agree that the extra load induced by a valley fill can significantly increase the likelihood of a breakthrough into an underground mine, if one underlies an impoundment. The two remaining issues, (1) inadequate compaction of the course refuse embankments of slurry impoundments and (2) construction of impoundments on top of excess spoil fills, do not pertain to underground mine breakthroughs. However, it should be kept in mind that the flow characteristics of refuse following an impoundment-embankment or foundation failure are every bit as important as those following a mine breakthrough.

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TECHNICAL ASSISTANCE REPORT TO:
THE APPALACHIAN REGION MANAGEMENT COUNCIL

The Flowability of Impounded Coal Refuse

A review of recent work and current ideas in the engineering profession

Appendix: Comments on the August 31, 2004 Draft Report.

(Presented in alphabetical order according to commenter's last name).

Bush, S.C.

ERNIE FLETCHER
GOVERNOR

LAJUANA S. WILCHER
SECRETARY

COMMONWEALTH OF KENTUCKY
ENVIRONMENTAL AND PUBLIC PROTECTION CABINET
DEPARTMENT FOR NATURAL RESOURCES
FRANKFORT, KENTUCKY 40601
SUSAN C. BUSH
COMMISSIONER

June 4, 2004

William J. Kovacic
United State Department of the Interior
Office of Surface Mining Reclamation and Enforcement
2675 Regency Road
Lexington, KY 40503-2922

OSM LEXINGTON
JUN 14 2004

Re: Comments on Draft Literature Review
"The Flowability of Impounded Coal Refuse"

Dear Mr. Kovacic;

Thank you for the opportunity to review and comment on the draft report on "The Flowability of Impounded Coal Refuse". The Kentucky Department for Natural Resources offers the following comments.

The purpose of the report, as defined by it's own sub-title, was to review recent work and current perspectives in the engineering profession with regard to the flowability of impounded fine coal refuse. The report was successful to the extent that it provided an informative, and fairly comprehensive, summary of the literature and current thinking regarding soil mobilization.

The report further articulated a number of problem areas, including the need for further testing of coal refuse rheology, the fact that thixotropic refuse may appear stable prior to mobilization, the absence of any empirical data on the rheology of impounded coal refuse, and the difficulty in modeling the extremely complex inter-relationship given the variable conditions encountered in different impoundments.

These very valid concerns call for further consideration. It is felt that the report should contain either specific language outlining a course of further study, or at a minimum, put forth a recommendation for an ensuing report to address the issue of further study mechanisms.

Additionally, we offer the following specific commentary regarding the technical issues addressed. In accordance with the report's "Summary and Introduction," these comments exclusively address impounded coal refuse and the associated impounding structures. These comments do not consider non-impounding disposal structure configurations.

The following comments relate to that section of the findings entitled "Question 1: What is the flow potential of impounded fine refuse?"

- It was noted that the term "pressure" was applied to the coal refuse "material." The term pressure is almost exclusively applied to materials behaving in a fluid form, which is continuous and immediate deformation resulting from any shear stress. However, the report acknowledges, and DNR agrees, that many partially consolidated slurries/fines behave similar to a Bingham plastic/fluid. That is, they are capable of resisting small shear stresses, mobilizing only under larger shear stresses. The ability to resist movement under shear stress is a solid material behavior characteristic. Accordingly, the term 'stress' should be used in lieu of 'pressure.'

- The report notes that "Matric suction tends to be more effective in materials with lower hydraulic conductivity". Typically settled fine coal refuse has an inherently low permeability, especially those at depths (where the concern of breakthrough is typically greatest). Therefore, in most instances, matric suction is not going to be of major concern in these analyses.

- Generally speaking, the refuse condition of greatest concern is fully saturated (as opposed to "partially" saturated). The moisture content in the saturated sample is very significant and is directly coupled to consolidation of the fine refuse in a completely saturated material. The in-situ moisture content is particularly relevant when considering testing of the fine coal material and the various testing methodologies, even as applied to the static (non-flowing) material testing (i.e. in-situ vane shear tests and saturated, un-drained, triaxial tests). This is addressed more fully in the following comment.

- The "Low shear strength of fine refuse and tailings in existing impoundments" should be highlighted and recommended for further investigation. It should be noted, however, that even though the in-situ strength may be low, the strength associated with the steady state seepage conditions might be substantially greater. Two common methods of testing the saturated fines material strength are direct vane shear testing and saturated, un-drained, triaxial tests. Each method has both advantages and disadvantages. The vane shear does allow for in-situ testing under actual field conditions. Therefore, saturation, moisture content, and

consolidation are fully representative. However, this testing is more analytical in nature and does not usually represent the material in its 'steady-state seepage' condition. (DNR regulations stipulate demonstration of safety factors at steady-state seepage condition.) Therefore the vane shear tests may be overly conservative. Triaxial testing is prone to consideration of complete consolidation, which could yield higher strength characteristics than actual field conditions. This testing literally establishes parameters representative of the long-term 'steady-state seepage' condition, but it is uncertain how long it will take to reach this seepage state. Therefore, for all practical purposes, this methodology may not be representative. It is important, when performing the triaxial tests, that the sample is tested at a 100% saturated state and that the confining stresses need to be representative of the field loading conditions (due to the true curvilinear Mohr's failure envelope). As noted in the report, small fluctuations in the moisture content can greatly affect the un-drained strength in partially saturated samples. Consequently, a higher applied total stress is required to decrease the voids, subsequently forcing the pockets of air into solution within the pore space water. If a partially saturated sample is inadvertently tested and considered as saturated, or if the confining stresses are too low, it may yield an artificially inflated material strength.

- The report notes (on page 7) that "Wick drains are closely-spaced artificial vertical drainage paths to which pore water can flow...". A review of the referenced site reveals this to be an accurate recounting of the site's description of these drains. However, it should be noted that wick drains are commonly installed in slurry impoundments using horizontal placement, with the drain outlet discharging into a perimeter rock drain.

The following comments relate to that section of the findings referenced as "Question 2", addressing the nature of flow into an underground mine.

- The description of the Reynolds number (Re) as a direct separation of laminar and turbulent flow at a value of 2000 is incorrect. As a very basic rule of thumb, a Re at or below approximately 2000 is laminar flow and a Re at or above approximately 4000 is turbulent. (While not uniformly accurate, this is an acceptable standard for basic flow theory.) The area between these values is considered a transitional flow regime. Pictorial clarification can be gained by examining the Moody or the Nikuradse graphs showing the relationships of the friction factor, relative roughness, and Re. Note that the Nikuradse graph provides more detail in the transition zone, although being able to predict the flow behavior within this zone is difficult. The most familiar empirical equation in the US using these graphs is the Darcy-Weisbach equation, which relates frictional head loss to the square of the mean flow velocity. These graphs coupled with the

Darcy-Weisbach equation are an effective way to show the empirical relationship of head vs. velocity and its relationship to Re and relative roughness.

- The text also states that for turbulent flow the "...friction force...increases with the square of the velocity." That is not necessarily accurate, though seemingly supported by equations like the Darcy-Weisbach, Chezy, etc, (which relate the head loss to the velocity squared). It is valid relationship for high Re flows, where turbulence is fully established, but not necessarily for lower Re values. A review of the Moody or the Nikuradse graphs shows that when the Re increases the relative roughness curves start becoming horizontal, leading to an approximately constant friction factor. This is the only region that the head loss is approximately, directly proportional to the square of the velocity. The friction factor is not a physical property relating to the pipe. It is an empirical value used to satisfy the head loss, velocity squared relationship. The relative roughness and the Re, which are used to obtain the friction factor, are physical properties associated with the flow. In actuality, the flow behavior can be described as head loss proportional to velocity raised to a variable. This variable can range from 1 to 2. Note that for laminar flow the empirical friction factor is 64/Re and Re is directly proportional to the velocity making the velocity exponent variable equal to 1. As the Re increases beyond the laminar flow regime, the relationship changes and the velocity exponent variable increases and approaches 2.

If you have any questions regarding our comments, you may contact me at (502) 564-6940 or Larry Adams at (502) 564-2320.

Sincerely,

Susan C. Bush

Susan C. Bush, P.G.
Commissioner

c: Larry Adams

United States Department of the Interior

OFFICE OF SURFACE MINING
Reclamation and Enforcement
530 Gay St., S.W., Suite 500
Knoxville, TN 37902

JUL 23 2004

Memorandum

To: Mike Robinson, Chief
Program Support Division

Through: Douglas K. Siddell, Acting Field Office Director
Knoxville Field Office

From: Danny Rahnema, Civil Engineer
Knoxville Field Office

Subject: Review of Current Information on the Flow Characteristics of Impounded Coal Refuse

As requested, we asked Dr. Eric Drumm, Department of Civil and Environmental Engineering at The University of Tennessee to review and comment on the subject technical report. Attached is Dr. Drumm's feedback.

Attachment

THE UNIVERSITY OF TENNESSEE

Department of Civil and Environmental Engineering
223 Perkins Hall
Knoxville, Tennessee 37996-2010

July 1, 2004

RECEIVED
JUL - 7 2004

Danny Rahnema, Civil Engineer
Office of Surface Mining
Reclamation and Enforcement
530 Gay Street, S.W., Suite 500
Knoxville, TN 37902

Dear Mr. Rahnema,

As per your request, I have reviewed the OSM Draft Report – May 4, 2004 "The Flowability of Impounded Coal Refuse." The document presents an extensive review of previous research related to the rheology of coal refuse as it affects the flow of refuse during a potential basin breakthrough. Below I have listed several aspects that in my opinion warrant additional research.

- Limited data on the rheological properties of coal refuse are available, and only slightly more data exists on the coal-water slurries. It would seem appropriate to conduct an investigation into the properties of refuse, and try to identify how the rheological properties vary from impoundment to impoundment, and within a given impoundment.

- Several rheologic models are discussed, but it may be appropriate to investigate the applicability of rheological models for particulates that have been developed in other fields within the broad discipline of materials science. Specifically, models developed for ceramics, refractory clays, and pharmaceuticals may hold promise. Obviously, this should be done in cooperation with researchers who understand the unique problems associated with coal refuse.

- While a single model (such as the Bingham-plastic) may adequately represent the rheological response of coal refuse, it would be expected that the parameters for this model will vary widely within a given refuse embankment. Further, since the refuse will transition from solid to fluid based on the pressure in the pore fluid, models incorporating the fluid phase should be investigated. The review noted the importance of the matrix pressure or suction in unsaturated refuse. It is possible that a more general model which incorporates the frictional strength as well as the viscous response may be found.

- Because of the spatial variability of refuse (due to the changes in depositional environment and different stress levels), a simple insitu test method would be desirable. Although lab testing is more common, sampling disturbance and the thixotropic characteristics of refuse suggest that it would be preferable to measure

Phone (865) 974-2503 FAX (865) 974-2669 e-mail: cee@utk.edu web: www.engr.utk.edu/civil/

the rheological properties in place. The insitu measurement of strength, compressibility, and permeability is common in geotechnical engineering practice, and this is a very active research area. Extension of current technologies to measure the rheologic properties in situ would seem natural.

- While not expressily within the scope of the review, little discussion is devoted to the types of information needed to conduct an analysis of the breakthrough stability. Since the flow properties of the refuse will depend upon the stress state that exists around the area of the potential collapse, both the geometry of the breakthrough and the rheology of the refuse must be modeled correctly. It would seem appropriate that probabilistic methods be employed in the breakthrough analysis (and perhaps in the modeling of the refuse) to account for the uncertainty with respect to roof thickness, roof span or pillar spacing, etc. The most sophisticated model for refuse flow will not provide meaningful results if it is not subjected to the stress, pore fluid, and geometric constraints that may exist around the collapse zone.

The draft review was very well prepared, and the authors are to be commended for a thorough piece of work. The flow of refuse is not a trivial problem, and the analysis of these materials at the transition from solid to fluid is complex. My comments are offered in a constructive manner, and I would be happy to discuss this further if additional questions arise.

Sincerely,

Eric Drumm, P.E., Ph.D.
Professor, Department of Civil and Environmental Engineering
The University of Tennessee
Knoxville, Tennessee 37996-2010

voice: (865) 974-7715, email: edrumm@utk.edu

Peter Michael

From: Andy Fourie [andyf@civil.wits.ac.za]
Sent: Monday, July 05, 2004 11:34 AM
To: Peter Michael
Subject: [Fwd: RE: Request for assistance--review of draft report.]

Attachments: Andy Fourie.vcf

Andy Fourie.vcf
(225 B)

Hi Peter

I have now had time to re-read the review and would like to offer the following comments (I have put them in bullet form for convenience - please feel free to come back to me on any issues that you would like to discuss further).

- I agree that the approach of using previously reported studies on coal refuse must be used with caution. Each site is likely to be different and it is important (I would suggest vital) to carry out relevant tests (both laboratory and in-situ if necessary) to adequately characterise a particular deposit. Although an empirical approach, using results from previous studies, is useful for benchmarking purposes, it is not reliable.

- A parameter that addresses much of what is discussed in the document is the coefficient of consolidation. This is directly proportional to permeability and indirectly proportional to compressibility - it thus includes the two effects you discuss, but in one parameter. There are very simple and routine tests for measuring this parameter. Check it out in any geotech handbook.

- The rate of rise is a crucial factor in determining the stability of any tailings impoundment and is directly related to the coefficient of consolidation.

- Although you do not say so explicitly, I think you have identified the two key factors that need to be considered when looking at the risk scenario sketched in your report: one - is a particular material susceptible to liquefaction, and two - if something occurs to trigger liquefaction of this material, what will the consequences be (ie how far, fast and deep will it flow?).

The first of these factors (is it susceptible to liquefaction) is governed by the relative values of in-situ density (or void ratio) and effective stress. Although underdrainage is extremely beneficial, a tailings deposit can be fully drained and yet still susceptible to liquefaction. It all relates to the conditions under which deposition occurred and the 'fabric' that thus developed. For example, sub-aqeous (below water) deposition will result in a much lower density than sub-aerial deposition, even when the deposit is fully consolidated. This may be somewhat counter-intuitive but is a true phenomenon. Such material then behaves in a contractive fashion when loaded undrained, causing spontaneous liquefaction. I have taken the liberty of attaching two papers of ours that discuss this issue and relate it to a failure that occurred in South Africa in 1994. One remaining problem is that although we can determine whether a particular material can exist in a so-called metastable state (ie susceptible to liquefaction) by carrying out laboratory tests, we do not yet have the tools to determine whether material in a particular deposit is in such a state. To my mind there is an urgent need to develop these in-situ testing techniques.

The second factor, how far, etc will it flow is one that has not been adequately addressed. It is not presently possible to carry out an adequate risk analysis with the tools at our disposal. The techniques you suggest (such as those described by Jeyapalan et al and on the wise website) are probably the best we have, but are inadequate. Much more work needs to be done (as you mention) on the rheology of mine waste before really good models of flow failure are possible. We have done some work on one aspect of this (the yield stress) and I attach a paper describing this work.

- Moving on: caution must be exercised when considering the use of wick drains. They will usually only be of benefit if their installation is followed by the placement of a surcharge load (eg a sand fill), because they require the existence of an excess pore pressure to cause flow of water to the drains, ie they are essentially a passive system. Although there may be instances where the tailings is not fully consolidated and wick drains may be of some use, it is quite likely that in most cases they will have little impact without the construction of an expensive surcharge.

- I agree that the effect of matric suction is likely to be minimal, especially in the application you mention, where a breach is envisaged below the deposit base. This material will be below the phreatic surface and thus effectively saturated. Suction has no role in this case.

I hope the above is of some use - please come back to me with any questions.

Now my turn: we have limited library facilities here and in fact there is not a single library in South Africa that subscribes to the journal Soils and Foundations. Would it be possible for you to fax me a copy (or send it electronically if you have it) of the paper by Vallejo and Scovazzo that appeared in Volume 43 in 2003 (its in your reference list)? Also, is there any chance of you mailing me a copy of the National Research Council report that is listed in your references?

I look forward to hearing from you.
Postscript to this message: I sent this message, with 3 attachments, but it bounced back, indicating that the message was too large for your system. What size messages can you receive? I will email the 3 papers separately if necessary.

Andy Fourie
Department of Civil Engineering
University of the Witwatersrand
Private Bag 3, WITS 2050
South Africa
Tel +11-717-7108
Fax +11-339-1762

>>> "Peter Michael" <PMICHAEL@osmre.gov> 06/28/04 08:48PM >>>
Hello, Andy.

This is just a follow up to our previous communication concerning your willingness to review our (U.S Office of Surface Mining's) draft refuse flowability report. We do not have a looming deadline, but a word from you as to the status of your review would be most appreciated. If you have any questions, please let me know.

Again, I'm very greatful for your help.

I hope all your students past their examinations with flying colors!!

Regards

Peter Michael
Geologist
U.S. Office of Surface Mining
3 Parkway Center
Pittsburgh, PA 15220
412-937-2867
pmichael@osmre.gov

>>> Peter Michael 5/24/2004 8:46:05 AM >>>
Sounds terrific!! I appreciate this very much, Andy.

Best,

Peter

>>> "Andy Fourie" <andyf@civil.wits.ac.za> 5/24/2004 1:07:01 AM >>>
Hi Peter

Good to hear from you.

For work of this type I do for companies in South Africa I do request compensation (academic salaries in South Africa are rather poor).
However, if your organisation does not permit payment for this type of review, too bad. I am happy to review it without compensation, but do need a little time as we are about to go into a very heavy examination period. I should be able to complete it by about 21st June. Sound OK?

Regards

Andy Fourie
Department of Civil Engineering
University of the Witwatersrand
Private Bag 3, WITS 2050
South Africa
Tel +11-717-7108
Fax +11-339-1762

>>> "Peter Michael" <PMICHAEL@osmre.gov> 05/21/04 05:35PM >>>
Dear Dr. Fourie:

I'd like to follow up on Dr. Shackelford's kind response to my query (below) by asking you if you would be able to review our draft report on coal-refuse flowability (see attached).

Since I don't know your affiliation, it is possible that you would require compensation for your services. In that case, I must apologize that this assignment does not have a budget, but gladly offer the attachment as a professional courtesy, fyi.

Sincerely yours,

Peter

REVIEW OF DRAFT REPORT

DATE: July 1, 2004

REVIEW BY: Brian H. Greene, Ph.D.
Engineering Geologist

SUBJECT: DRAFT Report titled The Flowability of Impounded Refuse, A review of recent work and current ideas in the engineering profession, by Peter Michael, Raul Marguia, and Lisa Kosareo from OSM Pittsburgh

COMMENTS:

1. Page 1. Suggest that the section Introduction be retitled Purpose of Study, or Objectives of the Study. This would seem to better fit what is being presented in this section.

Page 2. Suggest changing section title from Findings to Statement of Problem. In the first sentence under Question 1, suggest rewording to "...the strength and flow mobility characteristics of the refuse..."

Page 3. 1st sentence at top of page. Suggest adding to end of sentence "and the subsequent reduction of void space between soil particles."

Page 3. Moisture Content: I totally agree that the undrained shear strength of partially saturated fine grained coal refuse is very sensitive to moisture contents. Moisture content will be the primary governing factor affecting strength. You have cited Huang et al., 1987 but I might suggest three additional potentially applicable references as well. Although not specifically involving coal refuse, these studies do address the behavior of soils and sediments as related to varying water contents.

Brooks, T.D., 2001, Effects of Molding Water Content on the Engineering Properties of Compacted Soils

Surrena, T, 1998 A Geotechnical Investigation of the Failure of the Upper Ivex Dam with Special Emphasis on the Engineering Properties of the Reservoir Sediments

Bonner, C., 1996, Effect of Initial Water Content and Dry Density on the Swelling Potential of a Bentonitic Clay

Any of these theses can be obtained form the Kent State University Library, Inter Library Loan Program (330) 672-2670.

Page 3. Last Para. Consolidation Rate and rate of impoundment construction. Concur that it is critical that the rate of impoundment construct ion be accomplished in a controlled, slow manner permitting time for consolidation to occur with subsequent soil strength development. An excellent example of this from my own experience is the Corps of Engineers Michael J. Kirwan Dam (formerly West Branch Dam) located near Ravenna, Ohio. Due to rapid construction of the embankment founded on fine grained soils, failure occurred. Due to the rapid raising of the earthen structure, pore pressures were unable to dissipate and portions of the embankment failed.

Page 4. Matric Suction. Suggest that you define matric suction in the initial paragraph, much the same way you do for thixotrophy on the following page.

Page 4. Footnote 3. You mention that seismic activity may cause liquefaction, and that "static liquefaction" can occur from a load increase or loss of foundation support... An excellent example of static liquefaction would be with the Rissa Landslide which took place in Norway and was captured on film. I am mailing to you a copy of the video that you can keep. It portrays how sensitive soils can completely loose their shear strength and flow for great distances. In the case of the Rissa slide, the trigger was a load increase on the soils due to the creation of a small embankment. The soils were fine grained silts and clays of marine origin having very high water contents. The video provides a summarization of engineering properties based on testing at the Norwegian Geotechnical Institute laboratories. This is video is not readily accessible. I have made you a copy of my file copy to keep. I think you will find it fascinating and hopefully relevant to your research into the flowability of impounded coal refuse.

Page 7. Last sentence cites that "wet thixotropic refuse may appear to be stable under static conditions before changing to a liquid state when agitated.". The Rissa Landslide would fully support this finding. Sensitive soils or refuse can be liquefied by agitation or simply by the application of additional loading as you describe as "static liquefaction" on page 4. The Rissa experience would indicate that the remolded shear strength of such materials dramatically decreases with disturbance (or agitation) until it reaches zero (i.e. when in a liquid state).

Page 8. Martin County Coal Company event. It seems confusing as to which study relates to which agency. Are the MSHA findings tied to Thacker, 2002; and are the NASE findings related to the study by Hagerty, et al., 2004?

Page 8 through 11. Your descriptions of viscosity and fluid behavior as applied to coal refuse coal-water mixtures is very clear and concise. I concur that the behavior of fine coal refuse would be <u>best</u> described by the Bingham-Plastic flow model.

Page 13. The Bingham-Plastic flow model applied to mudflows would appear to be closely related to behavior of fine grained coal refuse. Research is this area should provide the best comparable data that could be utilized for predictions of flow behavior of coal waste.

Page 13. Findings concerning the rheological properties of impounded coal refuse. The first sentence cites the total lack of empirical data of the rheology of impounded coal refuse. This would indicate that there is a strong need for laboratory testing. This should be done with trials based on different refuse compositions and varying water contents. There are local universities that have the equipment, or could fabricate the equipment, necessary to conduct such testing. One that I am aware of is the soil mechanics / engineering geology labs of Kent State University. If I can be of any assistance in exploring arrangements for this laboratory testing, I would be pleased to do so.

Michalek, S. J.

Comments on Office of Surface Mining Report
"Flow Characteristics of Impounded Coal Refuse Material"

By MSHA – Pittsburgh Safety and Health Technology Center
Mine Waste and Geotechnical Engineering Division
May 2005

MSHA's Mine Waste and Geotechnical Engineering Division has reviewed the draft report prepared by the Office of Surface Mining titled "The Flowability of Impounded Coal Refuse; A review of recent work and current ideas in the engineering profession." Our comments are provided below.

1. On page 6 under the "effects of additives . . . ," it is stated "Objectives of additive use include accelerating consolidation and increasing shear strength, and may also include viscosity reduction for pipeline transport to the impoundment." In our experience, mine operators generally are not concerned with increasing consolidation or improving shear strength. Rather, they want to accelerate the rate at which the particles drop out of suspension so that they can decant clear water.

2. The "slimes" of tailing dams used in the metal mining industry can be much finer than the fines in coal refuse impoundments. Direct comparison of the properties of the two materials may not be correct.

3. On page 8 of 17, the report mentions the progressive internal-erosion failure scenario that MSHA concluded caused the Martin County Big Branch Impoundment breakthrough incident. The report states, "Under this scenario, it may be an open question of as to whether the slurry itself flowed into the mine, or was piped into it by clear water." It is the opinion of one of the investigators of that incident that the piping that occurred at the Big Branch Impoundment was of the "seepage barrier" material, not the slurry itself. Once the internal erosion of the "seepage barrier" material created a "piping" opening that had worked its way up through the "seepage barrier" and close enough to the impoundment's pool, the pressure from the slurry broke through the remaining portion of the barrier and the water/slurry mixture flowed into the mine. It was primarily the soupy slurry near the top of the impoundment that flowed out, not the deeper, older fines lower in the impoundment. (Note that the approximately 300 million gallons that was released from the impoundment was only 22 percent of the total volume impounded above the level of the mine workings. When the flow was stopped, there was over a billion gallons of slurry still impounded – to a depth of 70 feet - above the level of the 1-C Mine.)

4. On page 3, the report indicates that inadequate drainage during refuse consolidation could result in liquefaction. MSHA also envisions liquefaction occurring by another mechanism. MSHA stated in their response to the National Research Council report on coal waste impoundments, "...if a subsidence event occurred underneath saturated, hydraulically placed fines, the sudden increase in shear stress in the fines would induce increases in pore-water pressure that could trigger "static liquefaction" and cause the fines to flow." Because of the danger of static liquefaction, until testing is performed to demonstrate the conditions under which slurry will and will not mobilize, we need to assume that the potential for liquefaction and flow exists in saturated slurry with low blow counts. A useful reference regarding the subject of static liquefaction is "Static Liquefaction of Tailings - Fundamentals and Case Histories," by Michael Davies, Todd Martin, and Ed McRoberts, Tailings Dams 2002, ASDSO, May 2002, Las Vegas, NV.

5. The report appears technically accurate. Unfortunately, it does not really shed any light on the issue of flowability. Some assumptions are made about what factors might be important in predicting and modeling flow. However, there are no conclusions as to whether these are the right factors or whether they can be determined for slurry.

Peter Michael

From: Morgan, Thomas [TMORGAN@osmre.gov]
Sent: Wednesday, March 16, 2005 9:26 AM
To: Mike Robinson
Cc: Jeff Wyrick; Mike Superfesky; Peter Michael; Roger W. Calhoun
Subject: Viscosity Report

Attachments: viscosity comments.doc

viscosity mments.doc (30 KB)

Mike, Roger asked me to have Mike Superfesky and Jeff Wyrick review the draft report and send you any comments we have. Their comments (combined and organized by me) are attached.

We think you are correct that the issue was related primarily to inactive and/or reclaimed impoundments, but there are liquefaction issues with active impoundments as well. The attached comments address both.

You also asked what we should do with the report. We think we should make it available to all technical agencies that actually review, inspect, oversight, and approve slurry and tailing impoundments. Even though the major concern remains unresolved, distribution of the report may help stimulate additional thought and input toward a resolution. We believe there is still to little coordination between MSHA, Office of Surface Mining, state regulatory authorities. Review documents and technical information about impoundments still are not shared between the agencies. This paper could serve as starting point for creating better coordination efforts. Trying to stimulate this interagency cooperation would be consistent with what OSM is attempting to do between the CWA program and SMCRA.

Let me know if you have any questions. - Tom

CHFO Comments on Draft Report on *The Flowability of Impounding Coal Refuse*
March 15, 2005

The report is a very professional and factual paper. Unfortunately (and not to the team's discredit), it was unable to resolve the concerns raised about the flowability of slurry in active and abandoned slurry impoundments. But it does reinforce our concerns about liquefaction. Since a definitive resolution could not be reached, we believe we need to complete more field and lab testing, with some modeling, as suggested in the last paragraph of the summary on page 1.

Any additional efforts should address the following concerns;

- Compaction standards should be addressed. Adequate compaction may not be achieved by using dozers. The only real compaction is when the large trucks provide pneumatic compaction as they haul and dump, but this is not usually uniform. Conveyor placement and dozer spread and compaction simply doesn't work. A lot of times during the winter months the moisture content of the coarse refuse is too high to even spread-let alone compact.

- The uncertainty of the upstream construction practice and its affect on pore pressure is a major concern. Should the impoundments be constructed like freshwater impoundments with large underdrains to be more conservative, but more expensive?

- The inability of the slurry material to free drain and de-water, even many years after abandonment, is another major unresolved issue.

- The fact that many old impoundments are being surcharged (loaded heavily from above) by spoil and valley fills being placed over the old slurry impoundment (which could already be over partially deep mined areas beneath the original impoundment is another serious concern.

- The fact that slurry impoundments, or in some cases, valley fills are actually being built on top of old spoil, without understanding the full implications before and after abandonment, is probably one of the most serious concerns. 30 CFR 816.71 (e) (3) prohibits permanent impoundments on excess spoil fills. Should this standard be expanded to abandoned spoil?

Peter Michael

From: Blumer, Ralph [RBLUMER@osmre.gov]
Sent: Friday, May 21, 2004 12:48 PM
To: Peter Michael
Subject: Slurry Flowability Paper, Meeting With Rick Sweigard, Univ of KY

On May 10, 2004, Bill Kovacic, Wendi Stephens, and I met with Rick at UK and discussed the paper.

Rick said that the paper was well written and did a good job referencing associated research. He did not offer any other research that could be used to further address the issue.

We discussed the potential for breakthroughs at the base of impoundment and also near the surface of the impoundment. His thoughts were that there would less potential for a breakthrough at the base because of the partial dewatering of the slurry at the base. This would especially be the case if an impoundment did not have a surface water pool.

TO: Peter Michael, OSM
FROM: Luis E. Vallejo, Dept. of Civil Eng., University of Pittsburgh
SUBJECT: Review of OSM Draft Report "The Flowability of Impounded Coal Refuse," By P. Michael, R. Murguia and L. Kosareo
DATE: July 2, 2004

The report is well written and covers a large portion of the geotechnical literature. However, a very important article about how soils similar to coal refuse gain in strength with time (aging) is not mentioned. This article is due to Schmertmann (1991). This article covers the subject of consolidation of soils with age and how aging affects their shear strength and their resistance to liquefaction.

Another article related to capillarity action on the resistance to liquefaction of soils that the authors of the report need to include is that by Wu, Gray, and Richart (1984).

The size of coal refuse particles is similar to that of silt. Silt does not respond well to compaction or consolidation. A discussion by Rogers, Dijkstra and Smalley (1993) needs to be reviewed by the authors of the report.

The flowability of coal slurry will depend on its permeability and shear strength. This last one being a function of viscosity and the yield strength.
Very little research has been conducted to date relating the permeability of coal refuse slurries and its flowability. Low permeability of the coal refuse will favor excess pore water pressures that cause the coal refuse to flow. The permeability of saturated coal slurries will be affected by the grain size distribution and the shape of the particles. Coal refuses are different depending of the plants and their location producing them. The reviewer agrees with the authors of the Report that permeability and rheological testing of various coal refuses is urgently needed in order to understand their flowability characteristics.

REFERENCES

Schmertmann, J.H. (1991). The mechanical aging of soils. Journal of Geotechnical Engineering, ASCE, Vol. 117, No. 9, pp. 1288 – 1330.

Wu, S., Gray, H., and Richart, F.E. (1984). Capillary effects on dynamic modulus of sands and silts. Journal of Geotechnical Engineering, ASCE, Vol. 110, No. 9, pp. 1188-1203.

Rogers, C.D.F., Dijstra, T.A., and Smalley, I,J. (1994). Discussion of: Human Factor in Civil and Geotechnical Engineering Failures. Journal of Geotechnical Engineering, ASCE, 120, No.8, pp. 1446-1447.

From: "Richard Volpe" <rvolpe@valleywater.org>
To: <PMICHAEL@osmre.gov>
Date: 7/20/2004 10:20:25 AM
Subject: FW: Draft refuse flowability report.

Peter:

I received your phonecall that you had not received a response from me. I sent you the following email on June 28. Good luck.

Dick

-----Original Message-----
From: Richard Volpe
Sent: Monday, June 28, 2004 6:05 PM
To: 'Peter Michael'
Subject: RE: Draft refuse flowability report.

Peter:

I had a chance to read your paper this afternoon and I am afraid that I can not help you very much. I can remember talking to Jey Jeyapalen when he was doing his doctoral thesis at UC Berkeley. You may want to talk to Mike Duncan, his thesis advisor, who is currently at Virginia Tech (jmd@vt.edu) to see if he can help, especially in the rheology aspects of tailings.

One of the things that I may have already mentioned to you that are very important attributes about "fine" coal refuse is its very low specific gravity, which averages less than 1.2. This, of course, is a direct result of it being derived from the washing of commercially viable coal. For any problem involving the seepage through fine coal refuse, its low specific gravity creates a significant potential problem due to the resulting critical gradient. As you are probably aware, the critical gradient (Icr) for flow through porous media is defined as Icr = (G-1) / (1+e); where G is the specific gravity and e is the void ratio. For most soils, with G=2.65 and e=0.65, the average Icr is about 1.0. I'm convinced that most geotechnical engineers think that the critical gradient for flow through porous media is in fact a given and the value is unity. Well as you can see from the above expression, with a G=1.2 and e=0.7, the average critical gradient for fine coal (especially at Buffalo Creek) was about 0.11, or only 11% of the "typical" value. This phenomenon was the likely reason for a "quick" condition developing in the fine coal tailings foundation under the coarse-grained downstream shell at Dam No. 3 that caused the failure at Buffalo Creek.

I studied another failure of a copper tailings dam in New Mexico (circa 1980) in which there was a major release from the tailings dam, but no one was killed. In this instance, although there was some controversy as to why the exterior shell of the dam failed (in typical fashion, the dam was being constructed using the upstream method of construction), it was pretty clear that the tailings liquefied due to strain-induced liquefaction. In typical fashion for the copper industry, the tailings were being deposited as a slurry. During this depositional process, the resulting slurry experiences a self-weight consolidation that may take hours or several days depending on the fines content. During this

process, the slurry material does not obey the laws of soil mechanics because the void ratios are so large that particles are not yet in contact with each other. The resulting slurry material obeys the laws of large-strain consolidation and is susceptible to rather large shear strains during normal operating conditions. Once the breach in the dam occurred, the tailings material behind the thin exterior shell began to deform and (I believe) developed a strain-induced liquefaction. The resulting tailings release (which did not involve the release of free standing water) flowed across the1/2 mile or so valley floor, sloshed up the opposite side, co-mingled with some water in the adjoining creek and flowed about 1.5 miles downstream.

Good luck with your draft report. I wish I could have been of more help.

Dick

-----Original Message-----
From: Peter Michael [mailto:PMICHAEL@osmre.gov]
Sent: Monday, June 28, 2004 11:25 AM
To: Richard Volpe
Subject: Draft refuse flowability report.

It's attached, per your request.

Thanks, again, Dick.

15 August 04
Wakeley/GSL

Comments on the OSM Draft Report Entitled
"The Flowability of Impounded Coal Refuse" by P. Michael, R. Murguia, and L. Kosareo
Comments prepared by The Geotechnical and Structures Laboratory (GSL)
U.S. Army Engineer R&D Center (ERDC)

The conclusions stated in the opening Summary section of the OSM draft report are valid and well supported by the literature review and by the discussions in the report. First, the authors state that pore water pressure strongly influences static liquefaction, a statement that is well supported not only in the literature they cite but also in the vast literature of earthquake engineering. Second, they note that not all coal-waste impoundments allow free drainage of excess pore water. Third, the flow behavior of coal waste is complex and cannot readily be modeled. And finally, even if the flow behavior of coal waste could be modeled, the geometry and geologic setting of an impoundment relative to a mine opening cannot be generalized, nor can it be predicted by a flow model.

The GSL reviewers offer the comments below in support of these four conclusions from the OSM draft report.

1. The flow properties of coal waste: The OSM authors found no studies that specifically address the rheology of coal waste, either in impoundments or in pipeline transport. They offer the possibility that application of the Bingham-Plastic flow model to mudflows may represent a condition similar to coal waste in an impoundment. Comparing the behavior of coal waste released from an impoundment to the behavior of a mudflow probably is valid. The mineralogy of coal waste, its grain size and grain properties, and even the water content of the waste in some cases, would resemble the properties of a mudflow.

2. Applicability of the rheology of coal pipeline slurry: The rheology of coal in a slurry pipeline is not an appropriate model for rheology of impounded waste. Coal- pipeline slurry has an extremely high water content. It is intentionally kept moving, and the solids are kept in suspension by the use of flow-controlling admixtures. There are industry-standard properties for coal slurry. The process of achieving the properties required to transport coal through a slurry pipeline is engineered and documented, and the resulting properties could be modeled. But the model would not be relevant to mine wastes. There are no industry-standard properties for waste. Flow properties are controlled by a highly variable and undocumented combination of factors including mineralogy, grain size and shape, and presence or absence of other processing chemicals. The water content is highly variable, possibly within a single impoundment and certainly among different geographic locations. The mineralogy and early-age water content are different for every mine and processing facility, as are the age and dewatering history. A model based on the flow properties coal-pipeline slurry might be achievable but is almost certainly irrelevant.

3. Applicability of the properties of waste from gold or other mineral mines: The mineralogy, grain size, grain shape, and other physical properties of mine waste are

attributable to the geologic setting of the substance that was mined. Coal usually is interbedded with shale and other sedimentary rocks. Separation of the coal from the enclosing rocks creates a waste that is rich in clay minerals and/or clay-size particles. Gold is associated with igneous and metamorphic rocks. Separating gold from its geologic setting creates a waste with small but hard and angular particles. The chemicals used to process gold also are different than those used in coal processing. Therefor the rheology of gold-mine waste is not an appropriate model for coal-mine waste.

4. De-watering and wick drains: The OSM authors noted that impoundments for coal wastes are not always constructed to allow adequate drainage of excess pore water. They have identified a factor that is not well controlled, but could be much better controlled to improve the safety of impoundments. They introduce the subject of wick drains in one paragraph. The GSL reviewers recommend further consideration of wick drains, an important geotechnical method to dewater construction sites prone to liquefaction (earthquake and landslide hazards). Additional information about wick drains is available at these websites (for information only, not an endorsement by the Corps of Engineers).

www.americandrainagesystems.com
www.americanwick.com
www.geotechnics.com
www.terrasystems-inc.com/wick.htm
mceer.buffalo.edu/research/HighwayPrj/ 094/TaskStatements/Year3/E2-1.html

5. Embankment failure and geometry of the impoundment: The water content of coal waste in an impoundment is a function of many variables, including but not limited to the type of processing at the facility that generated the waste, the water content of the slurry when impounded, the age of the waste, the depth of the impoundment, the location of the water table, the rainfall in the storage area, and presence or absence of wick drains. The likelihood of catastrophic failure and flow of waste is controlled by the geometry of a site, and the materials and construction methods used for the embankment, more than by any averageable waste properties. As the OSM authors determined, modeling slurry rheology cannot approach the understanding of the waste-storage system necessary to preclude failures.

6. Under-seepage, through-seepage, and overtopping: As stated above, failure of embankments leading to flow of coal waste is far more attributable to the geotechnical properties of the embankment itself than it is to the properties of the waste slurry. Whether or not the waste will flow into a pre-existing mine is a small subset of the more important issue of failure of embankments and uncontrolled release of coal waste into any environment. The GSL team did not see a convincing argument for considering the flow-into-mine issue as a special case. It is an issue that cannot be addressed separately from the issue of dewatering of waste and the causes of embankment failures.

Impounded coal waste cannot flow out of the impoundment unless an embankment fails. Failure of a levee embankment may be a comparable case. During widespread flooding

on the Upper Mississippi River system in the early 1990s, more than 70% of levee breaks occurred at the location of a pre-existing weakness: a buried river channel beneath the levee; or a junction, modification, patch, or other aberration in levee materials or construction. Water, whether in a river or in coal waste, will find a zone of weakness. When the load is increased, the weak zone can fail. The OSM authors presented examples of coal waste that flowed out of impoundments following heavy rain events. This is analogous to a river exploiting a pre-existing weakness during a flood event. A levee can fail because water exploits a weakness in the materials beneath the levee (as is the case with buried river channel deposits), or through the levee (pre-existing weakness attributable to use of coarser-grained material or poor construction practice during construction of the levee). A levee also can fail when it is overtopped, but this is actually less common than seepage failures.

The OSM authors cited one study that asserted that "the hydrostatic pressure from the impounded slurry was sufficient to push through the barrier (i.e. without the assistance of seepage)" (OSM, page 8 of 17). This suggests the possibility that flow of the coal waste can begin without a triggering event. If so, then the process of determining the safety of coal-waste impoundments becomes even more complex. This spontaneous "push through" is outside the extensive Corps experience with seepage and piping of levees. The OSM authors cite several other examples of real-world impoundment failures, each of which can be related to a triggering event (such as extremely heavy rain) that was able to exploit a pre-existing weakness and cause embankment failure.

7. Flow into a mine: The findings of the OSM authors suggest that the question of whether or not waste material will flow into a mine opening depends at least as much on the geometry of the system as it does on the rheology of the waste. The waste will flow downhill if the water content is high and the impoundment slope fails. If an opening is downhill, it may go there. The GSL reviewers agree with this conclusion.

8. Summary: The OSM authors conclude that modeling rheology of coal waste cannot include enough of the variables associated with a waste-impoundment failure to be generally applicable. The experience of the GSL reviewers supports all four of the conclusions presented in the summary of the OSM report. We recommend condition assessment of embankments to determine the safety of impoundments for coal-mine waste. We would be pleased to provide more information about seepage and piping, embankment failure, and condition assessment of levees and embankments.

GSL reviewers:
Dr. Lillian D. Wakeley, Chief, Engineering Geology and Geophysics Branch and Supervisory Research Geologist; and Dr. Richard W. Peterson, Senior Research Civil Engineer, Geotechnical and Earthquake Engineering Branch, Geotechnical and Structures Laboratory, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi

Peter Michael

From: Xiangwu Zeng [xxz16@po.cwru.edu]
Sent: Friday, May 14, 2004 10:03 AM
To: Peter Michael
Subject: Re: Coal refuse flowability--draft report.

Good morning, Peter,

I have finished reading through the drafted report. The following are my comments:

1. You and your colleagues have done an excellent job in reviewing the literatures, collecting relevant information, connecting the information to the problem you are concerned and pointing out the inadequacies of the current theories and practices.

2. I personally feel the Bingham Plastic Model is most likely the one that will fit this type of material.

3. Based on your report, I feel strongly that you need to put one section at the end of your report entitled "Research Need". It is obvious from your report that current state of the knowledge won't answer the critical questions you have asked. Therefore, some critical research focused on the information required to answer these questions is definitely needed. I have some suggestions for the research topics:

a) Measurement of viscosity of fine tailings at different water content and establish a relationship between them and find the influence of mineralogy and other factors.

b) Conduct tests to determine which type of model is most suitable to describe the behavior of slurry.

c) Conduct small scaled model tests such as centrifuge tests to simulate flow failure in a breakthrough situation. The model tests will tell us whether a flow failure would occur, why it occurs, and what are the important factors that contribute to such a failure. Since there are quite different explanations about the Martin County breakthrough, a repeat of the failure in a small scale test would settle the disagreement. I feel confident that such tests can be done on a centrifuge.

If you have any questions, please feel free to contact me. As I mentioned before, if some research needs to be done, we can always help.

Regards,

David

David Zeng, Ph.D.
Associate Professor
Dept. of Civil Engineering
Case Western Reserve University
10900 Euclid Avenue
Bingham Building
Cleveland, OH 44106-7201
Tel: 216-368-2923
Fax: 216-368-5229
e-mail: xxz16@po.cwru.edu