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Development of Immobilization Technology for Hanford Double-Shell Slurry Feed Waste

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DEVELOPMENT OF IMMOBILIZATION TECHNOLOGY FOR HANFORD DOUBLE-SHELL SLURRY FEED WASTE

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ABSTRACT

The leachabilities of technetium and nitrate wastes immobilized in cement-based materials (i.e., grouts) have been investigated using ANS-16.1 test procedures. Factors found to affect the leachabilities include grout/mix ratio, grout fluid density, dry/solid blends (including ground blast-furnace slag), and waste concentration.

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1. INTRODUCTION

The purpose of this investigation was to define conditions for the immobilization of Double-Shell Slurry Feed (DSSF) waste from the Westinghouse Hanford Company (WHC) in cement-based materials (grouts). The major emphasis was on leachability index (L_i) determinations of ^{99}Tc and nitrate for a number of grouts or grout specimens.

The presence of technetium in low-level radioactive waste is of increasing concern because of the potential biological hazard of the ^{99}Tc isotope. The method most frequently used to immobilize low-level radioactive waste involves the use of cement or cement-like materials that are chemically basic. The following reaction,

$$TcO_2 + 4OH^- \rightarrow TcO_4^- + 2H_2O + 3e^-,$$

which is thermodynamically spontaneous, indicates that in the long term, technetium can be expected to be present as the pertechnetate ion in such media. Because the pertechnetate ion is a highly soluble species, and because the grout method is recognized as an excellent way to

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*American Nuclear Society.

immobilize waste, the need to investigate technetium leaching properties from grout was recognized. Nitrate leachability properties are of general interest, with the Environmental Protection Agency standard for drinking water being 10 ppm.

Historically, a moderate amount of research and development has been required to match the grout method[1-5] to a given waste. This investigation has differed from previous investigations in several ways: an emphasis was placed on technetium (^{99}Tc) and nitrate leachability; ground-blast furnace slag (BFS) was used in all blends (except blend 32); and all grouts were cured at 60°C and 100% humidity. Leach tests were conducted using the ANSI/ANS*-16.1 procedure.[6] Processibility studies — including drainable water, compressive strength, and rheological tests — were conducted following standard procedures. Also, EP toxicity tests were conducted on specimens of several of the grouts.

2. EXPERIMENTAL METHOD

2.1 WASTE COMPOSITION

The waste used in this investigation was simulated DSSF from WHC. The composition of the waste is shown in Table 1. Major constituents include 8.7 M NaOH, 1.5 M $Al(NO_3)_3$, and 0.3 M Na_2CO_3. Most of the grouts that were investigated were prepared using a 50% dilution of the waste with water. A few grouts were prepared using a 33% dilution (i.e., with 2 volumes of waste with 1 volume of water). One series of tests was conducted with undiluted waste. The waste or diluted forms of the waste were mixed with dry/solid blends as described in the following section. At the time of mixing, ^{99}Tc tracer, as oxalate when required, was added.

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*American National Standards Institute/American Nuclear Society.

Table 1. Component concentrations of synthetic DSSF

Component	Concentration (M)
$Cd(NO_3)_2 \cdot 4H_2O$	1.4×10^{-2}
$Pb(NO_3)_2$	2.4×10^{-5}
$Hg(NO_3)_2 \cdot H_2O$	3.0×10^{-5}
$AgNO_3$	3.0×10^{-3}
$Fe(NO_3)_3 \cdot 9H_2O$	5.0×10^{-2}
$Mn(NO_3)_2 \cdot 4H_2O$	1.0×10^{-1}
$Zn(NO_3)_2 \cdot 6H_2O$	4.9×10^{-2}
$Ni(NO_3)_2 \cdot 6H_2O$	1.0×10^{-3}
$Ca(NO_3)_2 \cdot 4H_2O$	1.0×10^{-2}
$Al(NO_3)_3 \cdot 9HO$	1.5
$Na_2B_4O_7 \cdot 10H_2O$	4.3×10^{-3}
$Na_2Cr_2O_7 \cdot 2H_2O$	2.2×10^{-2}
$BaCl_2$	9.1×10^{-3}
NaCl	2.0×10^{-1}
KOH	4.4×10^{-1}
NaOH	8.7
As_2O_5	8.2×10^{-7}
SeO_2	1.1×10^{-4}
MgO_2	1.0×10^{-3}
KF	5.9×10^{-2}
$CuSO_4$	2.0×10^{-4}
Na_2CO_3	3.0×10^{-1}
PO_4^{3-}	1.2×10^{-1}
SO_4^{2-}	1.0×10^{-1}
EDTA	1.7×10^{-2}
$C_6H_2O_7 \cdot H_2O$ (citric acid)	2.1×10^{-2}
SiO_2	3.9×10^{-2}

2.2 DRY/SOLID BLENDS

The compositions of 22 dry blends that were mixed with the waste to prepare grouts for leach tests are shown in Table 2. These blends, except for No. 32, contained from 38 to 100 wt % ground BFS or kiln dust, from 0 to 47.5 wt % Type I,II Portland cement, from 0 to 47.5 wt % ASTM* class F fly ash (from Centralia, Washington), from 0 to 15 wt % lime, and from 0 to 7 wt % Indian Red Pottery Clay (IRPC).

Table 2. Blend compositions for DSSF waste

Blend No.	Ground BFS	Type I,II cement	Class F fly ash[e]	Lime $Ca(OH)_2$	IRPC
3	70[a]	25			5
6	49.8[a]	43.2			7
9	75[a]	20			5
14	100[a]				
15	90[a]	10			
17	95[a]			5	
18	88[a]			5	7
19	47.5[a]		47.5	5	
20	47.5[a]		40.5	5	7
21	38[a]	10	47	5	
22	38[a]	10	40	5	7
23	47.5[a]	5	47.5		
24	45[a]		45	10	
25	45[a]	10	45		
26	42.5[a]		42.5	15	
28	100[a]				
29	47.5[a]	5	47.5		
31	47.5[a]		47.5	5	
32	-	47.5	47.5	5	
33	80[a]	-	20		
36	47.25[d]	5.5	47.25		
37	47.25[c]	5.5	47.25		

[a]Ground BFS from Ash Grove Cement West, Inc., located in Seattle, Washington.

[b]Ground BFS from Standard Slag Co., located in Youngstown, Ohio.

[c]Kiln dust from Cement Dust Northwest, located at Spokane, Washington.

[d]Ground BFS from Blue Circle Atlantic, Inc., located in Sparrow Point, Maryland.

[e]Fly ash from Ross Island Sand and Gravel Co., located in Portland, Washington.

*American Society for Testing and Materials.

Table 3. Typical chemical analyses[a]

	Ground BFS	Class F fly ash	Type I,II Portland cement
SiO_2	31.8	45.0	20.7
Al_2O_3	15.1	22.3	4.8
CaO	41.1	11.1	64.3
SO_3	2.0	0.1	2.8
Na_2O	0.1	4.8	0.1
K_2O	0.2	3.8	0.1
Fe_2O_3	0.7	5.5	2.5

[a]The materials for these tests were obtained from the companies cited in Table 2.

2.3 SOURCES AND DESCRIPTION OF MATERIALS FOR USE IN DOUBLE-SHELL SLURRY GROUTS

In a previous milestone,[7] ORNL recommended sources of cement and fly ash for use in the Hanford Grout Program. Those sources are still valid and are not repeated in this report. The remaining ingredient recommended for use in DSSF grouts is BFS, as discussed in this section. Oak Ridge National Laboratory (ORNL) has identified three sources of BFS in the United States: Ash Grove Cement West, Inc., of Seattle, Washington, which has imported one barge load of BFS from the Kawasaki Steel Corporation, of Tokyo, Japan (ORNL has used this source of BFS for all grout-development work); Standard Slag Company, of Youngstown, Ohio, which markets BFS from Republic Steel Company's furnace No. 6 at its Cleveland, Ohio, plant; and Blue Circle, Inc., of Marietta, Georgia, which markets BFS from a Sparrow Point, Maryland, facility. Each company has been in business for many years and is well respected. ORNL has tested samples from each facility and found that the material produces a grout that meets or exceeds requirements and has been discussed in monthly reports. However, freight charges from the eastern United States make this material much more expensive than material imported from Japan; therefore, based on costs, ORNL recommends that Japanese BFS, meeting the ASTM C-989-85 specifications, be used. Specifications for grade 120 have a Blaine fineness of 5000 to 5800 cm/gram and a glass content >96%.

On a recent trip to Japan, Earl W. McDaniel inspected sources of BFS at the Nippon Steel Company and Kawaski Steel companies. Details are covered in his foreign trip report issued in early May 1988. Information can also be obtained from the following:

Jere H. Rose, Director of Technical Services
Blue Circle, Inc.
One Parkway Place, Suite 1000
Marietta, GA 30067

Kenneth R. Gould
Assistant District Sales Manager
Ash Grove Cement West, Inc.
3801 E. Marginal Way S.
Seattle, WA 98134

Joel H. Beeghly
Manager of Marketing and Product Development
The Standard Slag Company
1200 Stambaugh Building
Youngstown, OH 44503

2.4 MIXING AND CURING PROCEDURE

The mixing procedure consisted of adding the blended solids to the waste in a Model N-50 Hobart mixer for 30 s at a low stirring rate, ~139 rpm, and then increasing the stirring rate to ~285 rpm (medium speed setting on the mixer) for 30 s. The specimens for the leach test were prepared by pouring freshly prepared grouts into cylindrical Teflon molds 2.55-cm-diam by 4.80-cm-long and allowing the grouts to stand or cure at 60°C in a 100% humidity oven for 28 d.

2.5 LEACHING PROCEDURE

The cured grout specimens were leached following the ANSI/ANS-16.1 procedure. Each grout specimen, after being rinsed off, was suspended in a 451-mL volume of water for 2 h. Subsequently, it was moved to another 451-mL volume of water for 5 h and then similarly to other 451-mL volumes of water for 17-, 24-, 24-, 24-, 24-, 336-, 672-, and 1032-h intervals to give a total leach time of 90 d. Three specimens were prepared and leached from each grout mix.

The leach solutions were analyzed, in most instances, for both ^{99}Tc and nitrate. The ^{99}Tc beta count was determined using an LKB Model 1211 RackBeta or Packard Model 1500 liquid scintillation analyzer. The nitrate concentration was determined using an Orion ion-selective electrode with a pH meter.

2.6 LEACHABILITY INDEX CALCULATIONS

The effective diffusivity was calculated for each leach interval (when <20% of the leachable species was leached) from the following expression:

$$D = \pi \left(\frac{a_n/A_o}{(\Delta t)_n} \right)^2 \left(\frac{V}{S} \right)^2 \quad T \quad , \qquad (1)$$

where

a_n = activity of a nuclide released from the specimen during leaching interval n, corrected for radioactive decay;

A_o = total activity of a given radionuclide in the specimen at the beginning of the leach test (i.e., after the initial 30-s rinse);

$(\Delta t)_n = t_n - t_{n-1}$, duration of the nth leaching interval, s;

D = effective diffusivity, cm^2/s;

V = volume of the specimen, cm^3;

S = geometric surface area of the specimen as calculated from measured dimensions, cm^2;

T = $[\frac{1}{2}(t_n^{1/2} + t_{n-1}^{1/2})]^2$ leaching time, representing the "mean time" of the leaching interval, s.

When >20% of the leaching species had leached from the specimen, a slightly more complicated method involving the use of tables presented in the ANSI/ANS-16.1 procedure was used to calculate the effective diffusivity, D.

The calculated values of D were subsequently used to calculate Li values using the following expression:[6]

$$L_i = \frac{1}{10} \sum_{n=1} [\log (ß/D_i)]_n \quad , \qquad (2)$$

where ß is a defined constant (1 cm^2/s), and D_i is the effective

diffusivity of nuclide *i* calculated from the test data. Note from Eq. (2) that values of L_i become greater as the diffusion rate D_i values become smaller. For the purposes of this study, large values of L_i are desirable, and because L_i is a logarithmic term, small increases in the values may be significant, indicating large decreases in D_i values.

3. EXPERIMENTAL RESULTS AND COMMENTS

Typical leach-rate results are shown in Fig. 1 for technetium and in Fig. 2 for nitrate. The plots in the figures are of normalized cumulative leached fraction vs the square root of time in hours. The normalized cumulative leached fraction is the $(a_n/A_o)(V/S)$ term from Eq. (1). As Fig. 1 shows, the early part of the technetium leach curves are nonlinear up to ~5 d [$\sqrt{120}$ h]. This nonlinearity is considered to be a surface-related or washoff problem and not indicative of the long-term leach properties of the technetium in the grout specimens. Thus, values for what has been termed the "post-washoff leachability index"* have been calculated for several technetium leach series. This term is the average L_i for the specimens beginning with the 5th day and extending as far as the 90th day. The data in the figures are for 50 vol % dilutions of DSSF because all are ensuing data unless otherwise designated. Unless specifically designated as "post-washoff" values, the L_i values reported are average overall values.

3.1 GROUTS WITH ASH GROVE SLAG, WITHOUT ADMIXTURES, WITH A 28-D CURE TIME

Table 4 presents technetium and nitrate L_i values for grouts formulated using ground BFS from Ash Grove West without admixtures and with cure times of 28 d. Data in the table are for grouts formulated using blends 3, 6, 9, 14, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, and

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*The nonlinearity of the curves may result from a number of mechanisms other than "washoff." The characteristics of the plots and the associated times could, for example, indicate two or more kinds of sites in the grout where the leach rates are different. The term "washoff" has been commonly used in the past and is used here for that reason.

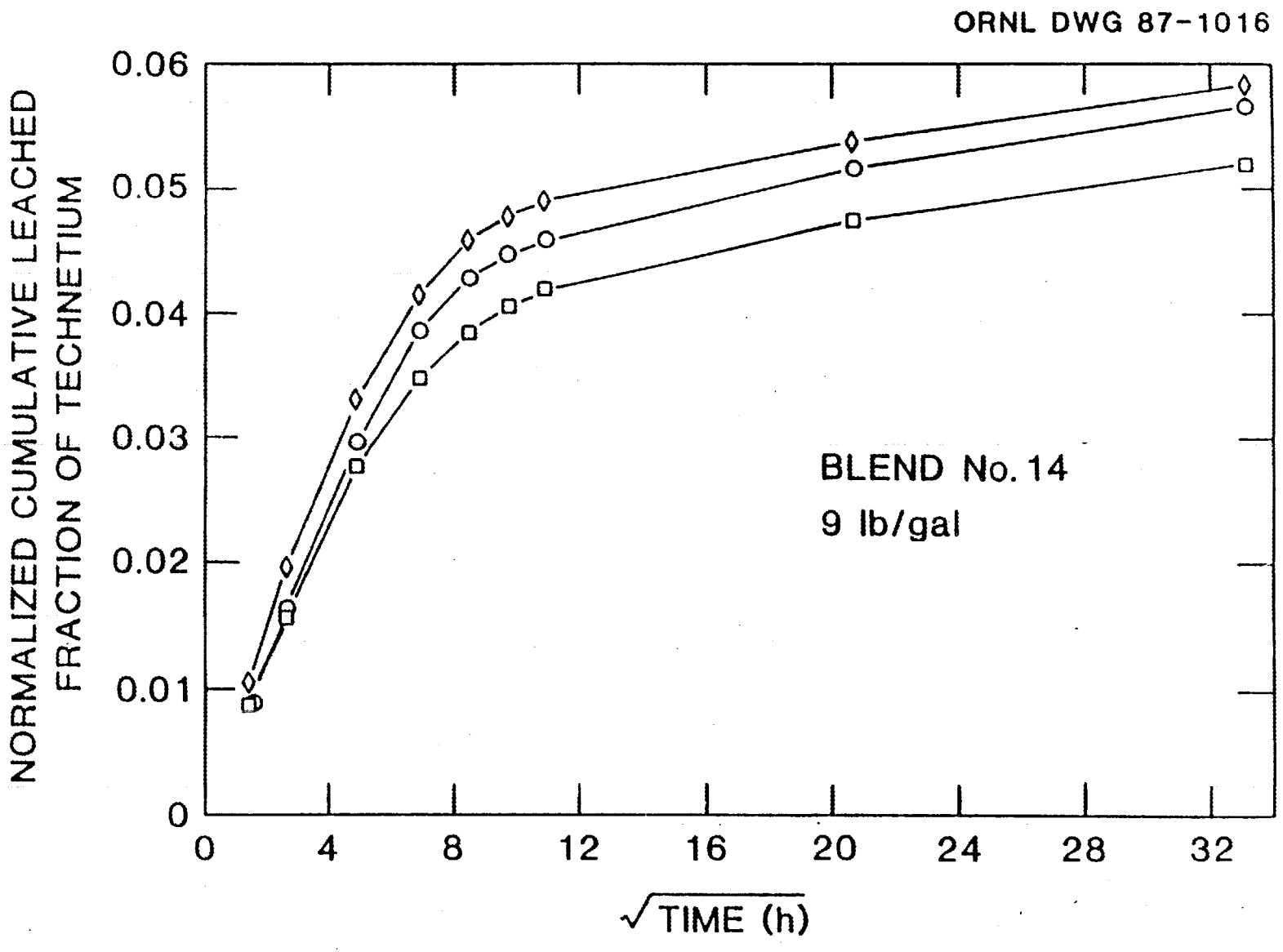

Fig. 1. Normalized cumulative leached fraction of technetium vs the square root of time.

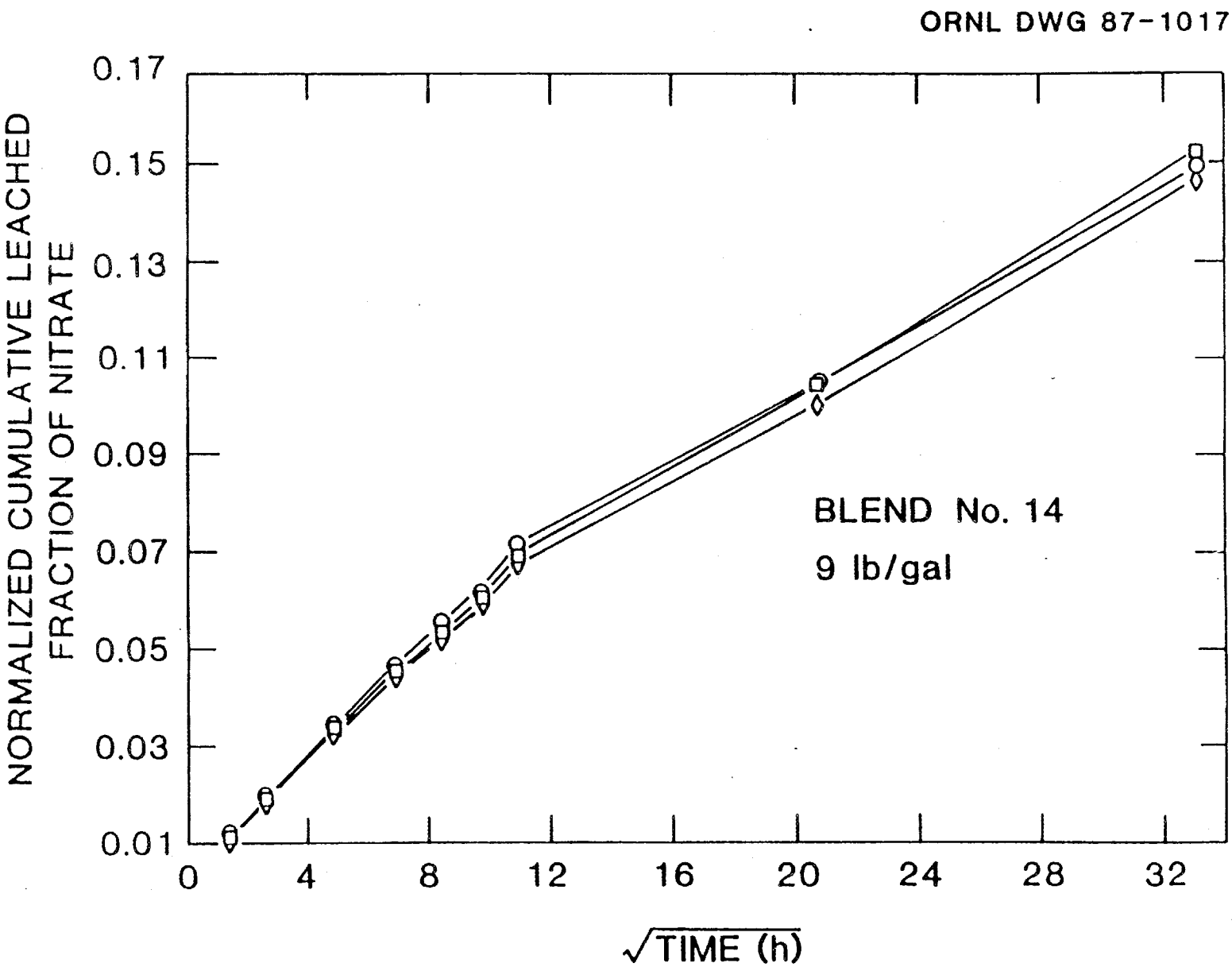

Fig. 2. Normalized cumulative leached fraction of nitrate vs the square root of time.

Table 4. Average technetium leach indexes (L_i) for grouts formulated with DSSF

Blend No.	Ground BFS (wt %)	Type I,II cement (wt %)	Class F fly ash (wt %)	Lime (wt %)	IRPC (wt %)	Waste dilution	Post-washoff average technetium L_i/time (d)	Overall average technetium L_i/time (d)	Overall average nitrate L_i/time (d)
					14.5 lb/gal				
14[a]	100					1:1	10.0/88	9.5/88	8.4/88
19	47.5		47.5	5		1:1	9.5/91	9.1/91	7.8/91
					9.0 lb/gal				
19	47.5		47.5	5		1:1	9.4/91	9.1/91	8.4/91
14	100					1:1	10.3/90	9.2/90	8.1/90
14	100					1:1	10.2/92	9.2/92	8.1/92
14	100					1:1	10.3/90	9.2/90	8.1/90
3	70	25			5	1:1	9.7/91	8.9/91	7.8/91
19	47.5		47.5	5		2:1	9.1/89	8.8/89	8.5/89
3	70	25			5	2:1	8.7/89	8.4/89	8.1/89
					8.5 lb/gal				
25	45		45	10		1:1	10.1/91	9.6/91	8.6/91
14	100					1:1	10.0/90	9.1/90	8.3/90
14	100					1:1	10.0/90	9.2/90	8.3/90
14	100					1:1	10.0/92	9.2/92	8.0/92
26	42.5		42.5	15		1:1	9.9/91	9.4/91	8.2/91
24	45		45	10		1:1	9.9/91	9.5/91	8.3/91
23	47.5	5	47.5			1:1	9.8/91	9.3/91	8.5/91
6	49.8		43.2		7	1:1	9.6/91	9.1/91	8.1/91
19	47.5		47.5	5		1:1	9.4/91	9.1/91	8.5/91
15	90	10				1:1	9.7/91	9.0/90	8.1/91
19	47.5		47.5	5		2:1	9.3/89	8.8/89	8.5/89
3	70	25			5	1:1	9.3/91	8.8/91	7.8/91
3	70	25			5	2:1	8.6/89	8.4/89	7.9/89

[a]Contains 1.0 vol. % Pozzolith 122-R.

Table 4 (continued)

Blend No.	Ground BFS (wt %)	Type I,II cement (wt %)	Class F fly ash (wt %)	Lime (wt %)	IRPC (wt %)	Waste dilution	Post-washoff average technetium L_i/time (d)	Overall average technetium L_i/time (d)	Overall average nitrate L_i/time (d)
					8.0 lb/gal				
14	100					1:1	9.6/91	9.1/91	8.4/91
14	100					1:1	9.5/91	9.1/91	8.4/91
21	38	10	47	5		1:1	9.5/88	8.5/88	7.1/89
19	47.5		47.5	5		2:1	8.9/89	8.5/89	8.3/89
19	47.5		47.5	5		1:1	8.6/88	8.4/88	7.6/88
20	47.5		40.5	5	7	1:1	8.8/88	8.3/88	7.6/88
22	38	10	40	5	7	1:1	8.8/88	8.2/88	7.0/88
17	95			5		1:1	8.1/91	8.1/91	7.7/90
18	88	20			7	1:1	7.9/88	7.5/88	7.2/88
9	75	20			5	1:1	7.9/88	7.5/88	7.6/90
					7.0 lb/gal				
3	70	25			5	2:1	8.7/92	8.7/92	7.4/92

26. The 14.5-lb/gal mix ratio data included in the table are given for comparison only because process requirement criteria dictate that mix ratios for the Transportable Grout Facility will not exceed 9.0 lb/gal. The average L_i values for ^{99}Tc ranged from 7.5 to 9.6, with the post-washoff values being greater by up to 1.1 index numbers. The nitrate values ranged from 7.0 to 8.6. Average technetium L_i values for reference blend 14 for 8.0-, 8.5-, and 9.0-lb/gal mix ratios ranged only from 9.1 to 9.2. The average technetium L_i values for blend 19 at 8.0, 8.5, and 9.0 lb/gal ranged from 8.4 to 9.2. Nitrate L_i values for reference blend 14 for the same mix ratios ranged from 8.0 to 8.4, whereas those for reference blend 19 ranged from 7.6 to 8.5. The blends for the mix ratio in Table 4 are listed in order of decreasing post-washoff average technetium L_i. Note that, in general, the grouts without cement and/or IRPC appear in the top half of the list for a given mix ratio, whereas those with cement or the clay appear in the lower half. Also note that grouts formulated with a 2:1 dilution of the waste (2 volumes of waste with 1 volume of water) appear in the lower half of the lists except for the 8.0-lb/gal blend 19 grout.

Processibility test results for grouts formulated without admixtures with blends 14, 15, 17, 18, 19, 23, 28, and 29 are given in Appendix A in Tables A.4, A.5, A.6, A.7, A.8, A.13, A.17, and A.18. The value ranges for reference blend 14 processibility data for 8.0-, 8.5-, and 9.0-lb/gal mix ratios were 0.1 to 3.3 vol % drainable water, 700- to 1552- psi compressive strength, and 33- to 48-gal/min critical flow rate (Table A.4). Similarly, the value ranges for blend 19 without Pozzolith 122-R for the same mix ratios were 0.0 vol % drainable water, 570- to 624- psi compressive strength, and 67- to 77-gal/min critical flow rate (Table A.8). Processibility criteria require a critical flow rate of 55 gal/min; thus, the grouts formulated with blend 19 without admixtures do not meet the criteria. This problem is corrected by adding Pozzolith 122-R admixture, as reported in Sect. 3.5.

3.2 GROUTS CURED FOR 90 D

Technetium and nitrate leachability indexes for grout specimens formulated with 8.0- and 8.5-lb/gal mix ratios using blends 3, 14, and

19 and curing for 90 d instead of 28 d are given in Table 5. The leachability indexes for the same blends with 28-d cures are included in the table for comparison. Note that increasing the cure time from 28 to 90 d either decreases the indexes or leaves them approximately unchanged.

3.3 EFFECT OF IRPC ON CESIUM LEACHABILITY INDEX

The data in Table 6 show the effect of IRPC on average cesium leachability indexes for grouts formulated with 1:1 dilutions of DSSF at an 8.0-lb/gal mix ratio. Data for blend 20, which contained 7 wt % IRPC, are shown in the table, along with data for reference blends 14 and 19, which did not contain the clay. The cesium leachability indexes were increased from values of ~7 for the reference blends up to ~12 for blend 20. Nitrate indexes appear to have been slightly decreased by the presence of the clay, as indicated by comparing data for blends 14 and 19 in Table 6 with data for blends without the clay in Table 4.

3.4 GROUTS WITH KILN DUST AND VARIOUS GROUND BFSs

Table 7 shows technetium and nitrate L_is for grouts formulated using 8.0-lb/gal mixes of blends containing one of three different ground BFSs or containing kiln dust. The highest technetium L_i was obtained for a grout using blend 36, which contained Sparrow Point ground BFS (Type I,II Portland cement, 5.5 wt %; ground BFS, 47.25 wt %; and ASTM class F fly ash, 47.25 wt %). The average overall technetium L_i for this grout was 9.9. The lowest technetium L_i was obtained for a grout formulated using blend 29 with slag from Youngstown, Ohio (Type I,II cement, 5 wt %; ground BFS, 47.5 wt %; and ASTM class F fly ash, 47.5 wt %). The average overall technetium L_i for this grout was 7.6. The average overall technetium L_i for a grout formulated using blend 37 containing kiln dust (Type I,II Portland cement, 5.5 wt %; kiln dust, 47.25 wt %; and ASTM class F fly ash, 47.25 wt %) was 8.0. The L_i values for grouts prepared using Ash Grove (blends 14 and 23) ground BFS (the slag used in most of the tests investigated for this report) are slightly less than those for the Sparrow Point slag.

Table 5. Average technetium leach indexes (L_i) for grouts formulated with DSSF after 28 d and 90 d of curing

Blend No.	Ground BFS (wt %)	Type I,II cement (wt %)	Class F fly ash (wt %)	Lime (wt %)	IRPC (wt %)	Waste dilution	28-d cure post-washoff average technetium L_i/time (d)	28-d cure Overall average nitrate L_i/time (d)	90-d cure post-washoff average technetium L_i/time (d)	90-d cure overall average nitrate L_i/time (d)
						8.0 lb/gal				
14	100					1:1	9.5/91	8.4/91	7.7/92	7.8/92
						8.5 lb/gal				
19	47.5		47.5	5		1:1	9.4/91	8.5/91	9.5/92	8.5/92
19	47.5		47.5	5		2:1	9.3/89	8.5/89	9.1/91	8.5/92
3	70	25			5	1:1	9.3/91	7.8/91	7.8/92	7.8/92

Table 6. Effect of Indian Red pottery clay on average cesium leach indexes (L_i) for grouts formulated with DSSF at a mix ratio of 8 lb/gal

Blend No.	Ground BFS (wt %)	Class F fly ash (wt %)	Lime (wt %)	IRPC (wt %)	Waste dilution	Post-washoff average cesium L_i/time (d)	Overall average cesium L_i/time (d)	Overall average nitrate L_i/time (d)
20	47.5	40.5	5	7	1:1	12.5/91	11.6/91	8.3/91
20	47.5	40.5	5	7	1:1	12.1/91	12.3/91	7.1/91
19	47.5	47.5	5		1:1	7.5/91	7.1/91	7.4/91
14	100				1:1	7.0/91	6.8/91	6.8/91

Table 7. Test results with kiln dust and various ground BFSs at a mix ratio of 8 lb/gal

Blend No.	Slag type	Ground BFS (wt %)	Type I,II cement (wt %)	Class F fly ash (wt %)	Kiln[a] dust (wt %)	Waste dilution	Post-washoff average technetium L_i/time (d)	Overall average technetium L_i/time (d)	Overall average nitrate L_i/time (d)
36[b]	Sparrow Point[c]	47.25	5.50	47.25		1:1	10.3/91	9.9/91	Not available
28	Youngstown[d]	100				1:1	10.1/91	9.6/91	8.3/91
14	Seattle[e]	100				1:1	9.6/91	9.2/91	8.0/91
23[b]	Seattle[e]	47.50	5	47.50		1:1	9.6/91	8.9/91	8.5/91
37[b]			5.50	47.25	47.25	1:1	8.1/91	8.0/91	Not available
20[b]	Youngstown[d]	47.50	5	47.50		1:1	7.7/91	7.6/91	8.0/91

[a]Kiln dust came from Cement Dust Northwest, located in Spokane, Washington.
[b]Contains 0.15 vol % Pozzolith 122-R.
[c]Ground BFS came from Blue Circle Atlantic, Inc., located in Sparrow Point, Maryland.
[d]Ground BFS came from Standard Slag Co., located in Youngstown, Ohio.
[e]Ground BFS came from Ash Grove Cement West, Inc., located in Seattle, Washington.

3.5 GROUTS FORMULATED WITH DSSF AND VARIOUS BLENDS WITH POZZOLITH 122-R ADMIXTURE

The emphasis in this investigation, as stated in Sect. 1, is technetium and nitrate leachability testing. Nevertheless, the grouts meet other process requirement criteria. Thus, the usual battery of rheological, phase separation, and compressive strength tests were conducted, and the results obtained are reported in Appendix A in Tables A.1 through A.20. To meet processibility requirement criteria, it was necessary in some instances to use an admixture, Pozzolith 122-R, Master Builders, Inc., in Cleveland, Ohio.

Given in Table 8 are technetium and nitrate L_i values for grout specimens formulated using blends 3, 19, 32, and 33 with Pozzolith 122-R admixture. The admixture increases the indexes for both technetium and nitrate. The overall average L_i for technetium increased from 8.4 to 10.0 (or 9.3 in a duplicate test) when 0.2 vol % Pozzolith 122-R was included in the 8.0-lb/gal mixes formulated using blend 19. The 10.0 and 9.3 values for blend 19 and the 9.2 value for blend 33 are the highest values obtained for any 8.0-lb/gal grouts tested with Ash Grove West slag. The blend 33 value is also interesting because it contained only slag, 80 wt %; and fly ash, 20 wt % (i.e., no lime or cement). The technetium L_i value of 7.8 for blend 32 is low, but note that it contained 47.5 wt % Type I,II Portland cement and no BFS.

The usual purpose for adding Pozzolith 122-R is to lower the critical flow rate and/or 10-min gel strength of freshly mixed grouts. Any increase in leachability indexes that may result as a side effect from use of the admixture is beneficial. Increase in drainable water, on the other hand, is a common harmful side effect associated with the use of this admixture.

The critical flow rate for 8.0-, 8.5-, and 9.0-lb/gal grouts using reference blend 19 without the admixture ranges from 66 to 77 gal/min (Appendix A, Table A.8). Processibility criteria require critical flow rates of $\leq$55 gal/min. With the addition of 0.2 vol % of the admixture, the critical flow rate decreases to <41 gal/min; however, the drainable water for the 8.0-lb/gal grout (Appendix A, Table A.10) increases to 6.2 vol % ($\leq$3.0 vol % is required).

Table 8. Average technetium leach indexes (L_i) for grouts formulated with DSSF showing the effects of Pozzolith 122-R

Blend No.	Ground BFS (wt %)	Type I,II cement (wt %)	Class F fly ash (wt %)	Lime (wt %)	Pozzolith 122-R content (vol %)	Waste dilution	Post-washoff average technetium L_i/time (d)	Overall average technetium L_i/time (d)	Overall average nitrate L_i/time (d)
						8.0 lb/gal			
19	47.5		47.5	5	0.20	1:1	10.1/46	10.0/46	8.6/98
33	80		20		0.15	1:1	9.9/91	9.2/91	8.6/91
19	47.5		47.5	5	0.20	1:1	9.7/46	9.3/46	8.3/93
19	47.5		47.5	5		1:1	8.6/88	8.4/88	7.6/88
32		47.5	47.5	5	0.20	1:1	7.8/91	7.7/91	8.0/91
						7.0 lb/gal			
3	70	25			0.50	1:1	8.0/88	7.8/88	7.4/88

The optimum amount of the admixture to use with blend 19 appears to be 0.15 vol %. With this amount (Appendix A, Table A.9), the critical flow rate, 37 to 55 gal/min, and the drainable water, 0.8 to 2.3 vol %, were both within processibility requirement criteria.

Technetium and nitrate L_is were obtained for blend DS-23 mixed with 1:1 DSSF containing 0.15 vol % Pozzolith 122-R and 1 M oxalic acid. The average ^{99}Tc and nitrate L_is after 90 d of leaching were 12.2 and 9.1.

The presence of oxalate, then, has a very positive effect on the L_is. Because this test is the only one that has been conducted, the amount of oxalic acid required for optimum results has not been determined. However, the quantity of oxalic acid probably could be reduced by at least one-half without altering the results shown here. The oxalate can be a reducing agent for the technetium and also benefit the physical structure of the grout. Processibility data are shown in Table A.15.

The other reference blend, No. 14, did not require the use of an admixture to meet processibiity requirement criteria.

3.6 SIMULATED VAULT GROUTS

Leach studies were conducted on simulated vault grout samples. The samples consisted of a construction-type cement (44.44 wt % slag, 22.22 wt % Type I,II Portland cement, 22.22 wt % water, and 11.11 wt % sand), ~2-mm thick, totally enclosing a standard-size leach sample (2.48-cm diam × 4.24-cm long) made with blend DS-9, 8 lb/gal. Three samples were leached; one enclosed within a condom (membrane), one without the membrane inside the concrete "vaults," and one not enclosed by the "vaults" that was used as the control specimen. The vault sample with a membrane surrounding the grout specimen yielded a technetium L_i of 13.4 and a nitrate L_i of 11.4. The grout specimen without the membrane yielded a technetium L_i of 14.3 and a nitrate L_i of 9.6 after 90 d of leaching. An additional 90 d of leaching (total 180 d) showed no additional diffusion of ^{99}Tc from the membrane-enclosed specimen. The control sample L_is were significantly less, 7.6 for the nitrate and 7.5 for the technetium.

Processibility data for an 8-lb/gal grout, formulated using blend 9 (the one used in the specimens discussed previously), are shown in Table A.3.

3.7 COMMENTS AND OBSERVATIONS ON TECHNETIUM, NITRATE, AND CESIUM LEACHABILITY

The following observations are based on careful inspection of data presented in Tables 4 through 8, along with additional data as designated. The observations apply to blends, listed in Table 2, used to formulate grout specimens with DSSF or diluted DSSF. Conditions that increase leachability indexes are considered beneficial, whereas those that decrease the indexes are considered deleterious.

1. Increasing the mix ratio is beneficial, particularly for ^{99}Tc (Fig. 3).
2. Increasing the ground BFS content in blends not containing ASTM class F fly ash is beneficial (Fig. 4).
3. Decreasing the waste concentration or increasing the amount of dilution is beneficial for ^{99}Tc (Figs. 5 and 6).
4. Small additions or increases in amounts of lime, Type I,II Portland cement, or IRPC are neither beneficial nor deleterious in blends that primarily contain ground BFS and ASTM class F fly ash.
5. Complete substitution of Type I,II Portland cement for ground BFS slag is highly deleterious to ^{99}Tc, $L_i = 7.7$, and nitrate $L_i = 8.0$) for a mix ratio of 8.5 lb/gal (Table 8).
6. Blend 33 (Table 8) with 80 wt % ground BFS and 20 wt % ASTM class F fly ash gave respective ^{99}Tc and nitrate L_i values of 9.2 and 8.6 for 8.0-lb/gal mixes.
7. IRPC greatly increases L_i values for ^{137}Cs. L_i values as great as 11.6 were obtained (Table 6).

Nitrate L_i values approximately track ^{99}Tc values but are lower, as Fig. 7 shows. The comparisons in the figure are for specimens

ORNL DWG 87-996R

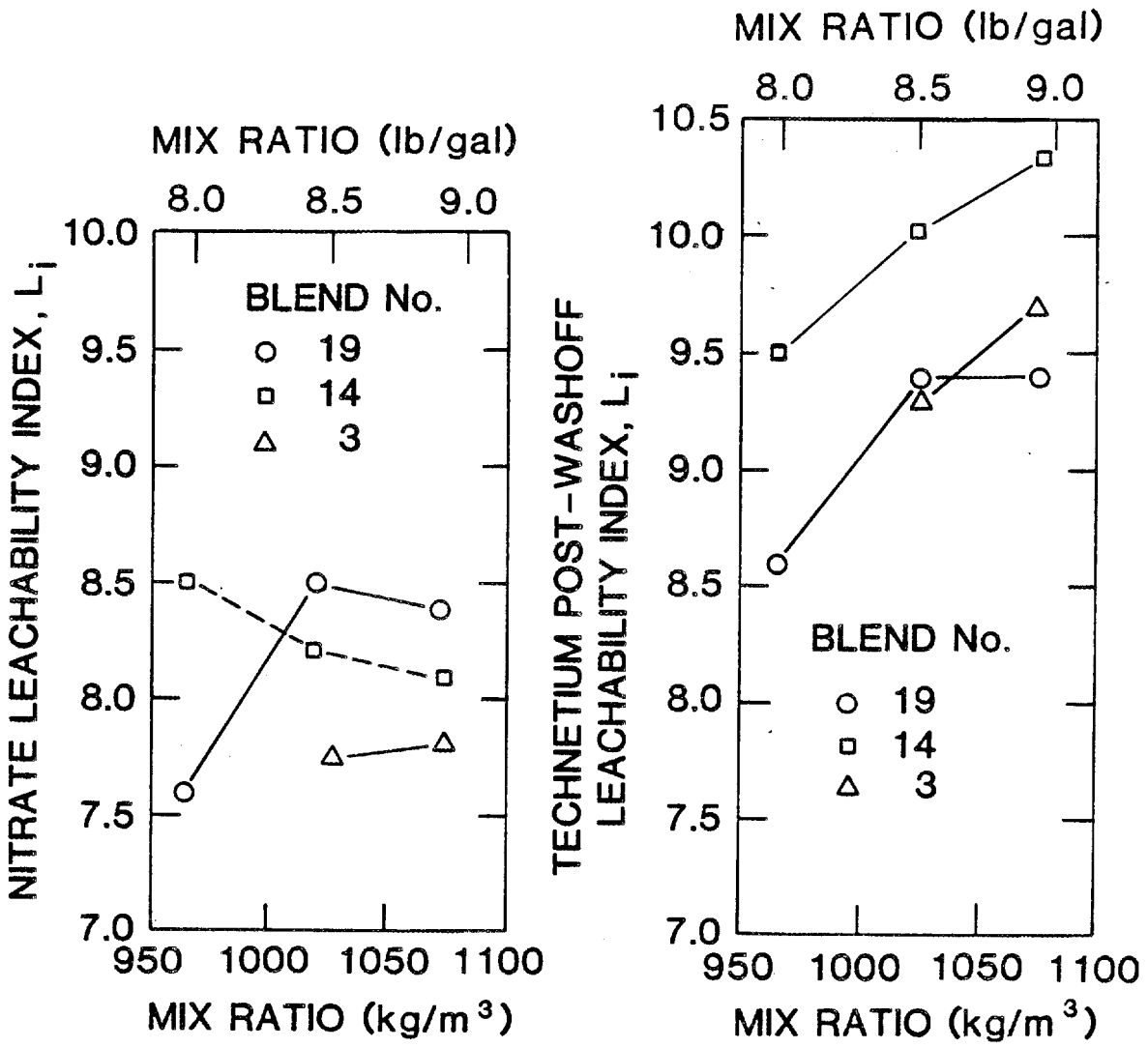

Fig. 3. Effect of grout/mix ratio on nitrate and technetium post-washoff leachability indexes.

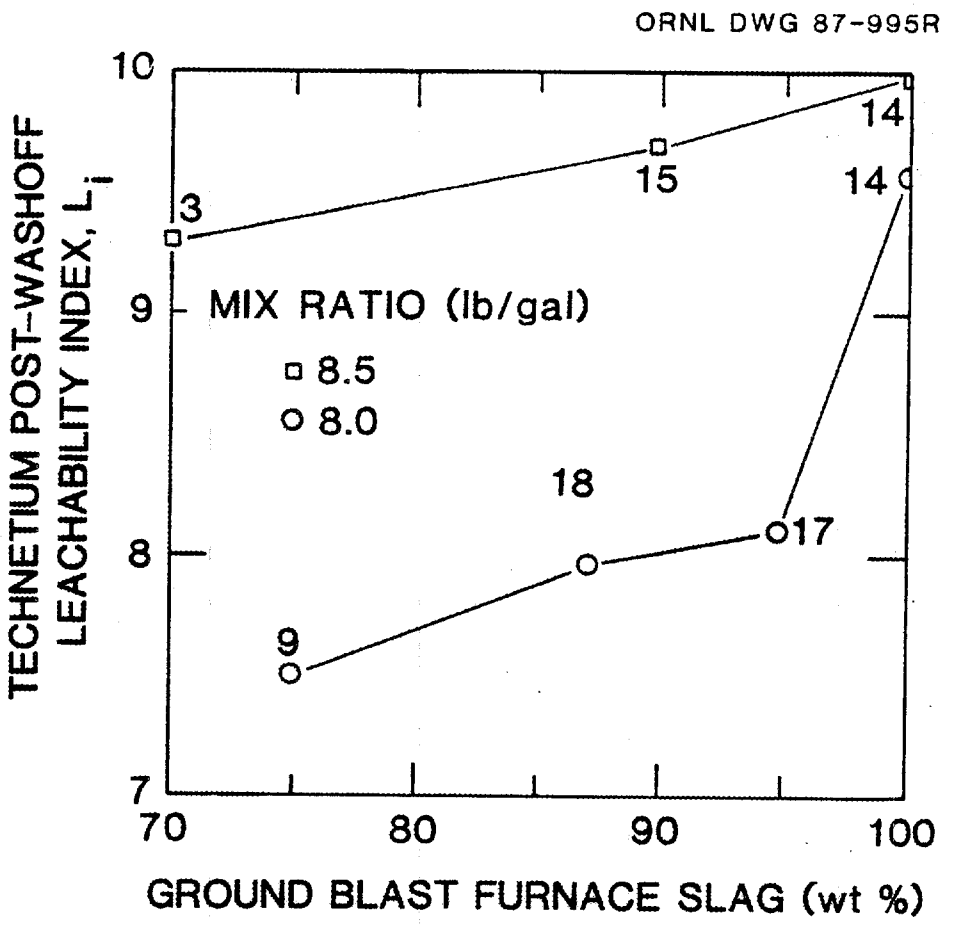

Fig. 4. Effect of ground BFS in blend contents on technetium post-washoff leachability index.

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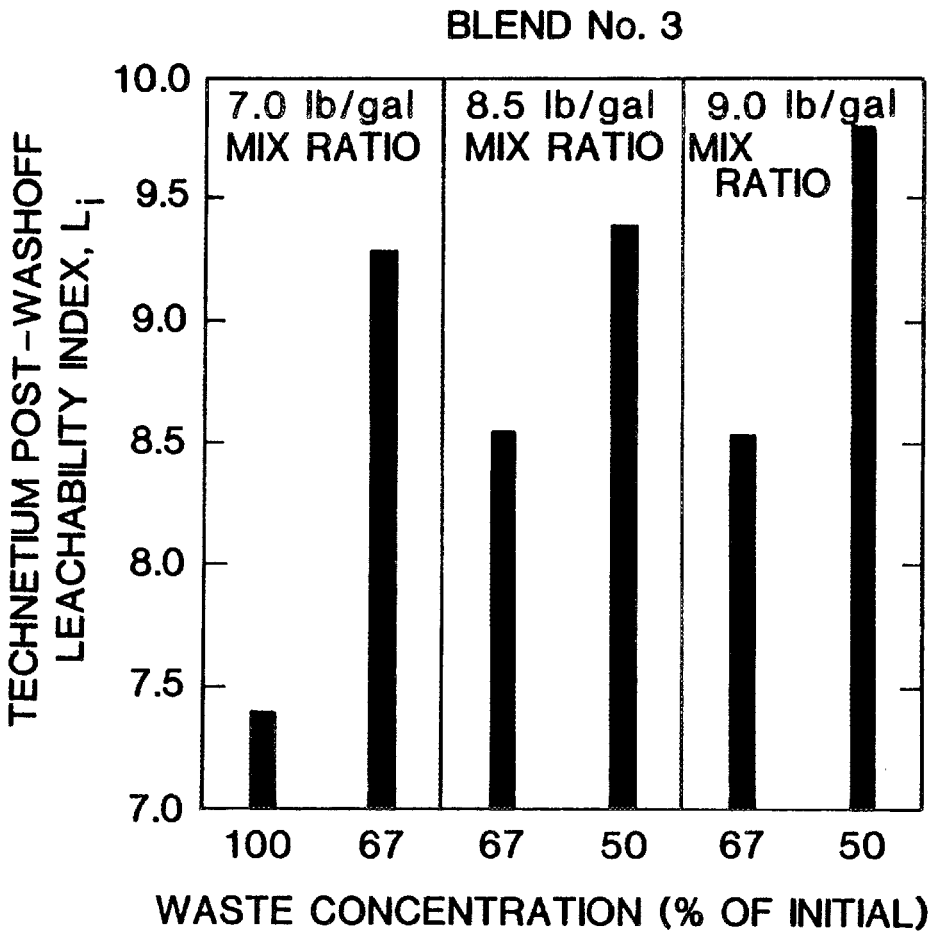

Fig. 5. Effect of waste concentration on technetium post-washoff leachability index for grouts formulated using blend No. 3.

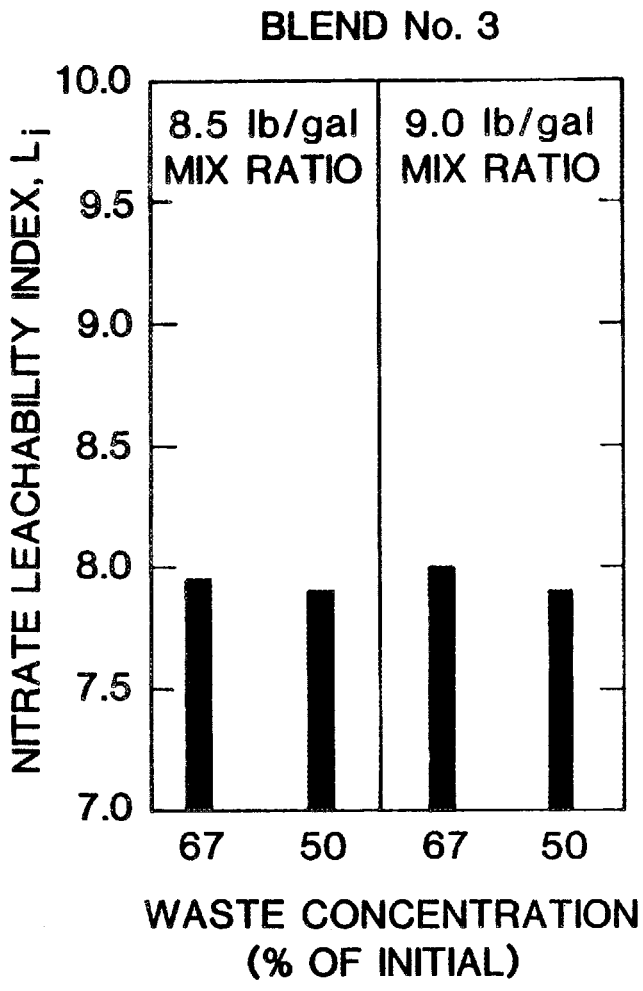

Fig. 6. Effect of waste concentration on nitrate leachability index for grouts formulated using blend No. 3.

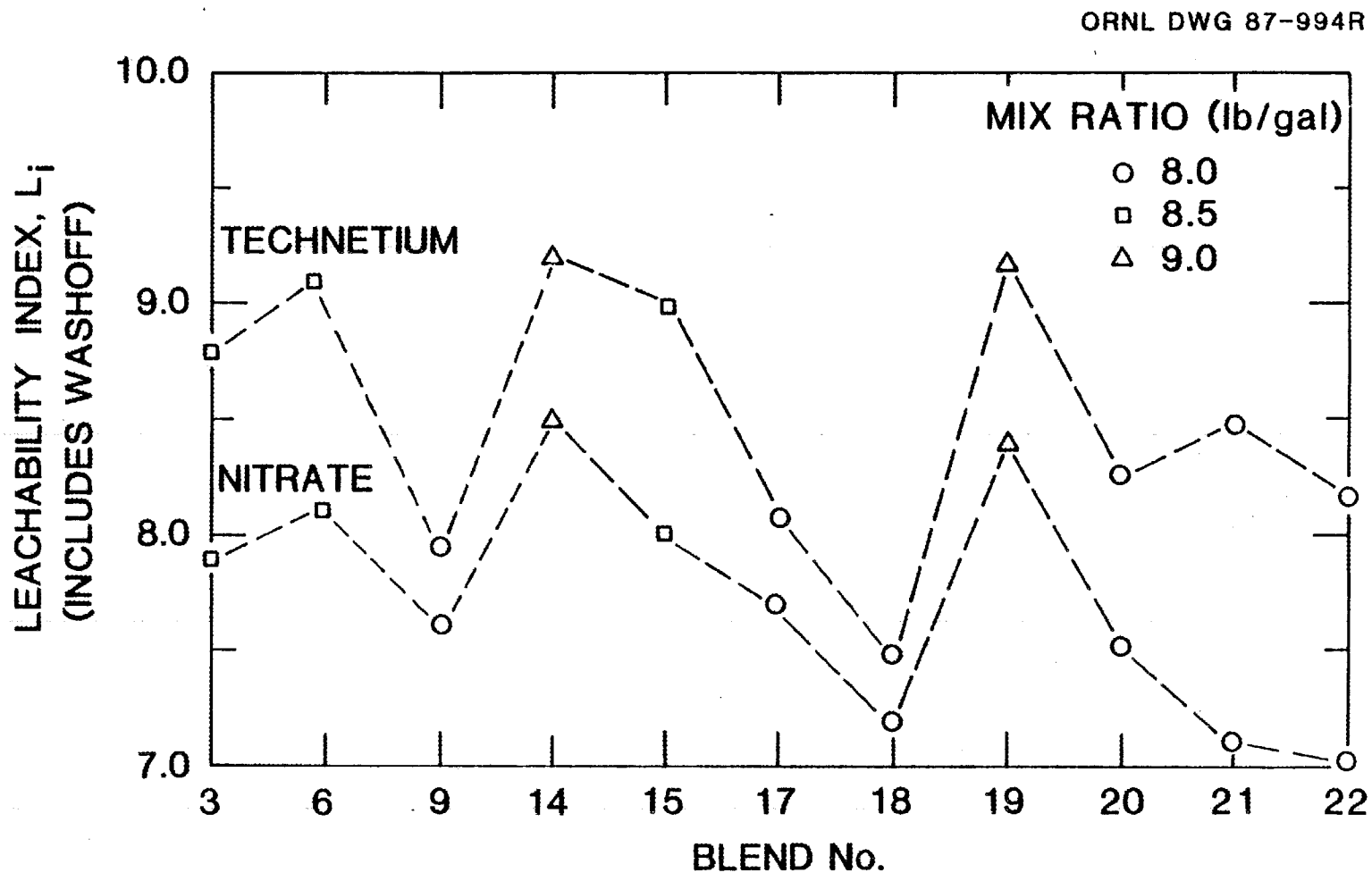

Fig. 7. Nitrate leachability index tracking of technetium leachability index in grouts formulated from different dry/solid blends with DSSF, 1:1 dilution.

formulated using the 1:1 dilutions of DSSF with the given mix ratios and blends.

A general objective of this investigation was to obtain L_is of ≥ 7.0 for most radioactive isotopes (or other materials). Both ^{99}Tc and nitrate L_i values for most grouts tested exceeded the 7.0 objective. A number of literature references[8-10] show that (1) blended cements containing ground BFS and/or fly ash form products with finer pore structures than are formed with ordinary cements and (2) diffusion through these products occurs more slowly. Our results — showing greater L_i values for both ^{99}Tc and nitrate with an increase in grout ground BFS content, an increase in the grout/mix ratio, and an increase in grout density — are consistent with the literature to the extent that such blend modifications decrease pore size or otherwise favorably affect grout pore properties. Also, the slag apparently increases the ^{99}Tc L_i values, because decreasing the waste concentration (or increasing the slag-to-waste concentration ratio) increases the ^{99}Tc. This effect is thought to result from the chemical properties of the slag, which reduce the technetium from the pertectnetate to the dioxide, a species that is less soluble and leaches more slowly.

3.8 EP TOXICITY TESTS

Specimens subjected to EP-toxicity tests were formulated using 1:1 dilutions of DSSF with blends 3 (7.0 lb/gal), 14 (8.0 lb/gal), and 19 (8.0 lb/gal). All specimens passed the test, as Table 9 shows. Tests were also conducted on ground BFS from Ash Grove Cement West, Inc., of Seattle, Washington, and on ASTM class F fly ash from Centralia, Washington. Both materials passed the test, as Table 10 shows.

3.9 PROCESSIBILITY REQUIREMENTS

All processibility criteria requirements [e.g., drainable water ($\leq$3 vol % in 28 d), compressive strength ($\geq$60 psi), 10-min gel strength ($\leq$100 lb_f 100 ft), critical flow rate ($\leq$55 gal/min), etc.] can be met using 8- to 9-lb/gal mixes of the blends listed in Table 2 with 1:1 dilutions of DSSF. Blends 3, 6, 9, 19, 20, 21, 22, 24, 25, 26, and 32

Table 9. EP toxicity leach results for DSSF grout with blends 3, 14, and 19 at a mix ratio of 8 lb/gal

Blend/ analysis	3[a] (mg/L)	14 (mg/L)	19 (mg/L)	Threshold limit (mg/L)
Arsenic	0.16	0.17	<0.05	5
Barium	0.13	<0.10	<0.10	100
Cadmium	<0.0030	<0.0030	<0.0030	1
Chromium	0.022	<0.010	<0.010	5
Copper	0.0085	<0.0040	<0.0040	
Lead	<0.050	<0.050	<0.050	5
Nickel	<0.050	<0.050	<0.050	
Selenium	<0.050	<0.050	<0.050	1
Silver	<0.010	<0.010	<0.010	5
Zinc	0.30	0.046	0.054	
Thallium	<0.01	<0.01	<0.01	
Mercury	0.0019	0.0002	0.0002	0.2
Chloride	<10	<10	<10	
Nitrate	370	197	147	
Sulfate	30	7.7	16	

[a]Mix with blend 3 contains 0.50 vol % Pozzolith 122-R and is a 7-lb/gal mix ratio.

Table 10. EP toxicity results for ground BFS (from Ash Grove Cement West Inc., Seattle, Washington) and class F fly ash (from Centralia, Washington)

Analysis	Slag (mg/L)	Fly ash (mg/L)
Arsenic	<0.050	0.64
Barium	<0.10	0.16
Cadmium	<0.0030	0.0049
Chromium	<0.010	0.023
Lead	<0.050	<0.050
Nickel	<0.050	<0.050
Selenium	0.13	<0.050
Silver	<0.010	<0.010
Zinc	0.24	0.23
Thallium	<0.01	<0.01
Mercury	<0.0002	<0.0002

require the use of 0.15 to 0.5 vol % Pozzolith 122-R admixture. Other blends, particularly Nos. 14 and 23, do not require an admixture. Pozzolith 122-R was found in several tests (Table 8) to increase L_is. This finding is thought to result from the increased densities of grouts containing the admixture.

4. BLEND RECOMMENDATIONS FOR FUTURE WORK

Inspection of the data in Tables 4 and 5 reveals that L_i values for specimens formulated using reference blends 14 and 19 remained among the highest of the index values measured. The values for 8.5-lb/gal mixes for ^{99}Tc for both blends were ≥ 9.0, and the nitrate values ranged from 8.0 to 8.5.

Note that although blend 14 (100 wt % ground BFS) formulates well with DSSF, a highly basic waste, it likely would not formulate as well with the wash water used to clean out the TGF between processes. This problem could be remedied by adding a small amount of cement to the blend (Appendix A-Tables A.6 and A.14).

Type I,II Portland cement can be successfully substituted for the 5 wt % lime in reference blend 19. Tests conducted with blend 23 with 5 wt % Type I,II cement (47.5 wt % ground BFS, 47.5 wt % ASTM class F fly ash) yielded essentially the same ^{99}Tc and nitrate L_is as did blend 19. Blend 23 did not require Pozzolith 122-R, whereas blend 19 did require 0.15 vol % of this admixture to meet rheological requirements.

5. ADDITIONAL COMMENTS

A few additional comments on this study follow.

1. Based on the results of this investigation, ground BFS decreases grout ^{99}Tc leachability more than it decreases nitrate leachability. This finding is thought to be caused by the reducing properties of the slag with the pertechnetate ion, TcO_4-, being reduced to the much less soluble dioxide, TcO_2, by the slag.

2. Nitrate L_i can be used as a worst-case measure of ^{99}Tc L_is. "Worst case" means that the technetium is totally present as TcO_4^- as is likely in the long term. The nitrate L_is are, in almost all instances, smaller than the ^{99}Tc L_is.
3. Grout specimens prepared using any one of the blends listed in Table 2 with 1:1 or 2:1 dilutions of DSSF at 8.5 ± 0.5-lb/gal mix ratios yield ^{99}Tc and nitrate L_i values ≥ 7.0.

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APPENDIX A

This appendix includes Tables A.1 to A.20, which consist of rheological, phase separation, and compressive strength data for the grouts tested during this investigation. Blend composition and leach rate data reported in the main body of the report are also included in the tables for reference.

Table A.1. Test results using DSSF (1:1 dilution) with blend 3[a] and 0.5 vol % Pozzolith 122-R

Property	Mix ratio (lb/gal)		
	8.0	8.5	9.0
Apparent viscosity (cP)	13.8 ± 0.2	38.5 ± 0.5	37.7 ± 9.3
10-min gel strength ($lb_f/100\ ft^2$)	7.0 ± 5.0	15.5 ± 5.0	16.5 ± 2.0
Density (lb/gal)	14.0 ± 0.1	14.1 ± 0.0	14.3 ± 0.0
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.0008 ± 0.0002	0.0011 ± 0.0000	0.0170 ± 0.0090
Flow behavior index (n')	0.819 ± 0.056	0.827 ± 0.004	0.510 ± 0.099
Phase separation, 2 d (vol %)	3.8	2.0	2.0
Phase separation, 28 d (vol %)	2.9	1.4	0.7
28-d compressive strength (psi)	1190 ± 181	894 ± 23	Undetermined
Technetium leachability[b] index [L_i(Tc)]	Undetermined	8.3	8.9
Nitrate leachability[b] index [$L_i(NO_3)$]	Undetermined	7.8	7.8
At reference conditions:			
Reynolds number	8901	6618	2592
Frictional pressure loss per 100 ft of pipe (psi)	1.3 ± 0.1	1.7 ± 0.0	4.5 ± 0.6
Critical flow rate (gal/min)	14.7 ± 0.3	19.2 ± 0.2	44.2 ± 3.5
Pump-head pressure (psi)	1.27 ± 0.9	2.6 ± 0.2	2.7 ± 0.3

[a]Type I,II Portland cement, 25 wt %; ground BFS, 70 wt %; and Indian Red pottery clay, 5 wt %.

[b]Pozzolith 122-R not used in leachability tests.

Table A.2. Test results using DSSF (2:1 dilution) with blend 3[a] and 0.5 vol % Pozzolith 122-R.

Property	Mix ratio (lb/gal) 7.0	8.5	9.0
Apparent viscosity (cP)	16.1 ± 4.0	26.5 ± 8.4	60.5 ± 28.9
10-min gel strength ($lb_f/100\ ft^2$)	10.6 ± 5.0	22.2 ± 5.3	25.0 ± 9.8
Density (lb/gal)	13.9	14.4	14.5
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.001 ± 0	0.003 ± 0.001	0.002 ± 0.001
Flow behavior index (n')	0.809 ± 0.021	0.747 ± 0.024	0.798 ± 0.037
Phase separation, 2 d (vol %)	2.9	0.0	0.0
Phase separation, 28 d (vol %)	0.25	0.0	0.0
28-d compressive strength (psi)	Undetermined	913 ± 42	Undetermined
Technetium leachability[b] index [$L_i(Tc)$]	Undetermined	8.4	8.4
Nitrate leachability[b] index [$L_i(NO_3)$]	Undetermined	7.9	8.1
At reference conditions:			
Reynolds number	8150	4735	4523
Frictional pressure loss per 100 ft of pipe (psi)	1.5	2.6	2.94
Critical flow rate (gal/min)	16.5	27.7	29.4
Pump-head pressure (psi)	1.8	7.0	4.1

[a]Type I,II Portland cement, 25.0 wt %; ground BFS, 70 wt %; and Indian Red pottery clay, 5 wt %.

[b]Pozzolith 122-R not used in leachability tests.

Table A.3. Test results using DSSF (1:1 dilution) with blend 9[a] and 0.5 vol % Pozzolith 122-R (grout used in barrier leachability tests)

Property	Mix ratio (lb/gal) 8.0
Apparent viscosity (cP)	12.5
10-min gel strength ($lb_f/100\ ft^2$)	39.0
Density (lb/gal)	13.8
Fluid consistency index, $K'(lb \cdot sec^n/ft^2)$	0.0008
Flow behavior index (n')	0.802
Phase separation, 2 d (vol %)	Undetermined
Phase separation, 28 d (vol %)	Undetermined
28-d compressive strength (psi)	Undetermined
At reference conditions:	
Reynolds number	9770
Frictional pressure loss per 100 ft of pipe (psi)	1.15
Critical flow rate (gal/min)	13.9
Pump-head pressure (psi)	6.5

[a]Type I,II Portland cement, 20 wt %; ground BFS, 7.5 wt %; and Indian Red pottery clay, 5 wt %.

Table A.4. Test results using DSSF (1:1 dilution) with blend 14[a] (no Pozzolith 122-R used)

Property	Mix ratio (lb/gal)		
	8.0	8.5	9.0
Apparent viscosity (cP)	33.0 ± 3.0	42.6 ± 8.4	47.0 ± 8.6
10-min gel strength ($lb_f/100\ ft^2$)	17.0 ± 3.0	25.5 ± 3.2	28.0 ± 5.2
Density (lb/gal)	13.8	14.0	14.1
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.006 ± 0.002	0.006 ± 0	0.017 ± 0.012
Flow behavior index (n')	0.637 ± 0.053	0.682 ± 0.024	0.567 ± 0.119
Phase separation, 2 d (vol %)	4.0	1.8	1.5
Phase separation, 28 d (vol %)	3.3	0.4	0.1
28-d compressive strength (psi)	700 ± 21	1552 ± 78	1188 ± 54
Technetium leachability[b] index [$L_i(Tc)$]	9.2	9.2	9.2
Nitrate leachability[b] index [$L_i(NO_3)$]	8.0	8.3	8.1
At reference conditions:			
Reynolds number	3221	2777	1910
Frictional pressure loss per 100 ft of pipe (psi)	3.5	4.2	5.2
Critical flow rate (gal/min)	32.6	41.5	48.2
Pump-head pressure (psi)	2.8	4.3	4.7

[a]Ground BFS, 100.0 wt%.
[b]Pozzolith 122-R not used in leachability tests.

Table A.5. Test results using DSSF (1:1 dilution) with blends 15[a] and 17[b]

Property	Mix ratio (lb/gal) 8.5[c]	8.0
Apparent viscosity (cP)	23.0 ± 5.6	32.5 ± 3.5
10-min gel strength ($lb_f/100\ ft^2$)	16.5 ± 10.6	73.0 ± 66.4
Density (lb/gal)	14.0	13.6
Fluid consistency index, $K'(lb \cdot sec^n/ft^2)$	0.003 ± 0.001	0.008 ± 0.002
Flow behavior index (n')	0.792 ± 0.093	0.008 ± 0.002
Phase separation, 2 d (vol %)	1.8	Undetermined
Phase separation, 28 d (vol %)	0.8	Undetermined
28-d compressive strength (psi)	1046 ± 23	887 ± 23
Technetium leachability[d] index $[L_i(Tc)]$	9.0	8.1
Nitrate leachability[d] index $[L_i(NO_3)]$	8.1	7.7
At reference conditions:		
Reynolds number	5328	3272
Frictional pressure loss per 100 ft of pipe (psi)	2.1	3.4
Critical flow rate (gal/min)	24.4	36.5
Pump-head pressure (psi)	2.7	12.1

[a]Type I,II Portland cement, 10.0 wt %; and ground BFS, 90.0 wt %.
[b]Ground BFS, 95.0 wt %; and lime, 5 wt %.
[c]Used 0.5 vol % Pozzolith 122-R for processibility tests.
[d]Pozzolith 122-R not used in leachability tests.

Table A.6. Test results with blend 15[a] and water instead of DSSF waste (no Pozzolith 122-R used)

Property	Mix ratio (lb/gal) 8.0	8.5
Apparent viscosity (cP)	21.0	22 ± 1.0
10-min gel strength ($lb_f/100\ ft^2$)	69.0	136 ± 26.0
Density (lb/gal)	12.4	12.5 ± 0.0
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.0361	0.0360 ± 0.0010
Flow behavior index (n')	0.285	0.291 ± 0.005
Phase separation, 2 d (vol %)	Undetermined	2.8
Phase separation, 28 d (vol %)	Undetermined	2.0
28-d compressive strength (psi)	Undetermined	Undetermined
At reference conditions:		
Reynolds number	3504	3459
Frictional pressure loss per 100 ft of pipe (psi)	14.9	4.9 ± 0.0
Critical flow rate (gal/min)	37.1	37.4 ± 0.4
Pump-head pressure (psi)	23.5	46.5 ± 0.2

[a]Type I,II Portland cement, 10.0 wt %; and ground BFS, 90.0 wt %.

Table A.7. Test results using DSSF (1:1 dilution) with blend 18[a] (no Pozzolith 122-R used)

Property	Mix ratio (lb/gal) 8.0
Apparent viscosity (cP)	105.0 ± 20.0
10-min gel strength ($lb_f/100\ ft^2$)	25.0 ± 13.2
Density (lb/gal)	13.5 ± 0.2
Fluid consistency index (K')($lb \cdot sec^{n'}/ft^2$)	0.0167 ± 0.0068
Flow behavior index (n')	0.675 ± 0.0422
Phase separation, 2 d (vol %)	1.0
Phase separation, 28 d (vol %)	0.0
28-d compressive strength (psi)	568 ± 7
Technetium leachability index [L_i(Tc)]	7.5
Nitrate leachability index [(L_i(Tc)]	7.2
At reference conditions:	
Reynolds number	1055
Frictional pressure loss per 100 ft of pipe (psi)	10.9
Critical flow rate (gal/min)	86.4 ± 15.7
Pump head pressure (psi)	4.2

[a]Ground BFS, 88 wt %; Indian Red pottery clay, 7.0 wt %; and lime, 5.0 wt %.

Table A.8. Test results using DSSF (1:1 dilution) with blend 19[a] (no Pozzolith 122-R used)

Property	Mix ratio (lb/gal) 8.0	8.5	9.0
Apparent viscosity (cP)	72.5 ± 3.5	76.5 ± 14.5	92.5 ± 11.0
10-min gel strength ($lb_f/100\ ft^2$)	33.5 ± 2.1	44.0 ± 8.0	27.3 ± 7.7
Density (lb/gal)	13.3 ± 0.3	13.5 ± 0.5	13.5 ± 0.0
Fluid consistency index, K' ($lb \cdot sec^{n'}/ft^2$)	0.0070 ± 0.0010	0.0098 ± 0.0015	0.001187 ± 0.0033
Flow behavior index (n')	0.755 ± 0.013	0.693 ± 0.007	0.700 ± 0.033
Phase separation, 2 d (vol %)	0.0	0.0	0.0
Phase separation, 28 d (vol %)	0.0	0.0	0.0
28-d compressive strength (psi)	Undetermined	570 ± 7	624 ± 36
Technetium leachability index [L_i(Tc)]	8.4	9.1	9.2
Nitrate leachability index [$L_i(NO_3)$]	7.6	8.5	8.4
At reference conditions:			
Reynolds number	1463	1278	1223
Frictional pressure loss per 100 ft of pipe (psi)	7.4 ± 0.5	7.52 ± 1.49	9.1 ± 1.3
Critical flow rate (gal/min)	67.0 ± 4.6	66.4 ± 9.4	77.1 ± 3.2
Pump-head pressure (psi)	5.6 ± 0.3	7.33 ± 1.3	4.5 ± 0.5

[a]Ground BFS, 47.5 wt %; lime, 5 wt %; and ASTM class F fly ash 47.5 wt %.

Table A.9. Test results using DSSF (1:1 dilution) with blend 19[a] and 0.15 vol % Pozzolith 122-R

Property	Mix ratio (lb/gal)		
	8.0	8.5	9.0
Apparent viscosity (cP)	33.5	45.0	57.0
10-min gel strength ($lb_f/100\ ft^2$)	66.0	48.0	57.0
Density (lb/gal)	13.4	13.4	13.5
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.0059	0.0059	0.0100
Flow behavior index (n')	0.6463	0.6909	0.6470
Phase separation, 2 d (vol %)	1.6	3.0	1.9
Phase separation, 28 d (vol %)	0.8	2.3	1.4
28-d compressive strength (psi)	Undetermined	Undetermined	Undetermined
At reference conditions:			
Reynolds number	3132	2446	1859
Frictional pressure loss per 100 ft of pipe (psi)	3.4	4.4	5.9
Critical flow rate gal/min)	37.2	44.5	54.6
Pump head pressure (psi)	11.0	8.0	9.5

[a]Ground BFS, 47.5 wt %; lime, 5.0 wt %; and ASTM class F fly ash, 47.5 wt %.

Table A.10. Test results using DSSF (1:1 dilution) with blend 19[a] and 0.2 vol % Pozzolith 122-R

Property	Mix ratio (lb/gal) 8.0	9.0
Apparent viscosity (cP)	38.0	42.0
10-min gel strength ($lb_f/100\ ft^2$)	14.0	21.0
Density (lb/gal)	13.4	13.5
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.0012	0.0045
Flow behavior index (n')	0.918	0.719
Phase separation, 2 d (vol %)	6.9	4.2
Phase separation, 28 d (vol %)	6.2	2.9
28-d compressive strength (psi)	Undetermined	Undetermined
Technetium leachability index [$L_i(Tc)$]	9.3	10.0
Nitrate leachability index [$L_i(NO_3)$]	8.3	8.6
At reference conditions:		
Reynolds number	3237	2724
Frictional pressure loss per 100 ft of pipe (psi)	3.37	4.02
Critical flow rate (gal/min)	33.5	40.8
Pump-head pressure (psi)	2.3	3.5

[a]Ground BFS, 47.5 wt %; lime, 5 wt %; and ASTM class F fly ash, 47.5 wt %.

Table A.11. Test results using DSSF (2:1 dilution) with blend 19[a] (no Pozzolith 122-R used)

Property	Mix ratio (lb/gal) 8.0	8.5	9.0
Apparent viscosity (cP)	21.7 ± 8.8	30.0	48.2 ± 29.3
10-min gel strength ($lb_f/100\ ft^2$)	34.5 ± 3.5	45.0	45.0 ± 36.7
Density (lb/gal)	13.6	13.8	13.7
Fluid consistency index, K'($lb \cdot sec^{n'}/ft^2$)	0.003 ± 0.0	0.002	0.006 ± 0.001
Flow behavior index (n')	0.707 ± 0.037	0.789	0.691 ± 0.083
Phase separation, 2 d (vol %)	4.2	3.4	1.5
Phase separation, 28 d (vol %)	3.3	1.4	0.4
28-d compressive strength (psi)	903 ± 68	Undetermined	653 ± 58
Technetium leachability index [L_i(Tc)]	8.5	8.8	8.8
Nitrate leachability index [L_i(NO3]	8.3	8.5	8.5
At reference conditions:			
Reynolds number	5638	4292	2957
Frictional pressure loss per 100 ft of pipe (psi)	2.1	2.6	4.5
Critical flow rate (gal/min)	24.8	28.3	45.0
Pump-head pressure (psi)	5.8	7.5	7.5

[a]Ground BFS, 47.5 wt %; lime, 5.0 wt %, and ASTM class F fly ash 47.5 wt %.

Table A.12. Test results using DSSF (1:1 dilution) with blends 20[a], 21[b], and 22[c] with 0.5 vol % Pozzolith 122-R

Property	Blend No. 20[d]	21[d]	22[d]
Apparent viscosity (cP)	69.3 ± 8.1	18.0 ± 2.6	17.3 ± 2.5
10-min gel strength ($lb_f/100\ ft^2$)	36.3 ± 19.9	25.3 ± 0.6	33.0 ± 12.5
Density (lb/gal)	13.2 ± 0.1	13.3	13.4
Fluid consistency index K'($lb \cdot sec^n/ft^2$)	0.0071 ± 0.0029	0.002 ± 0.001	0.002 ± 0.001
Flow behavior index (n')	0.7426 ± 0.0463	0.720 ± 0.025	0.693 ± 0.050
Phase separation, 2 d (vol %)	0.8	4.4	5.4
Phase separation, 28 d (vol %)	0.3	3.8	4.1
28-d compressive strength (psi)	1920 ± 53	536 ± 132	543 ± 294
Technetium leachability[d] index [L_i(Tc)]	8.3	8.5	8.2
Nitrate leachability[d] index [$L_i(NO_3)$]	7.6	7.1	7.0
At reference conditions:			
Reynolds number	1622	6059	6783
Frictional pressure loss per 100 ft of pipe (psi)	6.8	1.8	1.6
Critical flow rate (gal/min)	61.9 ± 7.2	22.1	20.6
Pump-head pressure (psi) (psi)	5.7	4.2	5.5

[a]Type I,II Portland cement, 0.0 wt %; ground BFS, 47.5 wt %; Indian Red pottery clay, 7.0 wt %; lime, 5 wt %; and ASTM class F fly ash, 40.5 wt %.

[b]Type I,II Portland cement, 10.0 wt %; ground BFS, 38.0 wt %; lime, 5 wt %; and ASTM class F fly ash, 47.0 wt %.

[c]Type I,II Portland cement, 10.0 wt %; ground BFS, 38 wt %; Indian Red pottery clay, 7.0 wt %; lime, 5 wt %; and ASTM class F fly ash, 40.0 wt %.

[d]Mix ratio = 8 lb/gal.

[e]No Pozzolith 122-R used in these leachability tests.

Table A.13. Test results using DSSF (1:1 dilution) with blend 23[a]

Property	Mix ratio (lb/gal) 8.0[b]	8.5
Apparent viscosity (cP)	13.0 ± 0.8	21.0 ± 0.0
10-min gel strength ($lb_f/100\ ft^2$)	7.0 ± 1.7	21.0 ± 1.4
Density (lb/gal)	13.4	13.6
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.0020 ± 0.0000	0.002 ± 0.001
Flow behavior index (n')	0.691 ± 0.083	0.741 ± 0.040
Phase separation, 2 d (vol %)	7.9	1.3
Phase separation, 28 d (vol %)	7.0	0.9
28-d compressive strength (psi)	432 ± 27	627 ± 0.8
Technetium leachability index [$L_i(Tc)$]	8.9	9.3
Nitrate leachability index [$L_i(NO_3)$]	8.5	8.5
At reference conditions:		
Reynolds number	8429	5525
Frictional pressure loss per 100 ft of pipe (psi)	1.3	2.0
Critical flow rate (gal/min)	17.1	23.7
Pump-head pressure (psi)	1.2	3.5

[a]Type I,II Portland cement, 5.0 wt %; ground BFS, slag, 47.5 wt %; and ASTM class F fly ash, 47.5 wt %.
[b]Used 0.15 vol % Pozzolith 122-R.

Table A.14. Test results with blend 23[a] using water instead of DSSF waste

Property	Mix ratio (lb/gal) 8.0
Apparent viscosity (cP)	9.8
10-min gel strength ($lb_f/100\ ft^2$)	15.0
Density (lb/gal)	11.9 ± 0.0
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.0102 ± 0.062
Flow behavior index (n')	0.393
Phase separation, 2 d (vol %)	Undetermined
Phase separation, 28 d (vol %)	Undetermined
28-d compressive strength (psi)	Undetermined
At reference conditions:	
Reynolds number	8238
Frictional pressure loss per 100 ft of pipe (psi)	4.7 ± 0.0
Critical flow rate (gal/min)	21.3
Pump-head pressure (psi)	5.1 ± 0.4

[a]Type I,II Portland cement, 5.0 wt %; ground BFS, 47.5 wt %; and ASTM class F fly ash, 47.5 wt %.

Table A.15. Test results using DSSF (1:1 dilution) with blend 23[a] using 90 g/L oxalic acid and 0.15 vol % Pozzolith 122-R

Property	Mix ratio (lb/gal) 8.0
Apparent viscosity (cP)	60.0 ± 0.0
10-min gel strength ($lb_f/100\ ft^2$)	23.7 ± 0.7
Density (lb/gal)	13.3 ± 0.0
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.0132 ± 0.0001
Flow behavior index (n')	0.536 ± 0.010
Phase separation, 2 d (vol %)	12.6
Phase separation, 28 d (vol %)	8.8
28-d compressive strength (psi)	949 ± 6
Technetium leachability index [L_i(Tc)]	12.7
Nitrate leachability index [(L_i(Tc)]	9.1
At reference conditions:	
Reynolds number	2548
Frictional pressure loss per 100 ft of pipe (psi)	4.2 ± 0.1
Critical flow rate (gal/min)	48.8 ± 0.5
Pump-head pressure (psi)	3.9 ± 0.1

[a]Type I,II Portland cement, 5 wt %; ground BFS, 47.5 wt %; and ASTM class F fly ash, 47.5 wt %.

Table A.16. Test results using DSSF (1:1 dilution) with blends 24[a] and 25[b]

Property	Mix ratio (lb/gal) 24[c,d]	25[d]
Apparent viscosity (cP)	55	22.3 ± 0.8
10-min gel strength ($lb_f/100\ ft^2$)	105	58.0 ± 8.4
Density (lb/gal)	13.5	13.7
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.016	0.002 ± 0.001
Flow behavior index (n')	0.630 ± 0.025	0.726 ± 0.043
Phase separation, 2 d (vol %)	Undetermined	0.0
Phase separation, 28 d (vol %)	Undetermined	0.0
28-d compressive strength (psi)	1396	719 ± 14
Technetium leachability[d] index [$L_i(Tc)$]	9.5	9.6
Nitrate leachability[d] index [$L_i(NO_3)$]	8.3	8.6
At reference conditions:		
Reynolds number	1968	5316
Frictional pressure loss per 100 ft of pipe (psi)	5.6	2.1
Critical flow rate (gal/min)	53.2	24.6
Pump-head pressure (psi)	17.5	9.7

[a]Ground BFS, 45.0 wt %; lime, 10 wt %; and ASTM class F fly ash, 45.0 wt %.

[b]Type I,II Portland cement, 10.0 wt %; ground BFS, 45.0 wt %; and ASTM class F fly ash, 45.0 wt %.

[c]Used 0.5 vol % Pozzolith 122-R in processibility tests.

[d]Mix ratio = 8.5 lb/gal.

[e]Pozzolith 122-R not used in leach tests.

Table A.17. Test results using DSSF (1:1 dilution) with blend 28[a] (no Pozzolith 122-R used)

Property	Mix ratio (lb/gal) 8.0
Apparent viscosity (cP)	24.5
10-min gel strength ($lb_f/100\ ft^2$)	20.0
Density (lb/gal)	14.3
Fluid consistency index, K'($lb \cdot sec^n / ft^2$)	0.0057
Flow behavior index (n')	0.601
Phase separation, 2 d (vol %)	4.88
Phase separation, 28 d (vol %)	2.92
28-d compressive strength (psi)	Undetermined
Technetium leachability index [L_i(Tc)]	9.6
Nitrate leachability index [(L_i(Tc)]	8.3
At reference conditions:	
Reynolds number	4403
Frictional pressure loss per 100 ft of pipe (psi)	2.64
Critical flow rate (gal/min)	29.4
Pump-head pressure (psi)	3.33

[a]Ground BFS (Standard Slag Co., Youngstown, Ohio), 100 wt %.

Table A.18. Test results using DSSF (1:1 dilution) with blend 29[a] (no Pozzolith 122-R used)

Property	Mix ratio (lb/gal) 8.0
Apparent viscosity (cP)	63.0
10-min gel strength ($lb_f/100\ ft^2$)	62.0
Density (lb/gal)	13.4
Fluid consistency index, $K'(lb \cdot sec^n/ft^2)$	0.0094
Flow behavior index (n')	0.679
Phase separation, 2 d (vol %)	0.0
Phase separation, 28 d (vol %)	0.0
28-d compressive strength (psi)	Undetermined
Technetium leachability index [L_i(Tc)]	7.8
Nitrate leachability index [(L_i(Tc)]	8.0
At reference conditions:	
Reynolds number	1642
Frictional pressure loss per 100 ft of pipe (psi)	6.65
Critical flow rate (gal/min)	60.2
Pump-head pressure (psi)	10.3

[a]Type I,II Portland cement, 5 wt %; ground BFS (Standard Slag Co., Youngstown, Ohio) 47.5 wt %; and ASTM class F fly ash, 47.5 wt %.

Table A.19. Test results using DSSF (1:1 dilution) with blend 31[a] and 0.2 vol % Pozzolith 122-R

Property	Mix ratio (lb/gal) 9.0
Apparent viscosity (cP)	41.0
10-min gel strength ($lb_f/100\ ft^2$)	80.0
Density (lb/gal)	13.1
Fluid consistency index, $K'(lb \cdot sec^{n'}/ft^2)$	0.0038
Flow behavior index (n')	0.747
Phase separation, 2 d (vol %)	0.0
Phase separation, 28 d (vol %)	0.0
28-d compressive strength (psi)	Undetermined
Technetium leachability index [L_i(Tc)]	8.0
Nitrate leachability index [(L_i(Tc)]	Undetermined
At reference conditions:	
Reynolds number	2701
Frictional pressure loss per 100 ft of pipe (psi)	3.9
Critical flow rate (gal/min)	40.8
Pump-head pressure (psi)	13.3

[a]Kiln dust, 47.5 wt %; ASTM class F fly ash, 47.5 wt %; and lime, 5 wt %.

Table A.20. Preliminary test results using DSSF (1:1 dilution) with blends 32[a] and 33[b]

Property	Mix ratio (lb/gal) DS-32[c,d]	DS-25[d,e]
Apparent viscosity (cP)	11.5 ± 0.8	16.1 ± 1.6
10-min gel strength ($lb_f/100\ ft^2$)	>105	9.5 ± 1.3
Density (lb/gal)	13.3	13.7
Fluid consistency index, K'($lb \cdot sec^n / ft^2$)	0.002 ± 0.001	0.002 ± 0.0
Flow behavior index (n')	0.678 ± 0.069	0.671 ± 0.037
Phase separation, 2 d (vol %)	0.0	5.4
Phase separation, 28 d (vol %)	0.0	5.0
28-d compressive strength (psi)	331 ± 16	932 ± 82
Technetium leachability[d] index [L_i(Tc)]	7.7	9.2
Nitrate leachability index [$L_i(NO_3)$]	8.0	8.6
At reference conditions:		
Reynolds number	9101	6673
Frictional pressure loss per 100 ft of pipe (psi)	1.2	1.7
Critical flow rate (gal/min)	16.6	21.0
Pump-head pressure (psi)	Undetermined	1.6

[a]Ground BFS, 45.0 wt %; lime, 10 wt %; and ASTM class F fly ash, 45.09 wt %.

[b]Type I,IOI Portland cement, 10.0 wt %; ground BFS, 45.0 wt %; and Class F fly ash, 45.0 wt %.

[c]Used 0.5 vol % Pozzolith 122-R in processibility tests.

[d]Mix ratio = 8.5 lb/gal.

[e]Pozzolith 122-R not used in leach tests.

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