POLYMER CONTAINMENT BARRIERS FOR UNDERGROUND STORAGE TANKS*

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ABSTRACT

Contaminated soils, buried waste and leaking underground storage tanks pose a threat to the environment through contaminant transport. One of the options for control of contaminant migration from buried waste sites is the construction of a subsurface barrier that consists of a wall of low permeability material. Brookhaven National Laboratory has been involved in several tasks to develop, demonstrate and implement advanced polymer materials for use in subsurface barriers throughout the DOE complex. Binders investigated as barrier composites include polyester styrenes, vinylester styrenes, high molecular weight acrylics, sulfur polymer cement, polyacrylic acids, bitumen and a furfuryl alcohol based furan polymer. Aggregates include: recycled glass, stone, sand, and natural soils (from Hanford).

A series of performance tests were used to determine the performance characteristics of polymer composites. This paper details a subset of this characterization pertaining to subsurface barriers for containing underground storage tanks with emphasis on the DOE's Hanford site. Testing includes measuring permeability to water, wet-dry cycling, chemical resistivity to ground water, acid, base, and nitrate brine, resistance to irradiation, and measuring compressive strengths.

Polymer grouts having a wide range of viscosities have been demonstrated to have desirable qualities for a subterranean barrier. The goal of soil mortar permeabilities of 1×10^{-10} m/s and "clean" aggregate composites of 1×10^{-11} m/s was met. Performance values indicate polymers exist that can meet the requirements for containment barriers for USTs throughout the DOE complex. Proper choice of binder and aggregate followed by the appropriate site specific compatibility testing will result in a durable, high strength, low permeability barrier.

INTRODUCTION

Contaminated soils, buried waste and leaking underground storage tanks (UST) pose a threat to the environment through contaminant transport. One of the options for control of contaminant migration from buried waste sites is the construction of a subsurface barrier that consists of a wall of low permeability material. In the case of underground storage tanks it has been proposed that an interim subterranean containment barrier be placed around the tanks. This would minimize or prevent future contamination of soil and groundwater in the event that further tank leakages occur before or during remediation. Use of interim subterranean barriers can also provide sufficient time to evaluate and select appropriate remediation alternatives. Portland cement grout curtains have been used for barriers around waste sites. However, large castings of hydraulic cements invariably result in cracking due to shrinkage and thermal stresses induced by the hydration reactions. For this and other reasons improved, low permeability, high integrity materials are being investigated through the Department of Energy's Office of Technology Development integrated demonstrations and programs.

Brookhaven National Laboratory (BNL) has been involved in several tasks to develop, demonstrate and implement advanced polymer materials for use in subsurface barriers throughout the DOE complex (1,2). The barrier material must be compatible with soil and waste conditions encountered in at the various Department of Energy (DOE) facilities and have as low an effective diffusivity as is in reasonably achievable to minimize or inhibit transport of moisture and contaminants. The materials being investigated were selected based on their applicability with conventional placement technologies (e.g., jet grouting, permeation grouting, trenching) and chemical and physical properties including low permeability to water, resistance to aggressive chemicals, radiation resistance and tolerance of an elevated temperature environment. Binders investigated as barrier composites include polyester styrenes, vinylester styrenes, high molecular weight acrylics, sulfur polymer cement, polyacrylic acids, bitumen and a furfuryl alcohol based furan polymer. Aggregates include: recycled glass, stone, sand, and natural soils (from Hanford). Laboratory testing and evaluation of soil mortars, blended sand mortars, concretes, and glass concretes has been on-going since early 1992. A series of performance tests were used to determine the performance characteristics of a variety of polymer composites. This paper details a subset of this characterization pertaining to subsurface barriers for containing USTs with emphasis on the DOE's Hanford site.

MATERIALS

Based upon site geochemical and geophysical characteristics encountered within the DOE complex, and UST performance requirements several candidate polymer grout systems were selected for development and characterization as barrier materials. The selection was based on the ability of candidate grouts to withstand high radiation doses, high temperatures and aggressive tank waste leachates. The candidates can be classified as either organic polymers, in this report generically termed polymer concrete, or inorganic polymers. Organic binders investigated include polyester styrene, vinylester styrene, a high molecular weight acrylic, and a furfuryl alcohol based furan polymer. For the UST the only inorganic polymer candidate investigated was sulfur polymer cement.

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Aggregates include: recycled glass, stone, sand, and natural soils (from Hanford). The choice of recycled glass as an aggregate was to reduce the binder requirements (compared to mortars), and utilize a waste product. For this report the following definitions apply: soil mortar consist of a polymer binder mixed with soil (in this case from Hanford), mortar is a polymer binder using a blended silica sand aggregate, concretes contain a binder and a 50-50 (by wt.) mix of coarse (<⅜") silica stone and blended sand, and a glass concrete utilizes crushed recycled glass and blended sand (40-60 by wt.).

For the Hanford site it is desirable to have a placement technology that does not require extensive amounts of excavated soils which are potentially contaminated. The first choice of barrier construction is to use the natural soil as it exists around the tanks as the aggregate in the polymer concrete. Polymer systems were chosen to have a wide range of viscosities (~1 to 300 cps) to accommodate soil conditions at the various DOE sites. The goal for soil mortar barriers is to achieve high durability barriers with permeabilities of 1 x 10^{-10} m/s or less.

Another choice for barrier construction is to use "clean" aggregate (e.g. sand or stone) that is brought to the site. Application would most likely be a displacement method (produces low amounts of excavated soil) such as vibrating beam or fracture grouting. The goal for "clean" aggregate barriers is to achieve high durability barriers with permeabilities of 1 x 10^{-11} m/s or less. A brief description of materials follows.

Methacrylate monomers (acrylic) are a low viscosity, inexpensive, and commonly used family of polymers. The methacrylate chosen is manufactured by the 3M company under the tradename 3M 4R 5742 Concrete Restorer and is a modified high molecular weight methacrylate (viscosity = ~1 cps).

Polyester styrenes (PES) are among the most widely used thermosetting resins. The basic components of a PES polymer consist of a mixture of a linear polyester resin and styrene monomer. BNL selected a modified bisphenol fumarate resin distributed by Reichhold Chemicals, under the tradename Atlac 4010A. This resin is especially formulated for alkali resistance. The viscosity of the polyester-styrene solution is approximately 300 cps.

Vinylester styrene (VES) polymers are extremely durable both chemically and physically. The VES system used in this study is manufactured by DOW Chemicals under the tradename Derakane 470-45 and is an epoxy novolac- based vinyl ester resin dissolved in styrene. This particular Derakane was formulated for good chemical resistance (including solvents), retention of properties at high temperatures and low viscosity (~100 cps).

A commercial, furfuryl alcohol (FA) based system, FA-Rok 913 manufactured by QO Chemicals, was used for this study. FA-Rok has a low viscosity (~3 cps), low vapor pressure, low flammability, and is soluble in water. This material produces a very resistant polymer using inexpensive and environmentally innocuous components. Set times and exotherms cannot be as tightly controlled as in the other polymer systems

Sulfur polymer cement (SPC) was developed by the U.S. Bureau of Mines to utilize surplus sulfur (3). SPC is a thermoplastic material that when heated above its melting point (119°C), can be mixed with aggregate, soil, waste, etc. Upon cooling, SPC forms a hard monolithic solid. SPC is used for construction of chemical vats, road repairs, and is a candidate for encapsulating radioactive, hazardous, and mixed wastes (4,5). The sulfur cement used in this study was manufactured by Martin Chemicals under the trade name Chement 2000 (viscosity = 28 cps @ 135°C).

SAMPLE FORMULATION/FABRICATION

The polymer systems were optimized to the chemical and physical properties of the Hanford soil, blended sand, concrete and glass aggregate. The furfuryl alcohol failed to gel with added Hanford soil because of the neutralizing effect of the high pH soil on the acid catalyst. All other systems followed expected gel times. This initial trial eliminated furfuryl alcohol as a candidate material for Hanford soil mortar barrier technologies. However, displacement/replacement might still use furfuryl alcohol with the neutral aggregates.

After confirmation of catalyst-promoter quantities to achieve reasonable gel times, sample fabrication techniques were refined. Porosity of the soil surrounding the tanks was estimated to be 35-45% based on the coarseness of the soil sample received from Hanford. This would correspond to approximately 20-25% by weight monomer required to fill the void volume of the soil. The soil samples received were unconfined and attempts to replicate the density of the confined soils would be difficult and unnecessary at this time, since an exact placement technology has not yet been chosen. Of primary importance is the interaction of the monomer/soil composite and its durability properties. BNL attempted to balance the requirement of staying near 20-25 wt% monomer and produced laboratory samples that were reproducible and homogeneous. Displacement/replacement grouts are independent of waste site soil porosity and the clean aggregate grouts were formulated to achieve the most economical mix that still resulted in a flowable grout.

Samples were fabricated by mixing together (in order) resin, promoter, catalyst and the as received soil in a Hobart mixer. The only exception to this is with the FA system. FA requires the catalyst to be mixed first with the aggregate and to be evenly dispersed through the aggregate. Samples were molded in ~1 meter long PVC pipe. After polymerization (or solidification for SPC) was completed, the pipe was cut to length. This resulted in cylindrical specimen measuring 5.1 cm x 10.2 cm for clean aggregate and 3.8 cm x 7.6 cm for the soil mortars (aspect ratio = 2:1). Final formulations are given in Table I.

TESTING AND RESULTS

Representative samples of the various binder/aggregate combinations were subjected to a series of performance tests to determine if the materials were capable of meeting the requirements of a subterranean barrier for USTs. Soil mortars, which were part of an initial comparative study directed at the USTID were conditioned to ~50% humidity for seven days after durability tests were complete but prior to destructive strength testing. The "clean" aggregate samples were tested at ~100% humidity with the exception of the baseline compressive strengths which were measured at "room humidity" of ~20-30%, in accordance to the ASTM procedure. In all cases samples were "cured" 30 days at room temperature and humidity prior to any testing.

Compressive Strength

Replicate (10 for soil mortars, otherwise 5) samples of each binder/aggregate combination were tested for

TABLE I
Formulations - Aggregate:Binder Ratios

Binder	Soil Mortar	Mortar	Concrete	Glass
VES	75:25	85:15	90:10	88.5:11.5
PES	73:27	82:18	88:12	85.5:14.5
Acrylic	77:23	87:13	91:9	89:11
FA	na	86:14	90:10	88:12
SPC	70:30	75:25	84:16	82:18

na = not applicable

unconfined compressive strength (ASTM D-695) (6) to determine baseline strength. Resultant values for polymer concretes showed low scatter which is evidence of good homogeneity. SPC samples showed larger standard deviations. Examination of the fractured samples indicated the presence of entrained air within the samples, typical of SPC. It is postulated that the amount and size of these air bubbles is dependent upon mix viscosity, soil loading, mix speed and mix time. The effect of these variables may explain the variability. Results are given in Table II.

90 Day Water Immersion

A subterranean containment barrier is expected to be exposed to aqueous environments either from leakage of the supernatant contained in the UST or percolate water. Exposure of barrier materials to aqueous solutions can result in swelling, cracking, dissolution, etc. The soils used as aggregate may also interact with the water through swelling (i.e., expansive clays) and dissolution of mineral components. Replicate (5) samples of each binder/aggregate combination were immersed in deionized water for a period of 90 days. At the end of the test period the samples were weighed, measured and destructively tested for compressive strength (ASTM D-695). Compressive strength data after immersion are given in Table II.

SPC soil mortars cracked after three to five days exposure to ionized water. This effect is probably due to a small expansive clay portion in the Hanford soils which would induce tensile stresses in the sample when exposed to water. During the fabrication of SPC samples, temperatures in excess of 120$C are required to melt the binder. At these temperatures the residual soil moisture is driven off and the clays shrink to their minimum volume. When the clays are re-wetted they expand with resultant internal stresses

For the clean aggregate samples, results were mixed. The FA, acrylic concrete and acrylic mortar samples showed no strength loses for any of the aggregate types after 90 days. The acrylic glass composite showed strength loss averaging 40%, which may indicate some reactivity between the polymer and the glass. SPC samples showed no statistical change in strengths, there was however, a large amount of scatter in the results. The PES samples showed losses averaging 17% while the VES averaged 26% losses. The results for PES and VES were unexpected based on the results previously obtained for soil mortars where no losses occurred. The most probable explanation for this lies in the pretest conditioning. The soil mortar immersion samples were returned to 50% humidity environments for 7 days after immersion but prior to destructive strength testing. This study was for comparative losses and all samples were conditioned to the ASTM conditions outlined in D-695. The clean aggregate samples, used in an engineering study, adhered to ASTM standard conditions for the baseline strengths but followed the Nuclear Regulatory Commissions (NRC) recommendations for the immersion test (7). The NRC test calls for strength testing of the immersed samples immediately after removal from the water which would keep the samples at 100% humidity. This water content difference may result in the strength differences seen for the PES and VES samples. These materials are to be used underground and the soil gases will be at 100% humidity, therefore it was decided that all future strength testing of the barrier materials (e.g., acid resistance, base resistance, wet-dry cycling) would be performed after conditioning the samples to 100% humidity for seven days.

Wet-Dry Cycling

The Hanford tank farm is located in a semi-arid region. The soil moisture content is fairly low and ranges between 1 and 3% (8). There are times when precipitation percolates the ground and recharges the aquifer. During these times the barrier will be under saturated conditions. Wet-dry cycling is known to have a severe impact on construction materials such as hydraulic cements. Replicate samples of the various binder/aggregate combinations were subjected to wet-dry cycling following ASTM D-4843 (9). SPC soil mortars were excluded based on water immersion results. Test samples are cycled from 60°C dry to 20°C wet, twelve times In addition to the test method, samples were compression tested (ASTM D-695) after the final cycle to determine mechanical integrity.

None of the samples showed any visible degradation after 12 cycles. Weight changes from beginning to end were minimal and ranged from a high of -1.2% for PES soil mortar to a low of 0.004% for PES concrete. VES and PES specimen showed no change for the soil mortars (conditioned at ~50% humidity) and similar strengths changes as observed after immersion, acid resistance and base resistance for the clean aggregate samples. Acrylic samples show a slight increase for the soil mortar , unchanged for the mortar and concrete, and similar losses for the glass composite as observed after immersion, acid resistance and base resistance. FA samples (clean aggregate only) showed significant strength increases, averaging 57%, after wet-dry cycling. This may be attributed to further curing induced by the elevated temperature during the dry cycle. All of the SPC samples tested lost strength during the wet-dry cycling. The losses were 47% for mortars, 56% for concretes and 81% for the glass concrete. The magnitude of the losses for mortars and concretes are similar to those for thermal cycling of the soil mortars and industry expectations for thermal cycling. The losses for the glass concretes are significantly greater and may be the additive effects of thermal cycling (see soil mortars) and immersion (see immersion for SPC\glass composites). Values for compressive strength are given in Table II.

Hot Nitrate Brine Resistance

In the event of leakage from USTs, the barrier will presumably be exposed to the supernatant from the tank. The supernatants in most of the USTs are nitrate-nitrite salt solutions (8). The liquid may also be at elevated temperature due to the heat production from radionuclide decay. To determine the durability of the polymers such an environment, soil mortar samples were subjected to immersion in a hot nitrate brine. The brine was 50% solids using a surrogate in proportions taken from reference 8. The temperature of 70°C was taken as the average tank temperature of the 11 high heat (>40,000

TABLE II

Compressive Strengths (in MPa ± Standard Deviation) of Polymer Composites After Testing

Binder	Aggregate type	Baseline	Immersion	Wet-Dry
VES	soil mortar	47.6 ± 2.6	51.1 ± 1.2	52.6 ± 2.7
	mortar	82.4 ± 3.2	55.5 ± 3.9	64.3 ± 3.7
	concrete	72.9 ± 2.5	49.2 ± 1.8	46.3 ± 3.8
	glass concrete	33.6 ± 1.4	29.4 ± 1.7	24.1 ± 1.8
PES	soil mortar	49.1 ± 3.6	47.4 ± 1.3	57.8 ± 5.4
	mortar	50.0 ± 12	43.8 ± 3.9	39.2 ± 6.9
	concrete	59.6 ± 1.4	45.8 ± 0.9	43.7 ± 2.1
	glass concrete	39.5 ± 3.0	34.4 ± 1.2	29.6 ± 2.7
Acrylic	soil mortar[b]	25.7 ± 2.6	23.1 ± 3.8	34.0 ± 5.1
	mortar	12.8 ± 1.5	11.2 ± 2.1	15.3 ± 3.6
	concrete	14.0 ± 2.9	11.3 ± 1.2	12.9 ± 0.9
	glass concrete	9.7 ± 1.1	5.8 ± 1.6	6.7 ± 1.6
FA	soil mortar	na	na	na
	mortar	35.6 ± 4.5	38.4 ± 5.4	59.1 ± 4.0
	concrete	31.3 ± 2.0	35.9 ± 1.0	53.7 ± 3.8
	glass concrete	29.3 ± 3.2	29.9 ± 1.3	39.1 ± 2.8
SPC	soil mortar	30.6 ± 5.8	failed	na
	mortar	38.1 ± 6.1	36.2 ± 7.0	19.9 ± 5.8
	concrete	34.1 ± 5.3	25.8 ± 4.2	15.0 ± 5.4
	glass concrete	27.4 ± 3.9	18.9 ± 7.5	5.1 ± 1.5

na = not applicable a = in percent b = high mod resin

Btu/hr) tanks at Hanford. Twelve samples of VES, PES, and acrylic soil mortars were immersed in the brine and placed in an environmental chamber at 70°C for 120 days. SPC soil mortar was excluded based on water immersion results. At 30 day intervals, three samples of each soil-mortar composite were removed for visual and destructive testing to determine sample integrity. After cleaning and inspection for cracking and spalling the specimens were conditioned at ~50% RH for seven days and tested for compressive strength. The results given in Table III show no loss in integrity for VES and PES soil mortars. The acrylic soil mortars show no strength losses up to the 60 day interval, at 90 days there is apparent degradation as evidenced by a 40% loss in strength. No further losses occur at 120 days.

Thermal Cycling

Thermal cycling of materials can be useful as a tool to indicate internal prestressing and as a comparative measure of quality. Six replicate samples of VES, PES, SPC, and acrylic soil mortars were tested in accordance to ASTM B-553 (10) with modifications recommended by the Nuclear Regulatory Commission (9). After cycling was complete, the samples were inspected and measured. No visible effects were observed and no dimensional changes recorded for any of the soil mortars. The samples were then subjected to compressive strength testing and compared to baseline values. Compressive strength values for VES and acrylic mortar samples remained basically unchanged. PES samples gained ~26% of their baseline strength after thermal cycling. This increase may be due to further crosslinking reactions induced by the higher temperatures in the thermal cycle. SPC samples were adversely affected by thermal cycling and lost an average of 51% of their baseline compressive strength. Such behavior is expected for SPC and in data sheets from National Chempruf Concrete, Inc. freeze-thaw cycling losses are given as 40 % (11). Data for compressive strength is given in Table III.

Irradiation Stability

At the Hanford demonstration site the containment barrier will receive an appreciable radiation dose during the projected 25 year lifetime. The radiation fields in many of the USTs are stated to be in excess of 1000 rad/hr (8). This translates to slightly more than 2×10^8 rad over 25 years for worst case tanks. The containment barrier will not see the full dose since the UST concrete and steel liner and surrounding soils will shield the barrier. In order to remain conservative, a total dose of 1×10^8 rads was chosen for testing purposes. Irradiation was performed in a Co-60 gamma facility at BNL. The dose rates ranged from 1×10^6 to 4×10^6 rad/hr. After irradiation, the samples were visually inspected and measured for dimensional changes. The samples were then destructively tested for compressive strength (ASTM D-695). The results are given in Table III. The three thermoset binders all show significant strength increases after irradiation. This is a commonly observed phenomena attributable to additional crosslinking of the polymer chains.

Acid Resistance

Clean aggregate samples were immersed in an aqueous nitric acid solution at Ph 2 for 90 days. Nitric acid was chosen as representative of conditions within the DOE complex. The Ph values are based upon the EPA characteristic corrosivity criteria for hazardous waste. The pH was checked daily and adjusted back to 2 if the pH changed by 0.5 units or more. Every 30 days, triplicate samples were removed from the media, rinsed, measured, weighed and subjected to compressive strength testing following ASTM-D695. No visual or dimensional changes were observed for any samples.

TABLE III
Compressive Strengths (MPa Standard Deviation) of Soil Mortars After Testing

Binder	Hot Nitrate Brine Resistance 30 days	60 days	90 days	120 days	Irradiation (10^8 rads)	Thermal Cycling
VES	59.3 ± 1.1	63.7 ± 1.4	56.4 ± 4.2	58.6 ± 1.6	62.6 ± 2.5	52.1 ± 1.6
PES	55.4 ± 2.4	55.8 ± 3.6	56.1 ± 1.6	58.3 ± 3.2	54.1 ± 1.6	51.0 ± 1.8
Acrylic	25.4 ± 2.0	24.5 ± 2.5	15.3 ± 3.0	17.8 ± 4.0	40.3 ± 5.9	23.0 ± 1.9
SPC	na				25.4 ± 3.7	12.8 ± 1.1

Compressive strengths are given in Table IV. Results were similar to the immersion test. PES, VES and acrylic\glass showed similar strength losses observed after water immersion. All other composites remained unchanged with the marked exception of the SPC\glass composite which showed continual loss of strength after 30, 60 and 90 day intervals.

Base Resistance

Clean aggregate samples were immersed in an aqueous sodium hydroxide solution at pH 12.5 for 90 days. Sodium hydroxide was chosen as representative of condition within the DOE complex. The pH values are based upon the EPA characteristic corrosive for hazardous waste. The pH was checked daily and adjusted back to 12.5 if the pH changed by 0.5 units or more. Every 30 days triplicate samples were removed from the media, rinsed, measured, weighed and subjected to compressive strength testing following ASTM-D695. No visual or dimensional changes were observed for any samples. Compressive strengths are given in Table IV. Results for PES, VES and acrylic were similar to the immersion and acid resistance tests. FA composites remained unchanged after 90 days. SPC composites all showed some loss of strength with the glass aggregate showing continual losses after 30, 60 and 90 day intervals. SPC is known to be attacked by base and the results are not unexpected.

Hydraulic Conductivity

One of the most important performance considerations for a containment barrier is the rate that liquids will penetrate the barrier. Hydraulic conductivity is a direct measure of the ability of the barrier to retain leakage from the UST. Hydraulic conductivities were measured following ASTM D-5084 (12) using a flexible wall permeameter. The permeant was deaired tap water having an electrical conductivity of 120 mhos. Test samples were 3.8 cm diameter by 3.0 cm cylinders for soil mortars and 5.1 cm diameter by 5 cm cylinders for clean aggregate samples. Full saturation was determined by measuring the compression B value according to ASTM D-4767-(88) (13). The soil mortar permeabilities were 6.7×10^{-12}, 2.2×10^{-12}, and 40.0×10^{-12} m/s for VES, PES and the acrylic, respectively. Preliminary results for the clean aggregate samples, based on single sample measurements, indicate permeabilities ranging from 1×10^{-12} to less than 2×10^{-13} (instrument limits).

SUMMARY AND CONCLUSIONS

Polymer grouts having a wide range of viscosities have been demonstrated to have desirable qualities for a subterranean barrier. Performance values indicate polymers exist that can meet the requirements for containment barriers for USTs throughout the DOE complex. Proper choice of binder and

TABLE IV
Compressive Strength (MPa ± Standard Deviation) of Clean Aggregate Composites After Testing

Binder	Mixture Type	Base Resistance 30 days	60 days	90 days	Acid Resistance 30 days	60 days	90 days
VES	mortar	75.3 ± 9.6	61.6 ± .4	52.8 ± 2.6	66.1 ± 4.6	62.9 ± 8.2	67.0 ± 12
	concrete	54.2 ± 0.9	48.5 ± 1.2	43.7 ± 1.9	51.2 ± 1.4	49.1 ± 2.3	47.2 ± 0.7
	glass	25.0 ± 1.7	25.1 ± 1.4	27.0 ± 1.8	27.5 ± 1.1	27.7 ± 2.0	28.9 ± 3.0
PES	mortar	46.5 ± 4.5	39.7 ± 3.5	39.6 ± 3.8	43.1 ± 6.6	43.7 ± 1.6	43.9 ± 3.7
	concrete	43.5 ± 2.0	38.8 ± .0	44.4 ± 2.9	42.2 ± 0.9	40.9 ± 2.6	42.0 ± 2.7
	glass	30.7 ± 2.2	33.7 ± 2.7	30.4 ± 1.6	32.3 ± 1.1	33.2 ± 2.4	33.6 ± 0.5
Acrylic	mortar	9.2 ± 2.1	11.4 ± 0.3	10.0 ± 0.4	10.8 ± 3.8	11.3 ± 3.11	2.1 ± 1.8
	concrete	8.4 ± 1.6	10.7 ± 0.9	10.0 ± 0.8	10.0 ± 2.8	8.1 ± 0.1	10.9 ± 0.9
	glass	3.7 ± 0.5	5.6 ± .2	4.6 ± 0.7	4.6 ± 0.8	5.0 ± 0.9	6.4 ± 0.6
FA	mortar	37.4 ± 4.6	46.1 ± 1.6	36.8 ± 3.8	32.9 ± 3.6	37.7 ± 2.1	35.3 ± 2.4
	concrete	29.5 ± 1.9	31.3 ± 2.3	33.2 ± 3.9	29.6 ± 1.4	30.5 ± 1.2	33.4 ± 2.9
	glass	29.5 ± 0.0	28.5 ± 2.1	28.0 ± 1.8	27.3 ± 1.8	28.9 ± 1.8	30.9 ± 3.0
SPC	mortar	36.5 ± 2.2	28.6 ± 8.6	28.6 ± 1.6	35.0 ± 1.8	31.5 ± 1.6	26.0 ± 7.4
	concrete	29.5 ± 3.3	19.8 ± 3.7	18.1 ± 5.7	32.8 ± 4.6	25.2 ± 4.8	21.1 ± 3.5
	glass	19.6 ± 6.3	9.5 ± 1.4	8.7 ± 2.1	26.0 ± 0.4	16.7 ± 2.4	7.3 ± 0.4

aggregate followed by the appropriate site specific compatibility testing will result in a durable, high strength, low permeability barrier.

SPC soil mortars failed in water immersion after 3-5 days exposure. This is attributed to some expansive quality of the Hanford soil. This serves to emphasize the importance of site specific testing when choosing barrier materials. Testing should include compatibility of the binder with: aggregate, (especially if using natural soils as in jet grouting), waste constituents, and site geology and geochemistry. Further evidence for the need of compatibility testing was seen in the results for acrylic glass concrete. After 90 days immersion these samples lost an average of 40% of their baseline strength whereas the mortars and concretes remained unchanged.

Immersion testing of VES and PES uncovered the need for further studies on the effect of moisture content on the unconfined uniaxial compressive strengths of polymers. There was an apparent loss of strength for VES and PES clean aggregate specimens conditioned at 100% humidity prior to compressive testing, but no loss for soil mortars conditioned at 50% humidity. It is recommended that all barrier material strength measurements be made at 100% humidity, since subsurface soil gases will be at 100% humidity (even for arid regions were soil moisture content is 1-2%).

Wet-dry cycling of polymer composites resulted in no visual damage and minimal weight changes. VES and PES specimen showed no strength changes for the soil mortars and similar strengths changes as observed after immersion, acid resistance and base resistance for the clean aggregate samples. Acrylic samples show slight strength increases for the soil mortar , unchanged for the mortar and concrete, and similar losses for the glass composite as observed after immersion, acid resistance and base resistance. FA samples showed significant strength increases, averaging 57%. SPC samples lost 47% of the baseline strength for mortars, 56% for concretes and 81% for the glass concrete.

Soil mortars made using VES, PES, and acrylics were subjected to additional site specific testing for the Hanford complex. This testing included irradiation, nitrate brine resistance, wet-dry cycling and thermal cycling. These polymers showed strength gains averaging 32% after 10^8 rads irradiation from a gamma source. The strength gains are attributed to additional crosslinking of the polymer. VES and PES were immersed for 120 days in 70°C concentrated nitrate brine with no detrimental effects. The brine is a surrogate for the Hanford UST supernatant and is an aggressive media. VES and PES samples showed no loss in strength while the acrylic samples showed 40% strength losses after the 90 day interval. VES, PES and acrylic samples survived thermal cycling with no strength losses.

Clean aggregate samples were immersed in an aqueous nitric acid solution at pH 2 for 90 days. Results were similar to the immersion test. PES, VES and acrylic\glass showed similar strength losses observed after water immersion. FA, SPC, and acrylic (mortar and concrete) composites remained unchanged with the marked exception of the SPC\glass composite which showed continual loss of strength after 30, 60 and 90 day intervals.

Clean aggregate samples were immersed in an aqueous sodium hydroxide solution at pH 12.5 for 90 days. Results for PES, VES and acrylic were similar to the immersion and acid resistance tests. FA composites remained unchanged after 90 days. SPC composites all showed some loss of strength with the glass aggregate showing continual losses after 30. 60 and 90 day intervals. SPC is known to be attacked by base and the results are not unexpected.

The goal for soil mortar barriers was permeabilities of 1×10^{-10} m/s or less. This goal was achieved with soil mortars produced having hydraulic conductivities on the order of 5×10^{-11} m/s. The goal for "clean" aggregate barriers was to achieve permeabilities of 1×10^{-12} m/s or less. Again the goal was met, preliminary results for the clean aggregate samples, based on single sample measurements, indicate permeabilities ranging from 1×10^{-12} to less than 2×10^{-13}.

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