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Flume Testing of Surrogate Waste Materials Leading to a Recommendation for the Lower Limit for TAUFAIL – 14172

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ABSTRACT

The Waste Isolation Pilot Plant demonstrates compliance with federal containment requirements by means of performance assessment calculations carried out to estimate the probability and consequences of radionuclide releases from the repository to the accessible environment for a regulatory period of 10,000 years. These calculations are performed using a system of computer codes which assess twenty-four peer-reviewed conceptual models. One of those is the Cuttings and Cavings model. One purpose of this model is to determine the amount of radioactive waste material that would be eroded off a borehole wall due to drilling mud flowing up the borehole during a hypothetical drilling intrusion that penetrates the repository. The ability of a material to resist erosion due to a fluid flowing across its surface is the hydrodynamic shear strength. The hydrodynamic shear strength – referred to as TAUFAIL in performance assessment models – is an experimentally determined parameter used in the Cuttings and Cavings model. This paper describes the results of an experimental investigation to better constrain the hydrodynamic shear strength of surrogate degraded waste materials used to represent the materials making up the borehole walls in the repository. The lower limit of the range of waste shear strength values, representing the most degraded state of the waste, is specifically addressed. This paper describes the development of a flume in which the flow is vertical upwards, mimicking the flow of drilling fluid up a borehole. The flume was used on a surrogate waste material representing the most degraded state the waste is expected to be in at the end of the 10,000 year regulatory period. This material has been accepted by a previous peer review panel and the repository's regulatory agency for the experimental determination of parameters for a different conceptual model. The results suggest that a more realistic value for the lower limit of the waste shear strength in performance assessment models is larger than the currently accepted value.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a deep geologic repository operated by the U.S. Department of Energy (DOE) in southeastern New Mexico as a disposal facility for transuranic (TRU) radioactive waste. The WIPP facility is regulated by the U.S. Environmental Protection Agency (EPA) according to the regulations set forth in Title 40 of the Code of Federal Regulations, Part 191 (40 CFR 191) and the associated Part 194 (40 CFR 194). The DOE demonstrates compliance with the containment requirements according to 40 CFR 194 by means of performance assessment (PA) calculations carried out by Sandia National Laboratories (SNL). WIPP PA calculations estimate the probability and consequences of radionuclide releases from the WIPP repository to the accessible environment for a regulatory period of 10,000 years after closure of the facility. SNL conducts performance assessments using a system of computer codes. The current WIPP PA technical baseline consists of twenty-four peer-reviewed conceptual models that are developed and implemented in these computer codes.

WIPP PA scenarios for radionuclide release include cases of human intrusion in which a hypothetical future oil or gas borehole intersects the waste in the repository. Drilling mud flowing up the borehole will apply a hydrodynamic shear stress to the borehole wall which, if high enough, could result in erosion of the material comprising the wall [1]. This eroded volume is called "cavings," whereas the volume of the material removed by the mechanical action of the drill bit is called "cuttings." Collectively known as the Cuttings and Cavings model, both processes could result in a release of radionuclides being carried up the borehole with the drilling fluid and are calculated by the computer code CUTTINGS_S. CUTTINGS_S also provides a third process for radionuclide release that is calculated using the Spallings model, in which spallings volumes are calculated as a function of repository pressure. A spallings event is a special case of the drilling intrusion in which the repository contains gas at high pressure that causes (1) localized failure of the waste material surrounding the borehole and (2) entrainment of the failed waste material into and up the borehole, carried ultimately to the land surface.

In the Cuttings and Cavings model, the borehole diameter is assumed to grow until the hydrodynamic shear stress, or simply shear stress, on the borehole wall produced by the drilling mud is equal to the ability of the waste to resist erosion, i.e. the waste shear strength. WIPP PA uses the parameter BOREHOLE:TAUFAIL (more simply TAUFAIL) to represent the shear strength of the waste. For previous WIPP PA analyses the parameter is sampled from a log-uniform distribution with a range of 0.05 to 77 Pa. This range of values was derived by the DOE from literature reviews of erosion tests performed on cohesive sediments and estimation of the mean particle size of WIPP waste [1-5]. The lower limit of this range of values was chosen to conform to what is hypothesized as the most extreme case of degradation of the waste and waste containers.

This paper describes a series of experiments designed to produce a recommendation for the lower limit of the parameter TAUFAIL. A vertical erosion flume was built to mimic the field situation where flow of the eroding fluid, representing drilling mud, is essentially vertical. The material being eroded represents the degraded waste in the repository which would make up the walls of the hypothetical intrusion borehole. This surrogate material has been accepted previously by a peer review panel and the EPA to establish parameters for the Spallings model to represent such a massively degraded state for the WIPP waste that it has been considered unobtainable. Because the surrogate material is extruded laterally into the flow of the eroding fluid, the strengthening effect gravity may have on the material is removed. Being a change to a parameter value, the recommendation herein is not subject to a peer review as would be the case for a conceptual model change.

Historical Development of the TAUFAIL Parameter

Berglund [1] created the original models for cuttings, cavings, and spalling for WIPP purposes and performed the first analyses. Originally Berglund assumed that, "In the absence of experimental data, the effective shear strength for erosion of the repository material is assumed to be similar to that of a montmorillonite clay, with an effective shear strength of 1 to 5 Pa."

After further consideration, the DOE assumed for the Compliance Certification Application (CCA) [6] a uniform distribution for TAUFAIL with a range of 0.05 to 10 Pa with a median of 5.0 Pa. This range was based on Berglund's [7] review of soil erosion tests. The lower limit of the range is based on erosion tests of San Francisco Bay mud [8]. The upper limit was arbitrarily chosen as a value less than the highest threshold value reported.

The sensitivity of the Cuttings and Cavings model to changes in the waste shear strength was studied by the EPA as part of their evaluation for the Performance Assessment Validation Test (PAVT) [9]. They found that the cavings model is sensitive to the values chosen for TAUFAIL, in particular the lower limit since a weaker material results in greater cavings release. As a result, the EPA required that the DOE to change its method for estimating the waste shear strength and use an estimation based on particle size [10].

For the PAVT, the waste shear strength was estimated based on particle size distributions determined by an expert panel elicitation [3]. The estimates used the Shields parameter, which relies on a measure of the central point of a population of particles of different sizes, to determine the critical shear stress for a sediment bed. With this approach, the calculated critical shear strength ranged from 0.64 to 77 Pa [4, 5].

For conservatism, the EPA required that the low value from the CCA be retained, while the high value from the Shields parameter method be used for the upper value [11]. A log-uniform distribution for the waste was selected for the PAVT to provide equal weighting over the three orders of magnitude in the range [12]. The range of values for TAUFAIL became 0.05 to 77 Pa with a log-uniform distribution.

Much of the reason mud or clay was chosen as an analog for the shear strength of the waste was a lack of experimental results on either real degraded waste or an adequate surrogate material. Jepsen et al. [13] performed erosional shear testing on surrogate highly degraded waste samples developed by Hansen et al. [14]. The waste recipes were conceived to represent the degraded waste in its weakest condition and can be divided into materials that simulate 50% and 100% degraded waste by weight. The percent degradation indicates the anticipated amount of iron corrosion and decomposition of cellulosics, plastics, and rubber. The surrogate 50% degraded waste material was used by Hansen et al. [15] to establish the parameters for the Spallings model, which was accepted by the Spallings Conceptual Model Peer Review Panel [16] and incorporated into the Compliance Recertification Application 2004 Performance Assessment Baseline Calculation (CRA-2004 PABC) [17]. Hansen [18] advocated the use of Jepsen et al.'s [13] experimental results to establish a lower limit for TAUFAIL.

Herrick et al. [19, 20] re-analyzed Jepsen et al.'s [13] results using a method proposed by Parchure and Mehta [21], and advanced in Teeter [22], to assess the bed strength. In addition, Herrick et al. [19, 20] conducted another thorough review of erosion of cohesive materials and methods of analysis, including the addition of other San Francisco Bay mud data. They also performed numerical modeling to assess the effect of compaction due to creeping salt and consolidation due to gravity on the degraded waste.

Despite numerous approaches to define a more realistic value of TAUFAIL, in particular the lower limit of its possible range of strengths, none have been adopted. The approach that received the most support was the use of flume tests to directly measure the erosion resistance of an acceptable surrogate degraded waste material. The primary criticism of this approach was that waste strength values were derived from horizontal flume testing [23]. The concern is that tests conducted in a horizontal configuration may overestimate the shear strength due to gravity holding the material in place.

In order to address the need of having flow moving vertically up a flume channel to more realistically simulate field conditions where a drilling fluid is moving up a borehole, a vertically flowing flume was designed and built.

TESTING APPARATUS DESCRIPTION

Vertical Flume Design and Operation

The vertical erosion flume is based on a horizontal flume first built and routinely used in the Department of Mechanical and Environmental Engineering, University of California, Santa Barbara (UCSB) [24-26]. The UCSB flume was named SEDflume, which is short for Sediment Erosion at Depth flume. SEDflume is considered the industry standard for measuring sediment erosion and is being widely used by the US EPA, the US Army Corps of Engineers (USACE), and consulting companies [27].

A picture of the vertical erosion flume is shown in Figure 1. It is a straight flume, containing a test section with an opening in the side through which a circular cross-section coring tube containing surrogate waste samples is inserted. The main components of the flume are the sample holder, the erosion channel including the erosion test section and inlet and exit sections, two fluid storage tanks, a pump, a diverter valve, and a step motor which is used in combination with a linear rail table to advance the sample. The test section is made of clear polycarbonate (Lexan®) so that the sample-fluid interactions can be observed visually. The fluid for the flume is contained in two storage tanks. The tanks act as a baffle to settle out heavier material and have screens on the transfer lines to prevent lighter material from recirculating and fouling of the pump.

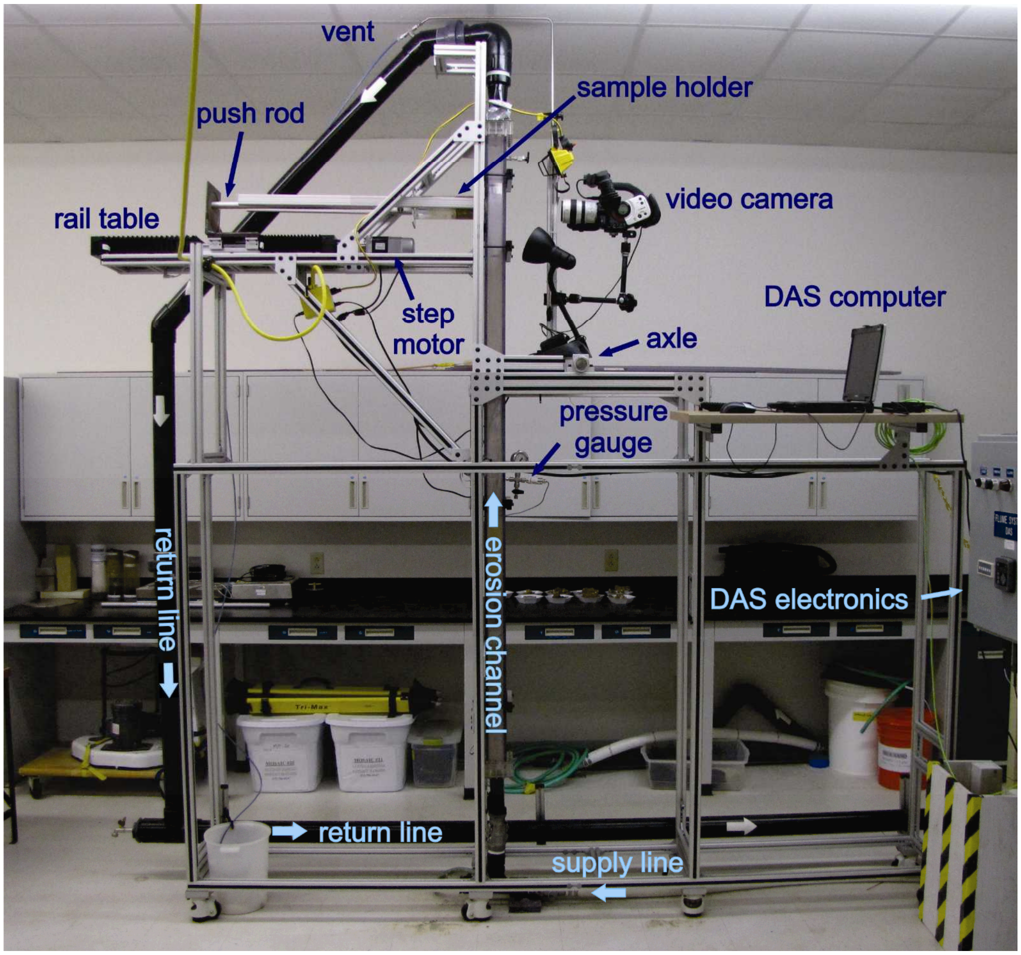

Figure 1. Picture of the fully enclosed erosion channel and components of the vertical erosion flume. The eroding fluid is delivered to the channel by a supply line from two storage tanks. The erosion channel is long enough to develop laminar flow at the lowest flow rates and fully turbulent flow otherwise. The vent is used to control the pressure on the face of the sample.

The fluid used in these tests was tap water. Of importance is that the density and viscosity of the fluid are determined through water quality measurements so that the flow can be regulated to subject the samples to a known hydrodynamic shear stress. A variable speed pump and three-way valve are used to control the flow into the channel. Both the pump and the valve are controlled through the data acquisition system (DAS). The flow rate of the circulating fluid can exceed 550 L/min (145 gal/min) and is monitored by an in-line flow meter. A small vent valve in the erosion channel immediately downstream from the test section is operated to maintain a small positive pressure gradient across the sample face.

The erosion channel can be rotated on an axle that allows the flume to operate in either a vertical or horizontal position. The flume's enclosed (internal flow) channel has a height of 5.4 cm, a width of 10.3 cm, and a length of 240 cm. As such, the height of the channel, that is the distance between the channel's far edge and the surrogate waste sample surface, matches the distance between the borehole wall and the drill stem in drilling operations typically conducted in the vicinity of WIPP. The erosion test section fits an 8.25 cm (3.25 in) diameter test specimen. The test section is preceded by 212 cm of enclosed channel needed to create fully developed turbulent flow over the sample. The sample diameter is narrower than the erosion channel in order to reduce the effect of the channel walls.

At the start of each test, the sample container and the surrogate waste sample are attached to the test section on the side of the channel. The operator moves the sample laterally using a piston inside the sample holder. The piston is connected to the linear rail table which is driven by the step motor. For this testing activity the samples were nominally 20 cm (7.5-8.0 in). The step motor is controlled through the DAS.

As a general test procedure, the fluid is forced upward through the enclosed channel and across the surface of the sample. The shear produced by this flow may cause the sample to erode. If at a particular flow rate no erosion is observed, the flow is incrementally increased until erosion is observed or the limit of the pump is reached. If the surrogate waste sample erodes, additional material is advanced laterally by the operator. The erosion rate is recorded as the lateral movement of the sample in the coring tube over time. Time and sample extrusion distance at each shear stress level are recorded by both the DAS and the operator in a scientific notebook.

Determination of Applied Hydrodynamic Shear Stress

Flow through pipes has been studied extensively, and empirical functions have been developed which relate the mean flow rate to the wall shear stress. An implicit formula relating the wall shear stress to the mean flow in a pipe of arbitrary cross-section can be obtained from Prandtl's Universal Law of Friction [28]. For a pipe with a smooth surface, this formula is

$$\frac{1}{\sqrt{\lambda}} = 2.0\log\left[\frac{UD\sqrt{\lambda}}{\nu}\right] - 0.8 \qquad (1)$$

where U is the mean flow speed, ν is the kinematic viscosity, λ is the friction factor, and D is the hydraulic diameter. For a pipe with a rectangular cross-section the hydraulic diameter is

$$D = 2hw/\left(h+w\right) \qquad (2)$$

where w is the duct width and h is the duct height. The friction factor is defined by

$$\lambda = \frac{8\tau}{\rho U^2} \qquad (3)$$

where ρ is the fluid density and τ is the wall shear stress. Inserting Eqs. (2) and (3) into Eq. (1) gives the wall shear stress τ as an implicit function of the mean flow speed U.

DATA ACQUISITION AND CONTROL

The incorporation of a data acquisition system (DAS) on the vertical flume greatly enhanced the accuracy and reliability of this experimental program. The DAS consists of three subsystem components that control processes and collect the data. The three components are: hardware, instrumentation, and the operator interface computer and software.

Hardware

The DAS hardware was designed and built utilizing a modular approach that incorporates components directly available from SIXNET, Inc. The SIXNET hardware includes the SixTRAK remote terminal unit (RTU), discrete input/ouput (I/O) modules, and analog I/O modules. The I/O modules can measure various types of analog signals to a 16-bit resolution and can be expanded from 8 to 512 channels with additional modules. The DAS components are mounted within a rack mounted enclosure, which also incorporates the power supplies, circuit breakers, fuses, and relays to protect and control the system.

Instrumentation

Flow through the flume system is measured by an in-line flow meter located in the upstream end of the flume supply line. The flow meter is capable of measuring the flow to an accuracy of ± 1% of the full scale range of the instrument. The flow into the flume supply line is controlled using the 3-way directional valve and variable frequency drive (VFD) controller to power the pump. The flow meter is used as the control variable for the 3-way valve position and the pump motor speed.

Water quality (temperature and specific conductance), used for the determination of fluid density and viscosity, is also measured in the flume supply line. The temperature is measured with a resistive temperature device (RTD) having an accuracy of ± 1.0°C. The conductance of the fluid used in the flume is measured using a specific conductance probe with an accuracy of ± 5.0% of selected range of measurement.

The sample feed rate and control systems for advancing the sample into the flow stream are based on a linear rail table that advances the sample by using an encoder to count the revolutions of the screw-type step motor. The number of revolutions correlates with the distance that the table advances. The extrusion speed of the surrogate waste sample can be controlled at a variable rate of 1-200 rpm, where one revolution is equal to 5.14 mm. When advancing a sample a step increment as small as 0.25 mm is measurable and controllable with this system.

Software

Using the Human Machine Interface (HMI) software the operator is able to select and configure system set points that are utilized to conduct the test. This includes setting flow rates for the test, sample advancement rate and distance, and data storage times. The operator interface visually displays real-time feedback on the test parameters being monitored. These parameters can be presented both graphically and in tabular form. The system automatically calculates certain test values such as the shear stress based on the measured parameters, eliminating the need to process the data off-line after test completion.

SAMPLE PREPARATION

The surrogate waste materials used for the present set of tests were developed by Hansen et al. [14]. They developed their model materials from the estimated inventory of standard waste drums, the anticipated future state of the waste, evolution of the underground environment, and experimental results. The surrogate waste comprised a mixture of raw materials including iron, glass, cellulosics, rubber, plastic, degradation byproducts, solidified cements, soil, and WIPP salt. Hansen et al. [14] considered degradation of each waste constituent. Subsurface processes leading to extreme degradation are based on several contributing conditions including ample brine availability, extensive microbial activity, corrosion, and the absence of cementation, and salt encapsulation effects. Hansen et al. [14] concluded that the degraded waste material properties represented the lowest plausible strength condition for the future waste because no strengthening processes were included such as compaction, cementation, mineral precipitation, more durable packaging, and less corrosion. It is believed that these materials represent an unobtainable degraded state of the waste, are thus far weaker than any possible future state, and will cover any changes that may occur in the waste inventory [15, 18]. Therefore, their use is expected to represent an adequate surrogate degraded material for use in flume experiments to assess the lower limit of TAUFAIL.

For the present tests, three surrogate waste types were used, 50%, 75%, and 100% degraded wastes saturated in brine made from WIPP salt. The surrogate 50% and 100% degraded materials were developed and cataloged by Hansen et al. [14], and the intermediate material was derived by Herrick et al. [29]. The material constituents are listed in Table 1 and the weight percentages for the different material types are listed in Table 2. For the surrogate 75% degraded waste samples, two different iron oxides were used; the results from which were indistinguishable from each other [29].

The surrogate waste materials were placed into a sample tube which in turn was placed in a steel form, i.e. a die, and subjected to the desired uniaxial compaction pressure overnight (nominally 15 hrs). Two compaction pressures were used, 2.3 and 5 MPa. On the upper end of the sample was a Lexan® platen the size of the inner diameter of the sample holder fitted with an o-ring. It was used to apply the compacting load. On the bottom was a metal platen, also fitted with an o-ring, but having bleed ports covered by metal gauze. As the sample was compacted, the brine used to saturate the specimen was allowed to drain out of the bottom platen through the bleed ports. This left the sample drained and without pore pressure, but still fully saturated. Neither platen was removed as the sample was sealed and the ends clamped to assure that they were not disturbed from their original state.

Ideally five samples of each compaction pressure and material type were used. The use of replicate samples provides repeatability in the testing results. In addition, replicate samples help assess the variability of the erosion rate measurements and critical shear stress determinations for different sample types.

Samples were fabricated in the SNL Geomechanics Laboratory in Albuquerque under WIPP Quality Assurance guidelines. The samples were picked up and hand delivered to SNL-Carlsbad in an automobile by Sandia staff members. The samples remained sealed and clamped until tested.

Table 1. Simulant materials used in the surrogate waste material recipes [14].

Simulant Material	Details and Particle Size
Iron, not corroded	Steel (1 to 2 mm thick), ~ 5 to 10 mm squares, (3/8" sieve material).
	Alloys are (1 to 2 mm thick), ~ 5 to 10 mm squares. Hardware includes bolts, nuts, washers, and nails.
Corroded iron and other metals	Iron oxide (goethite) to pass no. 18 (1 mm or 0.0394") sieve.
Glass	2 to 3 mm thick and pass a 3/8" (9.5mm) sieve.
Cellulosics	Paper (6 to 8 mm squares).
	Cotton (thin strands ~ 0.5 to 1" long).
	Sawdust (as received).
	Peat (as received).
Plastics	Poly-sheet (6 to 8 mm max. dimension).
	Poly-bottle (6 to 8 mm max. dimension).
	Shredded plastic grocery bags.
Rubber	Rubber gloves (6 to 8 mm maximum size).
	Rubber bands (6 to 8 mm maximum size).
	O-rings (6 to 8 mm maximum size).
Solidification cements	Sheetrock and Concrete: all pass 3/8" (9.5mm) sieve.
Soil	Typical soil (collected outside SNL Geomechanics Laboratory) - passes the 3/8" (9.5mm) sieve.
Salt	WIPP Salt: to pass the 3/8" (9.5mm) sieve.

Table 2. Weight percentages of the ingredients for each sample type: surrogate 50%, 75%, and 100% degraded wastes recipes [14, 29].

Simulant Material	Percent Degradation Represented		
	50%	75%	100%
Steel	9.16	4.26	0.00
Alloys	9.16	4.26	0.00
Iron Oxide	44.36	55.84	66.97
Glass	9.64	9.48	9.17
Paper	0.68	0.34	0.00
Cotton	0.68	0.34	0.00
Sawdust	0.68	0.34	0.00
Peat	0.68	0.34	0.00
Poly-Sheet	0.68	0.34	0.00
Poly-Bottle	0.68	0.34	0.00
Plastic Bags	0.68	0.34	0.00
Gloves	0.68	0.34	0.00
Rubber Bands	0.68	0.34	0.00
O-Rings	0.68	0.34	0.00
Sheetrock	5.79	5.73	5.50
Concrete	5.79	5.73	5.50
Soil	4.82	4.85	4.59
Salt	4.53	6.45	8.26
total	100	100	100

DETERMINATION OF CRITICAL SHEAR STRESS FOR EROSION

To determine the critical shear stress for the initiation of erosion, it is necessary to subject the sample to a range of shear stresses such that at the lowest applied shear stresses no erosion will occur. Progressively higher levels are applied, leading to the beginning of erosion and multiple erosion rates thereafter. Each shear stress level is targeted to be run for one hour which depends on whether or not the sample is eroding and how fast that is occurring. The DAS records the time, extrusion distance, and all test parameters automatically when the sample is moved. After the predetermined duration is reached at a particular stress level, the flow is increased to the next shear stress. This procedure continues until the highest shear stress is reached or the sample is completely eroded away.

Due to a gradual increase in erosion as the shear stress increases, it is difficult to precisely define a critical velocity or shear stress at which erosion first takes place. This complexity is compounded as the nature of the erosion which can occur in isolated spots over a larger surface. Critical shear stresses are calculated from the measurement of erosion rates in a number of ways. Two widely accepted methods are by a piecewise linear fit to erosion rate and shear stress data Figure 2 and interpolation to critical shear stress level.

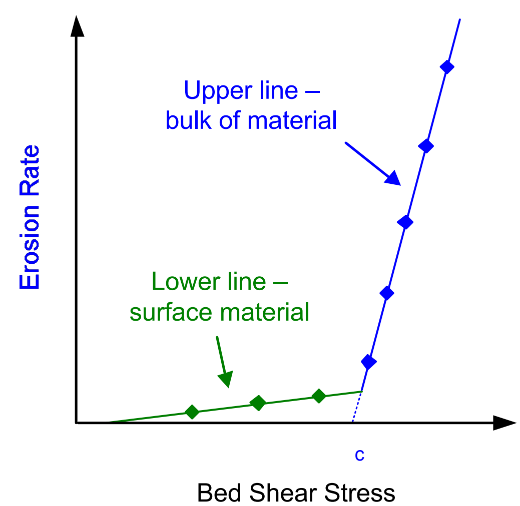

Figure 2. Idealization of the UF piecewise linear analysis method. Extrapolation of the upper line, which represents the erosion behavior of the bulk of the material, back to an erosion rate of zero represents the critical shear stress τ_c.

The piecewise linear method was originally proposed by Parchure and Mehta [21] at the University of Florida (UF). They showed that a plot of the erosion rate versus shear stress of their flume testing results can typically be divided into two distinct linear regions. The lower line (Figure 2, left side) corresponds to the behavior of the surface layer and the upper line (Figure 2, right side) to the bulk or mass of the material. Teeter [22] suggested that the most conservative estimate of the critical shear strength of the bulk of the material, of interest here, is given by an extension of the upper line back to the shear stress where the erosion rate is zero. In this paper, this shear strength determined by this method is labeled τ_c. By using this method possible surface effects caused by surface preparation are excluded and the strength of the bulk of the sample is assessed. Ideally, five or more different levels of shear stress including some before the beginning of erosion are desired for this method of analysis.

At UCSB, the critical shear stress of a sediment bed, τ_{cr}, is defined quantitatively as the shear stress at which a very small, but accurately measurable, rate of erosion occurs [24-26]. This rate of erosion was practically defined as 10^{-4} cm/s. Since it is difficult to measure τ_{cr} at exactly 10^{-4} cm/s, erosion rates are measured above and below 10^{-4} cm/s. The τ_{cr} is then determined by linear or power-law interpolation between the shear stress where the critical erosion rate is not achieved and where it is exceeded.

EXPERIMENTAL RESULTS OF FLUME EXPERIMENTS ON SURROGATE WASTE SAMPLES

Table 3 summarizes the results of flume tests performed on the three different surrogate degraded waste recipes, compacted at 2.3 and 5 MPa. Many of the results from the tests performed on the surrogate 100% degraded waste recipe are not included in the table. The surrogate 50% and 100% waste samples were the first made. These samples were made in Lexan® tubes. A number of issues were discovered using Lexan® tubes that had an especially strong, detrimental effect on the surrogate 100% degraded waste samples. The first problem with the Lexan® tubes was that they deformed. The tubes would undergo bulging at one end, barreling in the middle, bending in the middle, and/or shearing so that tube axis was no longer at right angles with its ends. In addition, some of the harder material would become imbedded into the plastic either upon preparation of the sample or as the material moved within the tubes. Finally, a strong frictional force existed between the polycarbonate and the surrogate waste material.

Several of the first surrogate 100% degraded waste samples could not be moved by the servo motor/rail table system. The material had become fixed to the sides of the plastic sample holders. Movement of these samples had to be initiated by hitting the end platen with a hammer. There was some evidence of pieces of surrogate waste material (typically glass) becoming impregnated into the polycarbonate, but mostly it appeared to be caused by friction along the inside surface of the tube and/or by deformation of the tube. To reduce friction, a thin coat of light oil was applied to the insides of the sample holders. This was quickly replaced with vacuum grease which is a better lubricant and less reactive.

Whether due to friction, particle impregnation, and/or deformation of the sample, material in the sample tube advanced in a stick-slip fashion. The samples would initially resist movement as the axial force was applied, then it would jump forward quickly. The quick jump forward, followed by a sudden stop, would cause material to break off of the sample's face for the surrogate 100% degraded waste samples. Material breaking off the face only occurred as the samples were advanced, whether there was fluid in the channel or not or whether the fluid was flowing or not. Material did not slough off the face by its own without movement of the specimens.

Table 3. Test results for vertical flume tests performed using three different materials representing 100%, 75%, and 50% levels of degradation under two levels of die compaction: 2.3 or 5.0 MPa. For the surrogate 75% degraded waste material tests, two different sources of goethite were used, "Socorro" and "Alb." Three different methods were used to assess the critical shear stress as discussed in the main text.

Sample No.	Starting Shear Stress (Pa)	Ending Shear Stress (Pa)	Critical Shear Stress (Pa)		
			UF, bilinear (τ_c)	UCSB, linear (τ_{cr})	UCSB, power law (τ_{cr})
100% degraded, 2.3 MPa compaction *					
WF-100-203-04	0.02	0.52	0.17	0.21	0.22
100% degraded, 5.0 MPa compaction *					
75% degraded, 2.3 MPa compaction					
75-080112 (Socorro)	0.05	2.08	1.60	1.46	1.62
75-082212 (Socorro)	0.52	2.08	1.22	1.06	1.34
75-082712 (Socorro)	0.52	2.47	1.79	1.75	1.85
75-082912 (Alb)	0.52	3.12	2.00	1.32	1.35
75-091012 (Alb)	0.52	1.82	1.06	1.05	1.05
75-091312 (Alb)	0.52	2.34	1.84	1.75	1.85
75-091912 (Alb)	0.52	1.95	1.19	1.25	1.34
75% degraded, 5.0 MPa compaction					
75-080212 (Socorro)	0.39	3.12	2.22	1.61	1.90
75-082312 (Socorro)	0.52	3.25	2.57	2.37	2.65
75-082812 (Socorro)	0.52	3.12	1.60	1.85	2.16
75-083012 (Alb)	0.52	3.50	2.64	2.08	2.01
75-091212 (Alb)	0.52	2.08	1.46	1.31	1.34
75-091812 (Alb)	0.52	3.12	1.93	1.83	1.86
75-092012 (Alb)	0.52	3.63	2.80	1.63	1.86
50% degraded, 2.3 MPa compaction					
WF-50-02	0.15	5.17	2.54	2.74	3.21
Flume 50-01	0.52	5.66	1.60	2.14	2.30
WF-50-203-02	0.52	5.64	3.09	3.05	3.35
WF-50-203-01	1.04	5.36	1.78	2.07	2.08
WF-50-203-03	1.04	4.66	2.10	2.91	3.29
50% degraded, 5.0 MPa compaction					
WF-50-5-01	0.52	5.69	5.69	5.69	5.69
WF-50-5-02B	1.04	5.68	5.68	5.68	5.68
WF-50-5-03	0.52	5.36	3.79	3.84	4.32
WF-50-5-04	0.52	5.61	5.13	5.28	5.48
WF-50-5-05	1.04	5.68	4.96	5.01	5.27

* The results for the 100% degraded, 2.3 MPa compaction pressure test specimens WF-100-01, WF-100-203-01, WF-100-203-02B, and WF-100-203-03 and the 100% degraded, 5.0 MPa compaction pressure test specimens WF-100-5-1, WF-100-5-02, and WF-100-5-03 are not reported because of stick-slip motion as discussed in the main text.

The deformation of the samples in the Lexan® sample holders and the high friction develop between the material and the polycarbonate prompted a change of sample holders. For the last surrogate 100% degraded waste sample (WF-100-203-04) and all of the surrogate 75% degraded waste samples, hard anodized aluminum sample holders impregnated with Teflon were used.

In addition, during the first six tests on the surrogate 100% degraded materials, up until Sample WF-100-5-03, a gasket was used between the sample holder and the reaction plate on the channel to keep the system from leaking. It was noticed that as the samples were pushed into the current they would scrape along the gasket. The surrogate 50% degraded waste samples, which were being tested at the same time as the surrogate 100% degraded waste samples, would shear the gasket off. However, the surrogate 100% degraded waste samples would not. It was felt that this scraping also negatively affected the test results for the more highly degraded waste samples so a new system was designed. Starting with Sample WF-100-5-03, a new channel reaction plate was fabricated and the seal was changed to an O-ring. The samples then had a clear path into the current.

For the above reasons, it is felt that none of the results from the surrogate 100% degraded waste samples that had these problems are reliable. By the time the testing issues were identified and resolved, all the surrogate 100% degraded waste samples had been tested with the exception of Sample WF-100-203-04. For this reason, it is the only surrogate 100% degraded waste sample result listed in Table 3. The surrogate 50% degraded waste samples, which were tested at the same time as surrogate 100% degraded samples, also underwent the above problems. However, the effects were ignored during analysis of the surrogate 50% degraded waste samples because it was not possible to show with assurance that the stick-slip motion or gasket caused damage to the face of the samples and altered the stress at which they eroded.

For the surrogate 75% degraded waste samples, two different sources for iron oxide in the form of goethite were used. The primary source of goethite is from Kirkland Air Force Base, Albuquerque, NM, in close proximity to the Geomechanics Laboratory where the samples were made. It is labeled "Alb" for Albuquerque goethite in Table 3. This goethite was used in all samples except for six surrogate 75% degraded waste material samples. The second iron oxide source is labeled "Socorro" goethite in Table 3 since it was mined at an outcrop just south of Socorro, NM. The goethite was purchased through Rio Grande Rock and Gems in Socorro, NM. As was shown in Herrick et al. [29], differences between mean critical shear stress results concerning specimens made using these two types of goethite are insignificant at a confidence level of 95%.

Below in Table 4 is a comparison of the average shear strengths, that is, average critical shear stresses, of the surrogate materials based on the three methods used to analyze the results. The results from the 100% degraded tests are not included since they are considered unreliable due to a number of testing issues that have been discussed previously.

It is apparent from Table 4 that the less the surrogate material represents degradation of the waste, the stronger the material. In other words, the surrogate 50% degraded waste samples are stronger than the surrogate 75% degraded waste samples which are stronger than the surrogate 100% degraded waste samples. It is also apparent from Table 4 that the more compaction the materials undergo, the better able they are to resist erosion. Therefore, the materials compacted at 5.0 MPa are stronger than the materials compacted at 2.3 MPa.

Table 4. Average shear strengths, or critical shear stresses, for each type of surrogate waste material and compaction pressure as determined by the three analysis methods.

Sample Type	Average Shear Strength [Pa]		
	UF, bilinear (τ_c)	UCSB, linear (τ_{cr})	UCSB, power law (τ_{cr})
100% degraded waste, 2.3 MPa compaction pressure	---- *	---- *	---- *
100% degraded waste, 5.0 MPa compaction pressure	---- *	---- *	---- *
75% degraded waste, 2.3 MPa compaction pressure	1.53	1.38	1.49
75% degraded waste, 5.0 MPa compaction pressure	2.17	1.81	1.97
50% degraded waste, 2.3 MPa compaction pressure	2.22	2.58	2.85
50% degraded waste, 5.0 MPa compaction pressure	5.05	5.10	5.29

* as discussed in the main text, the test results for surrogate 100% degraded waste samples were considered unreliable due to deformation of the sample holders and an inability to advance the samples smoothly.

Of the methods of analysis, the University of Florida (UF) model is considered more applicable to the surrogate materials reported herein than are the University of California, Santa Barbara (UCSB) methods, even though all methods produced reasonably similar results. The UF method was developed based on laboratory experimental results and acknowledges the existence of a surface layer [21]. It has also been used successfully on field sediments. It shows that the surface layer will behave in a manner quite different than the bulk of the material. The results obtained herein were obtained from samples built and tested in the laboratory; therefore, a method of analysis developed for those conditions is expected to work better. In general, the erosion behavior of the surrogate waste samples followed a clear bilinear manner. Also, as shown in Herrick et al [29] there were a few cases in which the critical erosion rate as defined by UCSB was exceeded while the erosion data and UF model showed these times to be prior to when bulk erosion had initiated. For these cases the suitability of the critical erosion rate criterion was questioned for surrogate materials without considering whether or not bulk erosion is taking place.

The surrogate 50% degraded waste material compacted to 5.0 MPa was accepted for use in obtaining the experimental parameters for a different WIPP PA model [16, 17]. Hansen et al. [14] showed that for the vast majority of the CCA PA calculations, half or more of the initial iron and cellulosics, plastics, and rubber inventory remained. They also advocated using 5.0 MPa compaction load as a conservative estimate of the compaction the waste will undergo. It is intimated in their report that they used the CCA BRAGFLO porosity results to back-calculate the vertical stress necessary to produce the deformation of the drum stack. The second compaction pressure, 2.3 MPa, used to build the test samples was obtained from structural calculations performed using the FEM code SANTOS to estimate compaction of the degraded waste with time [19]. The method used is identical to that used for the development of the porosity surface. The porosity surface is a compilation of time-dependent repository pressures and porosities under different gas generation rates.

It believed the BRAGFLO results provide the best representation of possible future repository conditions and should be used for predictive purposes. BRAGFLO results account for the most up-to-date chemical and environmental processes that lead to gas generation rather than assuming an idealized fixed gas generation rate as is done in the porosity surface calculations. A slower gas generation rate would allow for more salt creep in early times, which would lead to more compaction and higher stresses in the waste. Herrick and Kirchner [30] estimated vertical stresses acting on the waste from back-calculation of BRAGFLO porosities from the Compliance Recertification Application 2009 Performance Assessment

Baseline Calculation (CRA-2009 PABC) [31], the current baseline for WIPP PA calculations. They found a fairly consistent at 4.3 – 4.4 MPa stress regardless of the PA scenario. This range is slightly less than the 5.0 MPa used to make half of the samples. On the other hand, the 4.3 – 4.4 MPa range is considerably higher than 2.3 MPa, the compaction pressure obtained based on FEM analyses and used to make the other half of the samples. Because the flume experimental results are strongly dependent on the compaction pressure, data from the 5.0 MPa samples are likely to bias the estimated value for the lower limit of TAUFAIL somewhat high. The shape of the shear strength versus compaction pressure curve cannot be estimated using only two compaction pressures, but is more likely to be concave than linear or convex. Therefore, to be conservative, the DOE recommended using the experimental results from the surrogate 50% degraded waste samples fabricated using the considerably lower compaction pressure of 2.3 MPa rather than interpolating from the data to a 4.3 MPa compaction pressure. It is believed that the average shear stress value from the experimental samples compacted at 2.3 MPa represents a conservative, but defendable, estimate of the lower bound on the range representing uncertainty of TAUFAIL.

RECOMMENDATIONS

As seen from the experimental results, the shear strength of the surrogate waste material is highly dependent on the compaction pressure. Herrick and Kirchner [30] showed that the 2.3 MPa compaction pressure is indeed a conservative underestimate since the actual gas generation rates predicted from BRAGFLO are not as fast or as high as those modeled in the FEM structural calculations. Therefore, the DOE recommends using the experimental results from the surrogate 50% degraded waste samples fabricated using the lower compaction pressure of 2.3 MPa as an conservative estimate of the lower bound for the range representing uncertainty in the parameter BOREHOLE : TAUFAIL. Table 5 contains the information related to this distribution that has been input into the WIPP parameter database and used in CRA-2014 PA calculations.

Table 5. Statistics for the parameter BOREHOLE : TAUFAIL entered into the parameter database and used for CRA-2014.

Minimum	2.22 Pa
Maximum	77.00 Pa
Distribution	Uniform
Mean	39.61 Pa
Median	39.61 Pa
Standard Deviation	21.59 Pa

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