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Chapter 15

Waste Management: Conservation, Reuse, and Recycling of Materials and Components

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Since the enactment of the Resource Conservation and Recovery Act (RCRA) in 1976 and its amendments, the common approach to managing wastes is to follow the waste hierarchy. The waste hierarchy starts with the most environmentally preferred waste management option, conservation (also known as waste prevention, waste minimization, or source reduction); followed by reuse, recycling, and energy recovery; and ends with the least preferred option, disposal (landfilling). Recently, the waste hierarchy has also been called the resource efficiency hierarchy (Table 15-1) to emphasize that only resource consumption generates waste.

While the waste hierarchy has led to major improvements in waste management, this approach cannot address all issues. First, conservation, reuse, and recycling of some waste fractions (e.g., composites or generated hazardous materials) are difficult to implement once the waste is generated. Therefore, end-of-life considerations must be accounted for during the manufacturing phase of a component and the design phase of an infrastructure project. This is challenging because the responsible parties for the manufacturing and the end-of-life phases are often different.

Second, the use of carbon-intensive fuels must be minimized to reduce potential global warming impact. Therefore, in some cases energy recovery is preferable to material recovery, especially if material

Table 15-1. Resource Efficiency Hierarchy for Construction in Generally Decreasing Order of Preferability

1) **Reduce**
   - Prevent building and rebuilding—use no new material
   - Reuse site structures in place, in whole form
   - Use less material
   - Design for disassembly (DfD)

2) **Renew**
   - Use materials from renewable resources

3) **Reclaim and reuse**
   - Reuse components whole and onsite
   - Reclaim components whole for use on other sites
   - Use reclaimed materials from other sites

4) **Reprocess and recycle**
   - Reprocess existing structures and materials for use onsite
   - Reclaim onsite structures and distribute to offsite reprocessing facilities
   - Specify recyclable materials
   - Use recycled-content materials
   - Reclaim onsite materials and distribute to offsite recycling facilities
   - Facilitate onsite recycling with area for storage and collection of recyclables

5) **Recover**
   - Divert nonusable materials for energy recovery

6) **Dispose**
   - Dispose of materials in controlled landfills

Source: Modified from Calkins (2012)

recovery is very energy intensive. For example, Levis et al. (2014) show for an illustrative case of a municipal solid waste system of a hypothetical U.S. city of 100,000 people over 30 years that the maximum diversion goal does not necessarily result in the lowest lifetime energy consumption and global warming potential.

Third, some materials, e.g., rare-earth elements (Van Gosen et al. 2014) and aggregates in some areas (Recycled Materials Resource Center 2015) are becoming scarce. The stock of construction materials in the built environment is increasing worldwide (Fig. 15-1) and is considered an important resource, justifying higher resource input to recover them.

Fourth, not only environmental impacts need to be considered in waste management; technical, economic, and social issues are critical as well.

While the waste hierarchy is still a valid approach in waste management, these additional constraints require system thinking to minimize the overall environmental, economic, and social impacts. In Europe,

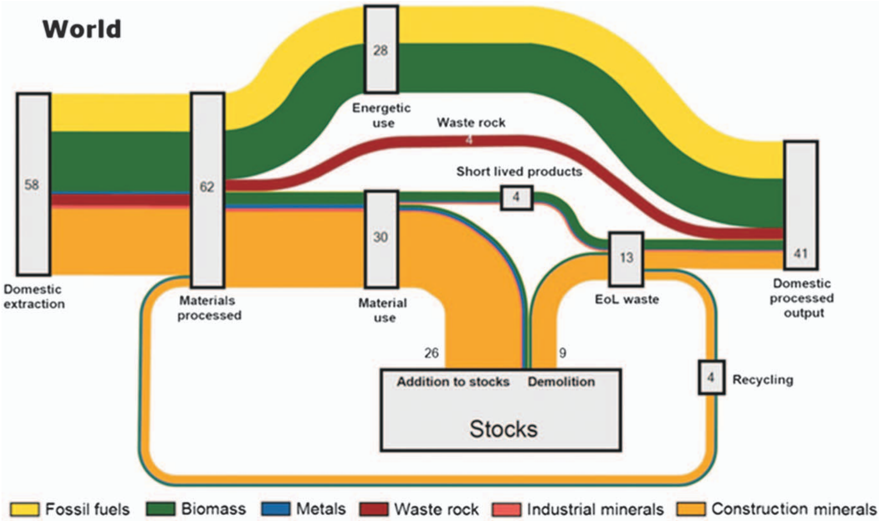

Figure 15-1. Material flows through the global economy in 2005 in Gt/yr (Note: EoL waste = End-of-life waste).
Source: Haas et al. (2015). Reprinted with permission

the term "circular economy" refers to system thinking in waste management, while in the United States the often misunderstood term "zero waste" is more common. Fig. 15-1 shows how far we were from a circular economy in the built environment in 2005.

Rating systems such as Envision, SITES, and INVEST help address system thinking in end-of-life aspects of infrastructure projects and systems. Waste is addressed in several ways in Envision under the category Resource Allocation. For example, credit RA1.3 calls for use of recycled materials where appropriate. Other categories assess opportunities to reuse waste materials and reduce waste of energy and freshwater. More details about the rating systems can be found in Chapter 20.

15.1. Construction and Demolition Waste Quantities and Composition

Construction and demolition (C&D) waste refers to materials produced in the process of construction, maintenance, and/or demolition of structures such as buildings and infrastructure projects and systems. Even though C&D waste is one of the largest waste fractions (Fig. 15-1), generation and recycling data, especially from infrastructure projects, are not tracked well in the United States. Projections vary widely. Townsend et al. (2014) estimate 435.9 million t of C&D waste for 2012, which consisted of 90.8 million t mixed C&D waste, 281.5 million t bulk aggregates (mainly concrete), and 63.6 million t recycled asphalt pavement (RAP). The authors reported an overall recycling rate over 70%, with 35% for mixed C&D waste, 85% for bulk aggregates, and 99% for RAP.

Relying on the same data source, USEPA (2015) estimates 481 million t of C&D waste were generated in 2013, including 147.2 million t from buildings, 220.8 million t from roads and bridges, and 113.0 million t from "other structures." These other structures are infrastructure projects other than roads and bridges. Clean fill and land-clearing debris are not included. Based on this report, C&D waste from roads and bridges consists of 86.9 million t portland cement concrete and 133.9 million t asphalt concrete. Because it was not determined whether the steel was used in building or infrastructure projects, all steel waste was attributed to building projects. Therefore, the waste from infrastructure projects should be higher. It was also assumed that C&D waste from "other structures" consists only of portland cement concrete.

The Cascadia Group (2006) performed a waste characterization study and determined a more detailed composition of C&D waste from infrastructure projects for four metropolitan areas in California in 2005. In that study, 93% of waste from infrastructure projects was found to be recyclable, while the remaining 7%. (i.e., municipal solid waste or MSW) was nonrecyclable. The 93% recyclable fraction consisted of 69% recyclable aggregates; 9% recyclable wood; 1% recyclable metal; 2% other recoverable materials; and 12% rock, dirt, and sand.

C&D waste is the waste at the end-of-life of materials and components and excludes waste generated throughout the entire lifecycle, including material extraction, processing, and manufacturing. Lifecycle assessment (LCA) considers wastes throughout the entire lifecycle of materials and components (see Chapter 8). When possible, wastes from the entire lifecycle should be considered. The following example illustrates the importance: Gambatese and Rajendran (2005) compare the amount of energy consumed and wastes generated from extraction to the end of construction of continuously reinforced concrete pavement and asphalt pavement roadways. For the continuously reinforced concrete pavement the extraction and production of aggregates and cement produced most of the waste, while for the asphalt pavement most of the waste was produced during the extraction and production of only the aggregates. Therefore, the asphalt pavement lifecycle generated less total waste.

Various guidance documents explain how to manage C&D waste. ASTM is developing a "Guide for Development of a Waste Management Plan for Construction or Demolition" that should be a useful reference (ASTM 2016). Local guidance documents or requirements for a construction waste management plan are also available; for example, New York City has a guide on managing C&D wastes to reduce the volume for disposal (Gruzen Samton and CityGreen 2003).

15.2. Regulatory Requirements

Most C&D waste is nonhazardous. If it is hazardous, it falls under the jurisdiction of the EPA or local jurisdictions with delegated authority to implement federal and state hazardous waste regulations. The regulatory framework, especially regarding hazardous waste identification, classification, generation, and management, is described in 40 CFR Parts 260 through 270 (collectively known as RCRA Subtitle C regulations). These regulations control hazardous wastes from the time they are generated until their ultimate disposal. Generators that produce less than 100 kg hazardous waste (known as conditionally exempt small-quantity generators or CESQG) can dispose this hazardous waste in state-permitted solid waste facilities. Nevertheless, avoiding hazardous waste in the first place is preferable. If this is not possible, disposing the exempt C&D waste as hazardous waste is the second-best option.

As most C&D waste is nonhazardous and is not classified under RCRA, it is regulated by state governments. However, little consistency exists in how states regulate C&D waste. About half of the states have unlined C&D landfills (Clark et al. 2006). However, these are becoming less common because C&D waste is not as inert as once thought (Powell et al. 2015). Many states have recycling regulations with recycling goals and diversion rates. The materials might not be specified, but to reach these goals C&D fractions must be diverted from landfills.

15.3. Conservation, Reuse, and Recycling

Although conservation, reuse, and recycling provide opportunities, they also present challenges. As discussed previously, asphalt concrete and portland cement concrete are the predominant fractions in C&D waste. Recycling of asphalt concrete and portland cement concrete are well-established and economical practices and will be discussed later in the chapter. Waste prevention, reuse, and recycling practices of other fractions are applied more often in building than in infrastructure projects. Therefore, examples are scarce. However, many practices from building projects can also be applied to infrastructure projects and systems.

Ideally, conservation, reuse, and recycling practices are assessed through an LCA and a lifecycle costing analysis (LCC). While the number of studies for infrastructure projects and systems is growing, in lieu of complete LCAs and LCCs, Field (2010) suggests the following reasoned approach to accounting for lifecycle environmental impacts when choosing a construction material:

- Extraction: ecosystem impacts, methods, toxicity;
- Refining/Manufacturing: toxicity, waste production, recycled content, energy demand, emissions;
- Transportation: distance, mode;
- Construction: waste reduction from re-assembly (such as prefabricated trusses or precast concrete components), associated material impacts (such as concrete formwork or epoxy anchors), material-handling equipment requirements and impacts (such as steel erection);
- In Use: durability and maintenance requirements, impacts on external and internal (occupant) environment; and
- Demolition/Deconstruction: longevity of material, design for deconstruction, options for reuse or recycling, disposal as waste (Field 2010).

15.3.1. Conservation

Conservation is at the top of the resource hierarchy. Other common terms are waste prevention, waste minimization, or source reduction. Waste prevention includes reducing both the amount of waste and its toxicity. Conservation practices include designing for increased durability and reduced maintenance, designing for disassembly and deconstruction, minimizing use of hazardous materials, and reducing excavated soils taken offsite. Most of these practices must be considered during the design and planning stage of a project when construction materials and components are chosen.

Designing for durability and reduced maintenance ensures that a structure resists environmental, structural, and operational demands without much maintenance during its lifetime. Appropriate material selection, design choices, and protective coatings can increase durability. Infrastructure projects that require specific attention to durability, such as bridges, tunnels, railroads, pipelines, roads, and foundations, might also benefit from preventive maintenance to increase durability (Field 2010). Adaptable structures that allow various uses without replacing an entire structure when a use changes will also conserve resources (Calkins 2012).

Designing for disassembly and deconstruction is more common in buildings, but some of the principles apply to infrastructure projects. Calkins (2012) suggests the following design principles for deconstruction:

- Design the site and structure for maximum flexibility and plan for adaptation of the site over time;
- Document materials and methods to facilitate deconstruction and disassembly after the useful life of the structure or site;
- Specify materials and products with good reuse or recycling potential;
- Specify materials that are durable, modular, and/or standardized to facilitate reuse many times;
- Design accessible connections;
- Detail connections that facilitate disassembly;
- Avoid finishes that can compromise the reuse or recyclability of the material; and
- Support the design for disassembly process in the design phase.

While during construction expected and unexpected hazardous substances from spills and leakages (e.g., from pipelines) must be handled appropriately, hazardous substances in materials and components should be avoided as much as possible to prevent future environmental degradation.

Minimizing excavated soils taken offsite has been shown to have economic and environmental benefits (Chittoori et al. 2012; Eras et al. 2013).