# USE OF PASTE TECHNOLOGY FOR TAILINGS DISPOSAL: POTENTIAL ENVIRONMENTAL BENEFITS AND REQUIREMENTS FOR GEOCHEMICAL CHARACTERIZATION

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## ABSTRACT

Use of paste technology for surface deposition and underground backfill of tailings provides an attractive method for minimizing the engineering and environmental challenges commonly associated with the disposal of mineral wastes. This paper describes and discusses the multiple environmental and operational benefits that are potentially associated with the use of paste, in particular as they relate to water quality. Also presented are examples of long-term laboratory studies and field investigations conducted on a variety of paste mixtures. It will be demonstrated that paste may offer an attractive alternative to traditional tailings management, but that comprehensive characterization of the paste is a prerequisite for its use, regardless of placement scenario.

**Key words**: paste, tailings, environmental benefits, characterization

## INTRODUCTION

In recent years, use of paste fill has evolved from an experimental backfill method with limited application to a technically viable and economically attractive alternative. This is primarily due to the development of dewatering and transportation systems that allow for controlled and consistent production and delivery of paste in a cost-effective manner. In addition, it has been recognized that underground backfill provides for a mechanism to safely dispose of mine wastes such as tailings, which results in cost savings and reduced immediate and long-term liability. Minimizing this liability through a reduction in surface disposal will have a beneficial effect on the feasibility of any mining venture.

In addition to use of paste for underground backfill, the improvements in dewatering and transport technology have generated industry interest in so-called "dry" disposal of tailings as a paste. This interest is further stimulated by increased regulatory pressure on hydraulic structures (dams) and other aspects (e.g., liners) of the more traditional subaerial tailings management methods. The public perception of tailings impoundments as being generally unsafe structures is another driving force behind the current revival of alternative tailings management concepts.

The benefits of paste technology are many, and cover a wide range of issues, including design, operation, reclamation, environmental, and above all, public perception. Several publications discuss the geotechnical advantages of using paste (e.g., Cincilla et al. 1997, Landriault et al. 1997; Robinsky, 1999). This paper focuses on some environmental and operational benefits associated with disposal of tailings in paste form, as well as the requirement to predict the paste's long-term environmental stability. It should also be noted that the general application of paste technology is now being expanded to include other large-volume waste types (e.g., fly ash) and natural materials such as (dredge) sediments. As long as the material has the requisite characteristics, in particular with respect to grainsize distribution, paste technology can be used to engineer and enhance its transport, disposal, and environmental properties.

## WHAT IS PASTE

Paste technology originated in the hard rock metal mining industry approximately 20 years ago. Tailings from metal mining operations were conventionally disposed of as a slurry in an engineered surface impoundment near a mine-mill complex. Such disposal can lead to a variety of environmental and other hazards, such as dust generation, dam failure, and leakage. Additional disadvantages may result from the requirement for large amounts of land with limited long-term beneficial use, as well as aesthetic impacts.

Tailings paste is defined as a dense, viscous mixture of tailings and water which, unlike slurries, does not segregate when not being transported. Paste has a working consistency similar to wet concrete, and several of the geotechnical characterization techniques have their origin in the concrete industry. One of the most distinguishing properties of paste is the grainsize distribution of the solids. Based on a large volume of empirical data and operational experience, it has been determined that a paste must contain at least 15 % by weight passing 20 micron to exhibit the typical paste flow properties and retain sufficient colloidal water to create a non-segregating mixture. According to Robinsky (1999), one of the pioneers of paste technology, virtually all mineral processing methodologies generate tailings amenable to paste production. When being transported either by gravity or through pumping, paste produces a plug flow, with the fine particles creating an outer annulus, thereby reducing friction. The coarse particles are forced into the center of the conduit with the finer fraction acting as the carrier. This allows for conveyance of very coarse fragments, the size of which is only limited by the pipe diameter.

## ENVIRONMENTAL AND OPERATIONAL BENEFITS FROM USE OF PASTE

Of all potential advantages associated with disposal of tailings in paste form, the environmental benefits are among the most promising. In particular as regulatory and societal demands on the mining industry continue to increase, use of paste technology may provide an avenue for minimizing or even eliminating various environmental issues.

The environmental benefits of surface disposal of paste can be divided into two main categories; those that stem from the physical and chemical characteristics of paste itself, and those that are more operational in nature. This paper focuses on the benefits resulting from paste properties. First, very little free water is available for generation of a leachate, thereby reducing potential impacts on receiving waters and biological receptors. In addition, the permeability of a poorly sorted, run-of-mill paste is significantly lower than that of classified, well-sorted tailings. In a surface scenario, this limits infiltration of rainfall and snowmelt, which also results in a reduction of the seepage volume. When placed underground, the paste may represent a hydraulic barrier to groundwater flow, thereby limiting generation of a potentially onerous leachate. Furthermore, the saturated conditions within the paste minimize the ingress of oxygen, thereby reducing the potential for generation of acid rock drainage. Second, the paste production technology allows for production of an engineered material by modifying the paste geochemistry in such a manner that environmental benefits result. For instance, addition of Portland cement has been shown to be very effective in reducing metals mobility. In addition, acid generation in the tailings can be markedly curtailed by mixing with alkaline materials. Third, co-disposal of other waste materials with paste is made feasible by the paste production technology. In particular, encapsulation of acid generating waste rock in appropriately designed paste may provide significant benefits in terms of environmental control and waste management. These environmental benefits are described in more detail in following sections.

There are additional, operational aspects of surface disposal of paste that benefit the mine owner and the environment. The placement of pastes on the surface allows for increased flexibility in both facility siting and disposal strategy. The absence of a pond affords the use of management strategies that are much less restrictive, thereby opening the way for siting and disposal options that are least detrimental to the environment. In addition, the footprint of a paste facility will generally be smaller than that of an impoundment designed for an equivalent amount of tailings. A second operational benefit results from the improved recovery of water. In particular in arid regions, the reduced water use may represent an important economic incentive. A third benefit stems from the potential for concurrent reclamation and creation of a true “walk-away” facility at closure. As reclamation strategies can be incorporated into the placement options, land disturbance can be minimized during operation. This results in a reduction of visual impacts and operational hazards (e.g., dust generation). In addition, unnecessary loss of pre-mining land uses (agriculture, timber, wildlife habitat, etc.) can be prevented.

### Reduction in Leachate Generation

The reduction in leachate generation results from two characteristics of paste: colloidal retention of water and reduced infiltration relative to traditional tailings.

The mechanism responsible for retention of water has not been investigated in any detail. Several processes may combine to create the properties unique to paste: surface phenomena (electrostatic attraction between water and charged particle surfaces); chemical interaction between particles and water (e.g., hydrogen bonding); and physical interaction (water held under surface tension due to high capillary or matric tensile stresses). Since empirical observations have demonstrated that water retention and other paste characteristics, such as rheology, are related to mineralogical composition of the tailings material, it appears that the chemical properties of the tailings particles at least in part govern water-particle interaction.

The result of this colloidal water retention is that leachate generation from paste is generally only a minor fraction of that in tailings or backfill. In general, the amount of water lost through gravity-driven draining and evaporation is observed to be only a few percent of the total moisture present in the sample. Even during placement of paste, especially under unconfined conditions, virtually no free water is generated (Figure 1). In a more confined setting, or as the volume of paste increases, small amounts of free water can be expelled from the paste surface. However, this process ceases quickly as the paste stiffens and takes on its final appearance and configuration. Given the fact that a leachate generally reports to a much larger groundwater or surface water reservoir, simple dilution may therefore be sufficient to meet the necessary water quality criteria. If treatment of leachate is required to achieve compliance, the treatment facility can be of a much smaller scale as the volume of leachate has been reduced.

Figure 1 – Paste placement. Note the absence of any free water despite low viscosity.

Laboratory and field testing have demonstrated that the permeability of paste is generally approximately half an order of magnitude lower than that of the corresponding tailings material. This is primarily caused by the fact that paste is produced from run-of-mill tailings that have not undergone the grainsize segregation commonly observed during tailings deposition. Consequently, the paste maintains the full distribution of particle sizes, which results in the reduced permeability characteristic of poorly-sorted materials. In addition to the effect of grainsize distribution, the tensile stresses in the tailing are responsible for reduced infiltration. This occurs because the gravitational downward pull on the liquid surrounding the tailings particles is countered by upward capillary suction (Robinsky, 1999). Admixture of small amounts (e.g., 1 to 2 percent by weight) of binder materials with pozzolanic and/or cementitious properties may further decrease the permeability of paste, thereby providing additional environmental protection.

A third reason for reduced infiltration and leachate generation under surface conditions is that paste disposal removes the direct cause for infiltration and seepage, which is the settling pond. As a consequence, the free hydrostatic head is eliminated as well, which may result in relaxation of a wide variety of environmental, operational, and regulatory requirements.

**Addition of Reagents**

In contrast with traditional approaches to tailings management, the geochemistry of paste can be readily modified to improve its environmental behavior. The components of the paste production system are very similar to those of delivery systems used for chemical fixation/solidification of hazardous materials, and therefore controlled administration of environmentally beneficial materials is highly feasible. The choice of reagent will depend on the nature and disposition of the paste as well as the need for specific environmental control. A detailed discussion of potential reagents is beyond the scope of this document and can in general be found in standard literature on treatment and stabilization. However, materials that are attractive for their pozzolanic and/or cementitious properties include Portland cement, fly ash, and slag. Additional components may include, for instance, lime for pH-control, specialty chemicals, resins and surfactants to enhance adsorption of metals, organic carbon and bacteria for biofixation, or topsoil, nutrients, and seed materials to enhance establishment of surface vegetation in support of reclamation efforts.

Of all potential reagents listed above, ordinary Portland cement (OPC) is the one that is currently used most in the production of paste. Apart from its geotechnical benefits, admixture of OPC leads to a reduced permeability of the paste, resulting in enhanced environmental protection by further limiting infiltration and leachate generation. In the cement matrix, contaminants are also entrapped through microencapsulation. This controls contaminant migration by limiting the transport of potentially soluble constituents. In addition, OPC has several geochemical benefits that may warrant its use. The alkaline conditions created by OPC may result in reduced metal solubility, enhanced adsorption, enhanced neutralization potential and reduced acid generation, reduced volatilization of cyanide, and reduced self-heating.

**Co-Disposal of Waste Materials**

Although largely unexplored, paste technology affords tremendous opportunity and potential for co-disposal of other waste materials. Paste production methods lend themselves very well to addition of environmentally-adverse products, either generated on the mining facility or off-site, and result in a uniformly distributed mixture. The material characteristics of paste, in combination with the flexibility to engineer the desired chemical and physical qualities, potentially allow for encapsulation of a wide variety of materials both underground and on the surface. This capability may provide powerful financial, operational, environmental, and regulatory incentive for use of paste as the method of choice for tailings disposal.

The premier mining waste that lends itself to co-disposal with paste is acid generating waste rock. Encapsulation of this material in an appropriately-designed paste may alleviate the environmental impacts commonly associated with ARD generation, and provide significant benefits in terms of environmental control and waste management. Other examples of mining wastes potentially amenable for incorporation in engineered paste are by-products from various separation circuits, process solutions, sludges from treatment operations, etc. In addition, in principle, the paste production technology can be used for landfilling of demolition debris, scrapped equipment, etc., in the paste deposit. In the latter cases, special permitting would likely be required as those materials would probably not be characterized as a mining waste from the regulatory perspective.

The application of encapsulating environmentally-adverse products in tailings placed in paste form may in the future be judged to be much broader than just for mining-related materials. It is not inconceivable that future co-disposal applications may extend to commercial disposal of non-mining toxic or chemically problematic wastes in a comparable manner, either in underground backfill or in tailings placed on surface in a paste form.

As existing landfills reach capacity, and new landfills are difficult to permit, the public is becoming increasingly aware of this impending (perceived or not) crisis, and continues to demand a solution with respect to the guaranteed availability of future waste disposal sites. Such societal awareness and pressure on the various responsible governmental agencies may be the catalyst for the thorough evaluation and subsequent implementation of paste as a viable and accepted disposal option. In the process, the public's perception of the mining industry might improve as well, as it is being realized that society can benefit from the technological developments advanced by the mining industry. The use of paste tailings for disposal of non-mining wastes may also introduce additional revenue streams for marginal mines, enhancing their economic viability.

## GEOCHEMICAL CHARACTERIZATION

As discussed above, the potential benefits of paste are many. In addition, empirical evidence indicates that virtually all tailings are amenable to paste production. However, thorough geotechnical and geochemical characterization is required before it can be decided to dispose of tailings in paste form. The characterization program needs to be tailored to the site-specific conditions, requirements, and expectations. Application of a generic characterization template to the paste investigation is bound to lead to inadequate design and operation parameters, with potentially catastrophic consequences.

Of particular importance is the paste's long-term environmental stability. The nature and extent of potential environmental impacts factor heavily in selection of the appropriate paste production and disposal scenario. A comprehensive geochemical characterization program must lie at the basis of such decisions.

Although individual aspects may vary, in our experience, the following components are generally required:

- Chemical analysis;
- Mineralogical analysis;
- Acid-base accounting;
- Short-term leach testing; and
- Long-term leach testing.

An understanding of the chemical and mineralogical composition of the paste is fundamental to any geochemical characterization program. In some instances, use of relatively robust analytical techniques (e.g., x-ray fluorescence and x-ray diffraction for chemistry and mineralogy, respectively) may suffice, but more sensitive techniques are generally required if a greater level of detail is desired (e.g., wet chemical analysis, electron microprobe, electron microscope). In particular when one is interested in monitoring compositional and mineralogical changes during weathering, use of sophisticated equipment may be necessary to identify any subtle differences over time.

Acid-base accounting is important when paste is expected or known to be acid generating. Also, when use of alkaline amendments is considered, acid-base accounting can assist in determining the necessary dosage. However, since acid-base accounting only identifies a material's potential to be acid generating, further testing is generally required to determine the likelihood and rate of acid generation. If paste is determined to be exceedingly reactive, a self-heating evaluation may be required, in particular if backfill of tailings paste in underground, dry stopes is envisioned.

Short-term leach testing is often included as a regulatory requirement. A large number of test methodologies are available, although their predictive value is limited. Short-term static tests rarely simulate anticipated disposal conditions. For most standard protocols, the static nature of the test, the elevated solution to solid ratios, the grainsize reduction, and the nature of the lixiviant combine to create an environment that has little in common with the future underground or surface setting. Although short-term tests are often considered to be worst-case indicators of leachate quality, the opposite can be true if the short-term nature of the test results in formation of stable mineral phases that would be absent under transient conditions. An example is the formation of ettringite (Ca-Al sulfate) during short-term leach testing of paste fly ash. Static tests may artificially enhance the stability of this mineral relative to transient conditions, which results in sequestration of a number of oxyanions (arsenic, selenium, antimony, chromium) that would have otherwise reported to the leachate (Verburg et al., in prep.). In general, therefore, the results of short-term leach tests should be used for semi-quantitative identification of possible elements of environmental concern rather than as absolute values that can be compared against water quality standards.

Long-term leach testing has long been a tool in the metal mining industry for prediction of future leachates from reactive mine wastes. As for the short-term testing, a considerable number of laboratory methodologies are advocated, although most merely reflect variations on a theme. Most laboratory protocols can be classified as either a column test or a humidity cell test. Both types have their advantages and disadvantages, which have been summarized by a number of authors (e.g., Mills, 1999; Price 1997). The humidity cell procedure is more standardized than the column test, which has resulted in development of a considerable database and permits comparison with earlier work.

These procedures have been successfully applied to paste. Figure 2 shows an example of a humidity cell setup for cemented, pyrite-rich tailings paste for a proposed copper mine. In this particular study, paste was leached under both subaqueous and subaerial conditions to help identify feasible tailings disposal options (i.e. underground vs. surface). Also included in the testing was an evaluation of the effect of grainsize reduction on paste leachability. This aspect of the study was aimed at differentiating between the behavior of paste monoliths and fragmented paste.

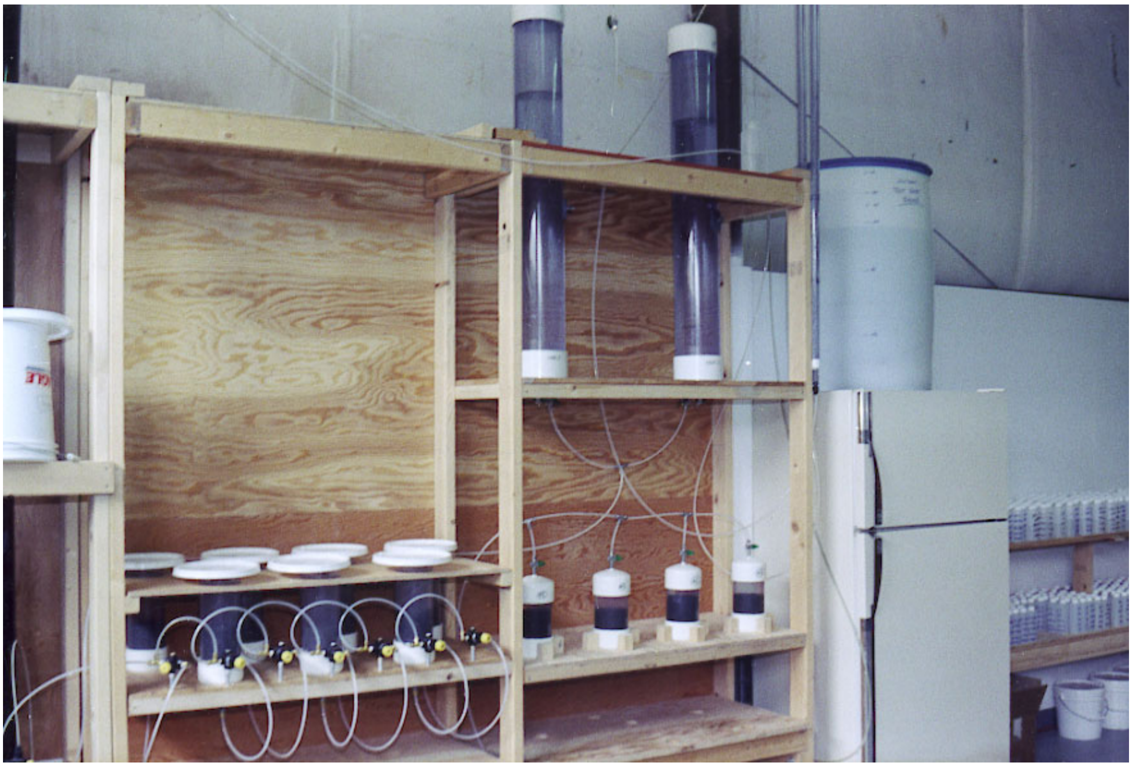

Figure 2 – Exposed (left) and submerged (right) humidity cell testing of paste tailings.

Figures 3 and 4 present selected test results to demonstrate the dramatic difference in leaching behavior that was observed under the two scenarios. As shown in Figure 3, the pH of the leachate was maintained at alkaline levels for the flooded material, whereas conditions rapidly became acidic in the exposed test cell. Figure 4 demonstrates how, in the subaqueous environment, sulfide oxidation was prevented, whereas under exposed conditions, oxidation of pyrite commenced at approximately week 15. An additional observation of potential importance was that the alkaline binder was leached preferentially from the submerged cell (Verburg et al., 2000), which confirms similar observations made by Bertrand et al. (2000). This may have important ramifications with respect to use of paste in an underground setting. In a dry environment, cemented paste will likely provide the expected bearing strength, but under wet conditions, its geotechnical and/or buffering properties may be affected over time. Clearly, an evaluation of long-term leaching behavior is required to identify and evaluate potential disposal alternatives.

Despite the advantages of long-term laboratory testing over short-term evaluations, the limitations imposed by the laboratory setting are such that the testing conditions rarely represent perfect simulations of the disposal environment. Large disparities may exist between laboratory and field conditions due to the need for sample preparation, and differences in climate conditions, solution application rates, sample size and representativeness, and particle size. In addition, leachate compositions derived from laboratory testing may differ from those obtained in the field due to the fact that humidity cells are designed to measure weathering rates of primary minerals, whereas monitoring of minesite drainage also accounts for formation and dissolution of secondary minerals (Price, 1997).

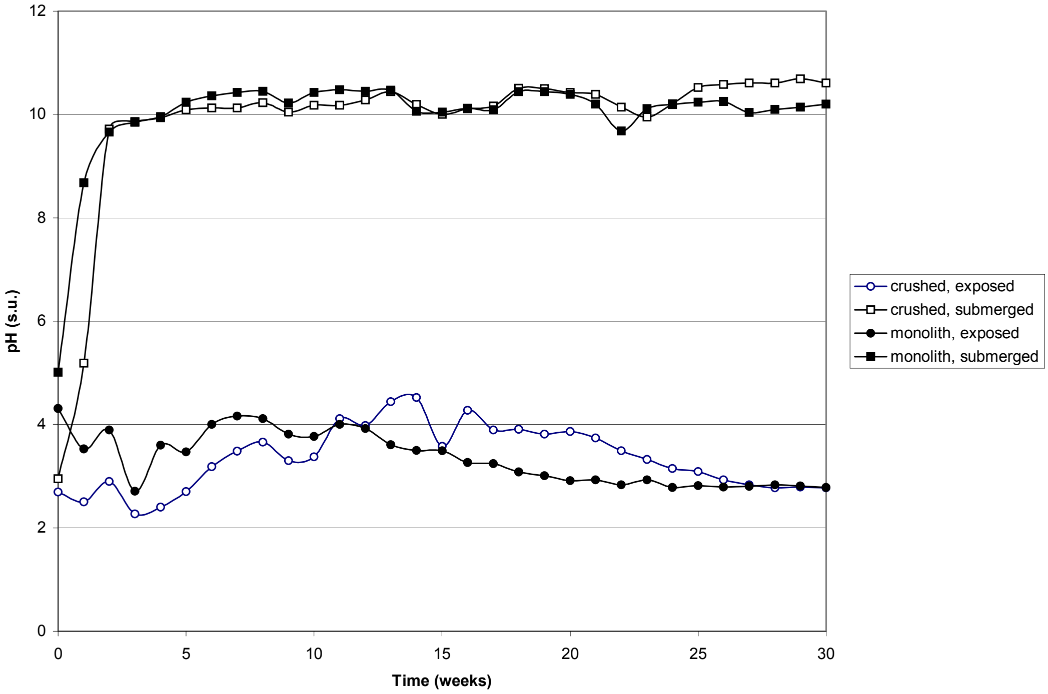


Figure 3 – pH trends in laboratory humidity cell testing.

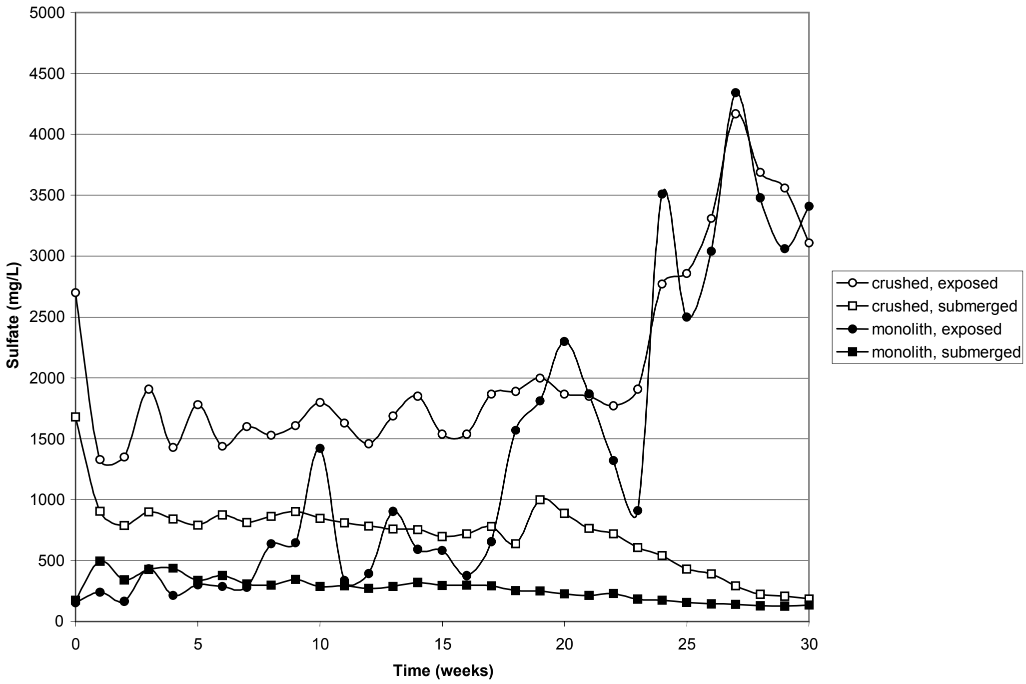


Figure 4 – Sulfate trends in laboratory humidity cell testing.

Use of field tests minimizes and eliminates some of the limitations associated with laboratory setups. Considerable flexibility exists with respect to design of field tests, as site-specific conditions will dictate different configurations and monitoring requirements. The following are two examples of field cells successfully used in prediction of long-term leachate quality from paste.

Figures 5 and 6 are a schematic cross-section and photograph of field cells designed for comparison testing of three tailings paste mixtures with different OPC contents. All tests were carried out in duplicate, resulting in a total of six cells as seen in Figure 6. Each cell contained approximately 1 $m^3$ of paste, and was instrumented with a variety of monitoring devices. Other than the upper surface of the cells, the paste was isolated from the environment. A monitoring well was installed in a gravel base for collection of seepage under saturated conditions. Nested lysimeters in the upper portion of the cell were used to collect leachate from the unsaturated portion of the paste. An aluminum standpipe provided access through the cell for in-situ measurement of moisture content, density, temperature, and other pertinent parameters. A weather station for monitoring of precipitation and wind direction/speed complemented the testing setup. Periodic sample collection and use of continuous meteorological data loggers allowed for development of a complete water and loading balance of the cells over time.

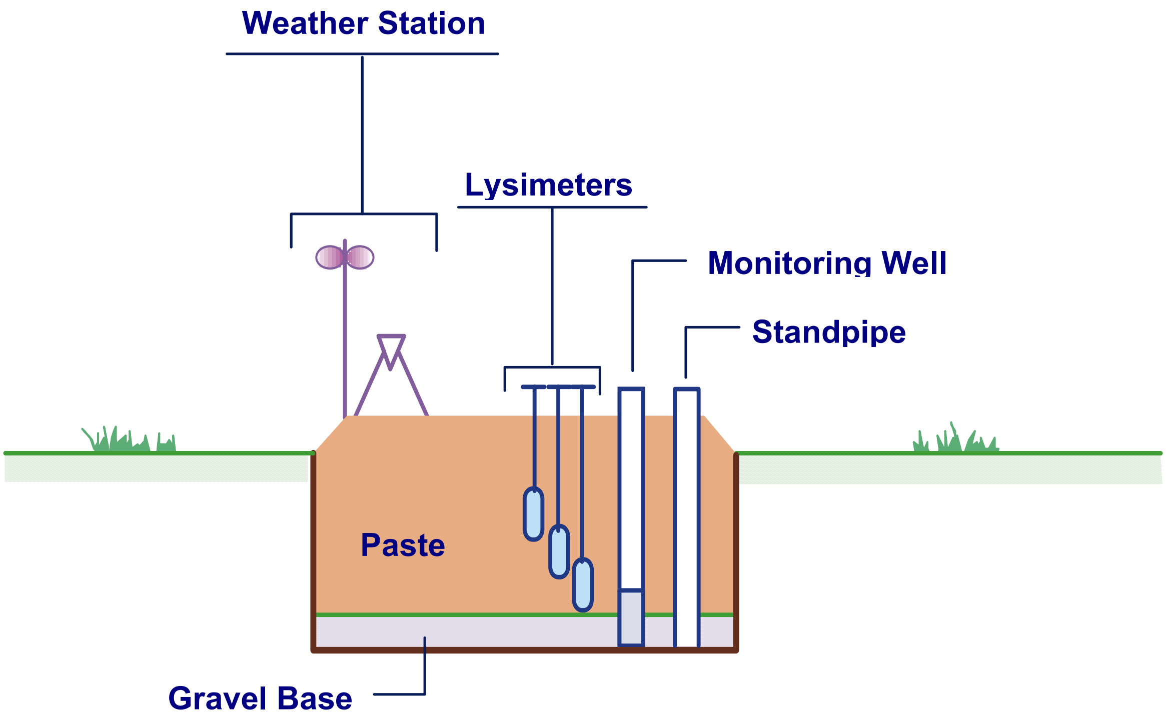


Figure 5 – Schematic design of field paste cell.

Figure 6 – Construction of field paste cells.

Considerably larger cells are shown in Figures 7 (design drawing) and 8 (photograph). This field testing program was aimed at determining in-situ environmental stability of fly ash paste at a lignite-burning power generation facility. Two test cells were constructed within an existing clay-lined ash landfill. One cell contained approximately 25 $m^3$ of paste; in the other cell, paste was absent so that it could be used as a reference.

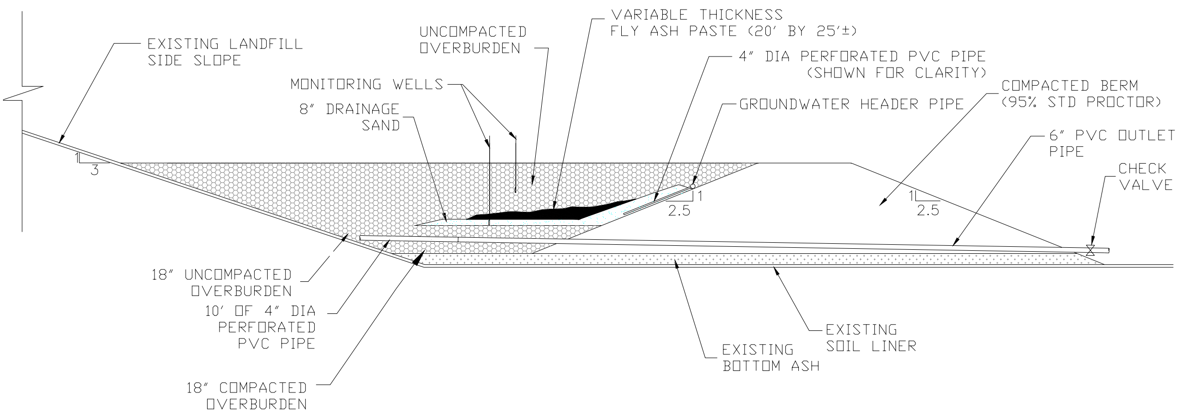


Figure 7 – Schematic design of field paste cell.

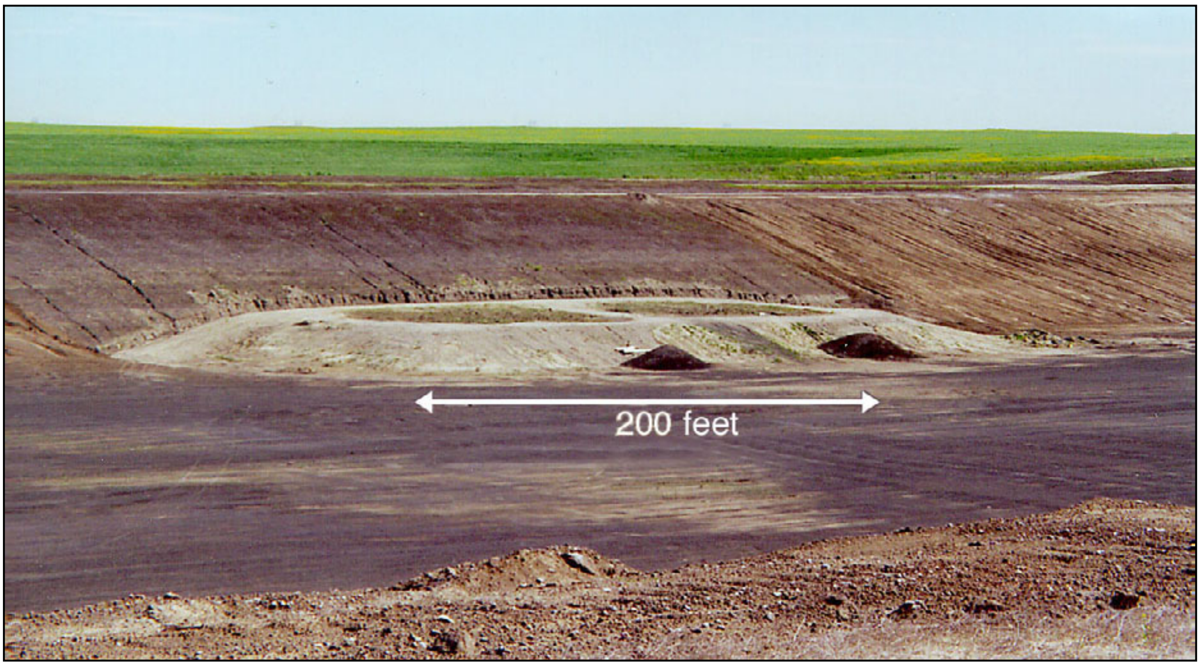


Figure 8 – Photograph of paste (left) and reference (right) cells.

The floor and sides for the cells were constructed using compacted clay from nearby mine spoils. A plumbing system was designed to draw the influent both above and below the paste. Paste was poured into the paste cell directly on a sand layer. The sand layer was used to provide 1) a means to distribute water in the cells, and 2) a zone for water/paste interaction. No paste was placed in the control cell. Both cells were backfilled with loosely-placed mine spoils. Continuous flow to the influent pipes was controlled by a float valve in a stilling basin supplied by a storage vessel filled with nearby pit water. The float valves were adjusted to maintain saturated levels in the influent pipe. After completion of the cells, a shallow and deep monitoring well were installed in the cells. The wells were constructed to measure water levels in each cell and for sampling, if desired.

After monitoring well installation, the field cells were filled with water. Once water levels in the cells were approximately equal, the effluent pipes were activated and adjusted to achieve the desired effluent flow rate. The flow rate was determined *a priori* and reflected a compromise between natural hydraulic gradients in a reclaimed setting and the need to provide meaningful results in a timely and useful manner. Furthermore, the total volume of water eluted through each cell at this rate for 10 weeks equaled the total estimated volume of water in each cell. At week 8, it was decided that, based on the time trends for all effluent constituent concentrations and the understanding developed from earlier long-term laboratory testing, the cells had reached a chemical steady state or near-steady state conditions. It is anticipated that the cells will be monitored for several years to augment the existing database and enhance our understanding of the fundamental principles that govern paste fly ash weathering. In addition, the cells may function as an early-warning system in the unlikely event of a drastic change in leaching behavior.

In both studies, the field cells provided invaluable information on long-term behavior of paste. Because of the similarities between the test environment and the anticipated disposal conditions, the monitoring results were considered representative of long-term leaching characteristics. Regulatory concurrence was obtained relatively easily due the regulators' high degree of confidence with regard to the test data.

## CONCLUSION

The use of paste for surface and underground disposal of tailings as an alternative to traditional methods is opening the way for a new era in mineral waste management practice. Paste disposal has many benefits related to the operational, environmental, and regulatory aspects of mineral extraction and processing facilities. In addition, paste technology holds great promise in altering the public perception of mining wastes and the mining industry in general.

Comprehensive geotechnical and geochemical characterization of paste are crucial to evaluation of paste designs and disposal alternatives. In particular, the use of large-scale field cells is proving to be of great value in determining and prediction the long-term environmental stability of paste.

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