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Blast Furnace Slag Usage and Guidance for Indiana



Tianqi Wang, Maryam Salehi, Andrew J. Whelton

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AUTHORS

Tianqi Wang

Graduate Research Assistant Lyles School of Civil Engineering Purdue University

Maryam Salehi, PhD

Postdoctoral Research Associate Lyles School of Civil Engineering Purdue University

Andrew J. Whelton, PhD

Associate Professor of Civil, Environmental, and Ecological Engineering Lyles School of Civil Engineering Purdue University (765) 494-2166 awhelton@purdue.edu *Corresponding Author*

JOINT TRANSPORTATION RESEARCH PROGRAM

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The project goal was to better understand the extent of air-cooled blast furnace slag (ACBFS) usage for completed INDOT pr factors that can influence slag leaching, review remediation strategies, and identify applications where future usage restrictions or criteria are needed. A literature review of government documents, peer-review, and trade industry literature was conducted. The team also conducted a site visit to an ACBFS storage facility and steel mill that generated the ACBFS and reviewed handling and procedures. The project team also contacted other state transportation agencies (IL, MD, MI, NY, OH) to determine the degree incorporated ACBFS into their projects and if product performance tests were required. Results show that changes to Indian methods and acceptance criteria are warranted. Indiana Test Method 212 should be revised to extend the test duration, pH acce criterion, and add additional material acceptance criteria. Unbound ACBFS should be avoided for construction applications (1) ground water could contact the material, (2) near environmentally sensitive and populated areas, (3) where a drainage system present. Additional work to improve the ability of INDOT to detect ACBFS that would cause short- or long-term chemical le problems could include (1) evaluating and optimizing stockpile sampling practices for representative sampling, (2) modifying ITM better predict worst-case leaching conditions and leachate quality, (3) conduct a head-to-head comparison of bench-scale and fiel leaching results.		
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EXECUTIVE SUMMARY

BLAST FURNACE SLAG USAGE AND GUIDANCE FOR INDIANA

Introduction

INDOT permits the use of air cooled blast furnace slag (ACBFS) as a conventional aggregate. The material can be used in granular base, hot mix asphalt, Portland cement concrete, embankments, and fill applications. ACBFS has been used in unbound applications at numerous sites in the LaPorte District in Northern Indiana. To lessen the chance of ACBFS causing leaching problems, INDOT required ACBFS products to pass the Indiana Test Method (ITM) No. 212. However, some INDOT staff have observed that leachate from sites where ACBFS has been used reportedly can have periodic greenish leachate and odor issues (Nevers, 2016). This project was conducted to better understand whether certain ACBFS usage applications were a problem, the extent of the problem, and how neighboring states addressed similar issues, as well as to help INDOT identify how they can modify their ITM to only permit ACBFS usage when it does not cause conditions that exceed Indiana water quality standards.

The project objective was to understand the factors that influence slag leaching, review remediation strategies, and identify applications where future usage restrictions or siting criteria are needed, if any. A literature review of government documents, peer-review, and trade industry literature was conducted to ascertain which factors could cause ACBFS chemical leaching issues such as high pH, color, and odor. The literature was also examined for adaptive measures that could lessen the chance of chemical leaching, thereby enabling ACBFS usage. The project team conducted a site visit to an ACBFS storage facility and steel mill that generated the ACBFS. The project team also contacted other state transportation agencies to determine to what degree they incorporated ACBFS into their projects.

Findings

- ACBFS has been used for roadway construction in and outside Indiana. Several states listed ACBFS in transportation agency specifications. Five state transportation agencies provided feedback to the authors: Illinois, Maryland, Michigan, New York, and Ohio. Illinois and Ohio use ACBFS as bound and unbound material. Michigan does not permit the use of ACBFS in concrete mixtures for trunk line pavement and bridge applications, and permits ACBFS use for unbound drainable base layers. Maryland only uses granulated blast furnace slag (GBFS), and therefore does not use ACBFS. The representative from New York reported that the state agency has never used ACBFS. None of the states stored ACBFS before construction. Where ACBFS has been used (Illinois, Michigan, Ohio), transportation agency representatives were unaware of leaching problems at construction sites.
- ACBFS contains both rapidly cooled glassy material and slowly cooled crystallized material. The most common compound in blast furnace slag (BFS) [type not specified] is melilite (65% by volume), containing akermanite (2CaO MgO 2SiO₂) and gehlenite (2CaO Al₂O₃ SiO₂). BFS contains a higher loading of many heavy metals than soil and also contains sulfur. The sulfur content in ACBFS is about 5–10 times higher than that in steel slag. Total sulfur in ACBFS has been estimated to be 1% to 2% by weight. In one study,

the total amount of sulfur in ACBFS was 10,000 mg S/kg slag.

- A variety of material properties and chemical, environmental, and experimental conditions can affect ACBFS leaching. The cooling process can influence ACBFS physical properties. The age of ACBFS, the pH and temperature of leachant, and the redox condition in the field can influence chemical leaching. Factors in the ACBFS production process (i.e., temperature, feedstocks), cooling method (whether or not water was used), how ACBFS was transported, and environmental conditions before it was tested may also influence the product's leaching performance. Few studies were found that compared ACBFS performance and isolated different material and environmental factors to determine which controlled chemical leaching.
- The ability of the existing ITM 212 testing procedure to help identify ACBFS that could pose problems once installed is unclear. For example, ITM 212 required leachate pH to be between 6.0 and 10.5, while Indiana water quality standards required surface water pH to be between 6.0 and 9.0. In addition, different construction applications (i.e., subbase vs. embankment) may require different levels of testing and performance criteria for ACBFS use, because the environmental exposure conditions in each application differ. Also, it is unknown if, by following the ITM 212 or 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) and where samples are collected are representative of the entire stockpile used for an INDOT application. Ohio requires ACBFS stockpiles to pass a leaching test, Supplement 1027, for unbound applications. The acceptance test includes criteria for leachate color, pH, conductivity, and total dissolved solids.
- Weathering, use of water before and during storage (i.e., washing ACBFS on belt, spraying water on stockpiles), coating ACBFS, and mixing ACBFS with other materials are reported as viable methods to reduce leaching. Constructed wetlands have indicated some effectiveness for reducing ACBFS leachate pH, salinity, sulfate, and some species levels. However, many studies did not report one or more of the following: the type of BFS tested (ACBFS vs. GBFS), the slag production process, initial composition before the leaching test, slag age when tested, and environmental conditions when it was stored. Lack of this information inhibited evaluating the feasibility of adopting these methods in Indiana.

Implementation

Based on results of this study, INDOT should consider the following actions:

- Revise 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 total sulfur (2%), conductivity (2,400 µmho/cm), and total dissolved solids (1,500 mg/L), and (4) adding an additional siting criterion for ACBFS usage at locations where water has long-term access to the material.
- Adherence to the ITM 207 sampling procedure at a minimum, because it is unclear if the stockpile sampling method influences ACBFS leachate performance.
- Prohibit unbound ACBFS from being used (1) for construction applications where ground water could contact the material,

(2) near environmentally sensitive and populated areas, and (3) where a drainage system is not present. This is to reduce the potential that ACBFS is incorporated into applications where leaching could be a short- or long-term challenge.

• Additional work to improve the ability of INDOT to detect ACBFS that would cause short- or long-term chemical leaching problems is needed. 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, and (3) head-to-head comparison of bench-scale and field-scale leaching results. It is recommended that INDOT consider incorporating input, like the present study, from ACBFS suppliers in future work. INDOT may consider inspecting former sites where ACBFS was used to assess their conditions.

CONTENTS

1.			. 1
	1.1 Problem Statement	• •	. 1
	1.2 Research Objective	••	. I
	1.5 Dusiness Case	••	. I 1
	1.5 Work Plan.	•••	. 1
2	AIR COOLED BLAST FURNACE SLAG USE BY INDOT		ົ່
2.	21 Use of ACBES	•••	. 2
	2.2 Existing Sampling and Testing Protocols	•••	. 2
3.	SITE VISIT TO AN ACBFS PROCESSING FACILITY AND PRODUCTION PLANT		. 3
4.	ACBFS USE OUTSIDE INDIANA.		. 4
	4.1 Tests and Requirements		. 7
5.	REVIEW OF THE SCIENTIFIC LITERATURE.		. 8
	5.1 Production and Storage	• •	. 8
	5.2 Properties	• •	. 9
	5.3 Leaching	• •	10
	5.4 Bench- and Pilot-Scale Leaching Studies.	• •	11
	5.5 Methods to Reduce Leaching: Treatment Strategies	•••	13
6.	DISCUSSION AND CONCLUSION.	• •	14
7.	RECOMMENDATIONS		16
R	EFERENCES		16

LIST OF TABLES

Table	Page
Table 3.1 Results of muffle furnace and TCLP tests used to evaluate ACBFS composition	3
Table 4.1 Construction applications where ACBFS can be utilized according to state transportation agency specifications	5
Table 4.2 Leaching test methods by national and international organizations	8
Table 5.1 Chemical composition and leachable fraction in BFS [type not specified] Mixed with Lime	9
Table 5.2 Factors influencing leaching	10
Table 5.3 Total element available for leaching from a BFS sample under "somewhat oxidized" and "fully oxidized" conditions	12
Table 6.1 Proposed ACBFS classification	15

LIST OF FIGURES

Figure	Page
Figure 3.1 (a) Yard map of ACBFS stockpiles, (b) stockpile approval sign, (c) stockpile rejection sign	4
Figure 4.1 Sample of question list the authors sent to state transportation agencies	6
Figure 5.1 Production flow of blast furnace slag (specific to the slag producer site visit)	8
Figure 5.2 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	13
Figure 6.1 Proposed siting criteria for ACBFS	16

LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ACBFS	Air Cooled Blast Furnace Slag
BFS	Blast Furnace Slag
FHWA	Federal Highway Administration
GBFS	Granulated Blast Furnace Slag
HMA	Hot Mix Asphalt
L/S	Liquid to Solid Ratio
MDOT	Michigan Department of Transportation
MDOT	Maryland Department of Transportation
NYSDOT	New York State Department of Transportation
IAC	Indiana Administrative Code
ICP	Inductively Coupled Plasma
IDOT	Illinois Department of Transportation
INDOT	Indiana Department of Transportation
ITM	Indiana Test Method
ITP	Illinois Test Procedure
IWQS	Indiana Water Quality Standards
ODOT	Ohio Department of Transportation
SMA	Stone Matrix Asphalt
TCLP	Toxicity Characteristic Leaching Procedure
PCC	Portland Cement Concrete
PCCP	Portland Cement Concrete Pavement

1. INTRODUCTION

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, Collins, & MacKay, 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, Schwab, Alleman, Hunter, & Hickey, 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.

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.

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) (Indiana General Assembly, 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.

1.4 Technical Approach

A literature review of government documents, peerreview 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 an 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.

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. AIR COOLED BLAST FURNACE SLAG USE BY INDOT

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 offodor 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 Existing Sampling and Testing Protocols

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 frontend 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 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 T 248, 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 (2003). Approximately 20 to 25 lbm of that material is placed in a 5-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.

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 (SO₃) content was $2.55 \pm 0.23\%$ (Table 3.1). 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 (1/2 to 1 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 and 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 (2003), 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

TABLE 3.1 Results of muffle furnace and TCLP tests used to evaluate ACBFS composition.

Muffle furnace ACBFS composition (%)			
Sodium Oxide (Na ₂ O)	0.30 ± 0.05		
Magnesium Oxide (MgO)	10.86 ± 0.56		
Aluminum Oxide (Al ₂ O ₃)	7.58 ± 0.92		
Silicon Dioxide (SiO ₃)	37.19 ± 0.92		
Phosphorus Pentoxide (P_2O_5)	0.10 ± 0.01		
Sulfur Trioxide (SO ₃)	2.55 ± 0.23		
Potassium Oxide (K ₂ O)	0.34 ± 0.03		
Calcium Oxide (CaO)	38.79 ± 1.22		
Titanium Dioxide (TiO ₂)	0.43 ± 0.06		
Chromium (III) Oxide (Cr ₂ O ₃)	$0.00~\pm~0.00$		
Manganese Oxide (MnO)	0.66 ± 0.12		
Iron (III) Oxide (Fe ₂ O ₃)	0.57 ± 0.19		
Zinc Oxide (ZnO)	< 0.0001		
Sulfur (S)	1.02 ± 0.09		
Loss on Ignition % (L.O.I.)	0.7 ± 0.36		
Total	101.09 ± 1.93		

TCLP test results (mg/L)

	Results	Reporting limit
Mercury	ND	0.0010
Arsenic	ND	0.0100
Barium	ND	0.500
Cadmium	ND	0.00200
Chromium	ND	0.00300
Lead	ND	0.00750
Selenium	ND	0.0300
Silver	ND	0.0100

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 $\mu g/L$ to mg/L. References used for this table include Beemsterboer (2017) and Microbac (2016).

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 3.1). 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 3.1).



(a)



Figure 3.1 (a) Yard map of ACBFS stockpiles, (b) stockpile approval sign, and (c) stockpile rejection sign.

4. ACBFS USE OUTSIDE INDIANA

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 4.1). 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 Figure 4.1.

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

TABLE 4.1 Construction applications where ACBFS can be utilized according to state transportation agency specifications.

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

*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), and ODOT (2016).

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 greenishyellow 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

- 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%?
- 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?
- 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?
- Is there any leaching test for the acceptance of ACBFS? Is it for bound or unbound applications?
- What are the sampling protocol for aggregate test and ACBFS test? Are they different?
- Who conducts the sampling and test? ACBFS suppliers or the DOT? Who conducts the leaching test?
- When should ACBFS be sampled and tested? Right after the production? What were the sampling and testing frequencies?
- If the suppliers conduct the sampling and tests, how do you supervise their sampling and test procedure?
- 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?
- 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)
- Do you know the size of the stockpile when ACBFS was weathered?
- 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?
- Was there any leaching problem because of ACBFS usage? If there was:
 - 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?
 - What materials were under and above the layer of ACBFS? Do you have the record of the pH, chemical composition of these materials?
 - What chemicals were leached? Do you have any record of the quantity, color, odor, pH, chemical composition of the leachate?
 - Did the leachate ooze up to the ground or permeate into the deeper construction layer and soil?
 - What was the groundwater level at the leaching site? What was the distance from the groundwater to the leaching site?
 - Was there any mechanical failure along with leaching?
 - How did you solve the leaching problem?
- Was there any other problems with bound or unbound ACBFS? How did you solve the problem?

Figure 4.1 Sample of question list the authors sent to state transportation agencies.

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, 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.

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 $\frac{1}{2}$ 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 and 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"

TABLE 4.2Leaching test methods by national and international organizations.

Test method	Name
ASTM D3987 (2014)	Standard Practice for Shake Extraction of Solid Waste with Water
EPA SW-846 Method 1311 (U.S. EPA, 1992)	Toxicity Characteristic Leaching Procedure (TCLP)
EN 12457*	Characterization of Waste - Leaching - Compliance Test for Leaching of Granular Waste Materials and Sludges
NEN 7345*	Leaching Characteristics of Soil, Construction Materials and wastes –Leaching Tests – Determination of the Release of Inorganic Constituents from Construction Materials, Monolithic Wastes and Stabilized Wastes
NT ENVIR 002*	Solid Waste, Granular Inorganic Material: Column Test
NT ENVIR 003*	Solid Waste, Granular Inorganic Material: Availability Test
EN 1744*	Tests for Chemical Properties of Aggregates

*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



Figure 5.1 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.

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 4.2).

5. REVIEW OF THE SCIENTIFIC LITERATURE

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 (FHWA, 2008). 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 5.1).

5.2 Properties

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).

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 & 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 5.1. 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 5.1.

TABLE 5.1 Chemical composition and leachable fraction in BFS [type not specified] Mixed with Lime.

Compound	Composition (%)	Leachable fraction (%)*
Ca	17.8	20
Mg	6.31	14
Na	0.49	45
SO_4^{2-}	2.49	45
Sb	0.000005	13
As	_	ND
Cd	0.000002	ND
Cu	0.0016	0.8
Мо	0.0015	2.7
F	0.036	18
Se	0.00018	18
U	0.0015	ND
V	0.0213	NA
W	0.00005	63
Zn	0.0022	10
Total	27.152087	_

*Percent leachable part in each species. Data from van der Sloot, De Groot, and Wijkstra (1989).

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 5.2). This process can cause elevated pH of ACBFS leachate and produce heat.

 $CaS + H_2O + CO_2 \rightarrow H_2S + CaSO_4 + CaCO_3 + S \quad (5.1)$

$$CaO + H_2O \rightarrow Ca(OH)_2$$
 (5.2)

Proctor et al. (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 4.2 and Table 5.1). Also, the leachant pH ranged from 3 to 7 in these tests, and leachant is static in most of the tests (Hill, 2004; U.S. 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 ($K_{spa}(PbS) = 3x10^{-7}$, $K_{spa}(FeS) = 6x10^2$ (Lide, 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 (HNO₃)) 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

TABLE 5.2Factors influencing leaching.

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

Note: Information reproduced from Hill (2004).

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):

$$CO_{2(g)} + H_2O \leftrightarrow H_2CO_{3(aq)}$$
 (5.3)

$$H_2CO_3 \leftrightarrow 2H^+{}_{(aq)} + CO_3{}^{2-}{}_{(aq)}$$
(5.4)

$$\mathbf{S}^{2-} + 2\mathbf{H^+}_{(\mathrm{aq})} \leftrightarrow \mathbf{H}_2 \mathbf{S}_{(\mathrm{g})} \tag{5.5}$$

$$H_2S_{(aq)} + O_{2(g)} \leftrightarrow S_{(aq)} + H_2O_{(l)}$$
(5.6)

$$n(\mathbf{S}_{(aq)}) \leftrightarrow (\mathbf{S} = \mathbf{S})_{n(aq)} \leftrightarrow (\mathbf{S}^{+} - \mathbf{S}^{-})_{n(aq)} \quad (5.7)$$

$$S^{2-}_{(aq)} + 2O_{2(g)} \leftrightarrow SO_4^{2-}$$
 (5.8)

$$\operatorname{Ca}^{2+}_{(aq)} + \operatorname{SO}_4^{2-}_{(aq)} \leftrightarrow \operatorname{Ca}^{2}_{\operatorname{SO}_4} \cdot 2\operatorname{H}_2\operatorname{O}_{(\operatorname{gypsum})}$$
 (5.9)

5.3 Leaching

Leaching can be defined as "extraction of soluble components of a solid mixture by percolating a solvent through it" (Daintith, 2008). Leaching generally refers to physical, chemical and biological reactions that mobilize a contaminant or carry the contaminant away from the matrix (Table 5.2) (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, Hickey, Hunter, & Banks, 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 ground-water (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.

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.

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, humiity, 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 benchscale. 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 ABCFS 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 H₂S_(g) to SO_{2(g)}, but also could inhibit sulfur bearing gas release. Then a mixture of steam and carrier gas (i.e., air, argon or argon+1% H₂) was passed through the samples. When Ar(g) was used as the carrier gas, 5,000 times higher amount of H_2S emission at 1,200°C was detected (42,000 $\mu g H_2 S_{(g)}/m^3$) compared to when air was used as the carrier gas (8 μ g H₂S_(g)/m³). SO_{2(g)} emission was several times greater when air was used as the carrier gas than when $Ar_{(g)}$ 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 ($Q_{in} =$ 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, lavalite, and sand-cement stabilization) generally showed a small release of trace elements compared with the

TABLE 5.3

Total element available for leaching from a BFS sample under "somewhat oxidized" and "fully oxidized" conditions.

Amount (mg/kg)	Element detected and leaching condition	
	"Somewhat oxidized"	"Fully oxidized"
10,000-100,000	Ca, Mg, Si*	Ca, Mg
1,000-10,000	K, S, Al	K, S, Al
100-1,000	Fe, Na, Ba	Na
10-100	V	Fe, Ba, V
1-10	Ni, Zn	Ni, Zn
0.1-1	Co, Cr**, Cu**	Co, Cr, Cu, Pb
0.01-0.1	As**, Pb**	As**, Cd
0.001-0.01	Cd**	

Note: 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.

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 5.3). 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.

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 wettingdrying 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, SO₄²⁻, 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 2 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 5.2). 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 quick-lime 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.



Figure 5.2 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.

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 SO_4^{2-} 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, SO_4^{2-} 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.

5.5 Methods to Reduce Leaching: Treatment Strategies

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).

5.5.2 Coating ACBFS

Muñoz, Sanfilippo, Tejedor, Anderson, and Cramer (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 SiO₂ and nanoporous TiO₂ solutions. Slag aggregate of ³/₄ 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 material 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 SiO₂ and TiO₂ coated ACBFS was about 40% and 70% less than the control group, respectively. The amount of calcium leached from SiO₂ and TiO₂ 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.

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.

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.

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 to 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 performancebased 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 (Equations 5.3–5.8).

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 6.1). 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; U.S. EPA, 2002). A similar approach is proposed for ACBFS (Table 6.1 and Figure 6.1).

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

TABLE 6.1 Proposed ACBFS classification.*

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

*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.

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.

Figure 6.1 Proposed siting criteria for ACBFS.

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.

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 μ mho/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.
- 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.

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About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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