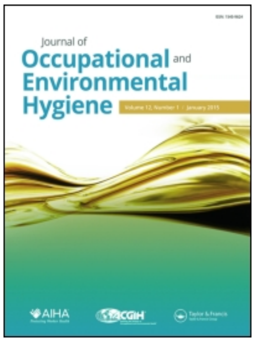


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# Elemental properties of coal slag and measured airborne exposures at two coal slag processing facilities

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**ABSTRACT**

In 1974, the National Institute for Occupational Safety and Health recommended a ban on the use of silica sand abrasives containing >1% silica due to the risk of silicosis. This gave rise to substitutes including coal slag. An Occupational Safety and Health Administration investigation in 2010 uncovered a case cluster of suspected pneumoconiosis in four former workers at a coal slag processing facility in Illinois, possibly attributable to occupational exposure to coal slag dust. This article presents the results from a National Institute for Occupational Safety and Health industrial hygiene survey at the same coal slag processing facility and a second facility. The industrial hygiene survey consisted of the collection of: (a) bulk samples of unprocessed coal slag, finished granule product, and settled dust for metals and silica; (b) full-shift area air samples for dust, metals, and crystalline silica; and (c) full-shift personal air samples for dust, metals, and crystalline silica.

Bulk samples consisted mainly of iron, manganese, titanium, and vanadium. Some samples had detectable levels of arsenic, beryllium, cadmium, and cobalt. Unprocessed coal slags from Illinois and Kentucky contained 0.43–0.48% (4,300–4,800 mg/kg) silica. Full-shift area air samples identified elevated total dust levels in the screen (2–38 mg/m$^3$) and bag house (21 mg/m$^3$) areas. Full-shift area air samples identified beryllium, chromium, cobalt, copper, iron, nickel, manganese, and vanadium. Overall, personal air samples for total and respirable dust (0.1–6.6 mg/m$^3$ total; and 0.1–0.4 mg/m$^3$ respirable) were lower than area air samples. All full-shift personal air samples for metals and silica were below published occupational exposure limits. All bulk samples of finished product granules contained less than 1% silica, supporting the claim coal slag may present less risk for silicosis than silica sand. We note that the results presented here are solely from two coal slag processing facilities, and more in-depth air monitoring is needed to better characterize occupational exposure to coal slag dust, metals, and silica at similar facilities.

**KEYWORDS**
Abrasive substitutes; coal slag; pneumoconiosis

## Introduction

In 1974, the National Institute for Occupational Safety and Health (NIOSH) recommended a ban on the use of silica sand abrasives containing more than 1% silica due to the elevated risk of silicosis and death among workers using silica-containing abrasives.[1] The NIOSH recommended ban on silica-containing abrasives gave rise to abrasive substitutes including coal slag. Greater than 85% of total recycled coal slag in the U.S. is now used in abrasive blasting and roofing granules[2] because it is relatively inexpensive.[3] The physical properties of coal slag make it a suitable abrasive substitute for silica sand. For example, the Mohs mineral hardness of coal slag (>7) is very similar to silica quartz in their potential to fracture into smaller particle sizes.[4]

Coal slag is a recycled byproduct from coal combustion and is often viewed and marketed as "green", non-hazardous, and environmentally friendly by manufacturers.[5,6] The coal slag processing and recycling industry employs between 6,600 and 14,200 workers nationwide.[7] It should be noted that these numbers do not include temporary workers. Many coal slag processing facilities are small and employ temporary workers due to seasonal variation and demand from the construction industry.

Limited previous scientific literature has assessed the elemental properties of bulk coal slag,[8–12] but the results varied, likely due to geographic variation of

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elements in coal seams.[3] Nevertheless, bulk sample analysis from Álvarez-Ayuso and Tomás,[8] Stettler et al.,[11] and MacKay et al.[12] all identified the presence of carcinogens or suspect carcinogens and other toxic elements.

There is limited information on the pulmonary toxicity potential of coal slag exposure. Some studies of coal slag exposure have demonstrated pulmonary injury, fibrosis, and pneumoconiosis in animal (rat) models.[3,12] At times, the markers of pulmonary inflammation and fibrosis in rats exposed to coal slag even exceed responses to silica sand blasting agents.[10]

Over the last few decades, a number of studies have assessed occupational exposure to metals and particles during abrasive blasting operations with silica sand[13–19] and fewer studies have assessed occupational exposure to metals and particles during abrasive blasting with coal slag.[13,20–22] To our knowledge, only a single Occupational Safety and Health Administration (OSHA) investigation in 2010 characterized occupational exposure to dust, silica, and metals during midstream production of coal slag granules at a coal slag processing facility in Illinois.[23]

## OSHA investigation

An OSHA investigation in 2010 uncovered a case cluster of suspected pneumoconiosis in four former workers at a coal slag processing facility in Illinois. The suspected pneumoconiosis cases were considered attributable to occupational exposure to coal slag dust.[23] Medical records including medical and occupational histories, physical examinations, pulmonary function tests, chest x-ray readings, and physicians' assessments and diagnoses for three of the four former workers were obtained by an OSHA medical officer. Three of the four workers were interviewed by the medical officer and described respiratory symptoms within months to years before the end of their employment at the plant. The OSHA compliance officer on-site noted that workers entered "dusty areas," specifically screening and crushing of coal slag granules areas, of the facility with no respiratory protection. Air sampling from the investigation resulted in multiple personal total dust samples from a plant operator and maintenance workers that exceeded the OSHA permissible exposure limit (PEL) of 15 milligrams per cubic meter (mg/m$^3$). One personal respirable crystalline silica (quartz) sample from a maintenance worker exceeded the American Conference of Governmental Industrial Hygienists' (ACGIH) threshold limit value (TLV®) of 0.025 mg/m$^3$ and approached the NIOSH recommended exposure limit (REL) and new OSHA PEL of 0.050 mg/m$^3$.

In response to that OSHA investigation, OSHA required management of the coal slag processing facility to request a health hazard evaluation from NIOSH to assess the potential respiratory health hazards at their facilities. In September 2014, NIOSH performed a comprehensive industrial hygiene survey at the facility where former workers were diagnosed with pneumoconiosis (facility A) and a second facility (facility B). We present here the results of those exposure assessments. Our work expands the current limited understanding of occupational exposures to dust, silica, and metals in coal slag granule production.

## Coal slag processing

Figure 1 presents the general flow of coal slag processing in the U.S. Many slag processing facilities are located in close proximity to coal-fired power plants that utilize wet-bottom boiler systems. Wet-bottom boilers have a solid base with an orifice that periodically opens to drop the spent molten slag into quenching water. When the molten slag comes into contact with the quenching water, the rapid cooling of the slag causes it to break apart into small, glass-like pellets. The water/slag mixture is usually transported by high pressure water lines from the power plant into outdoor collection basins where it is collected and brought to the slag processing facility. Most of the processes at the slag processing facility take place in the outdoor environment, although workers may operate controls and perform administrative tasks indoors.

The processing of coal slag typically involves crushing and screening of coal slag, and storing and/or bagging of finished product granules. In addition to receiving coal slag from a neighboring power plant, unprocessed coal slag may be delivered from coal-fired power plants in other areas of the U.S. for processing.

Coal slag is initially dropped into a feed hopper that funnels material onto a conveyor belt. A series of magnets on the conveyor belt may be used to remove unwanted metals. Next, the coal slag is placed in a rotating dryer oven to remove moisture content. The coal slag then goes through a screening process that sifts oversized coal slag pieces for reprocessing through a crusher until the desired particle diameter is achieved for a specific type of product. This process may be repeated numerous times depending on the number of screens and crushers at the processing facility. The finished product granules are conveyed for bagging, warehouse storage, or directly loaded for truck or rail transport.

Job titles reported during the NIOSH industrial hygiene survey included maintenance, plant operator, plant manager, bagger, heavy equipment operator,

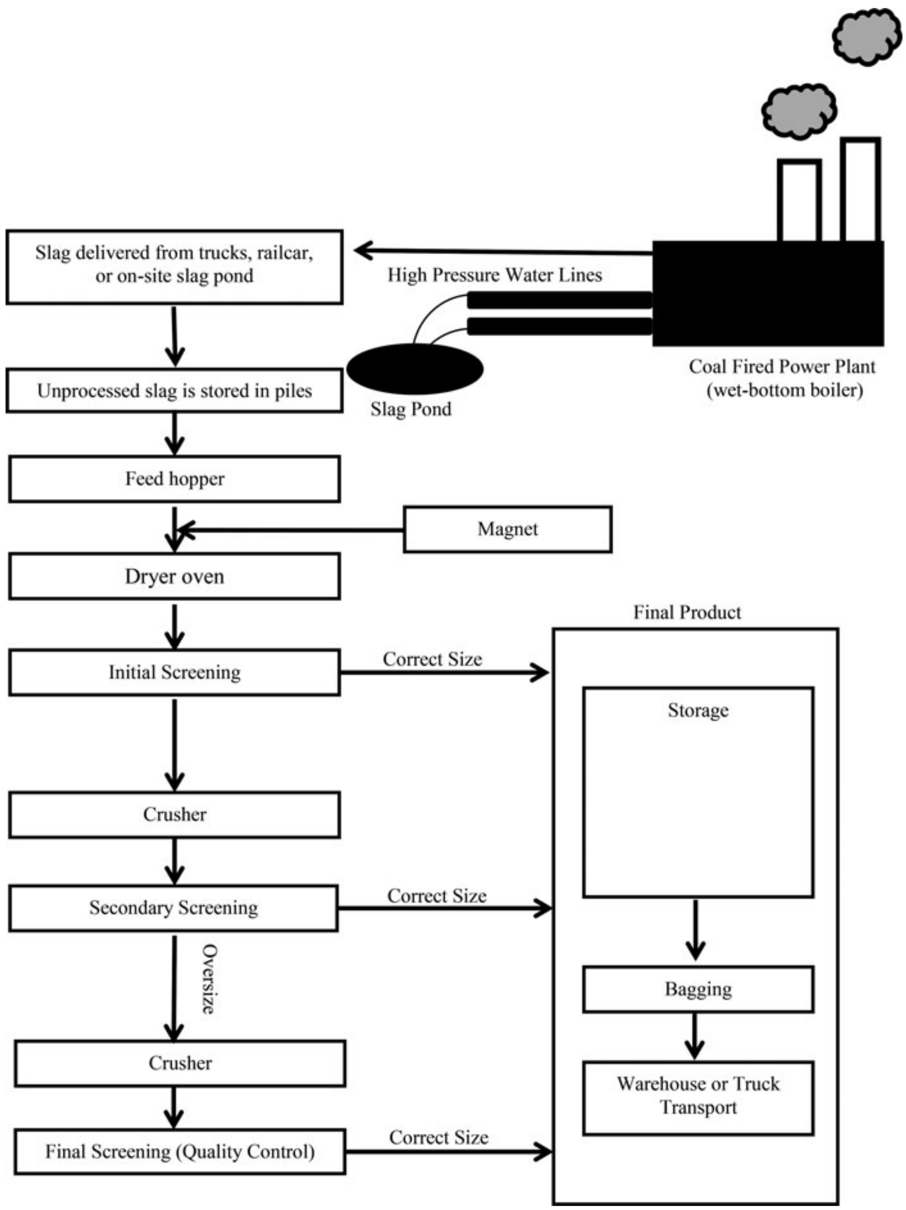


**Figure 1.** Generalized coal slag process flow diagram.

environmental health and safety (EHS) manager, and office coordinator.

## Methods

### *Industrial hygiene survey*

In September 2014, three NIOSH industrial hygienists performed a comprehensive industrial hygiene survey at two coal slag processing facilities. The survey was conducted over two days at each facility and included the collection of bulk material samples of unprocessed coal slag, finished product granules, and settled dust; and full-shift area and personal air samples for respirable and total dust, metals, and crystalline silica (quartz).

Bulk samples were collected by scooping the bulk material or settled dust into a 50-mL plastic Corning centrifuge tube while wearing nitrile gloves and excluding large solids. Bulk samples were analyzed following NIOSH Method 7500 (silica) and NIOSH Method 7303 (metals).[24] Bulk and air samples were digested and analyzed for the following metals: arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), titanium (Ti), and vanadium (V) using inductively coupled plasma atomic emission spectroscopy (ICP-AES). Platinum (Pt) was analyzed using inductively coupled plasma mass spectrometry (ICP-MS).

Full-shift personal and area respirable dust samples were collected using an aluminum cyclone (SKC, Inc.,

**Table 1.** Elemental analysis of bulk samples from two coal slag processing facilities, 2014 (mg/kg).

| Facility A | As | Be | Cd | Cr | Co | Cu | Fe | Pb | Mn | Ni | Pt | Ti | V | Quartz |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Settled Dust; Screen House; 3rd Floor | <LOD | <LOD | 1.5 | 80 | 21 | 51 | 46,000 | 14 | 280 | 66 | 0.08 | 4,000 | 130 | 18,000 |
| Settled Dust; Screen House; 2nd Floor | 20 | <LOD | 1.6 | 84 | 22 | 53 | 47,000 | <LOD | 300 | 69 | 0.07 | 4,200 | 130 | 12,000 |
| Settled Dust; Warehouse; Loading Station | <LOD | <LOD | 1.8 | 76 | 24 | 1,300 | 58,000 | 75 | 500 | 62 | 0.08 | 5,200 | 140 | 26,000 |
| Settled Dust; Warehouse; Bagging Station | <LOD | <LOD | 0.77 | 76 | 26 | 35 | 58,000 | <LOD | 450 | 50 | <LOD | 5,600 | 170 | <LOD |
| Finished Product Granule A | <LOD | <LOD | 1.1 | 76 | 29 | 51 | 59,000 | <LOD | 460 | 49 | <LOD | 7,100 | 190 | <LOD |
| Finished Product Granule B | <LOD | <LOD | 0.83 | 72 | 25 | 45 | 59,000 | <LOD | 440 | 44 | 0.07 | 5,800 | 180 | <LOD |
| Finished Product Granule C | <LOD | <LOD | 0.73 | 75 | 55 | 79 | 60,000 | <LOD | 460 | 160 | 0.04 | 6,700 | 190 | <LOD |
| Finished Product Granule D | <LOD | <LOD | 0.8 | 70 | 21 | 35 | 55,000 | <LOD | 480 | 42 | 0.06 | 4,200 | 160 | 3,400 |
| Finished Product Granule E | <LOD | <LOD | 0.9 | 78 | 28 | 47 | 60,000 | <LOD | 460 | 48 | 0.07 | 6,900 | 190 | <LOD |
| **Facility B** | **As** | **Be** | **Cd** | **Cr** | **Co** | **Cu** | **Fe** | **Pb** | **Mn** | **Ni** | **Pt** | **Ti** | **V** | **Quartz** |
| Raw Slag (IL) | <LOD | 0.26 | <LOD | 4.9 | 0.82 | 2.3 | 5,900 | <LOD | 25 | <LOD | <LOD | 92 | 5.6 | 4,600 |
| Raw Slag (KY) | <LOD | 4.1 | 0.95 | 41 | 16 | 8.1 | 61,000 | <LOD | 210 | 64 | 0.03 | 1,000 | 92 | 4,300 |
| Raw Slag (WY) | <LOD | <LOD | <LOD | 55 | 21 | 30 | 32,000 | <LOD | 150 | 36 | <LOD | 5,500 | 160 | <LOD |
| Raw Slag (IL) | <LOD | 0.22 | <LOD | <LOD | 0.93 | <LOD | 3,100 | <LOD | 9.8 | <LOD | <LOD | 44 | <LOD | 4,800 |
| Slag on Conveyor Belt | <LOD | 0.3 | <LOD | <LOD | <LOD | <LOD | 4,300 | <LOD | 17 | <LOD | 0.04 | 61 | 6.9 | 5,100 |
| Primary Magnet | 28 | <LOD | 8.4 | 93 | 340 | 320 | 520,000 | 10 | 830 | 1,400 | <LOD | 260 | 110 | 8,600 |
| Settled Dust; Bag House | <LOD | 1.7 | 1.5 | 43 | 15 | 30 | 51,000 | 16 | 200 | 100 | <LOD | 1,000 | 64 | 16,000 |
| Finished Product Granule A | <LOD | <LOD | 0.53 | 16 | 8.1 | 9 | 17,000 | <LOD | 73 | 17 | 0.02 | 1,400 | 44 | <LOD |
| Finished Product Granule B | <LOD | <LOD | 0.57 | 33 | 14 | 8.6 | 40,000 | <LOD | 150 | 35 | 0.02 | 1,900 | 72 | <LOD |
| *LOD* | *20* | *0.096* | *0.4* | *3* | *0.3* | *2* | *1.4* | *10* | *6.2* | *6* | *0.02* | *1* | *3* | *2,300* |

*Note*. arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), platinum (Pt), vanadium (V); mg/kg-milligrams per kilogram; <LOD-below the limit of detection; finished product granules vary in granule diameter and are designated by A-E.

Eighty Four, PA) with a two-piece, 37-mm cassette fitted with a polyvinyl carbonate (PVC) filter and analyzed using NIOSH Method 0600. Respirable silica was analyzed using NIOSH Method 7500. Full-shift personal and area total dust and metals samples were collected using an open-faced, 2-piece, 37-mm cassette (SKC, Inc., Eighty Four, PA) loaded with a PVC filter and analyzed using NIOSH Method 0500 and then analyzed for metals using NIOSH Method 7303.

All samplers were connected to a precision flow air sampling pump (Sensidyne, St. Petersburg, FL) set at the desired flow rate. Each sampling pump was calibrated prior to and after sampling using a high performance linear mass flow meter (TSI Inc., Shoreview, MN) to ensure flow rate accuracy.

## Results

The bulk sample results of unprocessed coal slag, finished product granules, and settled slag dust from the coal slag processing facilities are presented in Table 1. Fe was the major element identified in bulk samples. Some samples contained Mn, Ni, Ti, and V at levels above 100 milligrams per kilograms (mg/kg Be was detected in some unprocessed coal slag (0.22–4.1 mg/kg), but below the limit of detection (<LOD) in finished product granules. Unprocessed coal slag from Illinois, Kentucky, and Wyoming contained 0.43–0.48% (4,300–4,800 mg/kg) silica. Only one finished product granule bulk sample (facility A; Sample D) had detectable levels of silica (0.34%; 3,400 mg/kg). Settled dust collected from the warehouse and screen house at facility A ranged from <LOD – 2.6% (<LOD – 26,000 mg/kg) silica.

The area air sampling results are presented in Tables 2 (dust) and 3 (metals). The highest full-shift total dust

**Table 2.** Area air sampling results; total and respirable dust ($mg/m^3$) from two coal slag processing facilities, 2014.

| Facility A | Total Dust | Respirable Dust |
|---|---|---|
| Bagging Station (Indoor) | 0.65 | 0.16 |
| Control Room (Indoor) | 0.21 | 0.06 |
| Feed Hopper (Indoor) | 0.16 | 0.02 |
| Quality Control Screen (Outdoor) | 6.63 | 0.50 |
| Screen House, 2nd Floor (Indoor) | 11.1 | 2.29 |
| Screen House, 1st Floor (Indoor) | 2.00 | 0.31 |
| **Facility B** | **Total Dust** | **Respirable Dust** |
| Baghouse (Outdoor) | 20.8 | 0.09 |
| Drying Oven (Outdoor) | 6.84 | 0.04 |
| Control Room (Indoor) | 0.09 | <LOD |
| Loading Dock (Outdoor) | <LOD | <LOD |
| Screen House (Outdoor) | 37.6 | 0.03 |
| Screen House (Indoor) | 25.1 | 0.36 |
| North of Slag Plant, Towards the Power Plant (Outdoor) - A | 0.35 | <LOD |
| North of Slag Plant, Towards the Power Plant (Outdoor) - B | <LOD | — |
| *LOD (mg/sample)* | *0.04* | *0.04* |
| *OSHA PEL*[a] | *15* | *5* |

*Note*. $mg/m^3$-miligrams per cubic meter; <LOD-below limit of detection; "—" no sample collected; [a]Note that this limit applies only to personal samples and is only listed for guidance on workplace controls. The LOD for each analyte is below its respective OSHA PEL.

**Table 3.** Area air sampling results; metals ($\mu g/m^3$) from two coal slag processing facilities, 2014.

| Location | As | Be | Cd | Cr | Co | Cu | Fe | Pb | Mn | Ni | Pt | Ti | V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Facility A | | | | | | | | | | | | | |
| Bagging Station (Indoor) | <LOD | <LOD | <LOD | 0.35 | <LOD | <LOD | 42.4 | <LOD | <LOD | <LOD | <LOD | 4.68 | 0.32 |
| Control Room (Indoor) | <LOD | <LOD | <LOD | 0.4 | <LOD | 0.6 | 11.6 | <LOD | <LOD | <LOD | <LOD | 1.08 | <LOD |
| Feed Hopper (Indoor) | <LOD | <LOD | <LOD | 0.39 | <LOD | 1.05 | 22.7 | <LOD | <LOD | <LOD | <LOD | 0.92 | <LOD |
| Quality Control Screen (Outdoor) | <LOD | <LOD | <LOD | 1.1 | <LOD | <LOD | 231 | <LOD | 1.59 | 1.27 | <LOD | 24.5 | 0.79 |
| Screen House, 2n[d] | <LOD | <LOD | <LOD | 2.9 | 0.55 | 1.33 | 785 | <LOD | 5.46 | 1.88 | <LOD | 87.0 | 2.39 |
| Screen House, 1$^{st}$ Floor (Indoor) | <LOD | <LOD | <LOD | 0.87 | <LOD | <LOD | 286 | <LOD | 2.14 | <LOD | <LOD | 34.3 | 0.87 |
| Location | As | Be | Cd | Cr | Co | Cu | Fe | Pb | Mn | Ni | Pt | Ti | V |
| Facility B | | | | | | | | | | | | | |
| Bag House (Outdoor) | <LOD | 0.03 | <LOD | 2.23 | 0.37 | 1.06 | 2,531 | <LOD | 7.74 | 2.08 | <LOD | 32.8 | 1.64 |
| Drying Oven (Outdoor) | <LOD | 0.03 | <LOD | 1.71 | 0.36 | <LOD | 1,041 | <LOD | 3.99 | <LOD | <LOD | 25.7 | 1.38 |
| Control Room (Indoor) | <LOD | <LOD | <LOD | 0.51 | <LOD | 0.67 | 17.3 | <LOD | <LOD | <LOD | <LOD | 0.59 | <LOD |
| Loading Dock (Outdoor) | <LOD | <LOD | <LOD | 0.57 | <LOD | <LOD | 7.19 | <LOD | <LOD | <LOD | <LOD | 0.16 | <LOD |
| Screen House (Outdoor) | <LOD | 0.1 | <LOD | 2.6 | 0.67 | <LOD | 2,602 | <LOD | 9.4 | 2.89 | <LOD | 60.7 | 3.18 |
| Screen House (Indoor) | <LOD | 0.11 | <LOD | 3.76 | 0.78 | 0.95 | 2,507 | <LOD | 9.69 | 3.53 | <LOD | 44.5 | 3.08 |
| North of Slag Plant, Towards the Power Plant (Outdoor) | <LOD | <LOD | <LOD | 0.41 | <LOD | <LOD | 44.2 | <LOD | <LOD | <LOD | <LOD | 1.47 | <LOD |
| *LOD ($\mu g$/sample)* | *1* | *0.01* | *0.06* | *0.2* | *0.06* | *0.5* | *0.6* | *0.8* | *0.09* | *0.8* | *0.001* | *0.1* | *0.3* |
| *OSHA PEL[a]* | *10* | *2* | *5* | *1,000* | *100* | *100* | *10,00[b]* | *50* | *5,000[c]* | *1,000* | *NA* | *15,000* | *500[cd]* |

*Note.* arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), platinum (Pt), vanadium (V); $\mu g/m^3$-micrograms per cubic meter; [a]Note that this limit applies only to personal samples and is only listed for guidance on workplace controls. The LOD for each analyte is below its respective OSHA PEL; [b] iron oxide; [c] ceiling [d] respirable fraction; NA-no applicable OSHA PEL.

area air samples were observed outside the screen house (facility B: 38 mg/m$^3$), inside the screen house (facility A: 11 and 2 mg/m$^3$; facility B: 25 mg/m$^3$), outside the bag house (facility B: 21 mg/m$^3$), and outside the quality control screen area (facility A: 6.6 mg/m$^3$). The highest full-shift respirable dust area air samples were located inside the screen house (facility A: 2.29 mg/m$^3$; facility B: 0.36 mg/m$^3$) and outside the quality control screen area (facility A: 0.50 mg/m$^3$). Cr, Fe, and Ti were identified in all area sample locations. At facility A, measurable levels Co, Cu, Mn, Ni, and V were observed in the screen house, second floor. At facility B, measurable air levels of Be, Co, Mn, and V were observed outside the bag house, near the drying oven, and inside and outside the screen house. Most metals were <LOD in other area sample locations. Detectable levels of silica were measured inside the screen house at facility A (0.005 mg/m$^3$), however all other area sample locations were <LOD (silica data not shown in Table 2).

The personal air sampling results are presented in Tables 4 (dust) and 5 (metals). The highest total dust levels were measured on two baggers (6.56 and 1.98 mg/m$^3$), an office coordinator (1.26 mg/m$^3$), and a plant operator (1.14 mg/m$^3$). Overall, personal respirable dust levels were low, with all samples <0.5 mg/m$^3$. The highest respirable dust levels were measured on a maintenance worker (0.37 mg/m$^3$) and a bagger (0.14 mg/m$^3$). Full-shift TWA results of As, Be, Cd, Co, Pb, Ni, Pt, and silica were <LOD and below applicable OSHA PELs. The highest personal metal exposures were to Fe. However, no Fe exposures exceeded the OSHA PEL of 10,000 micrograms per cubic meter ($\mu g/m^3$). Cr, Mn, Ti, and V were all present in personal air samples, but below their applicable OSHA PELs.

**Table 4.** Personal air sampling results by job title; total and respirable dust (mg/m$^3$) from two coal slag processing facilities, 2014.

| Job Title | Dust: Total (mg/m$^3$) | Dust: Respirable (mg/m$^3$) |
|---|---|---|
| Maintenance | — | 0.08 |
| Maintenance | — | 0.37 |
| Maintenance | — | 0.12 |
| Maintenance | 0.34 | <LOD |
| Plant operator | 1.14 | 0.07 |
| Plant operator | 0.21 | <LOD |
| Plant manager | 0.27 | — |
| Plant manager | 0.12 | — |
| Bagger | 1.97 | 0.14 |
| Bagger | 6.56 | — |
| Heavy equipment operator | 0.34 | <LOD |
| Heavy equipment operator | 0.30 | <LOD |
| EHS manager | 0.62 | 0.06 |
| EHS manager | 0.22 | <LOD |
| Office coordinator | 1.26 | <LOD |
| *LOD (mg/samples)* | *0.04* | *0.04* |
| *OSHA PEL* | *15* | *5* |

*Note.* mg/m$^3$-miligrams per cubic meter; <LOD-below limit of detection; "—" no sample collected. The LOD for each analyte is below its respective OSHA PEL.

## Discussion

The collection of bulk samples was done to investigate if potentially hazardous materials are present in the coal slag that may contribute to lung disease. The bulk

**Table 5.** Personal air sampling results by job title; metals (μg/m$^3$) in total dust from two coal slag processing facilities, 2014.

| Job Title | As | Be | Cd | Cr | Co | Cu | Fe | Pb | Mn | Ni | Pt | Ti | V |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maintenance Worker | <LOD | <LOD | <LOD | 0.28 | <LOD | <LOD | 39.14 | <LOD | <LOD | <LOD | <LOD | 1.39 | <LOD |
| Plant Operator | <LOD | <LOD | <LOD | 0.7 | <LOD | 1.18 | 83.99 | <LOD | 0.93 | <LOD | <LOD | 13.14 | 0.51 |
| Plant Operator | <LOD | <LOD | <LOD | 0.95 | <LOD | 3.49 | 134.12 | <LOD | <LOD | <LOD | <LOD | 2.57 | <LOD |
| Plant Manager | <LOD | <LOD | <LOD | 0.64 | <LOD | <LOD | 22.79 | <LOD | <LOD | <LOD | <LOD | 0.85 | <LOD |
| Plant Manager | <LOD | <LOD | <LOD | 0.4 | <LOD | <LOD | 13.8 | <LOD | <LOD | <LOD | <LOD | 1.28 | <LOD |
| Bagger | <LOD | <LOD | <LOD | 0.9 | <LOD | <LOD | 155.14 | <LOD | 1.1 | <LOD | <LOD | 18.34 | 0.58 |
| Bagger | <LOD | <LOD | <LOD | 1.44 | <LOD | <LOD | 568.34 | <LOD | 3.93 | <LOD | <LOD | 59.02 | 1.68 |
| Heavy Equipment Operator | <LOD | <LOD | <LOD | 0.64 | <LOD | <LOD | 21.36 | <LOD | <LOD | <LOD | <LOD | 1.31 | <LOD |
| Heavy Equipment Operator | <LOD | <LOD | <LOD | 0.72 | <LOD | <LOD | 26.28 | <LOD | <LOD | <LOD | <LOD | 2.63 | <LOD |
| EHS Manager | <LOD | <LOD | <LOD | 0.47 | <LOD | <LOD | 20.27 | <LOD | <LOD | <LOD | <LOD | 5.03 | <LOD |
| EHS Manager | <LOD | <LOD | <LOD | 0.71 | <LOD | <LOD | 44.85 | <LOD | <LOD | <LOD | <LOD | 0.66 | <LOD |
| Office Coordinator | <LOD | <LOD | <LOD | 0.55 | <LOD | <LOD | 57.76 | <LOD | <LOD | <LOD | <LOD | 4.57 | <LOD |
| *LOD (μg/sample)* | *1* | *0.01* | *0.06* | *0.2* | *0.06* | *0.5* | *0.6* | *0.8* | *0.09* | *0.8* | *0.001* | *0.1* | *0.3* |
| *PEL* | *10* | *2* | *5* | *1,000* | *100* | *100* | *10,000*[a] | *50* | *5,000*[b] | *1,000* | *NA* | *15,000* | *500*[b,c] |

*Note*. Arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), platinum (Pt), vanadium (V); <LOD-below limit of detection. The LOD for each analyte is below its respective OSHA PEL; [a]iron oxide; [b]ceiling; [c]respirable fraction; NA-no applicable OSHA PEL.

samples collected in this study yielded different amounts of silica and metals. Interestingly, bulk samples from different regions of the country presented slightly different results. For example, unprocessed coal slag from Illinois and Kentucky yielded detectable amounts of silica, whereas unprocessed coal slag from Wyoming was <LOD for silica. Regional differences in geology and coal formation may explain this variability.[11,25] We observed that bulk samples of finished product granules contained less than 1% (10,000 mg/kg) silica. The small amounts of silica observed in the bulk samples support the claim that coal slag abrasives reduce silica exposure compared to silica sand and may reduce the risk of silicosis during blasting operations.

Personal air sampling results for dust and silica were much lower than previous OSHA air sampling results—particularly in plant operators and maintenance workers.[23] Although the OSHA investigation in 2010 resulted in several airborne measurements above the PEL for total dust, measurements from our surveys were all well below the OSHA PEL for total dust. We observed all personal samples with air levels of total dust below 2 mg/m$^3$ with the exception of one sample collected on a bagger (6.56 mg/m$^3$). Elevated levels of dust for the bagger may be due to the use of compressed air to seal the bag during bagging and its potential to make dust become airborne. The lower worker exposures to total dust observed in our survey were likely due to changes in operational procedures after the OSHA investigation. These changes included restricting workers from entering the screen house during operation and performing maintenance checks before start-up.

Although personal air samples were generally low, specific work areas were identified to have elevated levels of dust and metals. Total dust area air samples exceeded the OSHA PEL inside the screen house at both facilities and by the bag house of facility A. OSHA PELs are specified for personal samples, and area samples cannot be used for enforcement. However, the area sample results suggest that the screen house and bag house are areas with potential for high dust personal exposures and may be a source of exposure at other similar facilities. The screen house contained a series of screens and crushers that generated visible dust during operation and resulted in measurable airborne levels of Be, Cr, Co, Cu, Fe, Mn, Ni, Ti, and V. Fe was measured in all area samples, and highest in samples collected at the screen house and bag house. Iron oxide exposure is associate with "siderosis", a type of pneumoconiosis which is usually not fibrotic.[26] Exposure to both iron oxide and silica or silicates is associated with mixed dust pneumoconiosis (MDP) or "siderosilicosis." The OSHA investigators suggested the cases of pneumoconiosis at Facility A were consistent with siderosilicosis or MDP.[23]

Our findings may have implications for other similar coal slag processing facilities. In addition, the case cluster of pneumoconiosis discovered during the facility's OSHA inspection suggests that workers at similar facilities may be at risk for lung disease associated with coal slag dust. Workers involved in tasks near high risk areas (e.g., screen house and bag house) may be exposed to elevated levels of metal or silica containing dust that may contribute to potential coal slag dust related lung diseases. Additional personal and area air monitoring is needed to accurately characterize airborne exposures at similar coal slag processing facilities, with special attention given to high risk areas. In addition, ongoing health surveillance of workers who process or use coal slag is needed to better characterize the risk of lung disease in this industry. Regional variations in coal content suggest bulk sample analysis should be conducted routinely to further assess regional differences in geology and coal formation.

It is important to note that coal slag is not the only substitute in use since NIOSH's recommended ban on silica sand abrasives containing > 1% silica. Occupational exposure to other slag abrasives, such as copper slag, have not been well characterized, but may present similar risks during processing. Copper slag is a byproduct of smelting operations and processed in similar fashion to coal slag. Previous studies have assessed the elemental composition of bulk copper slag[11,12,27] and identified the presence of carcinogens or suspect carcinogens and other toxic elements. Thus, exposures during the processing of copper slag also warrant investigation.

## Limitations

There are several limitations to our investigation. The scope of our survey was limited to only two coal slag processing facilities. During the time of the investigation, the company changed operations procedures that likely reduced worker exposure, which may have underestimated exposure when compared to similar facilities. There are also sample analysis limitations to take into consideration. The sample preparation technique used (spectroscopy) may not have been capable of completely digesting all chemical forms and sizes of analyte-containing particles to their dissolved form to yield accurate determinations of elemental mass levels. In addition, complete digestion followed by analysis using spectroscopy is only capable of determining the total mass levels in a sample and is unable to identify chemical form, which is biologically relevant.

## Conclusion

Results from this study contribute to the limited understanding of potential occupational exposure to dust, metals and silica at coal slag processing facilities. Harmful metals were identified in bulk samples of coal slag, however, we did not observe high levels of metals in full-shift area and personal air samples. Low levels of worker exposure to dust and silica were likely due to administrative controls that were implemented after the OSHA investigation. The regional variability observed in the bulk samples of coal slag in our survey suggest that additional bulk analysis should be conducted from other coal slags to further assess regional differences in geology and coal formation.

We observed risk for high exposures to total dust in the screen house and bag house. Because screening and crushing are critical steps in producing size specific granules and are used widely in coal slag production, workers at other processing facilities may be exposed to elevated dust and metal levels if exposure levels are not mitigated with engineering and/or administrative controls.

Further investigation is needed to better understand occupational exposures in this industry. Additional exposure monitoring and health surveillance among workers that process coal slag abrasives will help expand the limited understanding of occupational exposures and health outcomes.

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## Disclaimer

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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