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REGULAR ARTICLE

Characterization of physical and chemical properties of spent foundry sands pertinent to beneficial use in manufactured soils

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Abstract As of 2007, of the 2,000 United States foundries, 93% produce ferrous or aluminum castings, generating 9.4 million tons of non-hazardous spent foundry sand (SFS) annually. Only 28% of the SFS is beneficially used. The U.S. EPA Resource Conservation Challenge identifies SFS as a priority material for beneficial use, with soil blending as a potential reuse option. The objectives of this work were to measure: (1) select chemical and physical properties important to soil quality and function and (2) total and soluble elemental content of 39 SFSs, in order to evaluate SFS suitability as a component in manufactured soils. Total elemental concentration of the SFS was lower than natural background soil levels for most elements analyzed, suggesting limited to no contamination of the virgin sand during metal casting. Pore water elemental concentrations were generally below detection. However, both total and soluble elemental content indicate a potential contribution of plant nutrients. Lettuce (*Lactuca sativa*) planted in SFS mixtures had a median germination rate of 96.9% relative to the control. Blending SFS at varying ratios with other materials will allow "tailoring" of a manufactured soil's chemical and physical properties to meet specific growing needs. The SFS organic carbon, clay, and plant nutrient content are benefits of SFS that may make them good candidates as manufactured soil components.

Keywords Beneficial use · Manufactured soil · Spent foundry sand · Foundry sand

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Introduction

For a residual material or byproduct to be considered for beneficial use as a soil amendment or component of manufactured soil it must exhibit soil-like attributes, such as plant nutrients, texture, or organic matter, which contribute to soil quality/fertility, or provide a functional benefit (e.g. acid neutralization, water retention or release). Spent foundry sands (SFSs) often demonstrate soil-like qualities making them potentially attractive components in manufactured soils and useful for enhancing soil blend physical and chemical properties (Dungan et al. 2006, 2007; Lindsay and Logan 2005; McCoy 1998). They contain plant nutrients, organic carbon, and clay and their sandy texture provides for good drainage.

According to the American Foundry Society (AFS 2007), there are approximately 2,000 foundries in the

United States, with 93% producing ferrous or aluminum castings. Ferrous and aluminum foundries use silica sand to create metal casting molds and cores. The sands are reused multiple times before the repeated exposure to molten metal and mechanical abrasion, render them unsuitable for reuse. According to a foundry industry survey, approximately 9.4 million tons of non-hazardous SFS is generated annually in the United States (AFS 2007). Of this, 28% is beneficially used in construction fill, as a component of concrete and asphalt, in road construction, and/or in soil mixes. As of 2002, 18 states had implemented programs to encourage and regulate the beneficial use of SFSs (U.S. EPA 2002). To promote the further development of and to assist in the management of state SFS reuse programs, the U.S. EPA released the *State Toolkit for Developing Beneficial Reuse Programs for Foundry Sands* (U.S. EPA 2006). This toolkit assists states in improving or developing SFS beneficial use programs. It provides examples and approaches currently being used by states that could be adopted by others and discusses options for improved efficiency. In addition, the U.S. EPA Office of Resource Conservation and Recovery (ORCR), formerly the U.S. EPA Office of Solid Waste launched the Resource Conservation Challenge (RCC) in 2002, extending resource recovery activities implemented under the Resource Conservation and Recovery Act (RCRA). Among the goals of the RCC are promoting the reuse and recycling of nonhazardous industrial materials, such as foundry sand, construction/demolition debris, slags, and coal combustion products. The expectation is that industrial materials recycling will minimize pollution of water, air and soil resources, while conserving energy and raw materials. Under the RCC, non-hazardous SFSs are identified as a priority material for beneficial use, with soil blending emphasized as a potential reuse option (U.S. EPA 2009).

Soil quality is defined as "the capacity of a soil to function, within ecosystem and land-use boundaries, to sustain biological productivity, maintain environmental quality and promote plant and animal health" (Doran and Parkin 1996). A high quality, manufactured soil suitable for use in plant production should have desirable chemical (e.g. pH, salinity, fertility) and physical (e.g. drainage, texture) properties, to promote plant health and productivity. An advantage of manufacturing soil is that component ratios, such as soil separates, organics and amendments, can be adjusted or "tailored" to obtain a soil blend with chemical and physical properties appropriate for specific uses. For example, in horticultural applications, soil mixes used for market pack containers typically contain a large percentage of organic matter to promote proper drainage under irrigated production systems. In contrast, soils used for landscaping or container mixes for trees and shrubs often contain a larger percentage of mineral components to promote nutrient and water retention and reduce erosion by wind and water. In high traffic turf applications, such as putting greens or athletic fields, large amounts of sands are commonly used in mixes to optimize water movement and reduce compressibility (McCoy 1998). McCoy (1998) found increasing sand contents, particularly in low organic matter soils, resulted in increased air-filled porosity and saturated hydraulic conductivity (K_s). Similarly, Dungan et al. (2007) assessed changes in K_s of four agricultural soils blended with up to 50% SFS and found that, except where SFS clay content was dominated by sodium bentonite, increased sand content corresponded to linear increases in K_s, particularly in loam and silty clay soils.

Soil properties such as soil organic carbon (SOC), texture, and pH are important in moderating soil function, such as plant nutrient storage and availability, and water retention and release. While SFSs contain large quantities of silica sand, many also contain carbonaceous materials such as bituminous coal, cellulosic additives or organic resin binders, as well as sodium or calcium bentonite clays (Carey 2002). These materials are added as oxidizers, to allow gases to escape during casting or to bind cores within the mold (Carey 2002). These additions contribute finer silt and clay sized particles (Carey 2002) affecting textural class and organic carbon, making SFS more soil-like.

As SFS is an industrial byproduct, it is appropriate that a beneficial use program include screening for total elemental content, soluble constituents, as well as organic contaminants. Dungan (2006) found low concentrations of organic compounds such as polycyclic aromatic hydrocarbons and phenolics in SFSs. Dioxin and dioxin-like compounds were also found in low concentrations and were comparable to natural background soil levels (Dungan et al. 2009). To date, little work has been published characterizing the elemental and physical properties of SFS that would impact its use as a plant growth media (Dungan et al. 2009; De Koff et al. 2008). The objectives of this study were to measure: (1) select chemical and physical properties and (2) total and soluble elemental content of 39 SFSs, in order to evaluate SFS suitability as a component in manufactured soils.

Materials and methods

As part of a joint effort with the USDA-ARS (project number 1265-12000-035-01), 39 SFSs were collected from foundries in 11 states throughout the eastern and central United States. Thirty one SFSs were from iron foundries, three from aluminum foundries, and five from steel foundries. All SFSs were sieved (< 2 mm) and air dried at room temperature.

The particle size distribution of the 39 SFSs was determined using the pipette method (Gee and Bauder 1986) and the textural class determined using the USDA Soil Texture Calculator (USDA-NRCS 2009). Based on the particle size distribution, the SFS bulk density (D_b) was calculated using the Saxton equation (Saxton et al. 1986; USDA-NRCS 2009). Concentrations of non-crystalline metal oxides of Al and Fe were determined using an acid ammonium oxalate extraction (McKeague and Day 1993) followed by inductively coupled plasma–atomic emission spectroscopy (ICP-AES) analysis. The pH, electrical conductivity (EC), and pore water elemental content were determined in a 1:1 soil:deionized water suspension equilibrated for 24 h. Sand pH was measured using a combination pH electrode (Thomas 1996) and salinity with a platinum-iridium alloy conductivity cell with a cell constant of 1.0 cm^{-1} (Rhodes 1996). Organic carbon content of the SFSs was determined by dry combustion following an acid pretreatment (Nelson and Sommers 1996).

Elemental content was determined by U.S. EPA method 3051a (U.S. EPA 1994), a microwave-assisted aqua regia digestion followed by ICP-AES analysis. Inductively coupled plasma-mass spectrometry (ICP-MS) was used for elements below detection by ICP-AES. Pore water elemental content was determined by ICP-AES. Both ICP-AES and ICP-MS analyses for total elemental analysis were carried out according to U.S. EPA methods 6010C and 6020A (U.S. EPA 1994). Quality control operations included analysis of a laboratory control sample (CRM 059-050; RTC Corporation, Laramie, WY, USA) with each microwave tray, pre-digestion spikes, initial calibration verification, initial calibration blank, continuing calibration verification every ten samples, continuing calibration blank every ten samples, and low limit of quantitation verification every twenty samples. All checks were within the quality control limits set forth in U.S. EPA, ILM04.0b (U.S. EPA 1999), including relative percent difference <20% for duplicate samples as well as laboratory control sample. In addition, for procedures in which certified reference materials were not available, an intra-laboratory established control sample was included to evaluate method accuracy.

To further evaluate SFS as a plant growth media, lettuce seeds *(Lactuca sativa*) were germinated, according to ASTM E1963 (2002) *Standard Guide for Conducting Terrestrial Plant Toxicity Tests*. Twenty lettuce seeds were planted in 60 g blends of 50% SFS and 50% loam soil (*w*/*w*) (Kirkland series, fine, mixed, superlative, thermic Udertic Paleustoll) and a blend of 50% silica sand and 50% Kirkland loam soil as a control (Morel 1997). After seven days the range in germination relative to the germination in the control blends was evaluated.

Results

Sand (0.05 to 2 mm) was the dominant size fraction in the 39 SFSs ranging from 76.6% to 100%, with a median of 90.3% (Table 1). Silt size particles (2 to 50 μm) ranged from 0% to 16.9%, with a median of 2.55%, while clay size particles ranged from 0% to 11.1%, with a median of 6.55% (Table 1). The texture of the SFS ranged from sand to sandy loam and the calculated bulk density ranged from 1.58 to 1.70 g cm^{-3}, with a median of 1.66 g cm^{-3} (Table 1). The non-crystalline Al (Al_{ox}) content ranged from 0.072 to 2.43 g Al kg^{-1}, with a median of 0.386 g Al kg^{-1}, while the Fe (Fe_{ox}) content ranged from 0.213 to 32.1 g Fe kg^{-1} with a median of 1.37 g kg^{-1}. These values are within the typical range (<20 g kg^{-1}) for natural temperate soils (Brady and Weil 2002). The clay/silt component of SFS suggests that SFS could contribute to the water-holding capacity of coarse horticultural soil blends (Brady and Weil 2002). The higher bulk density (Table 1) compared with typical mineral soils (1.25 g cm^{-3}, Brady and Weil 2002) suggests SFS

Table 1 Summary of physical and chemical properties for 39 spent foundry sands

	pH	EC[a] dS m^{-1}	OC[b] g kg^{-1}	Al_{ox}[c]	Fe_{ox}[c]	Sand %	Silt	Clay	D_b[d] g cm^{-3}
Minimum	6.67	0.210	2.90	0.072	0.213	76.6	0	0	1.58
Maximum	10.2	2.99	67.4	2.43	32.1	100	16.9	11.1	1.70
Median	8.76	1.47	17.2	0.386	1.37	90.3	2.55	6.55	1.66
Mean	8.63	1.44	20.0	0.421	3.73	91.2	3.32	5.53	1.64

[a] Electrical conductivity

[b] Organic carbon

[c] Acid ammonium oxalate extractable aluminum (Al) and iron (Fe)

[d] Bulk density

alone could inhibit root penetration. Though SFS bulk density is within the range of sandy loam and sandy soils (1.3 to 1.8), according to Brady and Weil (2002) root inhibition in moist soil can occur at bulk densities >1.55 g cm^{-3}. The OC content (Table 1) of the 39 SFSs, measured after acid pretreatment to remove carbonate, ranged from 2.90 to 67.4 g kg^{-1} with a median of 17.2 g kg^{-1}. The SFS OC includes

Table 2 Summary of elemental content for 39 spent foundry sands (SFS). Comparison with the range and 95th percentile of elements found in North American soils (Smith et al. 2005) and percent of measurements below detection limit (bdl). Values bdl, were treated as half of the detection limit in statistical analysis of the data

	units	Spent foundry sands					U.S. Soils[a]			bdl[b]
		Min	Max	Med	Mean	95th	Min	Max	95th	%
Al	g kg^{-1}	0.193	11.7	5.56	5.14	10.6	<6.9	87.3	74.6	0
As	mg kg^{-1}	0.126	7.79	1.05	1.70	4.11	<1.0	18.0	12.0	0
Be	mg kg^{-1}	<0.1	0.599	0.151	0.169	0.370	0.20	4.00	2.30	20.5
Ca	g kg^{-1}	0.094	4.09	1.89	1.89	3.14	0.30	236	65.6	0
Cd	mg kg^{-1}	<0.04	0.360	0.051	0.070	0.188	<0.1	5.2	0.60	33.3
Co	mg kg^{-1}	<0.5	6.62	0.880	1.26	5.89	0.90	143	17.6	28.2
Cr	mg kg^{-1}	<0.5	115	4.93	17.6	96.5	3.0	5,320	70.0	2.6
Cu	mg kg^{-1}	<0.5	137	6.22	21.2	90.1	<0.5	81.9	30.1	5.1
Fe	g kg^{-1}	1.28	64.4	4.26	9.20	55.8	3.80	87.7	41.1	0
K	g kg^{-1}	<0.05	1.78	0.330	0.390	0.710	1.20	43.6	27.9	7.7
Mg	g kg^{-1}	0.050	3.20	1.28	1.26	2.36	0.40	173	18.2	0
Mn	mg kg^{-1}	5.56	707	54.5	112	501	56.0	3,120	1,630	0
Mo	mg kg^{-1}	<1	22.9	0.500	2.98	19.9	0.11	21.0	2.16	56.4
Ni	mg kg^{-1}	1.11	117	3.46	15.0	83.5	1.60	2,314	37.5	0
P	mg kg^{-1}	5.41	96.6	50.9	51.2	82.8	80	5,220	1,160	0
Pb	mg kg^{-1}	<1	22.9	3.74	4.38	9.29	5.30	245	38.8	5.1
S	g kg^{-1}	0.025	2.04	0.591	0.620	1.34	0.05	90.8	0.80	7.7
Se	mg kg^{-1}	<0.4	0.438	0.200	0.210	0.200	<0.2	2.30	1.00	97.4
Tl	mg kg^{-1}	<0.04	0.096	0.040	0.040	0.089	<0.1	1.80	0.70	48.7
V	mg kg^{-1}	<1	11.3	2.88	3.44	9.12	7.0	380	119	5.1
Zn	mg kg^{-1}	<10	245	5.00	20.0	64.5	8.0	377	103	61.5

[a] Data from Smith et al. (2005)

[b] Percent of results for 39 SFS below detection limit

carbonaceous additions made to the molding sands (i.e. seacoal, polymers) and is within the typical range for natural soils. The pH of the 39 SFS ranged from 6.67 to 10.2, with a mean of 8.76 (Table 1). Generally satisfactory plant nutrient availability occurs between pH 5.5 to 7.0, however final blend pH should be determined based on crop production needs (Brady and Weil 2002). Typical SFS additions will likely be <30% SFS (*w/w*). Blending SFS with other organic amendments (i.e. compost, biosolids, manure) and/or soil may buffer the final blend pH, thus ameliorating potential problems associated with high pH. The final pH of the soil blend is of more concern than the pH of the individual components

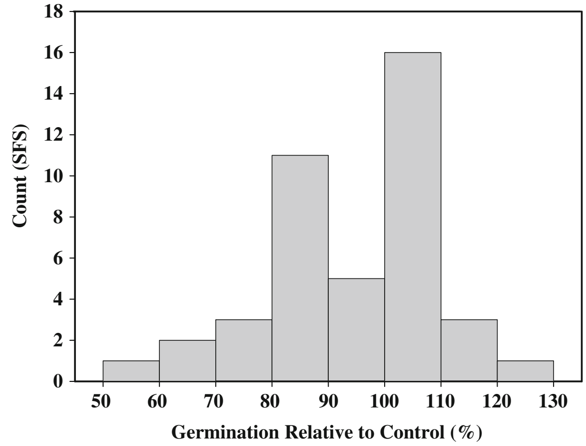

Fig. 1 Frequency distribution of the percent germination of lettuce (*Lactuca sativa*) seeds sown in soil blended with 50% spent foundry sand, relative to germination in a soil blended with 50% silica sand control

used in the blend, because every blend will need to be tailored to crop needs for pH as well as other blend attributes. The SFS salinity was generally low, ranging from 0.210 to 2.99 dS m^{-1}, with a median of 1.47 dS m^{-1} (Table 1). All SFSs had salinities below 4 dS m^{-1} the defining characteristic of saline soils (Brady and Weil 2002).

Table 3 Summary of elemental pore water content in 39 spent foundry sands (SFS) and percent of measurements below detection limit (bdl). Values bdl, were treated as half of the detection limit in statistical analysis of the data

	Minimum mg kg^{-1}	Maximum	Mean	Median	bdl[a] %
Al	<0.2	1,847	255	3.89	33.3
As	<0.02	0.162	0.045	0.024	41.0
B	0.118	42.2	1.84	0.531	0
Ba	<0.02	4.50	0.352	0.060	33.3
Be	<0.02	na[b]	na	na	100
Ca	4.37	261	49.1	32.5	0
Cd	<0.02	0.023	0.010	0.010	97.4
Co	<0.02	0.470	0.025	0.010	84.6
Cr	<0.02	0.290	0.031	0.010	82.1
Cu	<0.02	1.70	0.137	0.010	66.7
Fe	<0.02	402	55.7	1.14	35.9
K	10.6	854	53.5	27.3	0
Mg	0.464	313	48.7	13.5	0
Mn	<0.02	3.02	0.305	0.093	30.8
Mo	<0.02	1.12	0.149	0.111	17.9
Na	0.635	659	292	281	0
Ni	<0.02	2.90	0.125	0.010	59.0
P	<0.02	8.84	0.930	0.391	10.3
Pb	0.025	0.205	0.039	0.025	87.2
S	1.20	376	154	125	0
Se	<0.02	0.647	0.028	0.010	89.7
Tl	<0.02	na	na	na	100
V	<0.02	0.186	0.028	0.010	69.2
Zn	<0.02	2.25	0.295	0.045	43.6

[a] Percent of results for 39 SFS below detection limit

[b] Not applicable

Quality components of a soil blend should provide attributes to enhance plant growth such as providing plant available macro and micro nutrients. Although SFSs are not considered a primary source of fertility, they do contain plant nutrients (Table 2). The 39 SFSs evaluated had a median concentration of macro nutrients: Ca, Mg, K, P, and S of 1.89, 1.28, 0.330, 0.051 and 0.59 g kg^{-1}, respectively, and a median concentration of micro nutrients: Fe, Mn, and Cu of 4, 260, 54.5, and 6.22 mg kg^{-1}, respectively (Table 2). Although a measure of total elemental content, not bioavailability, results suggest SFS contain elements essential for plant growth. Total nutrient concentrations are comparable to those found in natural background soils (Table 2).

Total elemental content for a broad range of elements was determined to screen for potential problems that may limit SFS use in soil applications. In general, the elemental content of the SFS is similar to or lower than natural background soil levels as reported by Smith et al. (2005) for North American soils (Table 2), suggesting limited or no contamination of the sand during metal casting. It is thought much of the elemental content of SFS is due to the addition of bituminous coal, clay, and organic amendments to prepare metal casting molds (Carey 2002). Only two trace elements, Cu and Mo, occurred, in a few sands at levels outside the background range found in natural soils (Table 2). However, when SFS is used as a component in a manufactured soil it is thought the elements will not pose a problem. In a study conducted by Dungan and Dees (2007), trace elements were not accumulated by spinach, radish, or perennial ryegrass in concentrations high enough to cause harm when plants were grown in blends containing 50% (*w*/*w*) ferrous or aluminum SFS.

The SFS pore water elemental contents were low and many were below detection limits (Table 3). However, plant nutrients were evident in SFS pore water. The 39 SFS had a median soluble concentration of macro nutrients: Ca, Mg, K, P, and S of 32.5, 13.5, 27.3, 0.391 and 125 mg kg^{-1}, respectively, and a median concentration of soluble micro nutrients: B, Fe, Mn, Zn, and Mo, of 0.531, 1.14, 0.093, 0.045, and 0.111, mg kg^{-1}, respectively (Table 3). While pore water nutrient concentrations cannot be used directly as fertility measures, they do illustrate that SFS nutrients will be bioavailable. Pore water Al was elevated (> 4 mg kg^{-1}) in 17 samples and ranged from <0.2 to 1,847 mg Al kg^{-1} with a median of 3.89 mg Al kg^{-1}. However, 33.3 % of SFS pore waters were below the Al detection limit (Table 3) of 0.2 mg kg^{-1}. Given the neutral to high pH of the SFS, it is unlikely free Al^{+3} is present, but rather hydoxy or polymeric Al. It is unlikely the soluble Al found in the SFS will remain in solution once blended with other components in a soil mixture (Fuller and Richardson 1986; Kinraide 1990). However, soluble Al in finished soil blends should be evaluated to determine if potential Al phytotoxicity issues could arise.

The results of the lettuce (*Lactuca sativa*) germination study (Fig. 1) showed a range in germination relative to the control of from 56.3% to 125%, with a median of 96.9%. Eighty five percent of the SFS germination was between 80% to 120% relative to control blends (Fig. 1).

Discussion

A high quality manufactured soil suitable for plant growth should have desirable chemical (e.g. pH, salinity) and physical (e.g. drainage, texture) properties. For a residual material or byproduct to be considered for use as a soil amendment or component of a manufactured soil, it must exhibit soil-like qualities, contribute to soil quality/fertility, or provide a functional benefit (e.g. acid neutralization, water retention and release). Based on this work, SFS has potential for use as a soil amendment or a component of manufactured soils. In general, the elemental content of the 39 SFSs is similar to or lower than background soil levels. This suggests limited to no contamination of the sand during metal casting. Although the total and soluble elemental content of the SFSs were generally low, SFSs have the potential to contribute plant essential macro and micro nutrients when used in a plant growth medium. Because of its soil-like quality, blending SFS at varying rates with other materials will allow “tailoring” of manufactured soil chemical and physical properties to meet specific growing needs.

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