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Appendix 3

Human Health Risk Screening for Metals and Metalloids: Phosphogypsum in Road Construction

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Appendix 3 – Human Health Risk Screening for Metals and Metalloids: Phosphogypsum in Road Construction

Introduction

The Petitioners are pursuing reuse of phosphogypsum (PG) in road construction as an alternative to the current practice of stacking. As part of this request, a radiological risk assessment is required[1] and has been completed to evaluate potential public health impacts and demonstrate that the reuse is as safe as stacking. The radiological risk assessment (provided in Appendix 2) was completed with input and oversight from the U.S. Environmental Protection Agency (EPA) Office of Radiation and Indoor Air (ORIA) to evaluate radiological aspects of PG reuse, which, therefore, are not part of this chemical screening assessment. The radiological risk assessment is comprehensive, including multiple reuse scenarios.

Natural materials in PG contain low levels of radioactivity and contain various metals and metalloids. A chemical risk screening was conducted as described herein to evaluate potential risks of metals/metalloids in PG to supplement the radiological risk assessment. EPA's PG reuse guidance (ECRI 2005) requests information on "other toxic or hazardous constituents of the waste" and analyses to "assure that the proposed use does not cause non-radiological risks to human health and the environment."

The risk screening used the following four-step approach:

1. Develop an appropriately (reasonably) conservative screening scenario
2. Select health-protective and conservative screening levels
3. Screen PG data
4. Evaluate screening results.

Evaluation (step 4) included assessing PG concentrations of metals/metalloids in the context of average soil values within the United States. This risk screening employs

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[1] Required to demonstrate compliance with National Emission Standards for Hazardous Air Pollutants (NESHAP); promulgated in 1989.

generic EPA screening levels based on reasonably conservative assumptions to provide a reasonable upper-bound estimate of potential risk, as an initial evaluation of the composition of the PG. The risk screening does not constitute a risk assessment and exceedances of conservative risk screening levels should not be interpreted as unacceptable risks.

An evaluation of the leaching potential of metals/metalloids in PG and a comparison to other road construction materials was completed as part of this assessment. The constructed roadway will be paved, and if PG is mixed into the cement, it will be encapsulated. Given this, potential residential exposure pathways were determined to be incomplete (i.e., no exposure) and so were not included in this risk screening. Studies indicate that for the petitioned PG reuse in road construction, leaching to groundwater (or surface water) is likely not a complete exposure pathway of concern.[2] Paving limits water contact of PG isolated within the base layer placed above the water table.

Risk Screening Scenario

A conceptual site model (CSM) was developed in the radiological risk assessment, which included five exposure scenarios. The risk assessment found that the highest incremental dose and risk identified for the exposure scenarios considered was to the road construction worker. To utilize a conservative approach in the metals screening assessment, the exposure scenario with the highest risk (i.e., the road construction worker) was selected for the risk screening scenario. The construction worker screening scenario considered exposure to PG via three routes including incidental ingestion, dermal contact, and inhalation.

The proposed PG reuse in road construction involves mixing PG with soil and compacting to create road base with placement above the water table and paving with or without PG mixed into concrete cement. There are four basic layers in roadway construction, which are, from bottom to

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[2] A complete exposure pathway has four components: 1) a source and mechanism of constituent release to the environment; 2) an environmental transport medium for the released constituent; 3) a point of potential contact with the impacted medium (i.e., the exposure point), and 4) an exposure route at the exposure point. Exposure occurs when released constituents are transported to and contact a receptor. Without exposure, there is no risk.

top: embankment/foundation, subgrade, road base, and paving (i.e., concrete). These layers are illustrated in Figure 1 at the end of this memo. The specific use of PG for road construction is within the road base and/or pavement. PG is mixed in the road base (at or less than 50%) with soil or other materials such as sand and aggregates. Road base is a supporting layer of compacted material approximately 0.25 m in thickness[3] beneath the pavement and above the subgrade. It serves to provide resiliency to the road. PG may also be used in a smaller fraction (approximately 2.25%) in the paving. The surface paving serves to isolate the compacted base layer from the environment. This eliminates direct contact with the road base material once the road is paved and limits water contact of PG within the base layer.

Leaching to groundwater (or surface water) is likely not a complete exposure pathway for the petitioned PG reuse in road construction. This is because roadways are sloped to drain precipitation and paving will act as a barrier to infiltration through the compacted road base beneath. Despite this, literature regarding leaching and water quality was evaluated as part of this screening assessment (see the section titled "Leaching and Water Quality").

PG Composition Dataset

A comprehensive literature review was conducted to develop an understanding of the non-radiological composition of PG. PG concentration data were assembled from four domestic and one international study; concentrations from these studies are compiled in Table 1 at the end of this memo.

Florida

The U.S. Bureau of Mines studies published by May and Sweeney in 1984 were conducted to characterize PG under "a variety of conditions encountered in either processing or storage" (May and Sweeney 1984a,b). Nine stockpiles (i.e., stacks) were sampled in Florida from PG generated by two different manufacturing processes; six stacks were active and three were inactive. This published dataset provides average concentrations of trace metals measured in the stacks.

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[3] This thickness was selected for the risk analysis.

Calculated average concentrations for at least one part of the study (May and Sweeney 1984a) excluded non-detects, which results in averages that are biased high.

The Mostary (2011) study from University of Florida characterized PG from a stack in Mulberry, Florida. The published dataset provides multiple analyses, including total metals results for samples collected from the top of one stack at four walls.

Idaho

The Luther et al. (1993) study at University of Alberta characterized PG from a decommissioned plant in Southern Alberta that used beneficiated ore from southeastern Idaho. The published dataset presents maximum concentrations of trace metals measured in PG originating from Idaho phosphate rock.

Louisiana

The Taha et al. (1992) South Dakota State University and Louisiana State University study was a joint research program for evaluating PG use as a road base and included two engineering companies. The published dataset is a range of trace metals concentrations measured in Louisiana PG.

International

International PG data were collected and published by the International Atomic Energy Agency (IAEA) in 2013 (IAEA 2013). The IAEA published a dataset of reported minimum and maximum concentrations of trace metals in PG generated in the United States and worldwide.

EPA Screening Levels

The road construction worker scenario was evaluated for incidental ingestion, dermal contact and dust inhalation of PG using EPA's generic Regional Screening Levels (RSLs)[4] published for "composite worker" exposure to soil, which is defined by EPA as follows:

> *This is a long-term receptor exposed during the work day who is a full-time employee working on-site and spends most of the workday conducting maintenance activities outdoors. The activities for this receptor (e.g., moderate digging, landscaping) typically involve on-site exposure to surface soils. The composite worker is expected to have an elevated soil ingestion rate (100 mg per day) and is assumed to be exposed to contaminants via the following pathways: incidental ingestion of soil, dermal contact with soil, inhalation of volatiles and fugitive dust. The composite worker combines the most protective exposure assumptions of the outdoor and indoor workers. The only difference between the outdoor worker and the composite worker is that the composite worker uses the more protective exposure frequency of 250 days/year from the indoor worker scenario* (U.S. EPA 2019).

EPA's generic composite worker RSLs based on either a hazard quotient of 1 for non-cancer effects or a lifetime cancer risk of 1×10^{-6} to address cancer were used as a starting point to perform the human health screening assessment. Non-cancer-based screening levels were used as published by EPA. A simple adjustment was made to the carcinogenic screening levels. The cancer-based RSLs were adjusted from a lifetime cancer risk of 1×10^{-6} to 1×10^{-4} to be in the same range as EPA's cancer risk management level for PG use while maintaining the conservative nature of the exposure assumptions used to develop the screening levels. The lowest RSL (i.e., cancer or non-cancer-based) was selected for metals with cancer and non-cancer effects. The exposure parameter assumptions used by EPA to develop the generic composite worker RSLs are conservative.

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[4] https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables

All road construction materials, including PG, have varying chemical compositions and are used routinely by construction workers. Exposures may be absent or minimized through normal controls and best management practices (BMPs) such as wetting the construction area to prevent dust formation.

Average Soil Concentrations

The highest concentration of each element found in PG from the literature review was compared against the average surface soil (0–5 cm) concentration in the coterminous United States published by the U.S. Geological Service (USGS; Smith et al. 2013). This methodology is a very conservative screening approach since it compares maximum PG values to average soil values. For the elements boron, neodymium, ytterbium, and zirconium, where no data were available from Smith et al. (2013), average surface soil (up to 20 cm in depth) concentrations were taken from a previous USGS dataset (Shacklette and Boerngen 1984). For some rare earth elements (dysprosium, erbium, europium, gadolinium, lutetium, and samarium) without reported values in either Smith et al. (2013) or Shacklette and Boerngen (1984), the highest average concentration was gathered from a review by Tyler (2004). These average United States soil concentrations are summarized in Table 1. The chemical composition of PG is directly related to the mined phosphate ore used to manufacture phosphoric acid. Therefore, the concentration of many of the metals and metalloids in PG are similar to or below these average United States levels (e.g., aluminum, barium, iron, potassium, magnesium, manganese, lead, zirconium, and others), while some of these background constituents are concentrated in the manufacturing process and are higher in concentration in the PG.

Risk Screening

The highest published metals concentrations in PG for the United States and international studies discussed above were screened against the EPA RSLs for a composite worker. Only two metals, lanthanum (La) and zirconium (Zr), exceeded their risk-based composite worker RSLs in PG from some but not all sources in the literature reviewed. To put these maximum concentrations in perspective, both metals were then screened against average concentrations of these analytes in surface soils data published by the USGS (Shacklette and Boerngen 1984). Of these two metals, only La exceeded the USGS average concentration in soil.[5] However, PG will be mixed with other road construction materials. As much as 50% PG will be used in road base, and approximately 2.25% will be used in paving.[6] For these mixtures, the maximum La concentrations in PG used in road base and paving are expected to be less than the conservative EPA composite worker RSLs.

Zr is the twentieth most common element in the Earth's crust (Haxel et al. 2002) and resembles titanium in its physical and chemical properties (Shahid et al. 2013). Across the conterminous United States, Zr is found at an average concentration of 180 mg/kg in surface soils (Shacklette and Boerngen 1984), which is greater than the maximum PG concentration reported in the literature reviewed. More than 140 recognized mineral species contain Zr, but zircon and baddeleyite are the main naturally occurring compounds in soil. Zr is generally regarded as immobile in soil due its low water solubility and ability to form strong complexes with many different soil components (Shahid et al. 2013).

La is one of 15 elements commonly known as rare earth elements, and it belongs to a group of elements known as "lanthanides." It occurs naturally in the earth's crust at a concentration of approximately 39 mg/kg (Tyler 2004) and in surface soils in the United States at a concentration of 26 mg/kg (Smith et al. 2013). Among the rare earth group, La is the most electropositive element and occurs uniformly as a trivalent cation (La^{3+}) in a variety of carbonates, oxides, phosphates, and silicates (Gambogi 2013). La occurs naturally in phosphate rocks (such as the source rock for fertilizer production) through binding with PO_4^{3-} anions to form the mineral rhabdophane. In general, lanthanide salts of chloride, nitrate, and perchlorate are soluble, while the hydroxide, carbonate, phosphate, and fluoride salts are insoluble (U.S. EPA 2018). The solubility of La increases under acidic conditions (Larrañaga et al. 2016). La is added to sensitive

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[5] The RSL for La was based on data from the provisional peer-reviewed threshold values (PPRTV) for soluble La; insoluble salts are expected to have considerably different toxicokinetic characteristics. It is expected that only a small portion of the PG would become soluble under environmental conditions. This makes the comparison between maximum La concentrations in PG and the RSL overly conservative due to the limited La solubility.

[6] Cement would include 15% PG, but when it is mixed to generate the concrete paving the overall proportion of PG in the mixture is reduced to about 2.25%.

surface water bodies, including lakes, as the active component in Phoslock, which is used to remove phosphate. Use of La-containing Phoslock in these sensitive areas has been studied and determined to be of "low toxicity and safe to use in all naturally-occurring environmental conditions at the recommended dosages."[7] Therefore, although La occurs naturally in phosphate rocks, and, therefore, in PG, it is handled routinely in certain products, including application by workers in sensitive areas such as lakes.

Comparison to Other Road Construction Materials

All road construction materials have some level of naturally occurring radioactive materials and metals/metalloids. This includes soils, rock, Portland cement, and reused waste materials such as fly ash. As an example, Table 2 summarizes the maximum concentrations reported in literature for PG assembled for the risk screening compared with reported median concentrations in fly ash and Portland cement. As shown in Table 2, a more comprehensive PG dataset was developed for this Petition compared with fly ash and Portland cement datasets reported to EPA to demonstrate the safety of fly ash reuse in concrete and wallboard in 2014 (U.S. EPA 2014).

Of the metals/metalloids reported in fly ash, approximately half of the median concentrations are higher than the maximum concentrations reported for PG. Aluminum and iron concentrations are approximately 16 times higher in fly ash than in PG, and other constituents such as arsenic, chromium, and manganese are slightly higher in fly ash. Boron, barium, beryllium, lead, and vanadium are between approximately 3 to 7 times higher in fly ash compared with PG. EPA has approved the beneficial reuse of fly ash, and its use as a road construction material is excluded from federal regulation. State agencies have primary responsibility for regulating beneficial reuses. Although concentrations of many metals/metalloids are lower in PG than in fly ash, the petitioned reuse of PG in road construction involves applications above the water table in a compact and/or encapsulated form (i.e., in road base and/or paving).

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[7] http://www.phoslock.eu/en/phoslock/about-phoslock/

Leaching and Water Quality

In any situation with metals in soils or sediments, leaching is largely governed by pH and environmental conditions. Metals may leach from PG under certain conditions (e.g., laboratory testing; Taha et al. 1992). Some investigators have studied the leachability of PG. For the most part, these studies show limited leaching. This includes a recent University of Florida study by Mostary (2011) with comprehensive leachability testing for PG sampled from one stack in Florida. In this study, there were no exceedances of EPA's primary drinking water standards in synthetic precipitation leaching procedure (SPLP) testing and no exceedances of Resource Conservation and Recovery Act (RCRA) toxicity characteristic leaching procedure (TCLP) limits.

Leaching is not expected to be a complete pathway of concern for the petitioned use of PG in road construction. The specific use of PG for road construction is as road base when mixed (e.g., at or less than 50%) with other materials such as soil, sand, or aggregate. As shown in Figure 1, road base is a supporting layer of material ~0.25 m in thickness beneath the pavement and above underlying soil and fill. It serves to provide resiliency to the road. PG may also be used in a smaller fraction (~2.25%) as part of the surface pavement. The design of new roads as depicted in Figure 1 affects potential for exposures by creating a degree of isolation of the base layer from the environment. This limits direct contact by the community and limits water contact of PG isolated within the base layer.

The wide-scale use and attention paid to the risks of biosolids for land application provides a point of comparison for the risks of metals in PG and associated leaching. The use of biosolids for land application is regulated under the EPA Part 503 Rule,[8] which has been adopted by states (e.g., Florida Chapter 62-640, F.A.C.). Florida had 95 permitted biosolids application sites in 2016 (FDEP 2016). The guidelines establish application limits for nine metals:[9] arsenic, cadmium, copper, lead, mercury, molybdenum, nickel, selenium, and zinc. EPA selected these

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[8] See U.S. EPA 1995 for a guide on the Part 503 Rule.

[9] EPA has amended Part 503 periodically since initial publication, including deletion of numerical standards for chromium to be land-applied (60 FR 5464, October 25, 1995).

metals for risk assessment based on an initial risk screening of all the metals that may be present. EPA then evaluated risks to human health for 14 exposure pathways (Table 6 in U.S. EPA 1995). They identified the limiting pathways (i.e., the pathway resulting in the highest exposure risk; Table 11 in U.S. EPA 1995) and associated allowable metals loadings and concentrations in biosolids (Tables 10 and 16, respectively, in U.S. EPA 1995) for continual land application. Limiting pathways determined by EPA involved direct contact or uptake in plants that are subsequently ingested as would be the case for subsistence farmers. For metals in biosolids, EPA found that leaching into groundwater or runoff into surface waters were not limiting pathways.

As described in the metals screening assessment, direct contact exposure for workers applying PG in road construction is within acceptable risk limits. With the exception of two individual cadmium values reported for international studies, the maximum metals levels in PG in mixtures for road construction are also below those set forth by EPA for biosolid application to be safe for direct contact and plant ingestion by the public. These are not complete pathways for roads, inasmuch as the PG is embedded within the road, preventing direct contact and plant ingestion by the public.

It is important to consider that EPA deemed very high allowable metals (biosolids) loadings (many with unlimited risk-based pollutant loadings) to be safe for continuous application on fields that are watered, infiltrating precipitation through the soil column, and moving into surface and ground waters. Moreover, the footprint of a road on the landscape is very small compared to agricultural lands upon which biosolids and amendments with many higher allowable metal concentrations than those in PG are permitted for continuous use. The smaller footprint and lower likelihood of leaching from a constructed road compared to an agricultural field indicates that the influence on groundwater from PG in the road is likely to be comparatively very small. PG in road base is expected to be negligible in comparison and thus can be used safely in road construction given the lower metals content in PG and the smaller footprint and confinement of the base layer above the water table.

State and Federal Road Construction Requirements

The relevant department of transportation has responsibility to ensure that a state- or federal-funded new road project can be constructed and used in a manner that is judged adequately protective of the environment. State law primarily governs groundwater and surface water protection. Road construction projects also rely on local, state, and federal environmental guidance pertaining to water quality protection.

Agencies promote sustainability and use of recycled materials in road construction. The fact that road construction materials can impact the environment has been reported by the National Academy of Science (NAS; CEIRD 2005), states (Idaho; Casey et al. 2014), and other federal agencies (U.S. Department of Agriculture; Melton and Kestler 2013). This applies to all road construction material, not just PG. States provide comprehensive design of roadways with assessment of potential impacts during and after construction and mitigating measures if warranted, regardless of the source of construction materials. The following manuals and guidance documents illustrate agency considerations in the roadway design process.

U.S. Department of Transportation, Federal Highway Administration

The U.S. Department of Transportation, Federal Highway Administration (FHWA) released guidelines for use of coal fly ash and other materials (e.g., kiln dusts) in asphalt concrete, Portland cement concrete, stabilized base, flowable fill, and embankment or fill (FHWA 2016). When the guidelines were first published in 1997, fly ash had been "successfully used as a mineral admixture in PCC for 60 years," "as a substitute mineral filler in asphalt paving mixtures for many years," and "for several decades as an embankment or structural fill material."

FHWA also issued fly ash guidance documentation specifically for highway engineers (ACAA 2003). This included discussion of design issues and consideration of potential environmental impacts.

- "Design issues. The mechanical behavior and compaction characteristics of fly ash are generally similar to those of silt. For this reason, fly ash also shares some of the difficulties that are characteristic of silt such as dusting, erosion and frost susceptibility. These difficulties can be properly addressed during the design of the embankment."

- "Environmental impacts. The trace element concentrations in many fly ashes are similar to those found in naturally occurring soils. Although the leachates of some fly ashes may contain trace element concentrations that exceed drinking water quality standards, this is also true of certain soils. State environmental regulatory agencies can guide you through applicable test procedures and water quality standards. The amount of leachate produced can be controlled by assuring adequate compaction, grading to promote surface runoff, and daily proof-rolling of the finished subgrade to impede infiltration. When construction is finished, a properly seeded soil cover will reduce infiltration. For highway embankments, the pavement may be an effective barrier to infiltration.

California Department of Transportation

The California Department of Transportation (Caltrans) Highway Design Manual (Caltrans 2018) includes discussions on controlling water pollution, testing, and availability of road construction materials and encourages use of recycled materials.

- "Control of Water Pollution. Water pollution related to the construction of highways and to the drainage of completed highways should be limited to the maximum extent practicable. This objective should be considered from the early planning, through the detailed design phase, to the end of construction of each project."
- "Materials and Geotechnical Services. The Materials unit is responsible for conducting laboratory testing, field testing, specialized field inspections, and maintaining the test method procedures for the Department. The GS [Geotechnical Services] unit provides the Districts, Structures, and

Headquarters with expertise and guidance in soil related investigations and groundwater issues"

- "Availability of Materials. The availability of suitable materials such as subbase and base materials, aggregates, binders, and cements for pavements should be considered in the selection of pavement type. The availability of commercially produced mixes and the equipment capabilities of area contractors may also influence the selection of pavement type, particularly on small widening, reconstruction or rehabilitation projects. Suitable materials that are locally available or require less energy to produce and transport to the project site should be used whenever possible."
- "Recycling. The Department encourages and seeks opportunities to utilize recycled materials in construction projects whenever such materials meet the minimum engineering standards and are economically viable. Accordingly, consideration should be given on every project to use materials recycled from existing pavements as well as other recycled materials such as scrap tires. Existing pavements can be recycled for use as subbase and base materials to be surfaced with a flexible structural surface course, or as a partial substitute for aggregate in hot mix asphalt mixes. The decision to use recycled materials should be made based on a thorough evaluation of material properties, performance experience, benefit/cost analysis, and engineering judgment."

Florida Department of Transportation

The Florida Department of Transportation (FDOT) Manual of Uniform Minimum Standards for Design, Construction and Maintenance for Streets and Highways (the Florida Greenbook; FDOT 2018). Chapter 1 of the manual includes a section (C.8) for environmental impact planning to mitigate adverse impacts in the project planning stage.

Illinois Department of Transportation

The Illinois Department of Transportation's (IDOT's) Bureau of Local Roads and Streets Manual (IDOT 2018) includes discussion of considering potential groundwater impacts from highway projects. "In the development of proposed LPA [Local Public Agency] highway projects, potential impacts to groundwater resources consideration should be given to implementing practical measures for avoiding, minimizing, and mitigating adverse project impacts to those resources, see Section 26-22 of the BDE [Bureau of Design and Environment] Manual."

Washington State Department of Transportation

The Washington State Department of Transportation (WSDOT) Use of Recycled Materials in Highway Construction document (WSDOT 1992) detailed findings of a research study on the use of recycled materials in highway construction directed by Senate Bill 5143 that investigated tires, glass, asphalt concrete, fly ash, compost, mixed plastics, and aluminum sign stock. The document discusses strategies to test and monitor use of recycled materials in road construction, product specifications, programs to demonstrate feasibility, and identification of recycled material sources and vendors. It includes evaluation with the Washington State Department of Ecology as needed and highlights "large amounts of fly ash" used in WSDOT's reconstruction of the Lacey V. Murrow Floating Bridge (i.e., concrete floating bridge crossing Lake Washington in Seattle completed in 1993) (Lwin et al. 1995).

Roadway design is comprehensive; agencies governing road construction assess construction materials, potential impacts, and if necessary, mitigating measures. Thus, all construction materials, including but not limited to PG, are addressed by the highway construction process. This decision-making is in the purview of the agencies that govern road construction.

Conclusions

A conservative human health risk screening was conducted as a first step to determine whether further risk evaluation is warranted to assess construction worker exposure to metals in PG used for road construction. The conservative risk screening demonstrates that metals levels in PG are not expected to pose an unacceptable level of health risks to construction workers using PG in roadway construction. Furthermore, proper construction practices employ BMPs such as wetting surfaces to reduce dust formation, and these measures serve to further lower exposure. Studies and the nature of the petitioned PG reuse in road construction material compacted and/or encapsulated below pavement and above the water indicate that leaching to groundwater (or surface water) is likely not a complete exposure pathway. The relevant department of transportation has responsibility to ensure that construction, using materials including PG, is conducted in a manner that is judged adequately protective of the environment.

Limitations

This document summarizes work performed to date and presents the findings resulting from this work. The findings presented herein are made to a reasonable degree of engineering and scientific certainty. Exponent reserves the right to update this document as more information becomes available.

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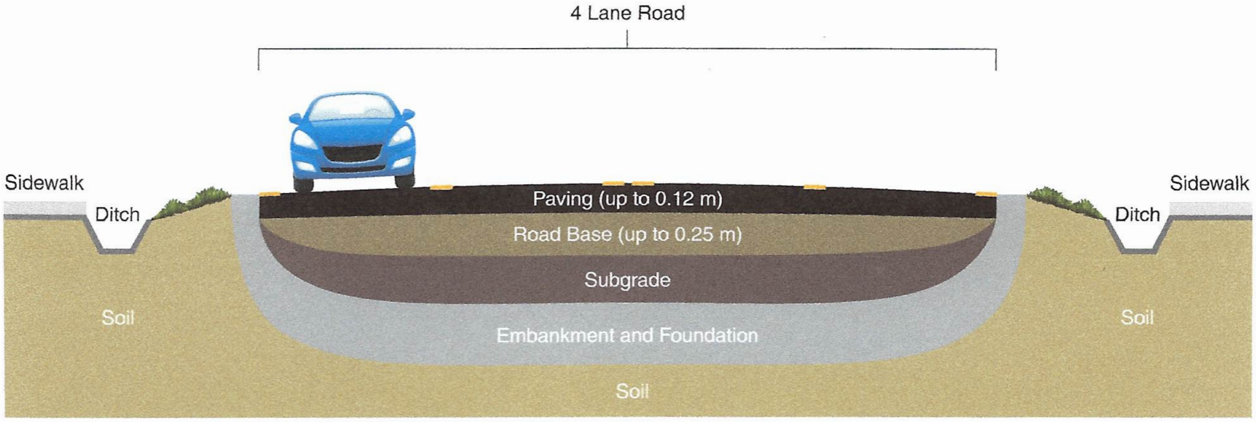

Figure 1. Typical roadway cross-section

Table 1. Concentrations of elements in phosphogypsum and comparison to EPA RSLs and U.S. soils

		Concentrations of Elements in Phosphogypsum (PG) from Literature Review														Comparison to EPA RSLs		Comparison to U.S. Soils	
		PG Stacks in Florida[a]	PG Stacks in Florida[b]	PG Stacks in Florida[c]		PG Ores from Idaho[d]			PG Produced in Louisiana[e]			PG Produced in Alberta, Canada[f]	PG for U.S. and Worldwide[g]		Max Concentration in Literature Reviewed	EPA RSL for "Composite Worker Soil"[h,i]	Does Max Element Concentration in PG Exceed EPA RSL?	Average Surficial Soil Concentrations Conterminous U.S.	Does Max Element Concentration in PG Exceed Concentration in U.S. Soils?
Symbol	Element	Average	Average	Min	Max	Average	Min	Max	Value	Min	Max	Value	Min	Max					
Ag	silver	<1	<1.3	–	–	3.6	1.2	10.7	–	0.1	0.2	–	0.4	5	10.7 [d]	5,800	No	< 1 [j]	–
Al	aluminum	1,400	2,000	625	875	–	–	–	–	–	–	5,500	–	–	5,500 [f]	1,000,000	No	45,900 [j]	–
As	arsenic	40	0.94	1.7	2.1	–	<1	2	–	1	5	–	1.0	42	42 [g]	300	No	6.4 [j]	–
Au	gold	–	0.013	–	–	0.009	0.003	0.015	–	–	–	–	–	–	0.015 [d]	–	–	–	–
B	boron	3	–	22	60	–	<10	30	–	–	–	–	–	–	60 [c]	230,000	No	33 [k]	–
Ba	barium	7	<210	30.8	48.0	50	20	140	50	–	–	–	20	236	236 [g]	220,000	No	518 [j]	–
Be	beryllium	1	–	–	–	–	1	2	–	–	–	–	–	–	2 [d]	2,300	No	1.3 [j]	–
Bi	bismuth	1	–	–	–	–	–	–	–	–	–	–	–	–	1 [a]	–	–	0.34 [j]	–
Ca	calcium	–	21,000	113,200	171,200	–	–	–	–	–	–	583,000	–	–	583,000 [f]	–	–	15,900 [j]	–
Cd	cadmium	7	–	–	–	20	9	28	–	0.3	0.4	138	0.8	40	138 [f]	980	No	0.3 [j]	–
Ce	cerium	–	49	–	–	36	31	45	–	–	–	55	21	143	143 [g]	–	–	52.1 [j]	–
Cs	cesium	–	0.07	–	–	–	–	–	–	–	–	–	–	–	0.07 [b]	–	–	<5 [j]	–
Co	cobalt	2	0.58	–	–	–	<1	1	–	–	–	120	0.05	2.3	120 [f]	350	No	8.9 [j]	–
Cr	chromium	–	6.0	1.3	1.9	–	<10	70	–	2	5	–	1.6	75	75 [g]	1,000,000	No	36 [j]	–
Cu	copper	8	<82	1.9	2.0	27.6	10.2	41.7	–	–	–	165	2	195	195 [g]	47,000	No	17.9 [j]	–
Dy	dysprosium	–	<3.5	–	–	–	–	–	–	–	–	8	–	–	8 [f]	–	–	4.5 [l]	–
Er	erbium	–	<330	–	–	–	–	–	–	–	–	8	–	–	8 [f]	–	–	3.5 [l]	–
Eu	europium	–	1.5	–	–	1.2	1.1	1.4	–	–	–	3	1.1	3	3 [f,g]	–	–	2.1 [l]	–
Gd	gadolinium	–	170	–	–	–	–	–	–	–	–	10	–	–	170 [b]	–	–	6.1 [l]	–
Ga	gallium	–	<3.0	–	–	–	–	–	–	–	–	–	–	–	<3.0 [b]	–	–	11.1 [j]	–
Fe	iron	670	1,000	615	932	–	–	–	–	–	–	1,710	–	–	1,710 [f]	820,000	No	21,400 [j]	–
Hf	hafnium	–	1.9	–	–	–	–	–	–	–	–	–	–	–	1.9 [b]	–	–	–	–
Hg	mercury	–	0.40	–	–	–	–	–	–	0.02	0.05	–	0.005	10	10 [g]	46	No	0.05 [j]	–
In	indium	–	<0.14	–	–	–	–	–	–	–	–	–	–	–	<0.14 [b]	–	–	0.04 [j]	–
K	potassium	11	230	126	187	–	–	–	–	–	–	3,970	–	–	3,970 [f]	–	–	14,600 [j]	–
La	lanthanum	–	39	–	–	80.6	69.1	89.9	–	–	–	58	42	90	90 [g]	58	**YES**	26 [j]	**YES**
Lu	lutetium	–	–	–	–	0.41	0.36	0.51	–	–	–	1	0.3	0.4	1 [f]	–	–	0.8 [l]	–
Mg	magnesium	1,200	< 940	–	–	–	–	–	–	–	–	–	–	–	1,200 [a]	–	–	5,800 [j]	–
Mn	manganese	15	25	1.7	4.2	–	<2	10	–	–	–	174	3.5	20	174 [f]	26,000	No	612 [j]	–
Mo	molybdenum	16	11	–	–	–	<1	2	–	–	–	–	1	16	16 [g]	5,800	No	1.04 [j]	–
Na	sodium	250	520	–	–	–	–	–	–	–	–	9,710	–	–	9,710 [f]	–	–	8,100 [j]	–
Nd	neodymium	–	33	–	–	36	30	46	–	–	–	46	30	67	67 [g]	–	–	46 [k]	–
Ni	nickel	2	–	–	–	9	3	15	–	–	–	–	1.7	250	250 [g]	22,000	No	17.7 [j]	–
Pb	lead	1	–	2.7	3.5	5	3	7	–	2	10	–	0.5	16	16 [g]	800	No	25.8 [j]	–
Pt	platinum	<1	–	–	–	–	–	–	–	–	–	–	–	–	<1 [a]	–	–	–	–
Rb	rubidium	–	3.2	–	–	–	<10	20	–	–	–	–	–	–	20 [d]	–	–	66.2 [j]	–
Re	rhenium	11	–	–	–	–	–	–	–	–	–	–	–	–	11 [a]	–	–	–	–
Sb	antimony	100	0.20	–	–	0.5	0.3	0.8	–	–	–	121	–	–	121 [f]	470	No	0.83 [j]	–
Sc	scandium	–	<0.40	–	–	–	–	–	–	–	–	–	–	–	<0.40 [b]	–	–	6.8 [j]	–
Se	selenium	–	2.1	–	–	20	4	67	1	–	–	–	0.5	75	75 [g]	5,800	No	0.3 [j]	–
Sm	samarium	–	–	–	–	5.4	4.7	6.3	–	–	–	22	5	13	22 [f]	–	–	8.4 [l]	–
Sn	tin	4	–	3.8	6.3	–	–	–	–	–	–	381	–	–	381 [f]	700,000	No	1.6 [j]	–
Sr	strontium	10	600	–	–	640	610	670	–	–	–	1,700	10	1,118	1,700 [f]	700,000	No	159 [j]	–
Ta	tantalum	2	0.12	–	–	–	–	–	–	–	–	–	–	–	2 [a]	–	–	–	–

Table 1. (cont.)

		Concentrations of Elements in Phosphogypsum (PG) from Literature Review														Comparison to EPA RSLs		Comparison to U.S. Soils	
		PG Stacks in Florida[a]	PG Stacks in Florida[b]	PG Stacks in Florida[c]		PG Ores from Idaho[d]			PG Produced in Louisiana[e]			PG Produced in Alberta, Canada[f]	PG for U.S. and Worldwide[g]		Max Concentration in Literature Reviewed	EPA RSL for "Composite Worker Soil"[h,i]	Does Max Element Concentration in PG Exceed EPA RSL?	Average Surficial Soil Concentrations Conterminous U.S.	Does Max Element Concentration in PG Exceed Concentration in U.S. Soils?
Symbol	Element	Average	Average	Min	Max	Average	Min	Max	Value	Min	Max	Value	Min	Max					
Tb	terbium	–	1.0	–	–	1	0.8	1.2	–	–	–	1	–	–	1.2 [d]	–	–	1.2 [l]	–
Th	thorium	–	1.9	–	–	–	1	1	–	–	–	–	0.4	4	4 [g]	–	–	8 [j]	–
Ti	titanium	4,000	440	–	–	–	–	–	–	–	–	–	26	470	4,000 [a]	–	–	2,700 [j]	–
U	uranium	–	9.6	–	–	9.4	5.5	13.3	–	5	10	–	0.5	13.8	13.8 [g]	230	No	2.1 [j]	–
V	vanadium	19	4.0	1.2	2.3	20	10	40	–	–	–	–	2	40	40 [g]	5,800	No	60 [j]	–
W	tungsten	30	<0.91	–	–	–	–	–	–	–	–	–	–	–	30 [a]	930	-	1.3 [j]	–
Y	yttrium	2	–	–	–	110	100	120	–	–	–	116	2	156	156 [g]	–	–	14.8 [j]	–
Yb	ytterbium	–	2.6	–	–	2.8	2.6	3.5	–	–	–	6	2.1	3.2	6 [f]	–	–	3.1 [k]	–
Zn	zinc	9	<340	3.1	5.3	60.0	18.1	112.0	–	–	–	112	4	315	315 [g]	350,000	No	66 [j]	–
Zr	zirconium	10	–	–	–	–	<10	110	–	–	–	–	10	110	110 [g]	93	**YES**	180 [k]	No

Note: All units are mg/kg; some values were reported in weight percent (weight percent x 10,000 ppm = mg/kg).

– - value not reported
EPA - U.S. Environmental Protection Agency
PG - phosphogypsum
RSL - regional screening level
U.S. - United States

[a] May and Sweeney (1984a), Table 11, "...the data summarized concentrations only in cores where elements were detected" (p. 137).
[b] May and Sweeney (1984b), Table 12.
[c] Mostary (2011), Table 4-1. Reported values are mean of three samples taken from each of four locations.
[d] Luther et al. (1993), Table II.
[e] Taha et al. (1992), Table 2.
[f] Walawalkar (2016), Tables 5 & 6.
[g] IAEA (2013), No. 78., Table 55.
[h] The lowest RSL is used, non-cancer or cancer, and adjusted to a target risk of 1E-04. Chemicals without published RSLs are not screened.
[i] RSL values above 1,000,000 were set to 1,000,000.
[j] Smith et al. (2013), Table 2. The mean of the surface soil samples collected from a depth of 0 to 5 cm in the conterminous United States.
[k] Shacklette and Boerngen (1984), Table 2, geometric mean.
[l] Tyler (2004), Table 1.

Table 2. Concentrations of elements in phosphogypsum, fly ash, and portland cement

Symbol	Element	Max Concentration in PG from Reviewed Literature	Median Reported Concentration in Fly Ash	Median Reported Concentration in Portland Cement
Ag	silver	**10.7**	0.55	8.6
Al	aluminum	5,500	**87,833**	26,250
As	arsenic	42	**50.1**	12.4
Au	gold	0.015	--	--
B	boron	60	**403**	42.5
Ba	barium	236	**1,189**	205
Be	beryllium	2	**10.5**	0.98
Bi	bismuth	1	--	--
Ca	calcium	583,000	--	--
Cd	cadmium	**138**	1.3	0.03
Ce	cerium	143	--	--
Cs	cesium	0.07	--	--
Co	cobalt	**120.0**	45.3	10.0
Cr	chromium	75	**107**	58.6
Cu	copper	**195**	108	36.0
Dy	dysprosium	8	--	--
Er	erbium	8	--	--
Eu	europium	3	--	--
Gd	gadolinium	170	--	--
Ga	gallium	<3.0	--	--
Fe	iron	1,710	**27,514**	N/A
Hf	hafnium	1.9	--	--
Hg	mercury	**10**	0.17	0.01
In	indium	<0.14	--	--
K	potassium	3,970	--	--
La	lanthanum	90	--	--
Lu	lutetium	1.0	--	--
Mg	magnesium	1,200	--	--
Mn	manganese	174	219	**465**
Mo	molybdenum	16	**16.3**	5.0
Na	sodium	9,710	--	--
Nd	neodymium	67	--	--
Ni	nickel	**250**	76.7	25.0
Pb	lead	16	**55.0**	6.3
Pt	platinum	<1	--	--
Rb	rubidium	20	--	--
Re	rhenium	11	--	--
Sb	antimony	**121**	6.2	0.10
Sc	scandium	<0.40	--	--
Se	selenium	**75**	8.8	2.0
Sm	samarium	22	--	--

Table 2. (cont.)

Symbol	Element	Max Concentration in PG from Reviewed Literature	Median Reported Concentration in Fly Ash	Median Reported Concentration in Portland Cement
Sn	tin	381	--	--
Sr	strontium	**1,700**	795	N/A
Ta	tantalum	2	--	--
Tb	terbium	1.2	--	--
Th	thorium	4	--	--
Ti	titanium	4,000	--	--
U	uranium	**13.8**	5.5	N/A
V	vanadium	40	**267**	64.0
W	tungsten	30	--	--
Y	yttrium	156	--	--
Yb	ytterbium	6.0	--	--
Zn	zinc	**315**	141	64.0
Zr	zirconium	110	--	--

Source: U.S. EPA (2014). Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard, Table 2.1.

Note: All units are in mg/kg.

Values in bolded text that are outlined represent the highest concentration between the maximum reported PG concentration from the literature review, the median concentration in fly ash, and/or the median concentration in Portland cement for elements that report more than one of these values.

-- - not reported
N/A - not applicable
PG - phosphogypsum