Use of Industrial By-Products in Urban Roadway Infrastructure
Argument for Increased Industrial Ecology

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- beneficial use
- industrial capital management
- industrial ecology
- life cycle assessment (LCA)
- road construction
- transportation impacts

Summary

Incorporating the beneficial use of industrial by-products into the industrial ecology of an urban region as a substitute or supplement for natural aggregate can potentially reduce life cycle impacts. This article specifically looks at the utilization of industrial by-products (IBPs) (coal ash, foundry sand, and foundry slag) as aggregate for roadway sub-base construction for the Pittsburgh, Pennsylvania, urban region. The scenarios compare the use of virgin aggregate with the use of a combination of both virgin and IBP aggregate, where the aggregate material is selected based on proximity to the construction site and allows for minimization of transportation impacts. The results indicate that the use of IBPs to supplement virgin aggregate on a regional level has the potential of reducing impacts related to energy use, global warming potential, and emissions of nitrogen oxides (NOₓ), sulfur dioxide (SO₂), carbon monoxide (CO), PM₁₀ (particulate matter—10 microns), mercury (Hg), and lead (Pb). Regional management of industrial by-products would allow for the incorporation of these materials into the industrial ecology of a region and reduce impacts from the disposal of the IBP materials and the extraction of virgin materials and minimize the impacts from transportation. The combination of reduced economic and environmental costs provides a strong argument for state transportation agencies to develop symbiotic relationships with large IBP producers in their regions to minimize impacts associated with roadway construction and maintenance—with the additional benefit of improved management of these materials.
**Introduction**

Industrial ecology proposes to see industrial systems (i.e., factories, eco-regions, or national or global economies) as not being distinct from the environment, but rather as unique types of ecosystems, based on infrastructural capital rather than on natural capital. In order for human industrial systems to be sustainable, they need to be modeled after natural systems, in which waste is all reusable. Industrial symbiosis is directly related to industrial ecology and is concerned with the flow of energy and materials through regional economies; collaboration opportunities offered by geographic proximity is important and allows the user to avoid the high costs and impacts of transportation (Chertow 2000). The by-products from one industry should be able to serve as a resource for another, ideally adjacent, industry (figure 1). Roadways are an integral part of any region’s infrastructure and in this context can be considered an industry, albeit a dispersed one. Roads are needed to move supplies and people, and, as an industry, the construction and maintenance of roadways is highly resource intensive. The demand for roadways increases in high-density regions, and with the increased roadway demand comes an increased demand for resources and a concomitant deficiency in regional natural resources to build and maintain them (Robinson et al. 2001). The most transparent impacts from roadways are due to the materials required (mining and processing), the construction, the transportation required to import materials, and the use of the roadway over its lifetime. Some impacts that are not so apparent are utilization and reduction of nonrenewable resources and end-of-life disposal. Indirectly, landfilling of industrial by-products that are not reused can also be considered an impact.

Incorporating roadways into the industrial ecology of a region requires shifting it from an open loop system that utilizes virgin resources and then disposes of them at the end of their life cycle to one that utilizes secondary materials for maintenance and reconstruction. In road construction and maintenance, some use of virgin resources may always be necessary, but the aim should be to minimize the amount required and with that the impact from their use. Utilization of industrial by-products (IBPs) helps to minimize impacts from mining and processing of virgin materials and disposal of IBPs. In addition, as industry is generally located in urban regions, the by-products are closely located to areas with higher roadway infrastructure needs, and transportation of building materials can be minimized. Different types of roadways will have different lifetimes; therefore, the type of roadway will determine how long the IBP material will potentially be in place. At this point, there does not appear to be any data to indicate that the use of IBP in

![Figure 1](image-url) Material flows within the industrial ecosystem should attempt to utilize the waste from one industry as the source material for another. Roadways can be considered an industry within the industrial ecosystem, utilizing the by-products of adjacent industries as a source material.
roadway structures reduces the longevity of the structures.

Research has been conducted to investigate not only the physical properties of secondary materials for roadway construction, but also the leaching properties (Kosson et al. 2002; Carpenter et al. 2007). Some European Union countries have maximized their utilization of recycled materials by using landfill and resource-extraction disincentives and other initiatives. The United States has more recently adopted these practices and in some regions is just beginning to utilize secondary materials for roadway construction (table 1). Without the pressures of needing to minimize landfill waste or of reduced access to virgin materials, there has not been a significant driving force to increase recycling rates further in the United States. Without regulatory incentives for beneficial use of IBPs or disincentives to landfilling in the United States, there currently is only a market-driven incentive. This means the materials will be used if the material is more readily accessible than virgin materials, if users are experienced and comfortable with handling the materials, and if the materials are proven to be safe for the environment.

By-products from road maintenance and construction have been used in road construction, and an extension of this is to generate roads from waste of other industrial processes—thereby including the construction of roads in a larger industrial ecosystem. This allows roadways to minimize their demand for natural capital (virgin materials).

This article evaluates the incorporation of roadways into a regional industrial ecosystem and compares the combined use of recycled materials (IBPs in this study) and virgin aggregate with virgin aggregate alone in the construction of the roadways. The study includes aggregate demand from not only roadways, but also from vertical infrastructure demand. In this study, the vertical infrastructure demand utilizes only virgin aggregate. A spatial analysis was conducted to simulate the use of the materials for “projects” (simulated roadway construction sites) in the closest proximity to the source and to compare the life cycle impacts as well as the transportation costs; the distribution of the vertical infrastructure demand was assumed to be the same as for the roadway demand.

Several studies are available that have utilized life cycle assessment (LCA) for roadways (Mroueh et al. 2001; Stripple 2001; Park et al. 2003; Birgisdottir 2005; Olsson et al. 2006; Carpenter et al. 2007). Mroueh and colleagues (2001) conducted an LCA of the use of industrial by-products in roadway construction. This article included the life cycle phases that were relevant to the comparison of the different materials (excluding use and maintenance of the roadway). The generation of the IBP was also excluded as the materials were considered waste and had no economic value. The impacts assessed were resource use (energy, natural materials, IBPs), air emissions (carbon dioxide [CO2], nitrogen oxide [NOx], sulfur dioxide [SO2], volatile organic compounds [VOCs], particulate matter [PM]), emissions to the ground (heavy metals, chloride, and sulphate), and other loadings (noise, dust, and land use). Stripple (2001) conducted a pilot study to compare asphalt and concrete roadways. The study included different methods of roadway construction, and low emission and normal vehicle comparisons as well as the disposal (removal or reuse of materials) of a roadway that was more than 40 years old. The impacts considered were energy use and NOx, SO2, and CO2 emissions. However, no alternative materials were considered in this study. Olsson and colleagues (2006) conducted an LCA on a roadway utilizing bottom ash as from a municipal solid waste (MSW) incinerator. The MSW ash was utilized as a replacement for aggregate in the sub-base of the roadway. The Olsson study followed the boundary guidelines recommended by Mroueh and colleagues (2001). In addition, Birgisdottir (2005) conducted an extensive LCA of roadways incorporating the use of MSW ash as an alternative material. This study assessed a range of environmental impacts (potential for global warming, acidification, nutrient enrichment, stratospheric ozone depletion, photochemical ozone formation, human toxicity, eco-toxicity, and stored eco-toxicity). These studies provide useful information on the life cycle impacts of specific lengths of different types of roadways in full construction. This article differs in that it is not connected to a specific length of roadway, but instead looks at the regional-level use of aggregates (natural or alternative) for sub-base construction in...
Table 1 Quantity and percentage of recycled material usage for roadway construction in the United States, Sweden, Germany, Denmark, and the Netherlands

<table>
<thead>
<tr>
<th>By-product</th>
<th>United States</th>
<th>Sweden</th>
<th>Germany</th>
<th>Denmark</th>
<th>The Netherlands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Reused</td>
<td>Qty reused (MMT)</td>
<td>% Reused</td>
<td>Qty reused (MMT)</td>
<td>% Reused</td>
</tr>
<tr>
<td>BFS</td>
<td>90%</td>
<td>11.40</td>
<td>45%</td>
<td>0.45</td>
<td>100%</td>
</tr>
<tr>
<td>Steel slag¹</td>
<td>67%</td>
<td>8.70</td>
<td>100%</td>
<td>0.20</td>
<td>92%</td>
</tr>
<tr>
<td>CBA</td>
<td>31%</td>
<td>4.00</td>
<td>n/a</td>
<td>n/a</td>
<td>96%</td>
</tr>
<tr>
<td>CFA</td>
<td>27%</td>
<td>13.20</td>
<td>n/a</td>
<td>n/a</td>
<td>87%</td>
</tr>
<tr>
<td>C&amp;D waste²</td>
<td>25%</td>
<td>31.00</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>MSW ash</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>69%</td>
</tr>
<tr>
<td>RAP</td>
<td>81%</td>
<td>30.00</td>
<td>95%</td>
<td>0.76</td>
<td>55%</td>
</tr>
<tr>
<td>Crushed concrete</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>81%</td>
</tr>
</tbody>
</table>

Source:¹ USA values are estimated from 2005 USGS Minerals Yearbook and American Iron and Steel Institute 2006 Statistical Report (AISI 2006).² USA values are based on USEPA estimates of 2.3 lb/day per capita (1998) and 2005 population census. Recycling rates are estimated at 20–30% by USEPA.

Note: BFS = blast furnace slag; CBA = coal bottom ash; CFA = coal fly ash; C&D = construction and demolition; MSW = municipal solid waste; RAP = recycled asphalt pavement; n/a = data not available.
roadways. The scope of the LCA is fairly narrow but allows the focus to remain on the aspect of regional management of IBP materials.

**Recycled Materials and Applications**

A wide variety of recycled materials may be used in roadway construction. Reclaimed asphalt pavement (RAP) and reclaimed concrete material (RCM) are the most widely used recycled materials. Other recycled materials used include slag, coal combustion products, foundry sand, asphalt shingles, and reclaimed concrete aggregate among a variety of other products. Their use is dependent upon their material properties and other environmental conditions. Guidelines have been developed for the use of different industrial by-products in various applications and provide information on specifications and material qualities (RMRC 2008). Although the construction material property specifications are met with the alternative materials, not all of the material properties are exactly the same; therefore, they cannot be used as direct equivalents. The use of IBPs is primarily dependent upon whether the material properties meet the material specifications (i.e., plasticity, shear strength, compaction, drainage, and durability) (USDOT 2004). Different states within the United States have different regulations concerning the type of uses allowed for industrial by-products (ASTSWMO 2007). The American Association of State Highway and Transportation Officials (AASHTO) publishes standards, specifications, and practices, some of which address the use of recycled materials (e.g., PP-056-06 Standard Practice for Evaluating the Engineering and Environmental Suitability of Recycled Materials). ASTM International also publishes standards that are specific to the determination of recycled materials properties (e.g., ASTM E2277-03 Standard Guide for Design and Construction of Coal Ash Structural Fills [ASTM 2003]). Whereas the quantity of RAP and steel and iron (BFS) slag that are recycled is high (table 1), that is not the case for other materials. This analysis considers the environmental and economic impacts from the use of slag, coal ash, and foundry sand available in the greater Pittsburgh urban region. Pennsylvania allows for the use of these industrial by-products for varying applications (ASTSWMO 2007).

**Slag**

A wide variety of slag is generated in the United States, such as steel furnace slag and iron slag (also known as blast furnace slag or BFS), which can be air-cooled, granulated, or pelletized, and lead, copper, bottom boiler, phosphorus, zinc, and foundry slag. Slag has been used in a variety of engineering applications for more than a century (NSA 2007). Some of the uses include aggregate substitution, fill material, railroad ballast, and Portland cement replacement. The optimal use depends on the type of slag (typically steel or iron slag) and the process in which it was produced. The weathering process of the slag also affects the physical properties of the slag. The USGS reports that between 19 and 26 million tonnes\(^1\) of iron and steel slag were sold or used in the United States in 2006 (van Oss 2006); however, unused portions end up being stockpiled or landfilled. In the greater Pittsburgh region alone, the Pennsylvania Department of Environmental Protection (PA DEP) recorded close to 18 million tonnes of material generated and stockpiled for disposal for 2003–2004 (PA DEP 2004).

**Coal Combustion Products**

Coal combustion produces a variety of ash products, including coal fly ash (CFA), coal bottom ash (CBA), and flue gas desulfurization (FGD) products. Approximately 64 million tonnes of CFA is produced each year in the United States, 15 million tonnes of CBA, and 2 million tonnes of boiler slag. Of this, approximately 25 million tonnes of the CFA, 7.2 million tonnes of the CBA, and 1.8 million tonnes of the boiler slag are recycled (40%, 47%, and 90% recycling rates, respectively [ACAA 2004]). The highest value use is for the high-calcium CFA, which is mostly used as an additive in Portland cement concrete. Additional uses of CFA include structural fills and embankments, stabilization of soils, flowable fill, and grouting mixtures. CBA and boiler slag may be used as road base material, structural fill material, for snow and ice control,
and as an aggregate in asphalt pavement (more frequently in base courses).

**Foundry Sands**

Foundry sand is a recyclable material from the metal casting industry. Production in the United States is approximately 5 to 9 million tonnes per year. The majority of foundry sand is composed of silica sand with smaller amounts of organic additives and binders (with bentonite being the most common binder). The majority of foundry sand in the United States comes from iron and steel casting; sands from brass, bronze, and copper foundries are generally not suitable for recycling because of their metal leaching properties. The primary use of foundry sand for construction of transportation-related facilities is for construction of embankments and structural fills. It is also suitable for use in road base applications and for the stabilization of sub-base materials. It is an excellent material for use as flowable fill aggregate and hot mix asphalt (FIRST 2006; USDOT 2004).

**Transportation Component**

The Eno Transportation Foundation has tracked trucking costs from 1960–2001 (Eno 2002). The cost per tonne-kilometer (tonne-km) in 2001 was 38.3 cents/tonne-km (44.6 cents in 2007 dollars, not accounting for increase in fuel cost). Fuel costs have increased by 45% from 2001 to 2006, which would result in an overall cost of 45.6 cents/tonne-km in 2006. IBPs are generally assumed free on board (FOB), and therefore the cost is on the generator to transport the materials to the market (or to the landfill, plus tipping fees). The market for the materials must be close enough to make it more cost effective to transport the materials to a customer than to take it to a landfill due to a lack of incentive structure for reducing disposal. Roadway infrastructures exist in all areas and could provide a beneficial use application that would be close to the point of production of the IBPs. In a regional context, municipality, city, and state governments could look to optimize the use of the IBPs in their region, thus allowing them to minimize the cost and environmental impact from the mining and extraction of virgin aggregates that would otherwise be utilized for their roadway construction, repair, and maintenance projects. Some virgin aggregate would likely still be required as the IBP generators would likely not be able to generate sufficient quantities to meet the region’s entire aggregate demand (Robinson et al. 2001). In addition, some IBPs are usable for only certain applications (i.e., Portland cement concrete) (RMRC 2008). For sub-base applications, as used in this study, depending on the supply, some regions may be able to meet all their roadway needs.

In comparing the two types of materials (virgin aggregate and IBPs), the virgin aggregate supplier would typically mine and process the aggregate and have it available at the processing site. The user would pay for the aggregate, plus transportation to the construction site. Although the economics of IBP management can vary from one region to the next and can be different for different types of IBPs, it is typical in many regions of the United States for the suppliers to provide the IBP material and transportation to the construction site (at some maximum distance) or pay to transport and dispose of the IBP at a landfill; typically, IBP users save on cost of the material as well as cost of transporting it to the construction site (RMRC 2008).

Lack of experience in the use of the IBP materials can be a deterrent as it brings uncertainty for the user. Contractors have to understand the physical properties of each of the different materials available in their region and how to handle and apply them to their projects. Use of IBPs may require different techniques during construction. In addition, lack of readily available information on the quantities and properties of IBPs being generated in a particular region prevents users from taking advantage of the potential cost-savings of the use of the IBP materials. An IBP/recycled-materials exchange for different urban regions would help to inform the market of the availability of the materials.

**Methodology**

This study looks at the relation between urban aggregate demand for vertical and horizontal infrastructure and industrial by-product availability for Pittsburgh. The 2007 Pennsylvania...
Department of Transportation (PENNDOT) aggregate demand for the Pittsburgh region was obtained (1.2 million tonnes). The Pittsburgh region (figure 2) was defined as a square block extending 80 km out from the Pittsburgh downtown (defined as the city center for this analysis). The portion of the block extending outside of the Pennsylvania state line is excluded.

Using GIS data for PENNDOT roadway systems (PENNDOT 2008), a grid was overlaid onto the Pittsburgh region and broken into twenty 32 × 32 km large blocks. Each large block was further broken down into 3.2 × 3.2 km small blocks, and the road density for each small block was calculated. The small block with the highest road density was designated as the high-density “point” for each large block. The total roadway density for each large block was also calculated, and the 2007 PENNDOT aggregate demand was allocated into each large block based on the block’s total roadway density. Locations and aggregate generation rates were found for the PENNDOT approved aggregate sources (PENNDOT 2008). Sources where the generation rates were not available were assumed to be 180,000 tonnes/year (based on quantities being generated by other sources). IBP sources were determined from the Pennsylvania Residual Waste Report (PA DEP 2004), which provided locations and quantities for residual waste generators to include generators of coal ash, foundry sand, and slag. Appropriate “sources” of aggregate were determined for each large block that minimized the required distance to transport aggregate materials from “source” to “project” (“project” is the high-density point for each large block). This was done using virgin aggregate only (PENNDOT approved sources) for one case scenario and using a combination of IBP and virgin aggregate sources together for a second case scenario. The combined IBP and virgin aggregate usage scenario allowed for the use of whichever material was closest to the “project” and thus minimized transportation requirements. A portion of the virgin aggregate was allocated for vertical infrastructure demand for each block, thus restricting it from use for roadways. This restriction forces the analysis to assume a farther transportation requirement for materials. The scope of the assessment includes extraction, processing, and production for the virgin materials, post-use processing for the IBPs, and construction for both types of materials. The extraction and initial use of the IBPs are not included because at this point they are considered a waste product with no economic value. If they were to develop an economic value then allocation of the impacts from their extraction and initial processing would need to be assessed. The life span of the different scenarios is considered to be equal as there is no current evidence to indicate a significant difference.

Incorporation of the vertical demand (residential and industrial construction—1.1 million tonnes) was based on the U.S. Census data (2002, 2006). Census payroll data for the
Pittsburgh Metropolitan Statistical Area (MSA) was available for 2006 for the construction NAICS 236 (Building Construction—vertical infrastructure) and 237 (Heavy and Civil Engineering Construction—horizontal infrastructure). Value of work for these NAICS were not available for the Pittsburgh MSA but were available on the national level for 2002. A relationship between payroll and value of work was determined based on the national level data and used to calculate value of work for the Pittsburgh MSA for NAICS 236 and 237. Horizontal construction (NAIC 237) value of work was 51.1% of the total construction value of work. This value of work was then entered into the economic input–output life cycle assessment (EIO-LCA) tool (CMU GDI 2008) and an economic output for stone quarrying was calculated for each NAIC. USGS minerals yearbook data (Ewell 2002) was used to disaggregate the stone quarrying economic output to provide just the sand and gravel (S&G) economic output. The value of construction gravel was $5.61 per tonne (Ewell 2002) and allowed for the calculation of the required tonnage of aggregate for horizontal and vertical construction.

The vertical demand impact was included in the transportation cost calculation, but impacts from the vertical demand were not used to provide environmental impacts.

The material was assumed to be used for sub-base coarse aggregate only, and all other factors (construction processes, longevity, traffic loading) in a roadway design were assumed to be the same. The construction processes for the different materials are not significantly different as the materials are required to have certain material properties to meet the roadway construction standards. At this point no evidence is available to indicate that the use of IBPs reduces the life spans of roadways. The Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) program was utilized to assess life cycle impacts for this study. The boundaries of the life cycle assessed by PaLATE include material extraction (virgin material only), material processing, transportation, and construction as illustrated in figure 3. IBP materials are currently considered a waste product, not a coproduct; therefore, the initial material generation impacts are allocated only to the initial use. The use phase is not considered relevant to this study; the disposal phase is relevant, but no data are available to be included at this point. Data for the material quantities, type, and distance transported were entered into the PaLATE program to determine differences in the LCA impacts between using virgin aggregate and IBPs in roadways on a regional level. The PaLATE program was developed by the Recycled Material Resource Center (RMRC) to assess life cycle impacts for roadways. It is a hybrid model that includes EIO data as well as process data (Horvath 2004). The model has not yet been formally validated but is the only existing model for U.S. roadways to include IBP materials. As such, it was determined to be the most appropriate tool for this assessment. The tool allows users to provide input on the specific type of roadway that is being constructed (type of materials, number, and thickness and width of wearing courses and base courses and embankments). The tool also allows the user to input information on the type of maintenance that may be performed. For the purposes of this study, the focus was on the impacts from the sub-base. The number and type of wearing courses
were assumed to be the same for both scenarios. In addition, the maintenance portion of the tool was not utilized, as the maintenance for both scenarios was also assumed to be the same. This is reasonable, as the use of IBPs is permitted in various states in the United States, and no data are currently available to indicate that the use of IBPs in the sub-base reduces the longevity of roadways. As the other parts of the roadway (embankments, wearing courses) were the same, the maintenance required for them also were assumed to be the same.

PaLATE considers materials, design parameters, equipment, maintenance, and cost inputs, and provides a full life cycle costs and environmental assessment on a semi-industrial system level (impacts from generating the recycled materials are not included) based on the U.S. Department of Commerce census data. The PaLATE analysis estimates impacts related to energy, global warming potential (GWP), emissions of carbon monoxide (CO), SO₂, NOₓ, PM₁₀, Hg, Pb, Resource Conservation and Recovery Act (RCRA) Hazardous Waste, human toxicity potential (HTP) cancer, and HTP noncancer (Horvath 2004). These impacts were selected as they were available from the EIO data. More extensive impact categories as utilized in the Birgisdottir (2005) study would be useful to provide a more comprehensive assessment; however, those inventory data are not currently available for the United States. The impacts assessed were compared for the usage of different IBPs throughout the region with the use of virgin aggregate. Person equivalents (PE) were also determined for all impacts (WRI 2007; UNSD 2004; USEPA 1999, 2005) except the HTPs (no information was available to make valid PE conversions for HTPs). Tonne-kilometers were also calculated for each case, and the transportation cost was calculated based on 45.6 cents/tonne-km (Eno 2002).

**Results**

The annual aggregate demand for the Pittsburgh region was 2.3 million tonnes, 51% of which was utilized for horizontal construction. For the mixed IBP and virgin aggregate scenario, 26% of the total aggregate demand was met by using IBP materials and the rest was using virgin aggregate.

### Table 2

Regional impact values per process (material production, material transportation, and process [equipment]), and totals for the use of virgin materials and industrial by-products in roadway sub-base construction for the greater Pittsburgh urban area.

<table>
<thead>
<tr>
<th>Impact</th>
<th>Unit</th>
<th>Virgin materials</th>
<th>Industrial by-products &amp; virgin materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mat prod</td>
<td>Mat trans</td>
</tr>
<tr>
<td>Energy</td>
<td>TJ</td>
<td>274.8</td>
<td>73.1</td>
</tr>
<tr>
<td>Water</td>
<td>Mg</td>
<td>38.3</td>
<td>12.4</td>
</tr>
<tr>
<td>GWP</td>
<td>Gg</td>
<td>19.5</td>
<td>5.5</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Mg</td>
<td>39.2</td>
<td>291.2</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>Mg</td>
<td>278.9</td>
<td>56.8</td>
</tr>
<tr>
<td>SO₂</td>
<td>Mg</td>
<td>19.1</td>
<td>17.5</td>
</tr>
<tr>
<td>CO</td>
<td>Mg</td>
<td>25.6</td>
<td>24.3</td>
</tr>
<tr>
<td>Hg</td>
<td>g</td>
<td>0.7</td>
<td>52.8</td>
</tr>
<tr>
<td>Pb</td>
<td>kg</td>
<td>5.6</td>
<td>2.5</td>
</tr>
<tr>
<td>RCRA HW</td>
<td>Mg</td>
<td>319.4</td>
<td>526.9</td>
</tr>
<tr>
<td>HTP cancer</td>
<td>million</td>
<td>33.2</td>
<td>1.6</td>
</tr>
<tr>
<td>HTP noncancer</td>
<td>billion</td>
<td>467.1</td>
<td>1.9</td>
</tr>
</tbody>
</table>

**Notes:** Mat prod = material production; Mat trans = material transportation; Proc (equip) = processing (equipment); GWP = global warming potential; RCRA HW = Resource Conservation and Recovery Act Hazardous Waste; HTP = human toxicity potential; TJ = terajoule; Mg = megagram (tonne); Gg = gigagram; g = gram; kg = kilogram.
The results from data entered into PaLATE (table 2) indicate that the use of virgin aggregates in the base course for roadway construction generates greater impacts in all the categories calculated except HTP cancer, which is about 10% greater for the combined IBP and virgin material usage than for virgin material alone. The HTP cancer impacts for the IBPs are based on the leaching potential of the materials that PaLATE has allocated to the material production process. The HTP calculations, however, are highly conservative and do not account for availability of elements for release or sorption of the contaminants in the soil layer as the leachate moves through the vadose zone (Carpenter et al. 2007).

For this study, for seven of the twelve impact categories (energy, water, GWP, PM$_{10}$, Pb, and HTP cancer and noncancer), the majority of the impacts are due to materials processing. The impact from equipment processes are minimal, ranging from 0% to 18% of the total emissions for an impact. The NO$_x$ and Hg impacts are mostly due to transportation; SO$_2$ and CO impacts are about the same for materials processing and transportation. Knowing the primary contributor can be important when trying to target certain types of impact reduction.

The PE impacts from GWP and SO$_2$, CO, and Hg emissions are depicted in figure 4. Impacts are greater in all categories for the scenario with virgin material use alone, approximately doubling the PE impacts for the combined IBP and virgin aggregate usage scenario.

The energy consumption, NO$_x$, PM$_{10}$, and Pb emissions and RCRA Hazardous Waste generation PE impacts are depicted in figure 5, ranging from 500 PEs (energy) to 7,700 PEs (RCRA Hazardous waste generation). Again, the impacts...
Figure 6  Transportation costs in millions of U.S. dollars for the use of virgin aggregate and industrial by-products in building and roadway construction for the greater Pittsburgh urban region. IBP = industrial by-product; VM = virgin material.

The transportation component of this study includes a simple cost analysis based on tonne-km. The virgin aggregate scenario requires the transportation of almost 36 million tonne-km more than the combined IBP and virgin aggregate scenario for vertical and horizontal infrastructure construction. At the adjusted transportation rate of 45.6 cents/tonne-km, this increased tonne-km requirement costs PENNDOT (and the taxpayers) almost $9 million over the transportation cost for the combined IBP and virgin aggregate use (figure 6). When accounting for the assumed free-on-board delivery of IBPs, the transportation cost savings increases to $15 million.

Discussion

The use of IBPs in combination with virgin aggregate for roadway sub-base construction has lower life cycle impacts than the use of virgin aggregate alone, with the exception of HTP cancer. The HTP cancer values are derived from total content of elements in the materials to groundwater and are highly conservative, not accounting for availability or fate and transport through subsurface materials.

Comparison with previous roadway LCAs are difficult as the boundaries of the different studies vary, with functional units closely tied to specific lengths of roadway. This study is regionally oriented around aggregate demand but not connected to any specific length of roadway. In addition, it does not include construction of other components of the roadway (embankments, wearing courses, base courses) nor does it include the use and maintenance phases. The impacts considered are similar, however, to other studies, with the exception of the RCRA Hazardous Waste impact. This is an impact that is specific to the United States.

This study has several limitations that carry some uncertainty. The analysis attempts to account for vertical infrastructure aggregate demand. The data used were from sources for different years and assume there is not a significant change from year to year. The vertical infrastructure aggregate demand data required some disaggregation and translations that also add to the uncertainty. The study also does not consider aggregate for concrete or asphalt applications in roadways. The total PENNDOT demand, however, is only 25% of the availability of IBPs as indicated in the PA Residual Waste Report (PA DEP 2004). The demand would be greater if all other beneficial-use applications were included; however, the availability of IBPs is much higher than what was required by PENNDOT for roadway construction. In the case of the state providing incentives for the use of IBPs for state funded projects, a scenario that utilizes IBPs alone would be more applicable. The virgin aggregate scenario would still be limited, as those sources have a much greater demand throughout and outside the region. The analysis done here can be considered...
conservative in that the virgin aggregate would be less available and would potentially have to be extracted from sources farther away.

The life cycle impacts of landfills or stockpiling of the IBPs that are not beneficially used (defined as residual waste by the state) is not accounted for and therefore again makes this analysis conservative. The cost of transporting the IBPs to their designated disposal facility (PA DEP 2004) would be almost $64 million (2007 U.S. dollars) on top of the cost of transporting the virgin materials used in place of the IBPs. The PaLATE analysis sheds more light on the environmental impact from the use of IBPs in roadways on a regional level that can lead to expanded beneficial use of the materials. The optimal scenario in terms of transportation costs may include a combination of both virgin aggregate and IBPs to meet the total demand of the region for all project types, servicing projects that are in the closest proximity to the material source points. The impacts these incentives might have on the market, supply chains, and relevant organizations are not covered in this study.

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Notes

1. One million tonnes = 10^9 kilograms (kg, SI) ≈ 1.102 × 10^6 short tons.
2. One tonne-kilometer ≈ 0.685 (short) ton-miles.
3. NAICS is the North American Industry Classification System—the standard used in classifying US businesses for statistical purposes.
4. Human toxicity potential (HTP) is an index that represents the potential harm of a unit of a given chemical released to the environment.

References


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