Waste Materials and Management: Lessons from the Flint Water Crisis in Michigan and Blast Furnace Slag Usage in Indiana

Tianqi Wang
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WASTE MATERIALS AND MANAGEMENT: LESSONS FROM THE FLINT WATER CRISIS IN MICHIGAN AND BLAST FURNACE SLAG USAGE IN INDIANA

by

Tianqi Wang

A Thesis
Submitted to the Faculty of Purdue University
In Partial Fulfillment of the Requirements for the degree of

Master of Science in Civil Engineering

Lyles School of Civil Engineering
West Lafayette, Indiana
August 2018
THE PURDUE UNIVERSITY GRADUATE SCHOOL
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Dr. Dulcy M. Abraham
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To my parents, Tian Xiuli and Wang Quanyou,

Your unfailing support and belief in me carried me through my master’s journey, where I never thought I could be. Your unconditional love has kept me going.

I am forever grateful.

This is for you.
ACKNOWLEDGMENTS

This thesis contains two independent manuscripts included as Chapters and were developed by the author with assistance from other individuals. The first Chapter focused on better understanding solid waste management before, during, and after the large-scale 2015 drinking water lead crisis in Flint, Michigan. For Chapter 1, the author collected information, analyzed the results, and wrote the Chapter; Jooho Kim, a Ph.D. Candidate in Construction Management at Purdue University, created one figure, described the POD results, and also helped review the overall Chapter. Dr. Andrew Whelton assisted the author obtain information from the organizations contacted, helped analyze and interpret information, and contributed to the recommendations. The second Chapter focused on blast furnace slag use in Indiana. For Chapter 2, the author reviewed scientific literature, conducted site visit, gathered and analyzed information from state transportation agencies, and wrote up the results. Dr. Maryam Salehi, a Postdoctoral Research Associate at Purdue University, provided feedback on some of the scientific literature, participated in the site visit, and reviewed the Chapter. Dr. Whelton assisted the author connect with the transportation agencies and material supplier, participated in the site visit and project briefings, identified the Chapter’s structure with collaboration from the author, contributed to writing to all part of the Chapter.

Special thanks are given to Dr. Andrew Whelton for his guidance and to Dr. Maryam Salehi and Jooho Kim for cooperating in this research. The author also thanks Dr. Kelsey Pieper of Virginia Tech, and representatives from the Michigan Department of Environmental Quality (MDEQ), City of Flint, Republic Services, Inc., and Schupan Recycling for providing insights into the water distribution and waste collection, disposal, and recycling activities. Feedback from the state transportation agencies of Indiana, Illinois, Maryland, Michigan, Ohio, and New York is also appreciated. These organizations providing insights regarding the use, approval requirements, test methods and experiences with air cooled blast furnace slag.
# TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................... vii
LIST OF FIGURES ........................................................................................................ viii
ABSTRACT ....................................................................................................................... ix

1. CASE STUDY: MANAGEMENT OF PLASTIC BOTTLE AND FILTER WASTE DURING THE LARGE-SCALE FLINT MICHIGAN LEAD CONTAMINATED DRINKING WATER INCIDENT ........................................................................................................ 1
   1.1 Introduction ...................................................................................................... 1
   1.2 Case Study Approach ...................................................................................... 3
   1.3 Results and Discussion ................................................................................... 6
      1.3.1 Waste management system prior to October 1, 2015 .............................. 6
      1.3.2 Waste management system after the drinking water was declared contaminated .... 7
      1.3.3 Points of distribution (POD) .................................................................. 8
      1.3.4 Water demand and water bottle waste estimates ..................................... 8
      1.3.5 Waste collection response ..................................................................... 14
         1.3.5.1 Overall material flow ....................................................................... 14
         1.3.5.2 Curbside pickup .............................................................................. 15
         1.3.5.3 Drop-off recycling and haulers ........................................................ 16
         1.3.5.4 Water filter cartridge collection ....................................................... 17
         1.3.5.5 Education ....................................................................................... 18
      1.4 Observations and Lessons Learned ............................................................ 19
   1.5 References ...................................................................................................... 23

2. BLAST FURNACE SLAG USAGE AND GUIDANCE FOR INDIANA ......................... 32
   2.1 Introduction ................................................................................................... 32
      2.1.1 Problem statement .............................................................................. 32
      2.1.2 Research objective ............................................................................ 33
      2.1.3 Business case ..................................................................................... 33
      2.1.4 Technical approach ............................................................................ 33
      2.1.5 Work plan ........................................................................................... 34
   2.2 Air Cooled Blast Furnace Slag Use by Indiana ................................................. 34
LIST OF TABLES

Table 1.1 Comparison of Recent Large-scale U.S. Drinking Water Contamination Incidents ...... 2
Table 1.2 Organizations and Their Activities in Response to the Recycling Program .................. 5
Table 1.3 Estimated Water and Filter Demand ........................................................................ 10
Table 1.4 Estimated Total Number, Volume, Weight, and Value of Recyclable Materials in Flint, Michigan ................................................................................................................... 12
Table 2.1 Results of Muffle Furnace and TCLP Tests Used to Evaluate ACBFS Composition .. 39
Table 2.2 Construction Applications Where ACBFS Can Be Utilized According to State Transportation Agency Specifications ................................................................. 41
Table 2.3 Leaching Test Methods by National and International Organizations ....................... 46
Table 2.4 Chemical Composition and Leachable Fraction in BFS [Type not Specified] Mixed with Lime ..................................................................................................................... 50
Table 2.5 Factors Influencing Leaching .................................................................................... 52
Table 2.6 Total Element Available for Leaching from a BFS Sample under “Somewhat Oxidized” and “Fully Oxidized” Conditions ................................................................. 55
Table 2.7 Proposed ACBFS Classification * ............................................................................. 63
Table A.1 Some Notable Events Related to the Large-scale Drinking Water Contamination Incident in Flint, Michigan .............................................................................................. 71
Table C.1 Information Found that Can be Used to Estimate Emergency Drinking Water Needs Following a Disaster (Lcapita · day) ......................................................................................... 75
LIST OF FIGURES

Figure 1.1 Overall Estimation Process Used to Examine Water Provision and the Waste Management System for the Present Study ................................................................. 6

Figure 1.2 Material Flow Diagram Created after Discussions with Organizations Involved in Flint Waste Management and Recycling Activities: (a) Water Bottles, and (b) Water Filter Cartridges ........................................................................................................... 15

Figure 1.3 Monthly and Cumulative Weight of Water Bottles Collected by a Recycler Who Supported the Flint Community, January 2016 to March 2017 .............................................. 17

Figure 1.4 Cumulative Number of Used Filter Cartridges Collected by GCMPC in Flint, Michigan Varied from March 2016 to June 2017 ................................................................. 18

Figure 2.1 (a) Yard Map of ACBFS Stockpiles, (b) Stockpile Approval Sign, (c) Stockpile Rejection Sign ............................................................................................................. 40

Figure 2.2 Production Flow of Blast Furnace Slag (Specific to the Slag Producer Site Visit) .... 47

Figure 2.3 ACBFS Leachate pH Test Results from ODOT Compared to Acceptance Criteria from ODOT (2002), INDOT ITM 212 (as of June 2015), and Indiana Administrative Code (IAC) Water Quality Standards ............................................................................. 57

Figure B.1 PODs Were Setup Across Flint to Provide the Community Access to Emergency Water Supplies: (a) Five PODs at Fire Stations Were Operating on January 9, 2016 and (b) Nine PODs Were Operating at Banks and Churches After the Change of Location. Symbols Indicate the PODs in Flint ........................................................................... 74

Figure D.1 Water Bottle Measurement ................................................................................. 76
ABSTRACT

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Institution: Purdue University  
Degree Received: August 2018  
Title: Waste Materials and Management: Lessons from the Flint Water Crisis in Michigan and Blast Furnace Slag Usage in Indiana  
Major Professor: Andrew Whelton

Two aspects of solid waste management were investigated for this thesis. The first effort focused on better understanding solid waste management before, during, and after the large-scale 2015 drinking water lead crisis in Flint, Michigan. When large drinking water systems are unable to deliver safe water, the provision of emergency water supplies becomes a necessity. The author investigated waste management challenges associated with the large-scale drinking water disaster. In October 2015, more than 90,000 people were directed not to use their lead contaminated water, but instead use emergency drinking water and in-home filters. Discussions with organizations that responded to the incident as well as a review of scientific literature and records were conducted. Results demonstrated that public and private partnerships enabled the water distribution and waste collection/recycling activities. Millions of water bottles were supplied to the community, but the actual amounts may have been less than the estimates for community water needs. During January 2016, the recycling participation rate increased from 13% to 27%. Water bottle and faucet filter recycling was encouraged by the establishment of drop-off locations and the curbside pickup program was expanded. Tens of thousands of filters were donated to the community, but government records found only about 2,600 filters were recycled. Points of distribution (PODs) were established to provide emergency supplies, increase waste management efficiency, but were relocated months after the initial response because their initial locations were not optimal. A lack of formal material flow tracking entering and leaving Flint inhibited a better understanding of waste management activities. Communities seeking to better prepare for large-scale emergencies should: pre-identify the roles of waste management organizations, setup a procedure for documenting emergency water supply materials entering and exiting the community, determine POD locations, draft public notifications about waste management activities, and centralize all data archiving.
The goal of second Chapter was to better understand the factors that can influence chemical leaching from air cooled blast furnace slag (ACBFS) for Indiana Department of Transportation (INDOT) projects. In July 2016 a green seepage with a sulfurous smell oozed from Ind. 49 and caused a Fire Chief and a police officer in hospital for breathing problems. To deal with a leaching problem lasting more than ten months at one site, a project was constructed, but INDOT spent more than $500,000 to remove slag several years later because of reoccurring problem. A literature review of government documents, peer-review, and trade industry literature was conducted. A visit to an ACBFS storage facility and steel mill that generated the ACBFS was also completed. ACBFS handling and testing procedures at the storage facility and those prescribed by INDOT were also reviewed. The project team also contacted other state transportation agencies (IL, MD, MI, NY, and OH) to determine the degree they incorporated ACBFS into their projects and to determine if product performance tests were required. Results showed that changes to INDOT test methods and acceptance criteria are warranted. Indiana Test Method (ITM) 212 should be revised to extend the test duration, pH acceptance criterion, and add additional material acceptance criteria. Unbound ACBFS should be avoided for construction applications 1) where ground water could contact the material, 2) near environmentally sensitive and populated areas, 3) where a drainage system is not present. Additional work to improve the ability of INDOT to detect ACBFS that would cause short- or long-term chemical leaching problems could include 1) evaluating and optimizing stockpile sampling practices for representative sampling, 2) modifying ITM 212 to better predict worst-case leaching conditions and leachate quality, 3) conduct a head-to-head comparison of bench-scale and field-scale leaching results.
1. CASE STUDY: MANAGEMENT OF PLASTIC BOTTLE AND FILTER WASTE DURING THE LARGE-SCALE FLINT MICHIGAN LEAD CONTAMINATED DRINKING WATER INCIDENT

1.1 Introduction

Large-scale disasters such as hurricanes, tsunamis, and earthquakes can damage drinking water systems, and also generate large amounts of solid waste. Drinking water systems can be physically and chemically damaged including drinking water sources, treatment facilities, distribution assets, and building plumbing. Often though, drinking water system recovery is relatively standard. This involves the repair or replacement of damaged equipment, and disinfection and flushing of affected assets. While the water distribution system or building plumbing systems are being recovered, communities are directed to seek alternate drinking water supplies (US EPA, 2011). The waste generated due to these natural disasters has been well-studied, and includes construction and demolition debris, vegetative debris, soil, mud and sand, and solid waste (Brown et al., 2011; Goodnough et al., 2016; Grzeda et al., 2014; Karunasena et al., 2009; Kim et al., 2018b). Sometimes infrastructure repairs cannot begin or continue until waste is removed from the area undergoing recovery.

Enabling the community to access life-saving and supporting emergency water supplies is critical following a disaster. The amount of drinking water needed following a disaster can vary based on the incident duration and the water use activities. The U.S. Environmental Protection Agency (EPA) has estimated 1.89 to 18.93 liters per person per day (L/cap-day) is needed for short-duration incidents; those less than 21-day duration (US EPA, 2011). However, longer-duration incidents require greater volumes of water (Veer, 2002), and up to 25.15 L/cap-day has been estimated by others (WHO 2011, Zdanowicz 2016). For both short- and long-term incidents, drinking water is often distributed as bottled water or bulk water at distribution points with tankers and trucks. Water delivery and handling can generate empty plastic bottles, wrapping, cardboard, and pallets; all materials that are discarded.

In recent years, several large-scale U.S. drinking water chemical contamination incidents have prompted communities to rely on emergency drinking water supplies (Table 1). Once the contamination was discovered, ‘do not drink or use drinking water’ orders were issued (Rogers, 2014; Whelton et al., 2017). The incident in Charleston, West Virginia was caused by a leaking
chemical storage tank, whereas another incident in Toledo, Ohio originated from Lake Erie freshwater algae blooms and algal toxins. Those were short-term ‘do not use’ incidents with durations of 3 and 9 days, respectively. While longer duration incidents took place in St. Joseph, Louisiana and Flint, Michigan. In St. Joseph, there was a need to replace the 90-year old water distribution system, whereas, in Flint, MI most of the city’s water pipes and sometimes resident plumbing needed repair. Health officials that responded to both incidents recommended that communities not drink municipal tap water for more than 6 months and 1.5 years, respectively. No studies were found that examined how the affected communities managed solid waste generated due to emergency water supply distribution. Also, a comparison of predicted emergency water supply needs to actual water supply used was not found.

<table>
<thead>
<tr>
<th>Location</th>
<th>Date*</th>
<th>Affected Population</th>
<th>Contaminant</th>
<th>Outage Duration</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flint, MI</td>
<td>2015-Present</td>
<td>97,386</td>
<td>Lead</td>
<td>-</td>
<td>Pieper, Tang, &amp; Edwards (2017); US Census (2016)</td>
</tr>
<tr>
<td>Charleston, WV</td>
<td>2014</td>
<td>300,000</td>
<td>Coal washing chemical mixture</td>
<td>9 days</td>
<td>Markham, Gianato, &amp; Hoyer (2014); Whelton et al. (2017)</td>
</tr>
<tr>
<td>Toledo, OH</td>
<td>2014</td>
<td>500,000</td>
<td>Mixture of microcystins</td>
<td>3 days</td>
<td>Spear (2014); Wines (2014)</td>
</tr>
</tbody>
</table>

* Water crisis publicly confirmed when the state of emergency was declared.

This case study was conducted to better understand waste management planning and operations pertaining to the Flint Michigan lead drinking water contamination incident. The City of Flint, Michigan is the county seat of Genesee County and in 2016 had 97,386 residents and 40,260 households (US Census, 2016). The average household income was $14,765 and 41.2% of the population lived in poverty (US Census, 2016). Census data indicated that the population was 37.4% Caucasian, 56.6% black or African American, and 6.0% other. Approximately 82.9% of people older than 25 years old had received a high school or higher education, and 11.2% of the population had earned bachelor’s degree or higher level of education. About 10.7% of the
population was 65 years and over, and 50.6% of the population who were at least 16 years old were in the civilian labor force (US Census, 2016).

In April 2014, the City of Flint discontinued purchasing treated drinking water from the Detroit Water and Sewer Department (DWSD) and began producing their own drinking water using the Flint River (City of Flint, 2016a). Failure to adequately treat their drinking water resulted in destabilization of lead-bearing corrosion rust layers on drinking water pipes (Olson et al., 2017; Pieper et al., 2017). The consequence was that Flint residents were exposed to lead in the drinking water at levels as high as 13,200 µg/L compared to the U.S. drinking water action level of 15 µg/L (EPA, 2009; Pieper et al., 2017). The EPA’s hazardous waste threshold is 5,000 µg/L lead for landfill leachate (US GPO, 2017). An outbreak of Legionnaires’ disease also occurred, resulting in multiple fatalities (Zahran et al., 2018). The City of Flint declared a state of emergency and the U.S. Federal Emergency Management Agency (FEMA) then began providing bottled water. Once the state acknowledged the drinking water was unsafe, residents were advised not to drink or cook with tap water (City of Flint, 2016b; Genesee County Board of Commissioners, 2015). Michigan State Government (2016b) reported the roles of government agencies leading up to and during the water crisis. Notable events related to the large-scale drinking water contamination incident were collected (Table A.1). Events related to water supply and advice of using bottled water and water filters are bold.

This case study focused on the Flint drinking water contamination incident because long-term provision of emergency drinking water was required for a large population. Additionally, several organizations involved in solid waste management were willing to discuss their experiences with the authors. The goal of this case study was to better understand the strategies and actions taken in response to the solid waste generated. The present case study was conducted by obtaining information from the government and other organizations involved in Flint waste management activities. Lessons learned and solid waste management recommendations for responding to large-scale drinking water incidents were determined.

1.2 Case Study Approach

This study reviewed information available between January 2016 and June 2017, and involved four tasks: (1) Review of waste management infrastructure in Flint before the water crisis, (2) Estimation of the number and mass of plastic water bottles, filter cartridges, and related waste
containers generated, (3) Evaluation of the waste management response from January 2016 to June 2017, (4) Provision of recommendations on how to address waste management challenges during future large-scale drinking water disasters. Organizations involved in the waste management response were queried about their emergency drinking water and water filter distribution actions, plastic water bottle and water filter cartridge collection, recycling, public education, and communication practices (Table 1.2). Coordination between these organizations was studied, and waste generation and handling statistics were provided by the contacted organizations and compared to the calculated estimates. Two surveys were also consulted to evaluate waste management response. The survey entitled Community Assessment for Public Health Emergency Response was conducted from May 17-19 2016, with 182 interviews in 30 blocks (US CDC, 2016). The survey entitled From Crisis to Recovery: Household Resources was conducted from December 11-15 and 18-22, 2017, with 2,029 responses from nine points of distribution (PODs) (Flint Cares, 2018). The purpose and location of PODs are described below.

The approach used to examine the waste management system is described in Figure 1.1. The amount of plastic bottle waste was estimated using emergency water supply demand methodology (Table C.1). While general water filters can be effective for 3 to 4 months or 378.54 liters (100 gallons), filters in Flint Michigan were reportedly replaced monthly (BRITA, 2017a; Flint Cares, 2017). The amount of solid waste generated due to emergency water supply provision was calculated using water provision statistics provided by the MDEQ.
Table 1.2 Organizations and Their Activities in Response to the Recycling Program

<table>
<thead>
<tr>
<th>Organization</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michigan Department of Environmental Quality (MDEQ), Lansing, MI</td>
<td>Facilitated waste management communications between the private and public sector; assisted the City of Flint in identifying organizations that could assist in water bottle recycling activities.</td>
</tr>
<tr>
<td>City of Flint, Flint, MI</td>
<td>Oversaw and contracted with organizations to conduct water bottle recycling activities.</td>
</tr>
<tr>
<td>Genesee County Metropolitan Planning Commission Flint, MI</td>
<td>Collected water filter cartridges and shipped materials to TerraCycle for recycling.</td>
</tr>
<tr>
<td>Michigan National Guard, Lansing, MI</td>
<td>Assisted in distributing emergency water supplies at fire stations.</td>
</tr>
<tr>
<td>Michigan Works Association Lansing, MI</td>
<td>Assisted in distributing emergency water supplies at nine PODs; contacted private companies to pick up full recycling trailers and drop-off empty trailers at PODs.</td>
</tr>
<tr>
<td>TerraCycle, Trenton, NJ</td>
<td>Accepted and recycled water filter cartridges of Brita and PUR brands.</td>
</tr>
<tr>
<td>Republic Services, Inc., Flint, MI</td>
<td>Conducted curbside recycling; donated containers for recycling to local organizations and businesses.</td>
</tr>
<tr>
<td>Metro Sanitation, LLC, Saginaw, MI</td>
<td>Provided containers for 4 to 6 drop-off locations for bottle recycling.</td>
</tr>
<tr>
<td>Schupan Recycling (Schupan &amp; Sons, Inc.), Kalamazoo, MI</td>
<td>Provided containers for 3 drop-off locations for bottle recycling, picked up the containers, transported them to a facility, and compacted the recyclable materials.</td>
</tr>
<tr>
<td>Young’s Environmental Cleanup, Inc., Flint, MI</td>
<td>Collected bottles from 3 drop-off locations.</td>
</tr>
<tr>
<td>Averill Refuse &amp; Recycling, Inc. (bankrupt)</td>
<td>Received and processed bottles from Metro Sanitation, LLC; managed most of the school bottle collections.</td>
</tr>
<tr>
<td>Star Truck Rentals, Inc., Grand Rapids, MI</td>
<td>Worked with Schupan Recycling and Metro Sanitation, LLC to collect, store, transport and process bottles for recycling.</td>
</tr>
<tr>
<td>General Motors Co (GM), Detroit, MI</td>
<td>Partnered with Schupan Recycling and accepted nearly 2 million Flint bottles into its recycling program.</td>
</tr>
<tr>
<td>Petoskey Plastics, Inc., Petoskey, MI</td>
<td>Donated 70,000 recycling bags to assist in bottle collection activities by Schupan Recycling.</td>
</tr>
</tbody>
</table>
1.3 Results and Discussion

1.3.1 Waste management system prior to October 1, 2015

In 2013, the City of Flint established a five-year contract with Republic Services, Inc. to manage solid waste in the community (Longley, 2013). Republic is the second largest provider of domestic non-hazardous solid waste collection, transfer, disposal, and recycling, and operates in 41 states and Puerto Rico (Republic Services, 2017). Under contract, Republic provided three services to Flint: (1) curbside garbage service, (2) curbside yard waste service, and (3) curbside recycling service (City of Flint, 2016c).

In May 2013, Republic began a curbside recycling program in Flint for co-mingled recyclables. Curbside co-mingled recycling pickups occurred bi-weekly at residences and included aluminum, steel, tin, glass, paper products, and various types of plastics. To participate in the recycling program, residents contacted Republic and were then sent a single 18-gallon (68.14-liter) bin. Republic operated a 28 yd³ (21.4 m³) compacting truck for co-mingled recyclables. Mixed recyclables were then transported 125.5 km to New Boston, Michigan. In April 2014, when the water source was switched to Flint River, approximately 13% to 15% of the population participated in the curbside recycling program according to Republic’s estimate.
1.3.2 Waste management system after the drinking water was declared contaminated

On October 1, 2015, the Genesee County Board of Commissioners issued an emergency advisory that warned tap water should not be used for drinking unless the water had been tested and did not contain elevated levels of lead. The county also stated that residents could drink filtered tap water through a National Sanitation Foundation International (NSF International) approved water filter (Genesee County Board of Commissioners, 2015). After two months, the Flint Mayor declared a state of emergency and told residents that their drinking water was not safe to drink because of high lead levels. The following month, the Genesee County Commission (January 4) and Michigan state (January 5) declared an emergency (Michigan State Government, 2016b; Moore, 2016a).

To support the community, public and private organizations provided emergency drinking water supplies to the City of Flint. The total amount of water and bottles that entered Flint could not be determined because records were not centralized nor was there full accounting of the organizations that provided assistance. Estimates in the present study were assembled from public reports and discussions with MDEQ and the City of Flint. On December 14, the FEMA sent 28,000 liters of bottled water (0.5 L) to Flint (Fonger, 2015). On January 10, Red Cross volunteers assisted in the distribution of bottled water and filters (Zarowny, 2016). On January 12, the Michigan State Police and Genesee County Sheriff’s Department started distributing cases of water, water filters, replacement cartridges and testing kits (Acosta, 2016). On January 14, the Michigan Governor activated the Michigan Army National Guard to assist in emergency water supply distribution (Fonger, 2016). Until December 2017, Flint residents could use state-funded bottled water services through the PODs, HELP Centers, and Access and Functional Needs (AFN) programs (Flint Cares, 2018). Michigan State University student athletes also assisted in water distribution efforts (Michigan State Government, 2016c). Walmart, Coca-Cola Company, Nestle, and PepsiCo announced they would donate up to 6.5 million bottles through the end of 2016, and many other companies pledged hundreds of thousands of dollars and cases of water (Graham, 2016). The United Auto Workers union, Detroit Lions, and celebrities also donated money or bottled water (Associated Press, 2016; Helsel, 2016; Rothstein, 2016). Shortly after the emergency declaration, the Association of Plastic Recyclers made a financial contribution to help begin a short-term plastic bottle reclamation program (Thomas, 2016).
1.3.3 Points of distribution (POD)

To assist the population obtain life sustaining commodities, in January 2016, PODs were created in Flint at five centralized locations (FEMA, 2010). PODs were initially established at fire stations to expedite emergency water supply distribution (Moore, 2016b) (Figure B.1). Over the following weeks, the National Guard distributed bottled water, water filters, replacement cartridges, and home water testing kits (Flint Cares, 2017b). Pennington (2017) reported residents visited PODs in cars, on foot, bikes and buses to collect water bottles. The maximum distance from any household to the nearest water point was estimated to be 500 meters (Pennington, 2017).

In April 2016, the City of Flint relocated and increased the number of PODs to nine locations. These actions were conducted to address the community’s continuing emergency water distribution needs such as increasing emergency water supply accessibility for residents and the provision of sufficient area for bulk water storage and waste collection activities on location (Moore, 2016c). Three PODs opened in mid-April, while the remaining six PODs opened during the following months. While the initial five PODs were located at fire stations, the nine PODs were located at churches and banks.

Discussions with organizations that participated in POD waste collection activities indicated much of the information the authors sought was not available. This included the total number of waste collection containers per site, the frequency of pickups for all participating organizations, and the total amount of waste collected per site. Organizations contacted provided different levels of details regarding their activities and activities they witnessed. For example, one waste collection company declared bankruptcy during the incident, but received recyclables from another waste collection company that participated in the recycling response. No records were obtained from that organization. However, one company involved in POD recycling pickup provided some insight into their operations. The transfer of waste/recyclables between companies and the lack of publicly available records inhibited a more detailed review of POD operations and waste management activities.

1.3.4 Water demand and water bottle waste estimates

Water use and water bottles generated by each household were reported by a nonprofit organization and the US Centers for Disease Control and Prevention (CDC). Flint Cares (2018) reported that 14.7 cases of bottled water were used by the survey participants. More than 95%
residents used bottled water for cooking, about 92% for brushing teeth, about 58% for bathing (Flint Cares, 2018). US CDC reported that from October 2015 to May 2016, 75.0% of households in Flint consumed bottled water from distribution sites for drinking and cooking, and two other main sources were bottled water from the store (51.6%) and filtered tap water (11.1%) (US CDC, 2016). In households using water filters for drinking and cooking, 91.4% responded to having filters on the kitchen faucet, and 12.6% on the bathroom sink.

Based on census records, emergency water demand factors (Table C.1), and that water filter cartridges were estimated to only be viable for 30 days, the authors estimated monthly water demand and water bottle and filter waste generated in the City of Flint (Table 1.3). A challenge in determining these estimates though, was that a wide range of water use estimates were found in the literature. Also, nearly all water use estimate factors were based on short-term water outages, but not long-term incidents like the emergency in Flint.

Water demand factors suggested by different organizations and data samples in Flint are described in Table 1.3 (US EPA, 2011; WHO, 2011; Zdanowicz, 2016). The consumption rates ranged from 1.89 L/cap-day to 25.15 L/cap-day. Based on the consumption rates, 4 to 51 million liters of water were required for three weeks. Thus, water supply provision could have resulted in approximately 8 to 103 million bottles in three weeks (Table 1.4).
Table 1.3 Estimated Water and Filter Demand

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Water Demand</th>
<th>Filter Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WHO</td>
<td>EPA</td>
</tr>
<tr>
<td>Drinking</td>
<td>2.5-3 L/cap-day</td>
<td>-</td>
</tr>
<tr>
<td>Cooking</td>
<td>3-6 L/cap-day</td>
<td>-</td>
</tr>
<tr>
<td>Personal Hygiene</td>
<td>2-6 L/cap-day</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>7.5-15 L/cap-day</td>
<td>1.89-18.93 L/cap-day</td>
</tr>
</tbody>
</table>

|                    | Estimated Total | 30,676,590 | 7,730,500 | 102,868,082 |
|                    | Consumed *      | L/3 weeks  | L/3 weeks | bottles/3 weeks |
| Bottles Generated** | 61,353,180 | 77,427,731 | bottles/3 weeks |

* The estimated total consumption was calculated for the whole city. Flint had 97,386 residents and 40,260 households in 2016.
** The estimated total number of bottles was calculated for 0.5 L bottle.
Note: The City of Flint provided the one-month lifetime of the filter cartridge.

The estimates above indicated 40,260 water filters per month were needed, however, no records were found that documented the actual number of filters provided or used. In addition, the actual use of filters may vary from predicted amounts for several reasons. While commercial certified filters were effective in reducing the level of lead up to 99.85%, some households (up to 15% by some estimates) did not have a water filter installed (Flint Cares, 2018; Flint Water Study, 2016; Pennington, 2017). Also, US EPA (2016) suggested only cold water should be run through filters, but some residents used hot water (Michigan State University, 2017; Pennington, 2017). Some residents reportedly did not replace filters on time or had difficulty getting replacement filter cartridges (Flint Cares, 2018; Pennington, 2017). Also reported was that some residents had difficulty with the filter cartridge replacement process. The EPA (2016b) recommended Flint residents clean their aerators once a week, though the effectiveness of the aerator cleaning training was not found (Pennington, 2017).

Three weeks after the State set up PODs, the authors contacted MDEQ to understand the amount of waste generated due to emergency water provisions. According to State of Michigan Emergency Operations Center during the first three-week supply, 196,456 cases of bottled water
were distributed by the State of Michigan to the community. MDEQ estimated that only about 50% to 75% of the bottled water being distributed to the community originated from government agencies and that many informal and non-profit organizations provided bottled water directly to the population. Based on discussions with MDEQ, waste generation estimates were determined for the number of bottles, plastic wrapping, and cardboard for each case [3 weeks and 6 months] (Table 1.4). Dimension and physical weight measurements for empty bottles, plastic caps, cardboard, and plastic wrap were conducted using a balance in the author’s laboratory. To calculate these values the following information was assumed:

1. All bottles were Aquafina® bottles [PET with HDPE caps and rings] holding 0.5 liters of water,
2. One case of Aquafina® bottled water contained 24 bottles with a cardboard insert and plastic wrapping,
3. The estimates did not consider HDPE milk jug bottles issued to the community or other sizes and brands of bottles of water.
4. The other brands differ in size and weight compared with Aquafina® used for this estimate (analytical measurement and example calculation are described in the Appendix C).
Table 1.4 Estimated Total Number, Volume, Weight, and Value of Recyclable Materials in Flint, Michigan

<table>
<thead>
<tr>
<th>Characteristic of Material</th>
<th>Short Term</th>
<th>Long Term (6 months**)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>By the Michigan State*</td>
<td>Total, if 25% more by others*</td>
</tr>
<tr>
<td>Number of bottles</td>
<td>4,714,944</td>
<td>6,286,594</td>
</tr>
<tr>
<td>Volume of bottles, uncompacted</td>
<td>203,740 m³</td>
<td>271,653 m³</td>
</tr>
<tr>
<td>Total Wt. of discarded bottles***</td>
<td>88,128 kg</td>
<td>117,503 kg</td>
</tr>
<tr>
<td>Total Wt. of PET portion***</td>
<td>75,270 kg</td>
<td>100,360 kg</td>
</tr>
<tr>
<td>Total Wt. of HDPE cap portion***</td>
<td>6,993 kg</td>
<td>9,276 kg</td>
</tr>
<tr>
<td>PET value, $0.066/kg</td>
<td>$4,979</td>
<td>$6,638</td>
</tr>
<tr>
<td>HDPE value, $0.066/kg</td>
<td>$463</td>
<td>$614</td>
</tr>
<tr>
<td>Total Wt. of plastic wrapping***</td>
<td>9,878 kg</td>
<td>13,171 kg</td>
</tr>
<tr>
<td>Cardboard value $0.22/kg</td>
<td>$2,173</td>
<td>$2,897</td>
</tr>
</tbody>
</table>

*According to State of Michigan Emergency Operations Center 196,456 cases of bottled water were distributed by the State of Michigan during the first three-week supply. MDEQ estimated that only about 50% to 75% of the bottled water being distributed to the community originated from government agencies; ** 30 days per month was assumed; ***See the Figure D.1. for the water bottle measurement.
The actual amount of bottle water theoretically required by the population and reportedly provided by the State and other organizations differed significantly. According to MDEQ records, more than 4.7 million bottles of water were likely generated in first three weeks of the disaster declaration (Table 1.4), which resulted in a significant amount of weight and waste materials. Because the MDEQ suspected that they accounted for 25-50% of the bottled water being provided to the community, it is reasonable that 6.3 to 9.4 million bottles of total waste were generated during the first 3 weeks of the disaster declaration. For comparison, if the population required 1.89-25.15 L/cap-day (per Table 1.3), a range of 8 to 103 million bottles of water were actually required for this same three-week period. According to Flint Cares (2018), 14.7 cases of bottled water was used per household per week on average. For that data set, residents who took the survey at Help Centers reported using 22.0 cases of water per week, while those surveyed who received bottled water deliveries through the AFN service reported using only 5.7 cases per week. Based on 14.7 bottled water cases/household-week, the author’s estimated the average water demand would be 10.42 L/cap-day and 42.6 million bottles were required for this same three-week period for the entire population. No prior studies were found for comparison that tracked bottled water use under similar water infrastructure disasters. Several factors increased the uncertainty of actual water consumption: use of water filters, amount of water used per person or household, persons who did not reside, but entered and left the area. Bottled water was being used for cooking (96.0%), brushing teeth (91.2%), bathing (58.7%), washing hands (48.2%), pets (37.1%), household cleaning (33.4%), baby formula (23.7%), other (20.4%), and flushing toilets (9.3%) (Flint Cares, 2018), while about 1.9% residents consumed unfiltered tap water for drinking (US CDC, 2016).

The economic value of the bottled water waste materials was low compared to the typical retail value of bottled water. This comparison implies other emergency water supply methods may be less costly for long-term emergency water distribution periods. Based on MDEQ’s estimate, for the first three weeks after the PODs set-up, the authors estimated 4.7 million bottles were provided to the community. This had a waste value of $4,979 (PET plastic bottles) and $463 (HDPE plastic caps) (Table 1.4). The retail value of bottled water ranges from about $0.41/L to $2.11/L ($1.57-$8 per gallon) (Lake, 2015). This price is likely associated water collection, treatment, plastic manufacture, bottling, transportation, and profit. In comparison, the typical cost of drinking water from DWSD was $0.00053/L (DWSD, 2015). George (2018) estimated that if a drinking water refill station was used, the price of water could be $0.053/L to $0.11/L ($0.2-$0.4 per gallon).
Therefore, the cost ratio of bottled water-to-refill water-to-tap water was about 2000-to-150-to-1. Bottled water was about 13 times more expensive than drinking water refilling stations. Others have reported that bottled water could be 2000 times more expensive than municipal tap water (Boesler, 2013).

Additional studies are needed to evaluate emergency water supply provision approaches based on the speed and logistics of provision as well as the economic value of bottled water waste materials compared to distributed drinking water refilling stations. There may be conditions where refilling stations are economically preferred if longer term outages are expected or necessary. For refilling stations, reusable and safe water containers would be necessary. The above estimates only pertain to the first six months of the disaster, and because bottled water provision continued for more than 1 year, differences between options for potential cost savings could have been more significant. Additional studies are needed to evaluate the economic differences between bottled water and alternate longer-term emergency drinking water supply options.

1.3.5 Waste collection response

1.3.5.1 Overall material flow

Overall waste generation and collection activities are described in Figure 1.2. According to the US CDC (2016), residents obtained bottled water from PODs or purchased water from stores. Used water bottles were deposited in curbside collection bins, trash bins, PODs and other temporary drop-off locations. Republic Services, Inc. managed curbside pickups and transported recyclable materials to ReCommunity Recycling for processing. The temporary drop-off locations were operated and managed by three waste companies, Schupan Recycling, Young’s Environmental Cleanup, Inc., and Metro Sanitation, LLC. Other used water bottles were discarded into trash bins and transported to landfills. Residents obtained water filters and replacement cartridges at PODs and stores, while used filter cartridges were deposited in trash bins or delivered to PODs for recycling.
1.3.5.2 Curbside pickup

To manage solid waste generated due to emergency water distribution, the City of Flint launched a water bottle recycling program in January 2016 (Moore, 2016d). This program, in collaboration with Republic, included more frequent curbside pickups. This program also established locations for residents to discard used water bottles and filter cartridges (Michigan State Government, 2016d). To address the amount of water bottle waste generated, Republic expanded its bi-weekly co-mingled recyclable pickup for residential customers, to weekly curbside collection. For water bottles that did not fit into the resident’s mixed recyclable bin, Republic directed residents to use plastic bags. Bags were then placed on the curb for mixed recyclable pickup. Republic estimated that the curbside recycling program participation rate increased from around 13% to 27% in January 2016. Based on discussions with the organizations involved in waste management in Flint, it is likely that the increased amount of waste was primarily due to emergency drinking water supply activities (e.g., plastic bottles, wrapping, cardboard).
To collect and dispose of used water bottles, Republic donated event boxes to churches, where parishioners could deposit used water bottles. Republic also provided 10 to 15 commercial buildings in Flint with plastic bags and collection boxes. Building owners placed these containers at the curb for waste pickup or delivered them to PODs. Several dumpsters were also donated to PODs for the collection of bottle, plastic wrap, and pallets.

1.3.5.3 Drop-off recycling and haulers

Schupan Recycling, Metro Sanitation, LLC, and Young’s Environmental assisted in water bottle waste pickup at PODs and at other areas such as Walmart and hospitals. Schupan Recycling had three drop-off locations, Young’s Environmental had three drop-off locations. Metro Sanitation, LLC’s also operated several drop-off locations. Drop-off locations by Metro Sanitation, LLC and Young’s Environmental were not identified.

Schupan Recycling, the largest PET bottle recycler in Michigan, assisted the City of Flint in January 2016 in water bottle recycling. Schupan picked up bottles 2 to 3 times a week from three fire stations (3 of 5 PODs). Trailers of different sizes (18 ft [5.49 m] trailer, 24 ft [7.32 m] trailer, and 53 ft [16.15 m] trailer) were operated at PODs. State employees and the Michigan Works team collected bottles at the nine PODs. Schupan provided three 53 ft dry trailers at PODs and hauled empty bottles once every 10 to 14 days during the stage two. Over 15 months, one recycler collected 81,106 kg of water bottles (Figure 1.3). Schupan took ownership of the bottles they collected and transported them to a processing facility in Wixom, Michigan. At this facility, empty bottles were compressed to about 180 to 250 kg/bail. Clean Tech, Inc. of Dundee, Michigan bought compressed water bottles from Schupan. Some of the processed bottles were converted into fleece, engine covers, air filters and insulation for coats (Price, 2016).
1.3.5.4 Water filter cartridge collection

Two types of filter cartridges were distributed at PODs: BRITA® and PUR® filter cartridges (Michigan State Government, 2017a). The City of Flint and Genesee County Metropolitan Planning Commission (GCMPC) oversaw used filter cartridge collection. GCMPC shipped the collected cartridges to TerraCycle for recycling (Flint Water Rescue, 2016). According to records provided to the authors, the total number of used cartridges collected by GCMPC was much less than the total cartridges donated (Figure 1.4). BRITA® donated 20,000 faucet filters and PUR® delivered 10,000 faucet filters and 40,000 replacement cartridges to Flint (ABC12 News Team, 2016; Brita, 2017b). However, many donated filter cartridges were not accounted for in the GCMPC records. While the City of Flint recommended residents take used cartridges back to the PODs, only 2,693 cartridges were collected from the PODs by June 17, 2017. Lack of available records impedes a more detailed understanding of filter cartridge disposal. Though, the water filter recycling program did divert waste from landfills. Also, if residents could replace activated carbon in filters rather than replacing filter cartridges, the plastic waste generated may have been reduced.
1.3.5.5 Education

Based on feedback from the organizations contacted, waste management public education efforts were necessary and effective. In particular, education activities informed residents about emergency water supply distribution, the curbside and POD based recycling programs, and influenced the waste management activities. Agencies, organizations, and companies conveyed messages to residents through the television, the internet, newspapers and flyers. Republic purchased and distributed mailers, billboards, radio, and TV public education programs to assist Flint residents understand how waste can be handled. Republic and a non-profit organization, Keep Genesee Country Beautiful (KGCB), also held public education seminars and recycle signup events for residents.

A major consequence of the contamination incident and provision of unsafe water to the public was that residents lost confidence in government agencies. Approximately 76% of households received information from the television, 32% from a neighbor/friend/family, 27% from social media, 24% from the radio, 21% from publicly available information fliers, and 20% from newspapers (US CDC, 2016). Comparison of these information sources revealed that 26%
of residents trusted news media most, followed by the Genesee County Health Department (GCHD) (9%), health professionals (8%). Notably, 24% of those surveyed chose others as their most trusted source of information, including trusted self/did not trust anyone (31%), did not trust any listed source (26%), and no trust in government (9%) (US CDC, 2016). No studies or surveys were found that examined whether the loss of confidence affected resident confidence in waste management activities.

An important issue identified by the US CDC was that despite the declared public health crisis several residents remained unaware that unsafe water was present, or of water distribution or filter use instructions in May 2016. About 8% of Flint households did not know there was an elevated lead level in water, 10% reported that they were not informed of bottled water/filter distribution, 20% reported they did not know the filter use instructions, 22% reported they did not know about the water testing resources available (US CDC, 2016), and 39% did not know how to test their water for lead (Flint Cares, 2018). Again, no survey question focused on waste management practices.

1.4 Observations and Lessons Learned

This large-scale drinking water contamination incident was unique in that the incident rendered the entire water distribution system and building plumbing systems incapable of distributing safe drinking water. The need for the community to obtain safe drinking water from other sources for many months also posed unique challenges. Due to the uniqueness of these circumstances and lack of prior studies found in the literature on waste management activities associated with these incident types, results from this study have value.

A major finding from this study was that public, private sector, and non-profit organizations supported waste management activities and formed a public-private hybrid system. Although organizations in each sector acted individually, several partnerships increased efficiency and the effectiveness associated with the waste management response. Genesee County, the City of Flint, and the State of Michigan cooperated to set up PODs for emergency water distribution. These organizations also partnered with waste management companies to initiate recycling programs for both water bottles and filter cartridges. Social organizations and volunteers also assisted in water distribution and recyclable collection. The impact of the waste management activities can be found by comparing the typical recycling participation rate and the participation
rate in Flint. For opt-in curbside recycling systems, where residents must sign up for recycling collection, typically 33% of residents elected to participate in recycling programs (Sustainable Packaging Coalition, 2016). According to Republic’s estimates, the participation rate was approximately 27% after the emergency declaration. Also, Republic estimated that based on the number of bottles picked up at places that were not officially a part of the curbside recycling program, about 65% of the population utilized curbside recycling. Lack of available records inhibited a greater understanding of the Flint recycling rate.

This study revealed the importance of collaborations formed between individuals, organizations, the government and private entities in the wake of a large-scale disaster. This finding agrees with many prior studies where public-private partnerships have been found to improve incident management (Auzzir et al., 2014; David Swanson and Smith, 2013; Stewart et al., 2009; Zhang and Kumaraswamy, 2011). In Flint, public and private partnerships enabled POD setup and operation, the conduct of public education activities, and waste tracking. Based on feedback from the organizations contacted, these relationships helped address waste management challenges during the incident. As a government centric approach might not solve the challenges encountered during a disaster, these public and private partnerships could enhance situational awareness, improve decision making and increase the effectiveness of the emergency management efforts related to waste management. Improvements in the system are possible through better record keeping and documenting of such efforts.

Flint residents were provided with emergency water supplies in a manner that produced large amounts of waste. Solid waste, including bottles, cardboard, plastic wrapping etc., generated due to the use of bottled water and filter cartridges can be reduced. FEMA has instructions of water and water container preparation and treating uncertain quality water for short-term natural disasters (FEMA and American Red Cross, 2004). It is possible to develop similar water supply plan for future long-term large-scale water outage. To develop the plan, it is necessary to build strategies to treat water and monitor water quality in household water containers, water tankers, or other types of water storage and transport devices. The importance of these activities was underscored during the 2014 water contamination ‘do not use’ drinking water incident in Charleston, WV. During the response, some bulk water haulers were filling their containers from the shutdown and contaminated water treatment plant and then were distributing that contaminated water into the
community (Craig 2014). Life-cycle assessment and economic analysis are necessary to assess which strategy is more environmentally friendly and which is less costly.

Unsolicited donations following a disaster can be a burden for a community and generate more waste (Edwards, 2009). Water donations directly distributed to community could cause water provision disequilibrium. This would compromise the accuracy of estimated water demand through other sources and estimated waste generated. Lack of information exchange and donation management could decrease recycling efficiency. Therefore, it is recommended that during disaster preparedness communities consider how to better monitor emergency water supply resources and donations.

The authors did not find much guidance about how to estimate water demand for long-term incidents (> 21 days) or waste management challenges associated with large-scale drinking water outages. FEMA and EPA documents only included water demand rates for short-term water outages (FEMA and American Red Cross, 2004; US EPA, 2011). Because several large-scale drinking water contamination incidents have occurred over the years, future work is recommended to document water demand rates for long-term water outages and make those data publicly available.

A stepwise decision process for siting PODs was not found by the authors during this case study. As discussed, five fire stations were used as PODs during the initial response. These PODs were moved and expanded to nine new locations around the city to increase service accessibility for residents. The PODs were operated to not only distribute water but also collect used bottles and cartridges. POD relocation and expansion was likely based on communications between public agencies and private waste management companies, but no records of these discussions were found. Researchers have developed GIS-based methods to locate temporary waste management sites (Grzeda et al., 2014; Kim et al., 2014, 2013; Pramudita et al., 2014). However, few studies were found that investigate strategies of POD location. This includes literature on the design and layout to increase accessibility and operational efficiency including economy, environmental and social perspectives. To improve emergency water supply and filter distribution to communities, future work could be conducted to determine a strategy for POD siting and factors that emergency planners should prioritize.

Public education activities influenced the public’s awareness of emergency water supply distribution and participation in recycling programs for water bottles and used filter cartridges. As
previously mentioned, some residents were not informed and others had different degrees of confidence in public information coming from different sources. Thus, emergency agencies should develop an effective strategy to deliver emergency information to the public in a timely manner. Special consideration should be dedicated to the type of media, information-delivery frequency, and on- and off-line public education systems responding to emergency and planning for emergency water supply and waste management. Also important is analyzing the effectiveness of the public notification activities in real-time, and adjusting when necessary to reach a larger audience or correct misunderstandings. When drafting advice or instruction, agencies should consider related problems, concerns by residents and release statements or explanations for such problems. Failure to explain related problems may result in residents not believing in and not conforming to advices/instructions. For example, Flint residents were concerned about whether unfiltered tap water would cause skin rashes or hair loss (Pennington, 2017). Materials reviewed for this case study did not mention whether or not washing with unfiltered tap water had these effects (GCHD and MDHHS, 2015; US EPA 2016d). Several studies identified that social media 1) influences social consciousness, 2) leads to rapid information delivery, and 3) reaches a broader and more targeted population than any conventional methods (Kim et al., 2018a; Kim and Hastak, 2018a, 2018b; Lindsay, 2011; Magsino and National Research Council, 2009; Yates and Paquette, 2011).

For effective waste management, tracking the material flow and documenting the amount of recyclables collected and transported is important. Without sufficient records, officials and organizers cannot effectively track the recycling rate or adjust the recycling program and practices according to data and changes in participating companies. Most companies involved in bottle and filter cartridge recycling contacted did not document their waste collection/recycling activities to the detail the authors sought. Reasons for lack of data include: difficulty to record the amount of bottles from co-mingled recyclables, company bankruptcy, information considered proprietary, etc. Thus, periodic reporting and data documenting to community officials is necessary so that more detailed analyses can be completed. Strategies of documenting high volume and co-mingled waste are needed. Automated waste monitoring systems can help paper records and anecdotal recollections form memory.
Until July 2017, Flint’s water had been meeting federal standards for over one year, and 90th percentile water lead level was 7 µg/L (Bondy, 2017; Michigan State Government, 2017b). For the transition from bottled water to filtered water, two of nine PODs were closed on August 11, 2017; three of the seven remaining PODs were closed on September 5 (Michigan State Government, 2018a). Free water program supported by the State ended on April 6, 2018, and the four remaining PODs closed when state funded water were all distributed to residents (Ahmad, 2018). However, free faucet filters, replacement cartridges and water testing kits were available at Flint City Hall and by calling Community Outreach Resident Education (CORE) until water service line replacement is complete (Fonger, 2018; Michigan State Government, 2018b).

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2. BLAST FURNACE SLAG USAGE AND GUIDANCE FOR INDIANA

2.1 Introduction

2.1.1 Problem statement

The Indiana Department of Transportation (INDOT) permits the use of air cooled blast furnace slag (ACBFS) as a conventional aggregate. ACBFS is reported to be a beneficial reuse material generated as a byproduct from steel production. Based on material price and hauling costs, ACBFS use can have considerable cost savings compared to the use of virgin materials (i.e., crushed rocks and gravels). ACBFS can be used in granular base, hot mix asphalt (HMA), Portland cement concrete (PCC), and embankment or fill applications (Chesner et al., 1998). The material is often crushed and screened to meet specified gradation requirements using conventional aggregate processing equipment. When this study was initiated, INDOT was aware ACBFS had been used at numerous sites in the LaPorte District.

At present, INDOT attempts to minimize the potential for negative impacts due to chemical leaching from ACBFS by requiring products pass a test procedure: Acceptance Procedures of Air Cooled Blast Furnace Slag for Leachate Determination, Indiana Test Method (ITM) No. 212 (INDOT, 2015a). An ACBFS sample is considered to have passed the ITM procedure if after seven days of soaking in distilled or deionized water, the water pH is between pH 6.0 and 10.5 and its color is lighter than “moderate greenish-yellow”. Recent field observations indicate that leachate has originated from ACBFS sites and periodic odor issues have also been reported (Nevers, 2016). In a prior study supported by INDOT, it was reported that ACBFS sites had storm water pH in excess of 10.5 and green colored water (Banks et al., 2006). To eliminate a reoccurring leaching problem at one site, INDOT recently spent about $500,000 to remove and replace ACBFS material from a completed constructed project. Also reported is that another construction site where ACBFS was used continues to leach after 17 years.

This study was conducted because INDOT desired to better understand ACBFS use in and outside Indiana. This study focused on better understanding leachate chemistry, standards and test methods, and how other DOTs handle ACBFS use and ACBFS leaching sites.
2.1.2 Research objective

The objective of the proposed research was to better understand factors that control ACBFS leaching, review remediation strategies, and identify applications where future ACBFS use restrictions or siting criteria were needed, if any.

2.1.3 Business case

The estimated cost to remove and replace ACBFS aggregate that was causing environmental issues at one INDOT site exceeded $500,000. This action was unexpected and costly. To avoid construction situations where pollutants are generated at levels unacceptable to INDOT and its stakeholders, INDOT supported the present study.

In response to internal decisions, INDOT plans to adjust their ITM to help minimize the potential for ACBFS leachate conditions that would exceed Indiana Water Quality Standards (IWQS) (State of Indiana, 2017). In particular, IWQS does not permit discharge to waterways in excess of pH 9.0 or when “offensive odors” occur. Completion of this project would equip INDOT staff with information that will enable them to make decisions about future ACBFS usage.

2.1.4 Technical approach

A literature review of government documents, peer-review and trade industry literature was conducted to ascertain factors that influence ACBFS chemical leaching issues such as high pH, color, and odor. The literature was also examined for adaptive measures that can enable ACBFS usage such as encapsulation in a more inert material and incorporation of wastewater treatment plant sludge into ACBFS. A prior INDOT study was reviewed along with other studies conducted outside of the INDOT (Banks et al. 2006).

The second task involved ACBFS data gathering from INDOT Districts with regard to Area Engineers and in addition to Project Engineers about ACBFS. Project information requested included the location of ACBFS used including the approximate year and application. In addition to data gathering from INDOT staff, the project team conducted a site visit to a ACBFS storage facility and steel mill that generated the ACBFS. The purpose of this visit was to learn more about the ACBFS storage and aging processes as well as the physical mechanics by which aged ACBFS is removed and transported.
The third project task involved contacting other state transportation agencies to determine the degree they incorporated ACBFS into their projects. This also included an assessment of ACBFS approval requirements, lab- and field-scale test methods applied for ACBFS leaching characterization, best practices they had developed based on experience such as required siting criteria or application restrictions, and current issues with existing ACBFS sites.

### 2.1.5 Work plan

The following tasks were defined in this project:

1. Research and determine factors that influence ACBFS chemical leaching issues such as high pH, color, and odor; and describe why each of these factors/conditions could be undesirable.
2. Research the adaptive measures considered or implemented in the literature for using ACBFS in roadway applications.
3. Determine whether or not ACBFS is used at many INDOT projects and if leaching is reported to be a problem at any sites.
4. Conduct site visits at locations where ACBFS is stored, aged and observe the physical mechanics by which aged ACBFS is removed and transported and incorporated into the final project site.
5. Ascertain how other DOTs are using ACBFS and the restrictions any test procedures used, if any.

### 2.2 Air Cooled Blast Furnace Slag Use by Indiana

#### 2.2.1 Use of ACBFS

ACBFS is used by some transportation agencies because of its physical properties and low cost. ACBFS has been used for bound and unbound applications for roadway construction. Bound applications have included HMA and PCC. Unbound applications have included road base, embankment, and borrow material. Challenges with using ACBFS have been reported to be chemical leaching of prompting elevated pH, colored water, and off-odor issues.

According to discussions with INDOT representatives and a review of INDOT documents, ACBFS has been used in a variety of applications. These include: Aggregate for underdrains, bed course material, B Borrow, borrow, dense-graded subbase, structure backfill, aggregate for end
bent backfill, subbase, warranted micro-surfacing, fine and coarse aggregate for Portland cement concrete pavement (PCCP), fine and coarse aggregate for HMA mixtures, fine and coarse aggregate for stone matrix asphalt (SMA) mixtures. ACBFS has mostly been used in the LaPorte District. In 2016, more than 117 thousand tons of ACBFS was used as coarse aggregate, which was about 70% of total coarse aggregate used by the LaPorte District. The approximate ratio of ACBFS coarse aggregate quantity to total coarse aggregate quantity increased from 15% to 70% from 2012 to 2016 in this district.

INDOT staff have reported that ACBFS has been less costly for construction projects than other alternatives (i.e., crushed stone). The main cost savings was reported as trucking and the savings varied with the distance to the suppliers to the usage site. For example, in 2016 INDOT reported that the average unit price of ACBFS was less than crushed stone for six applications: No. 2 stone, subgrade treatment, compacted aggregate No. 53 base, dense graded subbase, compacted aggregate No. 53, and aggregate for underdrains. Price differences that ranged from $2/ton to $11.27/ton. Though, ACBFS used as “aggregate for end bent backfill” was more expensive than crushed stone by $9.50/ton. Based on usage data, the cost of using crushed stone was estimated to be about $1.6 million greater if ACBFS had not been used for these seven applications.

2.2.2 Existing sampling and testing protocols

2.2.2.1 ITM No. 207-15T, sampling stockpiled aggregates

INDOT required ACBFS be sampled according to ITM 207 and tested according to ITM 212. INDOT’s ITM 207 describes the method of sampling fine and coarse aggregate stockpiles (INDOT, 2015b). A front-end loader is used to dig into the stockpile and a small pile of material (10 to 15 tons) is to be set aside. While forming the small pile, the operator is required to minimize the amount of segregation. The loader bucket is recommended to be kept as low as possible and the material should be rolled out of the bucket rather than dumping. The operator is then required to thoroughly mix the small pile with the loader. This includes pushing the bucket into the pile until the front of the bucket passes the midpoint of the original pile and slowly rolling the bucket forward. After mixing, the small pile is to be sampled by obtaining six full shovels of material. Material is to be obtained at equal increments around the pile and at one-third height of the pile. A square bit shovel is required for coarse aggregate sampling. A fire shovel or sampling tube shall be used for fine aggregate sampling. ITM 207 also specifies that when the height of fine aggregate
stockpiles do not exceed the height of the sampler and the segregation is not apparent, samples may be taken directly from the face of the stockpile. Another statement is that “the surface crust of the fine aggregate stockpile is required to be removed from the sampling area.” According to INDOT representatives, surface crust can form on fine aggregate slag piles. Sampling after surface crust removal would help better characterize ACBFS that could be used.

2.2.2.2 ITM No. 212-15T, acceptance procedures of air cooled blast furnace slag for leachate determination

INDOT’s ITM 212 sets forth the procedure for sampling and testing ACBFS leachate (INDOT, 2015a). The procedure includes sampling ACBFS aggregate in accordance with ITM 207 and reducing the original sample in accordance with American Association of State Highway and Transportation Officials (AASHTO) T 248, Standard Method of Test for Reducing Samples of Aggregate to Testing Size (AASHTO, 2003). Leachate tests are required for each stockpile of approximately 2,000 tons (4,000,000 lbm) of ACBFS. When ACBFS is used for HMA or PCC, leachate testing is not required.

After sampling 80 to 100 lbm of ACBFS according to ITM 207, the size is reduced according to AASHTO T 248. Approximately 20 to 25 lbm of that material is placed in a five-gallon bucket and covered with distilled or deionized water by ½ to 1 inch. This amount of ACBFS sampled represents roughly 0.0005% of the total mass of ACBFS in the pile. With the lid on the bucket, the sample is soaked for one day. Then the sample is thoroughly stirred and approximately 100 ml of water sample is collected. After filtration by medium grade filter paper, water pH is determined in accordance with ASTM E 70 (ASTM, 2006), and the water color is noted. If the sample meets acceptance criteria, the soaking is continued and the testing process is repeated until seven days from the start of initial soaking. The material is deemed acceptable if the results show that water pH is within 6.0 to 10.5 after one day, three day, and seven days of soaking, and water color is lighter than the moderate greenish-yellow color (Hue 10 y).

The ITM requires that to test the stockpiles, aggregate producers first contact the appropriate District Testing Engineer to initiate the approval process. The producers shall also conduct the sampling and testing. The producer is required to maintain the records of stockpile location, stockpile identification, and test results. Stockpiles that do not meet the acceptance criteria may be tested again after 30 days from the first test date.
2.3 Site Visit to an ACBFS Processing Facility and Production Plant

The team conducted a site visit to an ACBFS processing facility and the steel manufacturing plant that generated the ACBFS. This processing facility annually sells about 1 to 1.5 million tons of slag. During ACBFS production, the steel manufacturer sprayed water on the hot slag to accelerate the cooling process. After the cooling process some ACBFS was washed on a conveyor belt. Also, water was sprayed onto the stockpiles at storage sites. These actions, in effect, were likely facilitating the washing process. The ACBFS processing facility provided testing data to the authors. For one sample, the “sulfur content” (not specific to total sulfur, elemental sulfur, or other form of sulfur) was $1.02 \pm 0.09\%$, and sulfur trioxide ($SO_3$) content was $2.55 \pm 0.23\%$ (Table 2.1). Additional testing data were not reviewed.

During the site visit, the company indicated that a leachate test was conducted for every 2,000 tons of ACBFS produced (and received from the steel manufacturer) and for every 8,000 tons of ACBFS shipped from their stockpile. The ACBFS facility indicated that they followed ITM 212, though some deviations were observed according to their “Leachate Testing Procedure [undated]” (Beemsterboer, n.d.). The company followed the ITM 212 requirement that slag must be covered in 5-gallon bucket (0.5 to inch water depth) for a leaching test, and 1, 3, and 7 days of soaking occurred. In addition to the ITM requirement the company also evaluate leachate quality after day 5. While ITM 212 required water pH between 6.0-10.5, the company indicated that they had more stringent requirements (6.0-9.0). A difference between company discussion and procedure listed in ITM 212 was that in accordance with 212, the testing should also follow ITM 207 and AASHTO T 248. In accordance with ITM 207, aggregates should be sampled (80 to 100 lbm) and in accordance with AASHTO T 248, samples should be reduced (20 to 25 lbm). Their physical sampling method of stockpiles was not described in their leaching test procedure. According to ITM 207, a front-end loader shall set aside a small pile of 10 to 15 tons of material and thoroughly mix the small pile. Then aggregate is sampled 80 to 100 lbm with shovel or sampling tube, and is reduced to 20 to 25 lbm. Discussions with ACBFS facility representatives implied only ACBFS on the edge of piles was sampled.

The company handled ACBFS in accordance with ITM 212. First, ITM 212 required that the producer keep records of the location of stockpiles, their identification and test results. A map was available that described stockpile locations, ACBFS sizes, which stockpiles were approved [passed leachate test] and had not passed the leachate test at the time of sampling (Figure 2.1). To
lessen the chance newly created ACBFS was shipped to users, the company representative explained that they ship stockpiles out from oldest to newest whenever possible. This approach is described in the company’s leachate testing procedure. According to discussions with company representatives, the goal was to have a three- to four-month period between when the ACBFS is produced and when the material is shipped to a user. The chemical composition of an ACBFS sample was reported (Table 2.1).
Table 2.1 Results of Muffle Furnace and TCLP Tests Used to Evaluate ACBFS Composition

<table>
<thead>
<tr>
<th>Muffle Furnace ACBFS composition (%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Oxide (Na₂O)</td>
<td>0.30 ± 0.05</td>
</tr>
<tr>
<td>Magnesium Oxide (MgO)</td>
<td>10.86 ± 0.56</td>
</tr>
<tr>
<td>Aluminum Oxide (Al₂O₃)</td>
<td>7.58 ± 0.92</td>
</tr>
<tr>
<td>Silicon Dioxide (SiO₃)</td>
<td>37.19 ± 0.92</td>
</tr>
<tr>
<td>Phosphorus Pentoxide (P₂O₅)</td>
<td>0.10 ± 0.01</td>
</tr>
<tr>
<td>Sulfur Trioxide (SO₃)</td>
<td>2.55 ± 0.23</td>
</tr>
<tr>
<td>Potassium Oxide (K₂O)</td>
<td>0.34 ± 0.03</td>
</tr>
<tr>
<td>Calcium Oxide (CaO)</td>
<td>38.79 ± 1.22</td>
</tr>
<tr>
<td>Titanium Dioxide (TiO₂)</td>
<td>0.43 ± 0.06</td>
</tr>
<tr>
<td>Chromium (III) Oxide (Cr₂O₃)</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>Manganese Oxide (MnO)</td>
<td>0.66 ± 0.12</td>
</tr>
<tr>
<td>Iron (III) Oxide (Fe₂O₃)</td>
<td>0.57 ± 0.19</td>
</tr>
<tr>
<td>Zinc Oxide (ZnO)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Sulfur (S)</td>
<td>1.02 ± 0.09</td>
</tr>
<tr>
<td>Loss on Ignition % (L.O.I.)</td>
<td>0.7 ± 0.36</td>
</tr>
<tr>
<td>Total</td>
<td>101.09 ± 1.93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TCLP test results (mg/L)</th>
<th>Results</th>
<th>Reporting limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>ND</td>
<td>0.0010</td>
</tr>
<tr>
<td>Arsenic</td>
<td>ND</td>
<td>0.0100</td>
</tr>
<tr>
<td>Barium</td>
<td>ND</td>
<td>0.500</td>
</tr>
<tr>
<td>Cadmium</td>
<td>ND</td>
<td>0.00200</td>
</tr>
<tr>
<td>Chromium</td>
<td>ND</td>
<td>0.00300</td>
</tr>
<tr>
<td>Lead</td>
<td>ND</td>
<td>0.00750</td>
</tr>
<tr>
<td>Selenium</td>
<td>ND</td>
<td>0.0300</td>
</tr>
<tr>
<td>Silver</td>
<td>ND</td>
<td>0.0100</td>
</tr>
</tbody>
</table>

The chemical composition of ACBFS was reported by the ACBFS supplier. Eight elements were reported for a “Toxicity Characteristic Leaching Procedure (TCLP)” test. The production date and age of ACBFS sample analyzed was not reported. TCLP reporting limits were converted from µg/L to mg/L. References used for this table include (Beemsterboer, 2017; Microbac, 2016).
In 1994, seven states were using blast furnace slag (BFS) [type not specified] in construction: Indiana, Kentucky, Maryland, Michigan, Missouri, New York, and Ohio (FHWA, 2016). During the present study, a few other state transportation agencies mentioned BFS in their state specifications (Table 2.2). During the present study, the authors contacted transportation agencies in Illinois, Ohio, Maryland, Michigan, and New York. Each agency provided feedback
about their BFS experiences. Example information the sought about ACBFS use, regulations, sampling and testing protocols, and leaching problems can be found in Box 2.1.

Table 2.2 Construction Applications Where ACBFS Can Be Utilized According to State Transportation Agency Specifications

<table>
<thead>
<tr>
<th>Application</th>
<th>IN</th>
<th>GA</th>
<th>IL</th>
<th>MI*</th>
<th>NY</th>
<th>OH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underdrains</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bed course material</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bedding material</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B Borrow</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borrow</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate base</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate for asphalt concrete, prime coat, chip seal, and microsurfacing</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate for asphalt concrete base</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subbase</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dense-graded subbase</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fill</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure backfill</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>Aggregate for end bent backfill</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warranted micro-surfacing</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface course</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic compacted surface</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reconditioning shoulders</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Slope and channel protection</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Coarse aggregate for PCC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Fine aggregate for PCC</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine aggregate for HMA mixtures</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold mix bituminous pavement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine aggregate for SMA mixtures</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine aggregate for mortar or grout</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sand cover</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate cover (ERSC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Gravel access approach (ERSC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Screenings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Embankment construction</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stabilized crushed aggregate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Approaches and patching</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earthwork</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

* type of BFS not specified. Information within this table was compiled from reviewing construction specifications and discussions with state agencies. ERSC = erosion and sediment control. References used for this table include (GDOT, 2013; IDOT, 2016; INDOT, 2014; MDOT, 2012; NYSDOT, 2016; ODOT, 2016).
<table>
<thead>
<tr>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>The [XXXXX] has a total sulfur limit of 2% by weight for air-cooled blast furnace slag as coarse aggregate in Portland Cement Concrete. For what consideration did you set this limit (e.g., strength, cracking issue, leaching issue)? What is the foundation for the 2% maximum limit, not 1% or 3%?</td>
</tr>
<tr>
<td>What transportation applications do you use air cooled blast furnace slag (ACBFS) in? In each application, is ACBFS used as bound ACBFS or unbound ACBFS?</td>
</tr>
<tr>
<td>Except for the specifications and requirements for ACBFS listed in the State specifications, is there any other requirement or limit for ACBFS used in any transportation application?</td>
</tr>
<tr>
<td>Is there any leaching test for the acceptance of ACBFS? Is it for bound or unbound applications?</td>
</tr>
<tr>
<td>What are the sampling protocol for aggregate test and ACBFS test? Are they different?</td>
</tr>
<tr>
<td>Who conducts the sampling and test? ACBFS suppliers or the DOT? Who conducts the leaching test?</td>
</tr>
<tr>
<td>When should ACBFS be sampled and tested? Right after the production? What were the sampling and testing frequencies?</td>
</tr>
<tr>
<td>If the suppliers conduct the sampling and tests, how do you supervise their sampling and test procedure?</td>
</tr>
<tr>
<td>Do you know or do you have report of how long the ACBFS has been weathered when you acquire it? Does it vary with different applications?</td>
</tr>
<tr>
<td>Do you know or do you have report of what the weathering condition was for ACBFS? (i.e., temperature, pH, moisture condition, exposure condition (to air), drainage system)</td>
</tr>
<tr>
<td>Do you know the size of the stockpile when ACBFS was weathered?</td>
</tr>
<tr>
<td>How did you store ACBFS after you acquire it from suppliers? What size of each stockpile was? What conditions were at storage sites (i.e., temperature, indoors/outdoors)? How long did you store it before construction?</td>
</tr>
<tr>
<td>Was there any leaching problem because of ACBFS usage? If there was:</td>
</tr>
<tr>
<td>o What application was the ACBFS used in? Was the ACBFS bound or unbound? If ACBFS was used for roadway construction, what was the road number?</td>
</tr>
<tr>
<td>o What materials were under and above the layer of ACBFS? Do you have the record of the pH, chemical composition of these materials?</td>
</tr>
<tr>
<td>o What chemicals were leached? Do you have any record of the quantity, color, odor, pH, chemical composition of the leachate?</td>
</tr>
<tr>
<td>o Did the leachate ooze up to the ground or permeate into the deeper construction layer and soil?</td>
</tr>
<tr>
<td>o What was the groundwater level at the leaching site? What was the distance from the groundwater to the leaching site?</td>
</tr>
<tr>
<td>o Was there any mechanical failure along with leaching?</td>
</tr>
<tr>
<td>o How did you solve the leaching problem?</td>
</tr>
<tr>
<td>Was there any other problems with bound or unbound ACBFS? How did you solve the problem?</td>
</tr>
</tbody>
</table>

In 2008, the Michigan Department of Transportation (MDOT) was the largest single user of ACBFS in concrete pavement (FHWA 2008). Concrete pavements using ACBFS as coarse
aggregate were constructed in the Detroit freeway system, for interstate and primary highway pavements and structures, and local roads in Detroit and the surrounding communities (i.e., Detroit metropolitan airport pavement construction) (FHWA, 2008). According to information provided by MDOT, Michigan now does not permit the use of ACBFS in concrete mixtures for trunk line pavement and bridge applications. MDOT does permit ACBFS use for unbound drainable base layers. MDOT has not investigated instances of leachate from unbound base constructed with ACBFS. However, they indicated there have been isolated cases of "excessive amounts of precipitate at edge drain outlets.

The Illinois Department of Transportation (IDOT) uses ACBFS in both bound and unbound applications. Transportation applications included subbase, base course, porous/non-porous granular embankment, porous/non-porous backfill, French drains, PCC mixtures, and HMA mixtures. For bound ACBFS aggregate used in PCC and HMA mixtures, procedures must follow the policy memorandum: *Slag Producer Self-Testing Procedure* (IDOT, 2012a). According to the memorandum, fine and coarse aggregates shall meet limits and ranges in specific gravity and absorption. IDOT also has requirements for the quality of unbound ACBFS leachate following another memorandum: *Crushed Slag Producer Certification and Self-Testing Program* (IDOT, 2012b). According to that policy memorandum, ACBFS was recognized with the potential to leach out a greenish-yellow effluent and produce an objectionable odor. For unbound applications, ACBFS used for subbase, base course, porous/non-porous granular embankment, porous/non-porous backfill, and French drains shall conform to this policy memorandum. According to the memorandum, producers supplying ACBFS for these uses shall initiate a sampling and testing program as detailed in *Illinois Test Procedure (ITP) 202, Leachate Determination in Crushed Slag Samples*. Producers shall also submit a certification letter each year to the IDOT certifying that the producer will ship only material that has been tested and accepted.

The Ohio Department of Transportation (ODOT) also approved ACBFS use in bound and unbound applications. ODOT required that ACBFS stockpiles pass a leaching test, *Supplement 1027 Air Cooled Blast Furnace Slag Material Control and Acceptance Testing for Items 203, 204, 304, 410, 411, 503, 518, 611, 617, 850 and 851*, and only required this performance for unbound applications (ODOT, 2012). The ITM 212 required that the ACBFS suppliers were responsible for product sampling and conducting the product leaching test. In Ohio, both ODOT and ACBFS suppliers conduct leaching tests for ACBFS acceptance. The author’s discussions with ODOT also
indicated ODOT has had no known problem with the use of bound or unbound ACBFS, including leaching. It is noteworthy that ODOT’s acceptance criteria and testing procedures differed from ITM 212. This information is discussed below. ODOT also has a requirement that limits total sulfur in bound ACBFS coarse aggregate in PCC to 2%. This criterion was instituted for concern that ACBFS may facilitate PCC cracking and expansion from ettringite formation.

New York State Department of Transportation (NYSDOT) had specifications for ACBFS use in various construction applications. NYSDOT also had an acceptance procedure for aggregate sources (NYSDOT, 2007, NYSDOT, 2016). However, according to communications with NYSDOT, no ACBFS has been used in transportation construction because there was no available source. A representative of the Maryland Department of Transportation (MDOT) indicated granulated blast furnace slag (GBFS) has only been used in the state, not ACBFS.

2.4.1 Tests and requirements

Tests and requirements for ACBFS leaching by state transportation agencies are limited. Among the transportation agencies the authors contacted, IDOT and ODOT had ACBFS leachate determination procedure and criteria. IDOT required each stockpile of ACBFS pass ITP 202 for unbound use. Sampling and testing is conducted by individuals who have passed IDOT Aggregate Technician or Mixture Aggregate Technician training classes. Slag producers then provide the test results to IDOT. An IDOT inspector witnesses one sampling and sample reduction every 20 production days. The inspector also obtains one of two final split portions for IDOT testing as quality assurance. ITP 202 sets forth a detailed sampling frequency. ACBFS can be sampled when the stockpile is being created or after the stockpile has been created. If sampling is conducted “as the stockpile is being built” each sample should be collected in random increments over each 1,500 tons stockpiled. A minimum of five samples should be collected for each stockpile. After a stockpile is created, samples are collected randomly from both the exterior and interior by shovel. IDOT also required that the producer use the services of heavy equipment for the excavation of interior material. Each sample should be 80 to 100 lbm, from which 20 to 25 lbm material is collected for testing in accordance with ITP 248 Reducing Samples of Aggregate to Testing Size. A 20 to 25 lbm test sample (except for densely graded material) is then rinsed over a 4.75 mm sieve to remove fine particles associated with larger particles. Next, the sample is covered by at least ½ in. of water [type not specified] in a 20 L bucket (not indicate whether with lid on or off).
After soaking for 24 hours, the water is thoroughly mixed and a 100 ml water sample is collected and filtered (filter paper not specified). If the color of water is equal to or darker than the moderate greenish-yellow color from the rock chart (Hue 10 y), this sample fails the test. If the water appears clear, the sample should continue to be soaked for another 24 hours. After 24 hours and 48 hours of soaking, products that pass the test should have no colored water. After all leaching test results of one stockpile is collected, acceptance of the stockpile is determined. Acceptable stockpiles have 10% or less samples failing the leaching test.

The ODOT required that every stockpile of ACBFS pass an acceptance test (Supplement 1027) for some construction items (ODOT, 2012). Supplement 1027 includes slag supplier quality control plan requirements, sampling procedure, sulfur leachate tests, acceptance criteria, retesting procedure, consequence of nonconformance, appeal process for probation status, and additional requirements for Items 203, 204, 503 and 611 (roadway excavation and embankment, subgrade compaction and proof rolling, excavation for structures, and pipe culvert, sewers, drains, and drainage structures). The field sample size is 80 to 100 lbm for each 2,000 ton stockpile, and the sample size to be tested is 20 to 25 lbm of material. The tested material should meet the following criteria: (1) no leachate has an observable color equal to or darker than moderate greenish yellow (Hue 10 y 7/4) during 15 days of the test; (2) leachate water has a pH between 6.5-9.0. at 15 days; (3) leachate water has a conductivity result less than 2,400 µmho/cm at 15 days; (4) leachate water has a total dissolved solids result of less than 1,500 mg/L after 15 days. For color, the 7 value pertains to lightness and the 4 value pertains to chroma saturation. Water pH, conductivity, and total dissolved solids are only tested after 15 days soaking and the tested sample is diluted (100 ml sample from bucket and 200 ml distilled water). ODOT (2012) also proposed, “suppliers that have 10 consecutive color tests passing the 1-, 2-, 7-, and 14-day color tests may eliminate the 15 day test.” Also notable is that when samples are retested because they failed acceptance criteria previously, suppliers must follow more detailed procedures. These pertain to test samples for each 1,000 tons of stockpile material, using five separate buckets for each sample, etc.

The ODOT had additional requirements for the use of ACBFS in 203, 204, 503, or 611 applications where water has long-term access to the material. A slag source that is accepted for the four aforementioned applications should have no previous history of environmental issues in the Department’s records. And if no previous history exists, the slag source owner should provide (1) the locations of all sites where the slag has been used in the four applications, (2) the date that
the material was installed, (3) results of slag tests in conformance with Supplement 1027, (4) “the chemistry of the slag material” that was used at each location. Supplement 1027 states that “if the Department determines that all sites have not exhibited environmental compliance issues the Department will notify the slag source owner”. Other leaching test methods were reported by domestic and international organizations (Table 2.3).

Table 2.3 Leaching Test Methods by National and International Organizations

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM D3987 (ASTM, 2014)</td>
<td>Standard Practice for Shake Extraction of Solid Waste with Water</td>
</tr>
<tr>
<td>EN 12457*</td>
<td>Characterization of Waste – Leaching – Compliance Test for Leaching of Granular Waste Materials and Sludges</td>
</tr>
<tr>
<td>NT ENVIR 002*</td>
<td>Solid Waste, Granular Inorganic Material: Column Test</td>
</tr>
<tr>
<td>NT ENVIR 003*</td>
<td>Solid Waste, Granular Inorganic Material: Availability Test</td>
</tr>
<tr>
<td>EN 1744*</td>
<td>Tests for Chemical Properties of Aggregates</td>
</tr>
</tbody>
</table>

* Method was cited in Hill (2004); CEN EN 12457 is composed of 4 parts: Part 1: One Stage Batch Test at A Liquid to Solid Ratio of 2 L/kg for Materials with High Solid Content and with Particle Size below 4 mm (without or with Size Reduction), Part 2: One Stage Batch Test at A Liquid to Solid Ratio of 10 L/kg for Materials with Particle Size below 4 mm (without or with Size Reduction), Part 3: Two Stage Batch Test at a Liquid to Solid Ratio of 2 L/kg and 8 L/kg for Materials with A high Solid Content and with A Particle Size below 4 mm (without or with Size Reduction), Part 4: One Stage Batch Test at A Liquid to Solid Ratio of 10 L/kg for Materials with Particle Size below 10 mm (without or with Size Reduction); CEN EN 1744 is composed of 4 parts: Part 1: Chemical Analysis, Part 2: Determination of Resistance to Alkali Reaction, Part 3: Preparation of Elutes by Leaching of Aggregates, Part 4: Water Susceptibility of Filler for Bituminous Mixtures

2.5 Review of the Scientific Literature

2.5.1 Production and storage

Blast furnace slag (BFS) is a byproduct of metallurgical operations. The material forms during the production of iron from iron ore. In the vertical-shaft blast furnace, coke and ore are supplied continuously through the top, while the air is blown into the bottom of the furnace
As material moves downward, the ore containing iron oxide is converted to metallic iron through a reduction process. The end products are molten pig iron and BFS, and each of them is tapped from the bottom of the blast furnace. Based on how the molten slag is cooled and hardened, BFS is classified into air cooled and granulated (Miyamoto, 2015). ACBFS is produced by letting molten slag slowly cool in open pits or yards by ambient air. Although some ACBFS is sprayed with water to expedite cooling process, it is still referred to as air cooled (FHWA, 2008). GBFS is produced by quenching molten slag with water. ACBFS looks like crushed stone and GBFS looks like sand. After cooling, slags are crushed, screened and then stored as stockpiles for use or for aging (Figure 2.2).

**Figure 2.2 Production Flow of Blast Furnace Slag (Specific to the Slag Producer Site Visit)**
1. Molten slag formed during iron production in blast furnace. 2. Cooling and hardening from molten slag in pit. Water is sprayed on slag to reduce the temperature. 3. Transporting ACBFS from pit to processing site. 4. Washing/wetting ACBFS on belt. Separation, crushing and screening are also performed at processing site. 5. Transporting ACBFS from processing site to storage site. 6. ACBFS stockpiles at storage site. Weathering happens during storage period. 7. Transporting ACBFS from producer to construction site. 8. Construction site.
2.5.2 Properties

2.5.2.1 Physical properties

ACBFS can be screened, crushed, and processed to various sizes. Physical properties can be influenced by the slag cooling process and cooling rate (FHWA, 2008). Aggregate material has a rough texture due to its porous structure. Voids in the material exist due to bubbles from the occluded gases, most of which is nitrogen (Tossavainen & Forssberg, 2000). ACBFS contains both rapidly cooled glassy material and slowly cooled crystallized material (Tossavainen & Forssberg, 2000). Cooling can occur by ambient air exposure and/or water application (spraying). The most common compound in BFS [type not specified] is melilite (65% by volume), containing akermanite (2CaO MgO 2SiO₂) and gehlenite (2CaO Al₂O₃ SiO₂) (Tossavainen & Forssberg, 2000). The ACBFS bulk specific gravity decreases with an increase in particle size. ACBFS specific gravity has been reported to range from 2.0 to 2.5. Compacted unit weight of ACBFS has ranged from 70 to 85 lbm/ft³ (FHWA, 2008). ACBFS porosity is typically high and material has shown to absorb as high as 7-8% of water (Fällman & Hartlén, 1994; FHWA, 2008). The color of ACBFS aggregate usually varies from light to dark grey depending on its chemical composition. BFS [type not specified] has shown to have a greater water storage and evaporation capacity than steel slag and municipal waste incineration bottom ash (Fällman & Hartlén, 1994).

2.5.2.2 Chemical properties

Chemical properties affect ACBFS’s leaching potential and leaching characteristics. Results of chemical analysis for two ACBFS samples and one rapidly cooled BFS sample showed lime and silica were present at the greatest mass (FHWA, 2008; Korkiala-Tanttu and Rathmayer, 2000; Stoehr & Pezze, 2012). From a leaching perspective, BFS [type not specified] contained a higher loading of many heavy metals than soil (Proctor et al., 2000), and contains sulfur. The sulfur in ACBFS originates mainly from the coke used in the iron production process (Fällman & Hartlén, 1994). The sulfur content in ACBFS is about 5-10 times higher than that in steel slag (Proctor et al., 2000). Total sulfur in ACBFS has been estimated to be 1% to 2% by weight (FHWA, 2008). In one study, the total amount of sulfur in an ACBFS was 10,000 mg S/kg slag (Fällman & Hartlén, 1994; Hill, 2004).

A comparison of chemical composition and leachable fractions in BFS [type not specified] is shown in Table 2.4. The predominant form of sulfur in BFS has been reported to be calcium
sulfide (CaS), with smaller amounts of iron and manganese sulfides (National Slag Association, 2008). CaS reacts with water to form a variety of species and dissolution increases as pH increases (FHWA, 2008). The chemical progression of the hydration process of calcium sulfide can be found in Equation 1. Sulfides are unstable under oxidizing conditions and materials that contain sulfides are prone to weathering (Tossavainen & Forssberg, 2000). As the largest component in ACBFS (30 to 45% by mass), lime also undergoes hydration with water contact (Equation 2). This process can cause elevated pH of ACBFS leachate and produce heat.

\[
\text{CaS} + \text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{H}_2\text{S} + \text{CaSO}_4 + \text{CaCO}_3 + \text{S} \quad \text{Equation 1}
\]

\[
\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 \quad \text{Equation 2}
\]

Proctor (2000) concluded that concentrations of heavy metals in BFS [type not specified] are elevated relative to those concentrations in soil, but these metals were tightly bound and tended not to leach. However, not all the forms in which these heavy metals exist in ACBFS were reported (Table 2.3 & Table 2.4). Also, the leachant pH ranged from 3 to 7 in these tests, and leachant is static in most of the tests (Hill, 2004; US EPA, 1992). Static tests differ from field conditions (i.e., continuous percolating fluid, horizontally pass-by ground water). A limitation of prior studies is that some forms of heavy metals tend to dissolve in leachant only after other specific compounds leach out. For example, the solubility product constant of lead sulfide is much less than that of iron sulfide \(K_{\text{sp, PbS}} = 3 \times 10^{-7}, K_{\text{sp, FeS}} = 6 \times 10^2\) (“CRC Handbook of Chemistry and Physics”, 2006). Therefore, it is likely iron would leach out before large quantities of lead (or other materials possibly) would leach. Acid digestible tests (i.e., using 1 mole/L nitric acid (HNO\(_3\))) could be used to investigate whether and the degree heavy metals could be released from new and aged ACBFS.
Researchers have proposed several chemical reactions could occur when ACBFS is in contact with water. While in laboratory experiments, many of the parameters are held constant while one or a few are changed to determine the influence of those parameters on leaching. However, under field conditions redox reactions can occur during leaching process. These processes can alter the leachate’s pH, species in leachate and consequently the leached amount of certain species. For example, when ACBFS is in contact with water and the leachate is exposed to air, the reduced sulfides will be oxidized and the pH can decrease. The rate of chemical release is suspected to increase at higher temperatures (Hill, 2004). Chemical reactions that may occur during this process can be expressed in the following equations (Banks et al., 2006):

\[
\text{CO}_2(\text{g}) + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3(\text{aq}) \quad \text{Equation 3}
\]

\[
\text{H}_2\text{CO}_3 \leftrightarrow 2\text{H}^+_{(aq)} + \text{CO}_3^{2-}_{(aq)} \quad \text{Equation 4}
\]

\[
\text{S}^{2-} + 2\text{H}^+_{(aq)} \leftrightarrow \text{H}_2\text{S}_{(g)} \quad \text{Equation 5}
\]

\[
\text{H}_2\text{S}_{(aq)} + \text{O}_2(\text{g}) \leftrightarrow \text{S}_{(aq)} + \text{H}_2\text{O}_{(l)} \quad \text{Equation 6}
\]

\[
\text{n(S}_{(aq)} \leftrightarrow (\text{S}=\text{S})_{n(aq)} \leftrightarrow (\text{S}^+ - \text{S}^-)_{n(aq)} \quad \text{Equation 7}
\]

\[
\text{S}^{2-}_{(aq)} + 2\text{O}_2(\text{g}) \leftrightarrow \text{SO}_4^{2-} \quad \text{Equation 8}
\]
\[ \text{Ca}^{2+}_{\text{aq}} + \text{SO}_4^{2-}_{\text{aq}} \leftrightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O}_{\text{gypsum}} \]  

Equation 9

2.5.3 Leaching

Leaching can be defined as “extraction of soluble components of a solid mixture by percolating a solvent through it” (Daintith, 2016). Leaching generally refers to physical, chemical and biological reactions that mobilize a contaminant or carry the contaminant away from the matrix (Table 2.5) (Hill, 2004). The solvent that initiates the leaching process is referred to as the leachant, and the resulting percolated fluid containing the leached material is termed the leachate. Prior ACBFS leaching studies have reported that field conditions are indicative of 0.34 of water to 1 lbm of slag (the type of BFS was not reported) (Schwab et al., 2006). The ratio of slag to water could influence the observed chemical concentrations in the water. A high amount of water may have a lower contamination concentration, whereas a lower amount of water could result in a more concentrated solution.

When ACBFS is used for some applications, the material can be exposed to rainwater and/or groundwater (Hill, 2004). After water contacts the ACBFS material, that water or leachate can sometimes pass through construction joints and cracks that lead to the surface, a drainage system, and/or experience capillary suction that leads to transport to the subgrade and soil (Hill, 2004). The fate of this water and its contents will depend on the site characteristics and environmental conditions. Leachate sometimes can travel into soil pore water beneath the road, adjacent drainage systems, aquifers and local rivers.

Three different processes have been identified by which chemicals enter water from slag: surface wash-off, dissolution, and chemical diffusion (Tossavainen, 2005). Surface wash-off is the initial wash-off of soluble species on the outside of the material (van der Sloot & Dijkstra, 2004). Dissolution is controlled by chemical solubility where equilibrium is achieved ultimately between solid phase and liquid phase or by availability where the constituent is completely dissolved. Diffusion is the net movement of a constituent from the material matrix (high concentration) to the surrounding media (low concentration). Where the leaching is diffusion-controlled, species are easily dissolved, but the dissolved components can reach the environment only after diffusing through the material (Mulder, 1991). Hill (2004) reported that leaching of ACBFS was generally rapid at the beginning of the test because of particle wash-off. This was followed by a period of less leaching influenced by diffusion.
Table 2.5 Factors Influencing Leaching

<table>
<thead>
<tr>
<th>Chemical Factors</th>
<th>Physical Factors</th>
<th>Biological Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH of the material and/or leachant</td>
<td>Particle size and therefore surface-to-volume ratio of the material</td>
<td>Colonization</td>
</tr>
<tr>
<td>Redox condition</td>
<td>Particle shape</td>
<td>Material degradation by boring organisms</td>
</tr>
<tr>
<td>Leachability of the chemical species</td>
<td>Porosity</td>
<td>Pore clogging by biological substances</td>
</tr>
<tr>
<td>Chemical speciation in the material matrix</td>
<td>Matrix and/or particle permeability</td>
<td>Changes in the chemical environment due to biological activity (redox)</td>
</tr>
<tr>
<td>Chemical interactions in the pores and at the surface</td>
<td>Pore structure</td>
<td></td>
</tr>
<tr>
<td>Changes in the chemical environment (pH, redox) in the material with time</td>
<td>Continuous or intermittent contact with water</td>
<td></td>
</tr>
<tr>
<td>Surface dissolution</td>
<td>Temperature in relation to diffusion rate and with respect to durability (freeze/thaw)</td>
<td></td>
</tr>
<tr>
<td>Chemical speciation in the pore water</td>
<td>Density differences in the material matrix (e.g., gravel in concrete)</td>
<td></td>
</tr>
<tr>
<td>Reaction kinetics</td>
<td>Homogeneity or heterogeneity of the solid matrix in terms of mineral phases</td>
<td></td>
</tr>
<tr>
<td>Chemical composition of the leachant</td>
<td>Hydrogeological conditions</td>
<td></td>
</tr>
<tr>
<td>Complexation with inorganic or organic compounds</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Water percolation, the passage of water through the material that comes in contact with ACBFS, is important. Water percolation will influence leaching. Rainwater flowing from the asphalt layer can percolate through the uncovered road base. Percolation can also occur through grass and soil to the foundation layer. In prior studies, laboratory column tests for mixture of BFS (did not indicate the type) and steel slag have shown percolation influences leaching (Mulder, 1991).

Leaching of ACBFS has occurred at Indiana Roadway sites: State Road 49 (SR-49) and Interstate 65 (I-65) (Lavalley, 2016; Schwab et al., 2006). ACBFS was used in the highway foundation layer in these two sites. Schwab et al. (2006) proposed a mechanism for the leaching of ACBFS in the foundation layer. Groundwater reacts with ACBFS and hydrates freshly exposed or residual free lime and results in rapidly produced alkalinity. Alkalinity further enables the
dissolution of interstitial glass and the release of major metallic components and sulfur. However, this is the only mechanism found in the literature.

2.5.4 Bench- and pilot-scale leaching studies

The literature review was conducted to identify the types, amounts, and duration of chemical leaching from ACBFS. Some studies were found that described experimental conditions. Though, many studies did not report one or more of the following: The type of BFS tested (ACBFS vs. GBFS), as well the slag production process, initial composition before the leaching test, its age when tested, how it was transported, and environmental conditions before it was tested (i.e., temperature, humidity, oxidizing/reducing environment). Lack of this information inhibited the comparison of existing data to INDOT applications. In addition, some of the studies examined leaching using mixtures of BFS slag with other materials (i.e., limestone and steel slag). For INDOT, ACBFS has been used as-is, and has not been mixed with other materials. Various leaching test methods have been reported in the literature. These include a column leaching test, rapid leaching test (availability test), tank-leaching test, static pH leaching test, and lysimeter test. The lysimeter approach is a pilot-scale test (i.e., 12 tons of BFS leached for one study), while the other approaches were at the bench-scale. The solution used to facilitate leaching for most bench-scale tests was deionized or distilled water. A few bench-scale studies utilized tap water or a salt solution. The pilot-scale leaching test was conducted outdoors and by default was subjected to precipitation. Liquid to solid ratios conducted in static leaching tests included 2, 10, and 20 L leachant to 1 kg material, 2:1 by mass, 5:1 by volume, and 5, 10, 19, 21, 100 not specified by mass or by volume. The following paragraphs describe leaching results from studies that were identified as relevant to the INDOT project and applications. Methods to reduce leaching from ACBFS by conditioning of the ACBFS and methods to treat ACBFS leachate are described in subsequent sections.

The type of cooling process BFS undergoes can control the amount of air emissions from that BFS, and may impact how that ACBFS leaches. Stoehr and Pezze (1975) conducted a bench-scale study using BFS directly from a Pittsburgh steel mill without that material contacting water. The material was allowed to rapidly cool before testing. The researchers discovered that a mixture of steam and air facilitated the transformation of $\text{H}_2\text{S(g)}$ to $\text{SO}_2\text{(g)}$, but also could inhibit sulfur bearing gas release. Then a mixture of steam and carrier gas (i.e., air, argon or argon+1% $\text{H}_2$) was
passed through the samples. When Ar\textsubscript{(g)} was used as the carrier gas, 5,000 times higher amount of H\textsubscript{2}S emission at 1,200°C was detected (42,000 µg H\textsubscript{2}S\textsubscript{(g)}/m\textsuperscript{3}) compared to when air was used as the carrier gas (8 µg H\textsubscript{2}S\textsubscript{(g)}/m\textsuperscript{3}). SO\textsubscript{2(g)} emission was several times greater when air was used as the carrier gas than when Ar\textsubscript{(g)} was used as the carrier gas. No studies were found that evaluated how the cooling method impacted ACBFS leaching.

Van der Sloot et al. (1989) found that chemical release from BFS [type unreported] is lower from products with high alkalinity, small surface-to-water volume ratios, and low porosity. These researchers investigated the leaching behavior of trace elements from a mixture of BFS and lime (99:1, by volume or by weight was not indicated). Static and dynamic tank-leaching tests were conducted at room temperature, and BFS was exposed to demineralized water. The water volume to BFS volume ratio was 5:1 for the static tank-leaching test. The effect of water flow rate was also studied at continuous inflow and intermittent inflow conditions (Q\textsubscript{in} = 0.014 L/s).

From 1986 to 1989, a two-year pilot-study was conducted to examine the leaching behavior of eight materials, including BFS, by the Netherlands Organization for Applied Scientific Research. Information was not found however about the type and age of BFS examined (Mulder, 1991). The study reported leaching results from a mixture of BFS and steel slag, and this was the only result that included BFS. Test bins measuring 1 x 2 meters were placed outside under normal weather conditions. Each bin contained a 20 cm of sand layer (constructed in a moist condition), 20 cm of road-base materials layer, and 5 cm of thick asphalt upper layer with a grass verge on both sides. During the two year study, run-off and water percolation was monitored. These liquids were also sampled and chemically analyzed. Only about 5% of the volume of water that entered as rain into the bins drained away as run-off and 10% of the water evaporated. The authors concluded that “a major part of rain water entering the test bins percolated through the foundation layer.” The water that percolated through the BFS and steel slag mixture was alkaline (pH 12-12.5). From leaching results, Mulder (1991) concluded that primary materials (sand, lava-lite, and sand-cement stabilization) generally showed a small release of trace elements compared with the BFS and steel slag mixture. Mulder (1991) proposed that the highest released trace elements could be used as in assessing the suitability of road base materials.

Using bench- and field-scale studies, Fällman and Hartlén (1994) concluded that bench-scale tests can help predict the ACBFS field behavior, but must be designed to reflect pH and redox conditions. Researchers examined ACBFS composition, leaching availability, leaching
availability under different conditions (i.e., reduced/oxidized, static pH, and in column/lysimeter). Though, the ACBFS’s age was not reported. BFS (12 tons) was placed in the lysimeter and was exposed to the atmosphere. Results showed that the amount of leachate generated by the BFS was lower than steel slag. Over the seven-month monitoring period, the leachate pH from the BFS lysimeter decreased from 7.7 to 4.1. Bench-scale results indicated a 10- to 100-fold difference between the amount of certain chemicals leached compared to field-scale tests. Greater amounts of chemicals were not always found in the field-scale tests compared to bench-scale testing. The ability of chemicals to leach from BFS [type not specified] under “somewhat oxidized” and “fully oxidized” conditions was found to be chemical specific (Table 2.6). The amount of iron released into water under “somewhat oxidized” conditions was about 900 mg/kg and under “fully oxidized” conditions was near 20 mg/kg. For other elements, little to no difference was detected (i.e., Na, V, Zn, and others). The concentration of 12 elements (Al, Ca, Fe, Mg, Mn, Si, Ba, Cd, Co, Cr, Ni, Zn) was greater in the pH 12 solution compared to the pH 4 solution; no difference was reported for 3 elements (As, Pb, V); copper (Cu) was not detected; potassium (K) decreased.

Table 2.6 Total Element Available for Leaching from a BFS Sample under “Somewhat Oxidized” and “Fully Oxidized” Conditions

<table>
<thead>
<tr>
<th>Amount (mg/kg)</th>
<th>Element Detected and Leaching Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>“somewhat oxidized”</td>
</tr>
<tr>
<td>10,000-100,000</td>
<td>Ca, Mg, Si*</td>
</tr>
<tr>
<td>1,000-10,000</td>
<td>K, S, Al</td>
</tr>
<tr>
<td>100-1,000</td>
<td>Fe, Na, Ba</td>
</tr>
<tr>
<td>10-100</td>
<td>V</td>
</tr>
<tr>
<td>1-10</td>
<td>Ni, Zn</td>
</tr>
<tr>
<td>0.1-1</td>
<td>Co, Cr**, Cu**</td>
</tr>
<tr>
<td>0.01-0.1</td>
<td>As**, Pb**</td>
</tr>
<tr>
<td>0.001-0.01</td>
<td>Cd**</td>
</tr>
</tbody>
</table>

Information reproduced from Fällman and Hartlén, (1994).
* Si data under “fully oxidized” condition was absent. A reason for the absence was not found.
** Values below detection limit.

Proctor et al. (2000) examined chemical leaching from composite BFS samples [type and definition of composite unreported] under acidic conditions and none of the constituents exceeded Toxicity Characteristic Leaching Procedure (TCLP) standards. As a result, the researchers...
concluded slag samples were not characteristically hazardous. Of the 11 “BFS composite samples” the content of sulfur was 5 and 7 times higher than electric arc furnace slag and basic oxygen furnace slag (two types of steel slag), respectively. In the two tests, carbon, sulfur, magnesium, calcium and phosphates were not evaluated.

Korkiala-Tanttu and Rathmayer (2000) tested GBFS leaching behavior under simulated field conditions of road structures. The testing was conducted in climate chamber test boxes subjected to 20 accelerated wetting-drying and freezing-thawing cycles. Results indicated that the climatic cycles did not increase leaching of the elements studied (Ca, Na, K, Al, As, Cd, Cr, Cu, Mo, Ni, Pb, Zn, Fe, Mg, Mn, $\text{SO}_4^{2-}$, V), and leached amounts of the metals were low. The materials were exposed to a solution that contained 10% salt and 90% tap water. Column tests were conducted on ACBFS and GBFS but the characteristics of the water solution were not described. The liquid to solid ratio in the column tests was 10:1. Column test results showed that the “cumulative concentration” (mg of chemical/kg of testing sample) of sulfate leached from ACBFS was more than 100 times greater (10,000 mg/kg) than sulfate leached from GBFS (30 mg/kg). The researchers thus proposed that the cooling method affected the leaching properties of some species.

In 2002, the Ohio Department of Transportation (ODOT) measured leachate pH of from fresh ACBFS, as well as ACBFS that was one and two years old (ODOT, 2002). The bench-scale study involved the addition of 500 grams of ACBFS in beaker followed by addition of distilled water to a level two inches above the ACBFS. Water pH was measured at Day 1, 2, 4, and 7 for all samples. The leachate pH for the fresh ACBFS sample was consistent (9.11, 9.37, 9.50, 9.41). The leachate pH for one year old (8.77, 8.74, 8.75, 8.86) and two-year-old ACBFS (8.62, 8.61, 8.47, 8.31), also were not different. When leachate pH was measured for the samples during a six-month period, the values ranged between 8.00 and 8.93 (Figure 2.3). A conclusion was that fresh ACBFS produced the highest leachate pH and the two-year-old ACBFS had the lowest pH. But, it is unclear if the ACBFS tested originated from the same batch and had undergone the same cooling and handling conditions, etc. As reported previously, leaching from ACBFS produced under different conditions can cause different leaching.
Hill (2004) investigated 14 conventional and alternative aggregate materials through a variety of characterization and leaching tests. The author also studied the effect of different binder treatments on the diffusive and advective leaching properties of the materials. ACBFS and a mixture of ACBFS, GBFS and quicklime were tested. From the rapid leaching tests, Hill concluded 10% to 50% of total sulfur in the ACBFS was released during their rapid leaching characterization test. The alkali and alkali earth metals were found to be the most mobile species with the exception of Mg. In other leaching tests, the magnitude of K, Ca, SO$_4^{2-}$, and S in the leachate did not change during the 65 day test. Though, water pH increased over this duration. The researchers concluded that the ACBFS leaching was not affected by material compaction. A theory was that ACBFS had high porosity and therefore there was little barrier to water percolation. From the advective leaching results of ACBFS, it was assumed that the leaching of most of the species was not controlled by solubility constraints. The lysimeter results showed that leaching was probably dependent upon a function of the rainfall, but the exact controlling function or combination of function of rainfall quantity, duration, intensity, event intensity and time since previous rainfall event were unknown. In the advective leaching tests and lysimeter tests, with increasing time or liquid to solid ratio, the cumulative release of chemicals increased at the beginning and then the
line tended to an asymptote. This indicated that leaching was controlled by the ACBFS release rate and/or diffusion. Additional leaching tests conducted by Hill (2004) and Tossavainen (2005) and it was found water pH was not stable after two months.

Schwab et al. (2006) found that ACBFS leachate was colored green and had a pungent sulfur odor under reduced (no oxygen) conditions. The oxidized environment was created by purging the closed system with ambient air, while the reduced condition was created by purging with Ar gas. Distilled-deionized water (resistivity of 16 megaohm cm⁻¹, pH 6.33) was used in capped flasks. The water: slag ratio was 2:1 on mass. Leachate SO₄²⁻ concentration for the oxidized condition increased from 225 mg/L on the first day to 914 mg/L on day 85. For the reduced condition, SO₄²⁻ in the leachate decreased from about 350 mg/L on the first day to about 100 mg/L on day 7 and remained up until day 34.

2.5.5 Methods to reduce leaching: treatment strategies

2.5.5.1 Weathering and use of water

Studies were reviewed that described processes for reducing chemical leaching from ACBFS and for treating ACBFS leachate. Weathering is considered effective in reducing leaching. In geology, weathering describes the process by which rocks are broken down at the Earth’s surface (University of Houston, n.d.). Chemical processes include conversion into clays, oxidation and dissolution, while physical process means rock broken apart by mechanical processes. According to the author’s discussions with MDOT, slag producers in Michigan have reported that weathering prior to use could reduce the amount of chemicals leached. Barišić, Dimter and Netinger (2010) has reported that the effective weathering period depends on the application method, and the type of slag itself, i.e., the quantity of free Ca and Mg oxides or leachable element. The researchers also stated that, according to Belgian and Dutch regulations, one year weathering was sufficient for the use of slag (not indicate type) in unbound base courses, whereas the need of eighteen-month weathering before use was also found.

INDOT currently does not have required minimum ACBFS storage times. Also, the effectiveness of weathering should be evaluated based on allowable chemical concentrations (i.e., criteria in water quality standards) in Indiana waters. The optimum weathering time and weathering conditions for ACBFS use Indiana should be determined from future research. Considerations should include the slag composition, physical and chemical properties,
construction application, and environmental factors. The use of water when ACBFS is produced may reduce leaching. Some species in ACBFS including sulfur and calcium are found to leach or be washed off at the beginning of leaching tests (Hill, 2004; Kanschat, 1996).

2.5.5.2 Coating ACBFS

Muñoz et al. (2009) coated ACBFS with a nanoporous thin-film and found a decrease of 70% sulfur and 80% calcium in the leaching test. They conducted a bench-scale study and used standard sol-gel processes to prepare nanoporous SiO$_2$ and nanoporous TiO$_2$ solutions. Slag aggregate of ¾ inch size was immersed into the sols, which was later drained from the aggregate at a constant speed. Slags were coated with one layer of either materials and left to dry. Then leaching tests were conducted. The methodology was designed by modifying Supplement 1027 from ODOT and ITM 212 from INDOT (INDOT, 2015a; ODOT, 2012). Following the two test methods the authors soaked slag in deionized water. Leachate was extracted and filtered after 24 and 48 hours for testing. However, the authors claimed that calcium salt in the solid phase, sulfates in the insoluble phase and colloidal polysulfide particles were retained and/or absorbed by the paper filter. Ca, Mg, S, and Si were measured by inductively coupled plasma (ICP) 60 days after mixing the slag with water [water type not specified]. The redox condition in bottles was near anoxic. Sulfur leaching from SiO$_2$ and TiO$_2$ coated ACBFS was about 40% and 70% less than the control group, respectively. The amount of calcium leached from SiO$_2$ and TiO$_2$ coated slag was 28% and 14% of the uncoated slag group, respectively. Also, only the uncoated slag bottle displayed a green color after 60 days.

2.5.5.3 Mixing ACBFS with other materials

Solidification and stabilization with binders is a method of mitigating highly contaminated materials (Hill, 2004). Hydration and curing can reduce the concentration of calcium, total sulfur, chlorine, lithium and chromium in leachate. Hill (2004) mixed ACBFS with GBFS and quicklime with a ratio of 84%, 15% and 1% by weight, respectively. The sample was cured for 90 days before testing. Tank-leaching results showed that the concentration of sulfate of the ACBFS-quicklime mixture was 0.1 to 0.5 times that of the concentration when only ACBFS was present. The concentration of calcium and nitrogen dioxide increased in leachate from the ACBFS-quicklime mixture and those of the rest species either remained similar or were reduced. While in the lysimter
tests, the leached quantities of about 14 species were less than those from the sample that contained ACBFS only, including calcium, sulfate and total sulfur. While the leached quantities of approximately other 22 species tested increased, including pH and conductivity. Other binders that reduced the cumulative release were Bitumen and flue-gas desulfur gypsum + quicklime. These two binders had little effect on leachate pH. However, these two binders were tested as mixtures with other materials that did not include ACBFS.

Mixing slag with water treatment residual (WTR) and encapsulating the mixture with clay soil is a method to deal with the high swelling potential and high alkalinity of steel slag in highway embankments (Aydilek, 2015). Water treatment residual (WTR) used in this study was an aluminum-based byproduct from drinking water treatment plant. As encapsulation layer was a common structure in embankment construction, the effects of encapsulation layer on leachate pH and metal concentration were studied. Results indicated that an increase in WTR decreased the pH in leachate and suppressed swelling, but usage of WTR greater than 30% by weight decreased the steel slag amount in the mixture significantly. Only when the leachate from the mixture of steel slag and 30% WTR passed through the encapsulation soil, the pH was below the Maryland Department of Environment limit of 8.5. Treated by WTR addition and encapsulation, analyzed metals except for aluminum in the steel slag leachate were below the U.S. EPA MCL (maximum contaminant levels for drinking water) and U.S. EPA WQL (water quality limits for protection of aquatic life and human health in fresh water). The WTR contained a high level of aluminum as 159,700 mg/L, compared to 10,600 mg/L in steel slag and 47,700 mg/L in encapsulation soil tested by inductively coupled plasma optical emission spectrometer (ICP-EOS). The sulfur content in steel slag, WTR and encapsulation soil in the test were 617 mg/L, 4,700 mg/L, and 110 mg/L, respectively.

2.5.5.4 Treatment of leachate: constructed wetlands

Banks et al. (2006) conducted a pilot-scale study to determine the effect of a constructed wetland to treat leachate from an ACBFS-based embankment. The system included a leachate collection system and constructed wetland. Three types of vegetation were chosen because of root structure and tolerance to high water pH in water. Total dissolved solids, salinity and sulfate concentration were found to be functions of inflow events and retention time between those events. The use of a constructed wetland proved to be effective in reducing pH, salinity, sulfate and some
species concentration in ACBFS leachate. The authors claimed that the best treatment for sulfate was < 500 mg/L at the end of the wetland cell, but the initial sulfate concentration was not found.

2.6 Discussion and Conclusion

ACBFS has been used in northern Indiana’s LaPorte District for a variety of roadway construction applications. Discussions with INDOT representatives have indicated that unbound ACBFS has not been used elsewhere in the state. Odors and a liquid of greenish-yellowish color have been reported by INDOT representatives at some ACBFS construction sites. For one site, ACBFS material continues to leach after 17 years.

ITM 212 as currently designed could result in ACBFS leachate that exceeds IAC water quality limits. One current ITM acceptance criterion permits ACBFS use when pH ranges from 6.0-10.5. Indiana water quality limits prohibit discharge to waterways at levels of 9.0 or above. Therefore, a change to the water pH ITM acceptance criterion is recommended. To further restrict the quality of leachate from ACBFS applications, the Ohio DOT requires that total sulfur levels in ACBFS shall not exceed 2.0%, the leachate test is conducted for 15 days, not 7 days like ITM 212. In Ohio, leachate water conductivity and total dissolved solids concentration are also conducted and levels shall not exceed 2,400 µmho/cm and 1,500 mg/L after 15 days of water exposure, respectively. Though, it is unknown if 15 days is sufficient time to determine the worst-case leachate result from ACBFS under a variety of different applications. These additional criteria should be considered in a revised ITM 212. A minimum stockpile age requirement could be considered, but this may not be desirable. If certain suppliers can expedite leaching and produce higher quality ACBFS in a shorter amount of time than others, storing the ACBFS just to comply with INDOT requirements may be cumbersome. For that reason, stockpile sampling and leachate performance-based testing is recommended to identify ACBFS acceptable for use in INDOT applications.

As the literature review indicates, a variety of material properties, chemical, environmental, and experimental conditions can affect the results of an ACBFS leaching test. Differences in ACBFS leaching can be attributed to differences between samples. Also, ACBFS from different producers may perform differently from a leaching perspective. To improve INDOT’s ability to identify ACBFS not suitable for certain applications, additional work and collaboration with ACBFS producers may be needed. The ability of the ITM 212 testing procedure itself to help
identify ACBFS that could pose problems once installed is unclear. For example, it is unclear if pH and color monitoring in ITM will enable INDOT to identify any ACBFS that is not ready for construction use. Also unclear is whether the ITM represents conditions in the field where green color and odors have been reported. Different construction applications (i.e., subbase vs. embankment) may require different levels of testing and performance criteria for ACBFS use, because the conditions in each application differ. For example, MDOT requires a drainage system when unbound ACBFS is used for a construction application.

It is unknown what redox conditions exist in the closed buckets during ITM 212 testing, and whether this changes during the 7-day exposure period. As prior studies indicated, reduced conditions (low to no dissolved oxygen) can generate higher pH and greenish-yellow colored leachate and odors. Though, exposure of ACBFS leachate to air can cause pH to decrease (Equation 3-8). Chemical release has found to be greater at low pH conditions (Schwab et al., 2006; Van der Sloot et al., 1989). Additional work is needed to identify worst-case leaching and odor conditions. Dissolved oxygen monitoring may help determine the redox condition in the leachate and bucket.

It is unknown if the ITM 212 and ITM 207 ACBFS physical sampling procedures result in tests where leachate is representative of the stockpiles. One question is whether or not the sample size tested (0.0005% of a stockpile) is representative of the entire stockpile used for an INDOT application. Also unknown is whether the exterior of the stockpile, where samples have been previously collected for ITM 212 testing according to an ACBFS supplier, is representative of the inner regions of the stockpile. During high-turnover of stockpiles, it may or may not be that the 5-gallon bucket sampling of the stockpile’s exterior (1 bucket for every 4,000,000 lbm of ACBFS) is representative of ACBFS located deeper in the pile. The use of front-end loaders, shovels, and additional physical activities to sort aggregate are recommended by ITM 207, though it is unclear if this process was followed by the ACBFS supplier. It is also unknown if this approach would influence the observed characteristics of ACBFS leachate in the ITM 212 test.

To reduce the possibility of a post-construction leaching problem, ACBFS should undergo a more stringent leaching test and could be classified according to its performance (Table 2.7). Classification and siting criteria have been used to help avoid other post-construction leaching problems. For example, several states have required waste foundry sand meet specific siting
criteria, including Indiana (Afzal & Jacko, 2002; Banks & Schwab, 2010; US EPA, 2002). A similar approach is proposed for ACBFS (Table 2.7 & Box 2.2).

Table 2.7 Proposed ACBFS Classification *

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Type II (most restrictive)</th>
<th>Type I (least restrictive)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Lighter than greenish-yellow color (Hue 10 y) from the rock color chart during 15 days</td>
<td>Lighter than greenish-yellow color (Hue 10 y) from the rock color chart during 15 days</td>
</tr>
<tr>
<td>pH</td>
<td>Between 6.0 to 9.0 during 15 days</td>
<td>Between 6.0 to 9.0 during 15 days</td>
</tr>
<tr>
<td>Conductivity</td>
<td>Less than 2,400 µmho/cm after 15 days</td>
<td></td>
</tr>
<tr>
<td>Total dissolved solids</td>
<td>Less than 1,500 mg/L after 15 days</td>
<td></td>
</tr>
</tbody>
</table>

* Material should be examined according to ITM 212, but classification criteria in the table are proposed for extended 15-day test period. The color and pH of an undiluted water sample should be tested at 1, 2, 7, and 15 days. The conductivity and total dissolved solids concentration of diluted water (100 ml water sample and 200 ml distilled/deionized water) should be tested after 15 days.

Box 2.2 Proposed siting criteria for ACBFS

ACBFS use is restricted to the following additional requirements:

1. Type I ACBFS shall not be permitted within 100 ft, horizontally, of a stream, river, lake, reservoir, wetland or any other protected environmental resource area.
2. Type I ACBFS shall not be placed within 150 ft, horizontally, of a well, spring, or other ground source of portable water.
3. Type I ACBFS shall not be used as road excavation and embankment, subgrade compaction and proof rolling, excavation for structures, and pipe culvert, severs, drains and drainage structures.
4. Type I ACBFS shall not be permitted where ACBFS can contact water and the leachate is exposed to air.
5. ACBFS shall not be used where a drainage system is not present.

A limited amount of information was available about ACBFS leaching in the literature. For that reason, information regarding steel slag, which differ from ACBFS materials, and GBFS were reviewed. As the literature review indicates, a variety of ACBFS physical and chemical properties, as well as environmental conditions can affect ACBFS leaching. Stockpile weathering by the application of water or exposure to rainfall is an option to facilitate leaching before ACBFS is used for construction applications. Leachate has often been monitored for water pH, color, conductivity, and metal concentrations. Bench-scale and pilot-scale studies can be used to help predict full-scale
results. Studies have indicated that the greatest chemical release (as indicated by pH elevation) generally occurs with newer ACBFS and decreases with time. Though, it is unknown if changes to environmental conditions where the ACBFS used (redox, groundwater exposure) could increase ACBFS leaching. One study revealed that leachate conductivity closely reflected the metals concentration of that leachate (Hill, 2004). Also found was that differences in ACBFS leaching can be attributed to differences between samples. Few studies were found that described methods to treat ACBFS leachate at full-scale sites. No studies were found regarding ACBFS impacts on stormwater, ground water or surface water. Bench-scale studies indicate that ACBFS encapsulation practices seem to be in developmental stages.

2.7 Recommendations

1. INDOT should consider revising ITM 212 by: (1) Extending test duration to 15 days, (2) changing the pH acceptance criteria from 6.0-10.5 to 6.0-9.0, (3) adding material acceptance criteria such as a maximum value of total sulfur (2%), conductivity (2,400 µmho/cm), and total dissolved solids (1,500 mg/L), (4) adding an additional criterion for ACBFS usage at locations where water has long-term access to the material.

2. Because it is unclear if the stockpile sampling method influences ACBFS leachate performance, INDOT should consider adherence to the ITM 207 sampling procedure at a minimum.

3. To reduce the potential that ACBFS is incorporated into applications where leaching could be a short- or long-term challenge, INDOT should consider prohibiting unbound ACBFS from being used for (1) construction applications where ground water is likely to contact the material, (2) near environmentally sensitive and populated areas, 3) where a drainage system is not present.

4. To improve the ability of INDOT to detect ACBFS that would cause short- or long-term chemical leaching problems, additional research could be considered. Efforts could include (1) Evaluating and optimizing stockpile sampling practices for representative sampling, (2) improvement of the ITM 212 to better predict worst-case leaching conditions and leachate quality, (3) head-to-head comparison of bench-scale and field-scale leaching results. It is recommended that INDOT consider incorporating input from ACBFS suppliers in future
work, as was done in this study. INDOT may consider inspecting former sites where ACBFS was used to assess their conditions.

2.8 References


https://nepis.epa.gov/Exe/ZyPDF.cgi/9101ZMM6.PDF?Dockey=9101ZMM6.PDF
Accessible at http://www.uh.edu/~geos6g/1330/weath.html.
## APPENDIX A

Table A.1 Some Notable Events Related to the Large-scale Drinking Water Contamination Incident in Flint, Michigan

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td></td>
</tr>
<tr>
<td>Apr 25</td>
<td>The City of Flint stopped purchasing Detroit water and switched to Flint River (City of Flint, 2016c).</td>
</tr>
<tr>
<td>May</td>
<td>Residents started complaining about the water odor and color (Goodnough et al., 2016).</td>
</tr>
<tr>
<td>Aug</td>
<td>Elevated level of <em>E. Coli</em> bacteria violating the National Primary Drinking Water Regulations Maximum Contaminant Level was found in drinking water in the City of Flint (Del Toral, 2015; US EPA, 2009).</td>
</tr>
<tr>
<td>2015</td>
<td></td>
</tr>
<tr>
<td>Jan 28</td>
<td>200 cases of bottled water were given out to Flint residents in 30 minutes in a giveaway program. More giveaways would follow in ensuing months (The Associated Press, 2016).</td>
</tr>
<tr>
<td>Feb</td>
<td>University of Michigan detected lead in campus drinking fountains, at levels as high as 390 µg/L (Brighton Analytical LLC, 2015).</td>
</tr>
<tr>
<td>Apr 28</td>
<td>30 samples from a Flint resident’ home revealed minimum, average and maximum lead levels of 200, 2,429, and 13,200 µg/L respectively (Del Toral, 2015).</td>
</tr>
<tr>
<td>Sept</td>
<td>Virginia Tech researchers reported that the 90th percentile drinking water lead level in Flint was 25.2 µg/L and exceeded 15 µg/L federal standard during Aug-Sept water testing (Parks and Mantha, 2015).</td>
</tr>
<tr>
<td>Sep 2</td>
<td>Anonymous company donated 1,500 kitchen water filters to Flint (Michigan State Government, 2016b).</td>
</tr>
<tr>
<td>Sept 24</td>
<td>Hurley Medical Center researcher demonstrated incidence of elevated blood-lead levels increased from 2.4% to 4.9% after water source change (Hanna-Attisha et al., 2016)</td>
</tr>
<tr>
<td>Sept 25</td>
<td>City of Flint issued a lead advisory that suggested residents install a water filter, and use water only from cold-water tap for drinking, cooking, and making baby formula (City of Flint, 2015).</td>
</tr>
<tr>
<td>Oct</td>
<td>Michigan Department of Health and Human Services (MDHHS) and Genesee County Community Action Resource Department partnered to distribute water filter to residents (Miller, 2015). State officials released a plan including free testing of water, $1 million for water filters for residents and complete anti-corrosion treatment of the city's water system (Erb and Gray, 2015).</td>
</tr>
<tr>
<td>Oct 1</td>
<td>Genesee County Board of Commissioners issued a Public Health Emergency and recommended residents not to drink water from the Flint River as the water source unless it was being filtered through approved filters (Genesee County Board of Commissioners, 2015). Private and public sources donated $105,000 to fund 5,000 water filters for Flint residents (Michigan State Government, 2016b).</td>
</tr>
<tr>
<td>Oct 16</td>
<td>Flint reconnected back to Detroit water (Emery, 2015).</td>
</tr>
<tr>
<td>Dec 14</td>
<td>Flint declared a state of emergency (City of Flint, 2016a). FEMA delivered 28,000 liters of water to Flint (Fonger, 2015).</td>
</tr>
<tr>
<td>2016 Jan 4</td>
<td>Genesee County Commissioners declared a state of emergency (Moore, 2016a).</td>
</tr>
<tr>
<td>Jan 5</td>
<td>Michigan State declared a state of emergency (Michigan State Government, 2016b).</td>
</tr>
<tr>
<td>Jan 7</td>
<td>Michigan’s chief medical executive, Dr. Eden Wells stated that Flint residents should either use water filters or bottled water until further notice (Egan, 2016). Continued national media coverage censuring the state’s failure to provide bottled water and water filters (Michigan State Government, 2016a).</td>
</tr>
<tr>
<td>Jan 9</td>
<td>The state set up water distribution sites to distribute bottled water, water filters, replacement cartridges, and home water testing kits (Emery, 2016).</td>
</tr>
<tr>
<td>Jan 16</td>
<td>President Obama signed an emergency declaration for the State of Michigan (The White House, 2016).</td>
</tr>
<tr>
<td>Jan 19</td>
<td><strong>State governor committed $28 million in short-term for more filters, bottled water, school nurses, intervention specialists, testing and monitoring</strong> (Michigan State Government, 2016a).</td>
</tr>
<tr>
<td>Jan 21</td>
<td>President Obama announced financial aid of $80 million for water infrastructure projects in Michigan (Michigan State Government, 2016a).</td>
</tr>
<tr>
<td>Mar</td>
<td>EPA’s drinking water sampling from Jan 28, 2016-Mar 21, 2016 revealed a maximum, minimum, and 90th percentile lead levels of 2976, 0.35, 25.45 µg/L respectively (US EPA, 2016c).</td>
</tr>
<tr>
<td>May</td>
<td>EPA’s drinking water sampling from May 12, 2016-May 16, 2016 revealed a maximum, minimum, and 90th percentile lead levels of 91.8, 0.5, 10.3 µg/L respectively (US EPA, 2016c).</td>
</tr>
<tr>
<td>June 1</td>
<td>EPA declared that filtered water is safe for everyone in Flint (US EPA, 2016d).</td>
</tr>
<tr>
<td>July</td>
<td>EPA’s drinking water sampling from July 12, 2016-July 22, 2016 revealed a maximum, minimum, and 90th percentile lead levels of 818, 0.5, 23.05 µg/L respectively (US EPA, 2016c).</td>
</tr>
<tr>
<td>Aug</td>
<td>The state of emergency declaration ended and FEMA stopped providing water, water filters, replacement cartridges and test kits (Dolan and Spangler, 2016).</td>
</tr>
<tr>
<td>Sept</td>
<td>EPA’s drinking water sampling from Sept 1, 2016-Sept 24, 2016 revealed a maximum, minimum, and 90th percentile lead levels of 67.9, 0.2, 10.65 µg/L respectively (US EPA, 2016c).</td>
</tr>
</tbody>
</table>
A.1 continued

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov</td>
<td>Flint Mayor signed a new Emergency Declaration to extend the state of emergency in Flint due to the ongoing effects of the Flint water crisis (City of Flint, 2016a).</td>
</tr>
<tr>
<td>Nov</td>
<td>EPA’s drinking water sampling from October 26, 2016-November 15, 2016 revealed a maximum, minimum, and 90th percentile lead levels of 714, 0.25, 9.6 µg/L respectively (US EPA, 2016c).</td>
</tr>
<tr>
<td>Dec</td>
<td>Virginia Tech scientist reported 57% of 154 homes tested in November had no detectable level of lead, but said water was still unsafe until old lines are replaced (Tang et al., 2016; White, 2016).</td>
</tr>
<tr>
<td>2017</td>
<td>Jan 24</td>
</tr>
<tr>
<td>Aug 11</td>
<td>Two of nine points of distribution (PODs) were closed (Michigan State Government, 2018a).</td>
</tr>
<tr>
<td>Sept 5</td>
<td>Three of seven remaining PODs were closed. Residents were able to pick up free water supply at other four PODs (Michigan State Government, 2018a).</td>
</tr>
<tr>
<td>2018</td>
<td>Feb 16</td>
</tr>
<tr>
<td>Apr 6</td>
<td>State free water program ended (Ahmad, 2018). Flint’s water quality 90th percentile lead level has bested below LCR action level for about two years (Michigan State Government, 2018c).</td>
</tr>
</tbody>
</table>
(a) Five PODs at Fire Stations Were Operating on January 9, 2016

(b) Nine PODs Were Operating at Banks and Churches After the Change of Location. Symbols Indicate the PODs in Flint

Figure B.1 PODs Were Setup Across Flint to Provide the Community Access to Emergency Water Supplies: (a) Five PODs at Fire Stations Were Operating on January 9, 2016 and (b) Nine PODs Were Operating at Banks and Churches After the Change of Location. Symbols Indicate the PODs in Flint
# APPENDIX C

Table C.1 Information Found that Can be Used to Estimate Emergency Drinking Water Needs Following a Disaster ($\frac{L}{\text{capita-day}}$)

<table>
<thead>
<tr>
<th>Org.</th>
<th>Timeframe</th>
<th>Drinking and food</th>
<th>Basic hygiene practice</th>
<th>Basic cooking needs</th>
<th>Other water use activities</th>
<th>Water needed (total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPA  (AWWA and CDM, 2011)</td>
<td>Short term &lt;21 d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.89-18.93</td>
</tr>
<tr>
<td>USACE (2015)</td>
<td>Short term*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;3</td>
</tr>
<tr>
<td>WHO (2011)</td>
<td>Basic survival supply*</td>
<td>2.5-3</td>
<td>2-6</td>
<td>3-6</td>
<td></td>
<td>7.5-15</td>
</tr>
<tr>
<td></td>
<td>2 wk to 1 mo.**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1 to 3 mo.**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>3 to 6 mo.**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;15</td>
</tr>
<tr>
<td></td>
<td>Longer term supply*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Development supply*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20-50</td>
</tr>
<tr>
<td>CNN (Zdanowicz, 2016) *</td>
<td>4.5</td>
<td>10.65</td>
<td>6</td>
<td>4</td>
<td></td>
<td>25.15</td>
</tr>
</tbody>
</table>

* without indication for specific timeframe

** time period that is 2 week to 1 month (1 to 3 moths, 3 to 6 months) from initial intervention

$L_{\text{capita-day}}$: liters per person per day
APPENDIX D

Figure D.1 Water Bottle Measurement
Analytical Measurement and Example Calculation

Our analytical measurements

The following data was obtained by weighing components of the case. All bottles were empty when weighed.
Cardboard = 50.28226 g
Plastic wrap = 36.6512 g
PET bottle (with cap, ring, label) = 18.6911 g
PET bottle (with cap, ring, no label) = 18.3330 g
PET bottle cap = 1.4834 g
PET bottle (stripped; no cap, ring, label) = 15.9642 g

Example calculations

Estimate the number of water bottles distributed into the Flint Community since January 9, 2016
196,456 cases x 24 bottles/case = 4,714,944 bottles issued by the State of Michigan

If 25% more bottles have been distributed by other groups…
[196,456 cases x 24 bottles/case]/0.75 = 6,286,594 bottles issued into the Flint Community

If 50% more bottles have been distributed by other groups…
[196,456 cases x 24 bottles/case]/0.5 = 9,429,888 bottles issued into the Flint Community

Based on physical measurements we made in the laboratory with real bottles we estimate 1 bottle takes up 0.04321 m$^3$ of space. So, by knowing the total number of bottles distributed we can estimate the total volume of space those bottles (uncompacted) occupy.
4,714,944 bottles x 0.04321 m$^3$/bottle = 203,740 m$^3$ issued by the State of Michigan
We can do this for each number of bottles we estimated.

Each bottle is approximately 0.2296 m in total length (with cap). So, by knowing this distance we can calculate the total linear distance if all the collected bottles are stacked end-to-end.
4,714,944 bottles x 0.2296 m/bottle x 1 km/(1,000 m) = 1,082.6 km issued by the State of Michigan

Estimate the number of water bottles to store in a single 20-gallon (75.7-liter) recycling bin
15 empty bottles (with caps) require 11.7-liter volume of space
For 20-gallon (75.7-liter) recycling bin, you could store 98 bottles

Estimate the weight of cardboard generated from the cases
196,456 cases x 50.28226 g/case x 1 kg/(1,000 g) = 9,878.3 kg of cardboard issued by the State of Michigan