

Physical and Chemical Characteristics of Blast Furnace, Basic Oxygen Furnace, and Electric Arc Furnace Steel Industry Slags

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Approximately 21 million tons of steel industry slag are produced each year in the United States, and many productive commercial uses of slag have been developed (e.g., road bed, fill material). However, because slag contains heavy metals at concentrations that are higher than in most soil, questions have been raised regarding the need to evaluate the potential human health and environmental hazards associated with current applications. To enhance general understanding of the physical and chemical characteristics of this material, slag samples from 58 active mills with blast furnaces, basic oxygen furnaces, and/or electric arc furnaces were examined. This study profiles the major and minor constituents of slag from each furnace type and reports the leachability of metals from slag under neutral and acidic conditions. Particle size distributions

and partitioning coefficients (K_d) are also reported. Although concentrations of metals in slag are elevated relative to concentrations in soil, the metals in slag are tightly bound to the slag matrix and not readily leached. This study represents the most complete characterization of steel industry slag currently produced in North America, encompassing mills that collectively produce over 47% of steel industry slag. These data provide insights that may be useful for evaluating the marketability of steel industry slag and for human and ecological health risk assessment of environmental applications.

Introduction

Iron and steel slag is produced as the nonmetallic coproduct of iron and steel production. There are three types of steel industry slag, each named for the process from which it is produced: Blast Furnace (BF) iron slag, Basic Oxygen Furnace (BOF) steel slag, and Electric Arc Furnace (EAF) steel slag. Blast Furnaces are used for iron production, while EAFs and BOFs are used for steel production. All three slag types are primarily comprised of fluxing agents (mainly lime), used during the iron and steelmaking process, and the molten impurities of iron or steel. For BF slag, the composition is primarily silica and alumina from the original iron ore, with calcium and magnesium oxides from the added flux (1). Fluxing agents are also used in the BOF and EAF processes, and thus the chemical composition of slag from these processes is similar to BF slag. However, the iron and manganese contents of BOF and EAF slags are substantially higher (1). Once slag is cooled and solidified, the metallic component is removed and fed back into the steel mill, and the nonmetallic slag is sized and may be crushed to diameter fractions that range from approximately 10 in. to 1 in. or less.

BF slag production in the United States is approximately 13 million tons per year or 220–370 kilograms per ton of iron produced (2). Approximately 8 million tons per year of BOF and EAF slag are marketed, which is about 10–15% by weight of steel output. Thus, approximately 21 million tons of steel industry slag are produced and used annually, with a commercial value of approximately \$147 million (3). Over the past 100 years of steelmaking, slag has been used for many productive purposes. Historically, slag has been used for the construction of roads and as fill material. However, more recently, slag uses have been expanded to include use as a cement additive, landfill cover material, and for a number of agricultural and construction applications. Table 1 presents a current list of the primary uses of iron and steel slag and typical environmental applications.

In 1994, the U.S. Environmental Protection Agency (U.S. EPA) investigated environmental concerns regarding a different type of slag, high-temperature metal recovery (HTMR) slag, which is produced during zinc reclamation (4). This investigation was initiated due to a petition filed by the Natural Resources Defense Council that forced the U.S. EPA to evaluate nonencapsulated uses of HTMR slag. U.S. EPA demonstrated through a risk assessment that no environmental threat was present from HTMR slag use (4).

Recently, questions have been raised regarding the use of steel industry slag because of its elevated metal content and the associated potential for impacts on human health and the environment. These concerns focus on exposures to

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TABLE 1. Uses of Steel Industry Slag

typical iron and steel slag uses	applications					
	applied to land surface	applied to land subsurface	placed in water	encapsulated uses	agricultural uses	landfill uses
aggregate in bituminous mixes such as pavement surfaces (wearing and binder courses), bases, surface treatments, seal coats, slurry coats, and cold patch				X		
concrete aggregate and as a cement ingredient				X		
antiskid aggregate (snow and ice control)	X					
surfacing stabilized shoulders, banks, and other select material	X		X	X		
bank stabilization (erosion control aggregate)	X		X			
gabions and riprap	X					
aggregate base courses and sub-bases	X	X		X		
unpaved driveways, surface roads, and walkways	X					
railroad ballast	X					
neutralization of mine drainage and industrial discharge	X	X	X			
agricultural uses such as soil remineralization and conditioning, pH supplement/liming agent, fertilizer	X				X	
controlled, granular fills, such as those required for unpaved parking and storage areas, pipe and tank backfill, berm construction and other industrial and construction activity	X	X				
at steel mills as construction aggregate or a fluxing agent	X	X	X	X		
landfill daily cover material						X
landscape aggregate	X	X				
trench aggregate/drain fields	X	X				
sand blast grit	X					
roofing granules				X		
bulk filler (e.g., paints, plastics, adhesives)				X		
mineral wool (home and appliance insulation)				X		
fill	X	X	X			X

humans who may incidentally contact slag or are exposed to metals that may leach from slag to drinking or surface water. In addition, concerns regarding ecological hazards resulting from pH fluctuations and metal leaching to surface water have been expressed. To investigate the potential human health and environmental impacts associated with slag uses, a risk-based characterization process was performed. The resulting data may also be used by both state and federal environmental regulatory agencies when considering the need for environmental regulation of slag.

The objective of this study was to describe the physical and chemical characteristics of each slag type to enhance understanding of steel industry slag and provide data that could be used to evaluate the potential environmental impacts associated with its application. The steel industry slag characterized in this study comes from samples collected at 58 active steel mills, which collectively generate more than 47% of the steel produced in North America. This study presents the largest and most comprehensive characterization of iron and steel slag produced in North America, and the data have been used for an extensive material-specific and use-specific human and environmental health risk assessment (5).

Materials and Methods

Materials. Fifty-eight steel mills throughout the United States and Canada submitted a sample of slag for analysis from each of the size gradations produced during 1995 and 1996. A composite sample per furnace type per mill was prepared by En Chem, Inc. (Madison, WI), by crushing the various slag sizes and combining the subsamples into one homogeneous sample. Composite samples were prepared based on 1994 sales volume by size. A total of 73 composite slag samples were collected from the 58 participating steelmaking mills as some mills operate more than one type of furnace. A total of 11 BF slag composite samples, 17 BOF slag composite samples, and 45 EAF slag composite samples were used for this study.

Analytical Methods. A variety of tests were conducted on the individual mill composite samples to determine the physical and chemical characteristics of steel industry slag. First, the slag samples were analyzed for major constituents (aluminum, calcium, carbon, iron, magnesium, manganese, phosphorus, silicon, and sulfur). Analysis of carbon was conducted by the American Standards for Testing Materials (ASTM) Method E 1019-83, sulfur via ASTM Method E350-90, magnesium by ASTM Method E663-86(91). ASTM 1085-87 was used to analyze for aluminum, calcium, iron, manganese, phosphorus, and silicon. Second, analytical procedures from the U.S. EPA Test Methods for Evaluating Solid Wastes (USEPA SW-846) were followed to achieve the lowest level of detection for minor metal constituents (antimony, arsenic, barium, beryllium, cadmium, total chromium, hexavalent chromium, cobalt, copper, lead, mercury, nickel, selenium, silver, thallium, tin, vanadium, and zinc). U.S. EPA Method 7197 was used to analyze for hexavalent chromium [Cr(VI)], and U.S. EPA Method 7471 was used to analyze for mercury. U.S. EPA acid digestion method 3050B and analysis Method 6010 were used to analyze for the remaining metal constituents.

Acidic and neutral leaching tests were also performed on each sample. The Toxicity Characteristic Leaching Procedure (TCLP) test was conducted to determine the mobility of metals from slag under acidic conditions (40 CFR 260.11, Appendix II). This analysis was conducted for total metals according to U.S. EPA SW-846 Method 1311 (6). To assess the mobility of metals in slag under neutral conditions, the ASTM distilled water leachate test (ASTM Method D 3987) was performed on a representative number of samples for each slag type (five BF, four BOF, and six EAF slag samples). As part of the ASTM water leachate test, pH of the leachate was measured for each sample.

Last, particle size fraction analyses were conducted. Samples used for this analysis were obtained from the original mill samples prior to crushing or compositing. Three representative samples were chosen of each slag type from

TABLE 2. Steel Industry Slag Characterization Results^b

metal	slag concentrations by furnace type (mg/kg)																				
	detection freq (%)			distribution type			mean			SD			minimum			maximum			95% UCL ^a		
	BF	BOF	EAF	BF	BOF	EAF	BF	BOF	EAF	BF	BOF	EAF	BF	BOF	EAF	BF	BOF	EAF	BF	BOF	EAF
Al	100	100	100	N	-	L	41245	23841	35009	5781	29845	11693	31000	100	14100	49800	108800	71600	44405	36479	38460
Sb	0	35	31	ND	-	-	ND	3.3	4.0	ND	2.0	3.4	ND	3	1.1	ND	8.8	18	ND	4.2	4.9
As	45	0	11	L	ND	L	1.3	ND	1.9	3.5	ND	1.1	0.5	ND	0.5	2.7	ND	5.8	1.9	ND	2.2
Ba	100	100	100	N	L	L	273	75	557	67	62	285	180	24	160	390	260	1800	309	103	640
Be	100	6	91	-	-	-	8.2	0.5	1.1	1.7	1.2	1.0	4.1	5.0	0.6	11	5.0	6.3	9.2	1.0	1.4
Cd	0	24	84	ND	-	-	ND	2.5	7.6	ND	4.1	5.9	ND	0.8	0.1	ND	15	19	ND	4.2	9.1
Ca	100	100	100	N	L	N	273855	280135	250653	18246	41651	30857	250100	206900	172300	311500	367200	324400	283826	299172	258382
C	100	100	100	-	L	-	2291	2600	2936	2214	1489	2591	300	500	100	8700	5800	12100	3501	3852	3585
Cr (total)	100	100	100	L	N	N	132	1271	3046	226	391	1373	10	440	320	740	2000	6200	600	1437	3390
Cr(VI)	0	0	29	ND	ND	-	ND	ND	1.2	ND	ND	1.6	ND	ND	1.0	ND	ND	9.1	ND	ND	1.5
Co	64	59	96	-	-	-	3.0	3.8	4.8	3.5	3.9	2.2	0.9	2	2.5	13	12	11	4.9	5.5	5.3
Cu	55	100	100	-	L	L	5.3	30	178	6.3	24	84	1.7	12	62	20	120	540	8.7	38	202
Fe	100	100	100	-	L	N	17355	184300	190211	30397	40016	65309	1400	115700	32700	105800	229000	312000	33966	201244	206569
Pb	27	100	100	-	-	-	3.57	50.0	27.5	9.1	89	43	1.4	2.4	4.5	31	330	220	8.6	88	38
Mg	100	100	100	N	N	N	69991	55318	54460	9395	11467	17561	54700	28700	23600	84500	72000	91500	75125	60173	58859
Mn	100	100	100	-	L	N	5527	32853	39400	4833	12321	7712	100	12900	18900	18600	65700	63800	8168	39410	41332
Hg	0	41	18	ND	-	-	ND	0.1	0.04	ND	0.1	0.0	ND	0.1	0.1	ND	0.1	0.1	ND	0.1	0.0
Mo	18	47	98	-	L	-	0.8	11	30	1.5	22	22	1.6	0.8	1.6	5.0	73	81	1.6	141	35
Nickel	18	94	100	-	N	-	1.4	4.9	30	0.9	2.5	47	3.1	2.1	5.2	3.4	10	310	1.9	6.0	42
P	27	100	98	-	N	-	220	3197	1781	322	1319	939	210	470	580	1180	5720	4290	396	3756	2017
Se	82	82	100	L	N	L	3.9	15	18	1.6	7.4	5.2	2.2	7.7	7.5	6.5	25	36	5.1	18	20
Si	100	100	100	N	-	-	170064	59653	74524	19952	20762	25647	124300	30900	39900	201400	114100	152700	180967	68444	80948
Ag	0	53	78	ND	-	-	ND	9.1	8.4	ND	23	18	ND	2.3	1.3	ND	100	100	ND	19	13
S	100	100	100	N	-	N	10268	1112	1891	3113	1120	711	3800	440	600	15100	5000	3310	11970	1587	2069
Tl	0	12	2	ND	-	L	ND	7.2	11	ND	5.7	7.5	ND	11	11	ND	11	11	ND	10	14
Sn	27	100	100	-	L	L	1.6	6.5	10	0.9	5.3	5.5	2.2	2.7	3.2	3.7	26	34	2.1	8.2	12
V	100	100	100	L	N	L	54	992	513	90	318	248	11	430	170	320	1700	1500	5.1	1127	582
Zn	100	94	100	-	-	L	20	46	165	37	39	148	3.5	8.5	31	130	150	690	41	63	209

^a For log-normal distributions, the log-normal 95% UCL is presented. For normal, or neither normal nor log-normal distributions, the normal 95% UCL is presented. ^b BF, blast furnace; BOF, basic oxygen furnace; EAF, electric arc furnace; ND, not detected; N, normal distribution; L, log-normal distribution; -, neither normal nor log-normal distribution.

TABLE 3. Toxicity Characterization Leaching Potential (TCLP) Test Results for BF, BOF, and EAF Slag^a

metal	total number of samples			detection frequency (%)			TCLP concentration (mg/L)								
	BF	BOF	EAF	BF	BOF	EAF	minimum			mean			maximum		
							BF	BOF	EAF	BF	BOF	EAF	BF	BOF	EAF
antimony	11	17	45	27	0	4	0.007	ND	0.006	0.005	ND	0.003	0.01	ND	0.01
arsenic	11	17	45	36	6	7	0.003	0.005	0.004	0.003	0.002	0.002	0.005	0.005	0.011
barium	11	17	45	100	100	100	0.41	0.03	0.34	1.0	0.41	1.4	1.8	4.60	7.9
beryllium	11	17	45	82	0	0	0.008	ND	ND	0.03	ND	ND	0.21	ND	ND
cadmium	11	17	45	82	29	24	0.00063	0.001	0.0005	0.002	0.001	0.002	0.005	0.010	0.04
chromium (total)	11	17	45	82	18	44	0.01	0.01	0.01	0.06	0.01	0.04	0.2	0.04	1.0
chromium(VI)	11	17	45	45	0	11	0.01	ND	0.011	0.01	ND	0.006	0.03	ND	0.018
lead	11	17	45	0	35	31	ND	0.003	0.003	ND	0.004	0.004	ND	0.015	0.063
manganese	11	17	45	100	71	67	11	0.0120	0.006	26	30.15	21	55	150.00	67
mercury	11	17	45	0	6	4	ND	0.0005	0.0009	ND	0.0003	0.0002	ND	0.0005	0.0009
nickel	11	17	45	0	12	49	ND	0.028	0.01	ND	0.012	0.07	ND	0.033	0.61
selenium	11	17	45	0	0	13	ND	ND	0.006	ND	ND	0.003	ND	ND	0.007
silver	11	17	45	0	6	2	ND	0.029	0.03	ND	0.0064	0.005	ND	0.03	0.03
thallium	11	17	45	0	0	0	ND	ND	ND	ND	ND	ND	ND	ND	ND
zinc	11	17	45	100	47	36	0.03	0.03	0.037	0.11	0.07	0.11	0.32	0.42	1.0

^a For log-normal distributions, the log-normal 95% UCL is presented. For normal, or neither normal nor log-normal distributions, the normal 95% UCL is presented. For metals for which TCLP (6) criteria are not available, 100 X the USEPA Maximum Contaminant Level is presented (20). When neither were available, 100 X USEPA Region III Tap water concentrations (RBCs) are presented (27). BF, blast furnace; BOF, basic oxygen furnace; EAF, electric arc furnace; ND, not detected.

the smallest size samples submitted by the mills (e.g., samples defined as "fines"), and the particle size distributions were determined using ASTM Method D 422.

Data Analysis

Statistical Methods. The 95th percentile upper confidence limit of the mean (95% UCL) concentrations of each metal in each slag type and TCLP leachate were calculated for each metal with a detection frequency greater than 50% by slag type. The 95% UCL is a statistical descriptor commonly used in health risk assessment to represent the reasonable upper-bound concentration of a chemical in environmental media (7). First, a statistical evaluation was conducted with either the D'Agostino or the Kolmogorov-Smirnov (K-S) test to determine the distribution of the data (log-normal, normal, or neither log-normal nor normal) for each metal. When the sample size was greater than 20, the D'Agostino test was applied (8). For data sets with fewer than 20 samples, the K-S test with Lilliefors modification was used (9). These tests were performed at the 90% confidence level. For data sets with normal distributions, the normal 95% UCL was calculated (7). When the distribution of a data set was log-normal, or if it was determined to be neither normal nor log-normal ("neither"), then the log-normal 95% UCL was calculated (10, 11).

Comparison to Background Concentrations of Metals in Soil. Metals detected in each of the three slag types were statistically compared to naturally occurring background levels of metals in U.S. soils (12). This comparison was made for total metals, and was accomplished through the use of the Behrens-Fisher *t*-Test (B-F test). The B-F test was used as it is designed to test unknown data distributions, such as the soil background level dataset used in this study (11). For this comparison, both populations were assumed to have normal (Gaussian) distributions (13) and were evaluated in the following manner.

1. For metals with detection frequencies of 50% or greater in slag samples, the arithmetic means were statistically compared to naturally occurring background concentrations using the B-F test (11).

2. Metals with detection frequencies less than 50% in steel slag samples could not be statistically compared to background because of data limitations; therefore, the mean background concentration plus 2 SD was used as a measure

of background variance and was compared to the 95% UCL or maximum background metal concentration.

3. Metals detected in slag samples that are rarely found in natural soils were considered to be above background (e.g., cadmium, silver, and hexavalent chromium).

Soil-to-Water Partition Coefficients. The data from the ASTM water leachate test were used to calculate soil-to-water partition coefficients (K_d) for each metal in slag. The K_d value represents the metal's adsorption relationship between soil and water; a higher K_d indicates a tighter adsorption to the slag matrix and, therefore, lower mobility from soil to water. The K_d was calculated by dividing the total metal concentrations in slag by the corresponding ASTM leachate concentrations (14). Arithmetic mean concentrations were calculated for each metal measured in slag samples subjected to the ASTM water leachate test, and only detected values were used in the calculation of this mean. Similarly, the arithmetic mean concentrations of metals in the leachate were calculated. If no detectable concentration could be measured in the leachate, then one-half of the limit of detection was used. The arithmetic mean K_d values were calculated by averaging specific K_d values for each metal.

Results

The concentrations of metals measured in each slag type are presented in Table 2. The primary constituents of slag are aluminum, calcium, iron, magnesium, manganese, phosphate, silicon, and sulfur. Because carbon, sulfur, magnesium, calcium, and phosphates are major elements of the earth's crust and are essential human nutrients, they were not evaluated further, consistent with U.S. EPA health risk assessment guidance for screening chemicals in soil (14). The remaining trace elements were further evaluated to determine their relevance for health risk assessment.

The data distribution types are presented (as normal, log-normal, or neither) in addition to the mean concentration, standard deviation, minimum and maximum detected concentrations, and 95% UCL concentration for each metal (Table 2). Table 3 presents the results of the TCLP analyses, including detection frequency, minimum and maximum detected concentrations, and the arithmetic mean. TCLP leachate concentrations were very low; the only metals detected at greater than 1 mg/L were barium and manganese. These metals were also measured at generally higher concentrations in the slag samples.

TABLE 4. American Standards for Testing and Materials (ASTM) Water Leachate Results and Soil/Water Partition Coefficients (K_d s) for BF, BOF, and EAF Slags^a

metal	BF			BOF			EAF		
	arithmetic mean slag concn (mg/kg)	arithmetic mean ASTM concn (mg/L)	arithmetic mean K_d value (L/kg)	arithmetic mean slag concn (mg/kg)	arithmetic mean ASTM concn (mg/L)	arithmetic mean K_d value (L/kg)	arithmetic mean slag concn (mg/kg)	arithmetic mean ASTM concn (mg/L)	arithmetic mean K_d value (L/kg)
aluminum	38420	3.8	20835	18.775	2.7	15852	41550	38	1820
antimony	ND	ND	ND	4.4	ND	1760	6	0.017	2373
arsenic	0.45	ND	300	ND	0.003	NDS	5.0	0.0040	819
barium	290	0.22	1686	86	0.11	1697	717	0.49	2043
beryllium	8.2	ND	16480	5	ND	10000	1.9	ND	3830
cadmium	ND	ND	ND	15	ND	61224	8.3	ND	33886
chromium	120.8	0.0038	78292	1285	ND	856667	2937	0.066	544105
chromium(VI)	ND	ND	ND	ND	ND	ND	3.5	0.023	535
copper	11	ND	7967	22	ND	14833	243	0.0049	124874
iron	32440	ND	1297600	180525	ND	7221000	181150	ND	7246000
lead	31	ND	20667	18	0.027	3194	83	0.018	28591
manganese	7820	0.0014	7112857	30525	0.0022	26502273	38220	0.0035	14953635
molybdenum	3.3	ND	1320	4.0	0.0080	700	30	0.044	1154
mercury	ND	ND	ND	0.10	ND	1000	0.090	ND	900
nickel	3.3	ND	1,300	4.3	ND	1720	37	ND	14600
selenium	4.8	0.0075	1015	17	ND	6627	19	0.011	5707
silver	ND	0.0037	ND	3.8	ND	1500	5.2	ND	2060
thallium	ND	ND	ND	11	ND	11000	ND	ND	NDS
tin	2.5	ND	500	6.3	ND	1250	15	ND	2930
vanadium	34	0.010	11753	848	0.0087	239230	502	0.015	72959
zinc	33	ND	3348	48	ND	4775	241	ND	24050

^a BF, blast furnace; BOF, basic oxygen furnace; EAF, electric arc furnace.

TABLE 5. Particle Size Distribution Results for BF, BOF, and EAF Slags^a

percent finer (mm)	BF		BOF		EAF	
	arithmetic mean	SD	arithmetic mean	SD	arithmetic mean	SD
% < 25.4					100.00	0.00
% < 19.05			100.00	0.00	99.60	0.57
% < 12.7	100.00	0.00	96.47	0.60	91.57	3.47
% < 9.525	99.97	0.05	83.47	5.66	83.23	2.64
% < 6.35	99.30	0.54	68.53	4.99	70.13	1.56
% < 4.75	95.53	2.53	60.57	3.96	61.33	2.74
% < 2.36	72.23	2.26	44.93	6.20	42.17	6.09
% < 2	67.70	2.47	42.30	7.17	38.90	6.56
% < 1.18	48.97	2.50	30.17	7.86	28.37	7.36
% < 0.85	36.63	2.32	23.67	7.70	23.23	7.35
% < 0.6	30.07	1.44	19.10	7.18	20.27	7.34
% < 0.425	23.07	1.02	15.83	6.49	17.70	7.10
% < 0.3	16.80	0.70	12.30	6.03	15.47	6.68
% < 0.177	10.67	0.53	8.37	4.46	12.73	5.95
% < 0.15	8.27	0.37	6.97	3.69	11.73	5.51
% < 0.075	4.60	0.73	2.87	1.11	8.03	3.51
% < 0.010	2.20	0.24	0.94	0.15	1.51	0.67
% < 0.005	1.92	0.25	0.79	0.12	0.96	0.56

^a BF, blast furnace; BOF, basic oxygen furnace; EAF, electric arc furnace.

Table 4 presents the results of the ASTM water leachate test and the calculated K_d values for each metal by slag type. The aqueous extraction of the metals in slag is extremely low, as noted by K_d values greater than 1000 L/kg for all metals in all slag types except hexavalent chromium (535 L/kg) and mercury (900 L/kg) in EAF slag. As part of this test, the pH of the leachate was also measured. The arithmetic mean pH of the ASTM leachate from BF slag was 11.1 s.u., and from both BOF and EAF slags, pH was 11.8 s.u.

The particle size distribution data including the arithmetic mean and standard deviation are provided in Table 5. The slag particle size distributions, for the finest slag fractions that are used commercially, are generally consistent with

sand (upper size limit of approximately 2 mm and lower size limit of 0.075 mm) (15). Slag is generally larger than silt or clay, which has an upper size limit of approximately 0.075 mm, and smaller than gravel which has a lower limit of approximately 2–5 mm (15). The larger size fractions of slag, used for example as riprap, have diameters of approximately 250 mm (approximately 10 in.).

Comparison to Background Concentrations of Metals in Soil. Background concentrations of metals in soil in the conterminous United States (12) were compared to BF, BOF, and EAF slag metal concentrations to determine which metals by slag type occur at concentrations statistically greater than background concentrations in soil (Table 6). Although slag and soil are different media, this comparison was deemed appropriate because naturally occurring levels of metals in soil are generally not considered to pose an environmental concern (14). Each slag type contained levels of certain metals in excess of background concentrations (Table 6). For BF slag, only beryllium, total chromium, manganese, molybdenum, and selenium were measured at concentrations that are statistically above background soil concentrations. For BOF slag, antimony, cadmium, total chromium, manganese, molybdenum, selenium, silver, thallium, tin, and vanadium were measured at concentrations statistically greater than background soil concentrations. EAF slag contained measured concentrations of antimony, cadmium, hexavalent and total chromium, copper, manganese, molybdenum, nickel, selenium, silver, tin, vanadium, and zinc that were statistically greater than background soil concentrations.

Hexavalent chromium was measured in 29% of the EAF slag samples but not in the BOF or BF slag samples (Table 2). Hexavalent chromium is not formed during steelmaking as steelmaking is a reducing process; rather it is produced at low concentrations (e.g., mean concentration in EAF slag of 1.2 mg/kg) as the molten slag cools under oxidizing conditions in ambient air. Concentrations of total chromium, primarily in the trivalent state, are highest in EAF slag, and for this reason, EAF slag is more likely to contain hexavalent chromium than BOF and BF slags. The levels of hexavalent

TABLE 6. Comparison of Steel Industry Slag Metal Concentrations to Metal Concentrations in U.S. Soils^a

metal	slag concentrations										
	U.S. background ^a		arithmetic mean (mg/kg)			SD (mg/kg)			above background?		
	mean (mg/kg)	SD (mg/kg)	BF	BOF	EAF	BF	BOF	EAF	BF	BOF	EAF
aluminum	70995	80376	41245	23841	35009	5781	29845	11693	no	no	no
antimony	0.67	0.66	ND	3.3	4.0	ND	2.0	3.4	ND	yes ^b	yes ^b
arsenic	7.2	6.8	1.3	ND	1.9	3.5	ND	1.1	no ^b	ND	no ^b
barium	588	520	273	75	557	67	62	285	no	no	no
beryllium	0.9	1.0	8.2	0.5	1.1	1.7	1.2	1.0	yes	ND	no
cadmium	ND	ND	ND	2.5	7.6	ND	4.1	5.9	ND	yes ^c	yes ^c
chromium	54	57	132	1271	3046	226	391	1373	yes ^d	yes	yes
chromium(VI)	ND	ND	ND	ND	1.2	ND	ND	1.6	ND	ND	yes ^e
cobalt	9.1	8.4	3.0	3.8	4.8	3.5	3.9	2.20	no	no	no
copper	25	28	5.3	30	178	6.3	24	84	no	no	yes
lead	19	13	3.6	50	28	9.1	89	43	no ^b	no	no
manganese	555	749	5527	32853	39400	4833	12321	7712	yes	yes	yes
mercury	0.09	0.10	ND	0.07	0.04	ND	0.07	0.04	ND	no ^b	no ^b
molybdenum	0.97	1.3	0.8	11	30	1.5	22	22	yes ^b	yes ^b	yes
nickel	19	19	1.4	4.9	30	0.9	2.5	47	no ^b	no	yes
selenium	555	749	3.9	15	18	1.6	7.4	5.2	yes	yes	yes
silver	ND	ND	ND	9.1	8.4	ND	23	18	ND	yes ^c	yes ^c
thallium	0.4	0.4	ND	7.2	11	ND	5.7	7.5	ND	yes ^b	yes
tin	1.3	1.3	1.6	6.5	10	0.9	5.3	5.50	no ^b	yes	yes
vanadium	81	78	54	992	513	90	318	248	no	yes	yes
zinc	60	45	20	46	165	37	39	148	no	no	Yes

^a Background concentrations from Dragun and Chiasson, 1991 (12). ^b For metals with a detection frequency less than 50%, the maximum concentration was compared to background mean plus 2 SD. ^c Assumed to be above background as this metal is rarely detected in background soils. ^d The BF test failed to determine a statistical difference from background; however, general examination of the data indicates that chromium in BF slag is elevated above background. ^e ND, this metal is rarely detected in background concentrations or not detected in slag; BF, blast furnace; BOF, basic oxygen furnace; EAF, electric arc furnace.

TABLE 7. Comparison of TCLP Slag Leachate Concentrations to TCLP Criteria^f

metal	TCLP screening criterion concn ^a (mg/L)	95% UCL TCLP leachate concn ^b			exceed criterion?		
		BF	BOF	EAF	BF	BOF	EAF
arsenic	5	0.0048 ^c	0.0054 ^c	0.011 ^c	no	no	no
barium	100	1.2 ^d	0.88	1.67 ^e	no	no	no
cadmium	1	0.0054 ^c	0.01 ^c	0.037 ^c	no	no	no
chromium(VI)	5	0.026 ^c	ND	0.018 ^c	no	no	no
chromium (total)	5	0.22 ^d	0.04	1.0 ^e	no	no	no
lead	5	ND	0.015 ^c	0.063 ^c	no	no	no
mercury	0.2	ND	0.0005 ^c	0.00089 ^c	no	no	no
selenium	1	ND	ND	0.0073 ^c	no	no	no
silver	5	ND	0.029 ^c	0.027 ^c	no	no	no

^a From Method 1311 Toxicity Characteristic Leaching Procedure (6). ^b Normal 95% UCL concentration used for comparison unless otherwise noted. ^c Maximum slag metal leachate concentration used for comparison as metal has a detection frequency less than 50%. ^d The maximum concentration was used when it was exceeded by the 95% UCL. ^e Log-normal 95 UCL used for comparison. ^f TCLP, toxicity characteristics leaching potential; BF, blast furnace; BOF, basic oxygen furnace; EAF, electric arc furnace; ND, not detected.

chromium in EAF slag are generally not considered a health concern as the concentrations of hexavalent chromium are far below USEPA health-based soil screening levels (SSLs) for oral exposures (240 mg/kg) and inhalation exposures (270 mg/kg) at residential sites (16).

The 95% UCL metal concentrations detected in the leachate of the TCLP results were compared to TCLP regulatory standards (Table 7) (6). These standards are based on the leaching of metals from a solid matrix into a drinking water source assuming 100-fold dilution (6). None of the

samples leached concentrations in excess of the TCLP standards. Exceedence of these levels would indicate that slag could be classified as "characteristically hazardous" as defined by the Resource Conservation and Recovery Act (RCRA) (40 CFR 261.24). These test results indicate that under acidic conditions (pH 2.8), the metals that are present in slag do not leach to any appreciable degree, and that steel industry slags should not be considered hazardous waste.

Discussion

The data collected through the slag characterization program may be utilized in health risk assessment to quantitatively assess the potential human and ecological health risks posed by the current uses of slag. While the data may not be used to characterize the variability of steel industry slag constituents by mill, the data variability by slag type among mills is relatively low. The low variability of metal concentrations by slag type is demonstrated by coefficients of variation less than 1 (data not shown) for all metals detected in at least 50% of samples. Because variability between mills is low, it is probable that variability within individual mills should also be low, and that the distribution of metal concentrations in slag are adequately characterized for health risk assessment.

Detection frequencies are fairly consistent for the major metal constituents of each slag type. However, for many of the minor constituents, particularly antimony, arsenic, beryllium, cadmium, hexavalent chromium, lead, mercury, molybdenum, nickel, phosphorus, silver, and tin, the detection frequency varied considerably by slag type (Table 2). For example, beryllium was measured in nearly all samples of EAF and BF slag but only in one BOF slag sample, and hexavalent chromium was measured in EAF slag but not detected in either BF or BOF slags. Because of the variability of minor metal constituents by slag type, it was determined that the potential for human and/or environmental risks should be evaluated separately by slag type (5). It is also

important to recognize for risk assessment that slag types are not likely to be mixed before application; therefore a single environmental application site is likely to have only one type of slag.

The TCLP results (Table 7) indicate that none of the slag types exceed the U.S. EPA standards for determining whether the slag is characteristically hazardous. Even the maximum concentrations for each metal and slag type measured in the TCLP analysis do not exceed leaching thresholds. These results indicate that the metals are very tightly bound and not released from the matrix, even under acidic conditions which generally render metals more mobile. This is an important consideration for human health risk assessment for two reasons. First, leachate from slag is less likely to impact groundwater above drinking water standards. Second, upon incidental ingestion of slag, only a fraction is likely to be extracted from the slag matrix by the acid conditions of the gastrointestinal tract and be available for systemic absorption. If metals in slag are not solubilized under acidic conditions (e.g. the stomach), then they should not be systemically absorbed and elicit a hazardous effect (17). Likewise, the low concentrations of metals measured in leachate from the ASTM water extraction test (Table 4) suggest that metals are not likely to be extracted under neutral conditions, such as sweat on the skin, limiting the dermal absorption of metals from slag. Thus, it is important to consider the "bioaccessibility" of metals in slag when evaluating human oral and dermal exposures in health risk assessment.

The ASTM water leachate data should be useful for assessing the potential ecological hazards associated with metals leaching from slag to surface water and the potential effects due to pH increases for slag applications into or adjacent to water bodies. The ASTM test is performed at a 20:1 water-to-slag ratio. This ratio may not be relevant to environmental conditions of dilution for leachate into surface water, which should be considered for any site-specific ecological health risk assessment.

The K_d data further demonstrate the tight binding of metals in the slag matrix under environmental conditions. A higher K_d value indicates a tighter bind of the metal to the slag. K_d values may be used to conduct site-specific leaching evaluations for groundwater modeling. Upon comparing the K_d values in Table 4 to those published by the USEPA (16), it is evident that nearly every K_d measured for slag exceeds those presented by the U.S. EPA for metals in soil. Accordingly, the potential for metals to leach from slag and migrate through environmental media is lower than from soil. It should be noted that the highest pH for soil listed by the U.S. EPA in the Soil Screening Guidance is 8 s.u., and the pH of the three slag types is approximately 11 to 12. s.u. As most of the metals investigated demonstrate increasing K_d s with increasing pH, it is not surprising that K_d values for slag are higher than K_d values for soil. Two exceptions are hexavalent chromium and selenium, both of which demonstrate decreasing K_d values with increasing pH (16). For these two metals, unlike the other metals analyzed, solubility increases with increasing pH. Nevertheless, the slag K_d values for hexavalent chromium and selenium measured in this study are still higher than the U.S. EPA's soil K_d values demonstrating the tight binding of these metals to the slag matrix regardless of the elevated pH.

Finally, an analysis of the particle size fractions indicates that, for all slag types, particles are generally larger than soil particulates. Thus, slag, as it is obtained from the mills, is less likely than soil to be suspended into ambient air and available for environmental transport and inhalation expo-

sure. This is an important characteristic for assessing potential inhalation exposure due to wind erosion of slag from land surface and suspension due to mechanical disturbances (e.g., plowing and traffic).

As slag weathers in the environment with time, it is expected to breakdown to smaller size particles increasing its potential for suspension to ambient air. However, with time many applications of slag will be ultimately covered or encapsulated (e.g., use as fill; landscape, construction, trench, or landfill aggregate), reducing the availability of slag for suspension. It should be noted that the slag sample analyses conducted for this study included an initial step where the slag was ground to fine particles. Therefore, the metal content of the slag, as reported here, is not underestimated for weathered slag of smaller size fractions and greater surface area per mass as compared to newly produced slag.

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