

Technical Awareness Group Meeting

Research Related to Recycling of WTE Bottom Ash as Aggregate in Concrete and Asphalt Pavement

October 6, 2017
Tallahassee, Florida

Research Support by the
Hinkley Center for Solid and Hazardous Waste Management
https://www.hinkleycenter.org/

Introductions

Two Hinkley Center Projects

- Use of Solid Wastes in Asphalt and Concrete in Florida
  - Ends December 31, 2017
- Research Advances on the Use of Solid Wastes in Concrete and Asphalt
  - Just starting
- Team: Townsend (PI), Ferraro (Co-PI), Laux (Co-PI), Clavier (GRA), Monroy (GRA), Oliveira (GRA), Schafer (GRA), Spreadbury (GRA), Townsend (GRA)

Meeting Agenda

- Background on ash recycling
- Use of WTE ash in portland cement concrete
- Use of WTE ash in asphalt pavement
- Environmental characterization of concrete and pavement made using WTE ash as aggregate
- New research areas
  - Ash processing and treatment
  - Markets and costs
  - Additional research needs

Background

Waste to Energy Facilities Worldwide

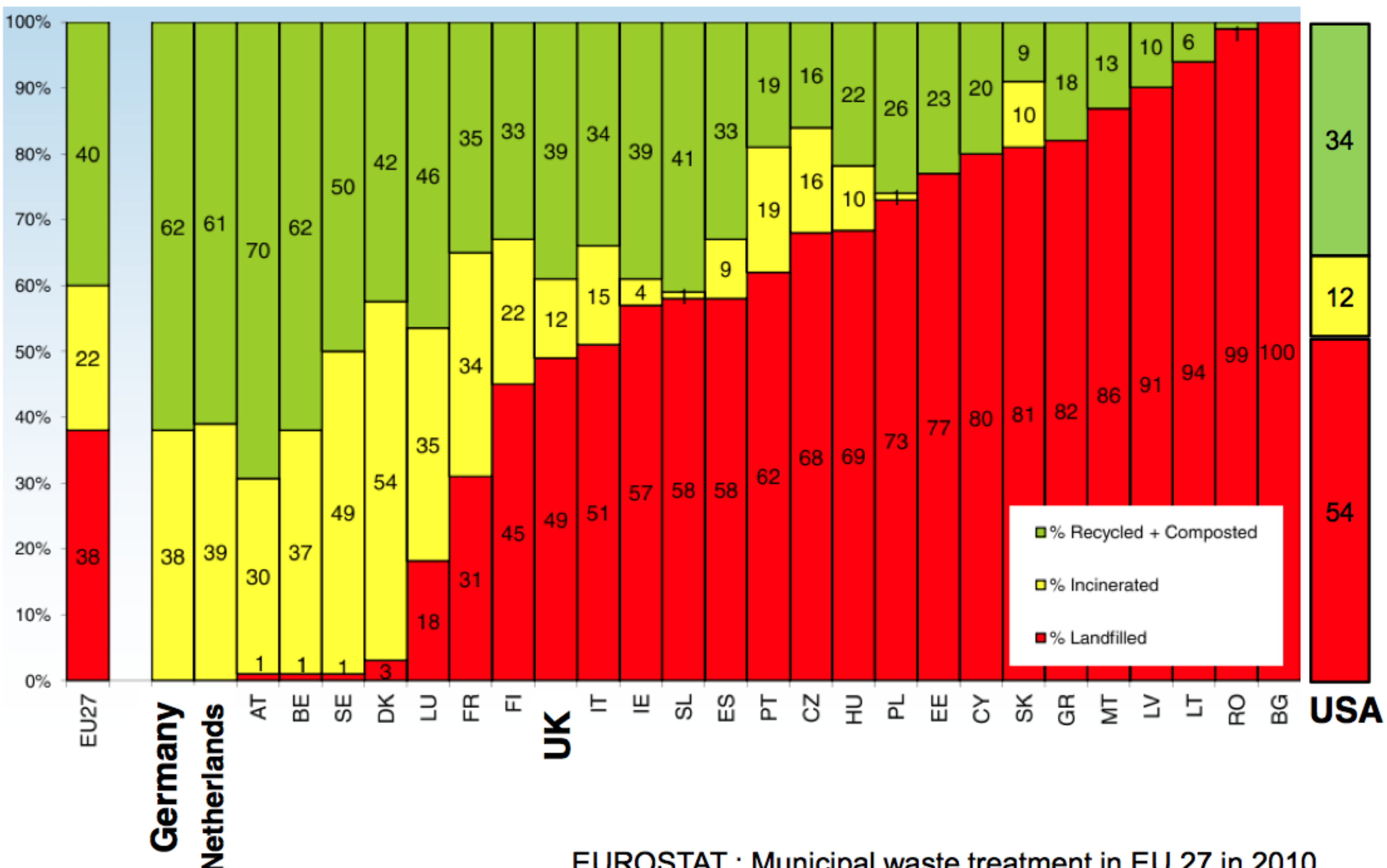
Europe

- 450 WTE Plants

United States

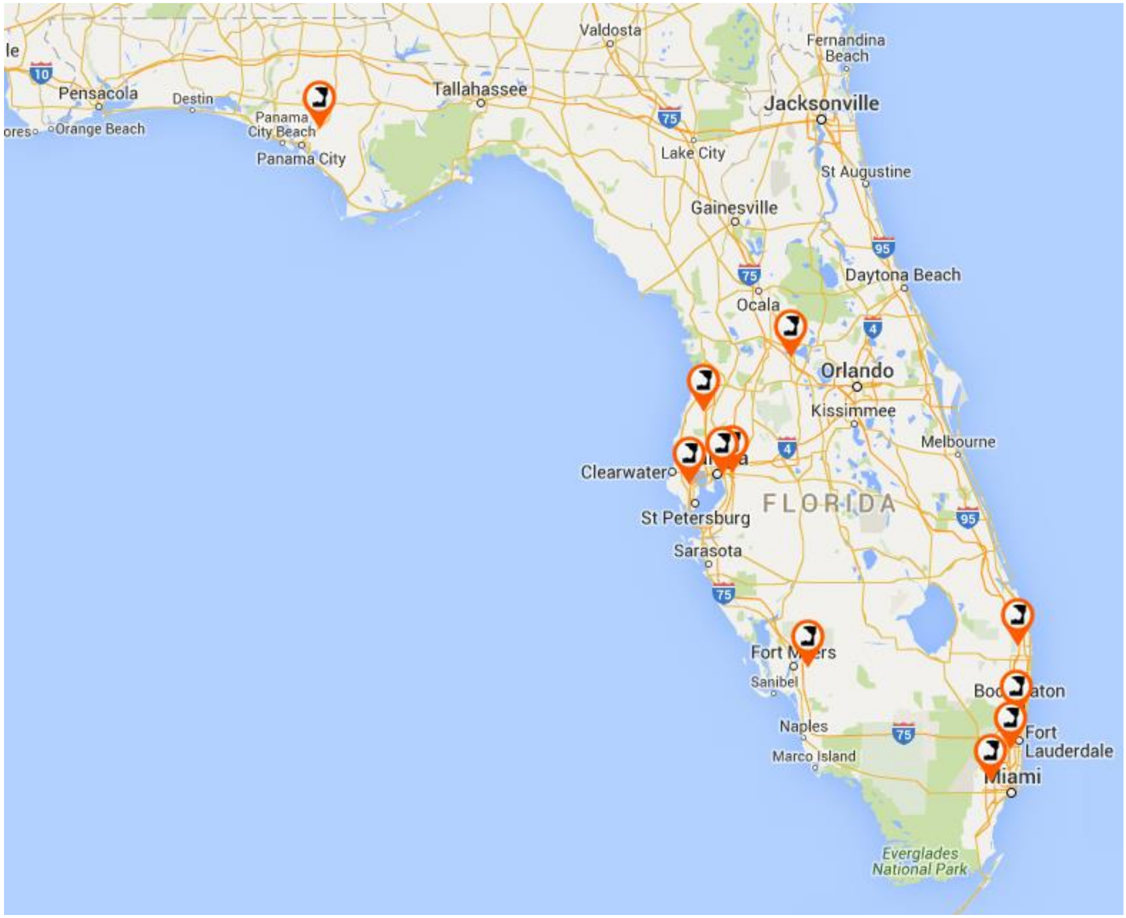
- 84 WTE Plants

Global MSW Management



EUROSTAT : Municipal waste treatment in EU 27 in 2010

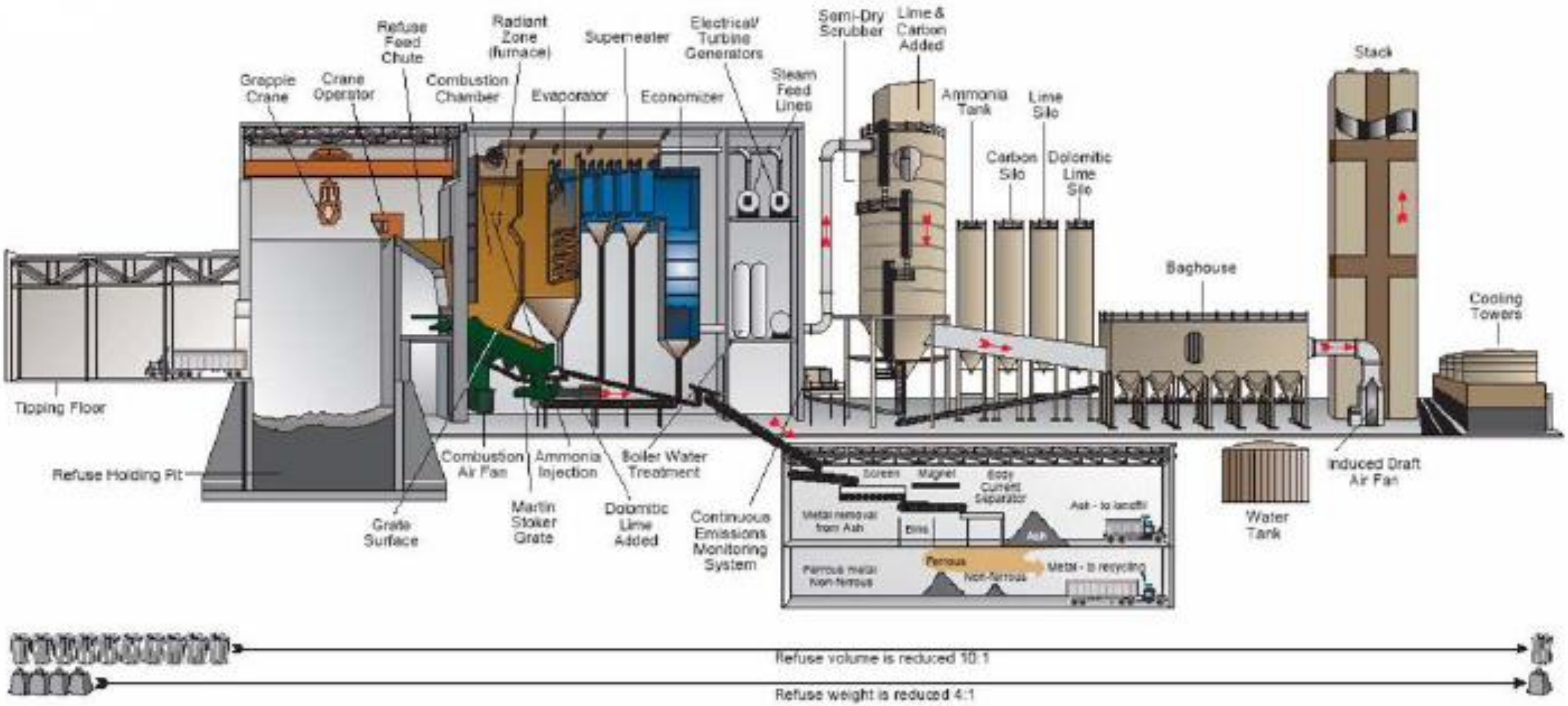
Facility Locations

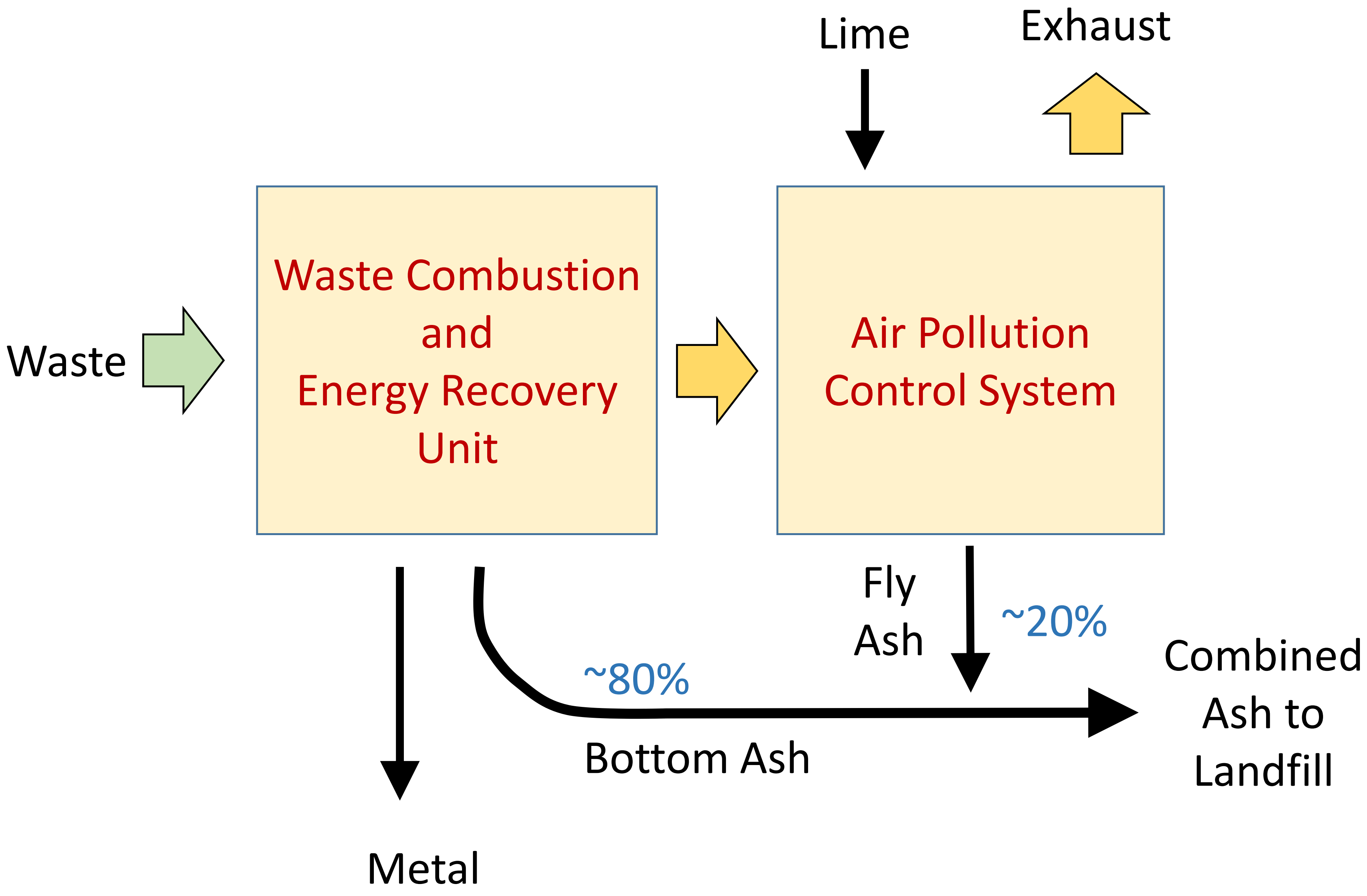


- Bay County-ENGEN
- Lake County – Covanta
- Pasco County – Covanta
- McKay Bay – Wheelabrator
- Hillsborough County – Covanta
- Pinellas County – Covanta
- Lee County – Covanta
- Palm Beach County #1/2 – B&W
- Miami Dade County – Covanta
- South Broward - Wheelabrator

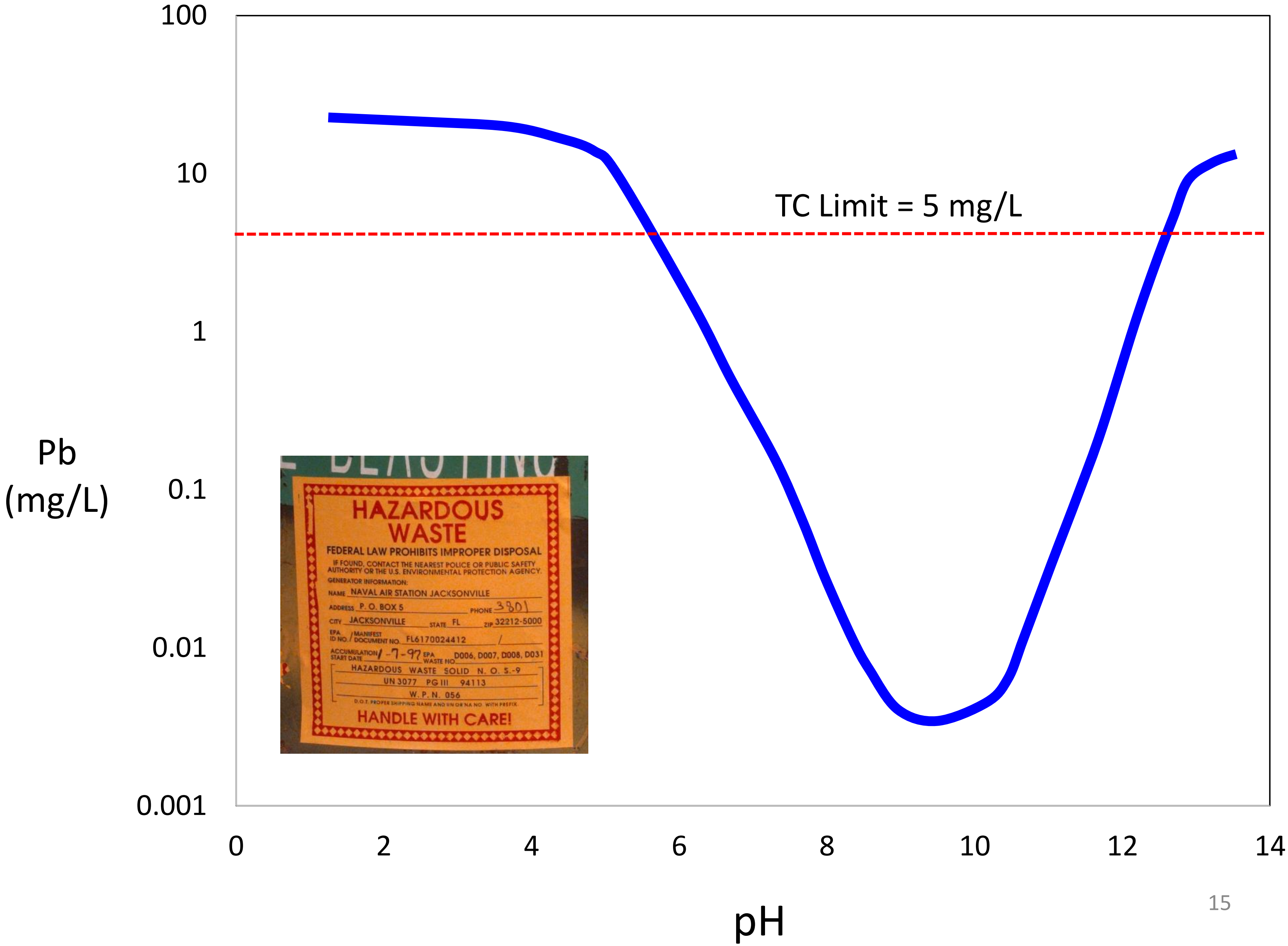

CATERPILLAR

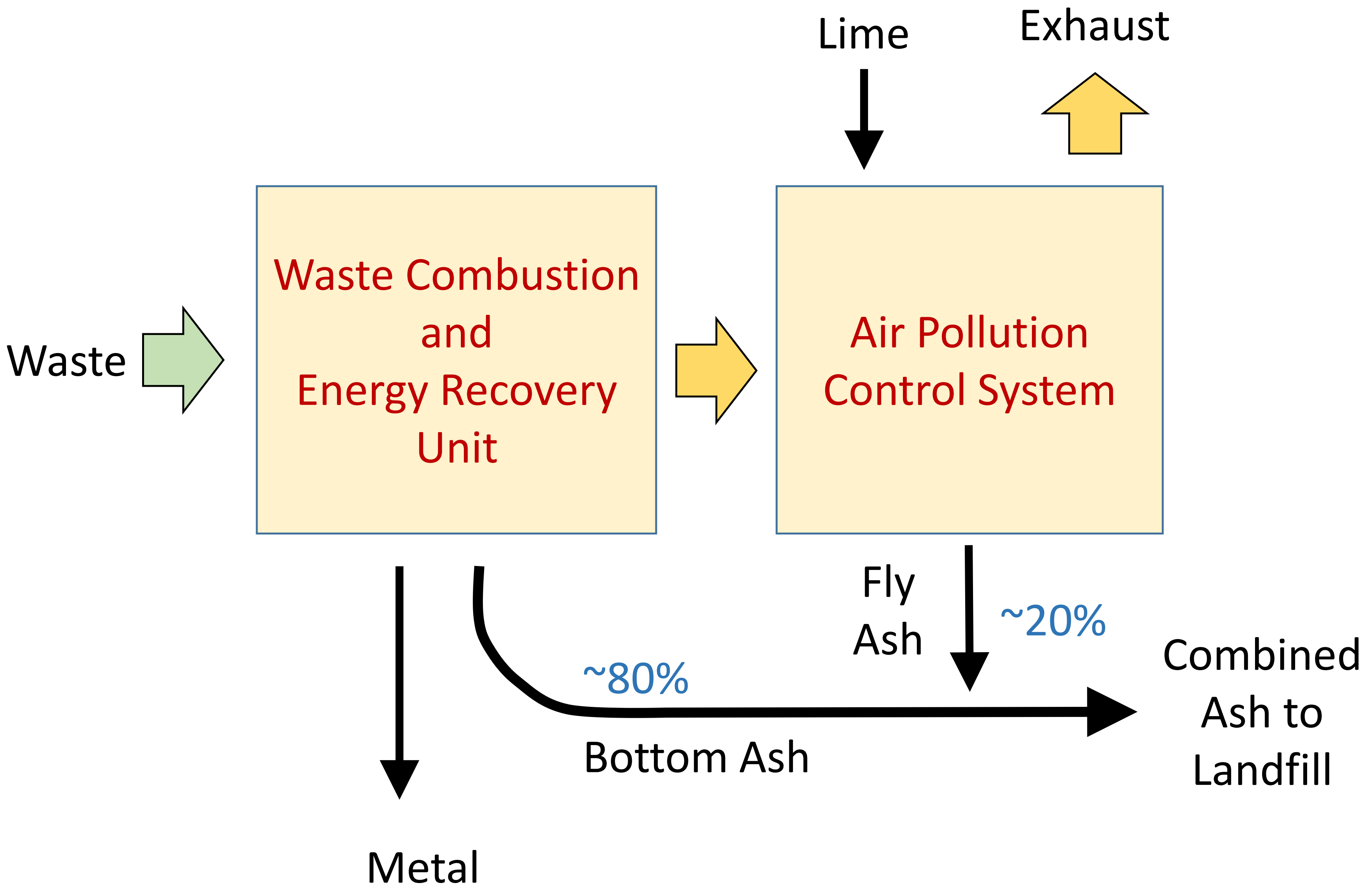
Modern Waste to Energy




Lime
Exhaust
Waste
Waste Combustion and Energy Recovery Unit
Air Pollution Control System
Fly Ash
~20%
~80%
Combined Ash to Landfill
Bottom Ash
Metal

Major Facility Focus: Do Not Generate Hazardous Waste!




Lime
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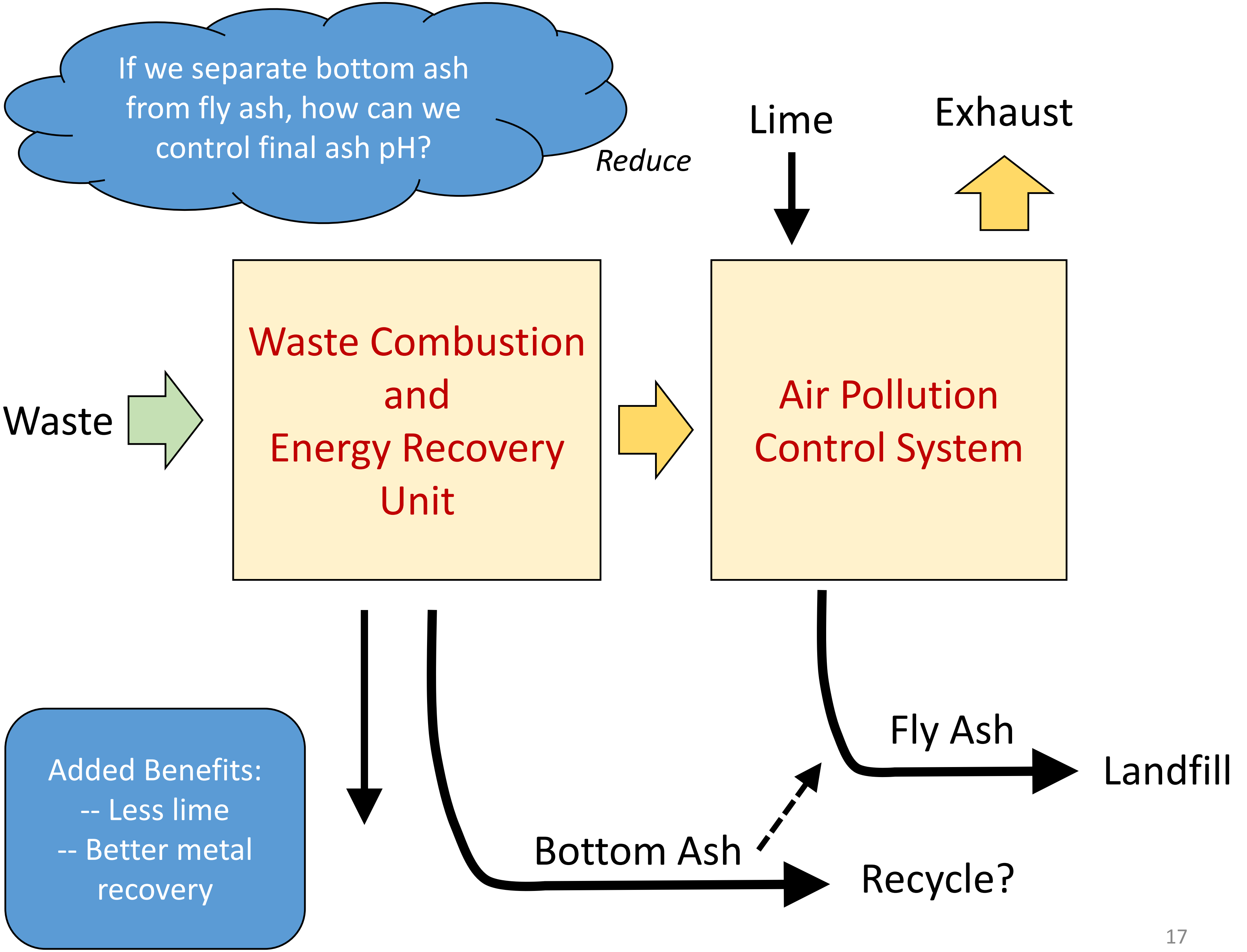

If we separate bottom ash from fly ash, how can we control final ash pH?
Reduce
Lime
Exhaust
Waste
Waste Combustion and Energy Recovery Unit
Air Pollution Control System
Fly Ash
Landfill
Bottom Ash
Recycle?
Added Benefits:
-- Less lime
-- Better metal recovery

Aggregate from WTE Ash

Aggregate Option	Type of Beneficial Use
Road base material	Unencapsulated/Unbound
Hot mix asphalt	Encapsulated/Bound
Portland cement concrete	Encapsulated/Bound
Portland cement	Integrated


Road Base


Asphalt Pavement Aggregate


Concrete Aggregate


Cement Kiln Feed

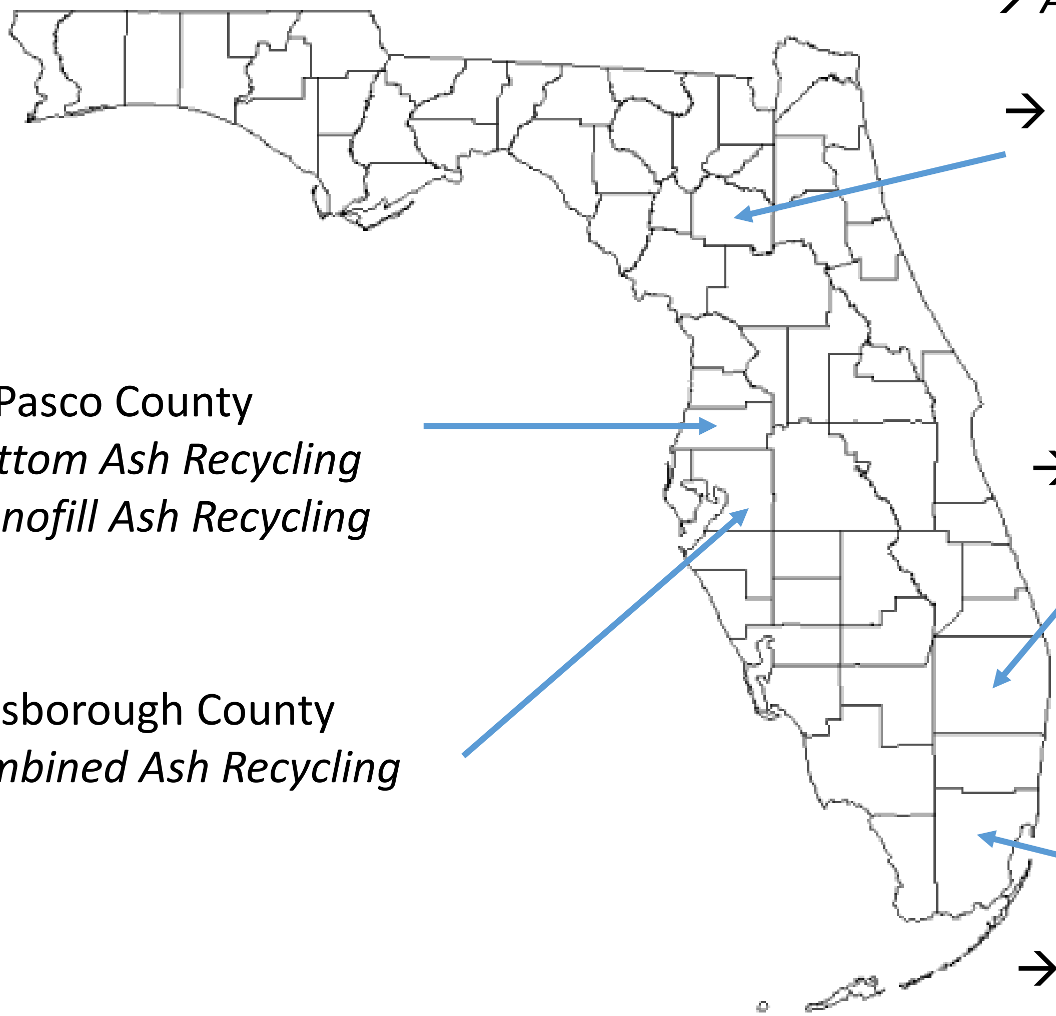

COARSE
FINES

Use in Cement Manufacture


CAT
311F
L RR


HR500-1E

Current Florida Efforts in Ash Reuse



Hinkley Center
→ *Application of LEAF for Beneficial Use*
→ *Issues Regarding Ash in Concrete*

Pasco County
→ *Bottom Ash Recycling*
→ *Monofill Ash Recycling*

Palm Beach County
→ *Bottom Ash Recycling as Aggregate*

Hillsborough County
→ *Combined Ash Recycling*

Miami-Dade County
→ *Bottom Ash Recycling as Cement Kiln Feed*

Use of WTE ash in portland cement concrete

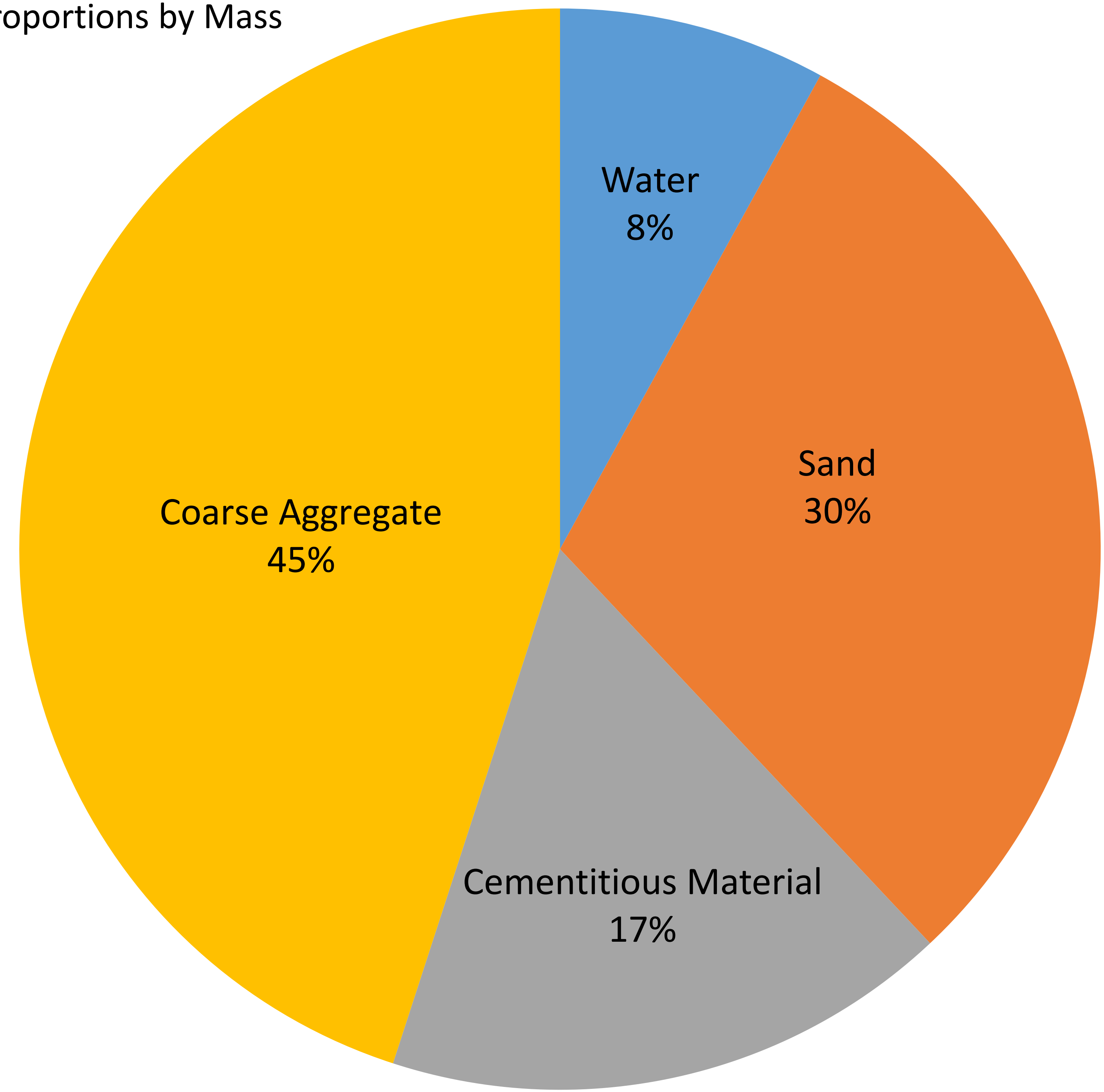

Water


Fine Aggregate


Coarse Aggregate


Portland Cement

Concrete Proportions by Mass



Concrete Performance

- Physical
- Environmental
- Durability

Some Literature

Recovery of MSWI and Soil Washing Residues as Concrete Aggregates, *Sorlini et al., 2011*

- Concrete specimens showed good compression strength results with low wastes amount, when ash replacement percentage was higher the mechanical properties showed a drastic decrease
- High aluminum content could bring swelling
- Washed bottom ash products show good chemical and physical quality for production of concrete

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

ELSEVIER

Recovery of MSWI and soil washing residues as concrete aggregates

Sabrina Sorlini [a,1], Alessandro Abbà [b,*,2], Carlo Collivignarelli [a,3]

[a] *Department of Civil, Architectural, Landscape and Environmental Engineering, University of Brescia, Via Branze 43, 25123 Brescia, Italy*

[b] *Department of Hydraulic and Environmental Engineering, University of Pavia, Via Ferrata 1, 27100 Pavia, Italy*

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ABSTRACT

The aim of the present work was to study if municipal solid waste incinerator (MSWI) residues and aggregates derived from contaminated soil washing could be used as alternative aggregates for concrete production.

Initially, chemical, physical and geometric characteristics (according to UNI EN 12620) of municipal solid waste incineration bottom ashes and some contaminated soils were evaluated; moreover, the pollutants release was evaluated by means of leaching tests. The results showed that the reuse of pre-treated MSWI bottom ash and washed soil is possible, either from technical or environmental point of view, while it is not possible for the raw wastes.

Then, the natural aggregate was partially and totally replaced with these recycled aggregates for the production of concrete mixtures that were characterized by conventional mechanical and leaching tests. Good results were obtained using the same dosage of a high resistance cement (42.5R calcareous Portland cement instead of 32.5R); the concrete mixture containing 400 kg/m^3 of washed bottom ash and high resistance cement was classified as structural concrete (C25/30 class). Regarding the pollutants leaching, all concrete mixtures respected the limit values according to the Italian regulation.

The Microstructure of Concrete Made with Municipal Waste Incinerator Bottom Ash as an Aggregate Component, *Muller et al.,* (2006)

- 80% mineral components such as glassy, crystalline silicates, aluminates, oxides
- Porosity double of reference concrete
- Concrete with WTE ash produced voids not present in reference concrete -> gas phase reaction during plastic state of cement binder (aluminum)
- ASR clearly linked to fragments of bottle glass and glassy silicates of bottom ash
- Outlined the need for treatment technology to reduce aluminum and bottle glass content

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Available online at www.sciencedirect.com

ScienceDirect

Cement and Concrete Research 36 (2006) 1434–1443

Cement and Concrete Research

The microstructure of concrete made with municipal waste incinerator bottom ash as an aggregate component

Urs Müller *, Katrin Rübner

Federal Institute for Materials Research and Testing (BAM), Division VII.1-Building Materials, Unter den Eichen 87, D-12205 Berlin, Germany

Received 18 August 2005; accepted 23 March 2006

Abstract

The interaction of municipal solid waste incinerator bottom ash (MSWI bottom ash), when utilized as an aggregate in concrete, with the cement matrix was investigated. The most prominent reaction observed in lab and field concrete was the formation of aluminium hydroxide and the release of hydrogen gas from aluminium grains reacting in the alkaline environment. The expansive aluminium reaction was identified as a main cause of extensive spalling on the concrete surface. Due to the higher content of bottle glass as part of the ash, in all samples, reaction products of an alkali-silica reaction (ASR) could be observed as well. However, damage due to ASR were less severe than those caused by the aluminium reaction. The expansion rates were low and only a few of the lab samples showed cracking. Microstructural analysis of the samples indicated clearly that a large quantity of the alkali-silica gel which was formed was accommodated in the pores and voids without exerting any strain on the material.

Traditional aggregate selection

- Hard and strong
- Free of contaminants
- Unreactive
- Appropriately sized

DIVISION III MATERIALS

AGGREGATES

SECTION 901
COARSE AGGREGATE

901-1 General.

901-1.1 Composition: Coarse aggregate shall consist of naturally occurring materials such as gravel, or resulting from the crushing of parent rock, to include natural rock, slags, expanded clays and shales (lightweight aggregates) and other approved inert materials with similar characteristics, having hard, strong, durable particles, conforming to the specific requirements of this Section.

Coarse aggregate for use in pipe backfill under wet conditions, underdrain aggregate, or concrete meeting the requirements of Section 347 may consist of reclaimed portland cement concrete meeting the requirements of 901-5. Coarse aggregate for use in bituminous mixtures may consist of reclaimed portland cement concrete meeting the requirements of 901-5, except that the reclaimed concrete shall be from a concrete mix which was produced and placed in accordance with applicable Department Specifications.

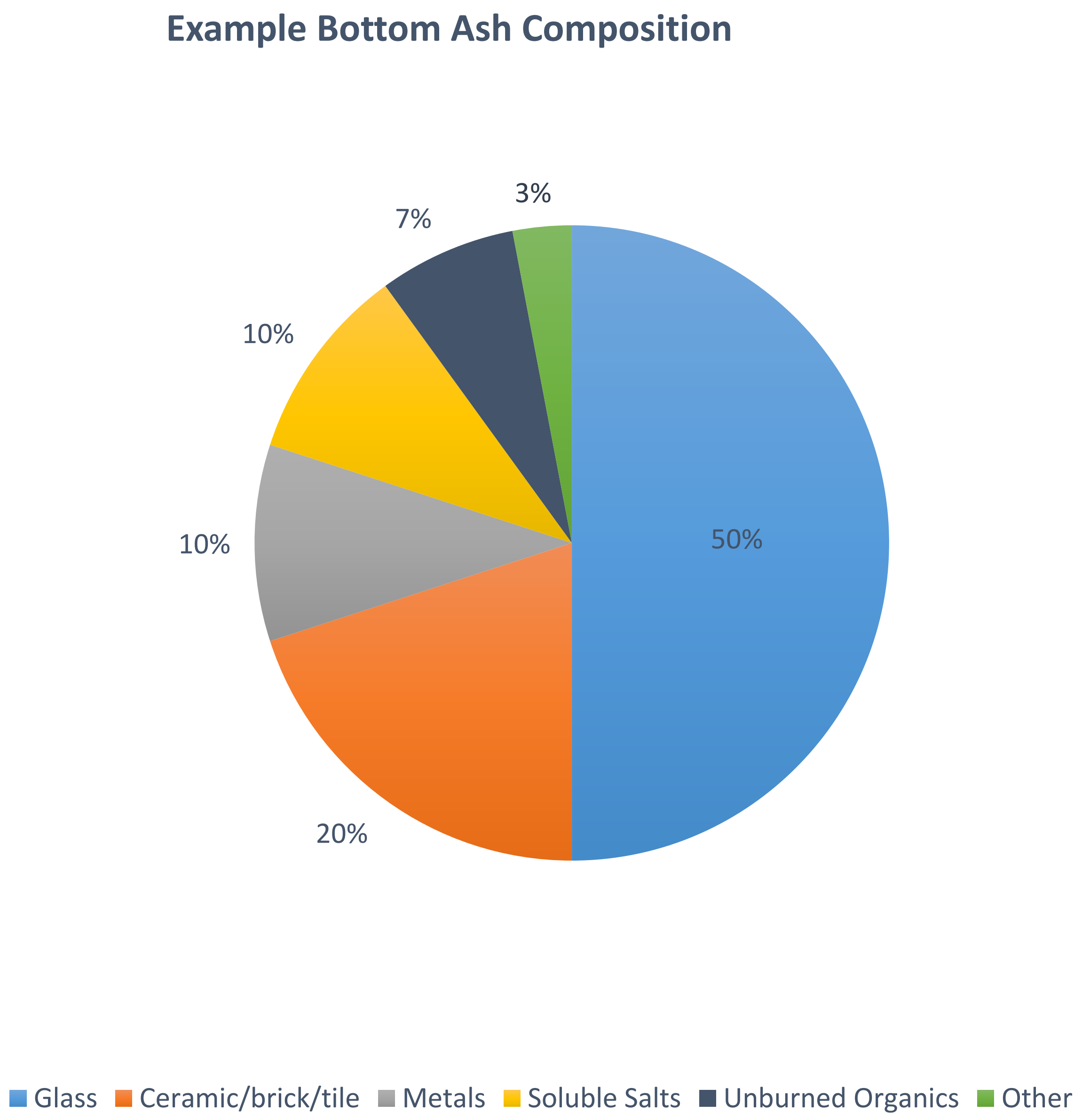
Materials substantially retained on the No. 4 sieve, shall be classified as coarse aggregate.

Approval of mineral aggregate sources shall be in accordance with 6-2.3.

901-1.2 Deleterious Substances: All coarse aggregates shall be reasonably free of clay lumps, soft and friable particles, salt, alkali, organic matter, adherent coatings, and other substances not defined which may possess undesirable characteristics. The weight of deleterious substances shall not exceed the following percentages:

WTE Ash

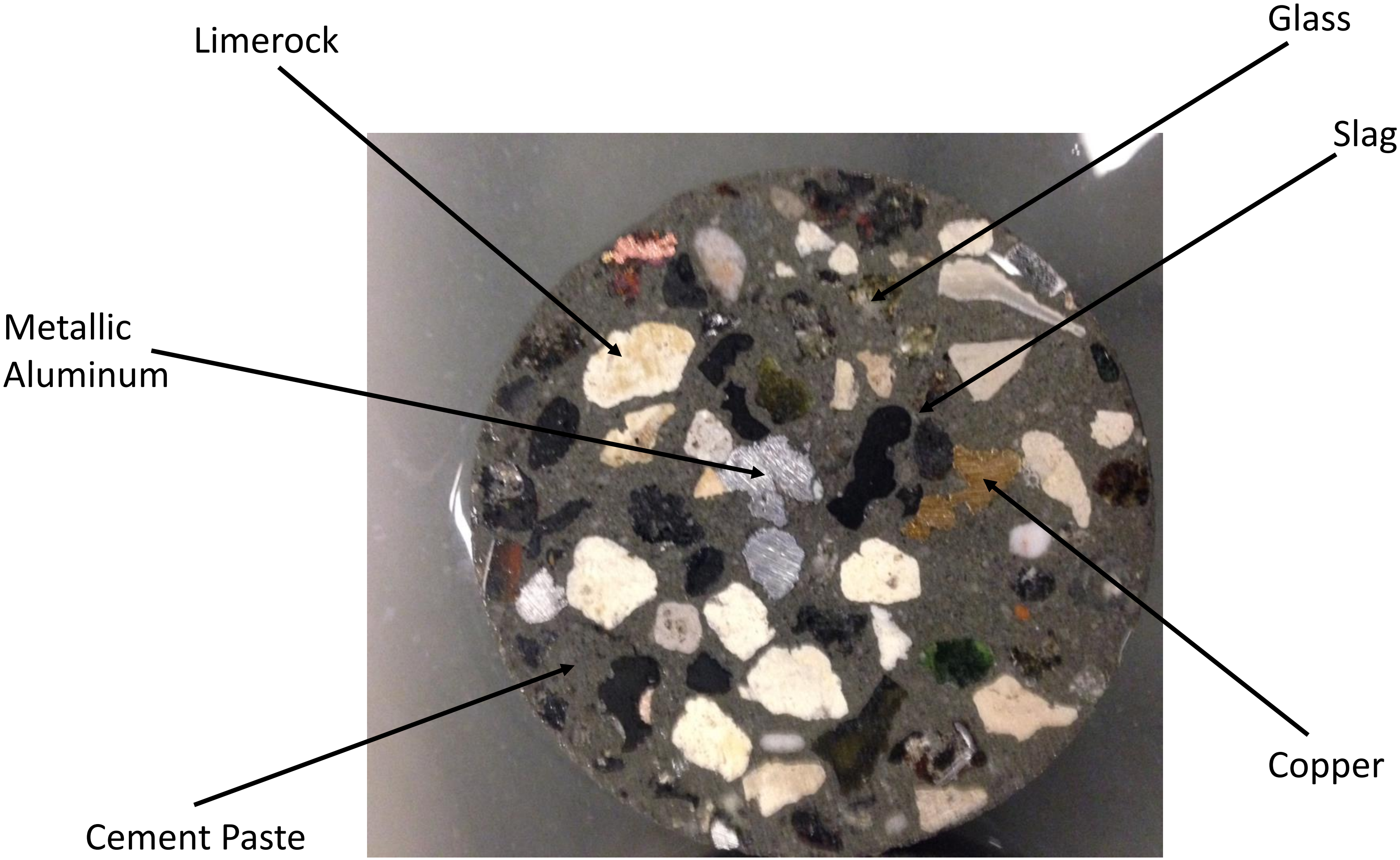
- Slag
- Glass
- Ceramics
- Metals
- Organic Material



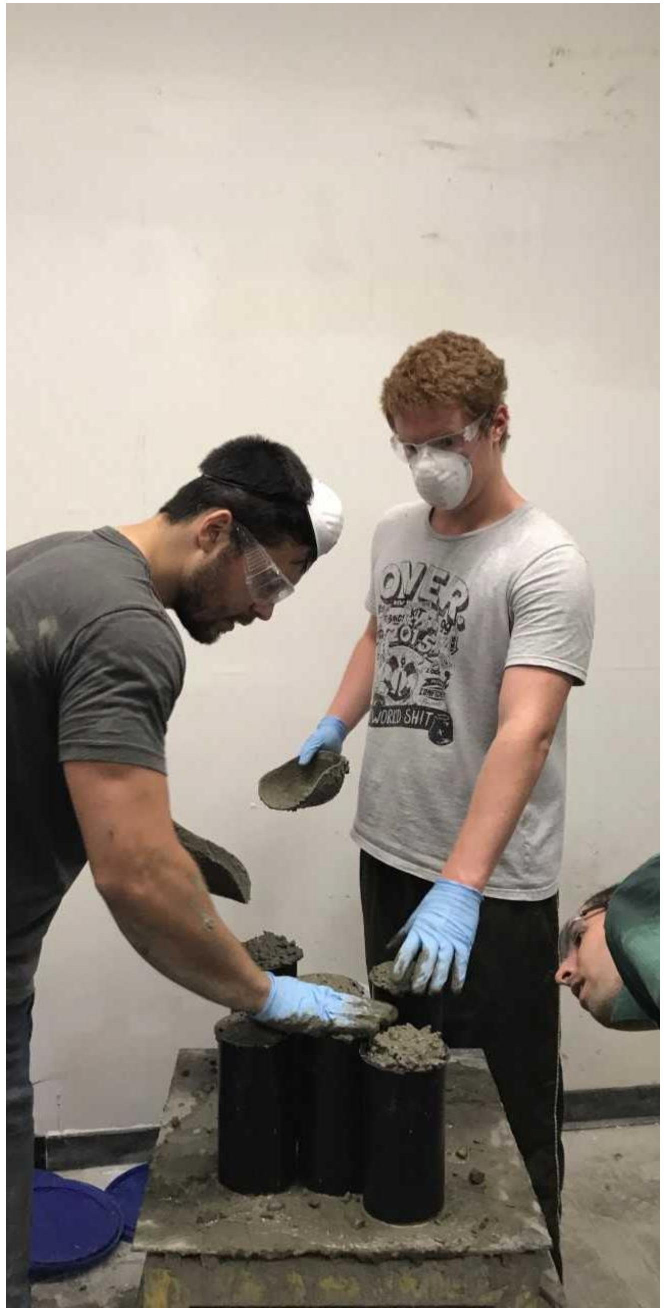
What the literature shows us: WTE Ash

Issues:

- Strength
- Particle density
- Metallic aluminum content
- Loss on ignition
- Chloride, sulfate, alkali content
- Appropriate size distribution
- Homogeneity
- Absorption


Limerock
Glass
Slag
Metallic Aluminum
Copper
Cement Paste


7 DAY B
2


OVER
WORLD SHIT

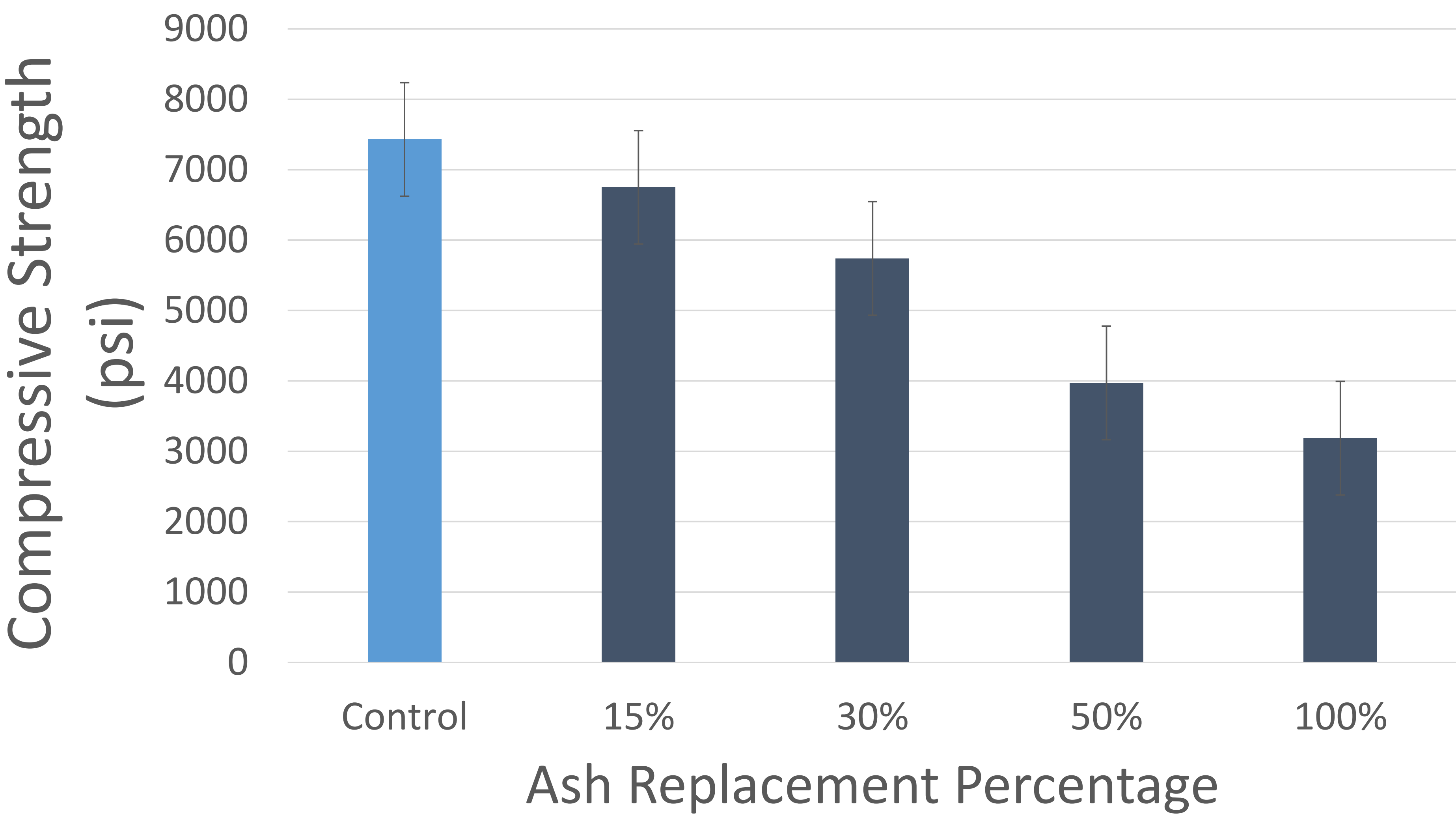
Special Importance: Decreasing Mechanical Strength

- Existing literature and work performed by University of Florida show that waste to energy ash can replace a traditional concrete aggregate at low percentages and yield a satisfactory compressive strength
- Increasing WTE ash addition yields a decrease in compressive strength
- Porosity of concrete inversely proportional to strength of the concrete, WTE ash amended concrete has significant increase in porosity compared to reference

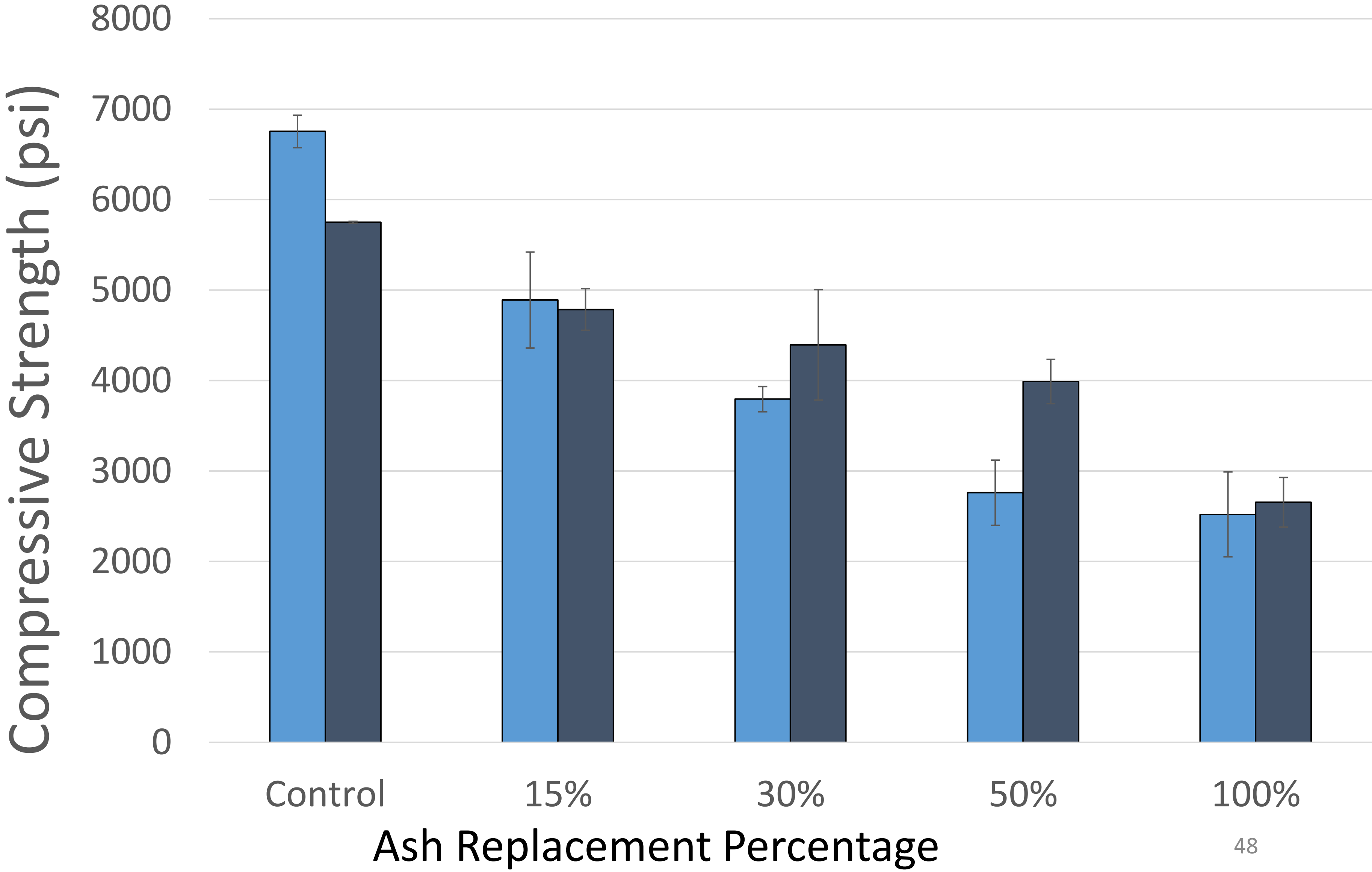
ASTM C39/C39

- Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
- Compressive axial load to molded cylinders at specific loading rate (35 +/- 7 psi/s) until failure
- Load divided by cross sectional cylinder area

28 Day Compressive Strength of WTE Ash Amended Concrete – Combined Ash Central Florida Facility



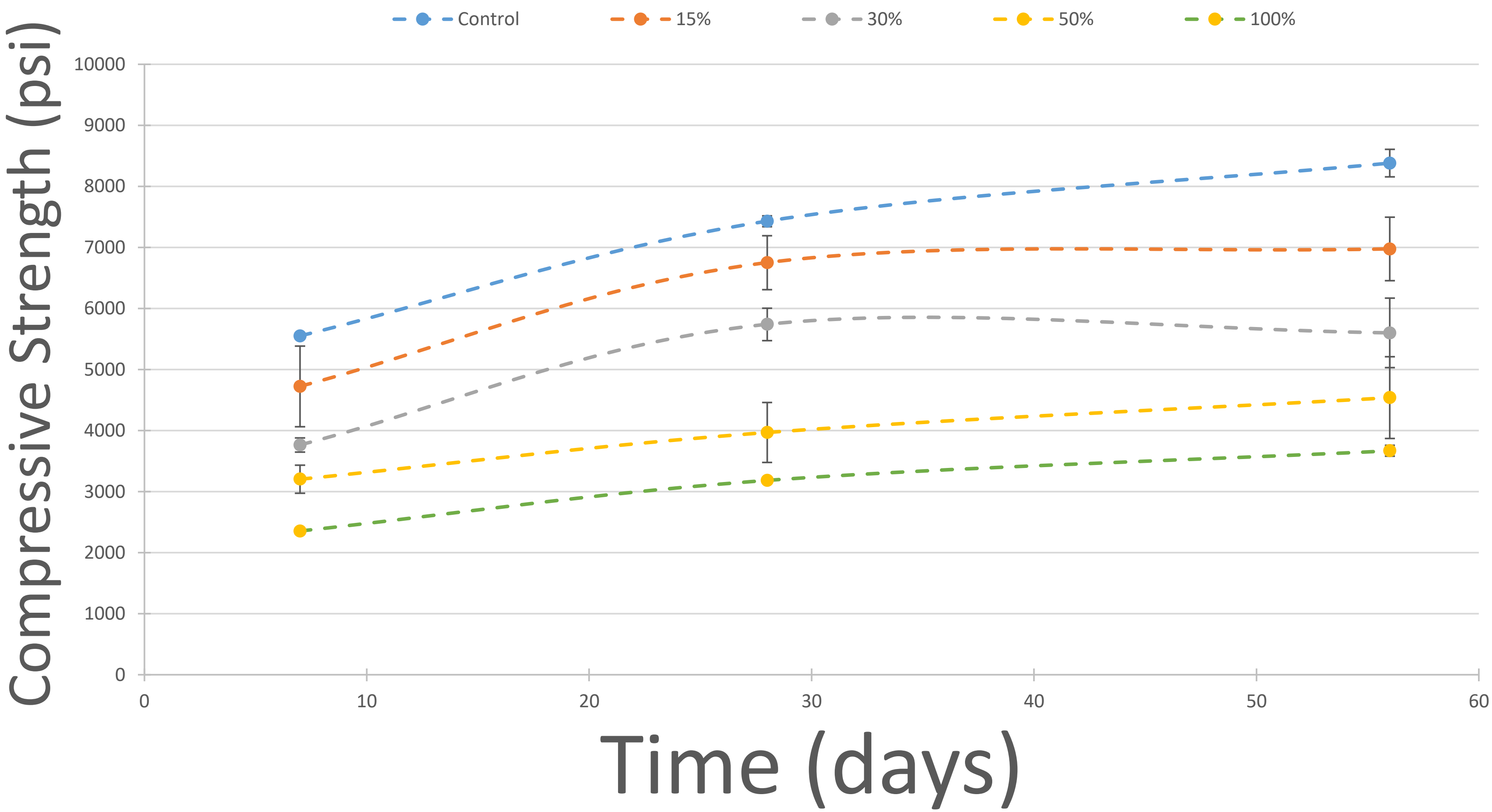
28 Day Compressive Strength of WTE Ash Amended Concrete – 2 South Florida Facilities



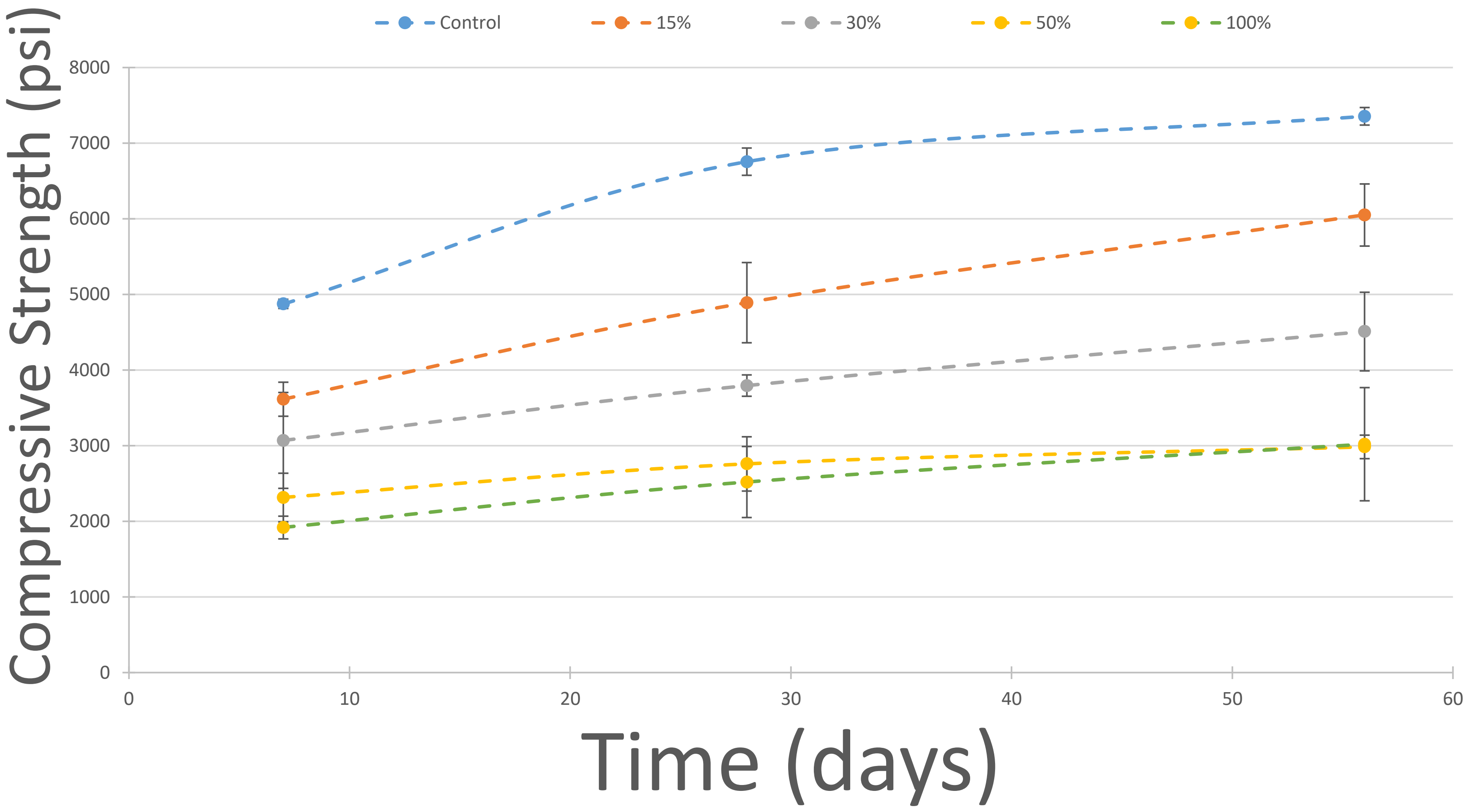
FDOT Standard Specifications for Road and Bridge Construction Section 346 – Portland Cement Concrete

TABLE 2		
Class of Concrete	Specified Minimum Strength (28-day) (psi)	Target Slump Value (inches) (c)
STRUCTURAL CONCRETE		
I (a)	3,000	3 (b)
I (Pavement)	3,000	2
II (a)	3,400	3 (b)
II (Bridge Deck)	4,500	3 (b)
III (e)	5,000	3 (b)
III (Seal)	3,000	8
IV (d)(f)	5,500	3 (b)
IV (Drilled Shaft)	4,000	8.5
V (Special) (d)(f)	6,000	3 (b)
V (d)(f)	6,500	3 (b)
VI (d)(f)	8,500	3 (b)

Compressive Strength Over Time



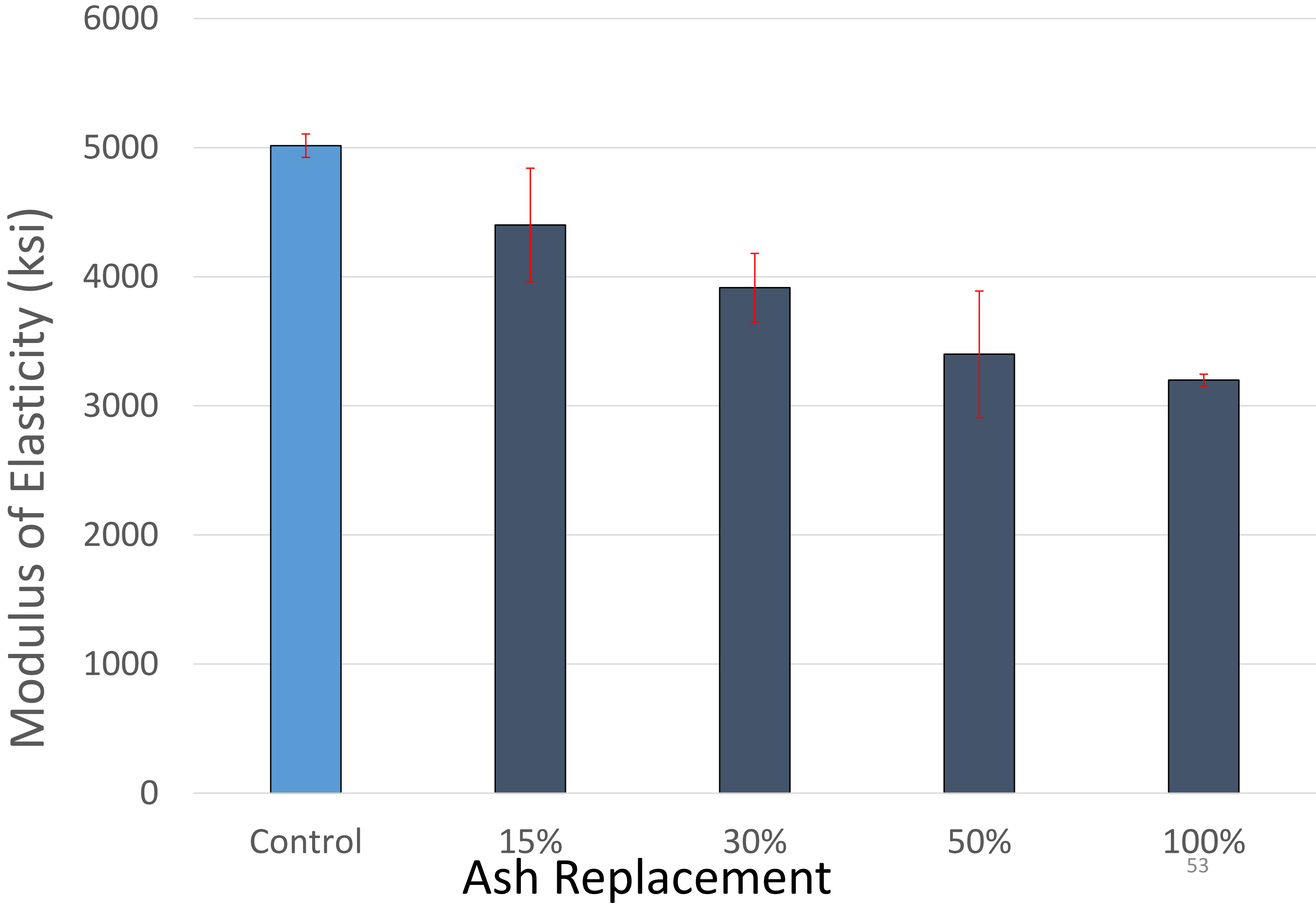
Compressive Strength Over Time



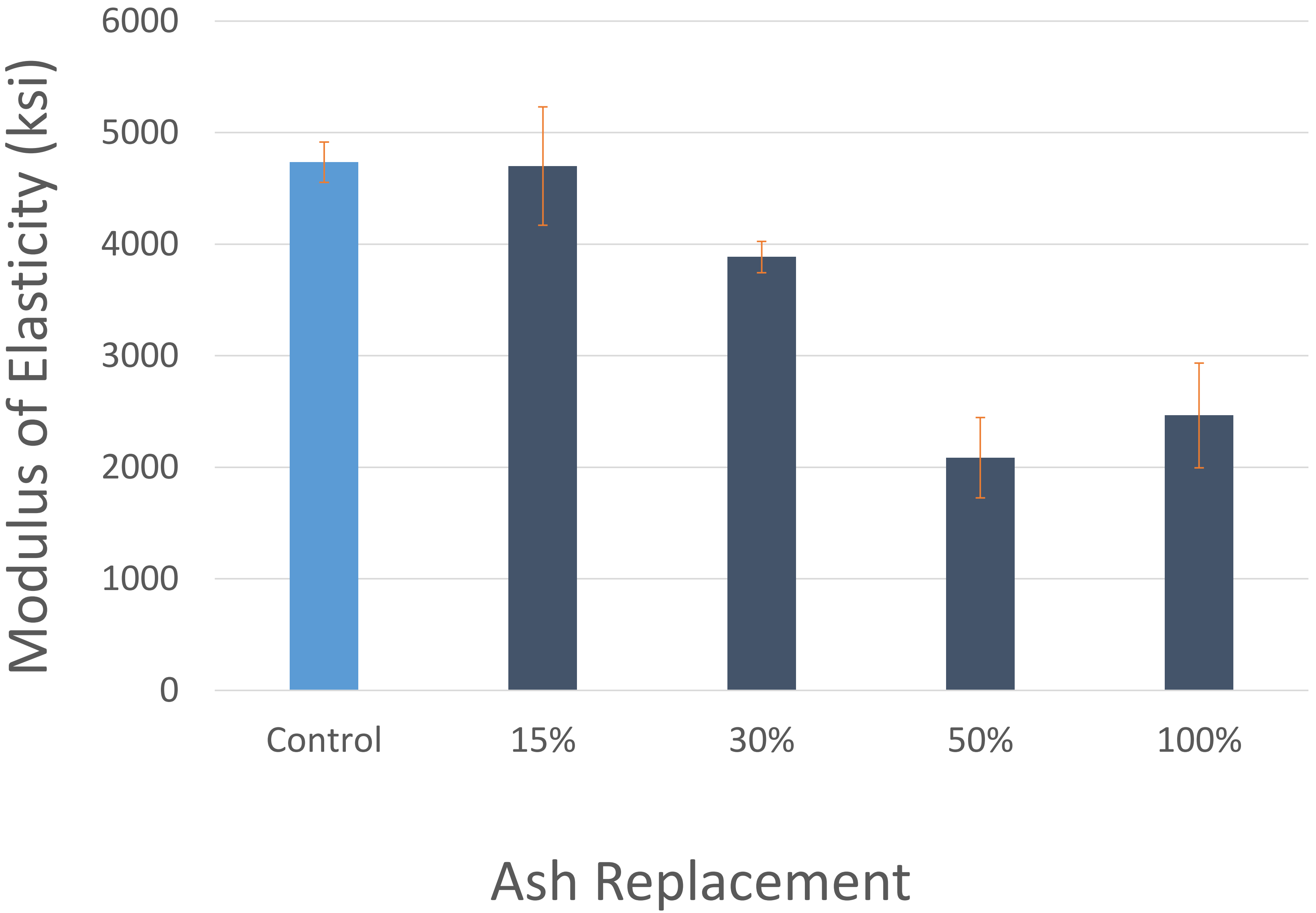
ASTM C469

- Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression
- Measure deformation as a function of load applied. Slope of a stress/strain graph.

28 Day Modulus of Elasticity- Central Florida Combined Ash Amended Concrete



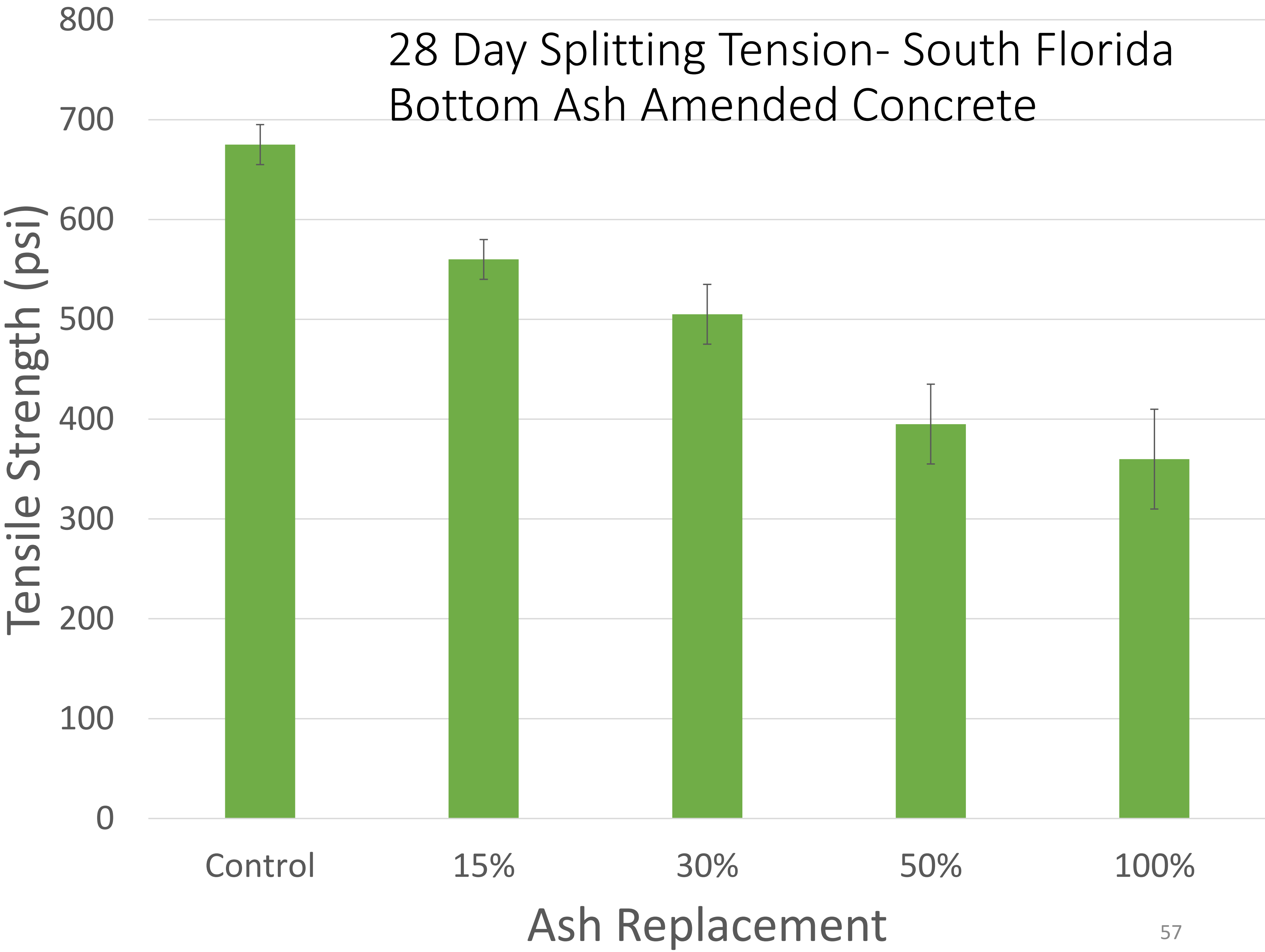
28 Day Modulus of Elasticity – South Florida RDF Facility Combined Ash Amended Concrete



ASTM C496

- Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
- Diametral compressive force along the length of a specimen following a prescribed load range until failure
- Rule of thumb

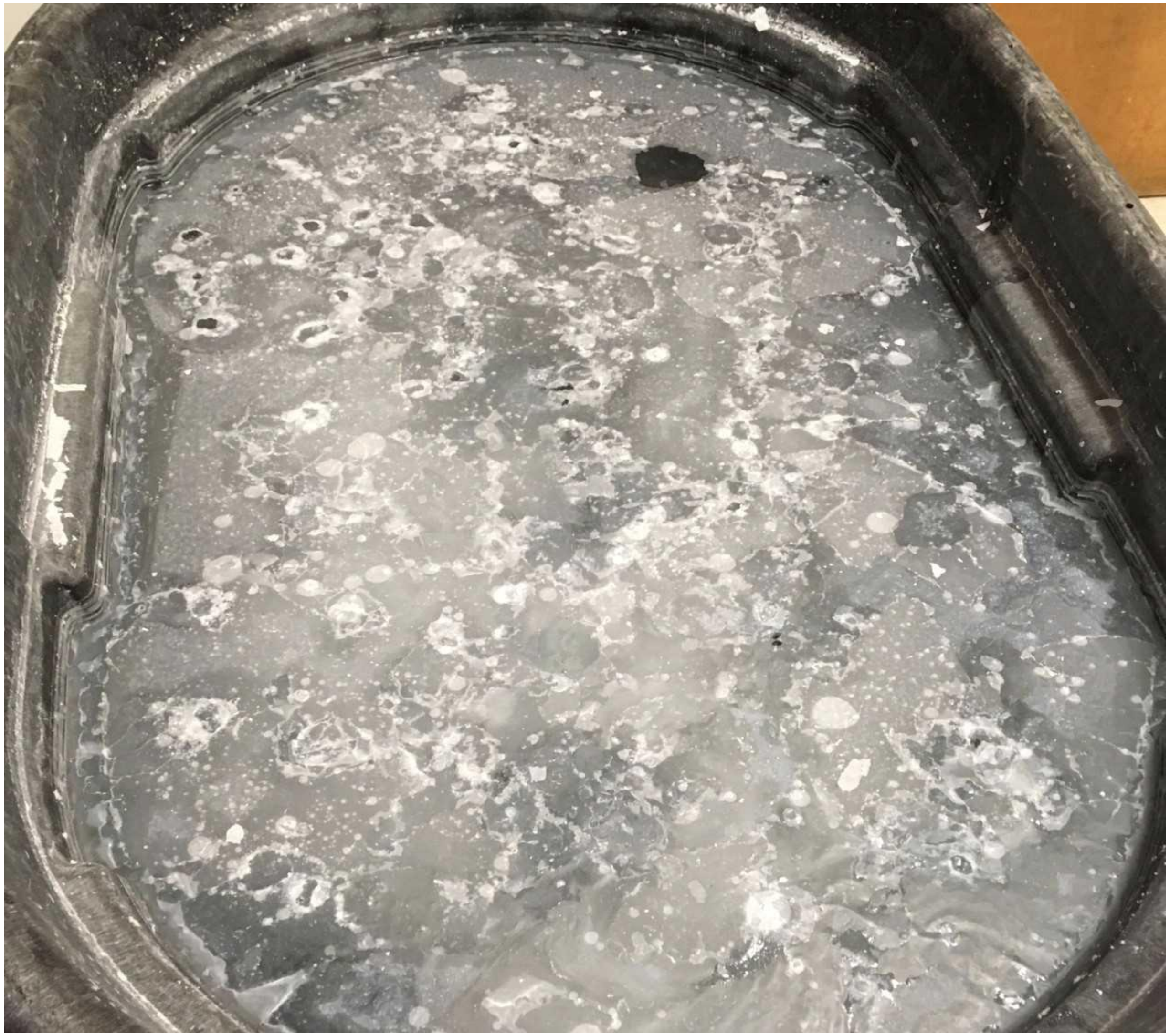
28 Day Splitting Tension-Central Florida Combined Ash Amended Concrete



28 Day Splitting Tension- South Florida Bottom Ash Amended Concrete
Tensile Strength (psi)
800
700
600
500
400
300
200
100
0
Control
15%
30%
50%
100%
Ash Replacement

Special Importance: Metallic Aluminum Content

- Concrete mixed with WTE bottom ash specimens react in highly alkaline environment of cement paste to produce hydrogen gas
- Elongated voids following contours of aluminum grains
- Spalling due to aluminum hydroxide production with aluminum grains near concrete surface
- Expansion and cracking of concrete specimens
- Could act as surrogate air entraining agents



A soak tank full of WTE ash amended specimens, hydrogen bubbles clearly visible

Special Importance: Metallic Aluminum Content

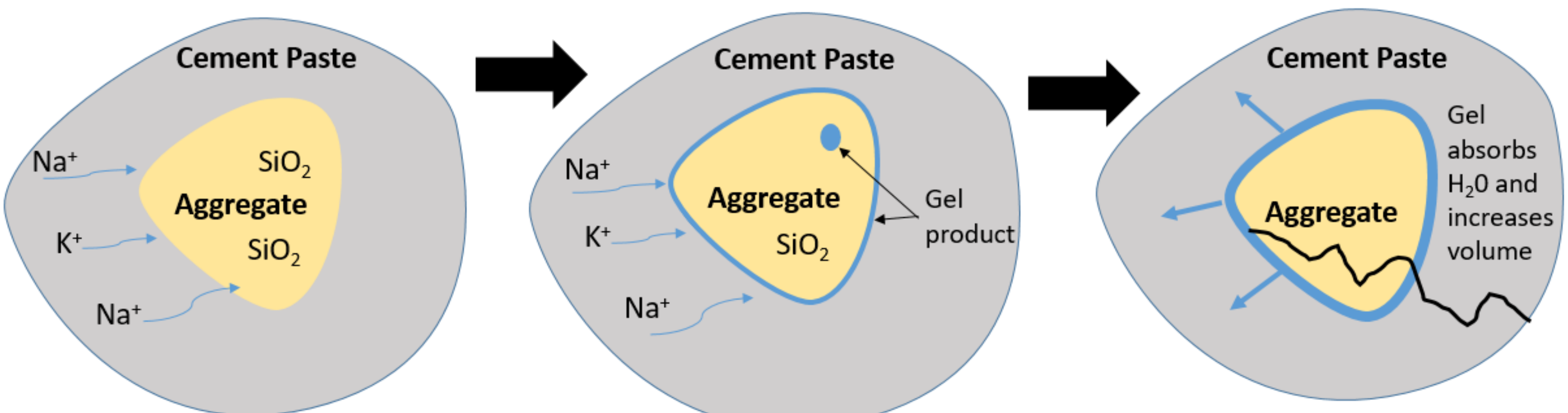
- Quite a few issues associated with high metallic aluminum content
- Removal of metallic aluminum (eddy current)
- Sodium hydroxide wash

$$NaOH + Al + H_2O \rightarrow NaAlO_2 + \frac{3n}{2} + H_2$$

Concrete durability issues associated with metallic aluminum content can be mitigated through treatment methods proposed

Special Importance: Alkali Aggregate Reactivity

- Deleterious reactions with the aggregate, specifically the alkali silica reaction (ASR)
- High alkali presence in concrete
- Expansive gels formed that expand in presence of moisture to induce cracking
- Linked to bottle glass and other glassy amorphous silica components of WTE ash.



1) Alkali ingress by diffusion

2) Reaction and Gel formation

3) Expansion/Cracking

ASTM 1260

- Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
- Detection of potential for deleterious ASR reaction in mortar bars within 16 days
- Mortar bars immersed in NaOH solution, comparator readings are taken periodically and compared to previous readings to calculate percentage change in length (expansion)
- Suggested that presence of alkali silica gels is confirmed via other methods if length change is present
- Short term test prone to false positives/negatives

INTERNATIONAL

Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)[1]

This standard is issued under the fixed designation C1260; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This test method permits detection, within 16 days, of the potential for deleterious alkali-silica reaction of aggregate in mortar bars.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard. When this test method refers to combined-unit standards, the selection of the measurement systems is at the user's discretion.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* A specific precautionary statement is given in the section on Reagents.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C109/C109M Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
C125 Terminology Relating to Concrete and Concrete Aggregates
C127 Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate
C128 Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
C150/C150M Specification for Portland Cement
C151/C151M Test Method for Autoclave Expansion of Hydraulic Cement
C295/C295M Guide for Petrographic Examination of Aggregates for Concrete
C305 Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency
C490/C490M Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete
C511 Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
C670 Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials
C856 Practice for Petrographic Examination of Hardened Concrete
D1193 Specification for Reagent Water
E11 Specification for Woven Wire Test Sieve Cloth and Test Sieves

3. Terminology

3.1 *Definitions*—For definitions of other terms relating to concrete or aggregates, see Terminology C125.

3.1.1 *relative density (OD), n*—as defined in Test Methods C127 or C128, for coarse and fine aggregates, respectively.

4. Significance and Use

4.1 This test method provides a means of detecting the potential of an aggregate intended for use in concrete for undergoing alkali-silica reaction resulting in potentially deleterious internal expansion. It is based on the NBRI Accelerated Test Method (1-4).[3] It is especially useful for aggregates that react slowly or produce expansion late in the reaction. However, it does not evaluate combinations of aggregates with cementitious materials nor are the test conditions representative of those encountered by concrete in service.

4.2 Because the specimens are exposed to a NaOH solution, the alkali content of the cement is not a significant factor in affecting expansions.

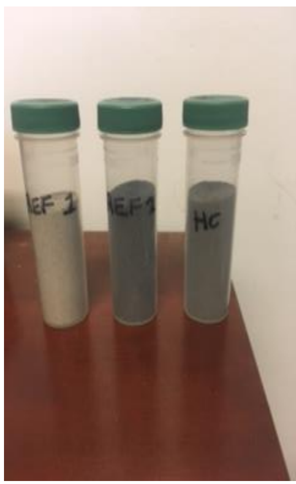
4.3 When excessive expansions (see Appendix X1) are observed, it is recommended that supplementary information

[1] This test method is under the jurisdiction of ASTM Committee C09 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.26 on Chemical Reactions.

Current edition approved Aug. 1, 2014. Published August 2014. Originally

UF ASR Research Initiatives

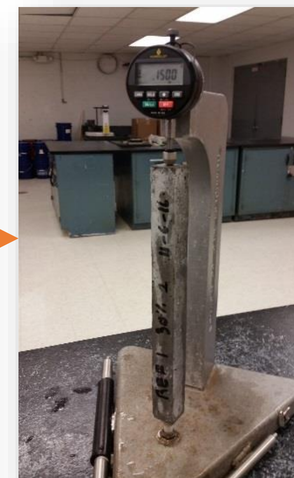
- The University of Florida research team casted cement mortars with WTE ash as a coarse aggregate replacement and showed that these mortars will exhibit this expansive reaction



3 bottom ash sources were sized reduced to a fine aggregate size (0 - 1/4”)

12” mortar bars cast using bottom ash as an aggregate replacement (15%, 30%, and 50%)

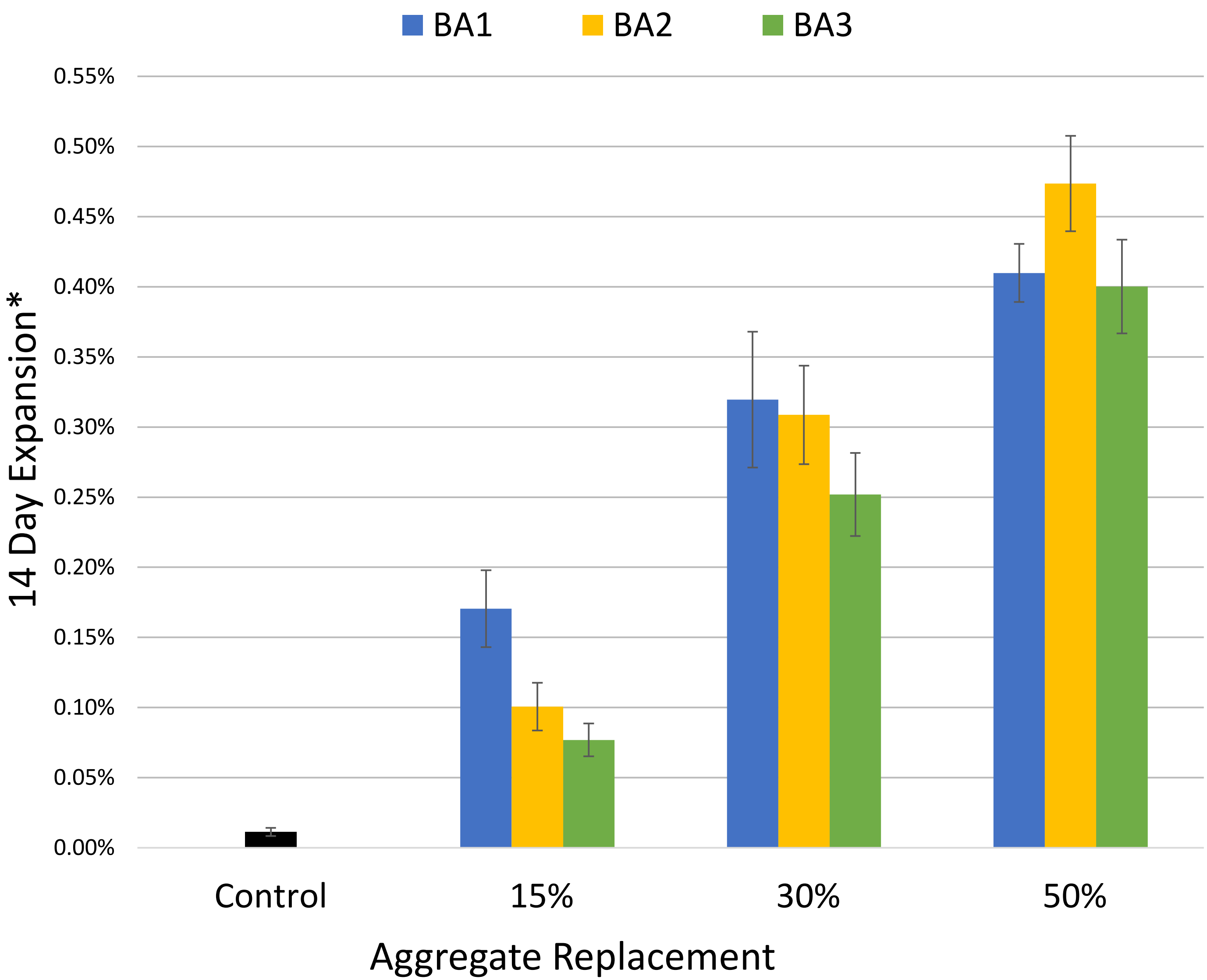
Bars submerged in alkali solution (1N NaOH) and heated at 40°C



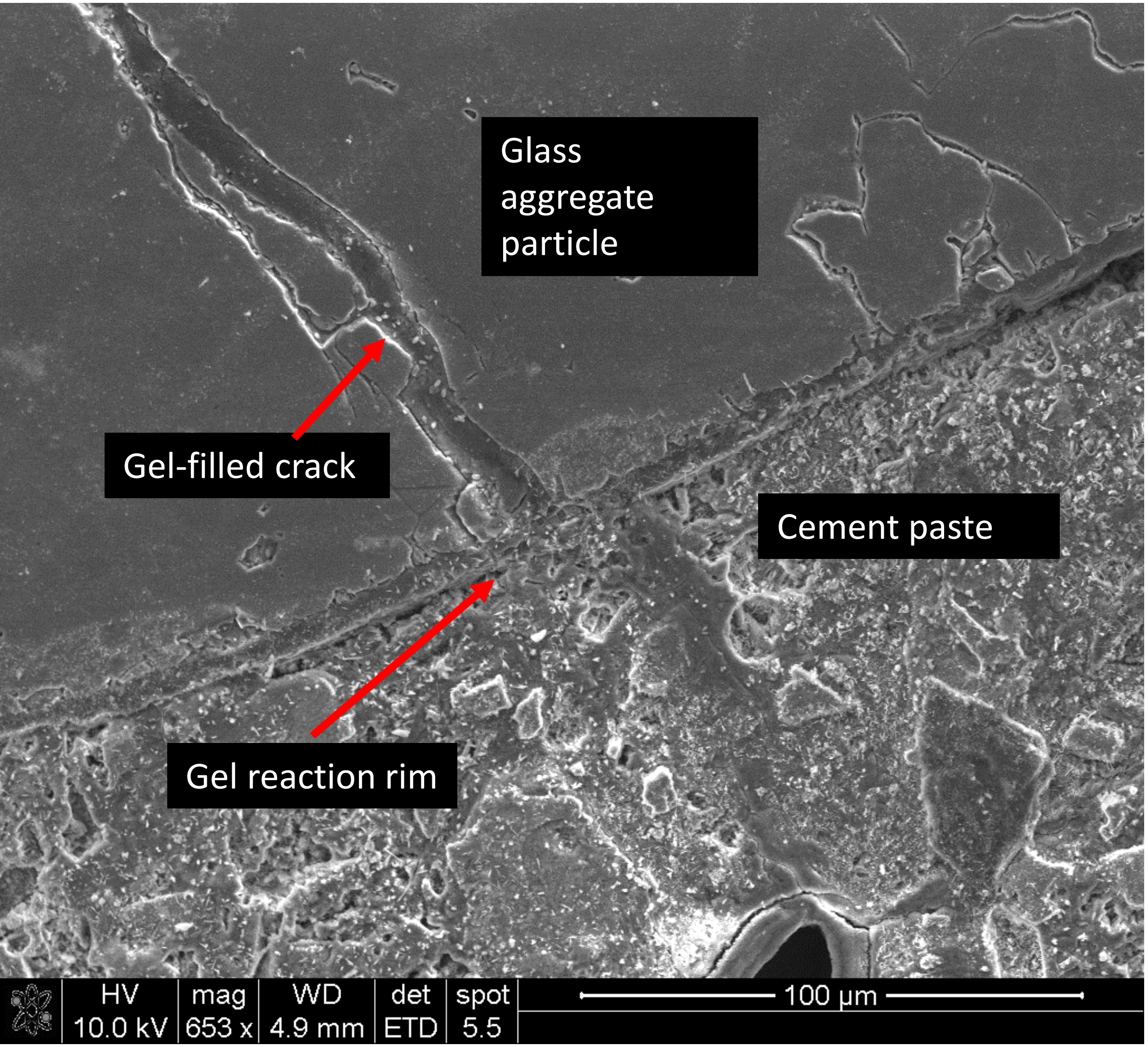
Expansion of specimens is measured over 14 days

UF ASR Testing Results

ASTM C1260 – MSWI Bottom Ash

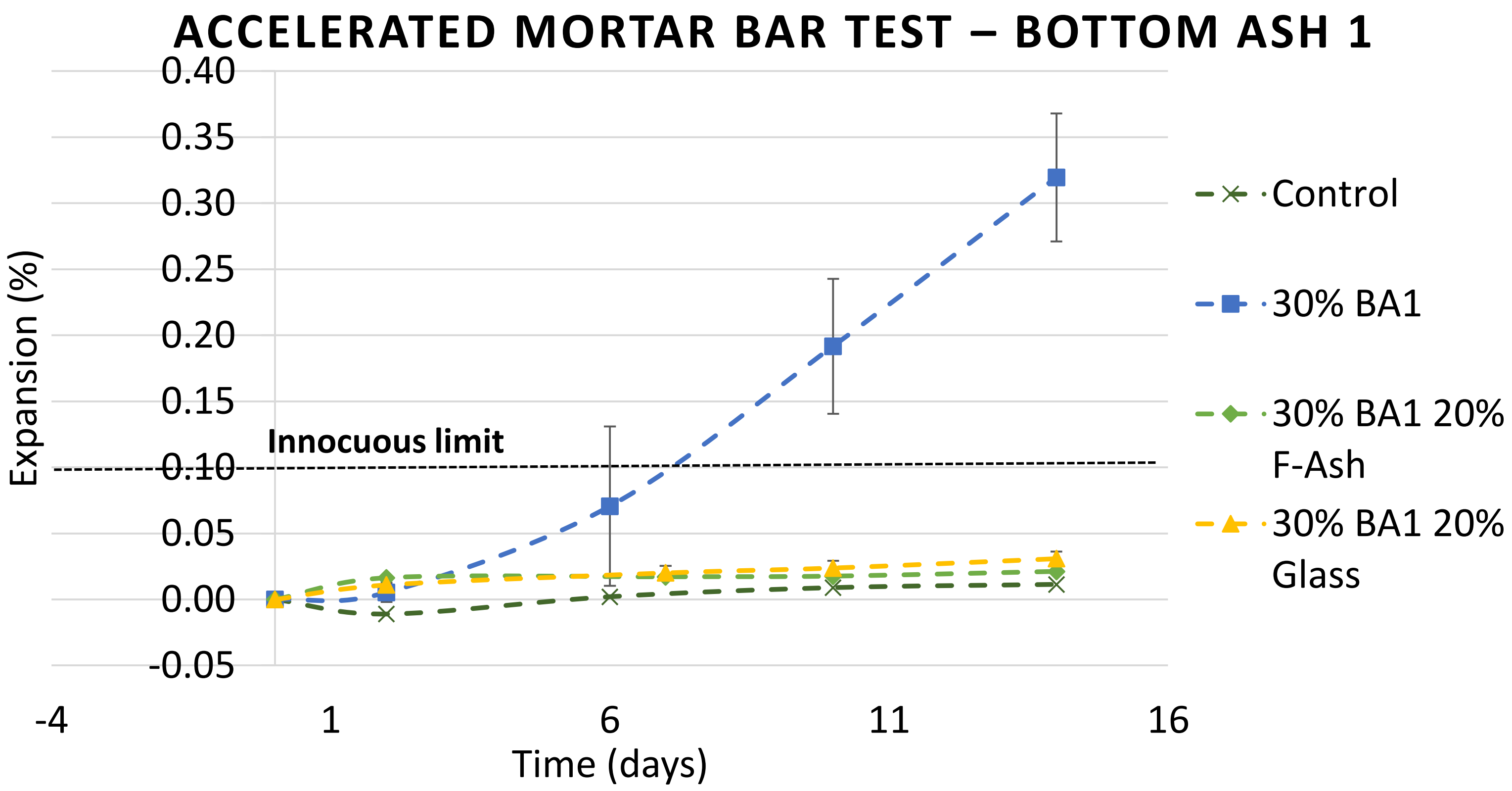


ASTM C1260 Criteria	
Aggregate Classification	**Expansion**
Innocuous	< 0.10% Expansion
Potentially Deleterious	0.10% - 0.20% Expansion
Deleterious	> 0.20% Expansion



ASR confirmed by SEM Analysis

ASR Mitigation with Pozzolans

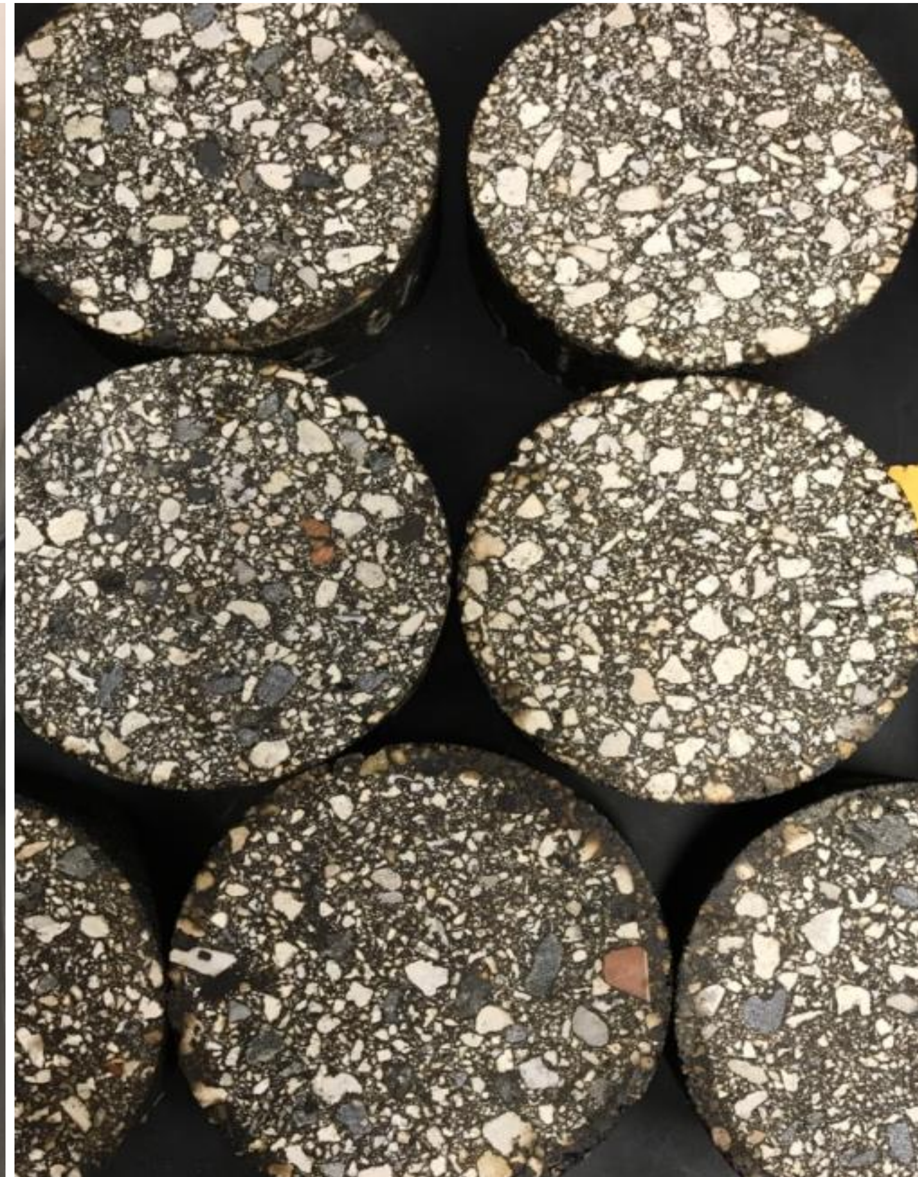


In summary, what we know from the literature and our own work about concrete

- The literature illuminates extensive WTE ash amended concrete research dating back several decades
- Ash amended concrete will still consistently meet required specifications as a suitable aggregate substitution, despite decreasing strength associated with increasing addition
- Metallic aluminum content is an issue and will require mitigation strategies
- ASR is an issue and will require mitigation strategies
- Testing has shown that use of SCMs can mitigate ASR in short term ASR testing of cement mortars
- Recent work seeks to address these issues
- WTE ash amended concrete can be done, if done correctly

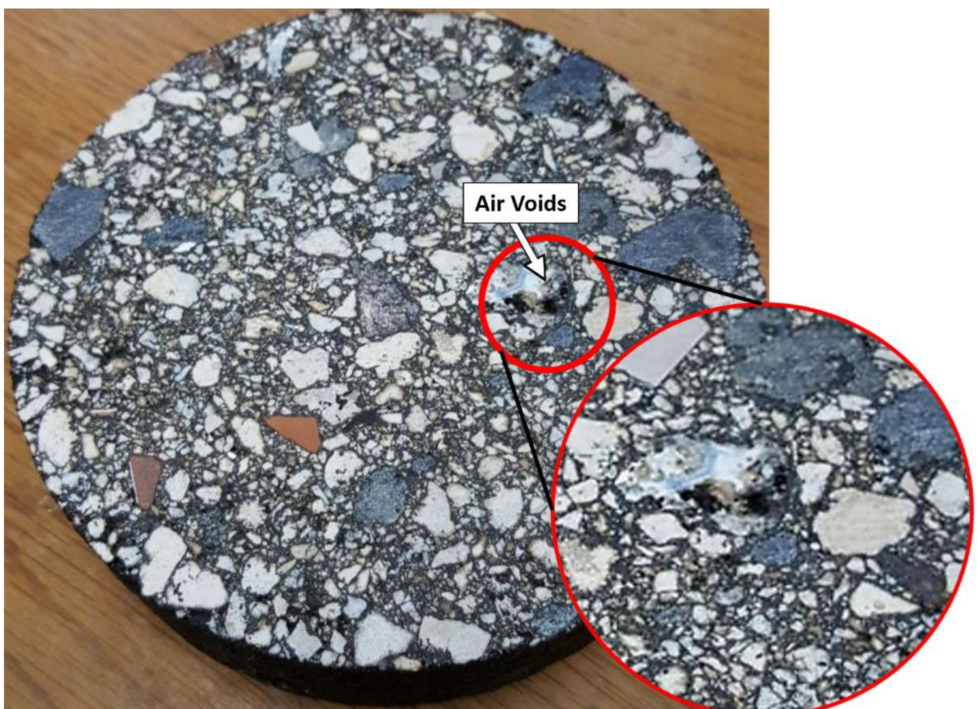
Use of WTE ash in asphalt pavement

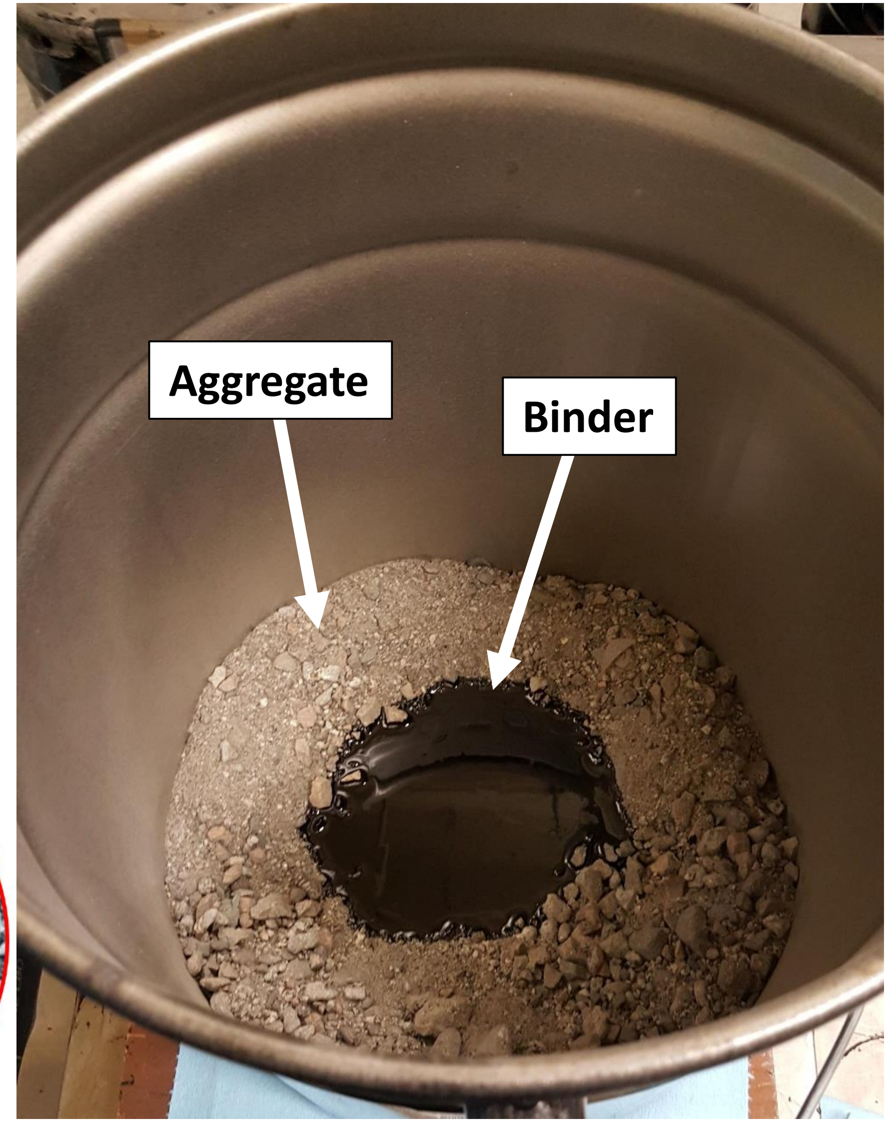
Use of WTE ash in hot-mix asphalt (HMA) pavement

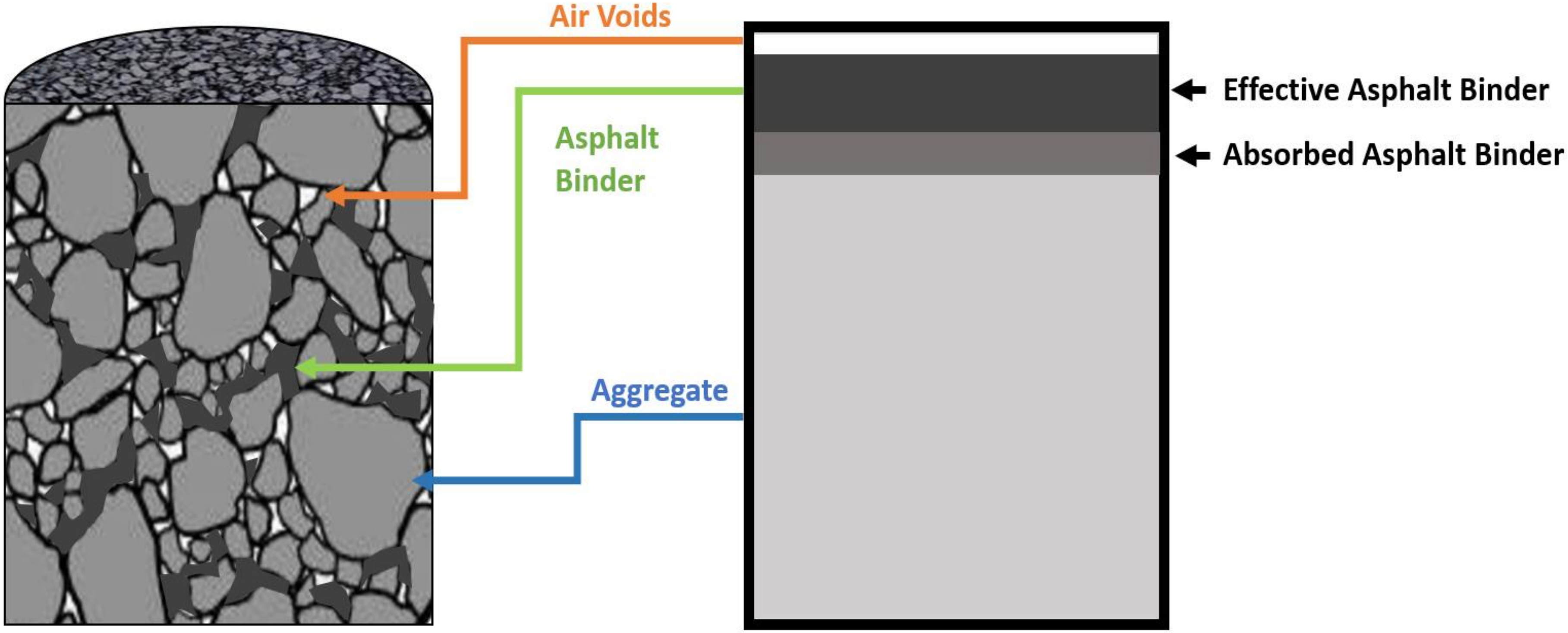


What is Hot-Mix Asphalt Pavement?

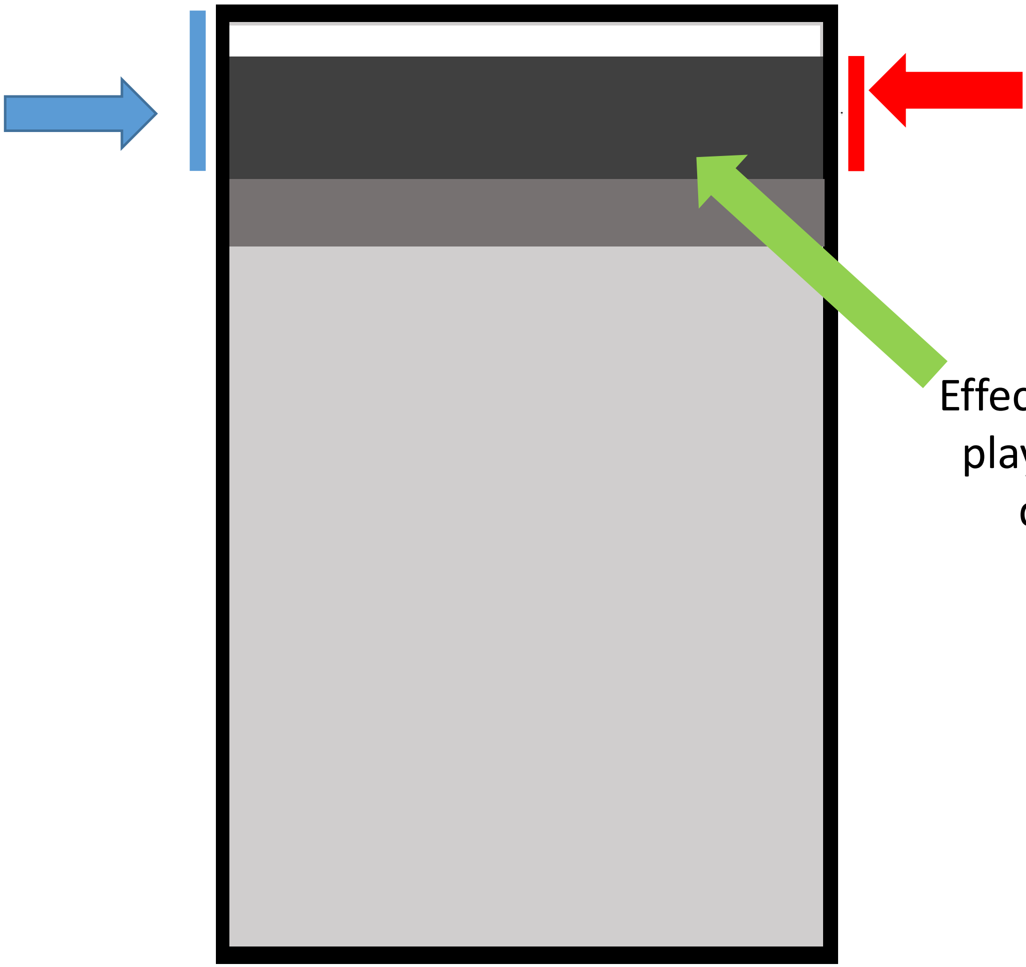
- A mixture of aggregates, asphalt binder, and air voids
- Asphalt binder = petroleum
- Asphalt pavement can be engineered for a wide variety of purposes using a wide variety of materials






Air Voids
Asphalt
Binder
Aggregate
Effective Asphalt Binder
Absorbed Asphalt Binder

HMA relies heavily on volumetrics!



Has WTE ash been used in HMA before?

- WTE ash use in HMA pavements has been documented throughout the US
  - FHWA: 1970s
  - Other initiatives: 1980s, 1990s
  - Pasco County: 2015
- Increased research from Europe and Asia in recent years

Location	Year	Replacement of total mix (%)	Length (ft)	Thickness (in)	Type of Ash Used
Houston, TX	1974	100	300	6	Combined ash
Philadelphia, PA	1975	50	90	1.5	Combined ash
Delaware County, PA	1975	50	60	1.5	Combined ash
Harrisburg, PA	1976	N/A	220	1.5	Combined ash
Harrisburg, PA	1976	100	N/A	1.5	Combined ash
Chambersburg, PA	1976	N/A	N/A	N/A	N/A
Washington, D.C.	1977	70% (mixture 1) 100% (mixture 2)	400, both sections	4.5	Combined ash
Lynn, MA	1979	N/A	N/A	N/A	Combined ash
Tampa, FL	1987	N/A	500	N/A	McKaynite
Ruskin, FL	N/A	N/A	N/A	N/A	McKaynite
Shelton, CT	1992	50	N/A	N/A	Bottom ash
Rochester, MA	1992	30	N/A	N/A	Boiler Aggregate
Concord, NH	1992	25	N/A	N/A	Bottom ash
Laconia, NH	1993	50	850	N/A	Bottom ash
Port Elizabeth, NJ	1996	50	750	N/A	Bottom ash
Oahu, Hawaii	1999	5	N/A	2	Combined ash
Pasco County, FL	2015	20	~200	~4	Bottom ash

Walter, 1976

- One of the earliest works utilizing WTE ash in HMA
- Lab results showed that replacements as high as 50% could be utilized while meeting performance requirements

FEBRUARY 1976 EE1

JOURNAL OF THE ENVIRONMENTAL ENGINEERING DIVISION

PRACTICAL REFUSE RECYCLING

By C. Edward Walter,[1] M. ASCE

TABLE 2.—Marshall Method Design Data Initial Baltimore Residue Laboratory Tests

Parameters	Bitumen, as a percentage			
	5.5	6.0	6.5	7.0
(1)	(2)	(3)	(4)	(5)
Marshall Stability, in pounds	775	885	1,015	840
Flow, in hundredths of an inch	13.0	17.0	16.7	18.0
Weight per cubic foot, in pounds	132.2	135.3	136.8	134.5
Air Voids, as a percentage	11.6	8.8	7.3	7.0
Voids in Mineral Aggregate, as a percentage	22.9	21.5	21.1	21.8
Voids Filled with Asphalt Content, as a percentage	49.4	58.9	65.6	68.0

New Hampshire Bottom Ash Paving Demonstration, 1993

- *Musselman et al., 1994*
- 50% aggregate replacement in structural HMA layer
    - Slight reductions recommended for construction and HMA plant reasons (excessive moisture)
- 850 ft test strip
- Touched on less focused concept: how plant operations and construction practices associated with using WTE ash

National Waste Processing Conference Proceedings ASME 1994

THE NEW HAMPSHIRE BOTTOM ASH PAVING DEMONSTRATION US ROUTE 3, LACONIA, NEW HAMPSHIRE

CRAIG N. MUSSELMAN
CMA Engineers
Portsmouth, New Hampshire

T. TAYLOR EIGHMY
Environmental Research Group
University of New Hampshire
Durham, New Hampshire

DAVID L. GRESS
Department of Civil Engineering
University of New Hampshire
Durham, New Hampshire

MATTHEW P. KILLEEN
Environmental Permitting
Wheelabrator
Environmental Systems
Hampton, New Hampshire

JAMES R. PRESHER
Concord, New Hampshire
Regional Solid Waste/Resource
Recovery Cooperative
Penacook, New Hampshire

MICHAEL H. SILLS
Waste Management Division
New Hampshire Department
of Environmental Services
Concord, New Hampshire

FIG. 5 COMPLETED DEMONSTRATION ROADWAY, LACONIA, NH

Chen et al., 2008

- WTE bottom ash used as 0, 10, 20, 30, and 40% replacement
  - Washed and unwashed
- High absorptivity of ash was found to be an issue
  - Improved after washing
  - Increased binder content needed to achieve necessary volumetrics and performance

Engineering and Environmental Characterization of Municipal Solid Waste Bottom Ash as an Aggregate Substitute Utilized for Asphalt Concrete

Jian-Shiuh Chen[1]; Po-Yen Chu[2]; Juu-En Chang[3]; Hsing-Cheng Lu[4]; Zen-How Wu[5]; and Kuei-Yi Lin[6]

Abstract: The preferred management option for the municipal solid waste bottom ash (MSW-BA) around the world is utilization rather than landfilling, but the current environmental quality criteria for bottom ash to be utilized in bulk quantities are rather strict. The purpose of this paper is to analyze the physical and environmental properties of asphalt mixtures containing different amounts of MSW-BA used as an aggregate substitute. The Marshall mix design method, water sensitivity, and wheel track rutting tests were conducted on MSW-BA asphalt mixtures to evaluate the engineering properties of the mix. Leach tests were performed to measure the concentration of heavy metals. The MSW-BA asphalt mixture had relatively lower rutting resistance when compared with the conventional one. The results of the water sensitivity test showed that the MSW-BA asphalt mixtures had a lower tensile strength ratio compared with the conventional asphalt mixtures. It is recommended that the use of the MSW-BA ash in asphalt concrete mixtures be limited to be 20% ash, by total weight of the mix, in binder or base course and 10% in surface mix to ensure satisfactory pavement performance. The test results obtained from the toxicity characteristic leaching procedure testing indicated that, after being mixed with asphalt binder, the concentration of heavy metals and the levels of toxicity were significantly reduced. The concentrations of MSW-BA all along were below regulation limits.

DOI: 10.1061/(ASCE)0899-1561(2008)20:6(432)

CE Database subject headings: Asphalts; Asphalt pavements; Municipal wastes; Bottom ash; Aggregates; Recycling.

Introduction

Municipal solid waste bottom ash (MSW-BA) plays an important role in waste management. MSW-BA is the by-product during the incineration of municipal solid waste in solid waste combustor facilities. The estimated annual incineration of $20-40 \times 10^6$ t of MSW-BA worldwide results in the production of approximately $4-10 \times 10^6$ t of bottom ash, which must be reused or landfilled (Wiles 1996). In accordance with European Union and Taiwan waste policy, utilization is generally preferred over landfilling, if it can be carried out in an environmentally and technically acceptable manner. Bottom ash, originating from municipal solid waste incineration, is a potential road construction material. In the Netherlands and Denmark, almost 50% of the bottom ash produced is used in construction applications, whereas lower percentages are used in France and Germany (Chimenos et al. 1999). The most common use is in granular road base applications. In the United States, about 10% of MSW-BA is used in road construction (U.S. Environmental Protection Agency 2007a,b). There has been a long tradition for utilization of MSW-BA in Taiwan. MSW-BA produced by the 19 waste-to-energy facilities in Taiwan could be introduced as an aggregate substitute used for construction projects if MSW-BA meets the engineering and environmental requirements.

Dwindling sources of virgin aggregates, ever increasing haulage distance, and diminishing landfills are the primary factors that favor the reuse of construction-quality waste materials in highway pavements. Numerous studies have been conducted on the utilization of municipal solid waste incineration bottom ash (Bagchi and Sopcich 1989; Styron et al. 1993; Berg and Neal 1998; Zhang et al. 1999; Ksaibati and Zeng 2003; Ogunro et al. 2004). Garrick and Chan (1993) used up to 32% MSW-BA ash in hot-mix asphalt concrete. The results indicated that the MSW-BA asphalt mixture needed a higher asphalt content than a normal mix, but could not draw firm conclusions about the potential toxicity of the MSW-BA mix. Eighmy et al. (1995) examined bituminous mixtures containing MSW-BA bottom ash, and showed that 45 elements were present in the ash. Their test data indicated that Ca, SO_4, K, Cl, Na, Mg, and Al had the largest potential for leaching, if the integrity of the asphalt mixture was compromised.

Few studies have been done on the physical and chemical characteristics of MSW-BA used in asphalt concrete, especially the long-term pavement performance. Reuse of MSW-BA as a substitute material in high volume construction will reduce the

[1]Professor, Sustainable Environment Research Center, Dept. of Civil Engineering, National Cheng Kung Univ., Tainan 701, Taiwan (corresponding author). E-mail: jishchen@mail.ncku.edu.tw

[2]Graduate Student, Sustainable Environment Research Center, Dept. of Civil Engineering, National Cheng Kung Univ., Tainan 701, Taiwan.

[3]Professor, Sustainable Environment Research Center, Dept. of Environmental Engineering, National Cheng Kung Univ., Tainan 701, Taiwan.

[4]Graduate Student, Sustainable Environment Research Center, Dept. of Environmental Engineering, National Cheng Kung Univ., Tainan 701, Taiwan.

[5]Graduate Student, Sustainable Environment Research Center, Dept. of Civil Engineering, National Cheng Kung Univ., Tainan 701, Taiwan.

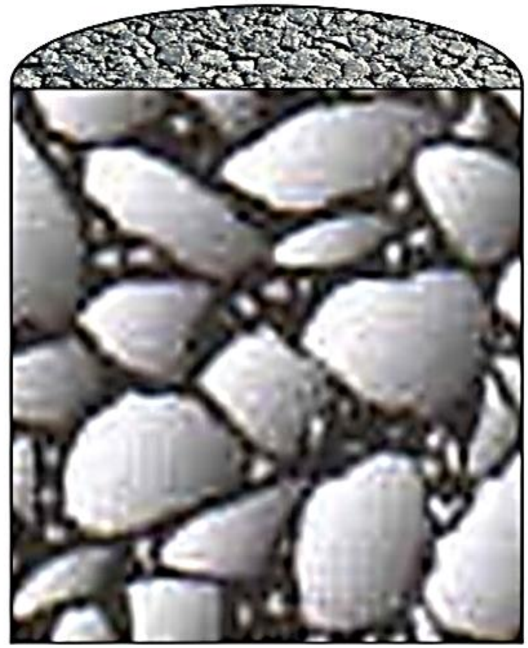
[6]Graduate Student, Sustainable Environment Research Center, Dept. of Civil Engineering, National Cheng Kung Univ., Tainan 701, Taiwan.

Note. Associate Editor: Hilary I. Inyang. Discussion open until November 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on November 27, 2006; approved on November 1, 2007. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 20, No. 6, June 1, 2008. ©ASCE, ISSN 0899-1561/2008/6-432–439/$25.00.

Not all asphalt is the same…

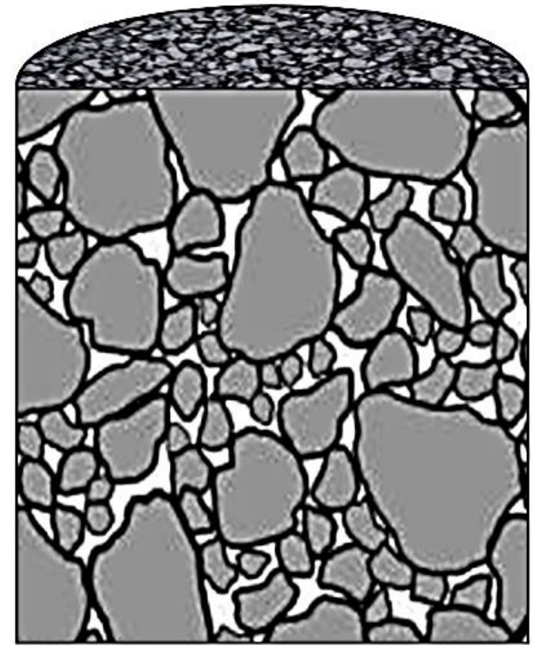
Dense-Graded

- Most common in US
- All size fractions
- Multi-purpose
- ***The focus for UF's work***



Stone Matrix

- Frequently used in Europe, emerging in US
- Gap-graded (large & small particles)



Open-Graded

- Highly permeable
- Large & medium particles (no small)
- Interstates

And not all mix designs are the same either...

Three methods used for developing an asphalt mix in the US:

- Hveem
  - Used rarely, mostly in western US
- Marshall
  - Commonly used in US and around the world (and in literature)
- Superpave
  - Developed to replace Hveem and Marshall
  - Beginning to be adopted across the country – Florida already uses it
  - ***<u>Used by UF in current work</u>***

Property	Marshall	Superpave
Aggregate	Owner/agency requirements	Gradation and aggregate property restrictions (e.g., angularity, durability, soundness)
Optimal Asphalt Binder Content	Ideally 4.0% air voids if minimum stability (strength), and flow (deformation) is met	Ideally 4.0% but between 3-5% air voids acceptable as long as other volumetrics met
Compaction Method	Marshall hammer	Gyratory compactor (more representative of loads from traffic levels)

Superpave mixes

- FDOT Standard Specifications for Road and Bridge Construction Section 334
  - Restrictions put on
    - Aggregate properties
    - Mix gradation and binder selection
    - Volumetrics

SECTION 334
SUPERPAVE ASPHALT CONCRETE

334-1 Description.

334-1.1 General: Construct a Superpave Asphalt Concrete pavement with the type of mixture specified in the Contract, or when offered as alternates, as selected. Superpave mixes are identified as Type SP-9.5, Type SP-12.5 or Type SP-19.0.

Meet the requirements of Section 320 for plant and equipment. Meet the general construction requirements of Section 330, except as modified herein, including the provision for Quality Control (QC) Plans and Quality Control (QC) Systems as specified in Section 105.

334-1.2 Traffic Levels: The requirements for Type SP Asphalt Concrete mixtures are based on the design traffic level of the project, expressed in 18,000 pound Equivalent Single Axle Loads (ESAL's). The five traffic levels are as shown in Table 334-1.

Table 334-1
Superpave Traffic Levels

Traffic Level	Traffic Level (1×10^6 ESAL's)
A	<0.3
B	0.3 to <3
C	3 to <10
D	10 to <30
E	≥30

Determines compaction effort →

Aggregate Properties

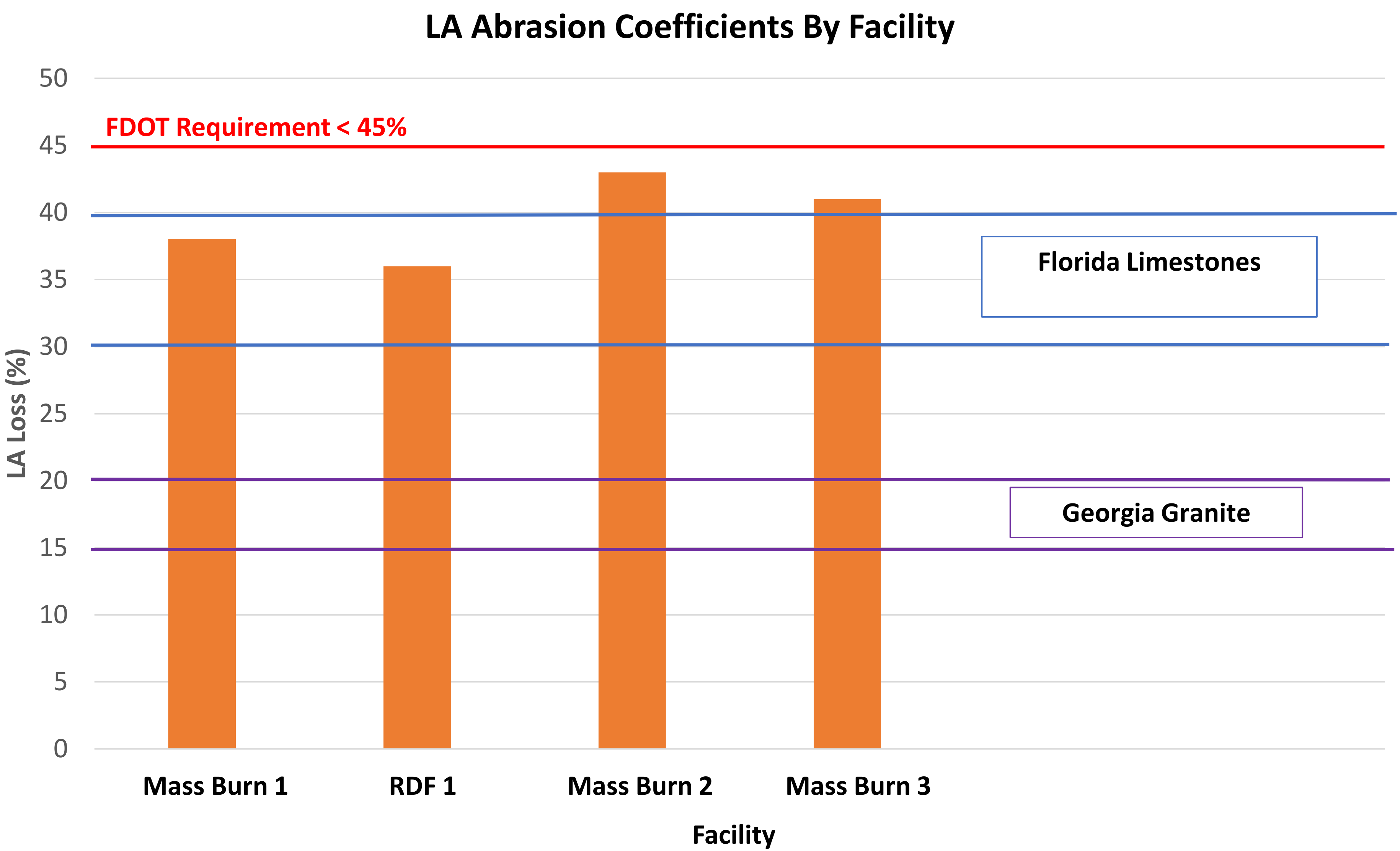
- Two categories:
  - “Physical”
  - “Source”

- “Physical” refers qualities such as:
  - Angularity
  - Flat & elongated particles
  - Clay content

- “Source” refers to qualities believed to be characteristic of all aggregates from a given source
  - Durability (Los Angeles Abrasion)
  - Soundness

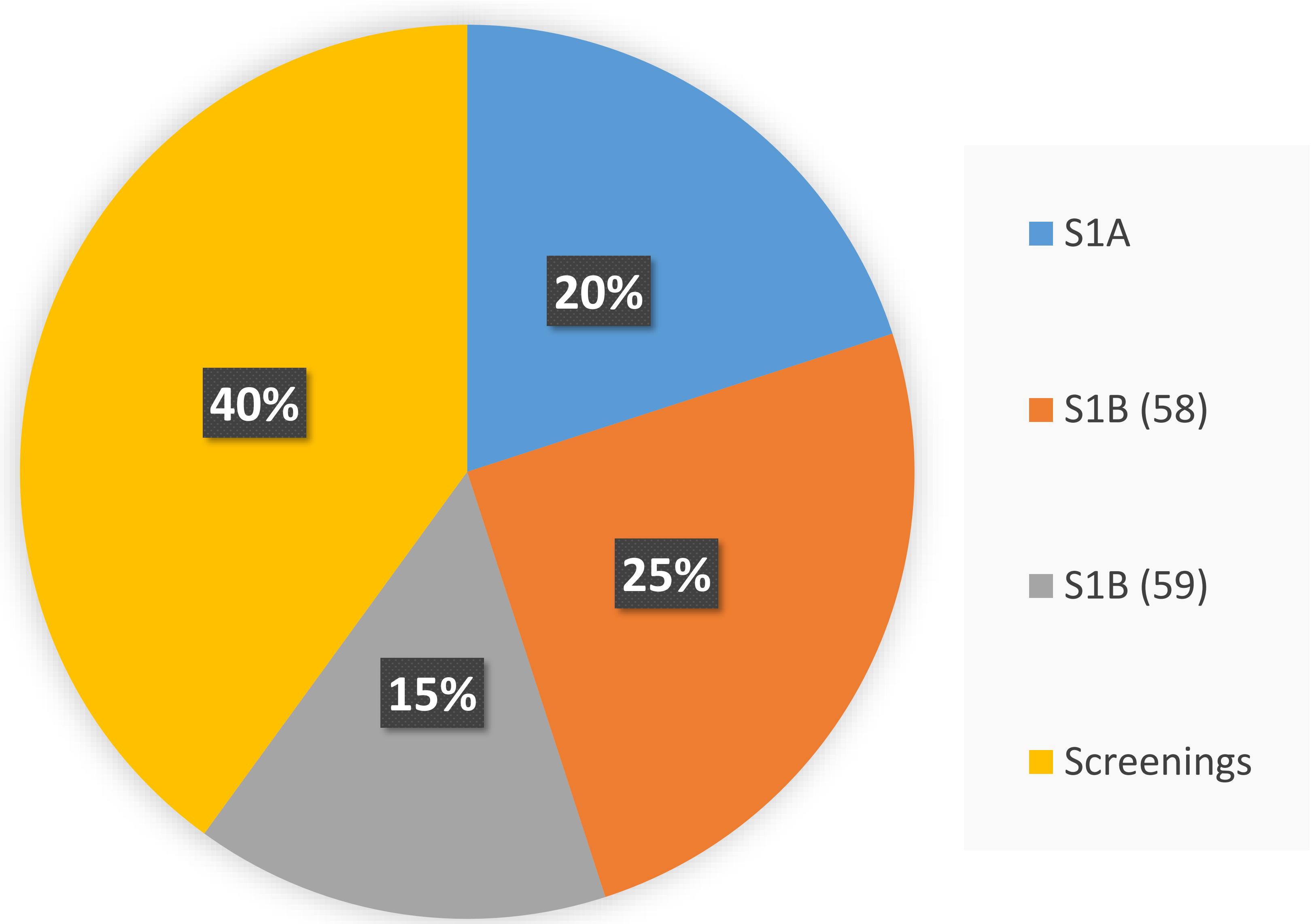
Aggregate durability is a big concern in HMA

- Can translate to durability of HMA product
- Can create problems during manufacturing HMA and even affect volumetrics
  - VMA can be problematic
- Therefore, ash used in mix designs was tested using Los Angeles (LA) abrasion (ASTM C131)
  - Ash rotated for number of cycles with steel charges (spheres)
  - % loss of material is measured



LA Abrasion Coefficients By Facility
FDOT Requirement < 45%
Florida Limestones
Georgia Granite
LA Loss (%)
50
45
40
35
30
25
20
15
10
5
0
Mass Burn 1
RDF 1
Mass Burn 2
Mass Burn 3
Facility

Example Mix Design



Multiple aggregates are usually needed to make a mix to achieve the right gradation

Contractor ______ Address ______

Phone No. ______ Fax No. ______ E-mail ______

Submitted By ______ Type Mix Fine SP-12.5 Intended Use of Mix Structural

Design Traffic Level D Gyrations @ Ndes 100

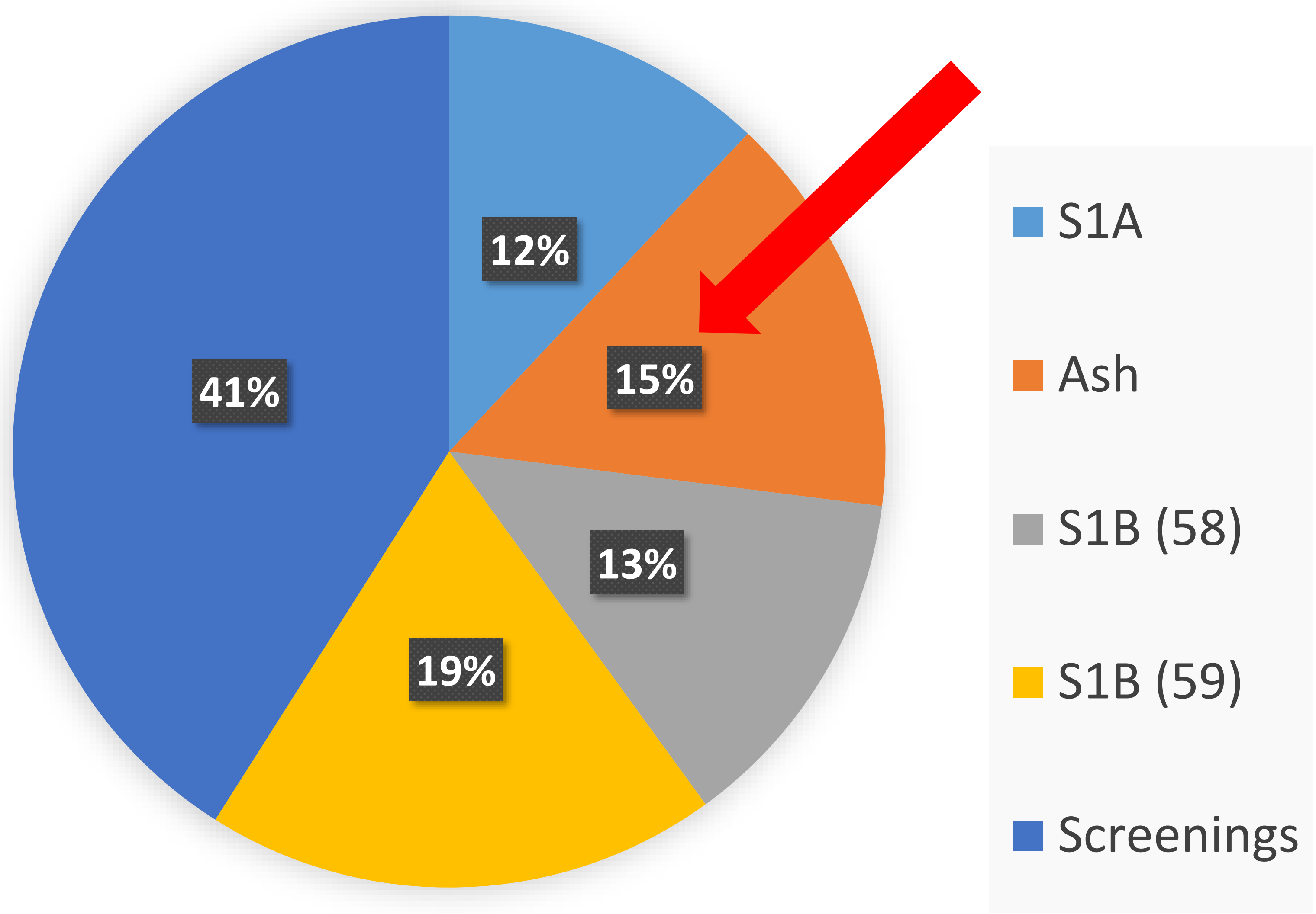
Product Description	Product Code	Producer Name	Product Name	Plant/Pit Number	Terminal
1. S1A Stone	C45	CEMEX	S1A Stone	87090	
2. S1B Stone	C58	CEMEX	S1B Stone	87090	
3. S1B Stone	C59	CEMEX	S1B Stone	87090	
4. Screenings	F21	CEMEX	Screenings	87090	
5.					
6.					
7. PG Binder	916-76PMA		PG 76-22 (PMA)		

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

Blend	20%	25%	15%	40%			JOB MIX	CONTROL	PRIMARY
Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
SIEVE SIZES 3/4" 19.0mm	100	100	100	100			100	100	
1/2" 12.5mm	99	100	100	100			100	90 - 100	
3/8" 9.5mm	45	99	100	100			89	- 89	
No. 4 4.75mm	1	50	73	100			64		
No. 8 2.36mm	1	13	12	93			42	28 - 58	39
No. 16 1.18mm	1	3	3	68			30		
No. 30 600μm	1	2	1	47			22		
No. 50 300μm	1	2	1	29			16		
No. 100 150μm	1	2	1	9			8		
No. 200 75μm	0.7	1.4	0.6	2.1			3.2	2 - 10	
G_{sb}	2.353	2.360	2.378	2.471			2.405		

JMF reflects aggregate changes expected during production

New Mix Design with WTE Ash



STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

ASPHALT MIX DESIGN

SUBMIT TO THE DIRECTOR, OFFICE OF MATERIALS, CENTRAL ASPHALT LABORATORY, 5007 NE 39TH AVE, GAINESVILLE, FL 32609

Contractor: Stephen Townsend Address:

Phone No.: Fax No.: E-mail:

Submitted By: Type Mix: Fine SP-12.5 Intended Use of Mix: Structural

Design Traffic Level: D Gyrations @ Ndes: 100

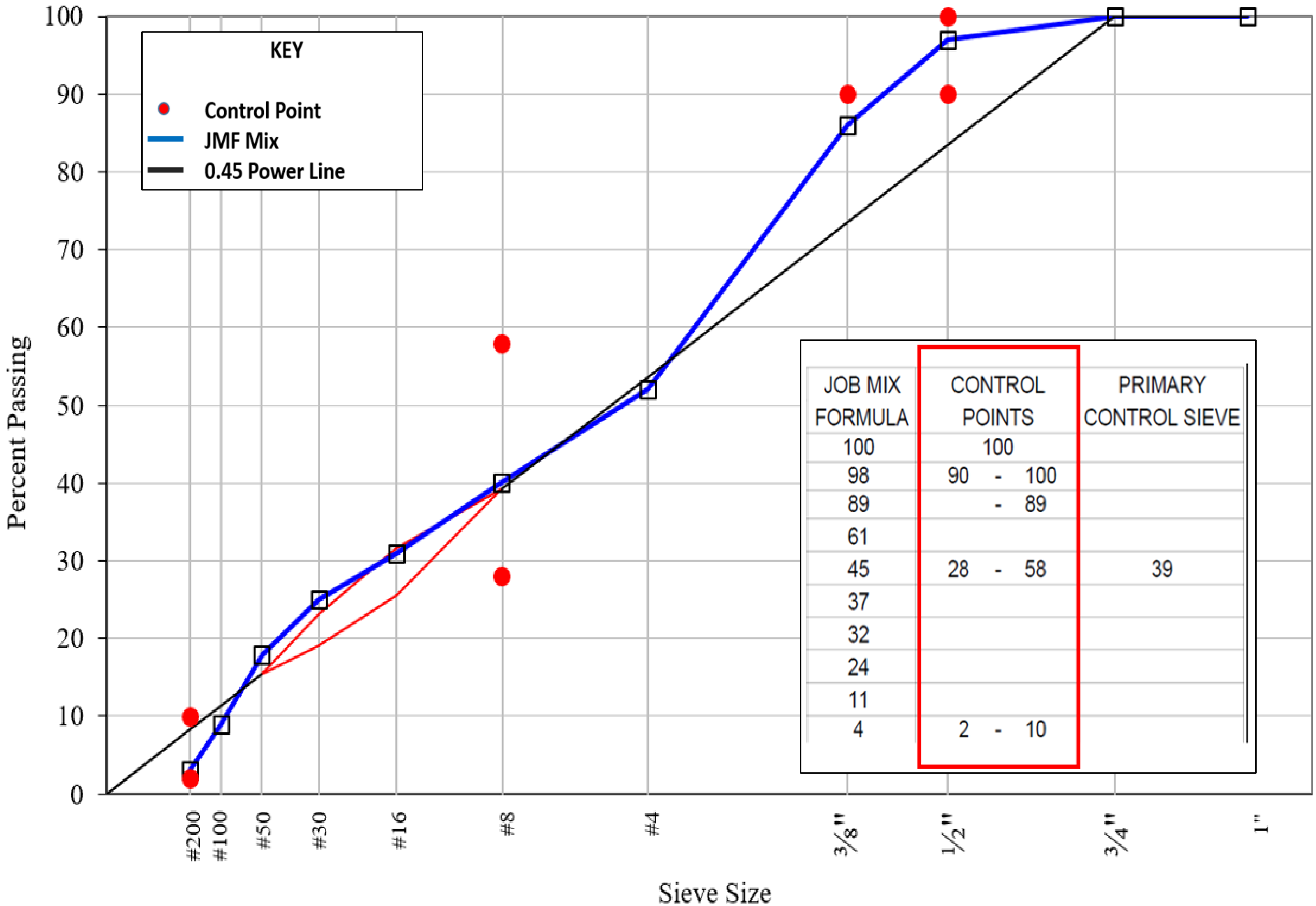
Product Description	Product Code	Producer Name	Product Name	Plant/Pit Number	Terminal
1. S1A Stone	C45	Cemex	87-090		
2. Bottom Ash		Facility Name			
3. S1B Stone	C58	Cemex	87-090		
4. S1B Stone	C59	Cemex	87-090		
5. Screenings	C21	Cemex	87-090		
6.					
7.					

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

	Blend	12%	15%	13%	19%	41%		JOB MIX	CONTROL	PRIMARY
	Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
	3/4" 19.0mm	100	100	100	100	100		100	100	
S	1/2" 12.5mm	99	75	100	100	100		96	90 - 100	
I	3/8" 9.5mm	45	44	99	100	100		85	- 89	
E	No. 4 4.75mm	1	7	50	73	100		63		
V	No. 8 2.36mm	1	5	13	12	93		43	28 - 58	39
E	No. 16 1.18mm	1	4	3	3	68		30		
	No. 30 600µm	1	4	2	1	47		20		
S	No. 50 300µm	1	3	2	1	29		13		
I	No. 100 150µm	1	2	2	1	9		5		
Z	No. 200 75µm	0.7	1.6	1.4	0.6	2.1		3	2 - 10	
E	G_{SB}	2.353	2.360	2.360	2.378	2.471		2.407		

The mix properties of the Job Mix Formula have been conditionally verified, pending successful final verification during production at the assigned plant, the mix design is approved subject to F.D.O.T. specifications.

JMF reflects aggregate changes expected during production


KEY
Control Point
JMF Mix
0.45 Power Line
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
#200
#100
#50
#30
#16
#8
#4
3/8"
1/2"
3/4"
1"
Sieve Size
JOB MIX FORMULA
CONTROL POINTS
PRIMARY CONTROL SIEVE
100 100
98 90 - 100
89 - 89
61
45 28 - 58 39
37
32
24
11
4 2 - 10

Volumetric Parameters

- Superpave requirements specify certain volumetric parameters that must be met in order to use the mix design

Parameters	Requirements for UF Mixes (Traffic Level C & D)
P_b	n/a
V_a	4.0%
VMA	Min. Req. 14%
VFA	65-75%
$P_{0.075}$ / P_{be}	0.6-1.2 (up to 1.6 with approval)

Determining volumetrics of our mix

- To find volumetrics, to know two properties of our mix:
  - Maximum specific gravity (G_{mm})
  - Bulk specific gravity (G_{mb})

- Once we know these values, we can determine all other volumetrics!

$$Air\ Voids\ (percent) = \left(\frac{G_{mm} - G_{mb}}{G_{mm}}\right) \times 100$$

$$VMA = \left(1 - \frac{G_{mb}(1 - P_b)}{G_{sb}}\right) \times 100$$

$$VFA = \frac{VMA - V_a}{VMA}$$

Theoretical Maximum Specific Gravity of the Mix (G_{mm})

- Test Associated: “Rice” Test (FM 1-T209)
  - Batch 1000g of aggregate following mix design
  - Add asphalt to desired Asphalt Content
  - Mix → Breakdown, no comglomerates > ¼”
  - Volume will be found from mix, compared with dry weight of sample

Preparing and gyrating an asphalt pill

Bulk Specific Gravity of the Mix (G_{mb})

- Once Gyratory Pill is gyrated and cooled, the Bulk Specific Gravity Test will be performed
- This Test leads to the G_{mb} value

Volumetric Results from Ash Amended HMA

Volumetric Parameters	Mass Burn Facility 1	RDF Facility 1 Ash Amended HMA	Mass Burn Facility 2 Ash Amended HMA	Mass Burn Facility 3 Ash Amended HMA
Original Binder Content (%)	5.1	6.8	6.8	5.0
New Binder Content (%)	5.6	6.5	7.0	5.8
Air Voids (V_a)	4.0	4.0	3.9	3.9
Voids in the Mineral Aggregate (VMA)	13.6	14.0	13.4	12.2
Voids Filled With Asphalt (VFA)	71	71	71	68
Dust-to-Binder Ratio	1.6	0.9	0.9	1.3

Not even non-ash mixes always meet VMA!

- Kandhal et al. 2004
  - Issues meeting VMA with non-ash amended mixes
  - Superpave gyratory compactor provides a greater compactive effort than Marshall hammer
  - Minimum VMA a tool to promote adequate asphalt film thickness
  - Reducing finer particles could improve VMA

TRANSPORTATION RESEARCH RECORD 1609 **Paper No. 98-0223** 21

Critical Review of Voids in Mineral Aggregate Requirements in Superpave

PRITHVI S. KANDHAL, KEE Y. FOO, AND RAJIB B. MALLICK

Reports of increased difficulties in meeting the minimum voids in mineral aggregate (VMA) requirements have surfaced with the recent use of Superpave volumetric mix design. The low VMA of Superpave mixes generally can be contributed to the increased compactive effort by the Superpave gyratory compactor. This has led to the increased use of coarser asphalt mixes (gradations near the lower control points). However, the minimum VMA requirements in Superpave volumetric mix design for these coarse mixes are the same as those developed for the dense mixes designed by the Marshall method. Literature review has indicated that the rationale behind the minimum VMA requirement was to incorporate at least a minimum permissible asphalt content into the mix to ensure its durability. Studies have shown that asphalt mix durability is directly related to asphalt film thickness. Therefore, the minimum VMA should be based on the minimum desirable asphalt film thickness instead of on a minimum asphalt content because the latter will be different for mixes with different gradations. Mixes with coarse gradation (and, therefore, a low surface area) have difficulty meeting the minimum VMA requirement based on minimum asphalt content despite thick asphalt films. A rational approach based on a minimum asphalt film thickness has been proposed and validated. The film thickness approach represents a more direct, equitable, and appropriate method of ensuring asphalt mix durability, and it encompasses various mix gradations.

One of the problems encountered by highway agencies implementing Superpave volumetric mix design is the difficulty in meeting the minimum voids in mineral aggregate (VMA) requirement. The low VMA of these mixtures often can be attributed to the increased compactive effort by the Superpave gyratory compactor and the increased use of coarser asphalt mixes (gradations below restricted zone).

Most conventional asphalt mixes in the United States have gradations above the maximum density line (*1*). Many highway agencies have made their asphalt mixes coarser than those conventionally used in order to meet the Superpave VMA requirements. Superpave also recommends the use of aggregate gradations below the maximum density line, especially for high-volume roads. Even then, it is not always possible to meet the VMA requirement.

Literature review has indicated that the rationale behind the minimum VMA requirement for conventional asphalt mixes was to incorporate a minimum desirable asphalt content into the mix to ensure its durability. Studies have shown that asphalt mix durability is directly related to asphalt film thickness. Therefore, the minimum VMA should be based on the minimum desirable asphalt film thickness instead of on a minimum asphalt content because the latter will be different for mixes with different gradations. Mixes with a coarse gradation (and thus a low surface area) have difficulty meeting the minimum VMA requirement based on minimum asphalt content despite thick asphalt films. A critical review of the minimum VMA requirement, therefore, is needed.

BACKGROUND ON DEVELOPMENT OF VMA CRITERIA

In a paper presented to the Highway Research Board in 1956 (*2*), McLeod pointed out that the basic criterion for both the design and analysis of asphalt paving mixtures should be a volumetric basis and not a basis of weight. Most specifications at that time specified a range of asphalt content by weight along with grading bands or limits for the aggregate, which in effect required a design on the basis of weight.

McLeod (*2*) illustrated the volumetric relationship of the total asphalt binder, air voids between the coated aggregate particles, and the total aggregate in a compacted paving mixture. He developed volumetric criteria such as VMA on the basis of specimens compacted with a Marshall hammer with 75 blows on each side of the specimen. He recommended that the VMA, which is the volume of voids between the aggregate particles, should be restricted to a minimum value of 15 percent, and the volume of the air voids (within the VMA) should lie between 3 percent and 5 percent, which in turn restricted the volume of asphalt cement binder in the compacted mixture to a permissible minimum of 10 percent by volume. Therefore, his proposal for a specification of a minimum 15-percent VMA, along with 5 percent air voids, automatically established a minimum asphalt content of about 4.5 percent by weight (10 percent by volume).

McLeod's calculations were based on a bulk specific gravity of 2.65 for the aggregate and 1.01 for the asphalt cement. No asphalt absorption was considered in the volumetric analysis.

Another paper presented by McLeod in 1959 (*3*) to the American Society of Testing and Materials advocated the use of bulk specific gravity of the aggregate for calculating both the VMA and the air voids. Absorption of the asphalt cement into the aggregate also was considered in the volumetric analysis. McLeod recommended again that the lowest permissible asphalt content in a hot mix asphalt (HMA) mix should be 4.5 percent by weight, to ensure mix durability. This amounts to about 10 percent asphalt cement by volume. No HMA performance data were presented to support the minimum asphalt content of 4.5 percent on which the minimum VMA requirement was based. In this paper, McLeod also proposed a relationship between the minimum VMA and the nominal maximum particle size of the aggregate, which was adopted by the Asphalt Institute in 1964 (*4*). He based this relationship on the bulk specific gravity of the aggregate and an air voids content of 5 percent for the compacted mix. However, the background data for relating the minimum VMA

P. S. Kandhal and R. B. Mallick, National Center for Asphalt Technology, 211 Ramsay Hall, Auburn University, Auburn, AL 36849. K. Y. Foo, Civil Engineering and Construction Department, Bradley University, 1501 West Bradley Avenue, Peoria, IL 61606-9989.

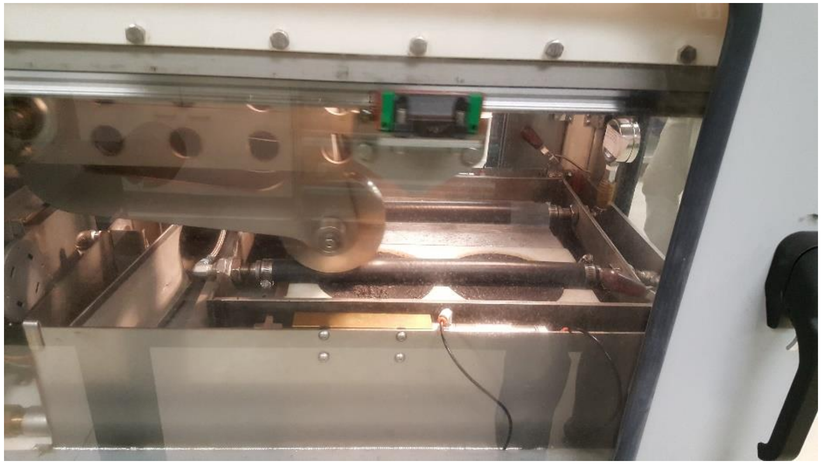
So besides an HMA's volumetrics…

- Does it also perform well from other physical parameters?
  - Tensile strength
  - Moisture susceptibility
  - Rutting susceptibility
  - Draindown (more so for HMA plant operations)

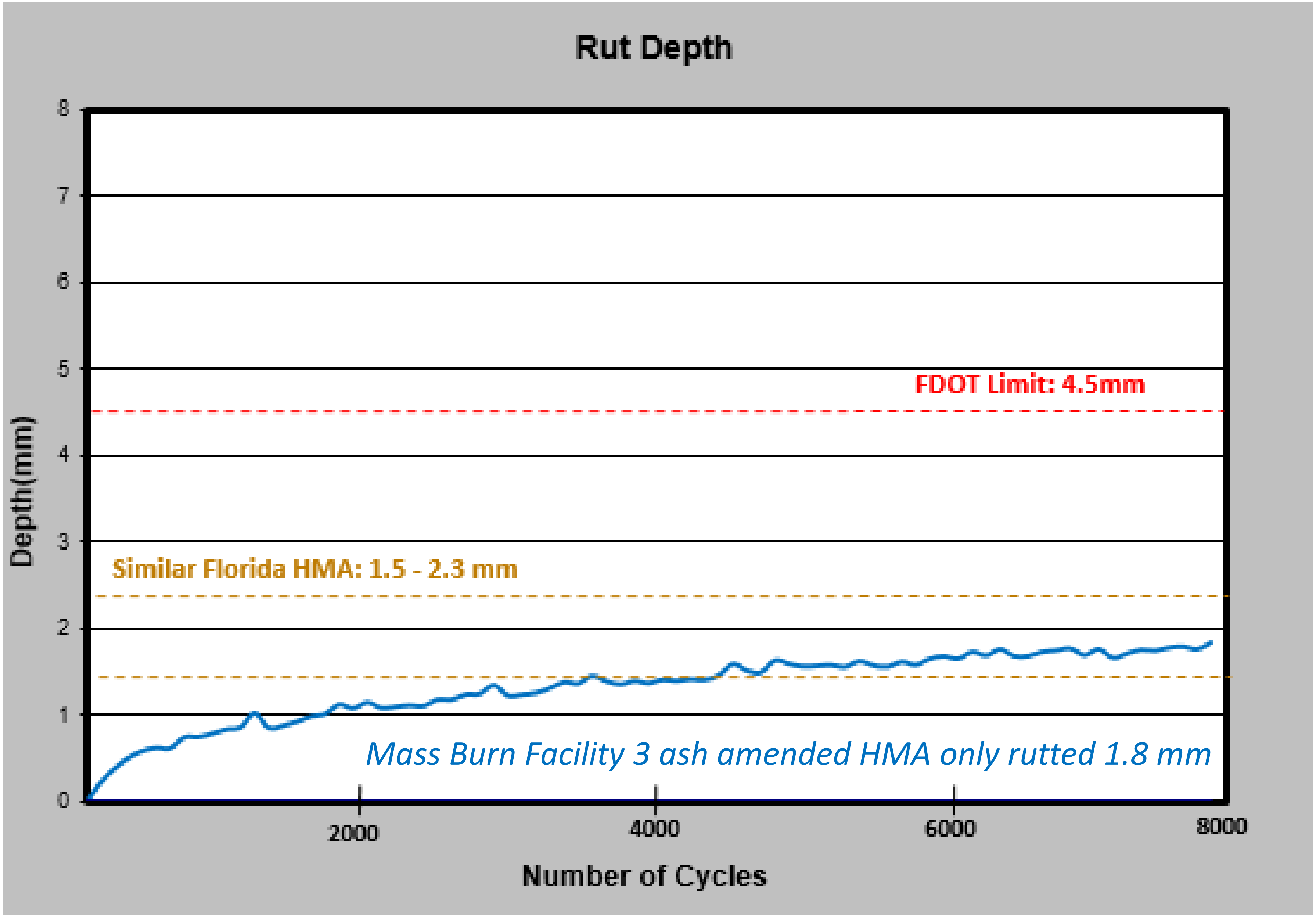
Physical Property	Rationale	Procedure	Common Testing Methods
Tensile strength	Identify cracking potential (higher tensile strengths correlate to higher resistance to cracking and vice versa)	Measuring HMA strength in tensile (across it's vertical diametral plane)	ASTM D6931
Moisture susceptibility	Identify how moisture may infiltrate and damage HMA pavement based on aggregate blend and asphalt binder content	Compare tensile strength before and after a series of weathering cycles to simulate long-term field conditions	Boiling test (ASTM D3625), Lottman test, Modified Lottman test (AASHTO T283), Lottman (Tunnicliff procedure)
Rutting/degradation susceptibility	Identify a HMA pavement's resistance to deformation	Compacted HMA specimens are subjected to physical wear and stresses, typically at elevated temperatures, to attempt to breakdown its structure	Empirical testing methods such as the Hamburg Wheel Tracking test and the Asphalt Pavement Analyzer (AASHTO TP 63)
Draindown	Identify potential storage and transport issues that may occur with large-scale usage of ash amended aggregate blends	An HMA mixture is tested to determine how much asphalt binder may drain off the aggregate blend during storage and transport	ASTM D6930

Rutting Susceptibility

- Asphalt Pavement Analyzer (APA) – AASHTO TP 63
- Measure of deformation over 8000 cycles (140 deg. F)
- Must meet specified limits
  - FDOT: < 4.5 mm



APA Rutting for Mass Burn Facility 3



Other performance tests in the literature

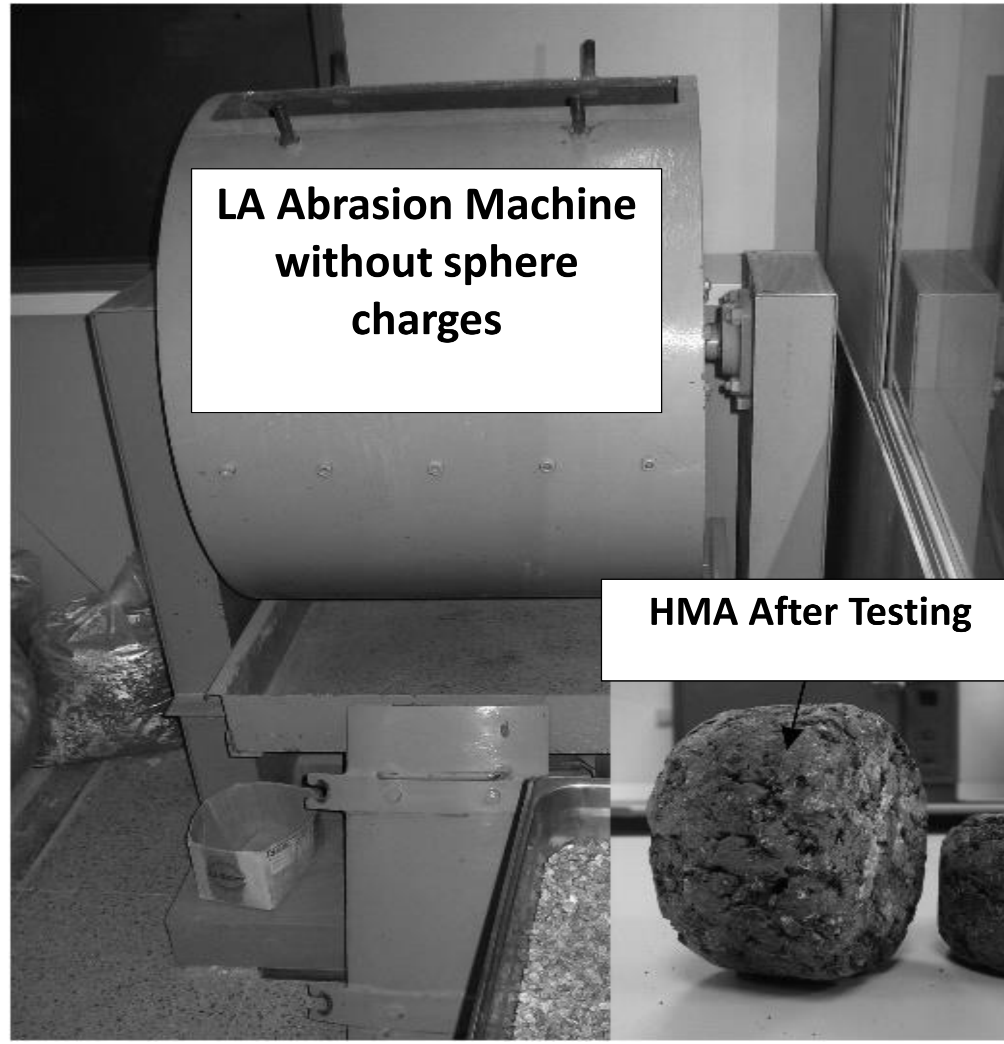
Indirect Tensile (IDT) Strength & Moisture Susceptibility

- IDT Depends on:
  - Interlocking particles
  - Aggregate strength
  - Aggregate surface chemistry
- Moisture susceptibility measured by IDT strength before and after simulated weather cycling
  - Adequate binder film thickness is crucial
- Conflicting results in the literature

Constant Load

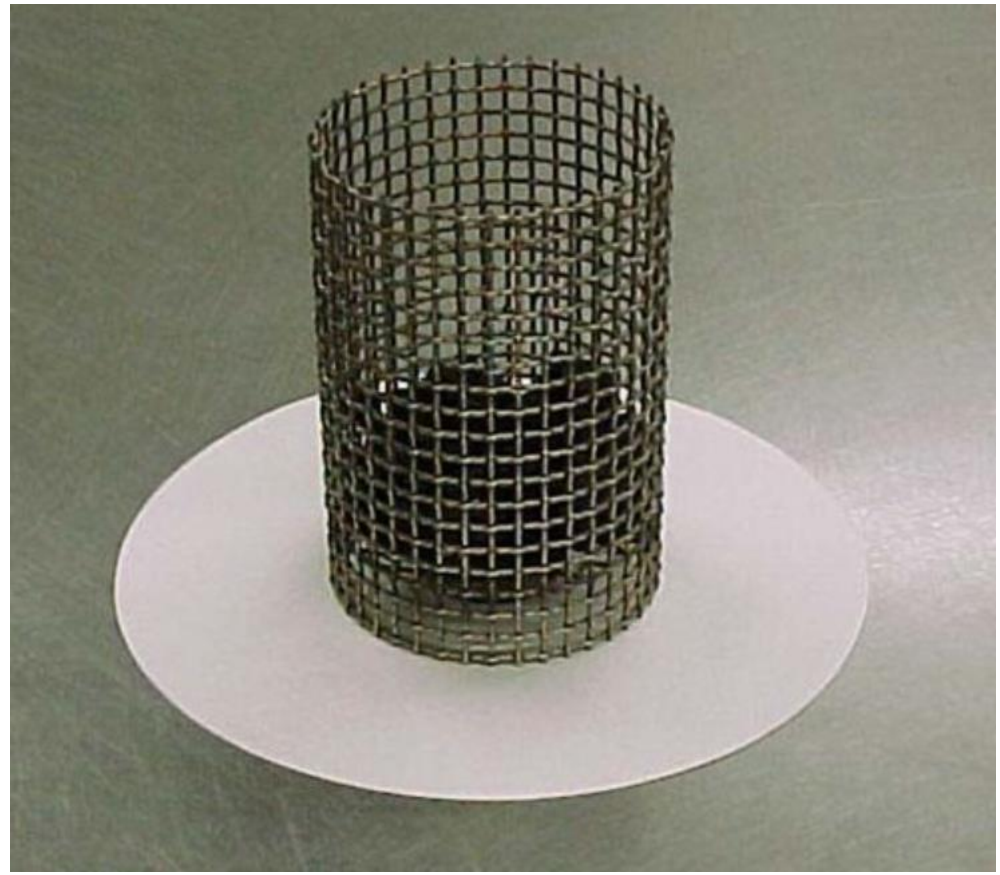
Cantabro HMA Test

- Another option for measuring rutting susceptibility
- Rotate specimen in an LA abrasion device for a number of cycles
  - Report % loss (or total disintegration)
- Mixed results in literature
  - Hassan, 2005 – increased susceptibility
  - Luo et al., 2017 – decreased susceptibility



Draindown

- Percentage of asphalt bitumen that drains from aggregate mix
- Important for HMA storage and transport at plants
- Conflicting findings
  - Slight increase but still under limit (Xue et al., 2009)
  - Decreased (Luo et al., 2017)



In summary, what we know from the literature and our own work about HMA

- Work in utilizing WTE ashes in HMA has been documented throughout recent decades around the world in both field and laboratory studies
- Literature and UF show that it is possible to meet requirements but replacements may vary
  - High absorptions cause problems with increasing binder content
    - Washing could help with this
  - Meeting VMA can be an issue
    - Reducing finer material could improve this
- Literature shows that physical performance can also vary
- Work by UF suggests that rutting susceptibility (APA) with 15% WTE ash is on par with other, non-ash amended Florida HMA mixes

Technical Awareness Group Meeting

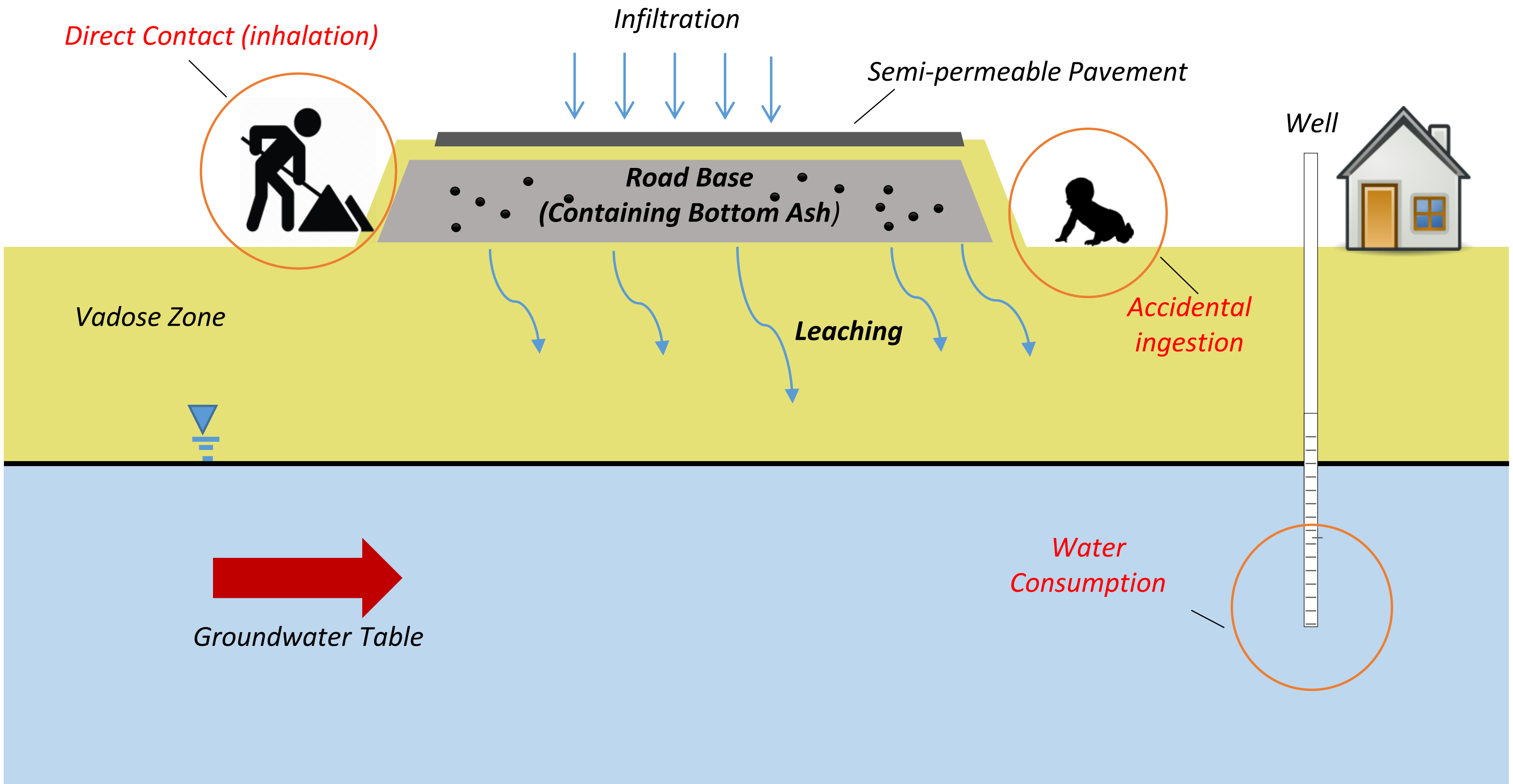
Research Related to Recycling of WTE Bottom Ash as Aggregate in Concrete and Asphalt Pavement

BREAK

Research Support by the
Hinkley Center for Solid and Hazardous Waste Management
https://www.hinkleycenter.org/

Environmental characterization of concrete and pavement made using WTE ash as aggregate

Examining the Risk to Human Health and the Environment Posed by WTE Ash Recycling



Risk Management Approaches

- Direct Exposure
  - Measure the "total" concentration of chemicals (mg/kg)
  - Assess risk using assumptions of direct exposure and chemical toxicity

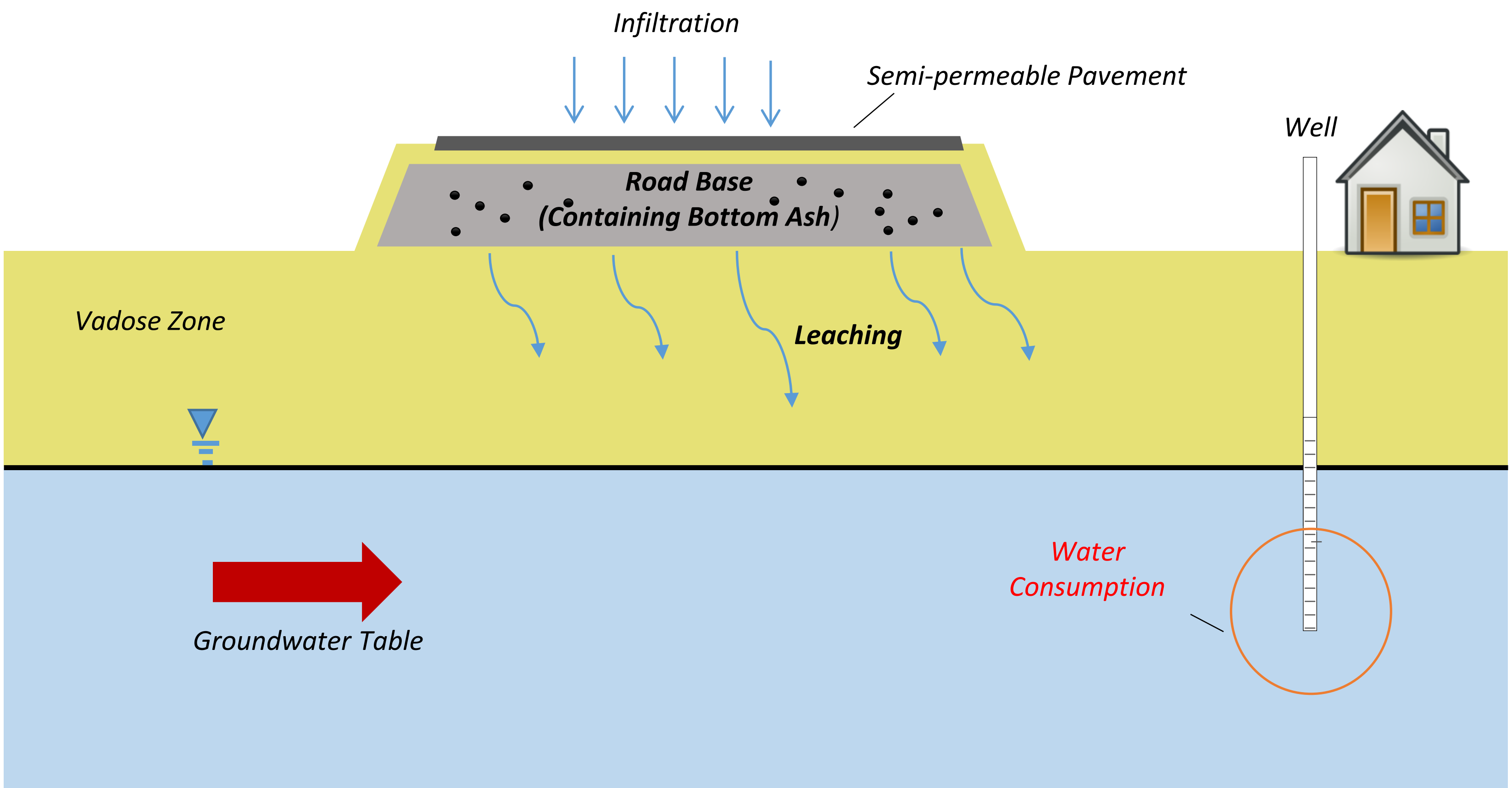
Compare measured concentrations to SCTL

- Leaching
  - Measure the "leachable" concentrations of chemicals (mg/kg)
  - Assessing risk by using leachate concentrations as input to fate and transport model

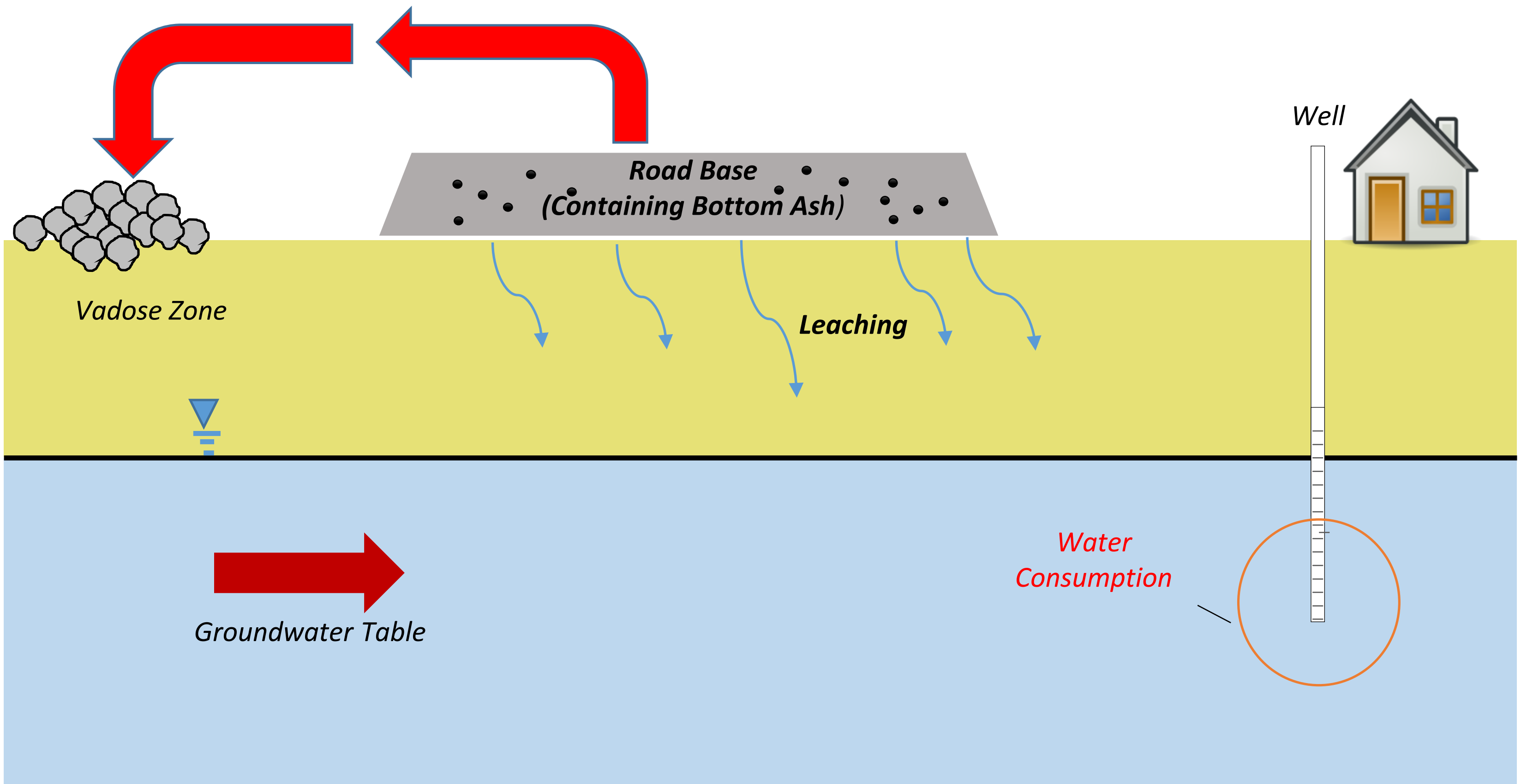
Use measured concentrations as input to fate and transport model and compare predicted concentration to GCTL

Leaching is the primary risk pathway of interest, but let's take a look at the direct exposure question.

Examining the Risk to Human Health and the Environment Posed by WTE Ash Recycling



Examining the Risk to Human Health and the Environment Posed by WTE Ash Recycling



Approaches to Managing Risk

- Approach 1
  - Control risk through engineering or institutional control

- Approach 2
  - Demonstrate that material will not pose a risk during "second life" or treat/blend to meet this condition.

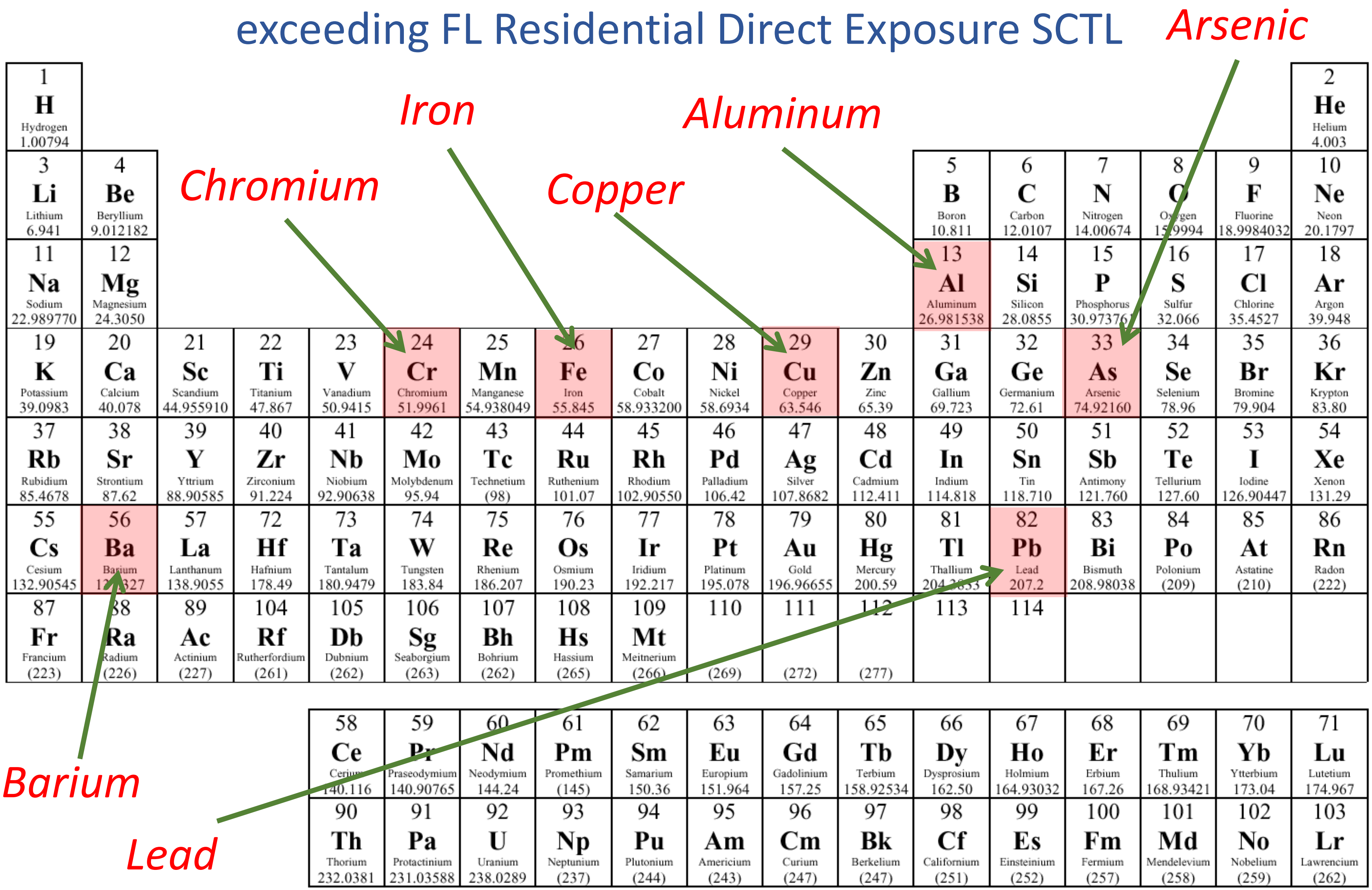
If the material is ever removed, it must be managed appropriately (e.g., in similar reuse application)

Ash treatment or blending

Are chemical concentrations in ash sufficiently high to pose a direct exposure issue?

Are chemical concentrations in ash sufficiently high to pose a direct exposure issue?

Chemicals in WTE bottom ash exceeding FL Residential Direct Exposure SCTL

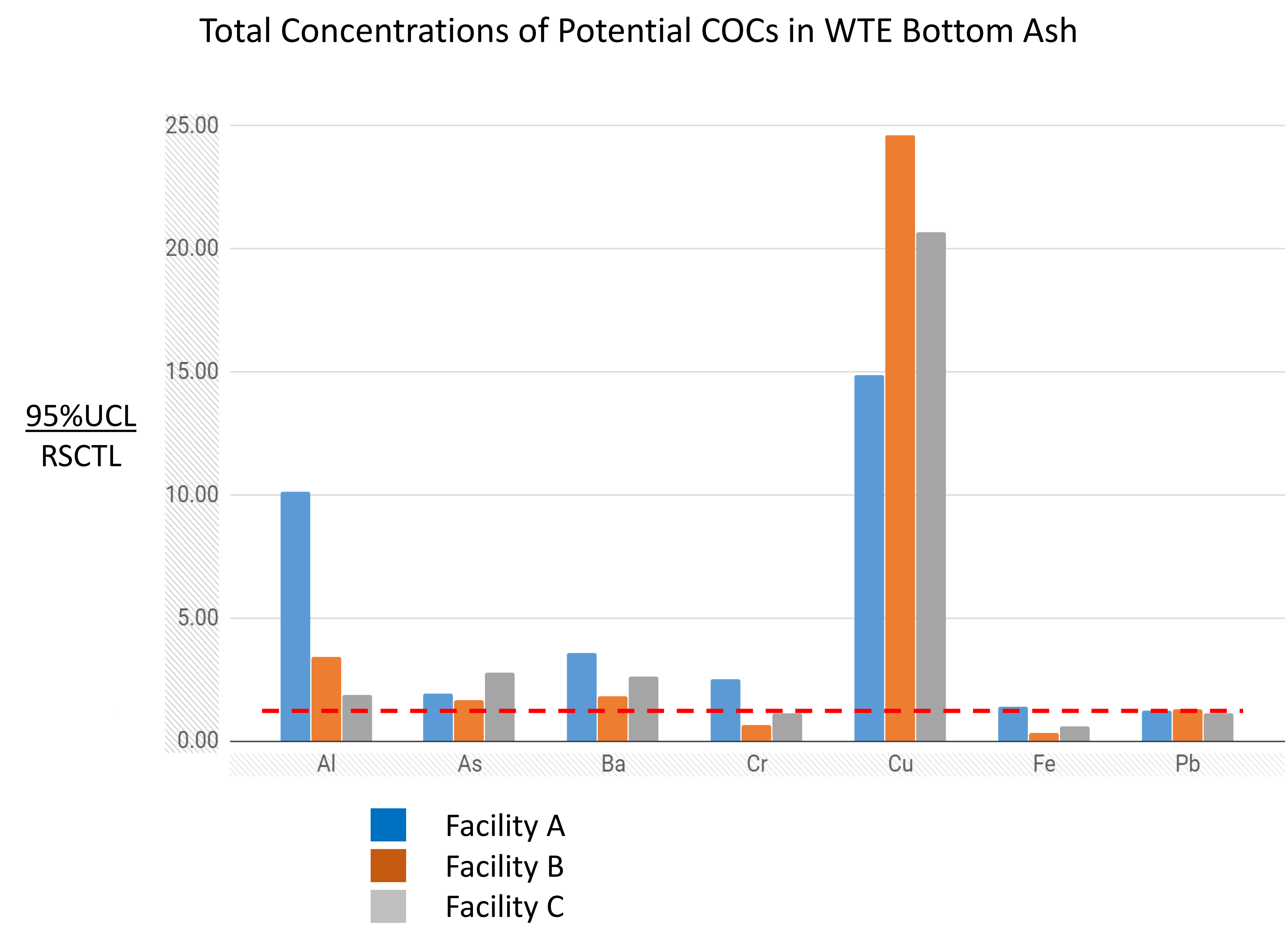


Chemicals in WTE bottom ash exceeding FL Commercial Direct Exposure SCTL

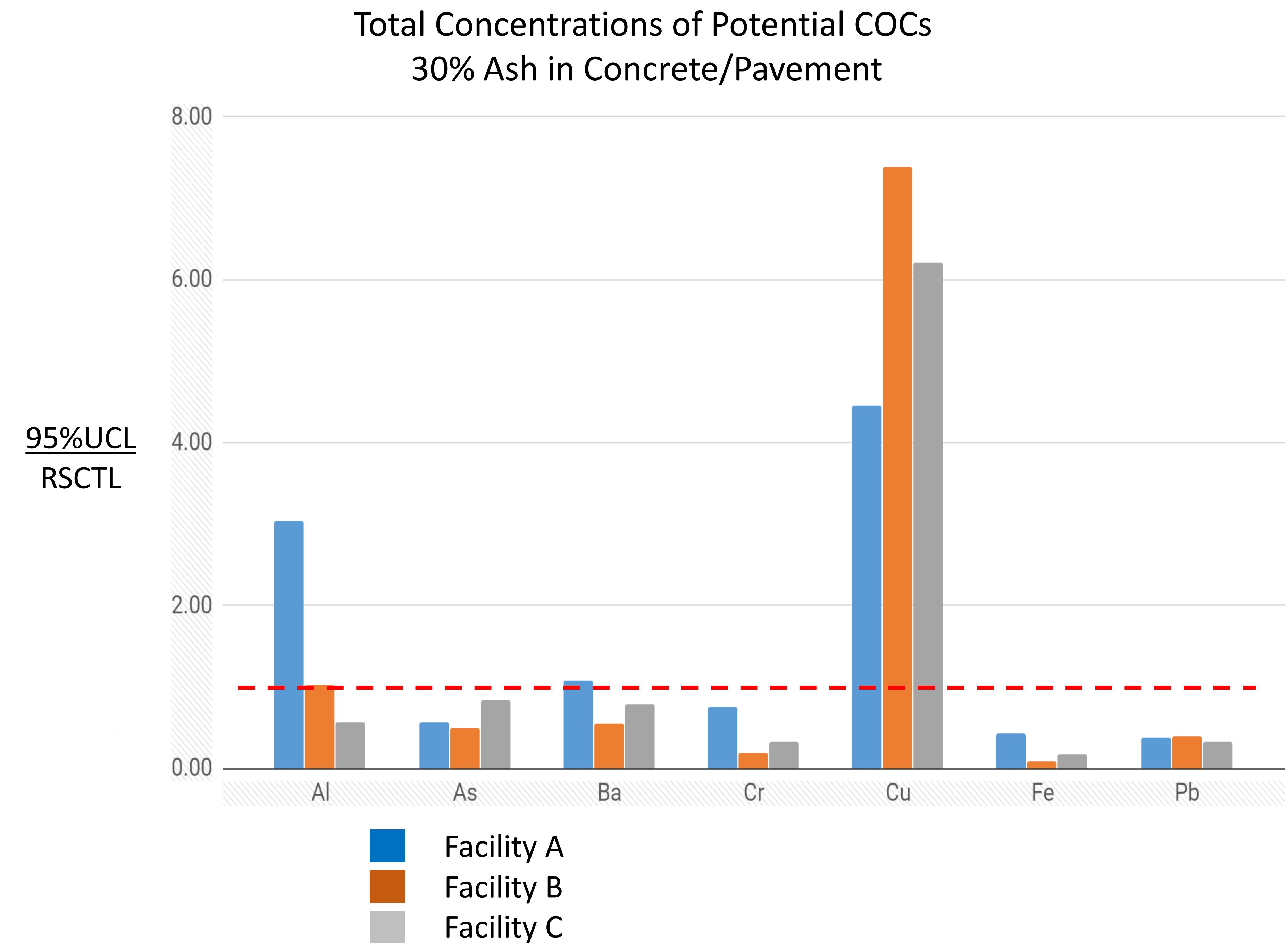
Chromium

1 **H** Hydrogen 1.00794																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012182											5 **B** Boron 10.811	6 **C** Carbon 12.0107	7 **N** Nitrogen 14.00674	8 **O** Oxygen 15.9994	9 **F** Fluorine 18.9984032	10 **Ne** Neon 20.1797
11 **Na** Sodium 22.989770	12 **Mg** Magnesium 24.3050											13 **Al** Aluminum 26.981538	14 **Si** Silicon 28.0855	15 **P** Phosphorus 30.973761	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.4527	18 **Ar** Argon 39.948
19 **K** Potassium 39.0983	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.955910	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.9415	24 **Cr** Chromium 51.9961	25 **Mn** Manganese 54.938049	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.933200	28 **Ni** Nickel 58.6934	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92160	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.4678	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.90585	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.90638	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.90550	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.8682	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.60	53 **I** Iodine 126.90447	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.90545	56 **Ba** Barium 137.327	57 **La** Lanthanum 138.9055	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.9479	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217	78 **Pt** Platinum 195.078	79 **Au** Gold 196.96655	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.3833	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98038	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium (226)	89 **Ac** Actinium (227)	104 **Rf** Rutherfordium (261)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (262)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				

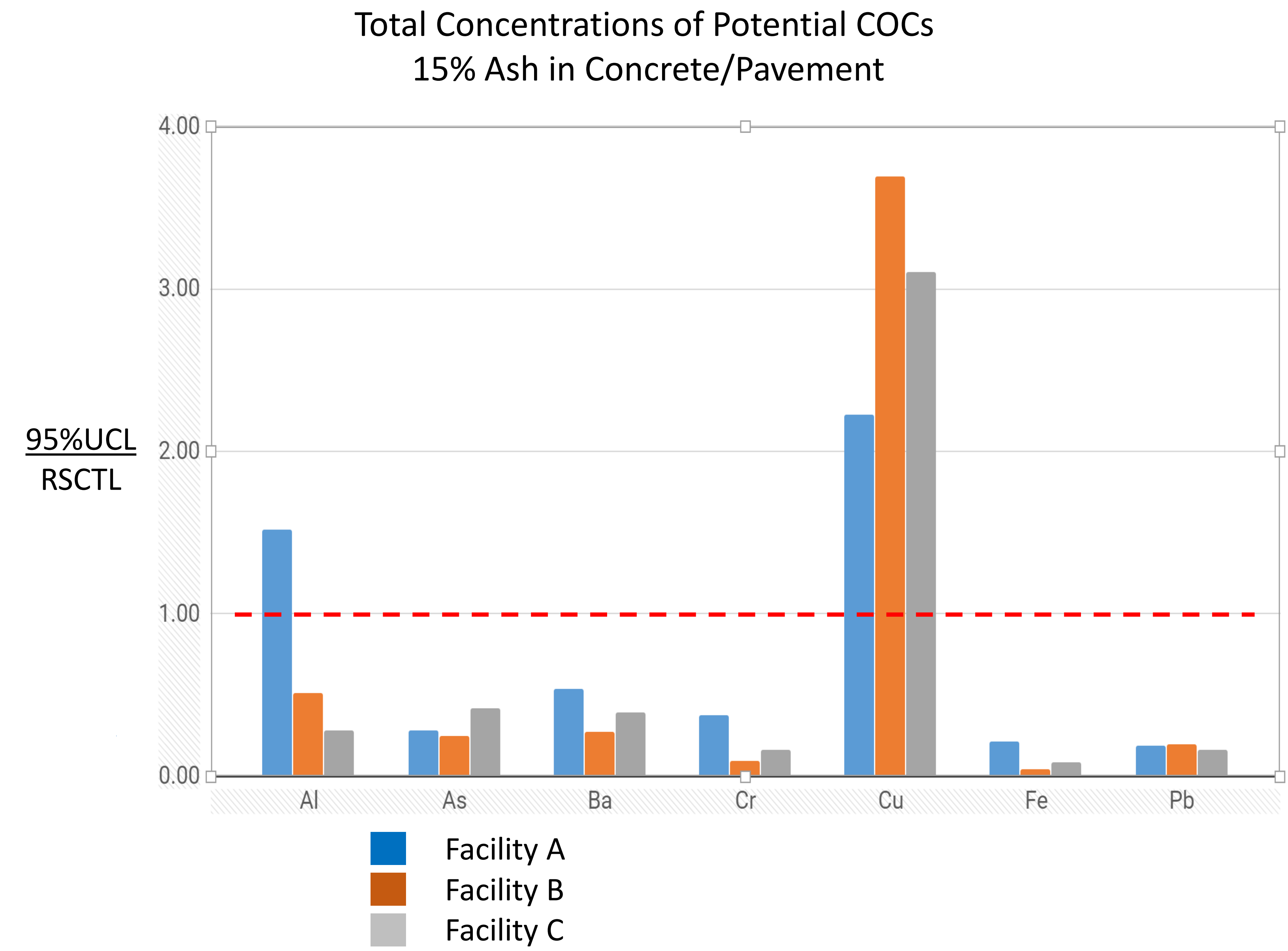
58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.90765	60 **Nd** Neodymium 144.24	61 **Pm** Promethium (145)	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.92534	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93032	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93421	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967
90 **Th** Thorium 232.0381	91 **Pa** Protactinium 231.03588	92 **U** Uranium 238.0289	93 **Np** Neptunium (237)	94 **Pu** Plutonium (244)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)	103 **Lr** Lawrencium (262)



Total Concentrations of Potential COCs in WTE Bottom Ash
95%UCL
RSCTL
25.00
20.00
15.00
10.00
5.00
0.00
Al
As
Ba
Cr
Cu
Fe
Pb
Facility A
Facility B
Facility C

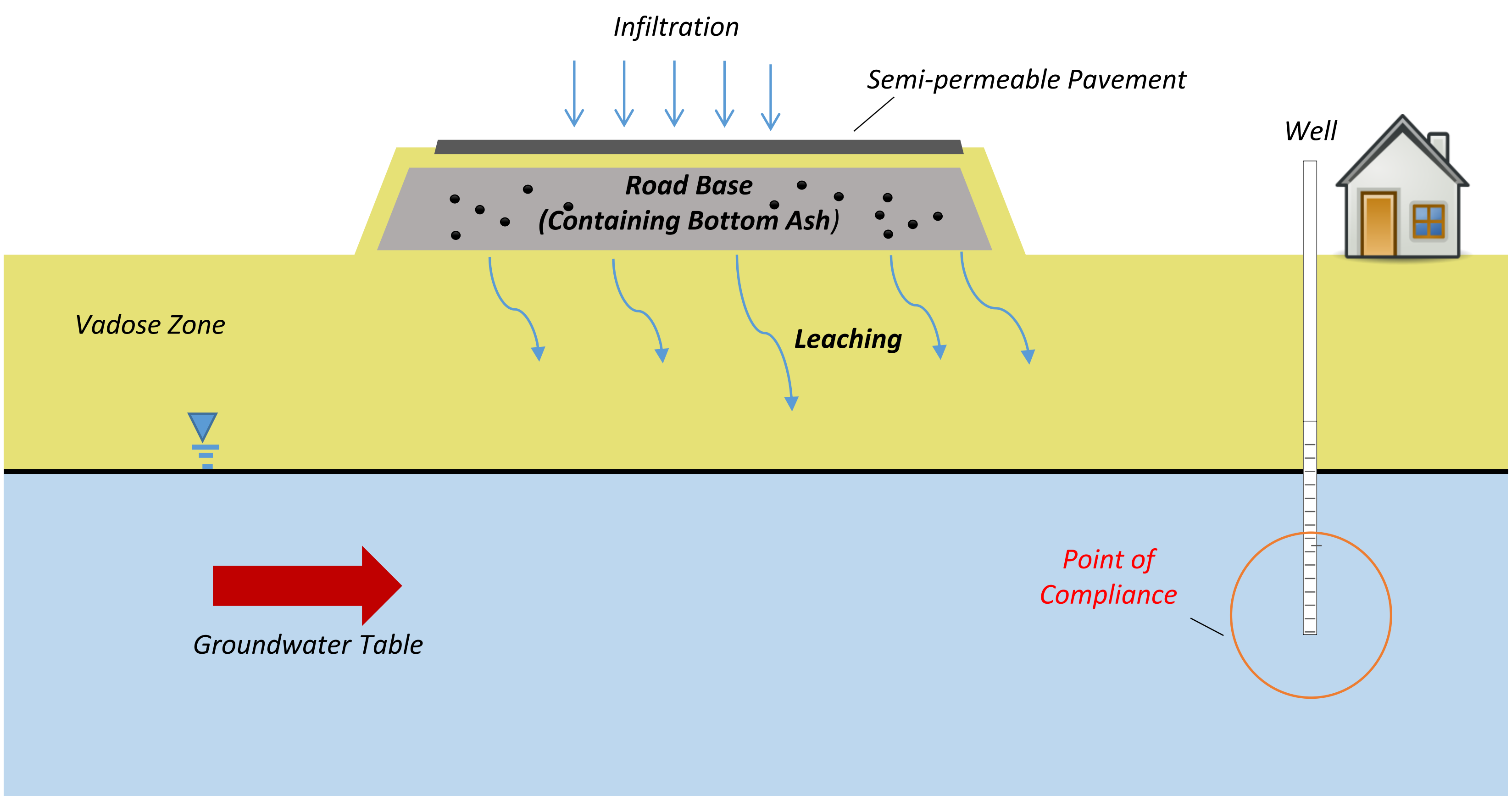


Total Concentrations of Potential COCs
30% Ash in Concrete/Pavement
95%UCL
RSCTL
8.00
6.00
4.00
2.00
0.00
Al
As
Ba
Cr
Cu
Fe
Pb
Facility A
Facility B
Facility C

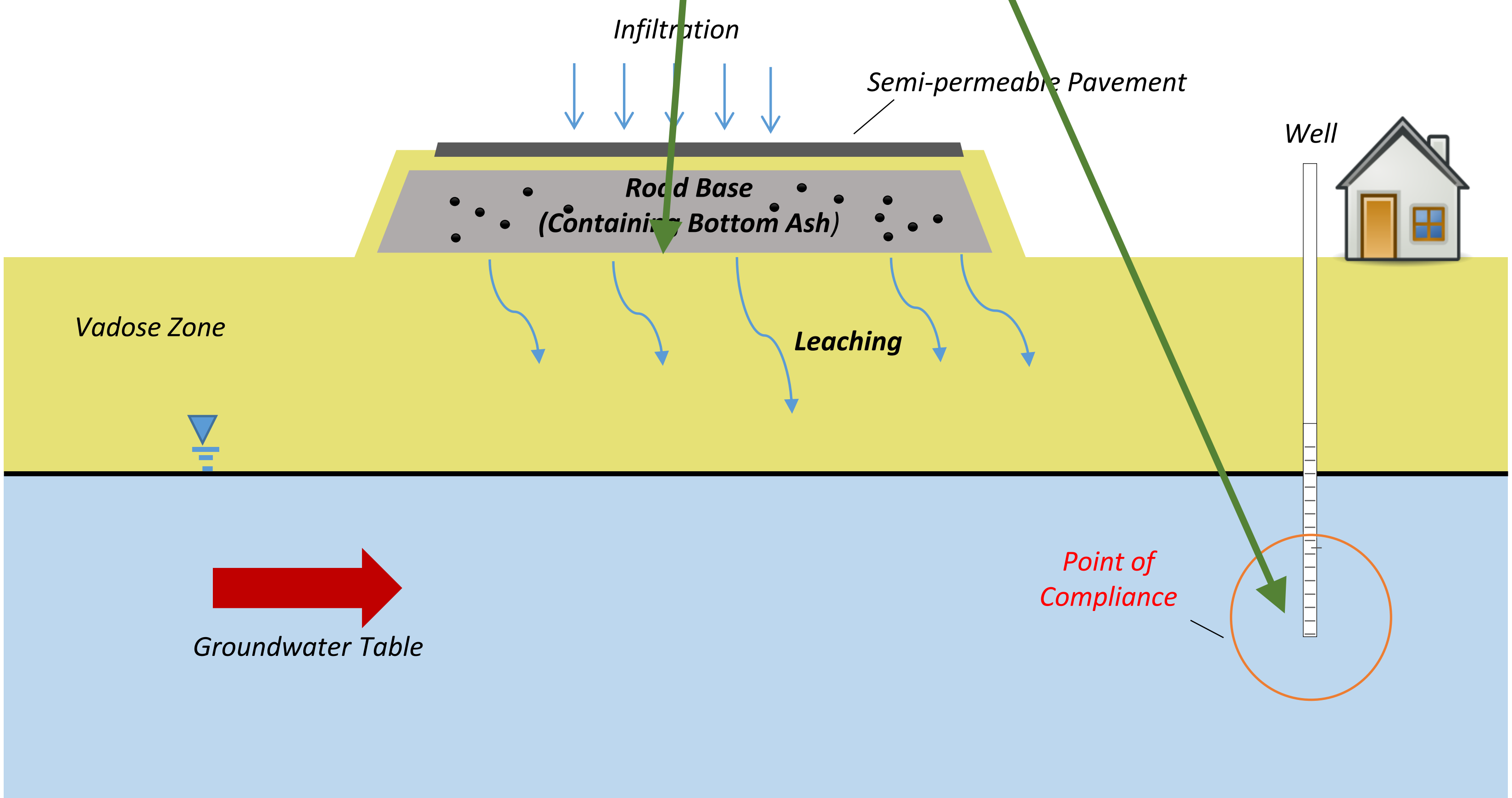


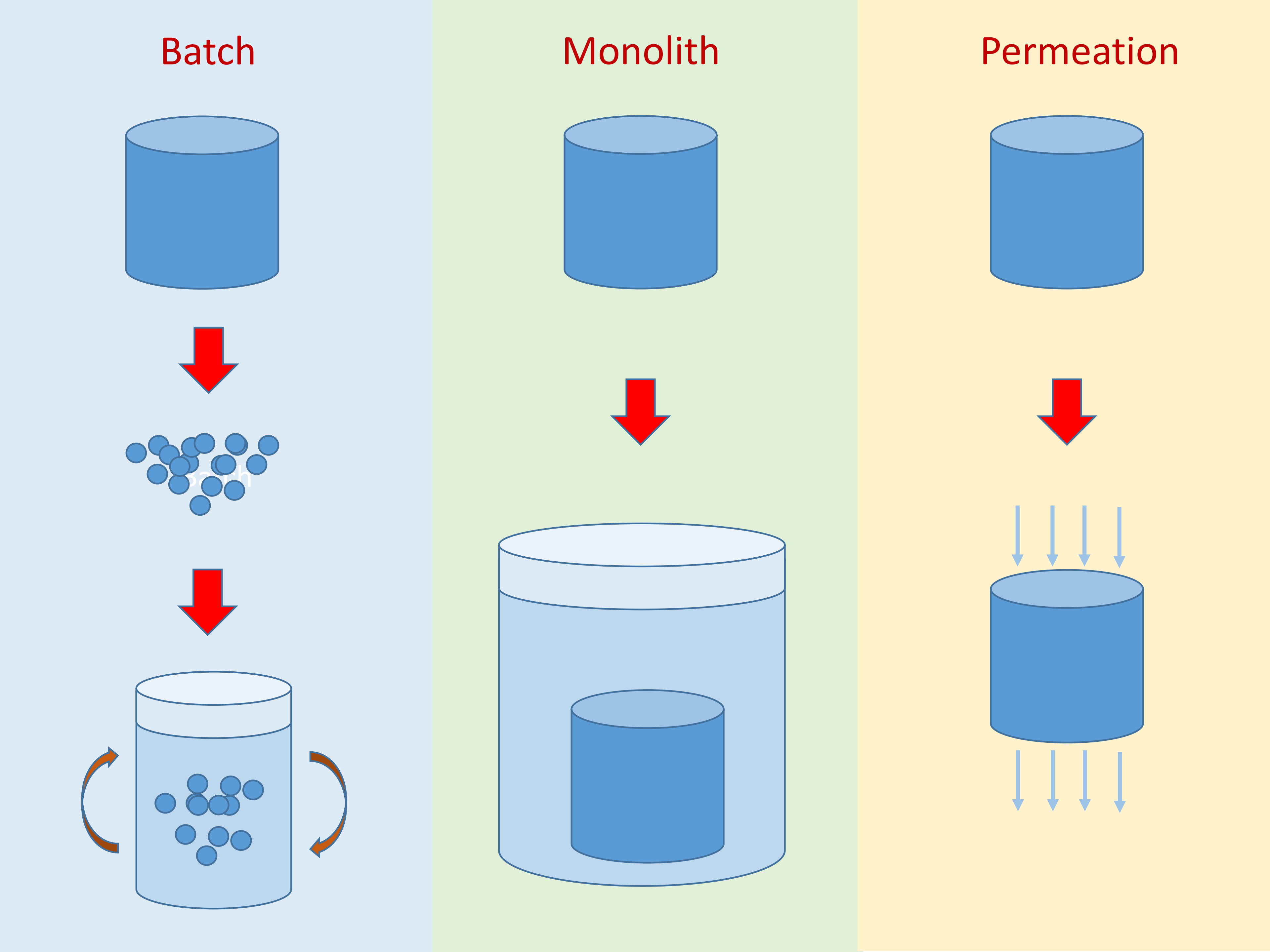
Total Concentrations of Potential COCs
15% Ash in Concrete/Pavement
95%UCL
RSCTL
4.00
3.00
2.00
1.00
0.00
Al
As
Ba
Cr
Cu
Fe
Pb
Facility A
Facility B
Facility C

Let’s Focus on Leaching Risk

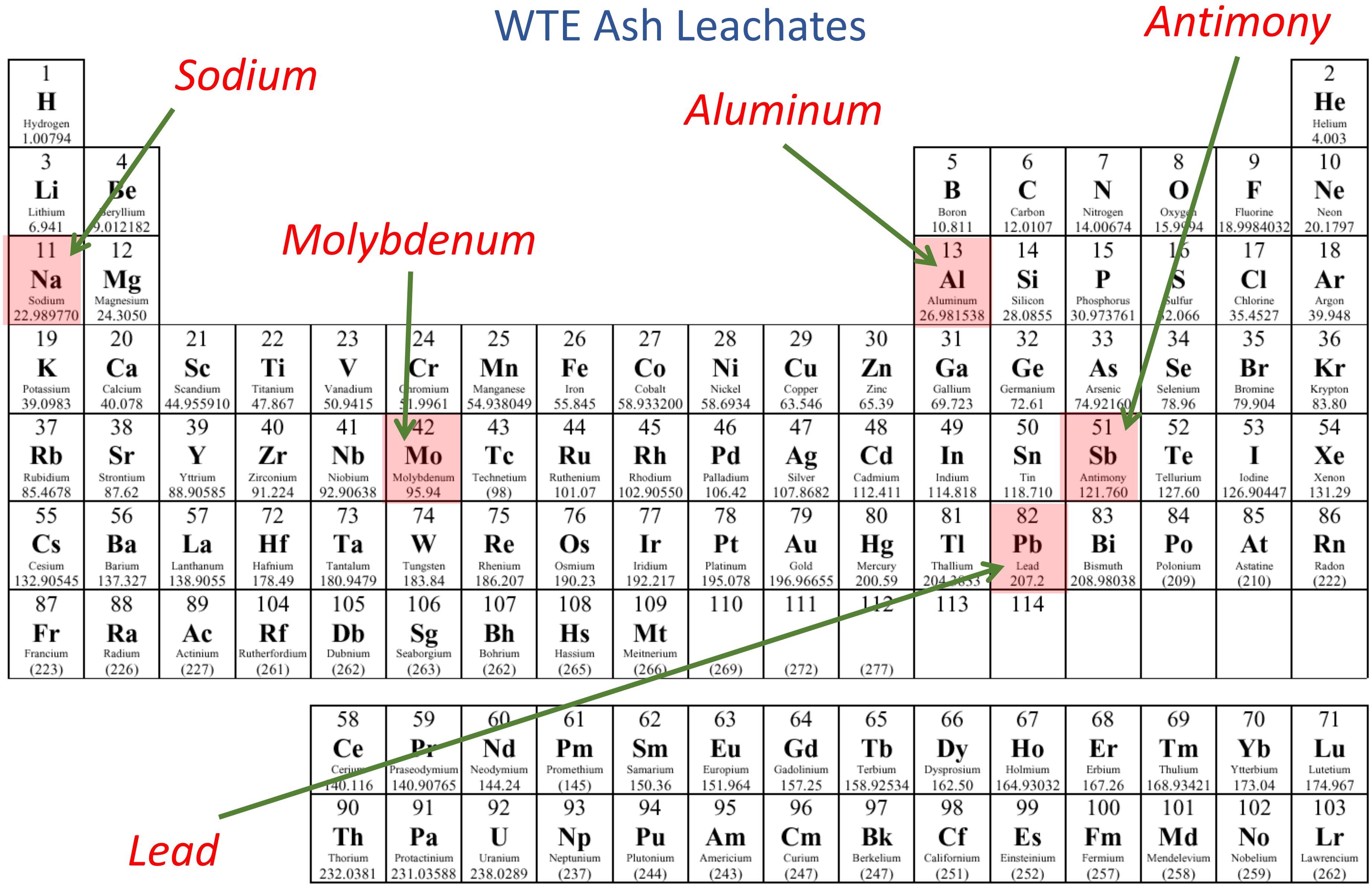


$$\text{Dilution Attenuation Factor (DAF)} = \frac{\text{Concentration in Leachate}}{\text{Acceptable Risk Threshold at Point of Compliance}}$$




Batch
Monolith
Permeation

Chemicals of Potential Concern in WTE Ash Leachates



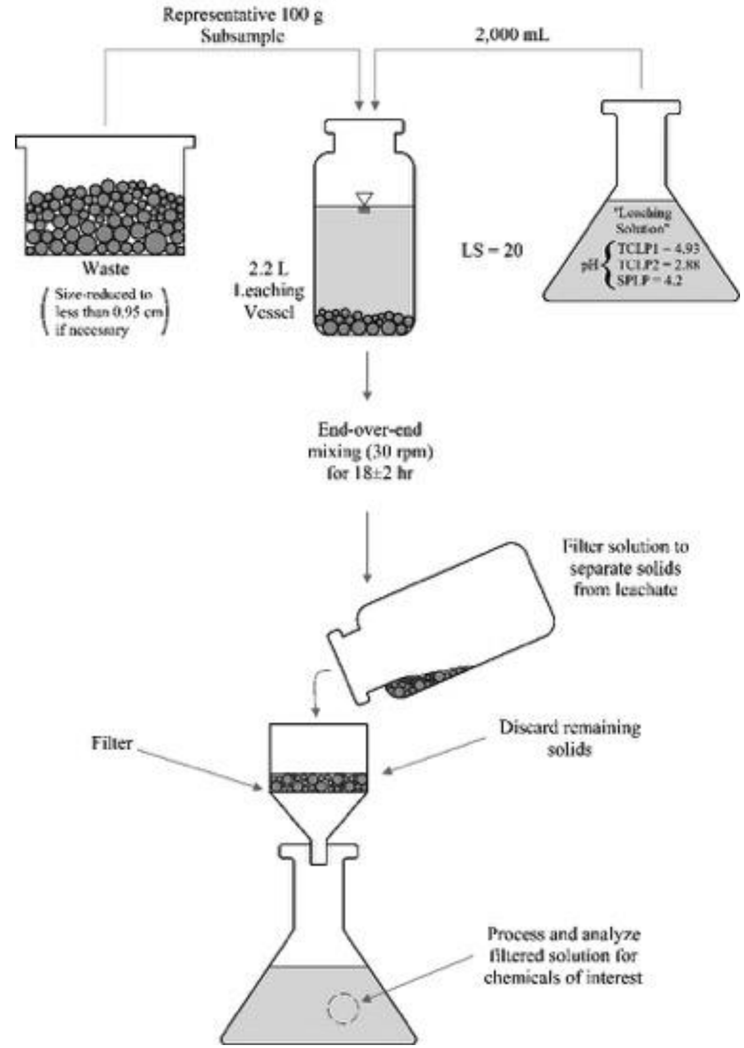
Leaching Results from WTE Ash Amended Concrete

Element	Observation
Aluminum	Encountered at concentrations above secondary drinking water standards but below risk-based thresholds. Also elevated in control concrete.
Molybdenum	Occasionally observed above risk thresholds in batch tests, but at similar concentrations as control concrete.
Lead	Usually always at concentrations below risk levels. On occasion in batch tests may see elevated concentrations in newly crushed concrete.
Antimony	Always below risk thresholds.
Sodium	Elevated, but same as control concrete.

Based on evaluation of UF testing data

Leaching from WTE Ash Amended HMA Pavement

EPA Method 1312: Synthetic Precipitation Leaching Procedure

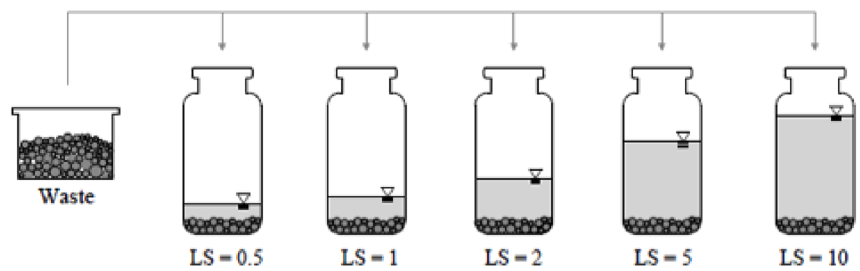


SPLP Results on WTE Ash Amended HMA

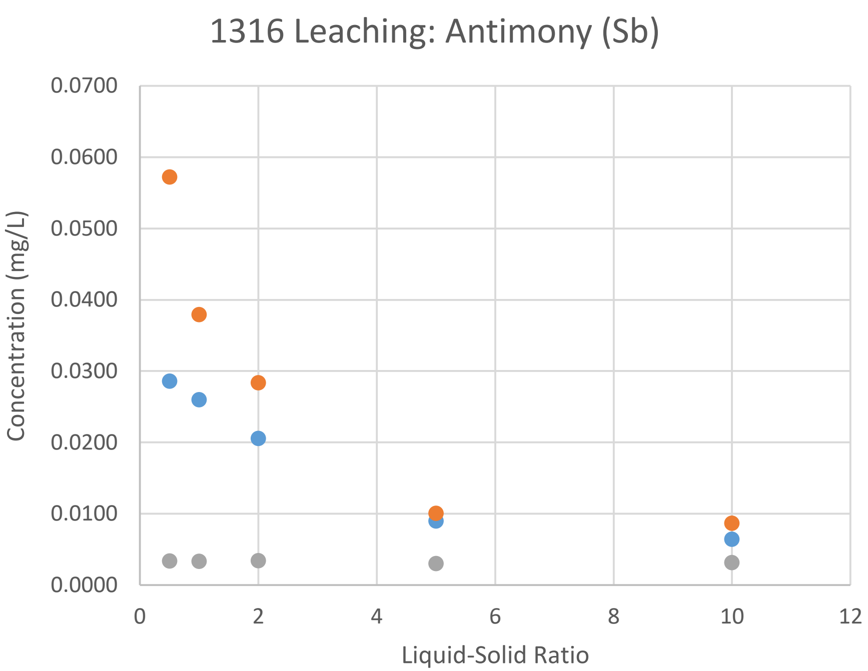
	Control Asphalt	15% WTE Ash Amended Asphalt (RDF)	15% WTE Ash Amended Asphalt (Mass Burn)	EPA Regional Screening Level (Residential Tap Water)
Element	(mg/L)	(mg/L)	(mg/L)	(mg/L)
pH	9.14	8.96	9.16	-
Al	0.518	1.11	1.04	20
As	<0.004	<0.004	<0.004	0.01
B	<0.01	0.072	<0.01	4.0
Ba	0.079	0.209	0.081	2.0
Be	<0.001	<0.001	<0.001	0.004
Ca	6.99	11.1	9.52	-
Cd	<0.002	<0.002	<0.002	0.005
Co	<0.006	<0.006	<0.006	0.006
Cr (total)	0.003	0.007	0.003	0.1
Cu	<0.004	<0.004	<0.004	1.3
Fe	0.008	0.014	0.034	14
K	<0.1	<0.1	<0.1	-
Mg	0.231	0.323	0.226	-
Mn	<0.002	<0.002	<0.002	0.43
Mo	<0.006	<0.006	<0.006	0.1
Na	<0.1	0.344	0.848	0.015
Ni	<0.001	<0.001	<0.001	0.1
Pb	<0.004	<0.004	<0.004	0.015
Sb	0.004	0.007	0.009	0.006
Se	0.004	0.004	0.002	0.05
Sn	<0.002	<0.002	<0.002	12
Sr	0.045	0.071	0.046	12
V	<0.002	<0.002	<0.002	0.086
Zn	0.003	0.004	0.003	6

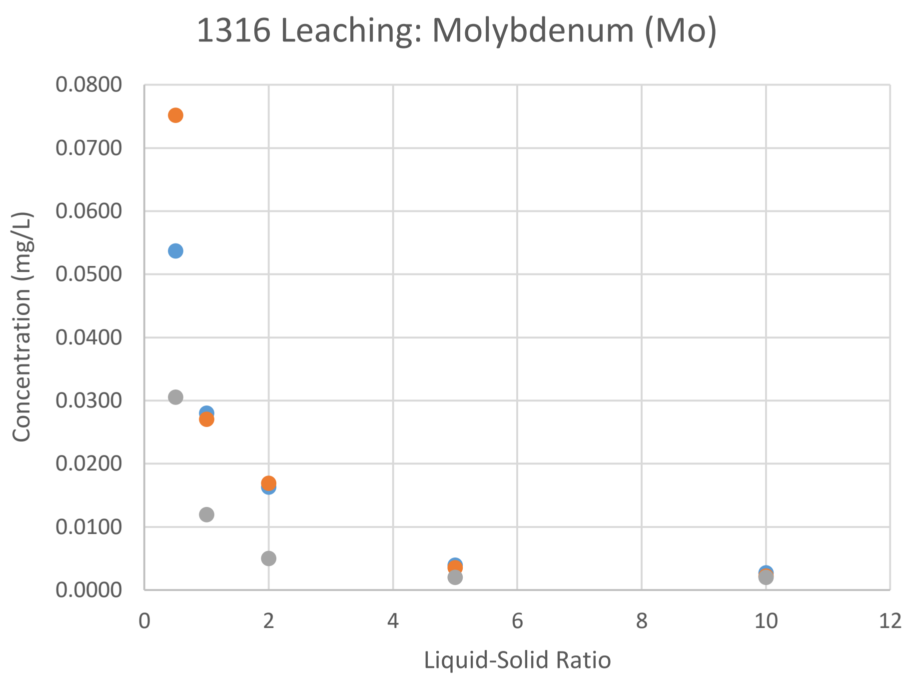
EPA LEAF Method 1316: Batch Liquid-to-Solid Ratio Test

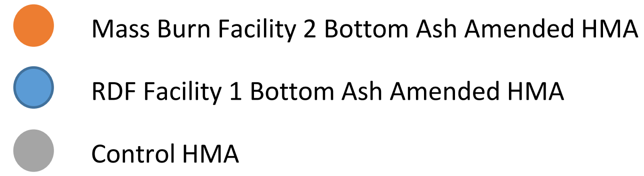
- Leaching across a range of Liquid-to-solid ratios



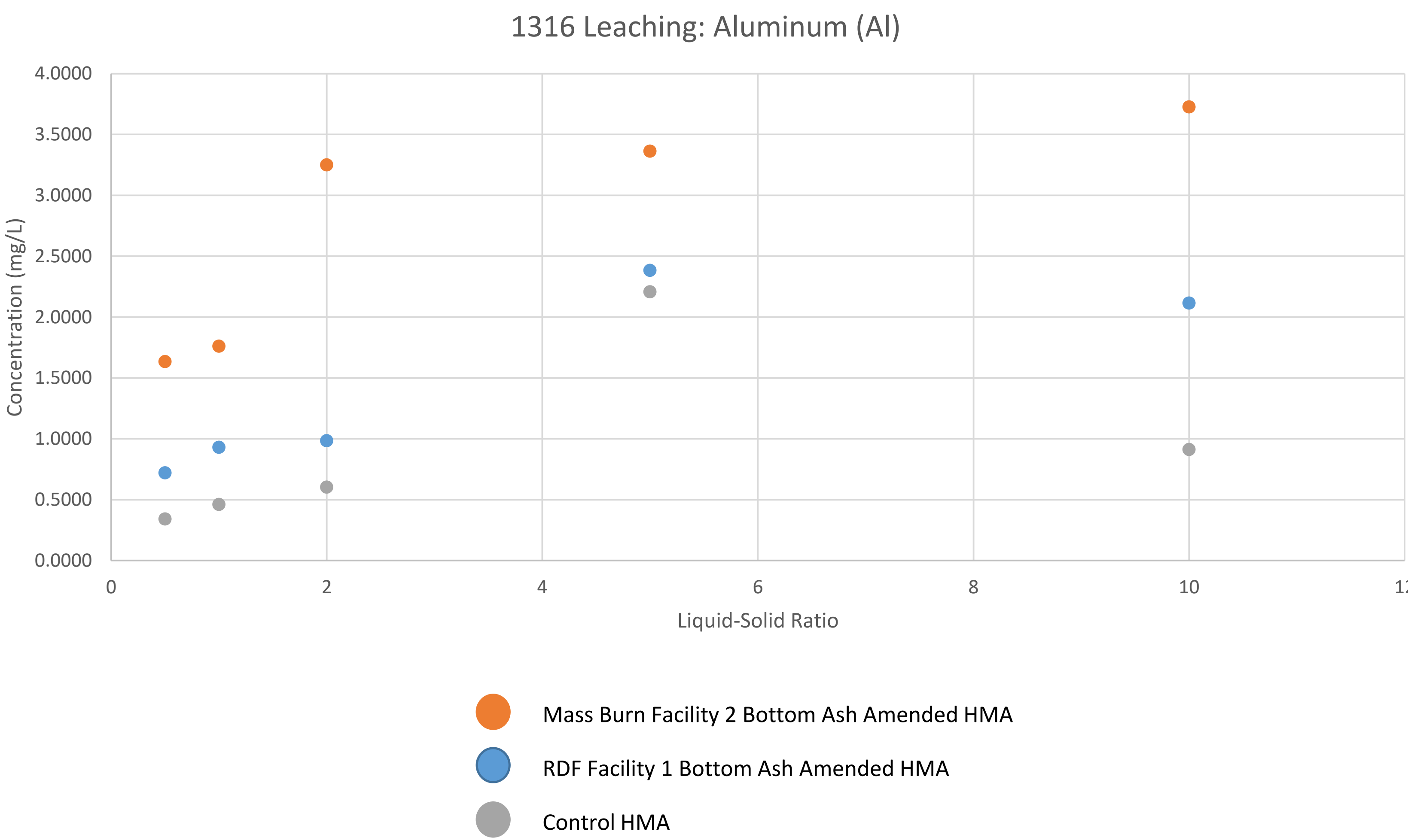
EPA 1316 Results: Bottom Ash Amended HMA





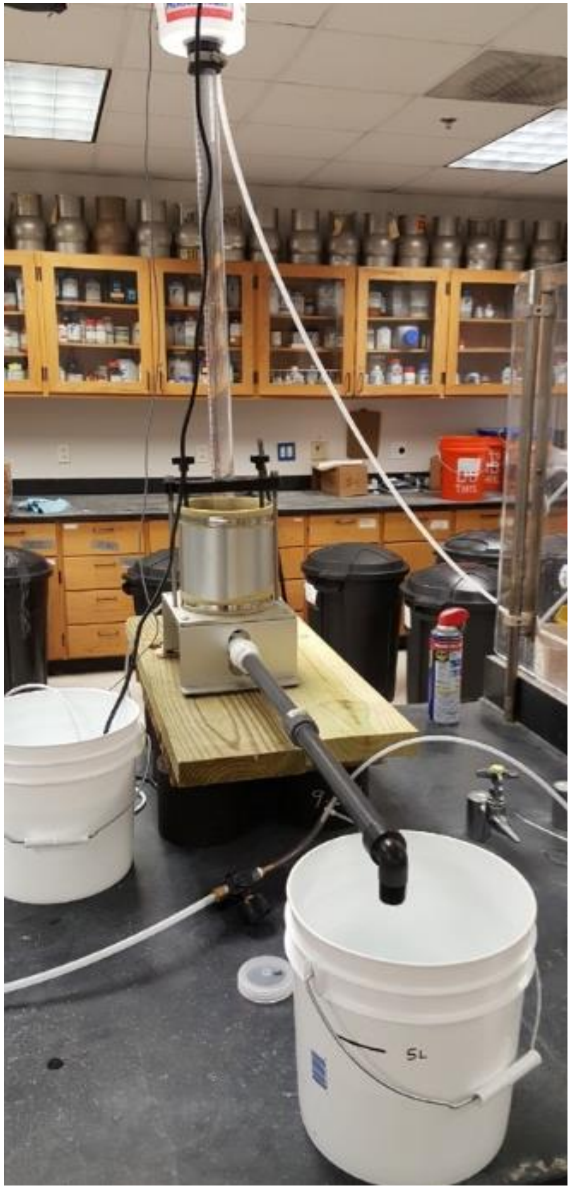


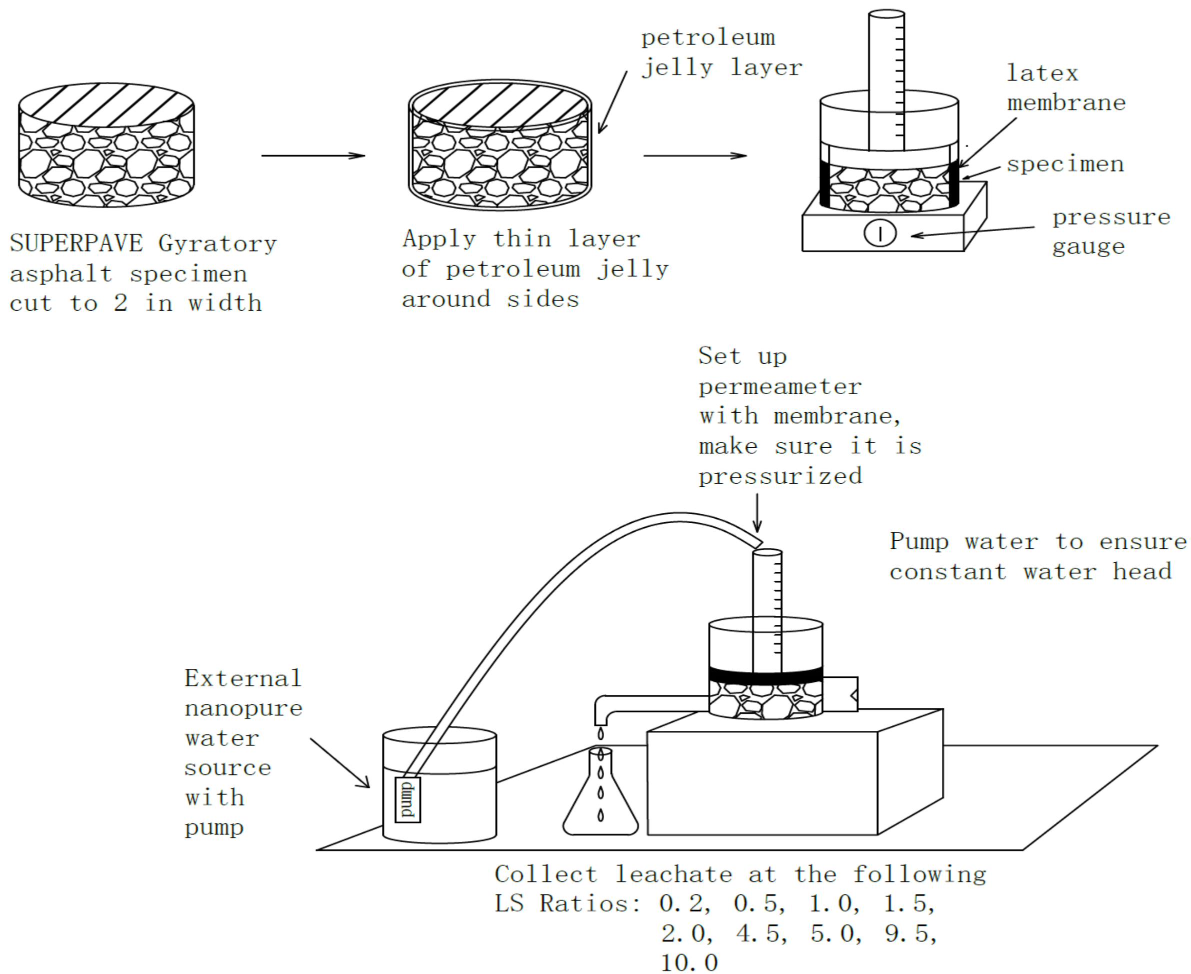
EPA 1316 Results: Bottom Ash Amended HMA



Modified Permeability Test

- Combination:
  - FM 5-565
  - EPA LEAF Method 1314
- Uses the apparatus from FM 5-565 (pictured left) but modified to create a constant head instead of a falling head
- Uses EPA Method 1314 schedule of sampling to quantify leaching over a range of Liquid-to-Solid Ratios




petroleum
jelly layer
latex
membrane
specimen
pressure
gauge
SUPERPAVE Gyratory
asphalt specimen
cut to 2 in width
Apply thin layer
of petroleum jelly
around sides
Set up
permeameter
with membrane,
make sure it is
pressurized
Pump water to ensure
constant water head
External
nanopure
water
source
with
pump
pump
Collect leachate at the following
LS Ratios: 0.2, 0.5, 1.0, 1.5,
2.0, 4.5, 5.0, 9.5,
10.0

Modified Permeability Test Results: 6% Air Voids

RDF Facility 1 Bottom Ash Amended HMA

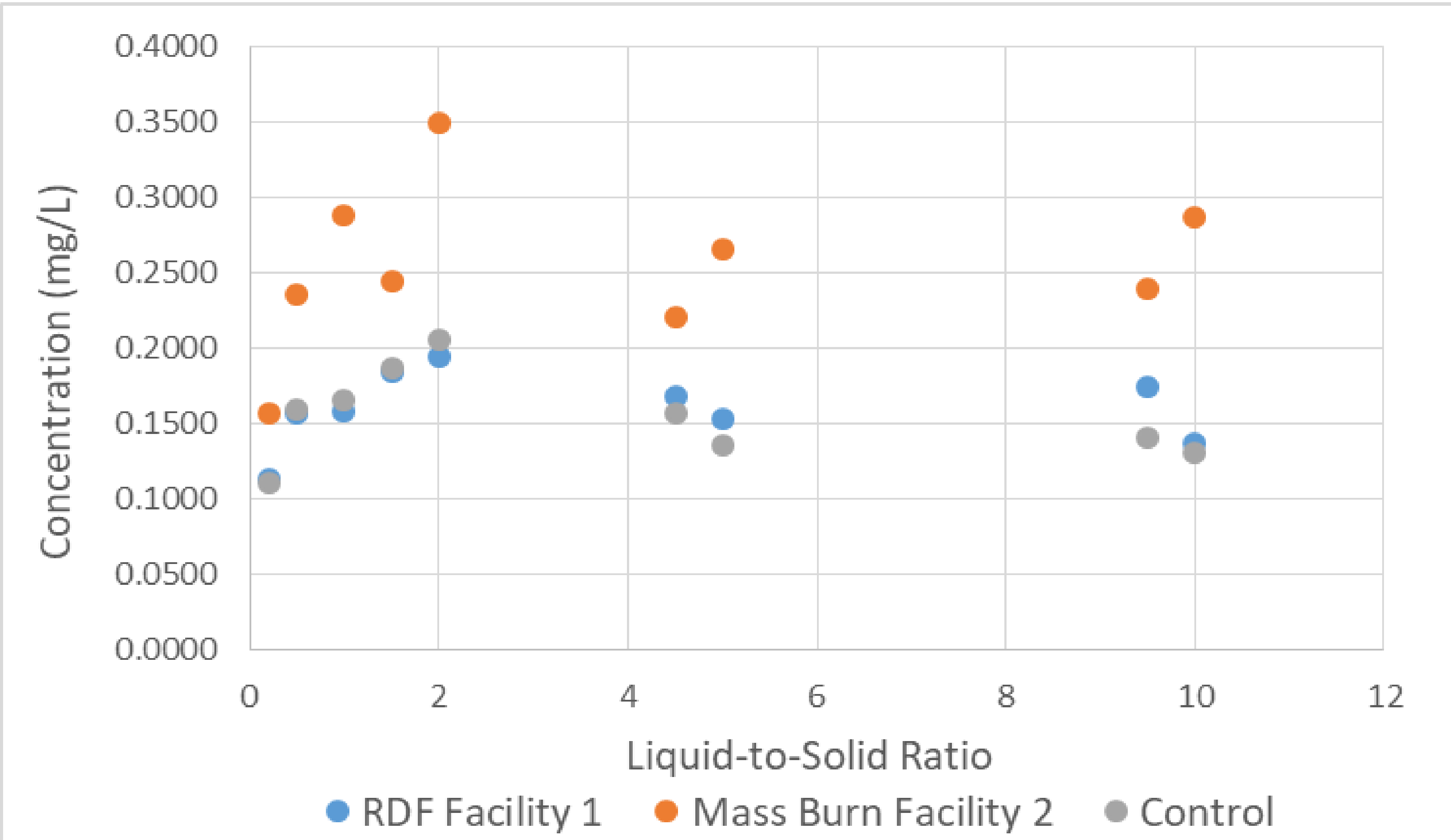
Liquid-Solid Ratio	pH	Al Conc. (mg/L)	Sb Conc. (mg/L)	Pb Conc. (mg/L)
		GCTL: 0.2	**GCTL: 0.006**	**GCTL: 0.015**
0.2	7.75	0.1136	0.0033	<0.004
0.5	8.12	0.1568	<0.003	<0.004
1	8.21	0.1580	<0.003	<0.004
1.5	8.52	0.1846	<0.003	<0.004
2	8.52	0.1941	<0.003	<0.004
4.5	8.24	0.1683	0.0032	<0.004
5	8.84	0.1535	<0.003	<0.004
9.5	8.55	0.1749	0.0036	<0.004
10	8.76	0.1369	<0.003	<0.004

Modified Permeability Test Results: 8% Air Voids

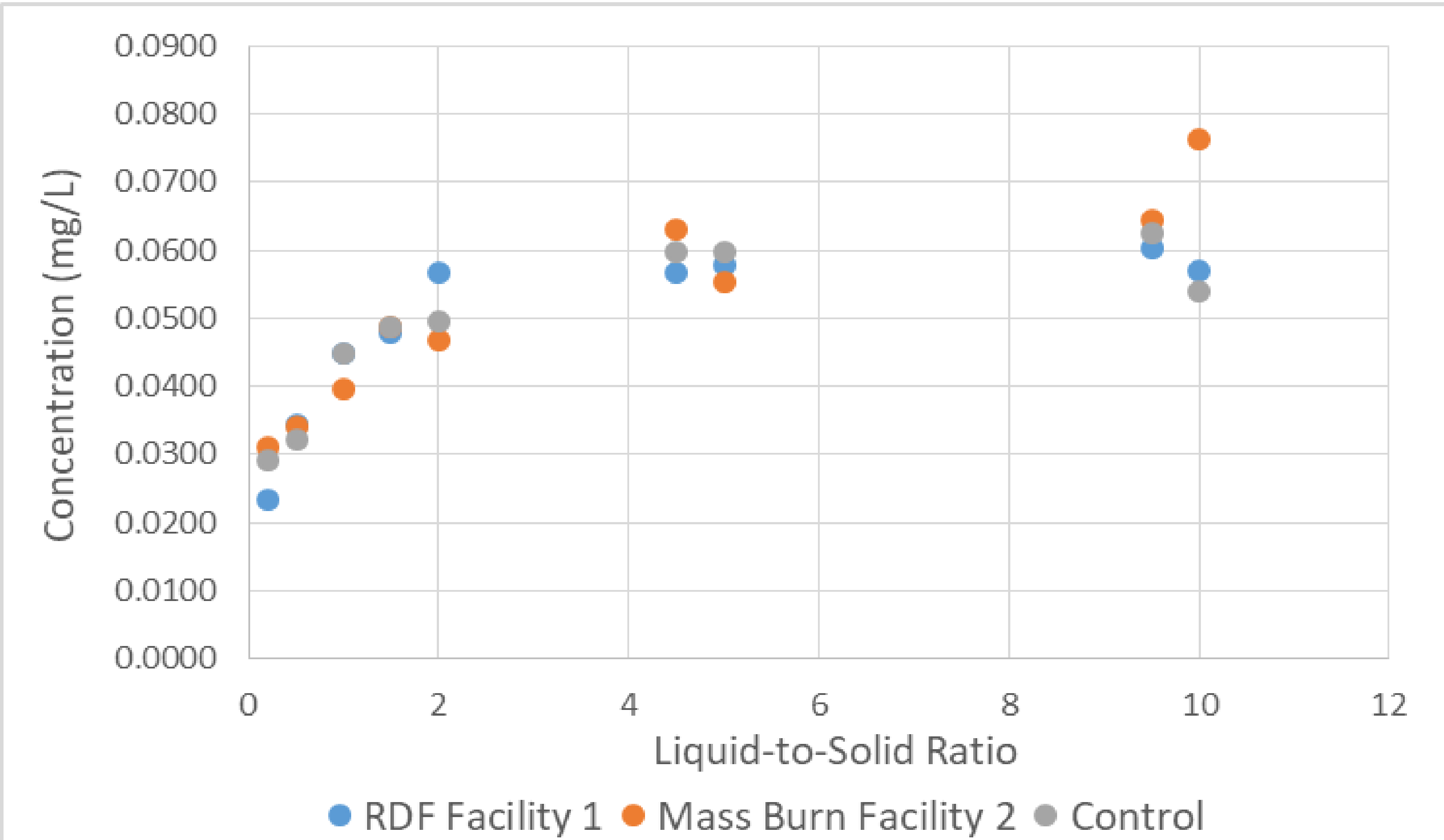
RDF Facility 1 Bottom Ash Amended HMA

Liquid-Solid Ratio	pH	Al Conc. (mg/L)	Sb Conc. (mg/L)	Pb Conc. (mg/L)
		GCTL: 0.2	**GCTL: 0.006**	**GCTL: 0.015**
0.2	7.21	0.0235	0.0035	<0.004
0.5	7.72	0.0343	<0.003	<0.004
1	8.16	0.0449	<0.003	<0.004
1.5	8.21	0.0480	0.0035	<0.004
2	8.25	0.0567	0.0033	<0.004
4.5	8.34	0.0566	0.0035	<0.004
5	8.31	0.0578	0.00335	<0.004
9.5	8.26	0.0603	0.0031	<0.004
10	8.39	0.0570	0.00315	<0.004

Modified Permeability Test Results: Aluminum in 6% Air Voids HMA Samples



Modified Permeability Test Results: Aluminum in 8% Air Voids HMA Samples

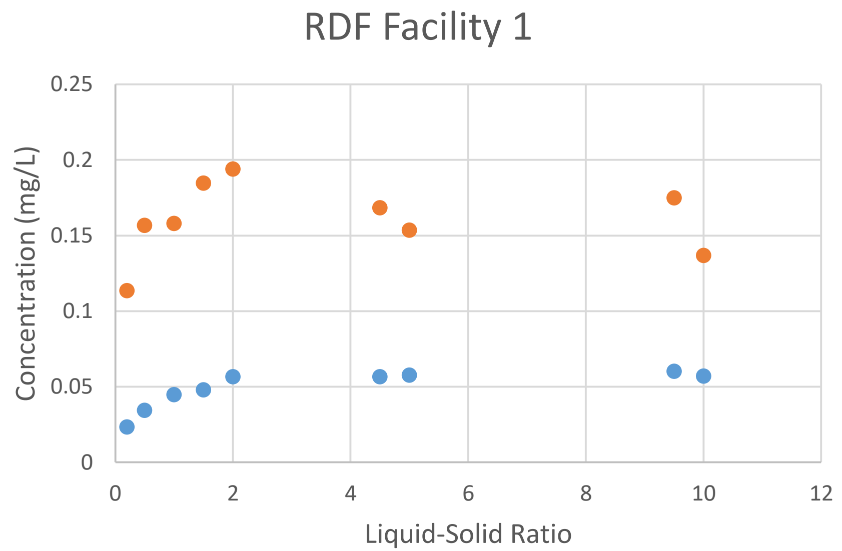


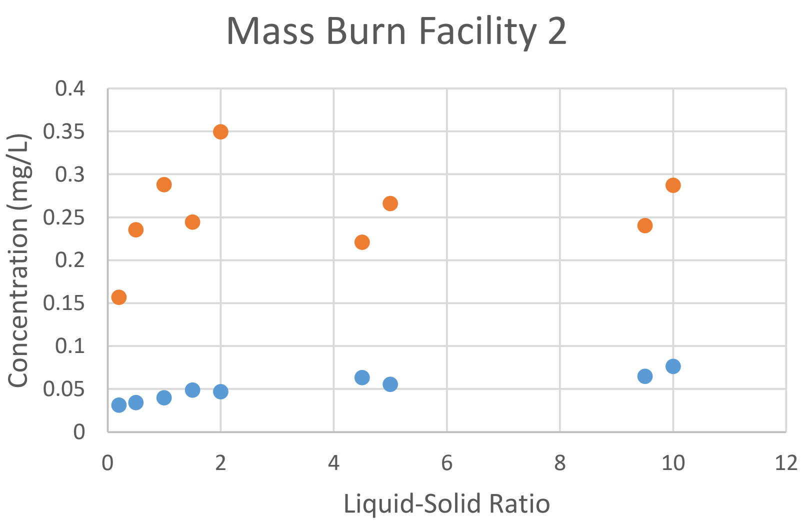
Modified Permeability Test Results: 6% vs. 8% Air Voids

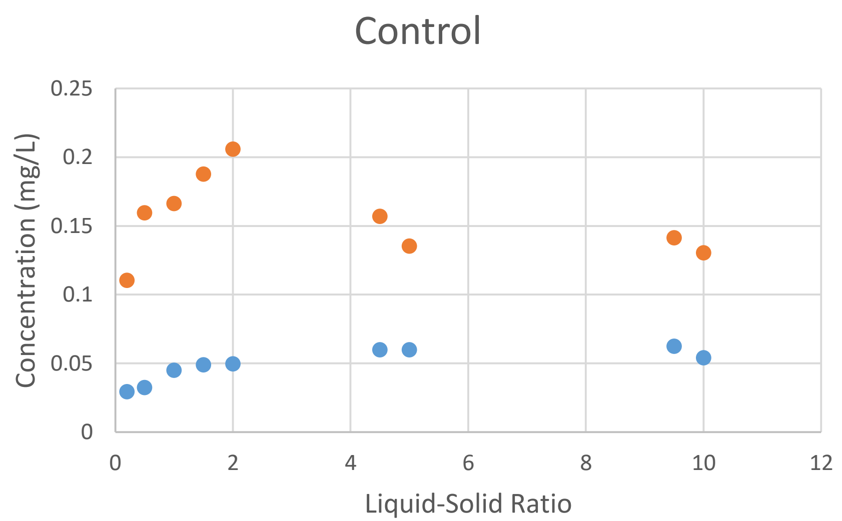
Aluminum Leaching

6% Air Voids

8% Air Voids







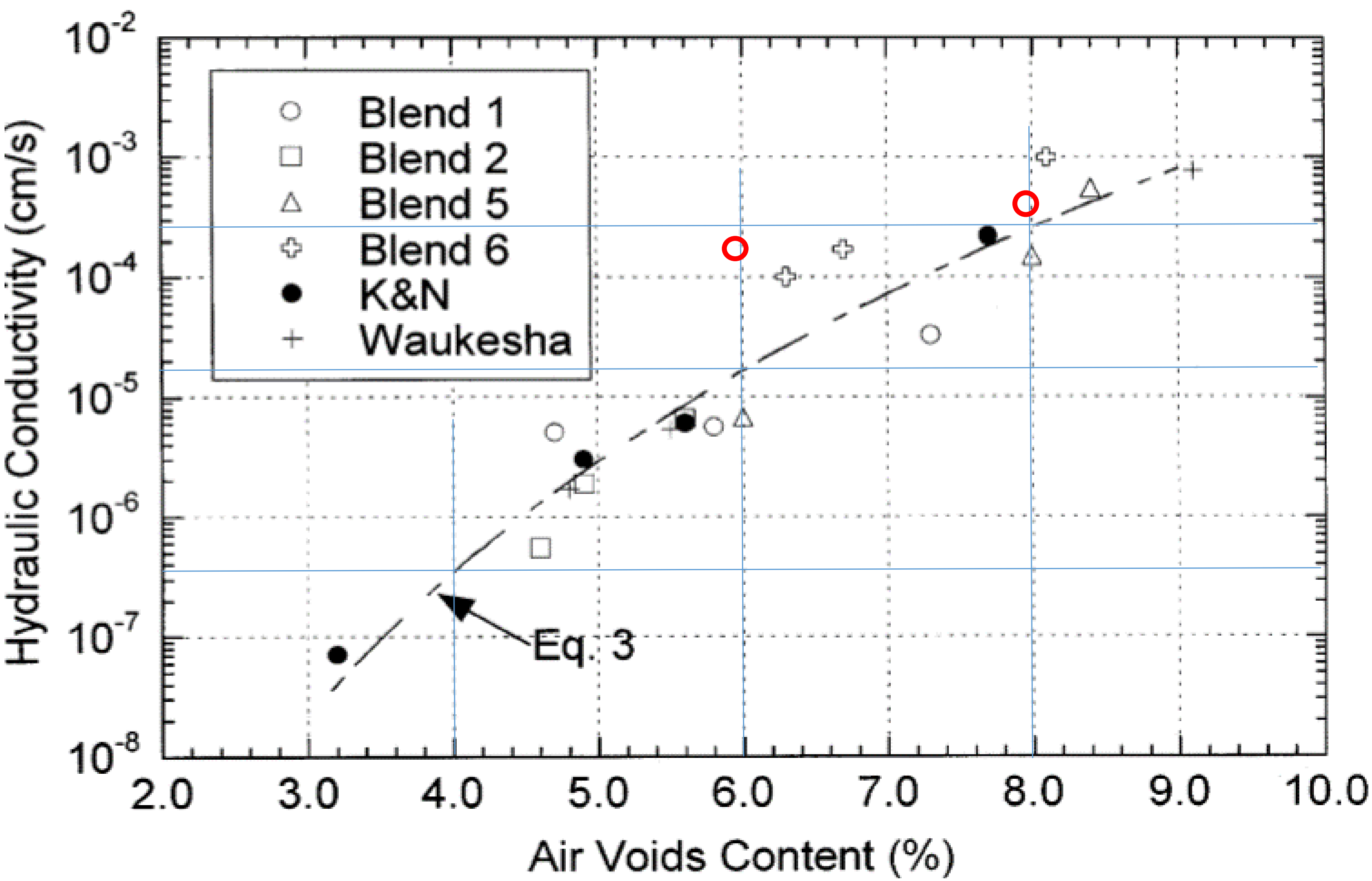
Modified Permeability Results: Hydraulic Conductivity (k) at 6% Air Voids

Liquid-Solid Ratio	Volume Water (mL)	Florida RDF Facility 1	Florida Mass Burn Facility 1	Control
		k (cm/s)	k (cm/s)	k (cm/s)
0.5	600.0	9.06E-05	8.61E-05	1.29E-04
1.0	1000.0	9.83E-05	9.06E-05	1.37E-04
1.5	1000.0	9.82E-05	9.04E-05	1.48E-04
2.0	1000.0	1.10E-04	9.05E-05	1.54E-04
4.5	5000.0	1.17E-04	1.09E-04	1.70E-04
5.0	1000.0	1.23E-04	1.16E-04	1.83E-04
9.5	9000.0	1.32E-04	1.10E-04	1.91E-04
10.0	1000.0	1.37E-04	1.08E-04	1.97E-04

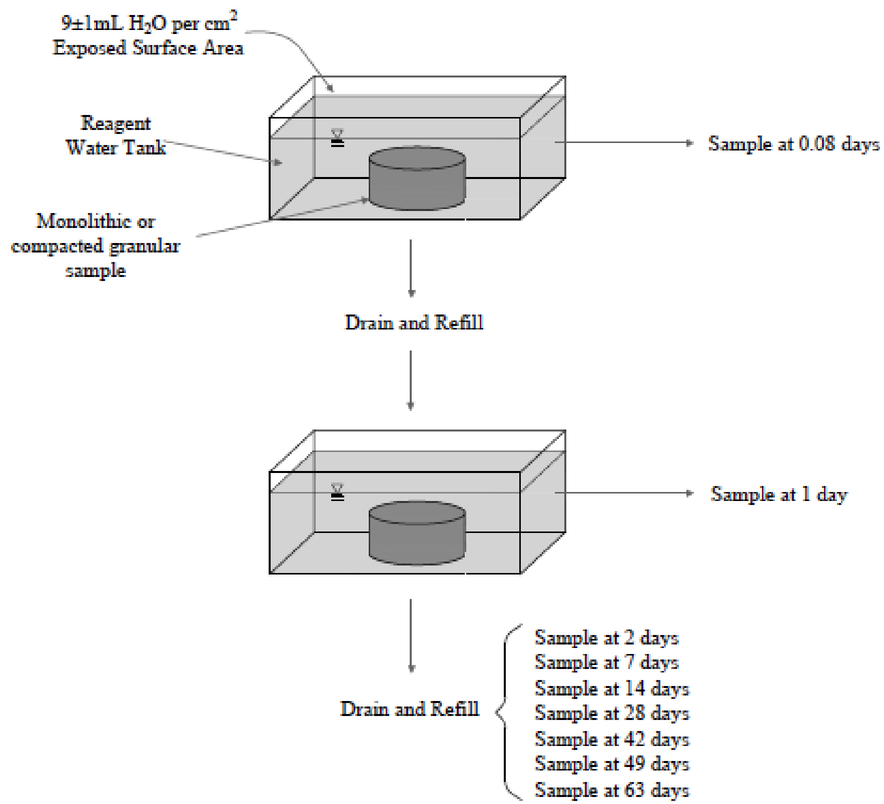
Modified Permeability Results: Hydraulic Conductivity (k) at 8% Air Voids

Liquid-Solid Ratio	Volume Water (mL)	Florida RDF Facility 1	Florida Mass Burn Facility 1	Control
		k (cm/s)	k (cm/s)	k (cm/s)
0.5	600.0	5.20E-04	3.20E-04	2.99E-04
1.0	1000.0	5.65E-04	3.24E-04	3.03E-04
1.5	1000.0	5.71E-04	3.40E-04	3.23E-04
2.0	1000.0	6.08E-04	3.53E-04	3.37E-04
4.5	5000.0	5.90E-04	3.60E-04	3.60E-04
5.0	1000.0	7.03E-04	3.85E-04	4.19E-04
9.5	9000.0	8.12E-04	4.12E-04	4.39E-04
10.0	1000.0	8.55E-04	3.90E-04	4.95E-04

Kantipong et al. Hydraulic Conductivity Data Compared to Perm Results



EPA LEAF Method 1315: Monolith Test



EPA Method 1315 Results: Bottom Ash Amended HMA

RDF Facility 1 Bottom Ash Amended HMA

Cummulative # of Days	pH	Al Conc. (mg/L)	Sb Conc. (mg/L)	Pb Conc. (mg/L)
0.08	7.005	<0.023	<0.003	<0.004
1.04	6.13	0.0375	<0.003	<0.004
2	6.415	<0.023	<0.003	<0.004
7	7.535	0.03345	<0.003	<0.004
14	6.805	0.0316	<0.003	<0.004
28	7.065	0.0571	<0.003	<0.004
42	7.82	0.036	<0.003	<0.004
49	7.8	0.03085	0.0033	<0.004
63	7.92	0.0467	<0.003	<0.004

EPA Method 1315 Results: Bottom Ash Amended HMA

Mass Burn Facility 2 Bottom Ash Amended HMA

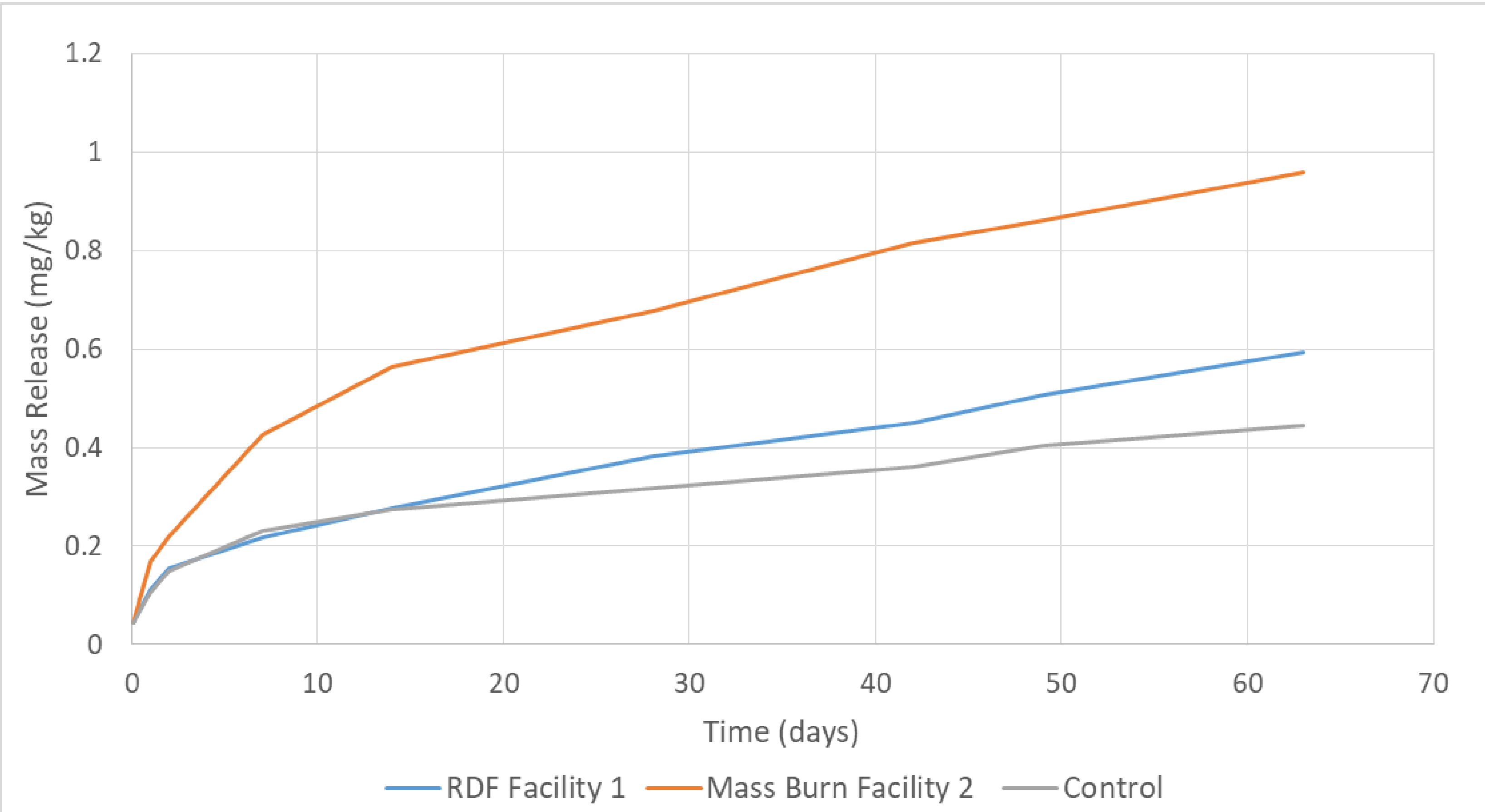
Cummulative # of Days	pH	Al Conc. (mg/L)	Sb Conc. (mg/L)	Pb Conc. (mg/L)
0.08	7.08	<0.023	<0.003	<0.004
1.04	6.04	0.0667	<0.003	<0.004
2	7.04	0.02815	<0.003	<0.004
7	8.215	0.1095	<0.003	<0.004
14	7.515	0.0741	0.0032	<0.004
28	7.165	0.06075	<0.003	<0.004
42	8.11	0.0751	0.00335	<0.004
49	8.05	0.0249	<0.003	<0.004
63	8.22	0.0522	0.00305	<0.004

EPA Method 1315 Results: Bottom Ash Amended HMA

Control HMA

Cummulative # of Days	pH	Al Conc. (mg/L)	Sb Conc. (mg/L)	Pb Conc. (mg/L)
0.08	6.56	<0.023	<0.003	<0.004
1.04	6.495	0.0331	<0.003	<0.004
2	7.41	<0.023	<0.003	<0.004
7	8.515	0.0445	<0.003	<0.004
14	7.585	<0.023	<0.003	<0.004
28	7.325	<0.023	<0.003	<0.004
42	8.195	<0.023	<0.003	<0.004
49	7.95	<0.023	<0.003	<0.004
63	8.28	<0.023	<0.003	<0.004

Mass Release of Aluminum in Monolith Testing



Summary of Environmental Evaluation of WTE Ash Amended Concrete and Asphalt

- At typical aggregate replacements percentages, most elements will be below risk thresholds for residential direct exposure.
  - The elements possibly above risk thresholds are the ones most likely reduced in future ash streams.
- Leaching results demonstrate minimal risk posed by leaching.
  - Aluminum exceeds secondary drinking water standard but is below human health based risk thresholds.
  - In concrete, newly crushed concrete may leach lead on occasion, but with aging, leaching diminishes rapidly.
  - In asphalt, small concentrations of antimony may be observed.

New research areas

New Hinkley Center Research Project

- Research Advances on the Use of Solid Wastes in Concrete and Asphalt
- Major Topics
    - Recycling of WTE ash (and benefits/necessity of treatment)
    - Recycling of post-consumer glass
    - The synergy of these two

Background and Motivation

- Research in Florida, couple with existing body on knowledge, supports that WTE ash can be recycled as aggregate.
- Ash treatment or processing should be able to provide higher quality aggregates.
- Recent research suggests that the use of recycled glass as a pozzolan may prove beneficial to WTE ash when used as aggregate in concrete.

Processing Ash to Make a Better Aggregate Product

- Advanced metals recovery is of growing interest in North America.
- The recovery of metals such as aluminum, copper and lead should make better aggregates.

Processing Ash to Make a Better Aggregate Product

- Ash treatment through washing has been demonstrated to improve ash quality for some uses.
- Washing:
    - Water
    - Sodium hydroxide
    - Other chemicals
- Could lead to better environmental characteristics (e.g., removal or fixation of problematic chemicals) and better aggregate properties (e.g., less aluminum, chloride, fines)

Ash Washing

Use of Incinerator Bottom Ash in Concrete, *Pera et al.* (1997)

- French research team poured concrete with bottom ash instead of gravel as a coarse aggregate
- They noted a high gaseous emission leading to a porous material and very low strength
- Cracks at 28 days and destroyed concrete at 90 days
- Reaction between metallic aluminum present in bottom ash and portlandite produced in the hydration of Portland cement
- Washed in sodium hydroxide bath until all hydrogen was produced
- Reaction completely avoided because of the wash. Bottom ash can replace natural gravel with no negative effects on durability

Pergamon

Cement and Concrete Research, Vol. 27, No. 1, pp. 1-5, 1997

0008-8846/97 $17.00 + .00

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USE OF INCINERATOR BOTTOM ASH IN CONCRETE

J. Pera, L. Coutaz, J. Ambroise, and M. Chababbet
Unité de Recherche Génie Civil-Matériaux
Institut National des Sciences appliquées de Lyon, France

(Communicated by M. Moranville)
(Received October 10, 1996; in final form November 15, 1996)

ABSTRACT

The aim of the present work was to show if municipal solid waste incinerator (MSWI) bottom ash could be an alternative aggregate for the production of building concrete presenting a characteristic 28-day compressive strength of 25 MPa.

The aggregates passing the 20-mm sieve and retained on the 4-mm sieve were considered for investigation. They showed lower density, higher water absorption, and lower strength than natural gravel. They could be considered as average quality aggregates for use in concrete.

When directly introduced in concrete, they led to swelling and cracking of specimens, due to the reaction between cement and metallic aluminium. Therefore, a treatment by sodium hydroxide was proposed to avoid such degradation, which made possible the partial replacement (up to 50%) of gravel in concrete without affecting the durability. *Copyright © 1997 Elsevier Science Ltd*

KEYWORDS: Bottom ash, aggregate, aluminium, concrete, strength, durability.

Sustainable High Quality Recycling of Aggregates from Waste to Energy, Treated in a Wet Bottom Ash Processing Installation, for Use in Concrete Products, *Van den Heede et al.,* (2015)

- Concrete cast with WTE ash replacement of coarse aggregate showed increased expansion in all specimens
- Reactive washing of aggregates with 1 M NaOH eliminated expansion issues completely and resulted in significant decrease in Al reactivity
- Strength after washing not an issue
- Researchers noted that this could get expensive

materials

MDPI

Article

Sustainable High Quality Recycling of Aggregates from Waste-to-Energy, Treated in a Wet Bottom Ash Processing Installation, for Use in Concrete Products

Philip Van den Heede [1], Niels Ringoot [1], Arno Beirnaert [1], Andres Van Brecht [2], Erwin Van den Brande [2], Geert De Schutter [1] and Nele De Belie [1,*]

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1 Magnel Laboratory for Concrete Research, Ghent University, Technologiepark Zwijnaarde 904, Ghent B-9052, Belgium; philip.vandenheede@ugent.be (P.V.H.); nielsringoot10@hotmail.com (N.R.); arno_beirnaert@hotmail.com (A.B.); geert.deschutter@ugent.be (G.D.S.)
2 Indaver nv, Dijle 17a, Mechelen B-2800, Belgium; andres.van.brecht@indaver.be (A.V.B.); erwin.van.den.brande@indaver.be (E.V.B.)
* Correspondence: nele.debelie@ugent.be; Tel.: +32-9-264-5522; Fax: +32-9-264-5845

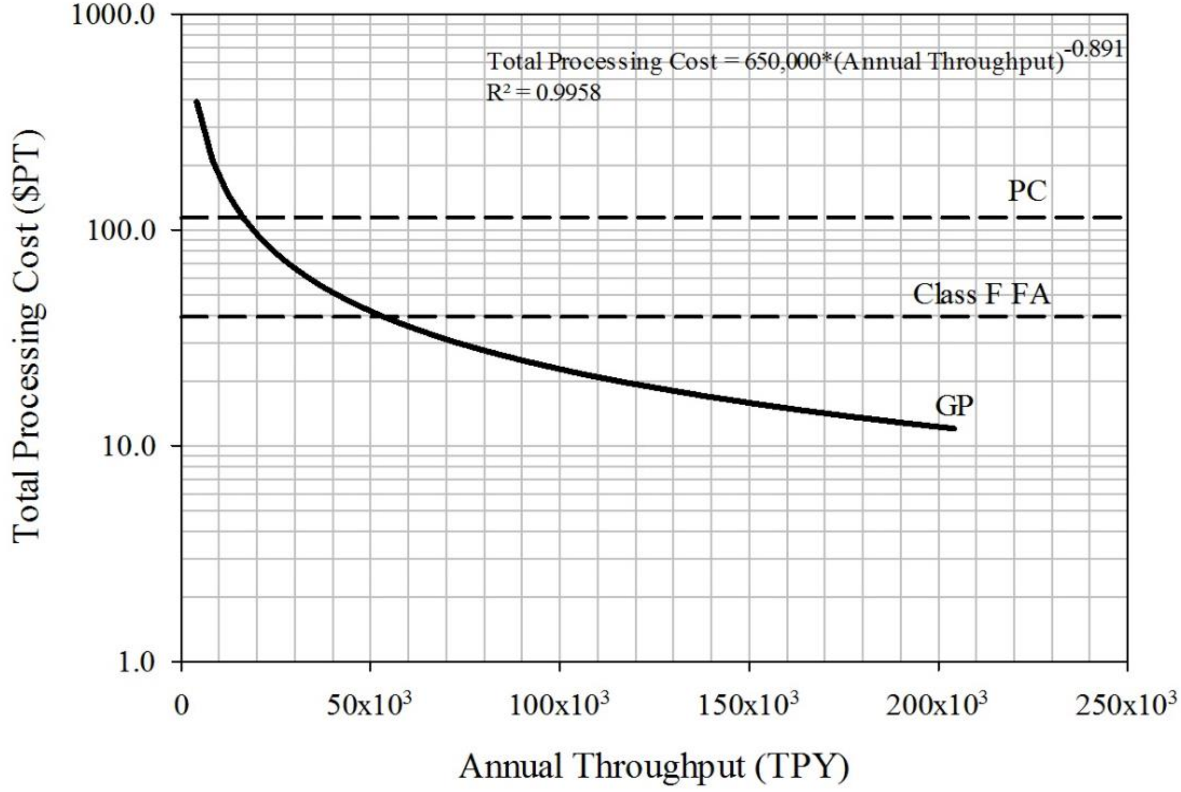
Abstract: Nowadays, more efforts towards sustainability are required from the concrete industry. Replacing traditional aggregates by recycled bottom ash (BA) from municipal solid waste incineration can contribute to this goal. Until now, only partial replacement has been considered to keep the concrete workability, strength and durability under control. In this research, the feasibility of a full aggregate replacement was investigated for producing prefabricated Lego bricks. It was found that the required compressive strength class for this purpose (C20/25) could be achieved. Nevertheless, a thorough understanding of the BA properties is needed to overcome other issues. As BA is highly absorptive, the concrete's water demand is high. This workability issue can be dealt with by subjecting the fine BA fraction to a crushing operation to eliminate the porous elements and by pre-wetting the fine and coarse BA fractions in a controlled manner. In addition, a reactive NaOH washing is needed to avoid formation of longitudinal voids and the resulting expansion due to the metallic aluminum present in the BA. Regarding the long-term behavior, heavy metal leaching and freeze-thaw exposure are not problematic, though there is susceptibility to acetic and lactic acid attack and maybe increased sensitivity to alkali-silica reaction.

Keywords: municipal solid waste incineration; bottom ash; concrete; aggregate replacement; prefabricated Lego brick

Research Efforts

- Expand on previous research regarding the use of GP as replacement for Portland cement by examining the combined use of GP and WTE ash in concrete mixes. A specific focus will be on the necessary mitigation for ASR through the use of GP (so both of these components can be beneficially utilized).
- Conduct research on the benefits of WTE ash washing as a pretreatment step to create products to be used as concrete aggregate and asphalt pavement aggregate.
- Examine the infrastructure needs and associated costs for the implementation of glass recycling to SCM and WTE ash recycling for aggregate, as well as the combined beneficial use of these materials.

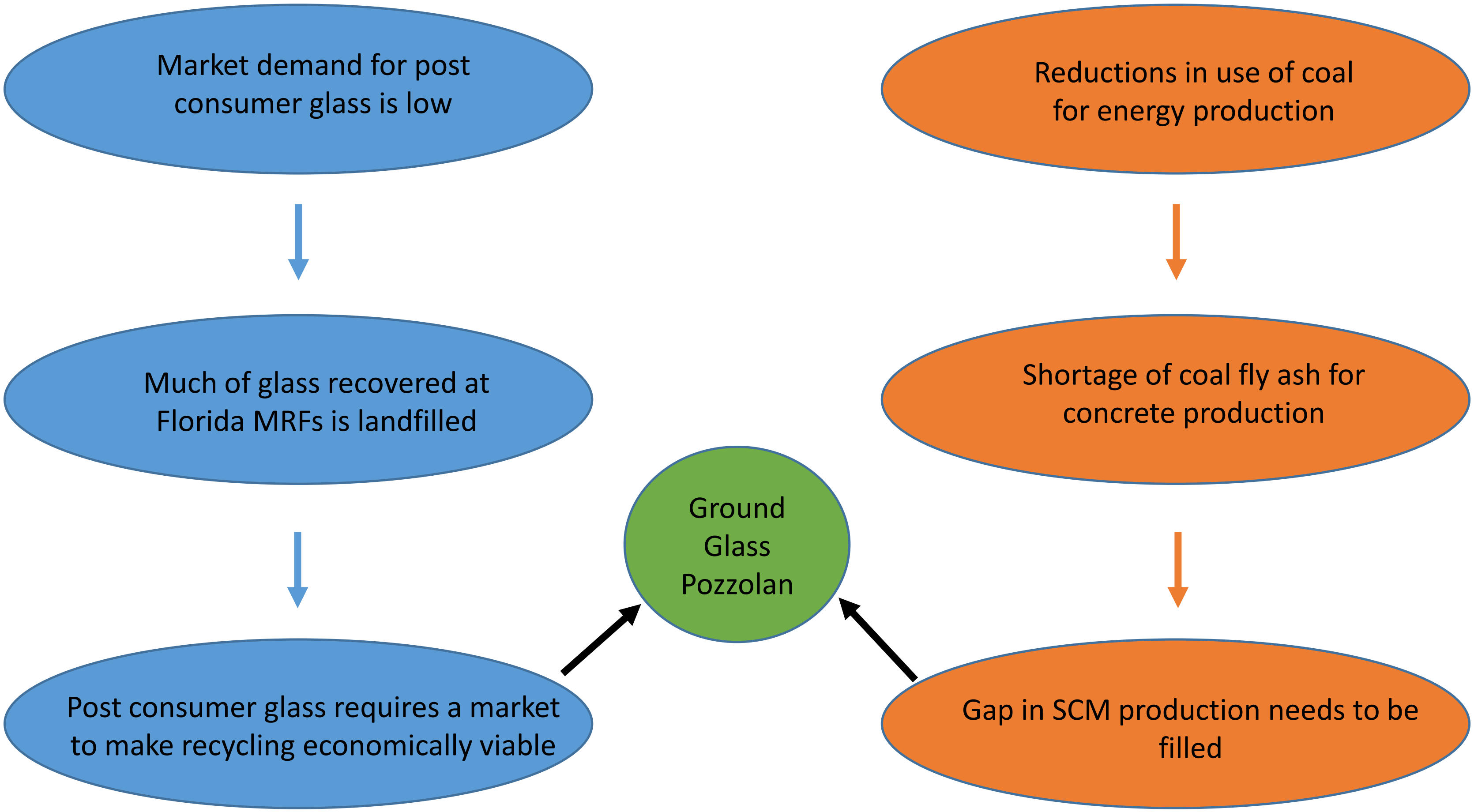
Is Glass Recycling as a Pozzolan Viable?



Using Glass to Mitigate ASR when WTE Ash Used as PCC Aggregate

Ground Glass Pozzolan

- Crushed and finely ground glass is a well known supplementary cementitious material
- Finely ground and processed to produce highly reactive product that behaviors similar to silica fume or metakaolin
- Passes No. 325 Mesh (0.044 mm)


Market demand for post consumer glass is low
Much of glass recovered at Florida MRFs is landfilled
Post consumer glass requires a market to make recycling economically viable
Ground Glass Pozzolan
Reductions in use of coal for energy production
Shortage of coal fly ash for concrete production
Gap in SCM production needs to be filled

Benefits

New market for post consumer glass

Reduced necessity for mining virgin materials

Addresses coal fly ash shortage

Landfill space

Reduced GHG emissions compared to PC production

ASTM 1293

- Determination of the susceptibility of an aggregate or combination of an aggregate with pozzolan or slag for participation in expansive alkali silica reaction by measurement of length change prisms
- Longer term test to "back up" the indication given by shorter ASTM 1260
- Concrete instead of mortar
- Concrete bars mixed with high alkali cement and NaOH included in mix water, suspended in sealed containers at 38 C and measured for length change

Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction[1]

This standard is issued under the fixed designation C1293; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This test method covers the determination of the susceptibility of an aggregate or combination of an aggregate with pozzolan or slag for participation in expansive alkali-silica reaction by measurement of length change of concrete prisms.

1.2 The values stated in SI units are to be regarded as the standard. No other units of measurement are included in this standard. When combined standards are cited, the selection of measurement system is at the user's discretion subject to the requirements of the referenced standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* (**Warning**—Fresh hydraulic cementitious mixtures are caustic and may cause chemical burns to skin and tissue upon prolonged exposure.[2])

2. Referenced Documents

2.1 *ASTM Standards:*[3]

C29/C29M Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate
C33 Specification for Concrete Aggregates
C125 Terminology Relating to Concrete and Concrete Aggregates
C138/C138M Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
C143/C143M Test Method for Slump of Hydraulic-Cement Concrete
C150 Specification for Portland Cement
C157/C157M Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
C192/C192M Practice for Making and Curing Concrete Test Specimens in the Laboratory
C227 Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
C289 Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)
C294 Descriptive Nomenclature for Constituents of Concrete Aggregates
C295 Guide for Petrographic Examination of Aggregates for Concrete
C490 Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete
C494/C494M Specification for Chemical Admixtures for Concrete
C511 Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
C618 Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
C702 Practice for Reducing Samples of Aggregate to Testing Size
C856 Practice for Petrographic Examination of Hardened Concrete
C989 Specification for Slag Cement for Use in Concrete and Mortars
C1240 Specification for Silica Fume Used in Cementitious Mixtures
C1260 Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
D75 Practice for Sampling Aggregates

2.2 *CSA Standards:*[4]

CSA A23.2-14A Potential Expansivity of Aggregates (Procedure for Length Change due to Alkali-Aggregate Reaction in Concrete Prisms at 38 °C)
CSA A23.2-27A Standard Practice to Identify Degree of Alkali-Reactivity of Aggregates and to Identify Measures

[1] This test method is under the jurisdiction of Committee C09 on Concrete and Concrete Aggregatesand is the direct responsibility of Subcommittee C09.26 on Chemical Reactions.

Current edition approved Aug. 1, 2015. Published October 2015. Originally approved in 1995. Last previous edition approved in 2008 as C1293 – 08b. DOI: 10.1520/C1293-08BR15.

[2] Section on Safety Precautions, *Manual of Aggregate and Concrete Testing*, *Annual Book of ASTM Standards*, Vol. 04.02.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] Available from Canadian Standards Association (CSA), 5060 Spectrum Way, Mississauga, ON L4W 5N6, Canada, http://www.csa.ca.

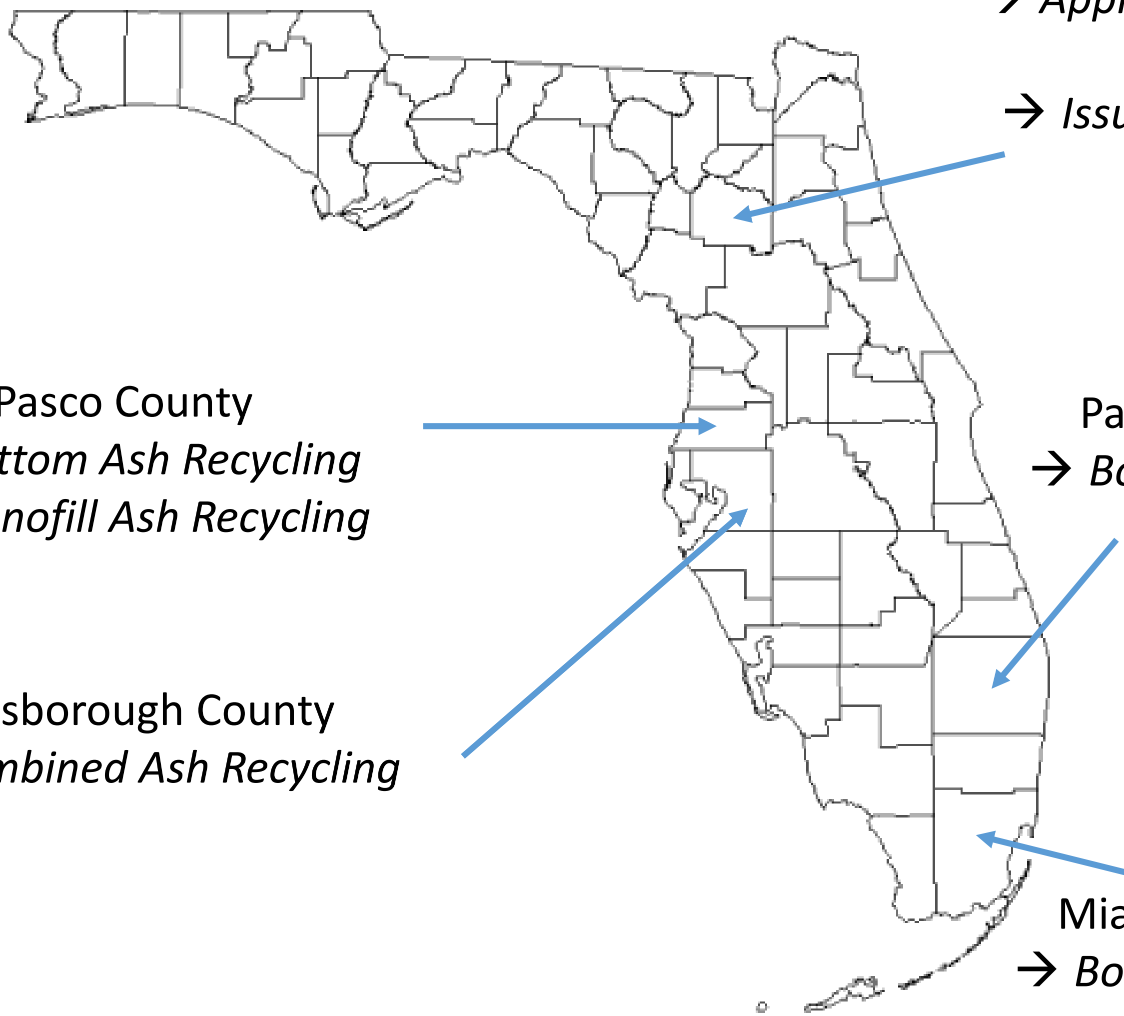
ASTM 1293

Coarse Aggregate	Treatment	Cementitious
100% Limerock (Control)	None	100% HA Portland Cement
30% WTE Bottom Ash (3 Facilities) 70% Limerock	None	100% HA Portland Cement
30% WTE Bottom Ash (3 Facilities) 70% Limerock	None	20% Ground Glass Pozzolan 80% HA Portland Cement
30% WTE Bottom Ash (3 Facilities) 70% Limerock	None	20% Class F Fly Ash 80% HA Portland Cement
30% WTE Bottom Ash (3 Facilities) 70% Limerock	Tap Water Washed BA	100% HA Portland Cement
30% WTE Bottom Ash (3 Facilities) 70% Limerock	Extensive metals recovery BA	100% HA Portland Cement
30% WTE Bottom Ash (3 Facilities) 70% Limerock	Washed & Metals Recovered	100% HA Portland Cement

Additional Research Needs

Hinkley Center
→ *Application of LEAF for Beneficial Use*
→ *Issues Regarding Ash in Concrete*

Pasco County
→ *Bottom Ash Recycling*
→ *Monofill Ash Recycling*



Palm Beach County
→ *Bottom Ash Recycling as Aggregate*

Hillsborough County
→ *Combined Ash Recycling*

Miami-Dade County
→ *Bottom Ash Recycling as Cement Kiln Feed*

Discussion and Next Steps

Technical Awareness Group Meeting

Research Related to Recycling of WTE Bottom Ash as Aggregate in Concrete and Asphalt Pavement

June 6, 2017
Tallahassee, Florida

Research Support by the
Hinkley Center for Solid and Hazardous Waste Management
https://www.hinkleycenter.org/