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Environmental life cycle analysis of pipe materials for sewer systems

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ABSTRACT

Wastewater system performance continues to be a matter of utmost importance to the development of sustainable communities today. Over the past few decades, we have seen dramatic increases in urbanization that has substantially added to an already-enhanced need for improvement of wastewater infrastructure systems. Traditionally studies on sewer system design have been focusing on maximizing the economic advantages, while limited work has been done on the analysis of environmental impacts of sewer systems made of different piping materials. In this paper, a comparative life cycle analysis (LCA) is performed for six different types of wastewater pipe materials: composite fiber reinforced polymer (FRP), PVC, high density polyethylene (HDPE), ductile iron, vitrified clay, and reinforced concrete. The functional unit is defined as one kilometer sewer infrastructure needed for a small city with population of 25,000 people for a period of 50 years. Considering various life cycle stages, environmental impacts were quantified and compared for all pipe materials in two types of sewer systems i.e. pure gravity sewer and sewer with lifting stations. The results indicate that the manufacturing stage in pure gravity sewer systems has the maximum impact, while for sewer systems with lifting use phase can have comparable or even higher impacts than manufacturing phase. Among the six pipe materials, ductile iron seems to be the worst option while reinforced concrete seems to be the best option. Results from the analysis may help current and future wastewater infrastructure designers and material manufacturers to understand and develop more sustainable sewer systems.

1. Introduction

With 52% of the world's population now living in urban areas, management of the urban wastewater cycle becomes utmost important (Closas, Schuring, & Rodriguez, 2012). Due to the high installing cost of sewer systems (Tafuri & Selvakumar, 2002; Burn, DeSilva, Eiswirth, Hunaidi, Speers, & Thornton, 1999), durability and service longevity are important factors to consider. The current approach is to improve life-cycle performance with the goal to achieve lower installation costs, reduced leakage, higher resistance to corrosion and temperature variation, and reduced maintenance over the lifetime of a pipe infrastructure system simultaneously (Savic & Walters, 1997; Dennison et al., 1999; Romanova, Mahmoodian, & Alani, 2014; Angkasuwansiri & Sinha, 2013). Pipe material is one of the most important decisions to make when designing and installing a sewer system (Turner, 2007; Du, Woods, Kang, Lansey & Arnold, 2013; Sægrov, Hafskjold, Ugarelli, Kristiansen, & Skaug, 2008; Turner, 2007). Table 1 shows the common sewer pipe materials and their advantages/disadvantages.

Traditionally studies on sewer system design have been focusing on maximizing the economic advantages (Mirza, 2007), while the environmental impacts and long-term socio-economic consequences are largely ignored. For example, it has been pointed out that PVC and FRP materials provide cost-effective alternatives to ordinary materials and their transportation, installation and use stages often have associated financial advantages (Bank, 2006; Turner, 2007; Hollaway, 2010). As concerns grow over environmental impacts, climate change and natural resource depletion, it is crucial to consider the environmental implications of these materials (Turner, 2007; Faria & Guedes, 2010).

Few investigations have assessed the environmental impact of wastewater systems from a life cycle assessment (LCA) perspective, although it is known that sewer systems could impact environment during all life cycle stages i.e. production, transport, installation and use stages. According to Anders and Anders (1997), the installation stage of a sewer system is of great importance, as it involves material removal, excavation and use of energy. Conversely, Du

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Table 1
Characteristics of common wastewater piping materials.

Material	Application	Key Advantages	Key Disadvantages
Ductile Iron	High pressure available sizes of 4–54 in.	Good resistance to pressure surges	More expensive than reinforced concrete and fiberglass
Reinforced Concrete	Moderate pressure available sizes of 12–72 in.	Low corrosion rate	Relatively brittle, heavy and high transportation cost
Vitrified Clay	Low pressure for larger-diameter applications	Low thermal expansion, long life cycle, raw materials availability, corrosion resistant	High transportation cost, heavy and labor-intensive to work
PVC	Low pressure for up to 36-inch pipe sizes	Light weight, no corrosion	Suitable for small pipe sizes and low pressure only
FRP	Moderate pressure available sizes up to 72 inches	Light weight, no corrosion	Expensive
HDPE	Moderate pressure available sizes of 4–63 in.	Light weight and flexible, leak-free joints	Sensitivity to temperature changes and mechanical loading

et al. (2013) pointed out that pipe manufacturing stage accounts for 92–99% of total global warming potential and both transport and installation have a relatively small contribution. Furthermore, based on Strutt, Wilson, Shorney-Darby, Shaw, and Byers (2008), if the pumping energy is excluded, the CO_2 emissions of the manufacturing and installation stage of different piping systems account for 98% of the total impact.

It is also reported that greenhouse gas emission of ductile iron pipes production is almost 15 times higher than that of reinforced concrete pipes production (Venkatesh et al., 2009). In the manufacturing of ductile iron pipes, the zinc coating is the main contributor to the total energy required (Dennison et al., 1999). Although, the greenhouse gas (GHG) emissions associated with production stage of plastic pipelines are 10–26 times greater than those associated with reinforced concrete, plastic pipelines made of PVC or PE (polyethylene) with smaller diameters are the most suitable materials given their ductility and price (Venkatesh et al., 2009). In addition, the life cycle energy consumption and related GHG emissions associated with the manufacture, use, recycling and final waste disposal of different pipe materials such as HDPE, PVC, ductile iron, polypropylene, and reinforced concrete pipes were studied by Recio, Guerrero, Ageitos, & Narváez 2005. The investigation showed that in terms of energy consumption and CO_2 emission, the most favorable piping material is PE and concrete pipes are the most unfavorable option for sewer piping systems.

From life cycle energy consumption and CO_2 emission perspective, studies of sewer pipes made of vitrified clay, reinforced concrete, polyvinyl chloride, ductile iron, and polyethylene (PE) suggest that the best option is reinforced concrete and the worst option is plastic pipes (Jeschar, Specht, & Steinbrück, 1995; Friedrich, Pillay, & Buckley, 2007). It was also shown that plastics and vitrified clay pipes have comparable energy consumption and carbon dioxide emission for smaller pipes (OD: 100 and 150 mm). For larger OD pipes, energy consumption is much higher for ductile iron and plastic pipes compared to vitrified clay and reinforced concrete pipes. With regard to GHG emissions, the same results are observed. It should be noted that lower OD concrete pipes have not been considered by Friedrich, Pillay, and Buckley (2007) and it may change the final results. To conclude, it was shown that vitrified clays and concrete pipes have better environmental performance than plastic and ductile iron pipes.

In this paper, two different LCA studies with and without "use phase" were analyzed. If a sewer system works with pure gravity system, no energy is required in wastewater transportation and use phase in LCA study can be ignored and other stages such as manufacturing, transportation and installation are considered. If we focus on flat areas where pump stations exist, friction loss and use phase should be involved into the LCA study and to the best of our knowledge, this investigation is the first attempt to include friction loss and energy required in the use phase in an LCA study. Energy requirement during the use phase is proposed to be applied to wastewater pumping in flat areas and compilation of such parameter in sewer systems would assist in comparing and benchmarking environmental performances of different piping materials. It will also highlight areas for improvement and reinforce the importance of the role of energy in sewer systems.

The main goal of this study is to quantify the environmental impacts of different pipe materials in sewer systems and to support the selection of pipe material for better life cycle environmental performance.

2. Methodology

Life cycle analysis (LCA) is defined by United States Environmental Protection Agency (U.S. EPA) as a methodology of assessing potential environmental impacts associated with a product or process through entire lifetime (SAIC, 2006). This technique can evaluate environmental impacts of products based on their materials and energy inputs and outputs. ISO 14040 (2006) LCA methodology is used which comprises the following steps:

- Goal and scope definition to determine the objectives and system boundaries of the analysis.
- Analysis of the life cycle inventory for the quantification of the collected data such as LCA inputs and corresponding outputs.
- Assessment of the LCA results and their impacts on different environmental factors. During this stage effects are assigned to different environmental impact categories to obtain category specific indicator values.
- Interpretation to assess and summarize the results obtained from the previous stages to reach a substantial conclusion.

A comparative LCA is often used to identify which product or material has the least environmental impacts. As stated previously, this study is to quantify and compare the environmental impacts of different pipe materials used in sewer systems. The system boundary includes pipe manufacturing, transportation, installation, and use. End of life management is excluded assuming all pipes will be disposed in landfill. The functional unit is defined as one kilometer sewer infrastructure needed for a small town with population of 25,000 people for a period of 50 years.

Inventory analysis is conducted using Ecoinvent 3 and SimaPro 8. USEPA TRACI method is used for impact assessment, and impact categories include are ozone depletion (kg CFC-11 eq), global warming (kg CO_2 eq), smog (kg O_3 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), carcinogenics (CTUh), non carcinogenics (CTUh), respiratory effects (kg $PM_{2.5}$ eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus). The traditional pollution categories of human health criteria (cancer and noncancer), ozone depletion, particulate pollutants which lead to respiratory impacts,