Steven R. Day[1]

# THE COMPATIBILITY OF SLURRY CUTOFF WALL MATERIALS WITH CONTAMINATED GROUNDWATER

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## REFERENCE:

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## ABSTRACT:

Slurry cutoff walls are frequently relied upon to block groundwater flows from toxic waste sites and landfills. The long-term effectiveness of slurry cutoff wall materials is critical to the successful containment of these facilities and the protection of groundwater resources. A variety of laboratory indicator tests have been attempted by engineers and academia to make compatibility determinations but at present there has been little published experience to show which tests produce meaningful results and how these tests can be used to demonstrate compatibility.

Hydraulic conductivity is a useful measure of chemical/soil compatibility but permeability tests alone cannot assure the long-term stability of a slurry cutoff wall. A suite of indicator tests are used where the leachate and the proposed materials are combined and tested in immersion, desiccation, sedimentation, and other modes. Each indicator test attempts to model a different scenario of the slurry cutoff wall installation and operation.

This paper presents the experience of a specialty contractor from a number of projects, where an incompatibility was discovered and alternate materials were used to find a successful solution. Monitoring results from these sites has proven the effectiveness of the chosen solution. The laboratory test methods described are relatively simple and rely on worst-case scenarios, performed in a step-by-step process, which culminates with flexible wall permeability tests. Based on the method described and the results from successful projects where these methods were used, engineers, owners and the public may better rely on long-term slurry cutoff wall performance with an increased level of confidence.

**KEYWORDS:** attapulgite, bentonite, compatibility, containment, deep soil mixing, hydraulic conductivity, jet grouting, slurry cutoff wall

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[1] District Manager, Pittsburgh Office, Geo-Con, Inc., 4075 Monroeville Boulevard, Pittsburgh, PA 15146

## INTRODUCTION

Slurry cutoff walls are permanent subsurface structures used to direct and control groundwater flow. Since the inception of this technique in the 1940’s, slurry cutoff walls have been used where relatively unpolluted groundwater was diverted for civil works such as dams, dikes and dewatering structural excavations (Ressi di Cervia 1992). With the beginnings of CERLA legislation and the environmental movement in the 1970’s, more and more slurry cutoff walls are built to contain contaminated groundwater at landfills, hazard waste and industrial facilities (Ryan 1987). The hydraulic conductivity or permeability of slurry cutoff walls is usually the performance criterion relied upon in the design, construction and contracting of these structures. For projects with an environmental function, the lowest practical hydraulic conductivity is typically specified for the maximum protection of the public and groundwater resources.

Hydraulic conductivity (permeability) testing has significantly improved over the last decade but is of limited use in determining incompatibility. The time and expense required for hydraulic conductivity tests limit the user in formulating compatible mixtures and complicates feasibility estimates. Furthermore, the flexible wall permeability test, the industry standard, requires the imposition of a confining stress, which can mask certain incompatibilities (Evans 1993).

In this paper, compatibility is defined as when two materials, i.e., contaminated groundwater (or leachate) and soil-bentonite, can be mixed together or coexist without reacting chemically or interfering with the performance of the soil-bentonite. An incompatible result is an increase in permeability in the soil-bentonite or chemical reaction which produces a degradation in the physical properties of the soil-bentonite.

Predetermining the compatibility of slurry wall materials with contaminated groundwater is generally recognized as good engineering practice (Ryan 1987; D’Appolonia 1980; Grube 1992; Millet and Perez 1981;Tallard 1984). Some methods, other than hydraulic conductivity testing, have been proposed to determine compatibility (McCandless and Bodocsi 1988; Khera and Thilliyar 1990; Wu and Khera 1990) but these have had limited experience and the results of some tests are poorly understood. This paper presents a suite of relatively simple and quick indicator-type tests which can be used in concert with hydraulic conductivity tests to more quickly and better determine the most applicable materials for the containment of contaminated groundwater with slurry cutoff walls.

## PURPOSE OF COMPATIBILITY TESTING

Compatibility tests should simulate the long-term, worst-case performance of slurry walls in a contaminated groundwater environment. As yet, no standards exist which can guide the user to determine compatibility.

The primary reason for performing compatibility tests is to ensure that the slurry cutoff wall performs as intended. Compatibility testing also makes the planning and construction effort more efficient and results in a higher quality installation. The most important reasons for completing compatibility tests are as follows:

1. ensure permanence of the materials,
2. estimate long-term performance,
3. estimate material and additive types and amounts,
4. ensure success of construction,
5. accelerate feasibility studies, and
6. address regulatory concerns.

In general, incompatibilities result from chemical reactions. It may be assumed that superior knowledge of the chemicals involved will preclude compatibility testing but practical experience has shown the current state of knowledge to be limited (Ryan 1987). In some cases (e.g. landfills) the types and concentrations of chemicals varies widely. On other sites with more definable chemistry, the subspecies which result from mixing with groundwater cause similar uncertainty. Therefore, while a thorough understanding of soil/waste chemistry is important, studies to detect incompatibilities must rely on experimental methods.

It is, therefore, the purpose of this paper to explain and illustrate, by example, tests which can be used to determine the gross compatibility or incompatibility of slurry cutoff wall materials when used in contaminated groundwaters.

## POTENTIAL FAILURE MECHANISMS

Slurry cutoff walls are susceptible to failure during construction and operation as a result of groundwater contamination. Because of the specialized nature of the construction process, the materials selected for the installation must meet workability restraints. In practice, this means that the materials must be suitable for the specialty contractors' requirements as well as the designers objectives for the installation to be effective.

The first and most important ingredient in slurry cutoff wall construction is the bentonite slurry. Ineffective slurry results in excessive material usage, the necessity for additives, and/or the loss of slurry workability. Fresh water for mixing and premium grade bentonite are the primary slurry ingredients. Poor quality water (e.g. hard or polluted water) and/or poor quality bentonite can usually be identified by testing trial mixture.

Excavating through refuse or concentrated wastes can have a detrimental effect on slurry performance. Unusual or excess material usage can result. Flocculation of bentonite in a slurry trench will often result in a trench collapse and/or massive settlement of solids on the bottom of the trench which limits backfilling. Contaminated groundwater has been a cause of bentonite flocculation and, therefore, tests to predetermine the potential for construction failures, material usage estimates and the need for additives is critically important.

Contaminants may react with the key ingredient, bentonite clay, more slowly, in a manner where the effect may be more gradual and not readily apparent during construction. The impermeability of slurry walls relies to a considerable degree on the swelling properties of bentonite. Contaminants which reduce or restrict bentonite swelling may increase permeability but also can damage the self-healing properties of bentonite.

Finally, contaminants can effect not only construction practice and bentonite behavior, but also the properties of the backfill. The slurry cutoff wall backfill may lose plasticity, shrink, experience weight changes, dissolve, or petrify in response to leachates all of which can affect the slurry cutoff walls' performance. Mixtures which use cementacious ingredients (i.e. cement and fly ash) require additional considerations. The more complex the blend of materials in the slurry wall (e.g. plastic concrete > cement-bentonite > soil-bentonite) the more critical the need for examining properties of the backfill other than hydraulic conductivity as they relate to compatibility.

The system used to enact and direct the testing program is critical to successful implementation as well as the timely completion of the project. By testing the materials systematically, under worst-case scenarios, the program quickly becomes focused on workable solutions. Relatively large numbers of simple and rapid tests can be performed to eliminate borderline materials.

## INDICATOR TESTS FOR COMPATIBILITY

Various indicator tests have been proposed to investigate the effect of contaminants on slurry cutoff wall materials; but to date, there is limited understanding of their applicability and even less experience to document the success of one method over another. The basis for these tests was previously developed by the petroleum, well drilling, and geotechnical disciplines. These are relatively simple tests which rely on observations and comparative results. In general, comparisons are made between performance or observations with tap water as a control (or 0.005 N $CaSO_4$) compared to a leachate. These tests are by intent worse case models of assumed field conditions; therefore, the user must be knowledgeable to interpret and apply the results. The tests described below are those most often used by the author to evaluate compatibility.

### Construction

Construction compatibility can be modeled by comparing the performance of a standard bentonite slurry in dilution with water and leachate using conventional

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bentonite slurry test procedures (API, RP13B-1 1990). Generally, a slurry with B/W = 5% (Bentonite/Water ratio by weight) is used and diluted 1:1 with tap water and with leachate. Depending on the application, variations in the B/W and dilution ratios may be appropriate. Because of the uncertainty in interpreting test results, it is often best to run a suite of tests. The usual tests include:

- relative filtrate loss (D'Appolonia, 1980),
- viscosity by rotational viscometer (McCandless and Bodocsi 1988), and
- sedimentation (Ryan 1987; Bowders 1985).

These tests generally give a gross indication of the expected performance of the bentonite slurry during construction and generally require only a few hours or days to perform.

The filtrate lost test is performed by pressurizing a chamber filled with slurry until a cake of pure bentonite (filter cake) is formed. The volume of water which flows out of the cake during the 30-minute long test is called the filtrate. Trench stability is dependent on a low filtrate. A second and longer test of two identical filter cakes can be performed by permeating the filter cakes with leachate and water. A ratio of flow rate with water and leachate is calculated. generally, a rate which exceeds two indicates an incompatibility. See Figure 1.

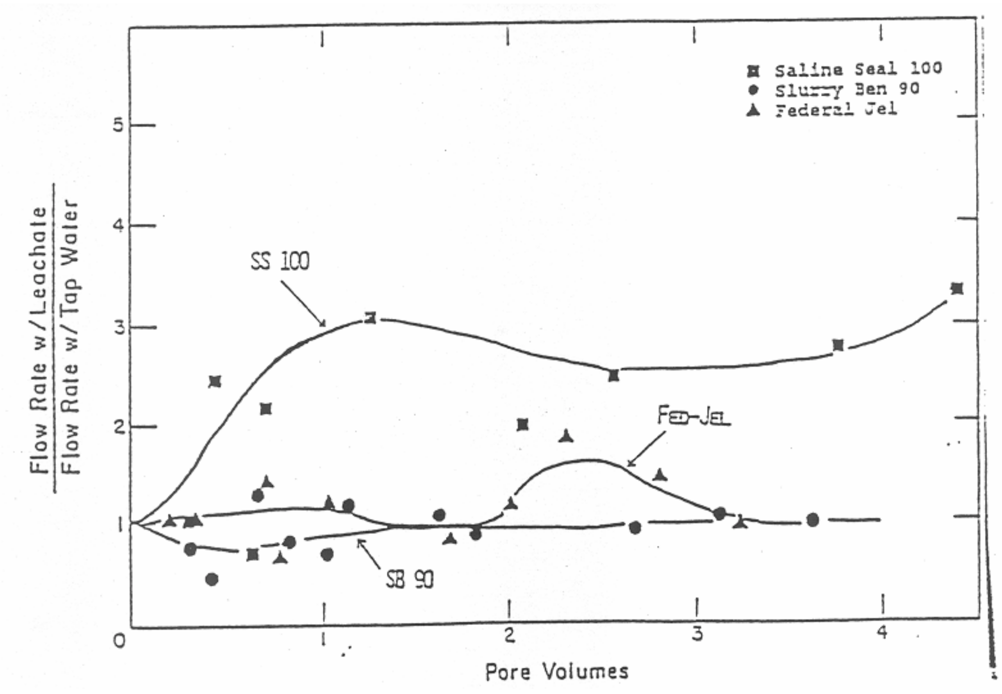

**Figure 1. Relative filtrate loss test using three bentonite clays with a landfill leachate.**

Similarly, a change in viscosity as measured by a rotational viscometer, may indicate the potential for construction difficulties. Identical slurries are made and then diluted with water and leachate. The viscosity of each diluted slurry is tested and compared. Changes in viscosity can be subject to various interpretations. A decrease in viscosity may result from flocculation or from a beneficial thinning of the slurry. Increases in viscosity can be the result of a viscose contaminant (e.g. petroleum) which may have no real effect on compatibility.

The sedimentation test has been used to model the construction process when the slurry is used to support the trench walls. Two identical bentonite slurries are diluted with leachate and water and observed. In this test, it is often informative to use a variety of B/W ratios for the slurry prior to dilution with the leachate because sedimentation or flocculation may be controlled to some extent by using a thicker (higher B/W) slurry or additives. Evidence of flocculation is by observation of the slurry in glass cylinders usually over a period of days.

In all of the above tests, the user must balance workability constraints (primarily viscosity and filtrate loss) with the need to address compatibility. These needs may conflict and require new materials or slurry additives to achieve the desired result.

## Commercial Clay

Direct observations of the commercial clay product (bentonite, attapulgite, etc.) in contact with the leachate may also be used to indicate compatibility. These tests generally require a few days to complete. Again, multiple tests are used and includes:

- chemical desiccation (Alther et al. 1985), and
- free swell (McCandless and Bodocsi 1988).

These tests tend to model the most severe exposure and must be considered with some caveats. The chemical desiccation test is the drying of the bentonite slurry in contact with the leachate on a glass plate. The same standard slurry and dilution described above are used. Often severe cracking, chemical reactions, or dissolution of the clay particles can be observed. The clay is prehydrated in this test and then air-dried, which may be analogous to the field situation near the water table. The desiccation pattern of all clays are not identical. Some clays (e.g. sepiolite) appear unsuitable even when tested with tap water.

The free swell test has been used to investigate compatibility but is limited in its application since the bentonite is not prehydrated. In this test, dry bentonite particles are sprinkled into a graduated cylinder filled with water or leachate. If the bentonite does not swell, an incompatible result is indicated. In general, there is no field situation analogous to this test.

These two tests can often be used to confirm results obtained from the construction compatibility testing. The appearance of the bentonite filter cake from the free swell test. It is not uncommon to have apparently contradictory results.

## Backfill

The slurry wall backfill material can be tested for compatibility using procedures which test the stability of the material when in contact with the leachate. Modified versions of ASTM standard tests can be used as follows:

- immersion test (ASTM Annual Book of Standards, C-267, 1991),
- fixed-wall test (ASTM D-2434, 1991), and
- plasticity (ASTM D-4318, 1991; Bowders 1985).

These tests usually require a week to a few months to complete, although typically much less time than the flexible wall test. Experience has shown that indications of incompatibility with these tests usually occurs quite early in the procedure, thereby reducing the overall testing schedule.

With cement-bentonite (CB), soil-cement (SC), and plastic concrete mixtures, a modified version of ASTM C-267, Chemical Resistance of Mortars, Grouts, and Monolithic Surfacings can be used to investigate the physical stability of the slurry wall material. This is an immersion test where the weight and strength of the sample is measured over time in response to immersion in a leachate, as compared to immersion in water. Observations of the samples may give dramatic evidence of incompatibility. While immersion may model some conditions below the water table, only materials with a minimum unconfined strength (approximately 200 kPa) are applicable since slaking with water can produce similar weight changes in softer materials.

Soil-bentonite and other soft slurry wall materials may be tested in the fixed wall permeability cell to determine compatibility. The hydraulic conductivity developed in these tests is often of secondary importance, what is gained are observations of the potential of the material to swell, shrink, or chemically react with the leachate (Anderson et al. 1985). Since limited (or uncontrolled) effective stress is imposed, gross changes in the sample are possible which may not be possible with flexible wall permeability tests. The author has observed cases where the reaction to the leachate was so severe the sample foamed and then petrified (turned to stone), whereas no similar effect was observed in a flexible wall test. Other important physical characteristics such as resistance to high hydraulic gradients may be observed.

Replacement of pore water with leachate can change the plasticity of the backfill and therefore, hydraulic conductivity. This test works best with soil-bentonite in accordance with a modified ASTM D-4318, Liquid Limit, Plastic Limit, and Plasticity Index of Soils. The user must take care to avoid imposing artificially induced effects as a result of drying. In general, the materials are slowly air-dried and rewetted with tap water and contaminated groundwater and the results compared. Some mixtures can lose considerable plasticity yet retain a low permeability.

It has been the author's tactic to use these tests in approximately the sequence described above, using incompatible results from earlier tests, to guide in the elimination of materials with a low probability of success. The testing program usually culminates with a limited number of flexible wall permeability tests to document long-term hydraulic conductivity in the presence of the leachate. With a knowledgeable selection of tests, materials and additives based on the indicator tests, the final flexible wall tests are nearly always successful.

## CASE STUDIES

The projects described below have been selected from the author's files of over a hundred successful projects. These case studies have been selected because they represent projects where an incompatibility was discovered and/or alternate materials were used to provide a suitable solution. The author has, by intent, limited the discussion to the facts of the case related to the determination of incompatibility and the finding of an alternate solution.

### Case Study No. 1: Southern Wisconsin Landfill

An operating sanitary landfill was closing a formerly uncontrolled landfill cell which had received hazardous wastes. Physical and hydraulic isolation of the cell was necessary to comply with regulatory directives to protect the environment. Closure of the cell included a RCRA cap, groundwater collection trench and soil-bentonite slurry cutoff wall.

Leachate from the landfill was generally characterized by a black color and pungent odor with high chloride (about 500 mg/l) and sulfate (about 10 mg/l) contents. The groundwater plume emanating from the site was found to contain toxic levels of organic chemicals including vinyl chloride. Contaminant levels were high enough that reuse of trench spoil in the soil-bentonite backfill was not permitted. Compatibility testing of the soil-bentonite backfill began with the development of a bentonite slurry from trenching. Three products were tested; two premium grade, sodium (API 13A) bentonites and one ”contaminant-resistant,” SS100 bentonite. A stable slurry with a B/W = 5% was produced from all three bentonites with a viscosity (Marsh Funnel) of 40 to 50 seconds without the use of additives.

Relative filtrate loss tests using the leachate and tap water are shown in Figure 1. It was observed that the SS100 bentonite permeated with the leachate produced a relative filtrate loss three times greater than with tap water and much higher than either of the premium bentonites. In the desiccation test, a pattern of small cracks was observed with the SS100 which was not present in tests of the other bentonites. Finally, a sedimentation test of the bentonites was performed. In this test, all three bentonites performed similarly.

Based on these results, SS100 bentonite was excluded from further consideration. The remainder of the test program, including hydraulic conductivity testing, proceeded successfully.

A 1200 meter (400 ft) long by 10 meters (35 ft) deep slurry cutoff wall was installed which has, since 1987, prevented the further contamination of the area. Tests show that the slurry cutoff wall was effective and the vinyl chloride plume dissipated.

## Case Study No. 2: Eastern Michigan Chemical Facility

A chemical plant was operating a system of treatment lagoons which abutted a former brine production area separated by a relatively narrow earthen dike. Closure of the brine ponds without disturbance to the treatment lagoons, using a slurry cutoff wall, was the aim of the project. The brine contained high levels of metals including calcium (8.3%), magnesium (0.60%), and sodium (1.61%). Total dissolved solids in the leachate was 25 to 30% and the density of the brine was 1.04, gm/cc.

Implementation of the project was complicated by at least three compatibility concerns:

1. brine is known to flocculate bentonite slurry,
2. chemicals in the treatment lagoons could have an unknown effect on the slurry wall, and
3. the dike was unstable (safety factor < 1.0) and required reinforcing.

The compatibility testing for this project began with the selection of an alternate clay to replace bentonite. Testing of premium bentonite, “saline-resistant” bentonite, and attapulgite was conducted as shown in Figure 2. In this case, attapulgite, a nonswelling montmorilite clay (Tobin and Wild 1986) was found to be most effective. In addition, attapulgite could be mixed with brine water for the trenching slurry. Using attapulgite with the brine water and wastewater also produced successful results in the desiccation and sedimentation tests.

Stabilization of the dike required a cementacious backfill which would reinforce the dike and increase the factor of safety against sliding. Cement-attapulgite (a variation of cement-bentonite self-hardening slurry) and plastic concrete mixtures

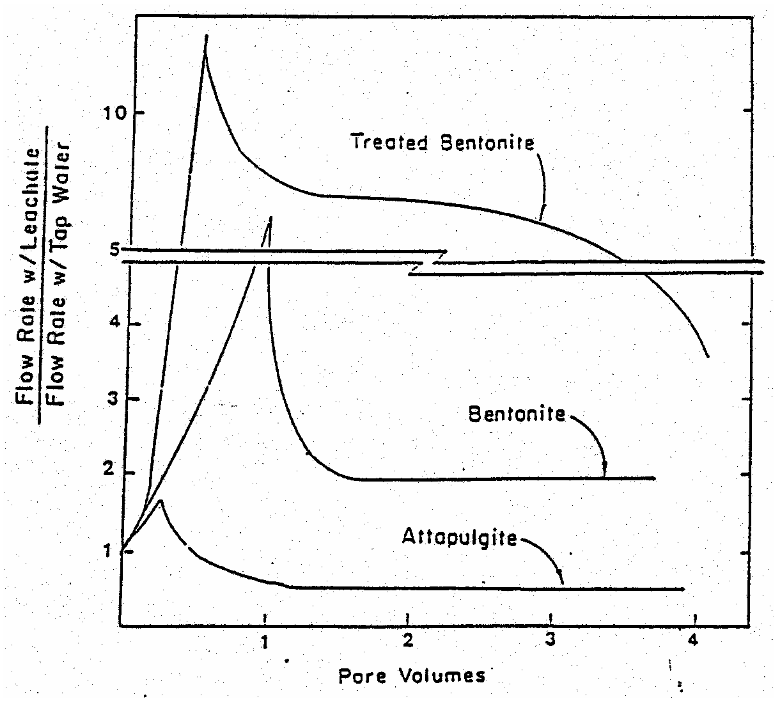

**Figure 2. Relative filtrate loss test using three commercial clays with brine water leachate.**

were tested with permeabilities less than 1 x $10^{-6}$ cm/sec. Results of the unconfined compressive strength tests are shown in Figure 3. Immersion tests and long-term permeability tests with the leachate were performed which demonstrated the compatibility of the cement-attapulgite with the brine water.

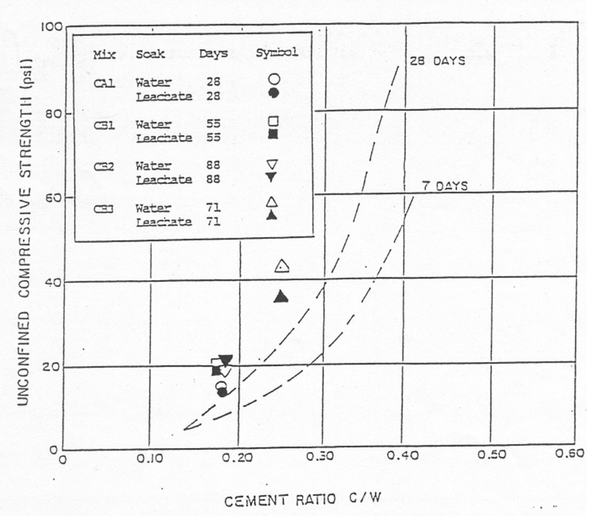

**Figure 3. Unconfined compressive strength of cement-attapulgite immersed in water and low pH leachate. Comparative trends for Millet and Perez (Millet and Perez 1981).**

Based on the results described above, a 700 m (2,000 ft) long cement-attapulgite slurry trench about 10 m (30 ft) deep was constructed through the center of the dike. Brine water was used as the mix water for the slurry. Since 1988, the project has served to separate the wastewater pond and the brine pond. The stability of the dike has been ensured by the use of the cement-attapulgite.

### Case Study No. 3: Upstate New York Lagoon Closure

A former mine and processing plant produced two byproducts which were co-mingled in a single earthen-lined lagoon. One byproduct, semet, has a pH < 0.5 and the other byproduct has a pH > 13. Storage of the two byproducts in a single lagoon did not produce neutralization and the leachates were found to be existing separately and seeping out of the lagoon into the groundwater.

At this time, one of the potential remedies to the sites is containment with a cutoff wall. The wall will be more than 30 m (100 ft) deep so deep soil mixing (DSM) and plastic concrete are considered as prime candidates for the cutoff wall. Compatibility testing for this site provides an opportunity to test the limits of the testing methods.

Testing began with separate tests of the high and low pH leachates with a variety of commercial clay products. As previously described, a step-by-step process was enacted which focused the program on the most critical compatibility challenge. The high pH leachate was compatible with all clays in the filtrate, sedimentation, and desiccation tests. Therefore, the majority of the program was focused on compatibility of materials with the low pH semet leachate. Filtrate, sedimentation, and desiccation testing proved that attapulgite was the best commercial clay to resist the semet. What remained, therefore, was to find a combination of soil and/or cement to complement the attapulgite. Initial tests with soil-attapulgite were carried out with fixed wall permeameters. The results were dramatic and unsuccessful. The leachate reacted violently with soil-attapulgite producing a gas and turning the sample into a petrified mass. Immersion tests with soil-cement-attapulgite (at relatively low total cement contents) were equally unsuccessful. Many of the samples dissolved in the immersion tests. Finally, cement-attapulgite blends (with relatively high total cement contents) were found which survived the immersion tests. The strength of immersed cement-attapulgite was similar to cement-bentonite mixture as shown in Figure 3. Long-term flexible wall permeability tests confirmed the compatibility of the cement-attapulgite by the display of a stable hydraulic conductivity over three pore volumes of flow.

### Case Study No. 4: Former Industrial Site in Vancouver, B.C.

A site which borders the bay in the center of Vancouver had been used since the city’s founding for a variety of industrial purposes including coal gasification, wood treatment, and fuel storage. A variety of toxins were found in the soils and groundwater including cyanide (10 ppm), hydrocarbons (100 ppm), pentachlorophenol (20 ppm), arsenic (1 ppm), lead (4 ppm), and zinc (6 ppm). In order to reclaim and develop the site, a DSM and jet grout wall was constructed to contain the contaminants. Development of the site requires excavation of an area of significant contamination and eventually building foundations; therefore, the cutoff walls were specified to have an unconfined compressive strength of up to 1.4 MPa (200 psi) as well as a hydraulic conductivity less than $10^{-6}$ cm/sec.

Due to the structural requirements and the availability of resources, the testing program focused on soil-cement blends which used a grout composed of Canadian calcium bentonite, Wyoming sodium bentonite, gypsum, fly ash, and cement. The use of gypsum was selected to provide improved strength with reduced permeability. Calcium bentonite is a low swelling bentonite clay which provides stability to the grout and reduces permeability. Concerns about the use of these innovative materials, as well as requirements for compatibility, resulted in an extensive testing program.

Testing of the bentonite resulted in the finding that at least three times as much Canadian calcium bentonite (B/W = 15%) as Wyoming sodium bentonite was necessary to produce a workable slurry. The addition of cement and fly ash to this slurry required thinners including both phosphate and lignosulfate based products.

The addition of gypsum provided beneficial thinning of the grout; and, therefore, the use of a relatively dense grout with no loss in workability. Once blended into the mix, the gypsum becomes a part of the cement matrix. No dissolution or other detrimental effects were noted with the use of gypsum.

Compatibility testing focused on immersion testing and flexible wall permeability testing of the soil-cement. Immersion tests were conducted for up to 90 days in the leachate. The immersed samples appeared identical in water and leachate with an average weight change of less than 1%. The majority of any weight change was usually discovered within the first 28 days of immersion. See Figure 4. Hydraulic conductivity tests on the hardened soil-cement confirmed the long term stability of the materials.

The cutoff wall was constructed in the summer of 1992. Each type of cutoff wall and grout mixture was subjected to extensive field testing including test sections which were excavated and examined. In total, over 600 m (2,000 ft) of cutoff wall were installed up to 16 m (50 ft) deep. In-situ testing and monitoring to date has shown the cutoff wall to be highly effective.

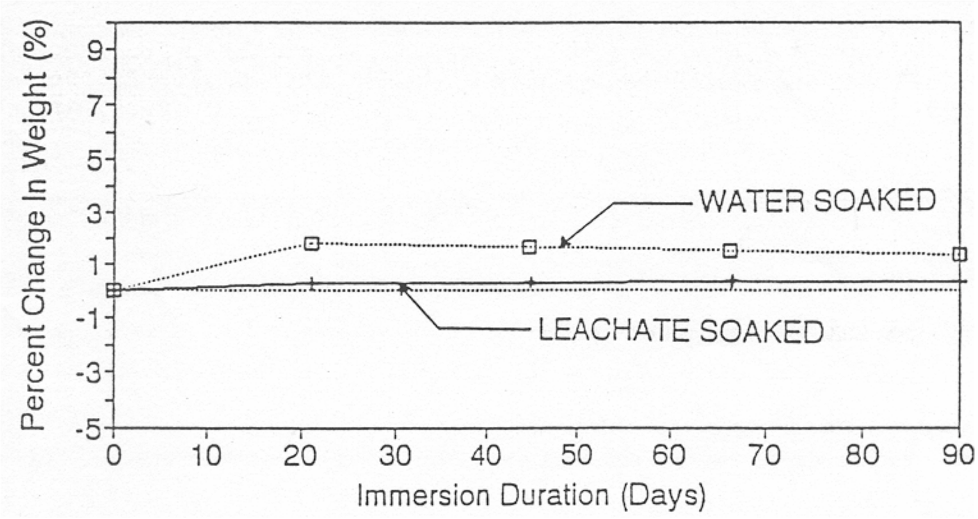

**Figure 4. Immersion test result of DSM sample in water and hazardous leachate.**

## CONCLUSIONS

A systematic approach to compatibility testing includes indicator tests along with permeability tests. Compatibility testing using indictor tests provides a relatively rapid and rational method for predetermining the compatibility of slurry cutoff wall materials with contaminated groundwater. Not all indicator tests are applicable on every project. Furthermore, some tests model situations which are impossible on some sites. The tests are relatively simple and rapid, but the application of the results to real remediation projects requires the expertise of a knowledgeable engineer and specialty contractor with experience in the materials selected for installation.

## References

Alther, G., J. C. Evans, Fang, H. Y. and K. Witmer, 1985, "Influence of Inorganic Permeants upon the Permeability of Bentonite," Hydraulic Barriers in Soil and Rock, ASTM STP 874, pp. 64-73.
Anderson, D. C., W. Crawley, and J. D. Zabcik, 1985, "Effects of Various Liquids on Clay Soil: Bentonite Slurry Mixtures, "Hydraulic Barriers in Soil and Rock, ASTM STP 874, pp. 93-103.

API, 13B-1, June 1990, "Recommended Practice Standard Procedure for Field Testing Water-Based Drilling Fluids."

ASTM, 1991, Annual Book of Standards, ASTM, Philadelphia, Pa.

Bowders, J., 1985, "The Influence of Various Concentrations of Organic Liquids on the Hydraulic Conductivity of Compacted Clay," PhD Dissertation, University of Texas, Austin, Texas.

D'Appolonia, D. J., 1980, "Soil-Bentonite Slurry Trench Cutoffs," Journal of the Geotechnical Engineering Division, Proceedings of ASCE, Vol. 106, No. Gt4.

Evans, J., 1993, "Hydraulic Conductivity of vertical cutoff Walls, "Hydraulic Conductivity and Waste Contaminant Transport in soils ASTM STP 1142, David E. Daniel and Stephen J. Trautwein, Eds., American Society for Testing and Materials, Philadelphia.

Grube, W. E., Jr., 1992, "Slurry Trench Cut-Off Walls for Environmental Pollution Control, "Slurry Walls: Design, Construction, and Quality Control, ASTM STP 1129, David B. Paul, Richard R. Davidson, and Nicholas J. Cavalli, Eds., American Society for Testing and Materials, Philadelphia.

Khera, R. P. and Thilliyar, M., 1990, "Slurry Wall Backfill Integrity and Desiccation, " Physico-Chemical Aspects of Soil and Related Materials, ASTM STP 1095, K. B. Hoddinott and R. O. lamb, Eds., American Society for Testing and Materials, Philadelphia, pp. 81-90.

McCaandless, R. M. and Bodocsi , A., August 1988, "Quick Indicator Tests to Characterize Bentonite Type," Office of Research and Development, U.S. EPA.

Millet, R. A. and J. Y. Perez, 1981, "Current USA Practice: Slurry Wall Specifications, "Journal of the Geotechnical Engineering Division, ASCE, Vol. 107, No. GT8

Ressi di Cervia, A. L., 1992, "History of Slurry Wall Construction, " Slurry Walls: Design, Construction, and Quality Control, ASTM STP 1129, David B. Paul, Richard R. Davidson, and Nicholas J. Cavalli, Eds., American Society for Testing and Materials, Philadelphia.

Ryan, C. R., 1987, "Vertical Barriers in Soil for Pollution Containment, " Hydraulic Barriers in Soil and Rock, ASTM STP 874.

Tallard, G., February 1984, "Slurry Trenches for Containing Hazardous Wastes, " Civil Engineering, pp. 41-45.

Tobin, W. R. and P. R. Wild, February 1986, "Attapulgite: A Clay Liner Solution?," Civil Engineering, pp. 56-58.

Wu, J. Y. and Khera, R. P., 1990, "Properties of a Treated-Bentonite/Sand Mix in Contaminated Environment, "Physico-Chemical Aspects of Soil and Related Materials, ASTM STP 1095, K. B. Hoddinott and R. O. Lamb, Eds., American Society for Testing and Materials, pp. 47-59.