UF Herbert Wertheim College of Engineering
UNIVERSITY of FLORIDA

# Research Advances on the Use of Solid Wastes in Concrete and Asphalt

The Hinkley Center for Solid and Hazardous Waste Management

Technical Advisory Group Meeting

May 13, 2019

POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Herbert Wertheim College of Engineering

POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Engineering School of Sustainable Infrastructure and Environment

# Introductions

# Hinkley Center Projects

- Previous: Use of Solid Wastes in Asphalt and Concrete in Florida (Ended December 2017)
  - Findings spurred the current project:
    - *Research Advances on the Use of Solid Wastes in Concrete and Asphalt (Ends May 2019)*

- Team: Townsend (PI), Ferraro (Co-PI), Laux (Co-PI), Clavier (GRA), Liu (GRA), Spreadbury (GRA), Tora-Bueno (GRA)

# *Ash Recycling Research Timeline*

Hinkley Center: Exploring Pathways and Limitations to Recycling Combustion Residuals in Florida

Issues to Address:
→Environmental Risk
→Performance

Major Reuse Markets:
→Road Base or Similar
→Aggregate in Concrete
→Aggregate in Asphalt Pavement
→Cement Kiln Feed

| 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|

# *Ash Recycling Research Timeline*



Pasco County Ash Recycling Research

| 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|

# *Ash Recycling Research Timeline*


SWA of Palm Beach County Ash Recycling Research

| 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|

# *Ash Recycling Research Timeline*

Hinkley Center: Use of Solid Waste in Asphalt and Concrete

| 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|

# *Ash Recycling Research Timeline*

Miami-Dade County
Ash Recycling Research

| 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|

# *Ash Recycling Research Timeline*

Hillsborough County
Ash Recycling Research

| 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
| --- | --- | --- | --- | --- | --- | --- | --- |

# *Ash Recycling Research Timeline*

Hinkley Center:
Research Advances on the
Use of Solid Waste in
Asphalt and Concrete

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |

# 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
  - Economics and infrastructure requirements for waste glass and WTE ash processing

# Background and Motivation

- Research in Florida, coupled 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 and create a recycling market for waste glass.

# Meeting Agenda

- Background on reuse recycling and updates in FL
- Review of glass as a pozzolan and co-use with WTE ash in portland cement concrete
- Effects of washing treatment on WTE ash
- Designing for WTE ash in asphalt concrete
- Economic considerations for of waste glass and WTE ash reuse
- Future work

# *Background*

# Waste to Energy Facilities Worldwide

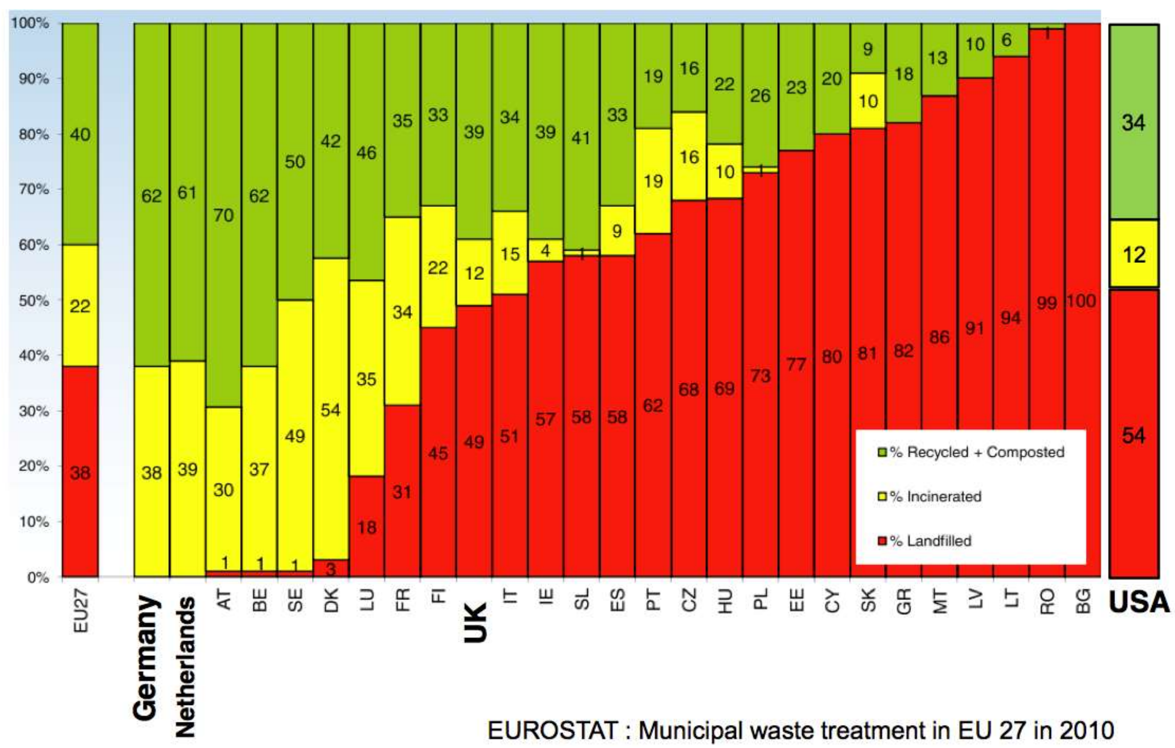
**Europe**

- 450 WTE Plants

**United States**

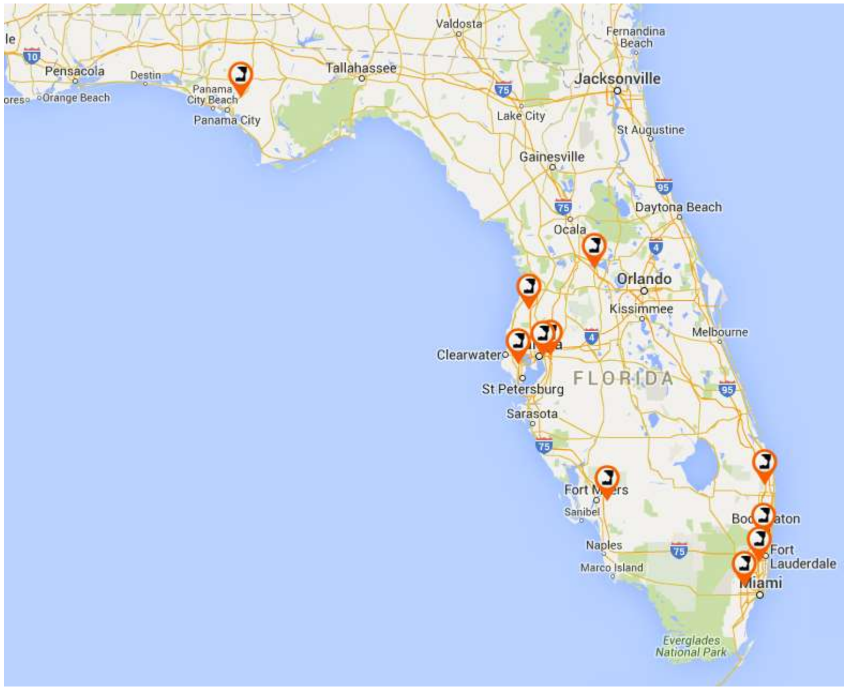
- 84 WTE Plants

# Global MSW Management

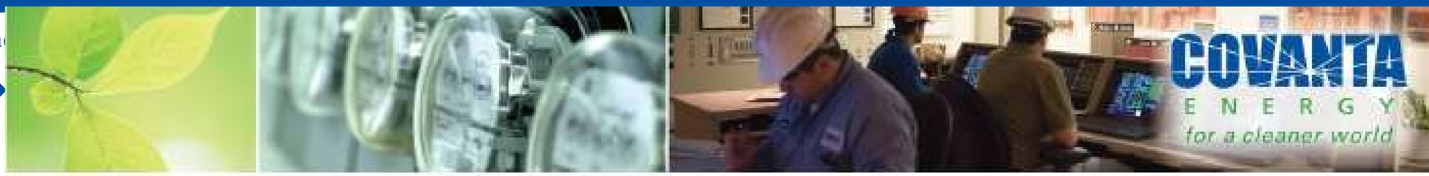



EUROSTAT : Municipal waste treatment in EU 27 in 2010

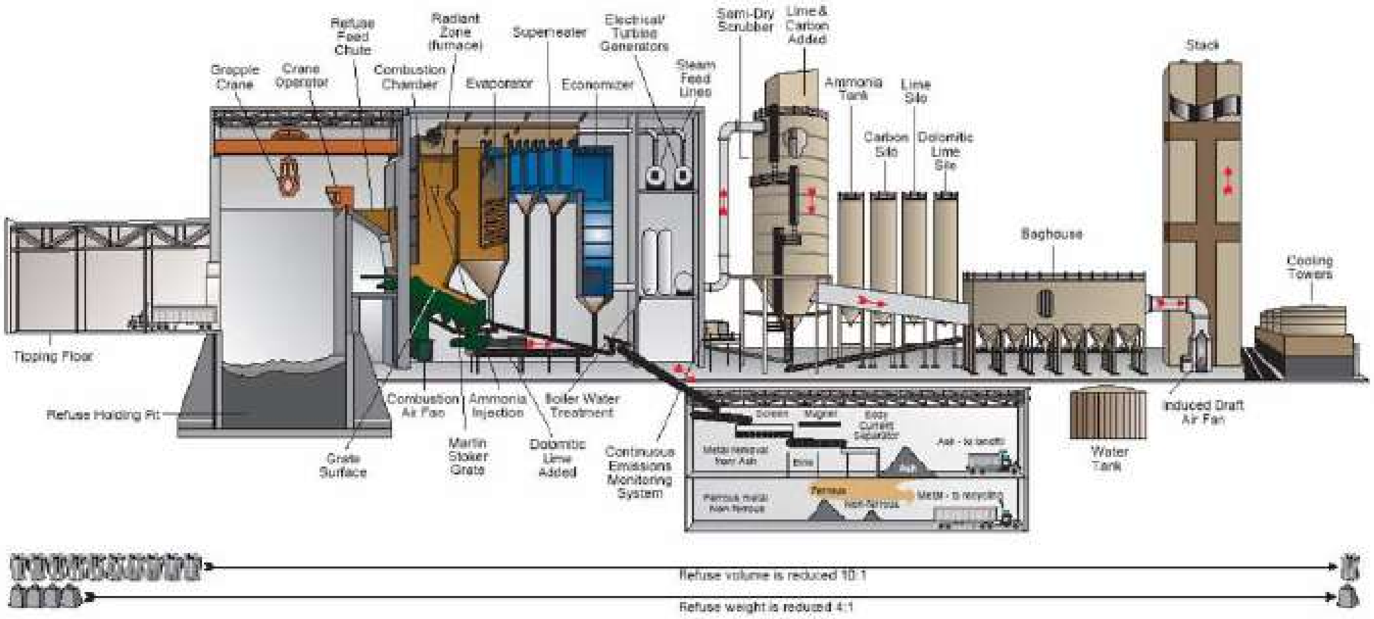
# Facility Locations

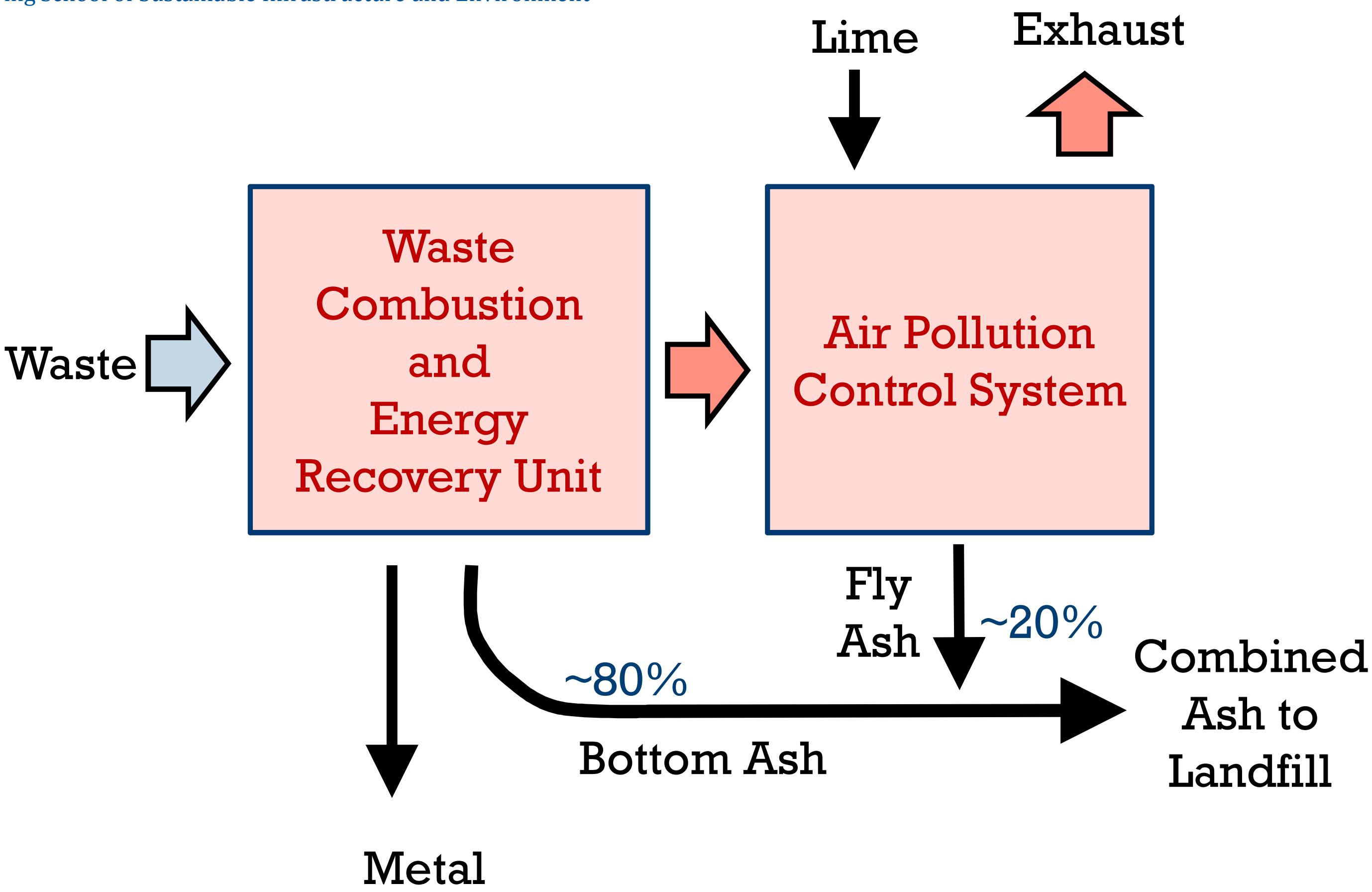



- Bay County-ENGEN
- Lake County – Covanta
- Pasco County – Covanta
- McKay Bay – Wheelabrator
- Hillsborough County – Covanta
- Pinellas County – Covanta
- Lee County – Covanta
- Palm Beach County #1/2 – Covanta
- Miami Dade County – Covanta
- South Broward - Wheelabrator

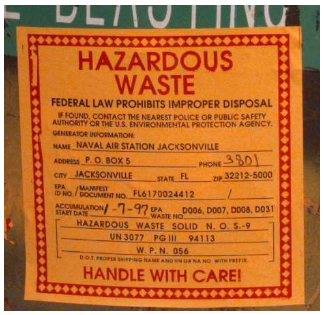


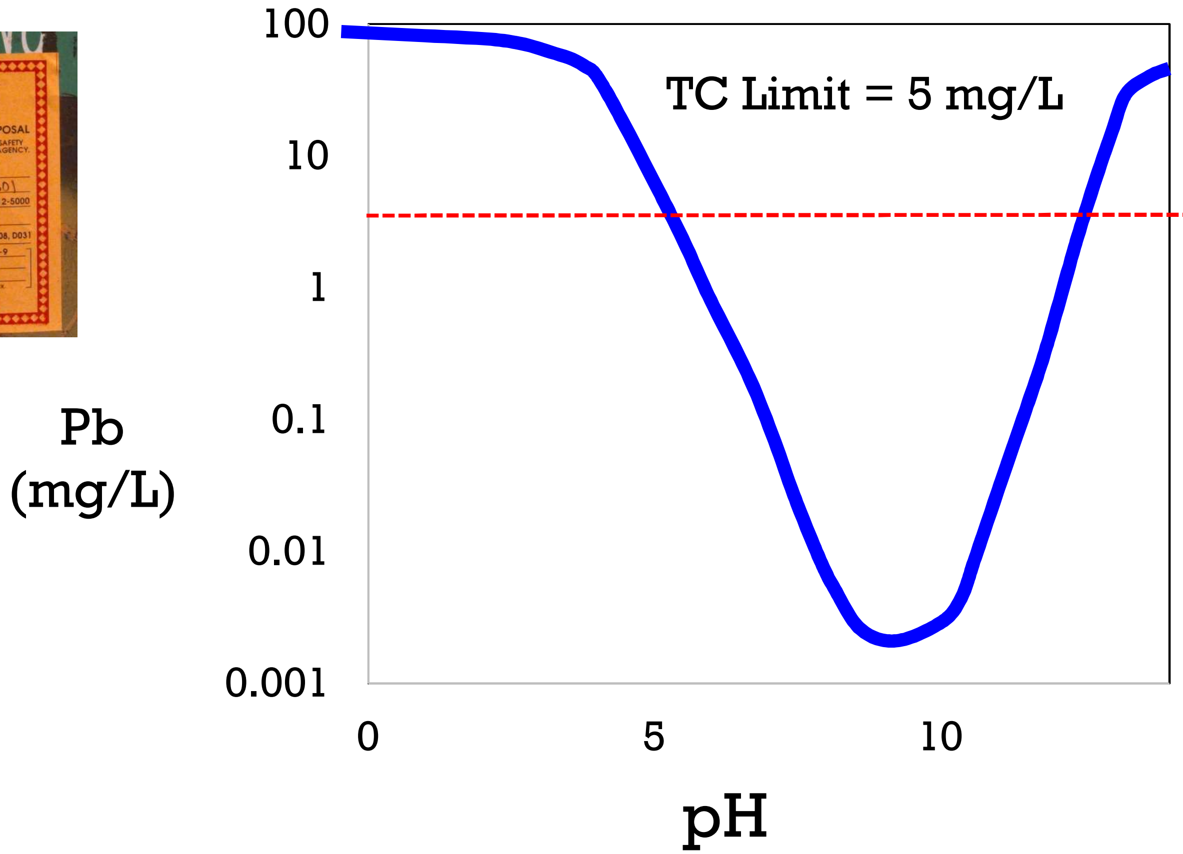

# Modern Waste to Energy




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!



# Aggregate from recycled 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

# Benefits

1) Waste volume to landfill reduced
2) Reduced rate of extraction of natural materials
3) Reduce overall impact to environment from construction industry (less greenhouse gases)
4) Saving $$$

# Considerations and Challenges

- Deleterious materials in WTE ash
  - Unburned organics (paper, plastic, yard trash)
  - Ferrous and nonferrous metals
  - Alkalis and chlorides
  - Glass
  - Golf balls?
- Need to assure reuse does not pose a risk to human health and the environment
  - Can be elevated concentrations of heavy metals such as lead, antimony, and molybdenum present
  - Need to manage risks

# Approaches to Managing Risk

- Approach 1
  - Control risk through engineering or institutional control

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

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

Ash treatment or blending

*This can also have benefits from a physical standpoint…*

# Ash Treatments

- Carbonation
- Thermal treatment:
  - Vitrification
  - Melting
  - Sintering
- Separation process:
  - Screening
  - Magnetic separation
  - Washing → *The focus for this work*

Carbonation


Thermal

Screening

Metal recovery

Herbert Wertheim College of Engineering

POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Engineering School of Sustainable Infrastructure and Environment

# Ash reuse in other countries

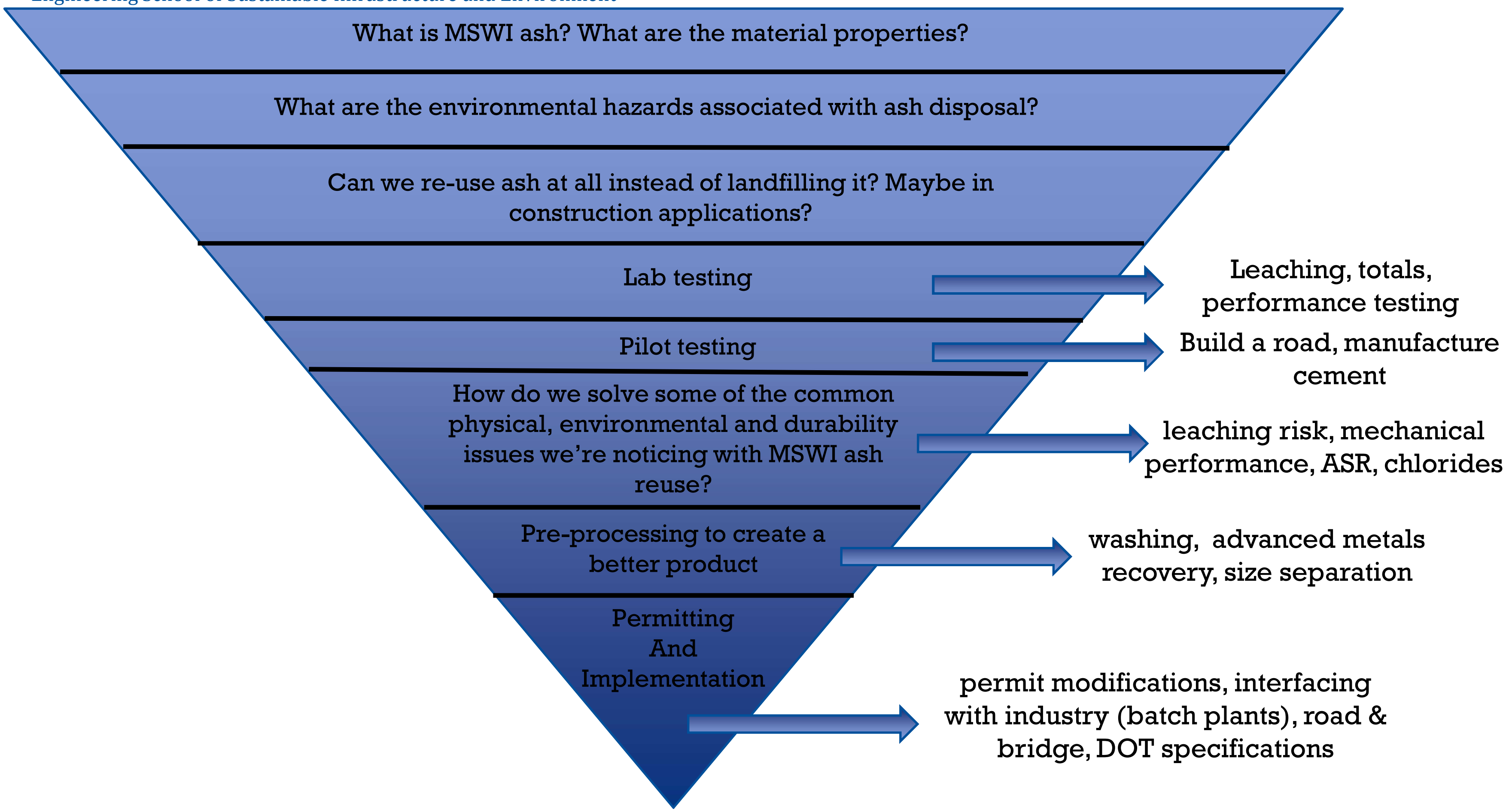


CAT
311F
L RR

# *Updates in Ash Research by UF*

# Status of Ash Reuse in the US?

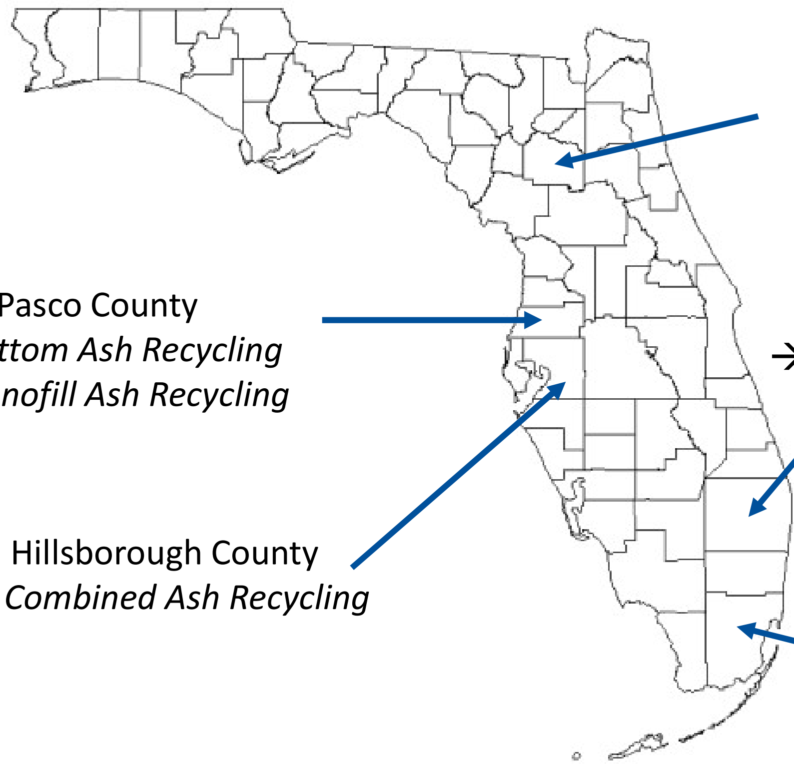
- 6 or 7 years ago there were almost no WTE ash recycling initiatives in the US
- We've been working hard to change that:
  - Lab testing
  - Pilot projects
  - Publishing
  - Workshops
  - Conferences
  - Interacting with local governments
  - Interacting with regulatory community
  - Interacting with industry


What is MSWI ash? What are the material properties?
What are the environmental hazards associated with ash disposal?
Can we re-use ash at all instead of landfilling it? Maybe in construction applications?
Lab testing
Leaching, totals, performance testing
Pilot testing
Build a road, manufacture cement
How do we solve some of the common physical, environmental and durability issues we're noticing with MSWI ash reuse?
leaching risk, mechanical performance, ASR, chlorides
Pre-processing to create a better product
washing, advanced metals recovery, size separation
Permitting And Implementation
permit modifications, interfacing with industry (batch plants), road & bridge, DOT specifications

# 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*

# Some of our recently published work

ELSEVIER
Resources, Conservation and Recycling
Volume 146, July 2019, Pages 270-279

Full length article

## Risk and performance assessment of cement made using municipal solid waste incinerator bottom ash as a cement kiln feed

Kyle A. Clavier [a], Benjamin Watts [b, c], Yalan Liu [a], Christopher C. Ferraro [c], Timothy G. Townsend [a]

⊞ Show more

https://doi.org/10.1016/j.resconrec.2019.03.047 Get rights and content

- Partnered with a local cement company to make 1,000 tons of cement on an industrial scale using WTE ash as a kiln feed
- Physical, chemical, environmental testing
- No excess increase in environmental risk associated with using WTE ash a kiln feed
- Negligible differences in performance and reactivity
- All necessary mineralogical phases for cement reactivity were present
- Promising reuse option already utilized in other countries not yet explored in US until this study

# Some of our recently published work

ELSEVIER
Journal of Hazardous Materials
Volume 373, 5 July 2019, Pages 204-211

## The efficacy of pH-dependent leaching tests to provide a reasonable estimate of post-carbonation leaching

Haiping Ai [a], Kyle A. Clavier [a], Benjamin E. Watts [b], S. Adrian Gale [a], Timothy G. Townsend [a]
Show more

https://doi.org/10.1016/j.jhazmat.2019.03.089



- Do available pH-dependent leaching tests accurately predict leaching from waste materials that have been carbonated?
- We know carbonation can change mineralogical structure in a material
- Different minerals may make trace elements more or less leachable
- We found that for many elements (Al, Sb), pH-dependent leaching tests are unreliable predictors of leaching

UF Herbert Wertheim College of Engineering

POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Engineering School of Sustainable Infrastructure and Environment

# The TCLP issue

Technical Paper

**Limitations of the toxicity characteristic leaching procedure for providing a conservative estimate of landfilled municipal solid waste incineration ash leaching**

Vicharana Intrakamhaeng, Kyle A. Clavier, Justin G. Roessler & Timothy G. Townsend

Pages 623-632 | Received 20 Nov 2018, Accepted 09 Jan 2019, Accepted author version posted online: 12 Feb 2019, Published online: 29 Mar 2019

Download citation https://doi.org/10.1080/10962247.2019.1569172 Check for updates

ELSEVIER

Waste Management

Volume 87, 15 March 2019, Pages 590-596

Limitations of the TCLP fluid determination step for hazardous waste characterization of US municipal waste incineration ash

Yalan Liu, Kyle A. Clavier, Chad Spreadbury, Timothy G. Townsend

Show more

https://doi.org/10.1016/j.wasman.2019.02.045 Get rights and content

- We find that the hazardous waste characterization requirements in the US are not very conducive to sustainable WTE ash management practices
- WTE facility operators may be creating a material that passes the TCLP but is actually less benign in its final disposal scenario
- The TCLP requirement is causing inefficient use of resources and mischaracterization of risk from WTE ash
- The TCLP does not fulfill its intended purpose. We are hoping to start the conversation
- More to come

# Other important publications

Waste and Biomass Valorization
pp 1–12 | Cite as

Use of Coal Fly Ash or Glass Pozzolan Addition as a Mitigation Tool for Alkali-Silica Reactivity in Cement Mortars Amended with Recycled Municipal Solid Waste Incinerator Bottom Ash

Authors | Authors and affiliations

Matthew L. Schafer, Kyle A. Clavier, Timothy G. Townsend, Christopher C. Ferraro, Jerry M. Paris, Benjamin E. Watts

ELSEVIER
Resources, Conservation and Recycling
Volume 129, February 2018, Pages 240-247

Full length article

Economic and life cycle assessment of recycling municipal glass as a pozzolan in portland cement concrete production

Emily L. Tucker [a], Christopher C. Ferraro [b], Steven J. Laux [a], Timothy G. Townsend [a]
Show more

https://doi.org/10.1016/j.resconrec.2017.10.025 

- Evaluating which waste materials we can use in concrete applications
- WTE ash tends to cause alkali-silica reaction (ASR), but waste glass pozzolan may mitigate
- Glass pozzolan feasibility highly dependent on throughput in order to be economical
- Potential new recycling applications for WTE ash and waste glass but we further investigation is needed…
- Part of this new Hinkley center project is expanding upon some of the work in these two publications to find feasible ways to incorporate waste glass and MSWI ash into construction products

# So What is a Pozzolan?

- Siliceous material that reacts in a cement/water matrix to create more calcium silicate hydrate (what makes concrete "hard")

- Often waste materials (coal fly ash, silica fume, rice husk ash, palm oil fuel ash)

- Different pozzolans may have different applications for different types of concretes (temperature, setting times, strength, workability etc.)

- Our group has worked extensively with alternative pozzolans

ELSEVIER
Journal of Cleaner Production
Volume 121, 10 May 2016, Pages 1-18

Review

## A review of waste products utilized as supplements to Portland cement in concrete

Jerry M. Paris [a], Justin G. Roessler [a], Christopher C. Ferraro [a], Harvey D. DeFord [b], Timothy G. Townsend [a]

⊞ Show more

https://doi.org/10.1016/j.jclepro.2016.02.013

# The Coal Fly Ash Shortage

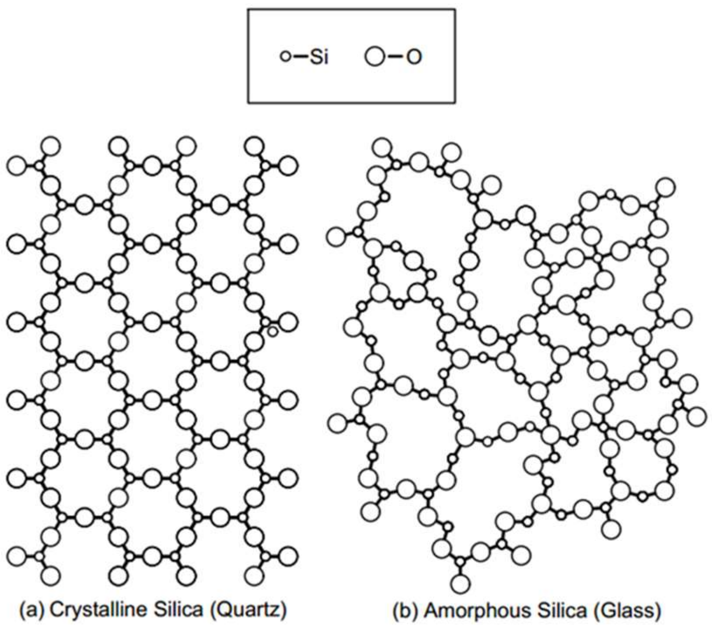
- Byproduct of coal combustion that has been used for 40 years as a supplemental replacement of cement in production of concrete
- Critically important to concrete production; cheaper than cement and greatly enhances the characteristics of concrete
- Decline in energy production from coal combustion (natural gas, renewables)
- Concrete industry is scrambling to find a replacement

# Waste Glass as an Alternative Pozzolan?

- Abundantly available as a waste material
- Predominantly silica -> potentially reactive
- Glass recycling is lacking in many parts of the country largely due to lack of a market for post consumer glass
- Must provide some benefit to the user (product performance, cost, etc.)

# Glass Chemistry

- Variable amorphous structure with low bond strength (different from rigid and less reactive crystalline silica structure)
- There is already a commonly used amorphous silica pozzolan on the market (silica fume)
- Soda lime "container" glass accounts for 90% of glass (60-75% silica)
- Ground glass has been shown to reduce ASR but... reactivity is heavily dependent on particle size…use as a pozzolan requires grinding to a fine powder
- Too big and you might actually exacerbate the ASR issue!

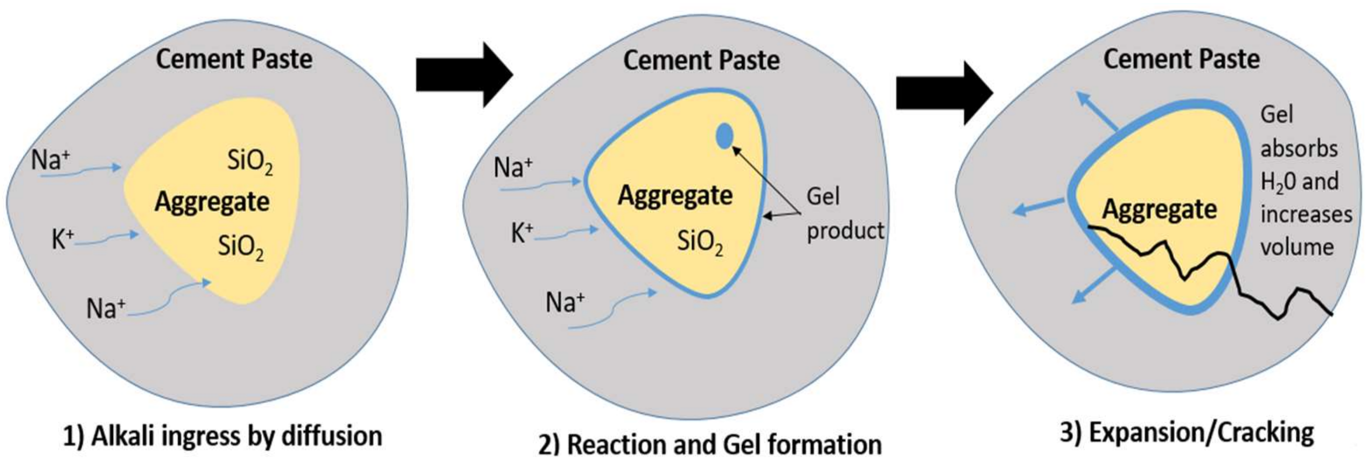


# Special Importance: Alkali Aggregate Reactivity

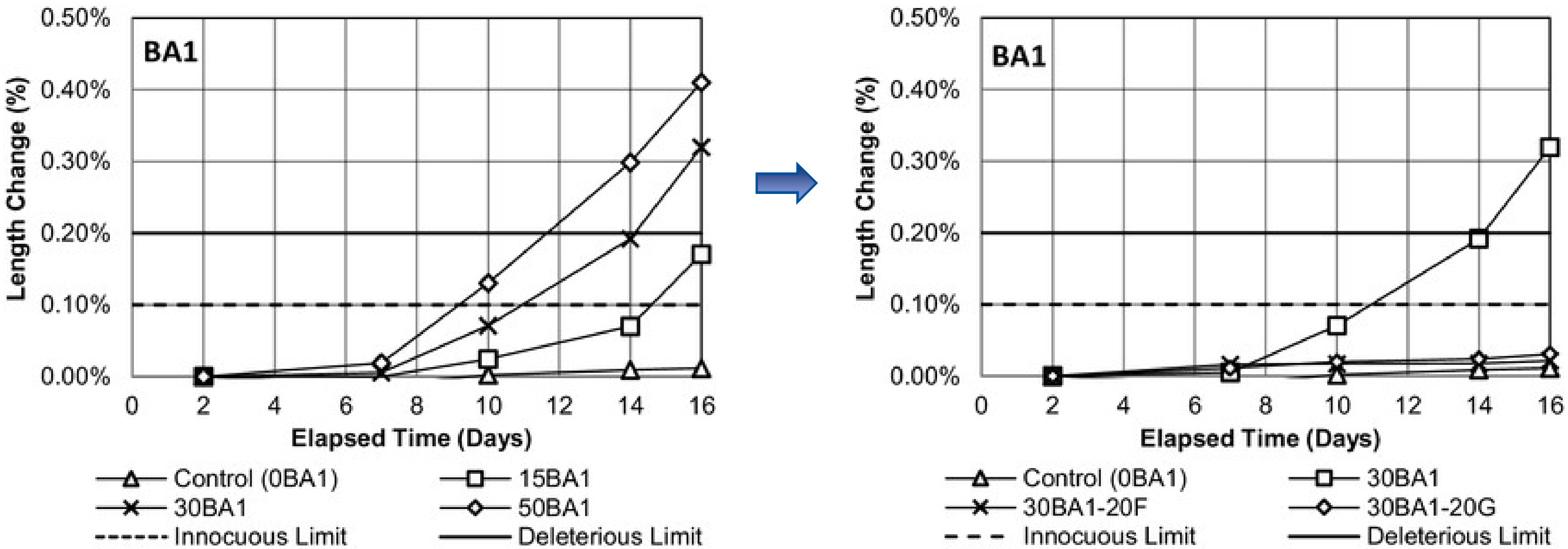
- Deleterious reactions with the aggregate, specifically the alkali silica reaction (ASR)
- High alkali presence in concrete
- Expansive gels formed that expand in presence of moisture to induce cracking
- Linked to bottle glass and other glassy amorphous silica components of WTE ash.

# Major Issue with WTE Ash in PCC

- ASR



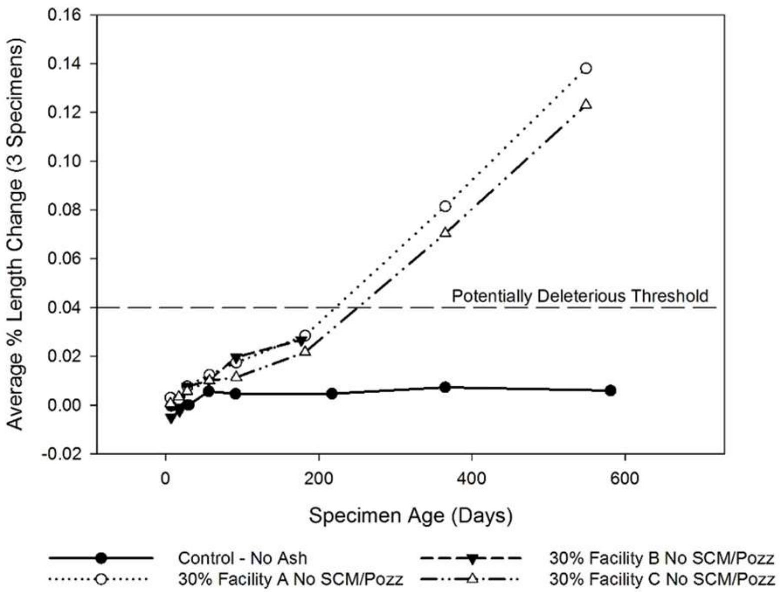
# The perfect test case for waste products in concrete…

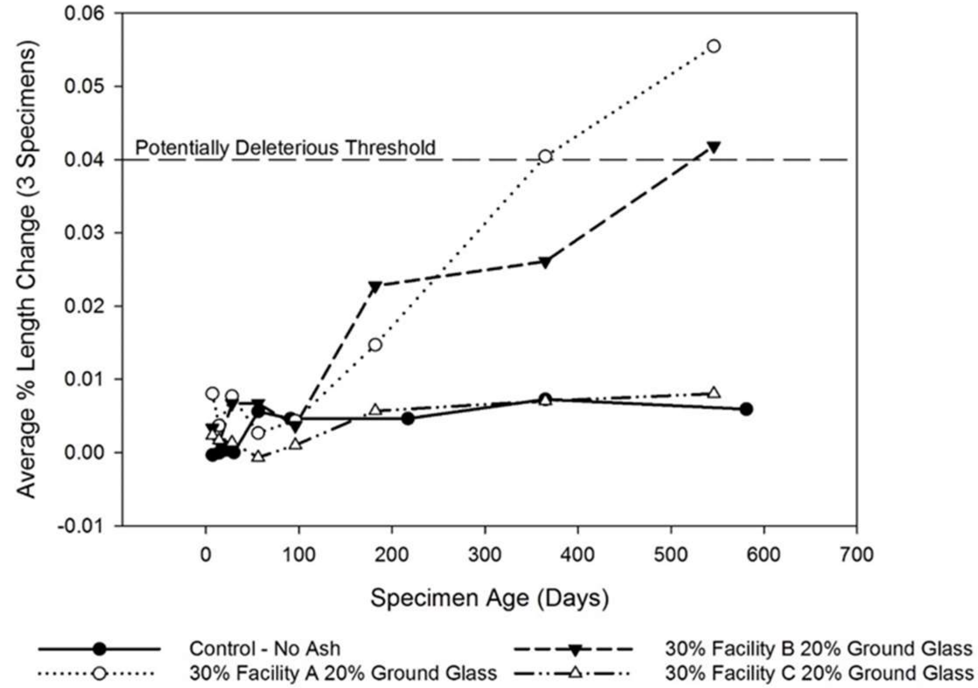



Accelerated mortar bar testing indicates that MSWI bottom ash may cause alkali-silica reaction and ground glass may mitigate…not always the best test though.

# Can we use one waste material to solve issues with another waste material in concrete?

- ASTM 1293 provides a longer term measure of alkali-silica reactivity in concrete specimens (2 years)
- Amend concrete specimens with 30% MSWI bottom ash and measure ASR reactivity
- See if we can mitigate measured reactivity using 20% replacement of ground glass pozzolan


Average % Length Change (3 Specimens)
Specimen Age (Days)
Potentially Deleterious Threshold
Control - No Ash
30% Facility A No SCM/Pozz
30% Facility B No SCM/Pozz
30% Facility C No SCM/Pozz


Average % Length Change (3 Specimens)
Specimen Age (Days)
Potentially Deleterious Threshold
Control - No Ash
30% Facility A 20% Ground Glass
30% Facility B 20% Ground Glass
30% Facility C 20% Ground Glass

# Big Picture?

- Ground glass seems to delay the onset of ASR from 200 days to about 500 days and mitigated completely in one specimen
- Though ground glass addition doesn't stop ASR completely, we tested only one combination of MSWI and pozzolan percentage (30% mass replacement of aggregate, 20% of cementitious material); our results should not be used to dismiss MSWI ash use in concrete or glass pozzolan use as a mitigatory procedure for ASR

# Further Considerations

- Size reducing glass to a powder is energy intensive ($) and the economics depend heavily on volume being processed
- Though most abundant and most obvious candidate for reuse, soda-lime glass contains high alkalis that may leach and cause ASR in high pH cementitious system
- Different replacement percentages of both aggregate and pozzolans should be investigated
- Different cement blends
- Pre-process the ash (washing) to remove prohibitive constituents (alkalis)

# Literature Review of Ash Washing

# What is Ash Washing

- Ash contact with solutions
  - Water
  - Chemicals
- Remove pollutants
  - Chlorides
  - Soluble salts
  - Heavy metals

# Why Ash Washing

- Safe disposal
- Recycling & Reuse
- Explore optimum washing

# Safe Disposal

- Fly ash detoxification
  - Single washing (*Chimenos et al., 2005*)
  - Pretreatment
    - Thermal treatment (*Chiang et al., 2010; Mangialardi et al., 2003; Wey et al., 2006*)
    - Stabilization/Solidification (*Mangialardi et al., 1999; Jiang et al., 2009*)
    - Ball milling (*Li et al., 2007*)
    - Bioleaching (*Wang et al., 2009*)

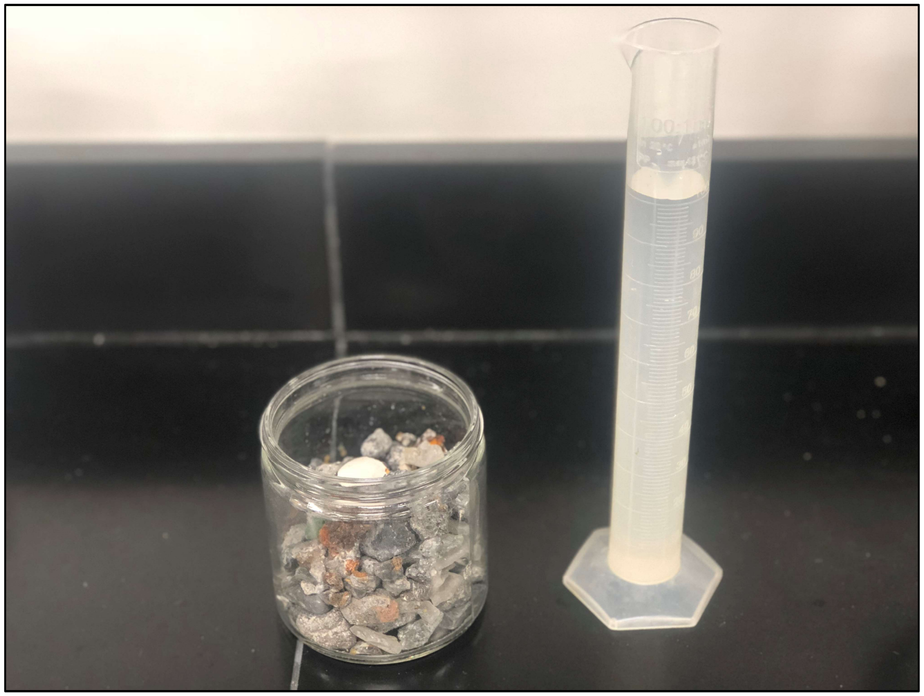
# Recycling & Reuse

- Cement production
  - Chlorides

| Author | Ash Type | Reuse application |
|---|---|---|
| Mangialardi et al., 1999 | WTE Fly Ash | Cement production |
| Zhu et al., 2009 | WTE Fly Ash | Cement production |
| Zhu et al., 2011 | WTE Fly Ash | Cement production |
| Deboom et al., 2015 | WTE Fly Ash | Cement production |
| Chen et al., 2016 | WTE Fly Ash | Cement production |
| Yang et al., 2017 | WTE Fly Ash | Cement production |
| Yan et al., 2018 | WTE Fly Ash | Cement production |
| Ito et al., 2008 | WTE Bottom Ash | Cement production |
| Saikia et al., 2015 | WTE Bottom Ash | Cement mortar |
| Hartmann et al., 2015 | WTE Bottom Ash | Concrete & Cement |

# Explore Optimum Washing Process

- Liquid to Solid Ratio (L/S)
  - Liters of solution/Kg of ash
  - 1-100
- Contact time
  - Washing duration
  - 1 minute-72 hours
- Washing speed
- Washing cycles



# How to Wash Ash


- Batch test (5g-100g of ash)
  - Shaking device
  - Glass vessel
  - Agitation apparatus
- Pilot study
- Washing parameters: L/S < 10; contact time < 2 hours
- Solution
  - Water
  - Acid/Base

# What were the Washing Results

- L/S ratios
  - Higher L/S remove more compounds
  - Notable for L/S ratios lower than 10
- Contact time
  - Rapid for chlorides & soluble salts
  - Reabsorb might occur
- Washing cycles
  - Improve washing performance

# What Were the Washing Results

- Chlorides & soluble salts
  - Rapid dissolution
- Heavy metals
  - Amphoteric heavy metals : Zn, Pb
  - Increase total concentration: mass loss
- Acid washing has promising metals removal
- Bubbling $CO_2$ enhance metals removal

# *Effects of Washing on WTE Ash Aggregate*

# Objective of Our Washing Treatment

- Washing of bottom ash and combined ash remove
  - Chlorides
  - Sulfate
  - Inorganic elements
  - Fines (<No.4)
- Small-scale washing:
  - Optimum washing parameters
- Large-scale washing:
  - Reuse in PCC and HMA

# Materials

- Materials:
  - Aged bottom ash
  - Aged combined ash

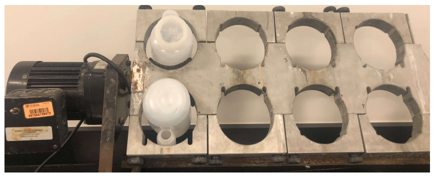
- Material processing for washing
  - Screening → coarse materials

# Small-Scale Washing

Processed Ash

↓

Washing

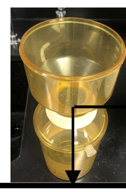


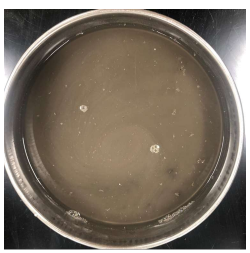
L/S ratios: 1,3,5,10,20
Contact time: 1min, 3min, 5min, 10min, 30min, 1hour, 2hours

↓

Sieving through a No.4 sieve

↓





Fines and wash water

Coarse

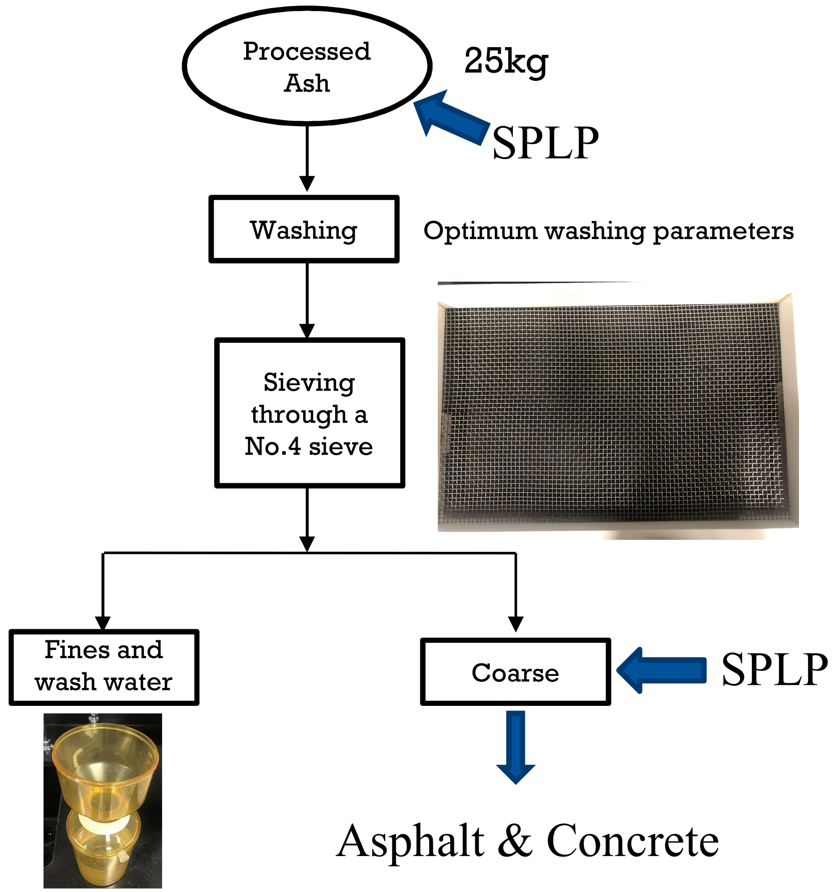
Equation $$\eta = \frac{C_{water} \times V_{water} + C_{fines} \times M_{fines}}{C_{unwashed\ ash} \times M_{unwashed\ ash}}$$

Water

Fines

Unwashed ash

# Large-Scale Washing

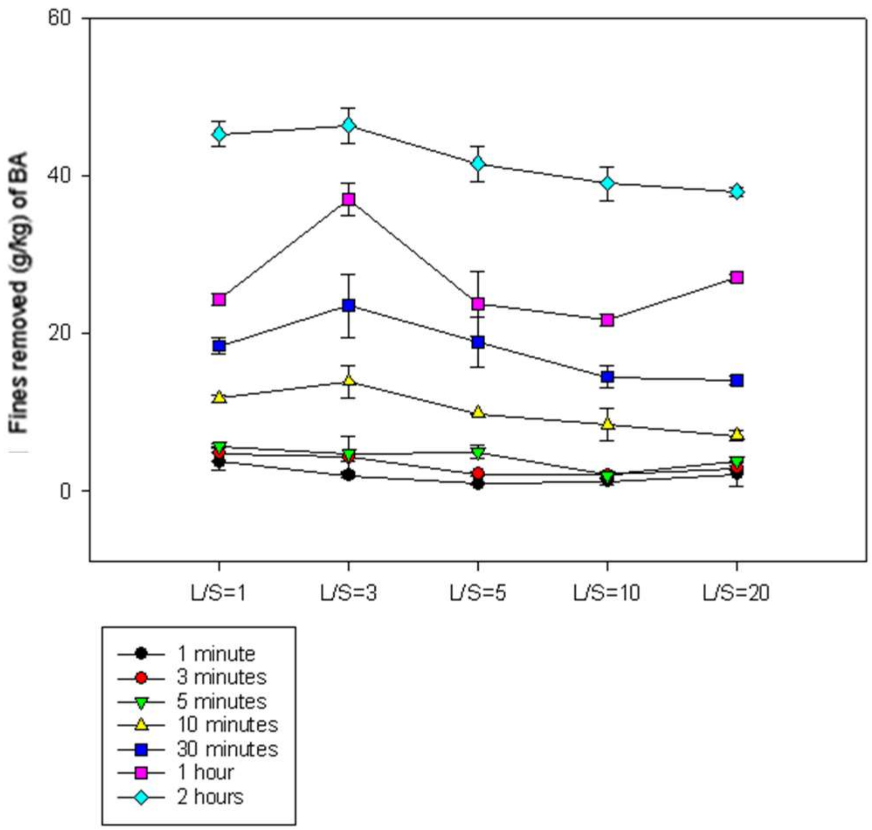



# *Results for Small-Scale Washing*

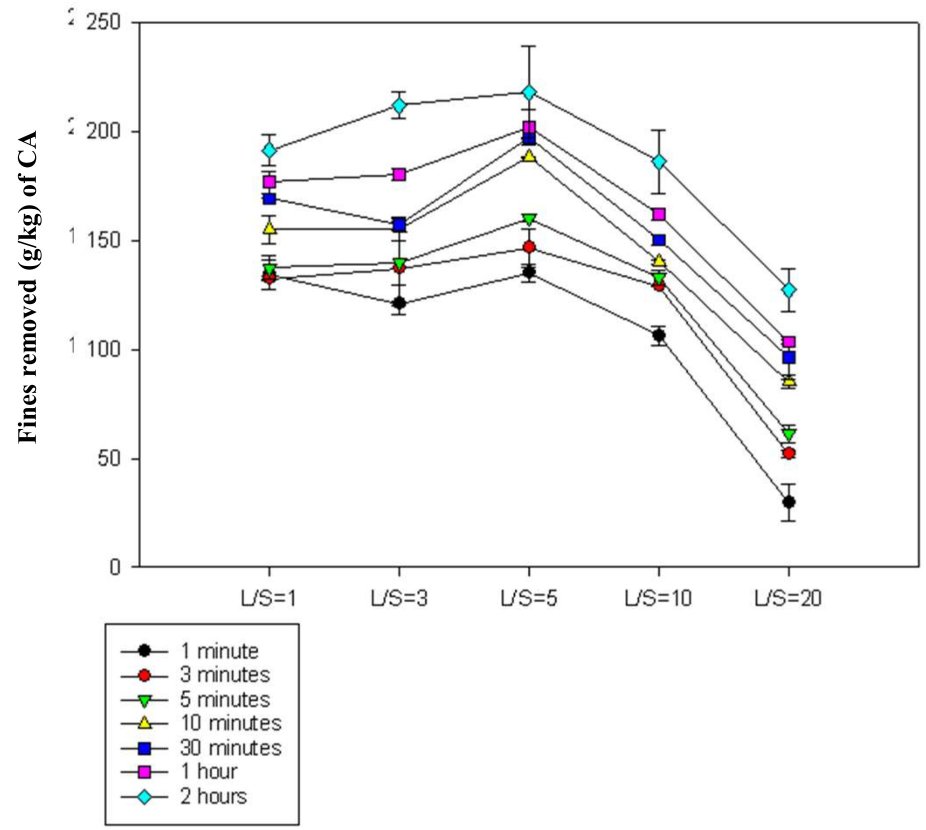
# Fines Removal

Why different?

Bottom ash

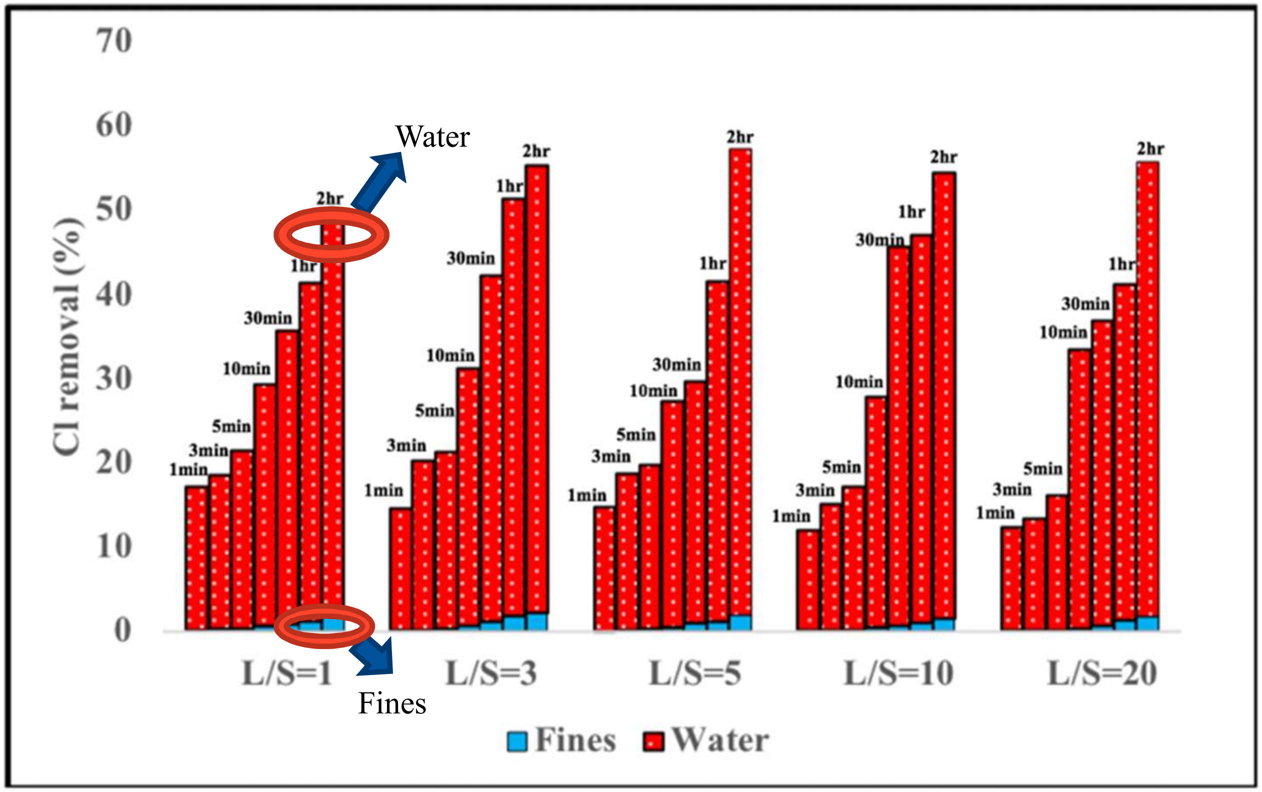



Combined ash



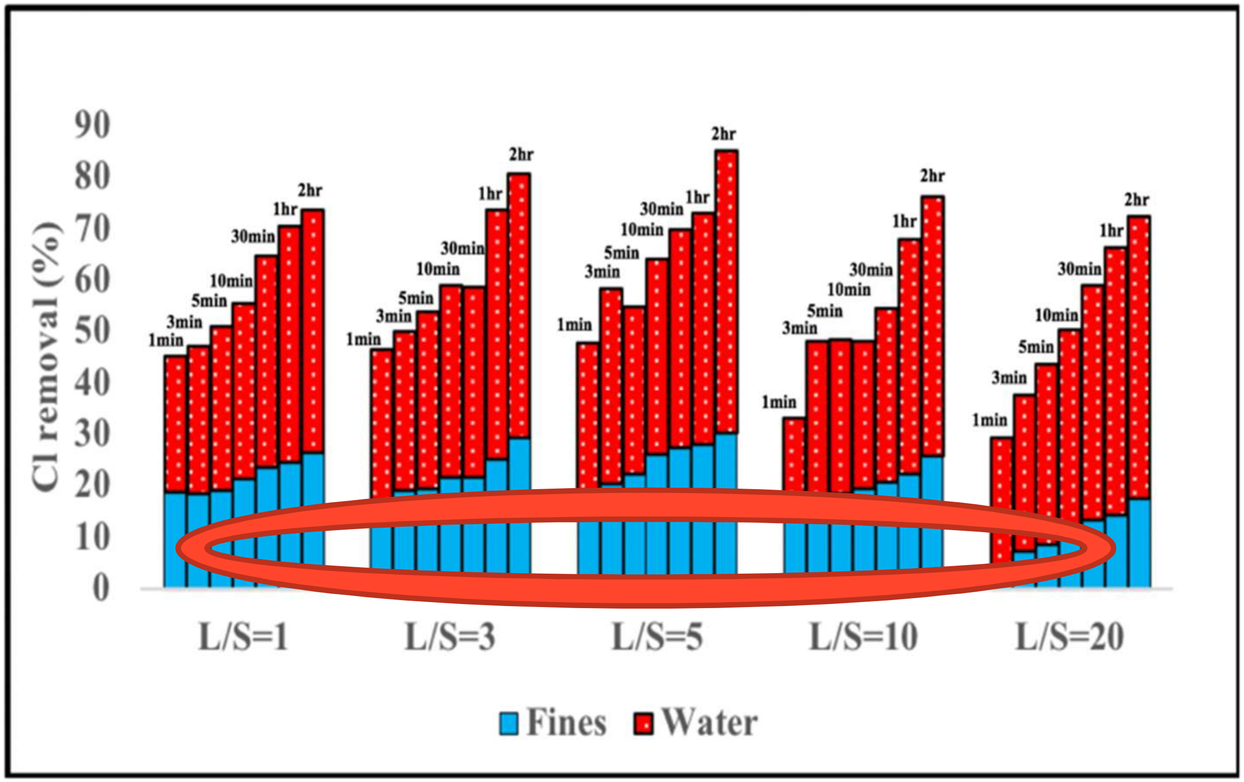
# Chlorides Removal

Bottom ash



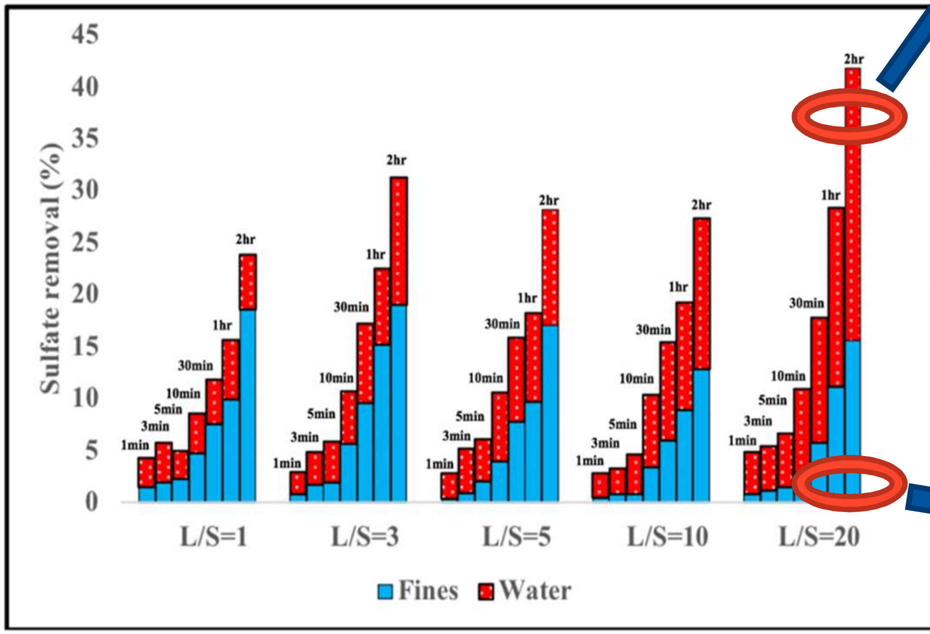
# Chlorides Removal

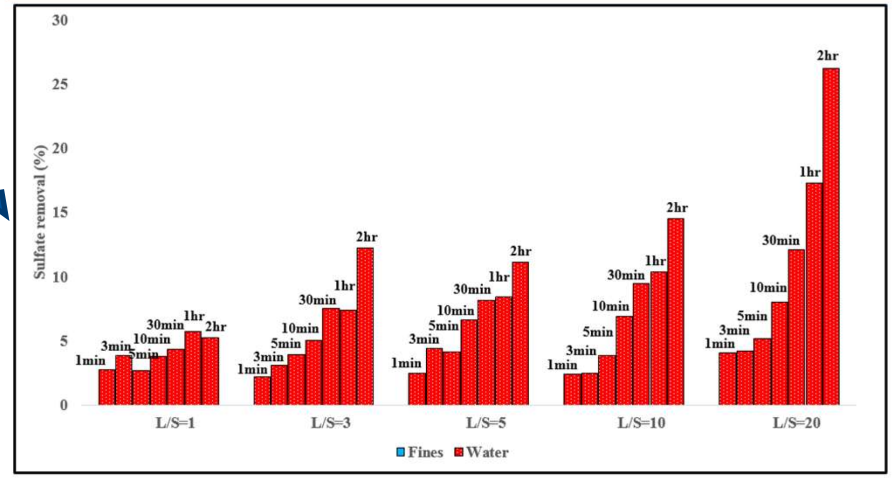
Combined ash

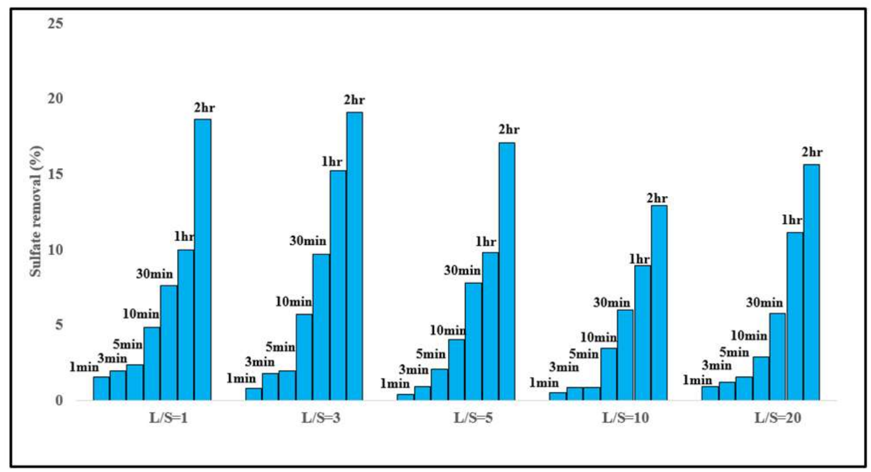


# Sulfate Removal

Bottom ash

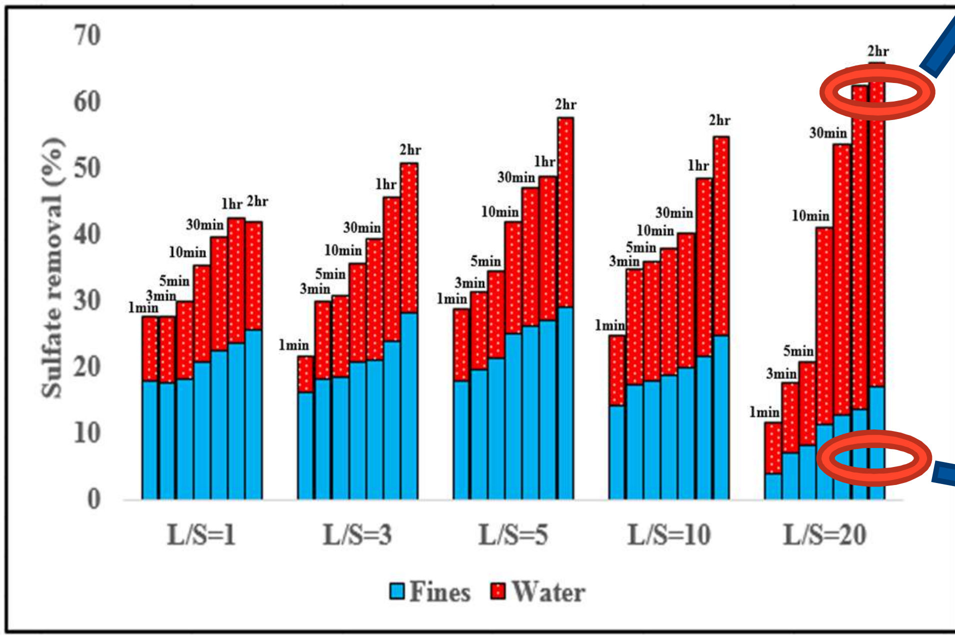


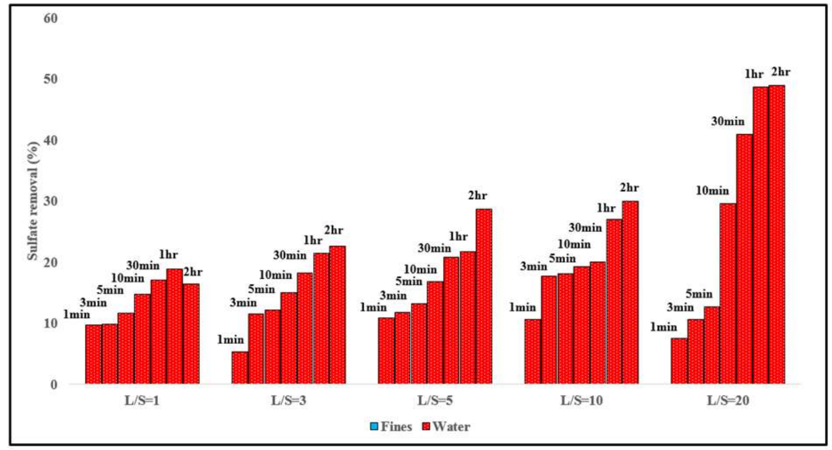



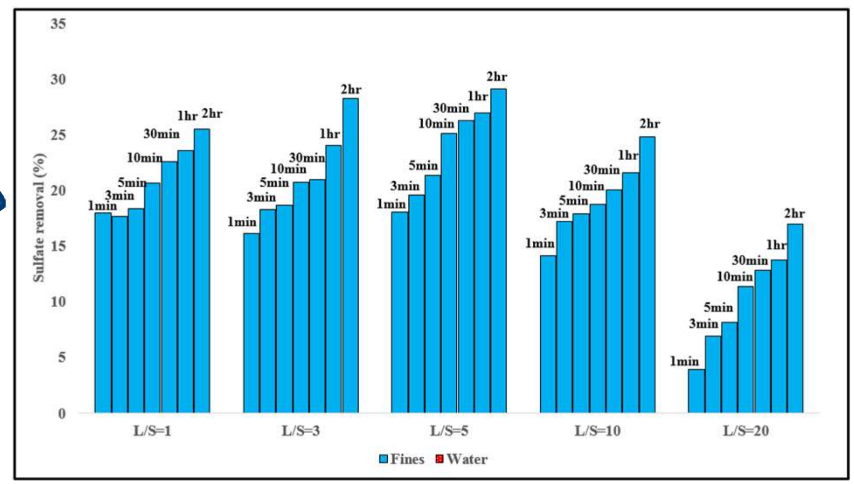



# Sulfate Removal

Combined ash

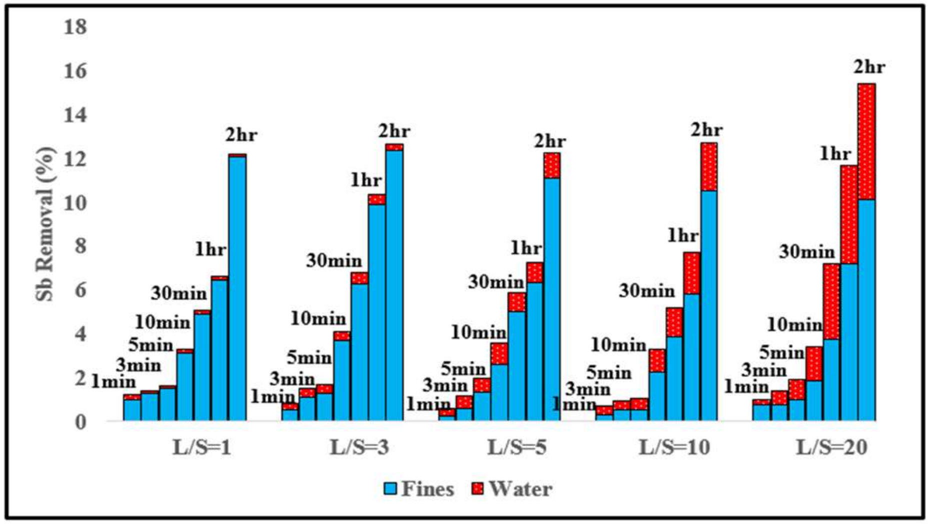


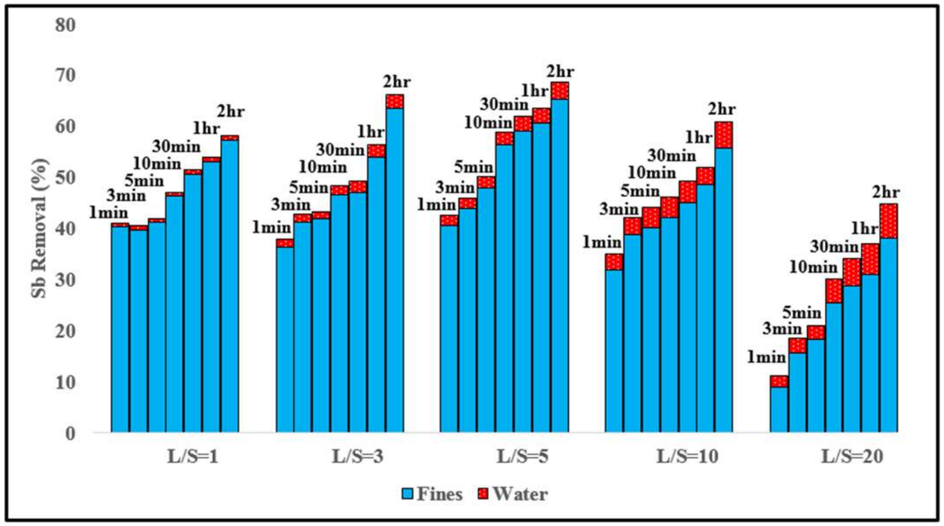



# Heavy Metal Removal

Bottom ash

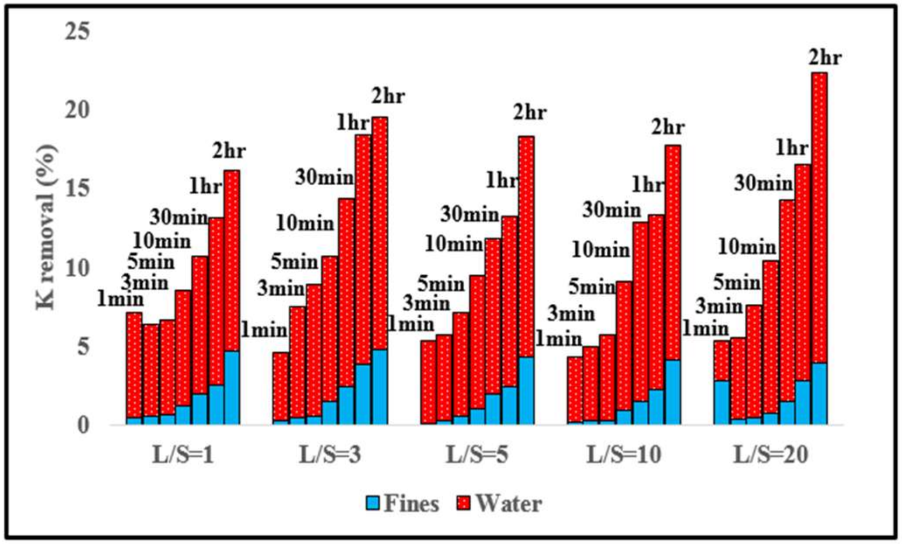



Combined ash

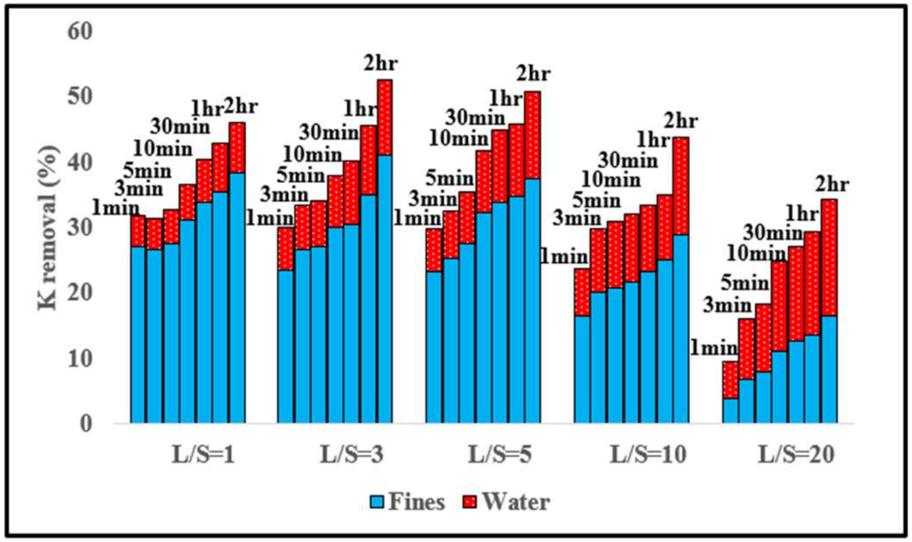


# Alkali Removal

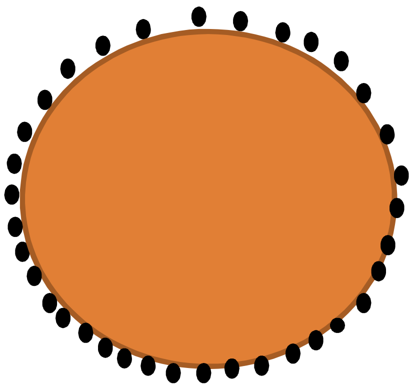
Bottom ash



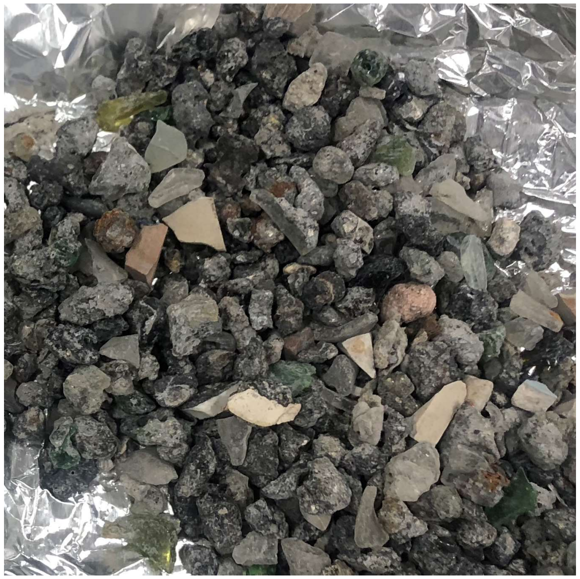

Combined ash



# Fines VS. Unwashed Ash



Unwashed Ash



Washed Ash

# Fines VS. Unwashed Ash

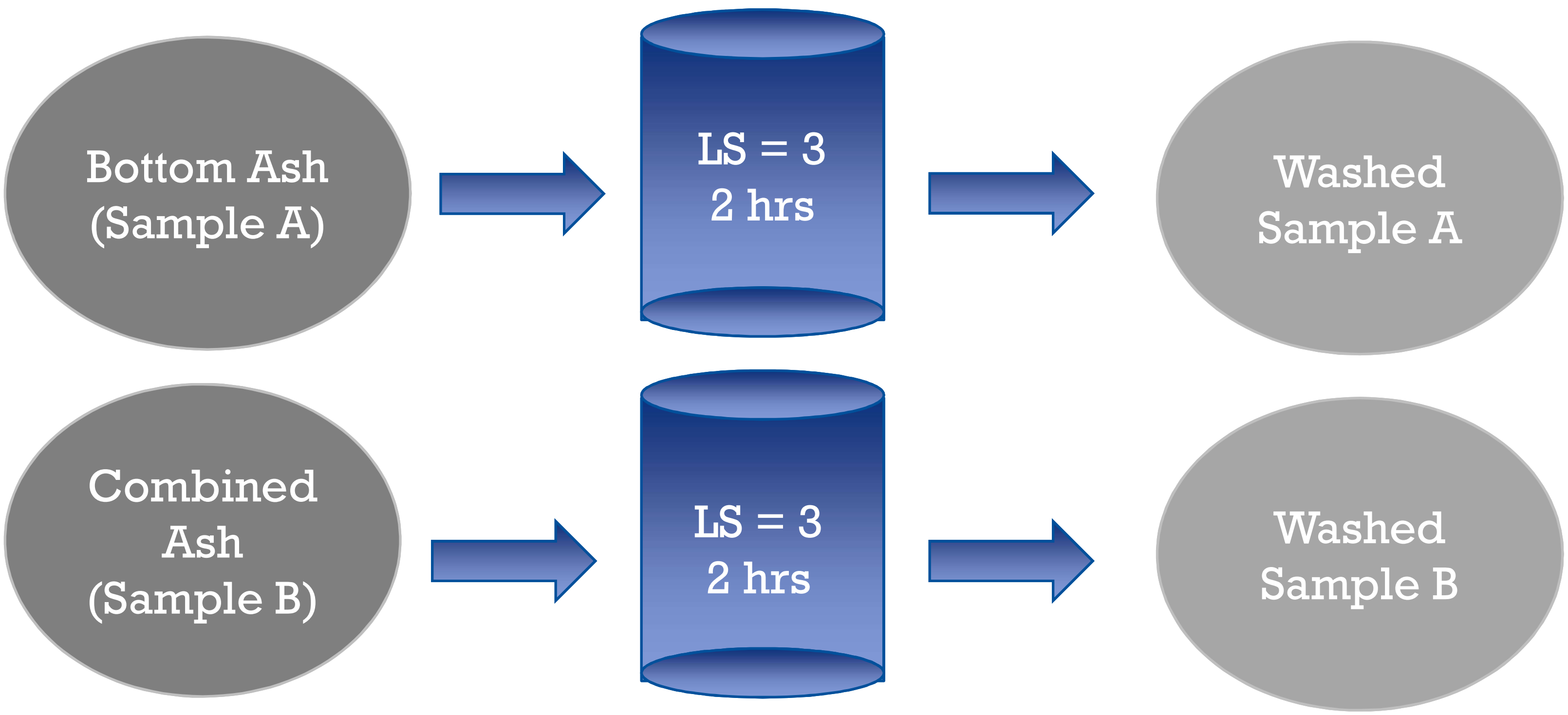
| Element | Fines (mg/kg) for Bottom Ash | Unwashed Bottom Ash (mg/kg) | Fines (mg/kg) for Combined Ash | Unwashed Combined Ash (mg/kg) |
|---|---|---|---|---|
| Soluble chlorides | 7310 | 3130 | 811 | 324 |
| Soluble sulfate | 9430 | 3760 | 10800 | 4300 |
| Al | 24500 | 15600 | 43900 | 23000 |
| As | 14.4 | 0.600 | 53.8 | 21.3 |
| Mo | 14.2 | 11.1 | 9.59 | 7.38 |
| Pb | 919 | 553 | 1460 | 500 |
| Sb | 33.5 | 20.5 | 131 | 49.7 |
| Cd | 20.8 | 7.75 | 74.8 | 31.3 |
| Ca | 77500 | 54200 | 99500 | 58400 |
| Na | 7400 | 8350 | 3790 | 6270 |
| K | 2400 | 1740 | 1370 | 1430 |

# Optimizing Washing

- Lower L/S ratios (1-5) should be used
- L/S of 1 might not be practical
- L/S of 3 is a feasible and economical choice
- Optimum washing: L/S ratio of 3 & 2 hours

# Results for Large-Scale Washing

# Large-Scale Washing for Ash-Aggregate



# SPLP of Washed & Unwashed Ash

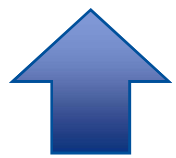
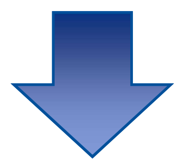
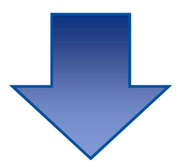
| | Unwashed Bottom Ash | Washed Bottom Ash | Unwashed Combined Ash | Washed Combined Ash | EPA Regional Screening Level (Residential Tap Water) |
|---|---|---|---|---|---|
| **Element** | (mg/L) | (mg/L) | (mg/L) | (mg/L) | (mg/L) |
| **pH** | 10.72 | 10.53 | 8.99 | 8.71 | - |
| **Al** | 20.2 | 12.3 | 3.93 | 2.05 | 20 |
| **As** | 0.00403 | <0.004 | <0.004 | <0.004 | 0.01 |
| **B** | 0.226 | 0.132 | 0.255 | 0.122 | 4.0 |
| **Ba** | 0.0846 | 0.0268 | 0.0383 | 0.0176 | 2.0 |
| **Be** | <0.001 | <0.001 | <0.001 | <0.001 | 0.004 |
| **Ca** | 82.2 | 42.3 | 67.1 | 28.2 | - |
| **Cd** | <0.001 | <0.001 | <0.001 | <0.001 | 0.005 |
| **Co** | <0.006 | <0.006 | <0.006 | <0.006 | 0.006 |
| **Cr (total)** | 0.00383 | 0.00283 | 0.00267 | 0.00187 | 0.1 |
| **Cu** | 0.0507 | 0.0109 | 0.0188 | 0.00830 | 1.3 |
| **Fe** | 0.0258 | <0.002 | <0.002 | <0.002 | 14 |
| **K** | 17.4 | 6.08 | 3.81 | 1.26 | - |
| **Mg** | 0.110 | 0.138 | 2.17 | 0.537 | - |
| **Mn** | 0.00327 | 0.00163 | 0.00500 | <0.001 | 0.43 |
| **Mo** | 0.0136 | 0.00623 | 0.0360 | 0.015 | 0.1 |
| **Na** | 46.0 | 16.8 | 11.4 | 7.54 | - |
| **Ni** | <0.001 | <0.001 | 0.00143 | <0.001 | 0.1 |
| **Pb** | 0.0347 | 0.00603 | <0.004 | <0.004 | 0.015 |
| **Sb** | 0.105 | 0.0311 | 0.0719 | 0.0269 | 0.006 |
| **Se** | <0.002 | <0.002 | <0.002 | <0.002 | 0.05 |
| **Sn** | 0.00300 | 0.00287 | <0.002 | <0.002 | 12 |
| **Sr** | 0.219 | 0.0949 | 0.142 | 0.0641 | 12 |
| **V** | 0.0107 | 0.0065 | <0.001 | <0.001 | 0.086 |
| **Zn** | 0.0276 | 0.0118 | 0.0127 | 0.00627 | 6 |

# Summary

- Lack of WTE bottom ash and combined ash studies
- Contact time > L/S ratios
- Fines attached on the surface of is more contaminated
- L/S of 3 is a feasible and economical choice
- SPLP leaching decreased

# *Effects of Washing on Physical Performance*

# Washed WTE Ash Physical Performance Properties

| Property | After Washing | Impact |
|---|---|---|
| Specific Gravity |  | **Effect:** Denser mixture, better volumetrics (asphalt pavement) |
| Absorption |  | **Effect:** Less asphalt binder, better workability (concrete) |
| Deleterious Materials (e.g., Dust, Alkalis) |  | **Effect:** Better aggregate-to-binder/cement bonding, durability |

# Performance Properties of Ash-Derived Aggregate Stockpiles

| Gradation | % Passing (by Mass) | | | |
|---|---|---|---|---|
| | Bottom Ash | | Combined Ash | |
| | Untreated | After Washing | Untreated | After Washing |
| 19 mm (3/4 in.) | 100 | 100 | 100 | 100 |
| 12.5 mm (1/2 in.) | 59 | 59 | 89 | 94 |
| 9.5 mm (3/8 in.) | 26 | 29 | 60 | 64 |
| 4.76 mm (No. 4) | 4 | 2 | 17 | 3 |
| 2.38 mm (No. 8) | 3 | 1 | 14 | 1 |
| 1.19 mm (No. 16) | 3 | 1 | 12 | 1 |
| 0.6 mm (No. 30) | 2 | 1 | 11 | 1 |
| 0.3 mm (No. 50) | 2 | 1 | 10 | 1 |
| 0.15 mm (No. 100) | 2 | 1 | 8 | 1 |
| 0.075 mm (No. 200) | 1.3 | 0.2 | 7.1 | 0.2 |
| **Other Aggregate Properties** | **Bottom Ash** | | **Combined Ash** | |
| | Untreated | After Washing | Untreated | After Washing |
| Specific Gravity | 2.311 | 2.392 | 2.090 | 2.353 |
| Absorption (%) | 5.0 | 2.8 | 9.3 | 3.2 |

*Only a slight reduction in finer material for Bottom Ash, but major reduction for Combined Ash*

*Reduction in fine material for Combined Ash is reflected in its specific gravity and absorption*

Herbert Wertheim College of Engineering

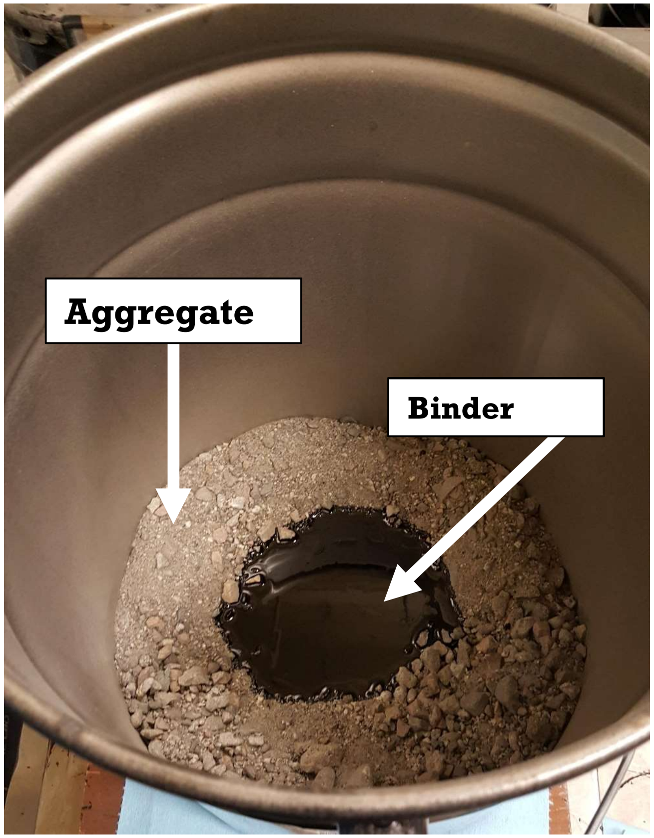
POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Engineering School of Sustainable Infrastructure and Environment

# *Utilizing WTE Ash in Asphalt*

# Asphalt 101

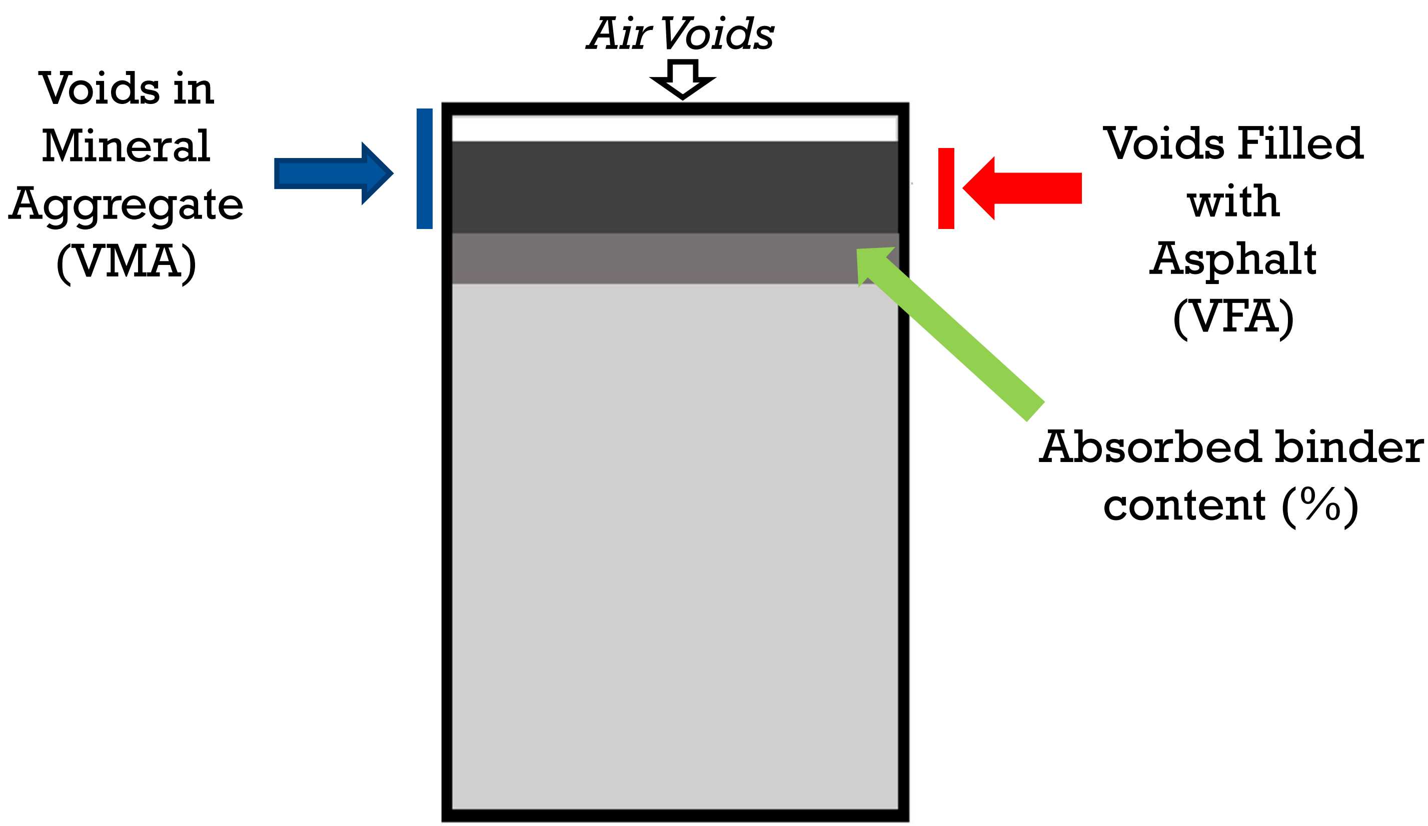
- Asphalt concrete ("HMA") is made of aggregates, binder (the asphalt!), and air
- Ash reuse as an aggregate in HMA goes back to pilot demonstrations in 1970s
- Asphalt concrete is engineered based on its intended use and expected traffic loading



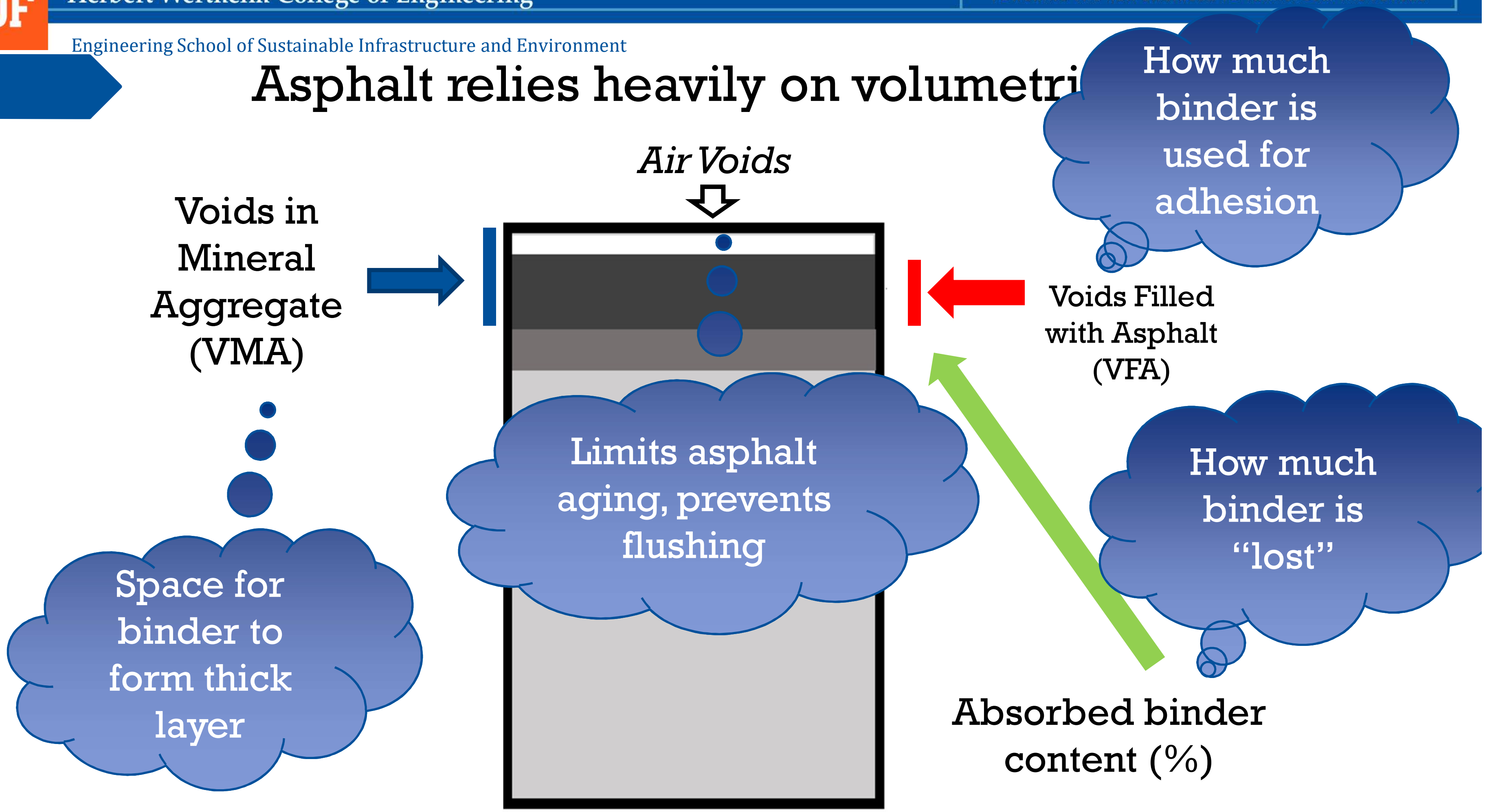
# Mixture Design

- HMA is made according to a specific method:
  - Most common: Marshall and Superpave
- Marshall: global, has existed for decades
- Superpave: emerged in the 1990s to fix stability issues with Marshall design
  - Standard used by FDOT
  - Prescribes gradation, volumetric, and moisture resistance requirements

# Asphalt relies heavily on volumetrics!

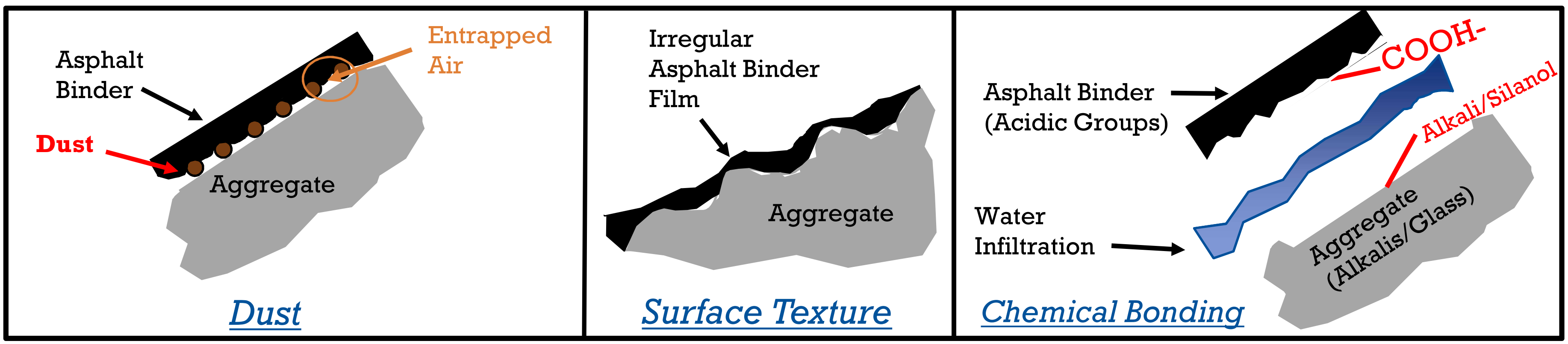


# Asphalt relies heavily on volumetri

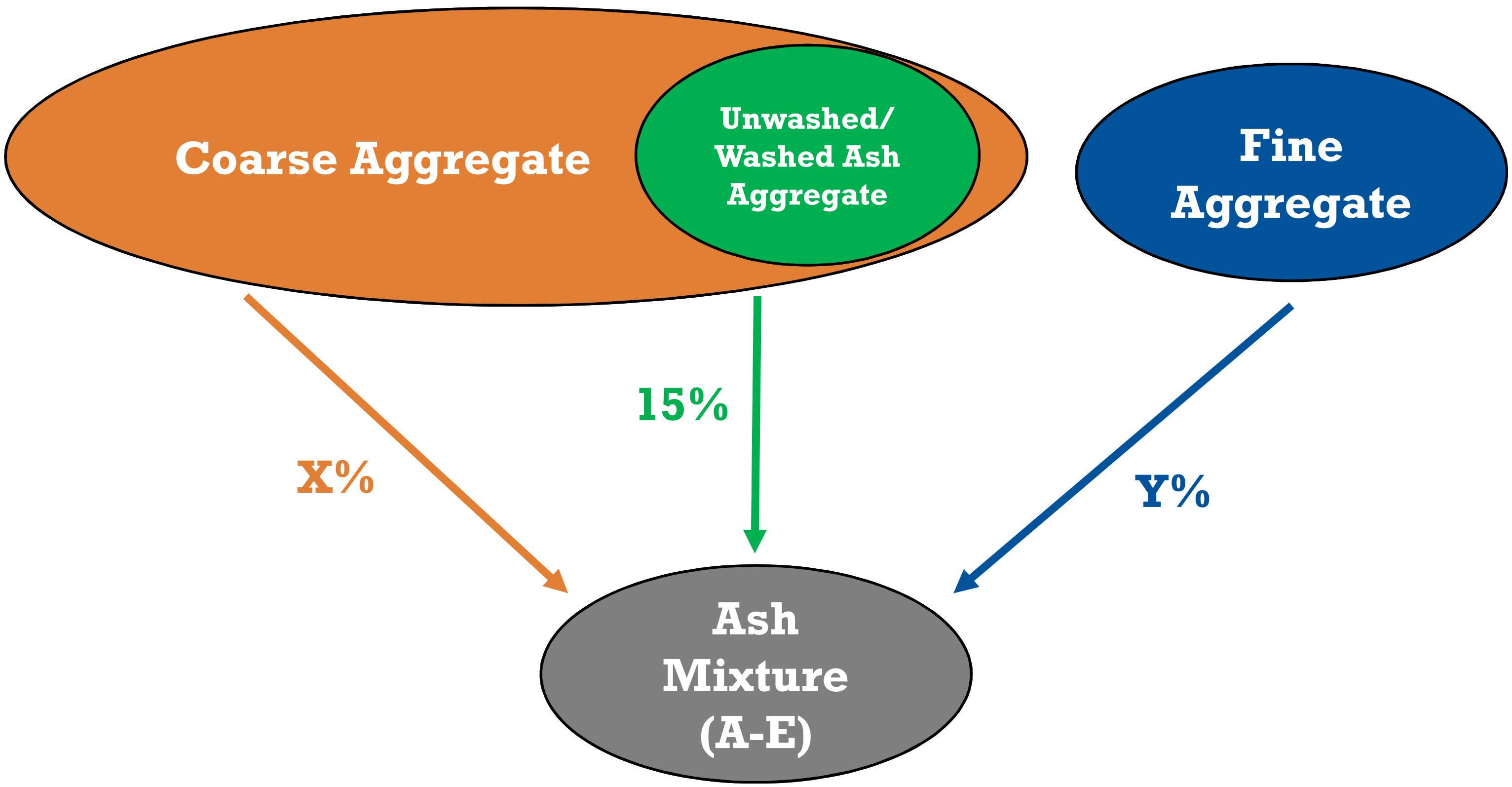


# Adhesion

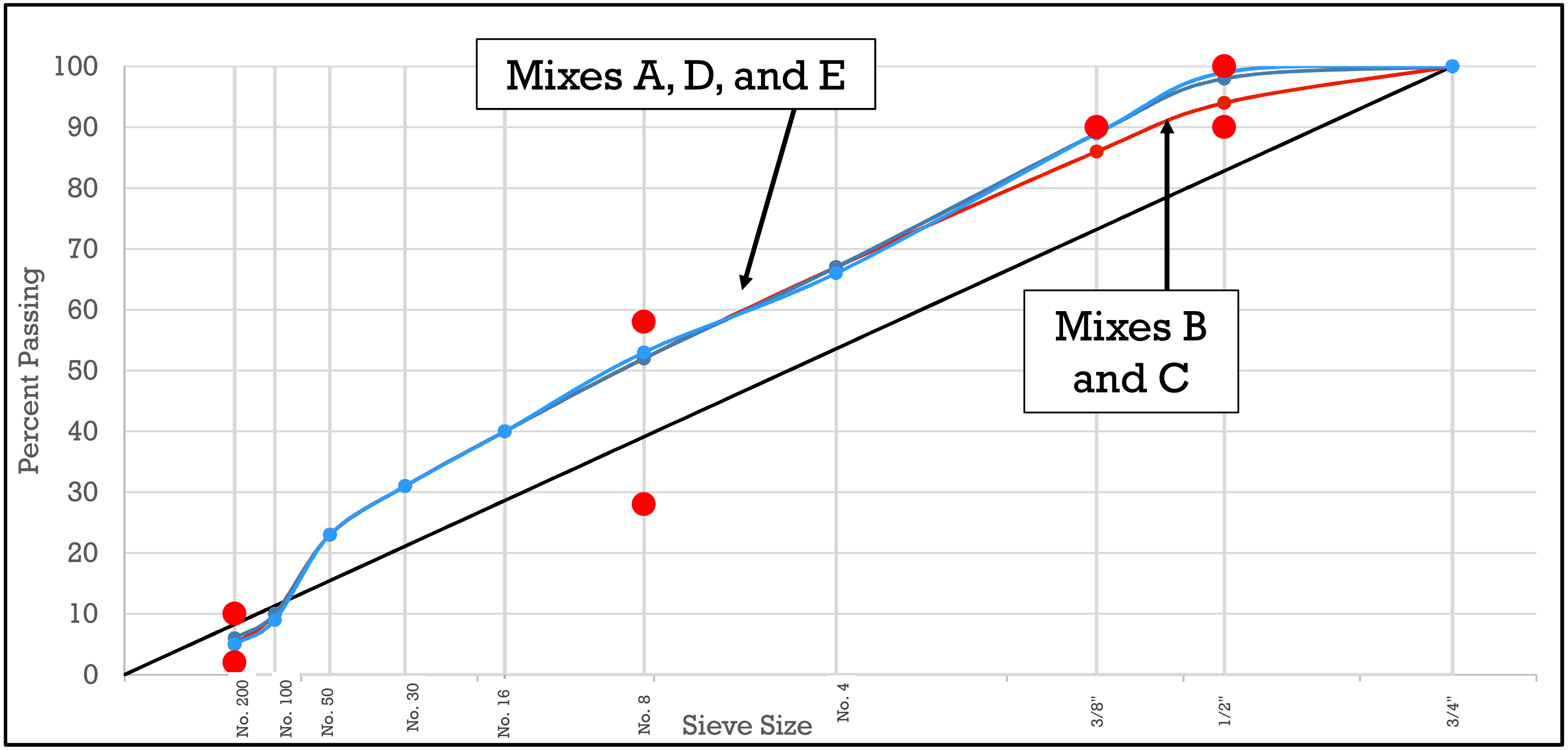
- Driver of HMA strength and durability
- Affected by asphalt binder thickness and bonding strength
    - Physical and chemical
- Dust, surface texture can interfere with adhesion
- Like PCC, alkalis and glass can have a negative effect:
    - Weaker (water soluble) bonds between the ash-aggregate surface and binder
    - Another situation where washing can be beneficial



# Designing Mixtures for Ash-Aggregate



# Five Test Mixtures



# Mixture Volumetrics

| Volumetric Parameters | Superpave Traffic Level C, SP-12.5 |
|---|---|
| Design Asphalt Binder (%) | n/a |
| VMA (%) | ≥14.0 |
| VFA (%) | 65-75 |
| Effective binder content (%) | n/a |

# Mixture Volumetrics

*A slight decrease in binder demand*

| Volumetric Parameters | Superpave Traffic Level C, SP-12.5 | Mix A | Mix B | Mix C | Mix D | Mix E |
|---|---|---|---|---|---|---|
| Design Asphalt Binder (%) | n/a | 5.3 | 5.4 | 5.3 | 5.8 | 5.7 |
| VMA (%) | ≥14.0 | 14.6 | 14.1 | 13.9 | 13.1 | 14.2 |
| VFA (%) | 65-75 | 73 | 73 | 71 | 69 | 73 |
| Effective binder content (%) | n/a | 4.6 | 4.5 | 4.4 | 4.0 | 4.5 |

# Mixture Volumetrics

*A coarser washed ash-amended mixture could reach the same design binder content as a non-ash blend*

| Volumetric Parameters | Superpave Traffic Level C, SP-12.5 | Mix A | Mix B | Mix C | Mix D | Mix E |
|---|---|---|---|---|---|---|
| Design Asphalt Binder (%) | n/a | 5.3 | 5.4 | 5.3 | 5.8 | 5.7 |
| VMA (%) | ≥14.0 | 14.6 | 14.1 | 13.9 | 13.1 | 14.2 |
| VFA (%) | 65-75 | 73 | 73 | 71 | 69 | 73 |
| Effective binder content (%) | n/a | 4.6 | 4.5 | 4.4 | 4.0 | 4.5 |

# Mixture Volumetrics

*Washing allowed more a more optimal use of binder (adhesion rather than becoming absorbed)*

| Volumetric Parameters | Superpave Traffic Level C, SP-12.5 | Mix A | Mix B | Mix C | Mix D | Mix E |
|---|---|---|---|---|---|---|
| Design Asphalt Binder (%) | n/a | 5.3 | 5.4 | 5.3 | 5.8 | 5.7 |
| VMA (%) | ≥14.0 | 14.6 | 14.1 | 13.9 | 13.1 | 14.2 |
| VFA (%) | 65-75 | 73 | 73 | 71 | 69 | 73 |
| Effective binder content (%) | n/a | 4.6 | 4.5 | 4.4 | 4.0 | 4.5 |

?

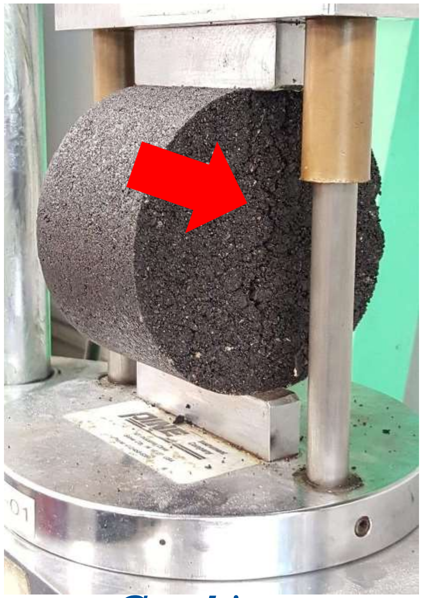
# Explanations for Higher Binder Demand

- Removing most of the finer material produced a slight drop in binder demand but maybe a combination of multiple factors:
  - High surface area and angularity
  - Still relatively high absorption compared to other aggregates used in mix (granites)
  - Ash-aggregate may breakdown during compaction which generates more fines that may absorb binder
  - Dust can also act as a “filler” reducing binder content, which means the increasing VMA also means that more binder is needed to fill in the space

# HMA Physical Performance

- Three primary ways for HMA to fail:

*Rutting (Deformation)*

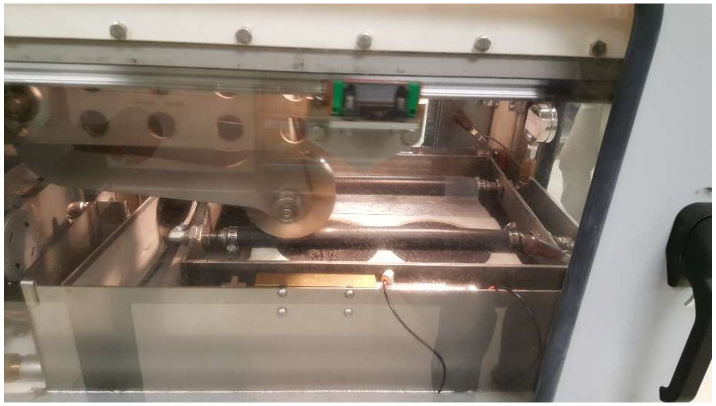


*Cracking*


*Stripping*

# Rutting Susceptibility

- Method used by FDOT:
  - Asphalt Pavement Analyzer (APA) – AASHTO TP 63
- Measure of deformation over 8000 cycles (140 deg. F) in mm



| Mixture | Deformation (mm) |
|---|---|
| **Mix A** | 1.878 |

*Why the increase?*

# Effects of Ash Particle Size

- Washing changed the gradation of the Combined Ash by increasing the ratio of 3/8 inch -No.4 material in this mixture
- Rutting susceptibility is dominated by the coarse aggregate – coarse aggregate is now increasingly made up of ash

| Gradation | % Passing (by Mass) | | | |
|---|---|---|---|---|
| | Bottom Ash | | Combined Ash | |
| | Untreated | After Washing | Untreated | After Washing |
| 19 mm (3/4 in.) | 100 | 100 | 100 | 100 |
| 12.5 mm (1/2 in.) | 59 | 59 | 89 | 94 |
| 9.5 mm (3/8 in.) | 26 | 29 | 60 | 64 |
| 4.76 mm (No. 4) | 4 | 2 | 17 | 3 |

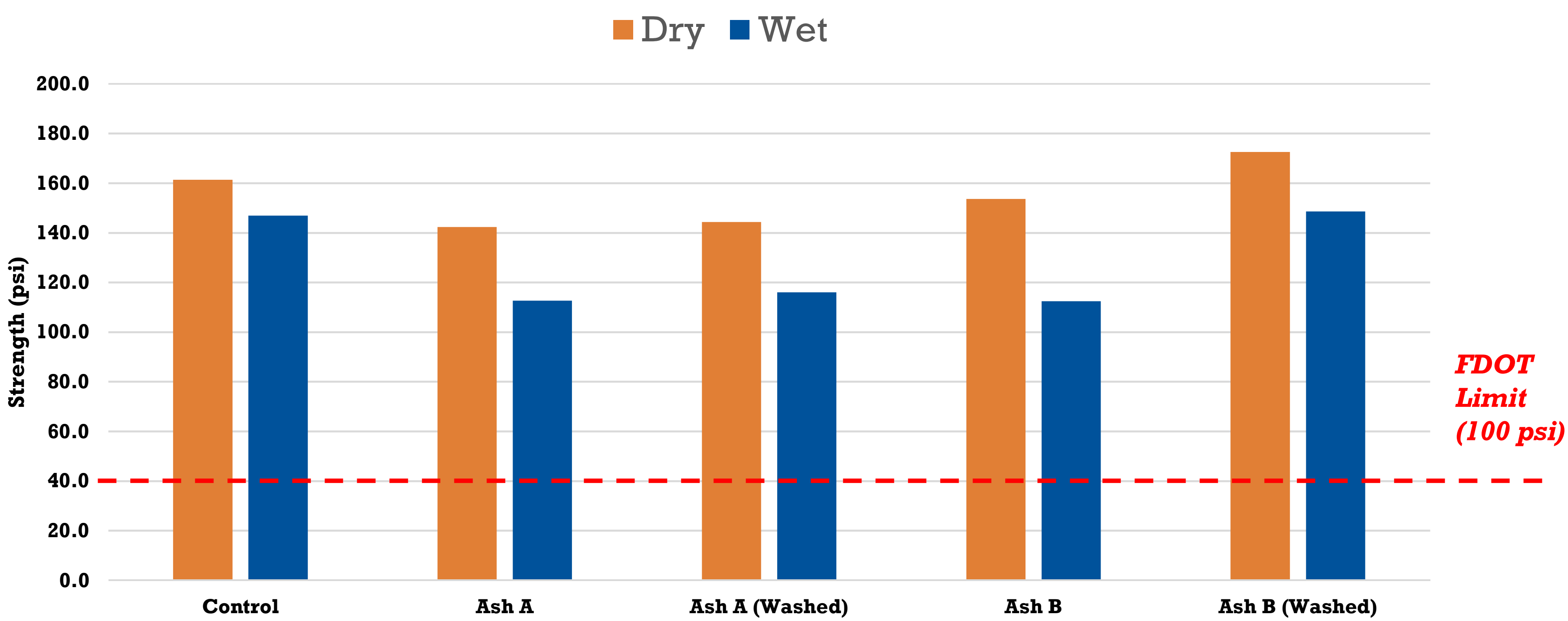
***43% Retained on #4 vs.***
***61% Retained on #4***

# *Indirect Tensile Strength and Moisture Susceptibility (FM 1-T283, FDOT Method)*

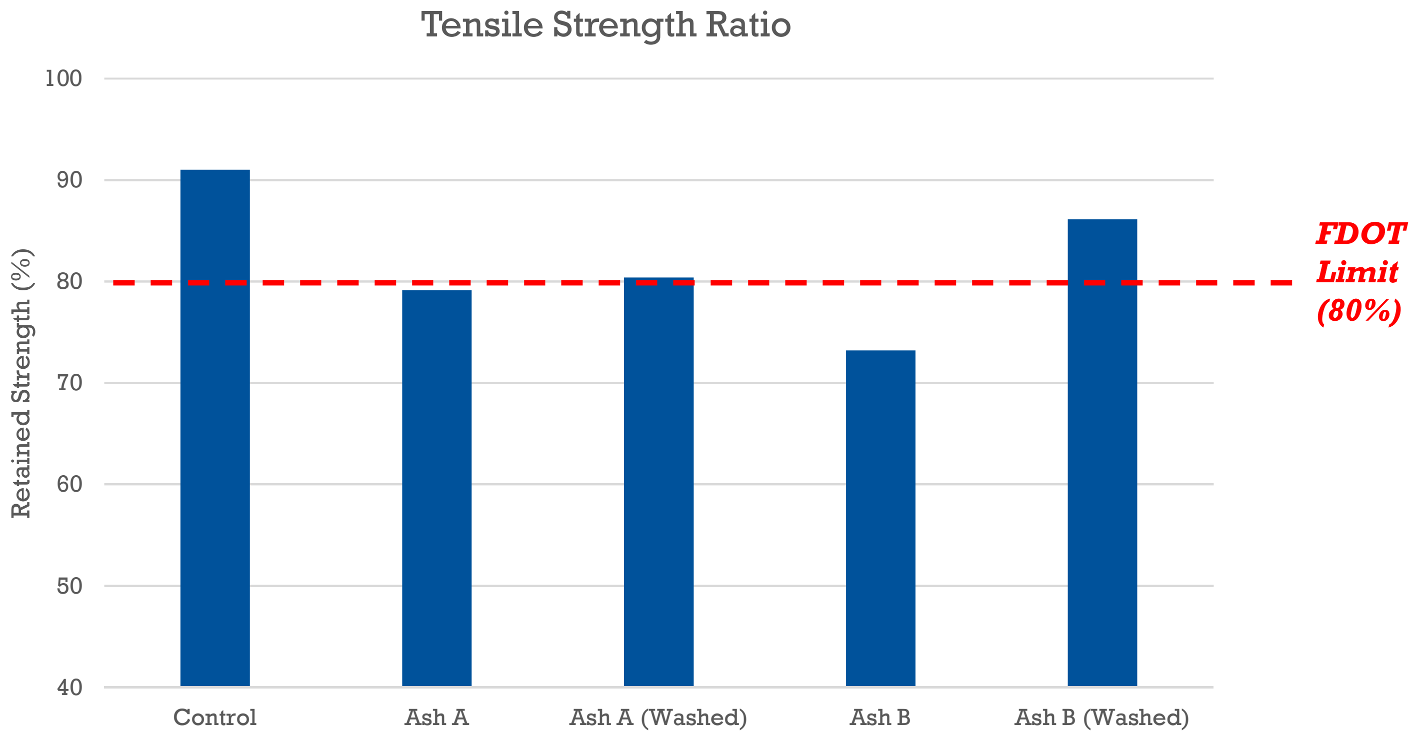
Vacuum Saturate: 70-80%

Indirect Tensile Strength

# Indirect Tensile Strength (Cracking)



# Moisture Susceptibility



# “Dry” Condition vs. “Wet” Condition


*“Dry”*


*“Wet”*

# Big Picture Takeaways

- Washing ash produces a higher quality aggregate (and by default, HMA product)
- Binder demand appears to be linked to other factors besides absorptive fine ash
- Need to ***design for*** ash-aggregate
  - Control asphalt binder content (5.3%) was met by an ash mixture by using less fine aggregate
- Large pieces (>3/8”) of glass and ceramics in WTE ash appear to be limiting factors in ash reuse in HMA

# Paving a Way Forward

- Glass powder and WTE ash show promise when used in PCC and HMA
- But how do we move from lab to market?
- What is the infrastructure needed to collect, process, and deliver this material to market – and how does it compare to its competitors?

# *Economic Feasibility of Waste Glass and WTE Ash Recycling*

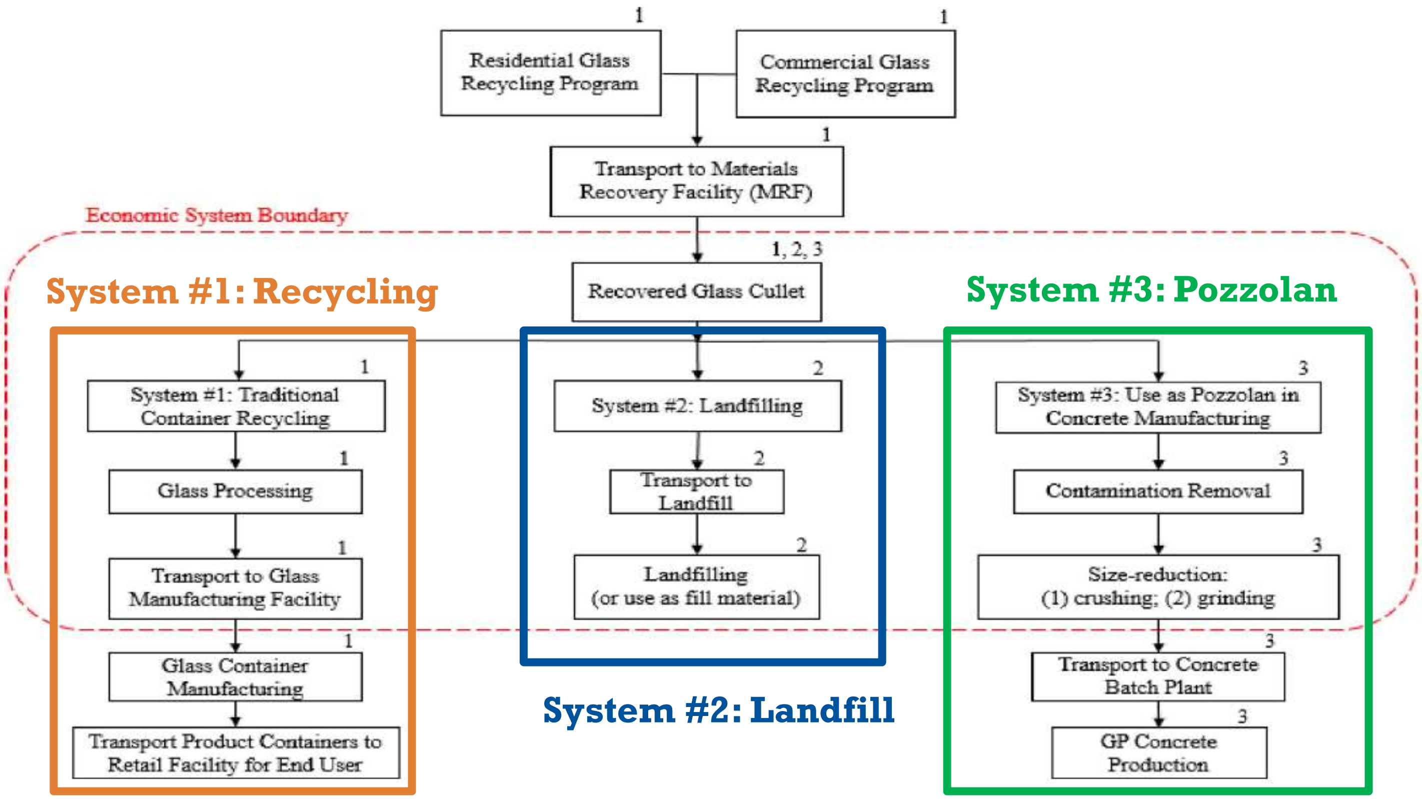
# *Waste Glass as a Pozzolan Recycling Economics*

# Waste Glass as Glass Powder

- A major issue for recycled waste glass is low market value
  - Contaminants, mixed colors
  - Landfilled in some places as a cheaper alternative

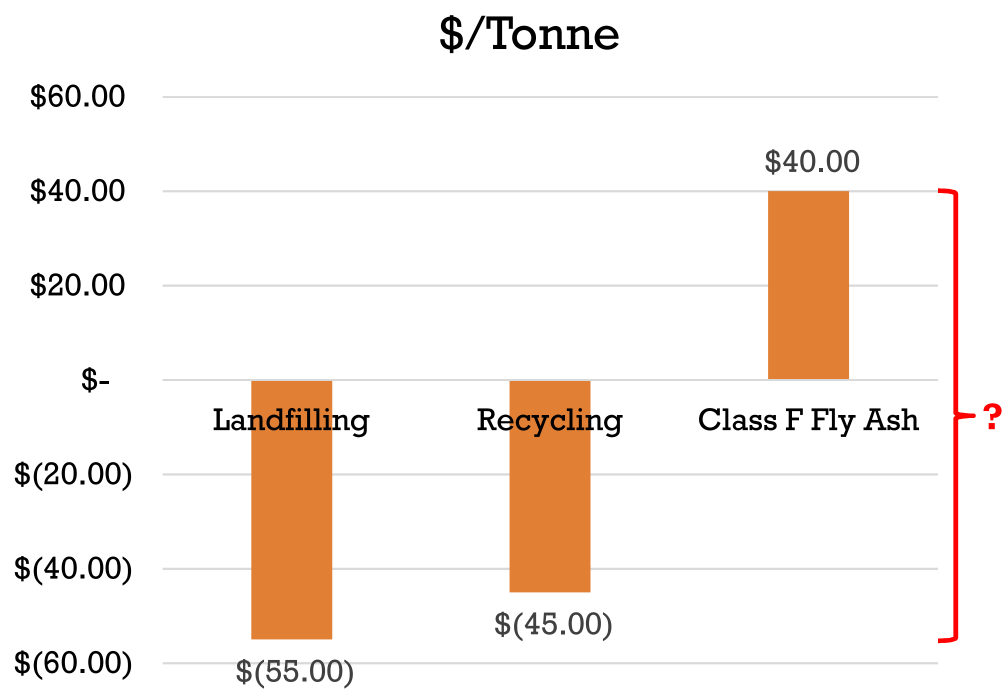
- Transforming waste glass to a pozzolan may be economically attractive option compared to:
  - Landfilling
  - Container recycling

# Waste Glass Economic System



# Landfilling v. Traditional Recycling v. GP Pozzolan Market

- Landfilling
  - National avg. tipping fee = $55 per tonne
  - Option to use cullet as landfill depression fill material
    - In FL, FDEP permitting is required
    - Virgin sand and soil retails for approx. $8 per tonne
- Traditional container-to-container recycling
  - MRF outsources to a glass processing company
    - ~$10 to ~$45 per tonne for contaminated MRF cullet
- GP Pozzolan Market
  - **Processing costs??**



# Glass Powder (GP) Pozzolan Size-Reduction Process

**Negatively sorted MRF Glass (end of line)**

**Step 1: Remove Bulk Contaminants**

**9,500 μm Crushed Cullet**

**Step 2: Crush to Cullet Size, Remove Additional Contaminants**

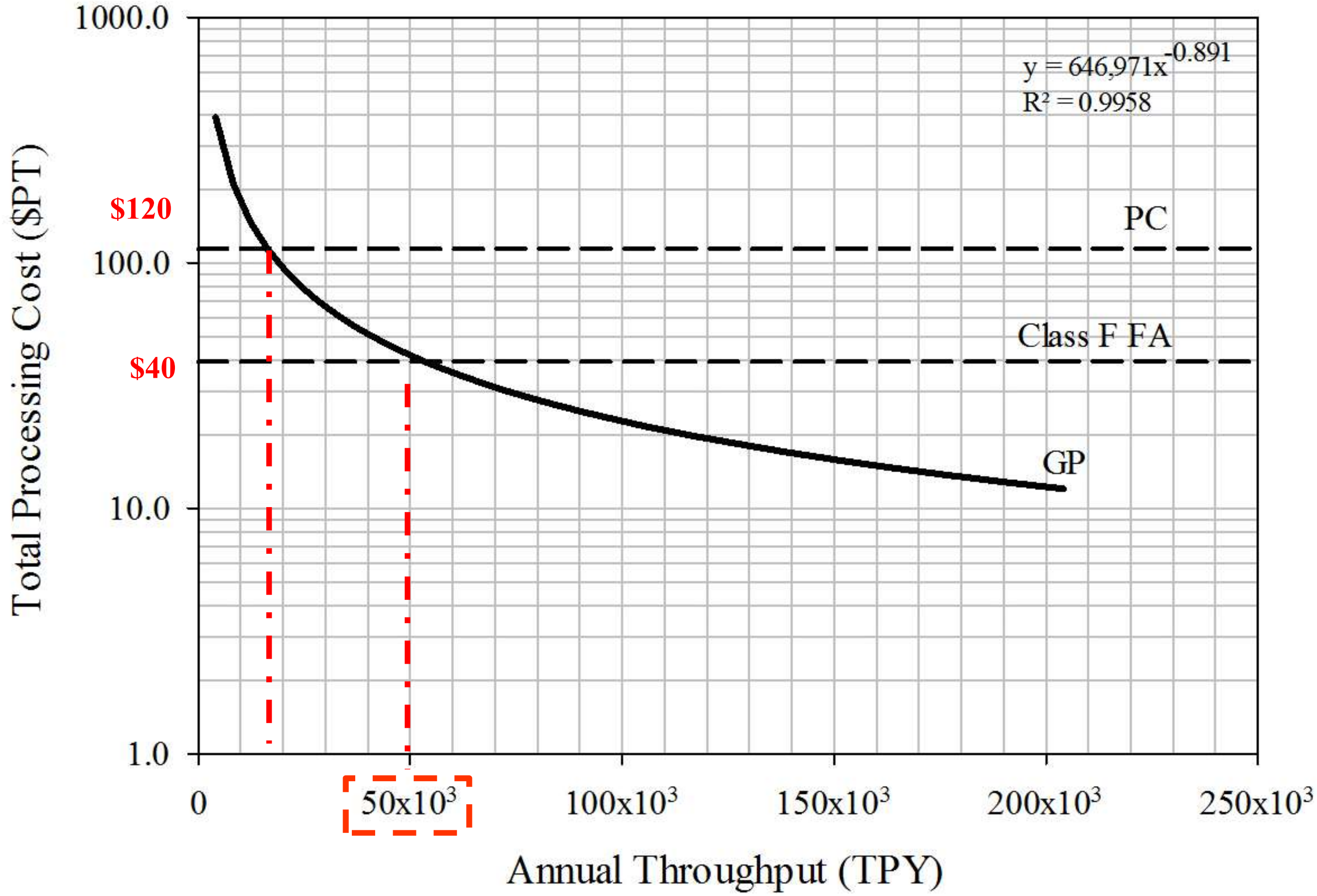
**GP Pozzolan (10 μm)**

**Step 3: Milling**

# Annual GP Pozzolan Costs

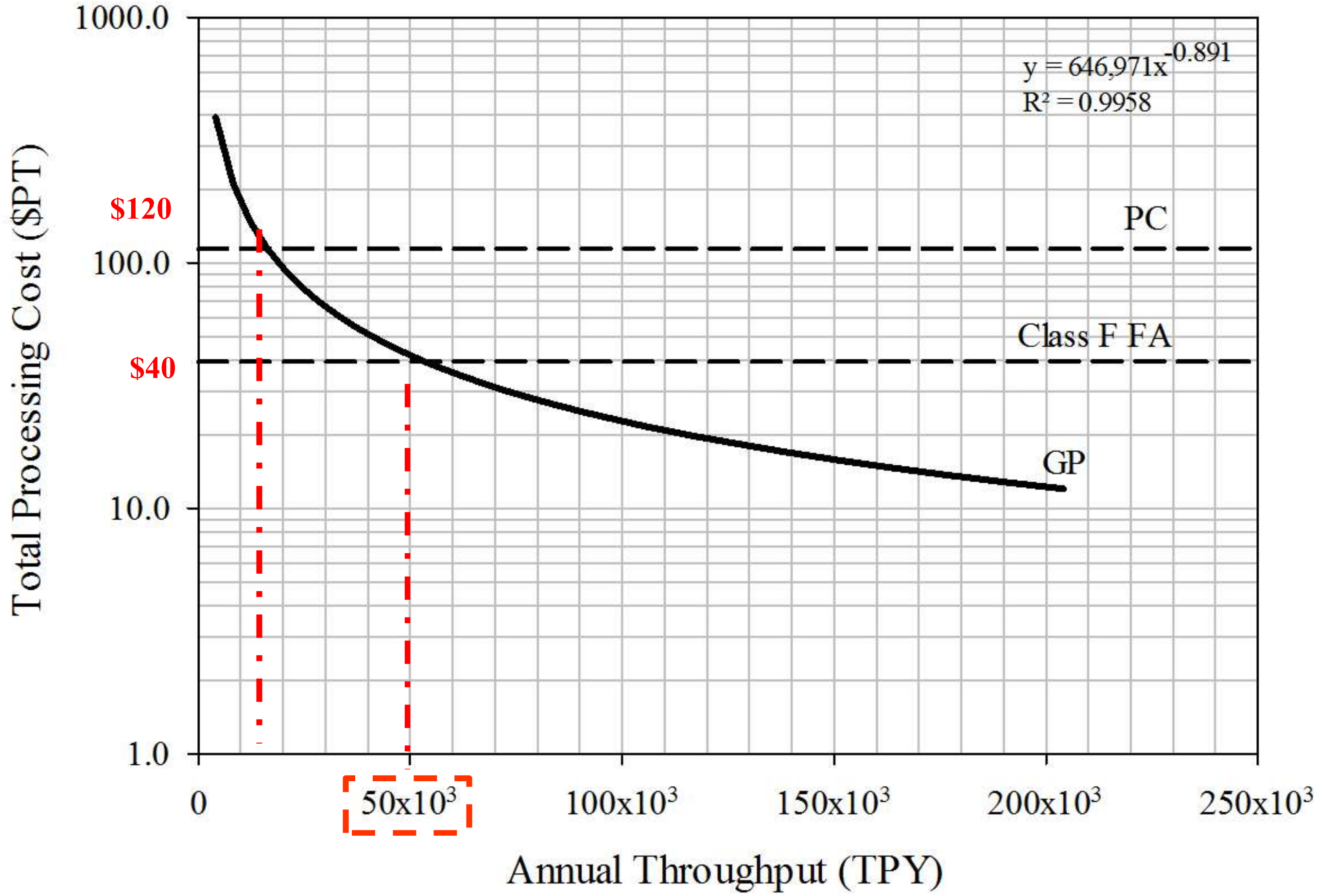
- Based on 1-45 tph throughput range; 4,500 hpy operating time; and 10-Year Lifespan
- Equipment (10-Year Lifespan)
  - 10 manufacturers → 17 quotes
- Building (30-Year Lifespan)
  - 930 m2 (based on 10 SMI facilities)
  - RSMeans: Warehouse Construction Cost
    - Annual Operating Cost
      - Electricity and fuel from 2016 USEIA commercial warehouse data
- Land (30-Year Lifespan)
  - 5 acres (SMI)

| Categories | Annual Cost ($PY) |
|---|---|
| *Fixed Capital* | |
| Purchased equipment + 43% Installation | 300,000 - 500,000 |
| Building (930 $m^2$) | 30,000 |
| Land (20,000 $m^2$), 6% purchased equipment | 5,000 - 7,000 |
| Property insurance, 1.0% total fixed capital | 4,000 - 5,000 |
| Property taxes, 1.5% total fixed capital | 5,000 - 8,000 |
| Total Annual Fixed Capital Costs | 345,000 - 550,000 |
| *Operating* | |
| Equipment | 175,000 - 350,000 |
| Building | 9,000 |
| Total Annual Operating Costs | 185,000 - 360,000 |
| *Maintenance* | |
| Building, $3/h (4,500 hpy) | 15,000 |
| Equipment, 7% purchased equipment | 15,000 - 25,000 |
| Ball mill media (25% loading, 1x annual replacement) | 5,000 - 275,000 |
| Total Annual Maintenance Costs | 35,000 - 315,000 |
| *Labor* | |
| Operating Labor | 600,000 |
| Supervision, 15% operating labor | 90,000 |
| Plant Overhead, 60% operating labor + supervision + equipment maintenance | approx. 400,000 |
| General Administration, 25% operating labor | 150,000 |
| Total Annual Labor Costs | 1,250,000 |
| **Total Annual Costs** | **1,815,000 - 2,475,000** |

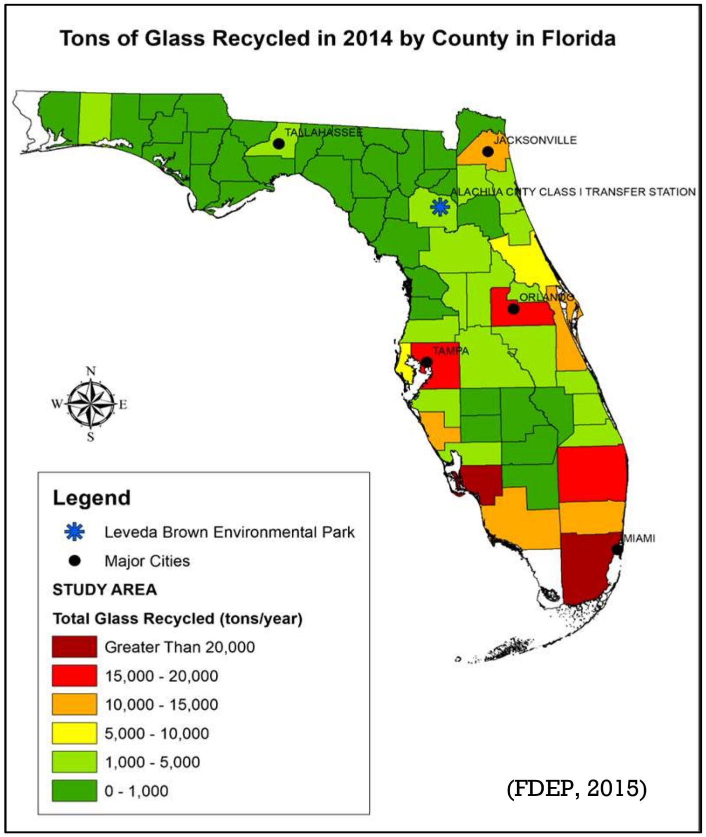

1000.0
100.0
10.0
1.0
$120
$40
Total Processing Cost ($PT)
y = 646,971x-0.891
R² = 0.9958
PC
Class F FA
GP
0
50x10³
100x10³
150x10³
200x10³
250x10³
Annual Throughput (TPY)

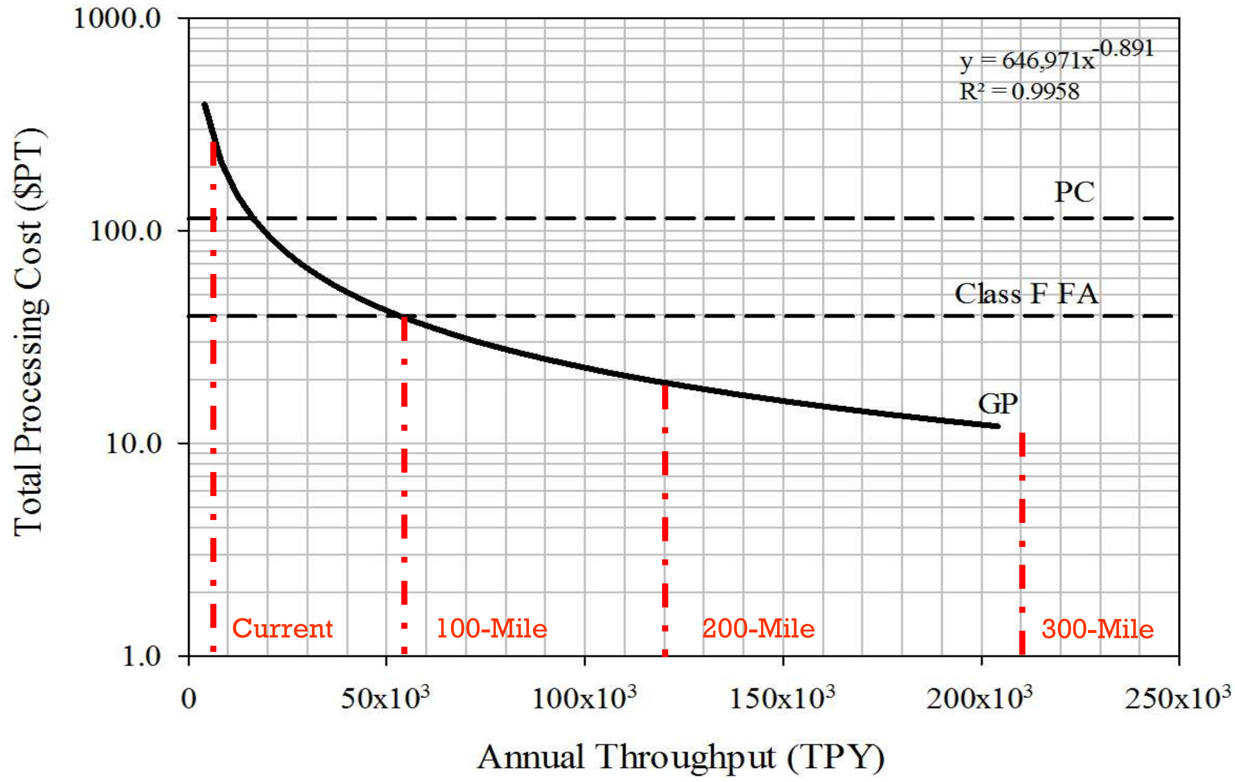
# Case Study: North Central FL, USA

- Alachua County = **max. 7,500 TPY** of glass
- Pays **$20 per tonne** to recycle
- Use as Fill Material
  - ~ **$5.50 per tonne** (including labor, landfill equipment operation, transportation and administration fees)
  - FDEP permit approval
- Combination Example:
  - Orange County, FL sends 90% of its recovered cullet to a company and 10% to Seminole County's landfill as alternative daily cover; both options **~$9 per tonne**


1000.0
100.0
10.0
1.0
$120
$40
Total Processing Cost ($PT)
y = 646,971x-0.891
R² = 0.9958
PC
Class F FA
GP
0
50x10³
100x10³
150x10³
200x10³
250x10³
Annual Throughput (TPY)

# Recycled Glass in FL




y = 646,971x^-0.891
R² = 0.9958
PC
Class F FA
GP
Current
100-Mile
200-Mile
300-Mile
1000.0
100.0
10.0
1.0
Total Processing Cost ($PT)
0
50x10³
100x10³
150x10³
200x10³
250x10³
Annual Throughput (TPY)

# Waste Glass Recycling Takeaways

- Waste glass processing for GP relies on throughput
  - More throughput = lower cost
- The largest challenge is accessing enough waste glass
  - Importing waste glass may be necessary for smaller-throughput MRFs
  - Transport fees may be offset by charging fees for MRFs that are still less than disposing/conventional recycling

# Ash Reuse Economics

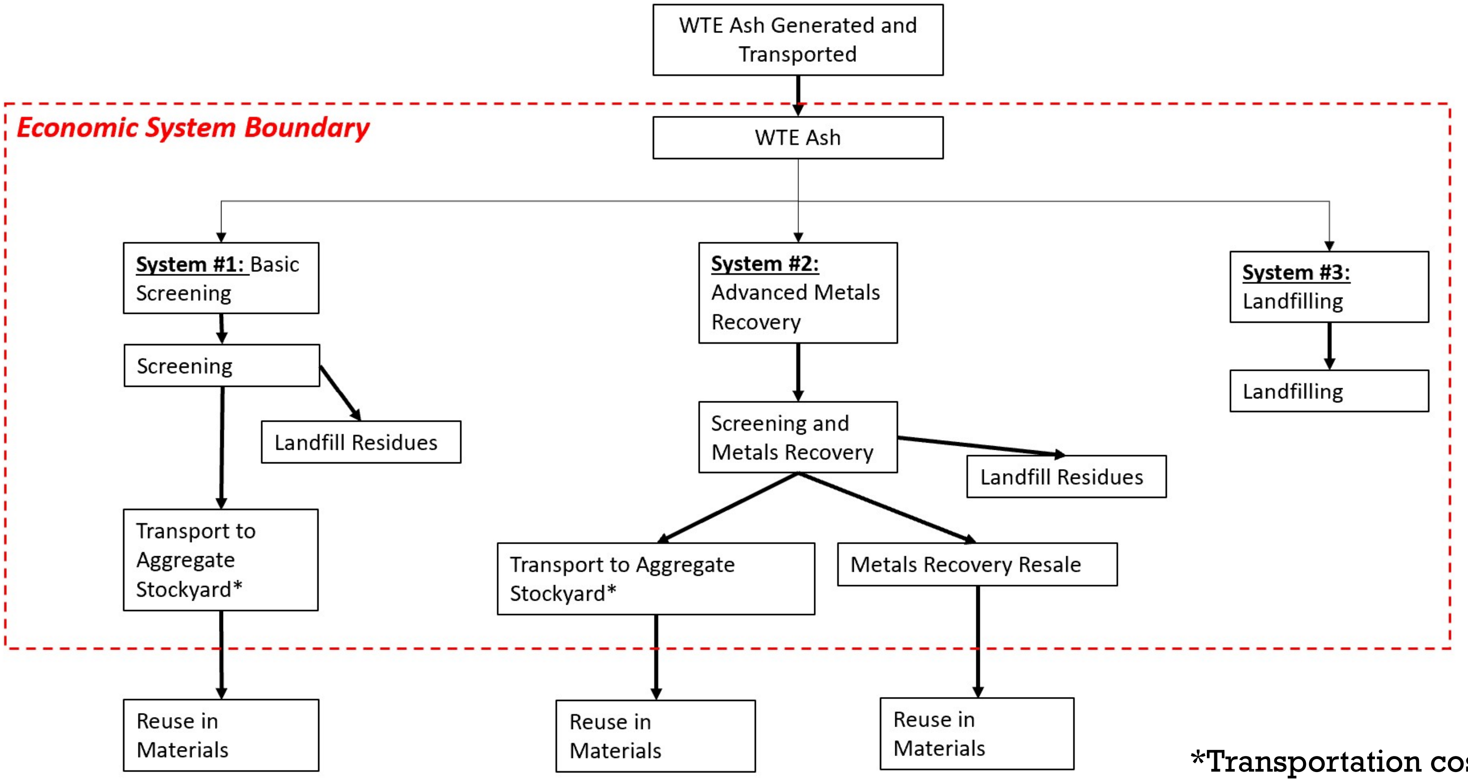
# Ash Recycling

- WTE bottom ash recycling already occurs in some parts of the world
  - Specifications exist to ensure proper handling and construction of ash-amended products
- A common use for bottom ash is as a road base aggregate
  - Requires a large particle size range – maximizes reuse of material

# The Cost of Ash Recycling

- Ash recycling costs have not been examined much in the literature
  - Especially what drives these costs
- Ash has to compete with other common aggregates for base
  - Crushed rock -- $11.90/tonne (national avg.)
  - Transportation costs to get ash-aggregate to stockyard
- However, there are some cost benefits to recycling ash
  - Landfill diversion (avoiding tipping fee)
  - Potential for advanced metals recovery

# Ash Recycling Economic Boundary




*Transportation costs factored in

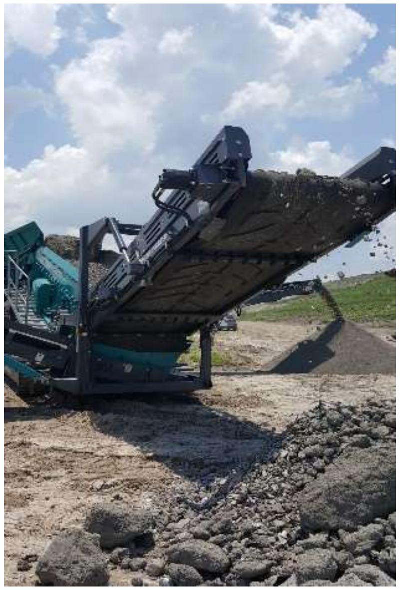
# Purpose of Screening and Processing

Screening for desired size fraction

- Remove excessive finer materials and large, cumbersome particles
- More consistent material
- Meet road base specifications

Residues sent to Landfill ~ 10%

- Overs (>2 in)
- Wasted (Unburnt waste)

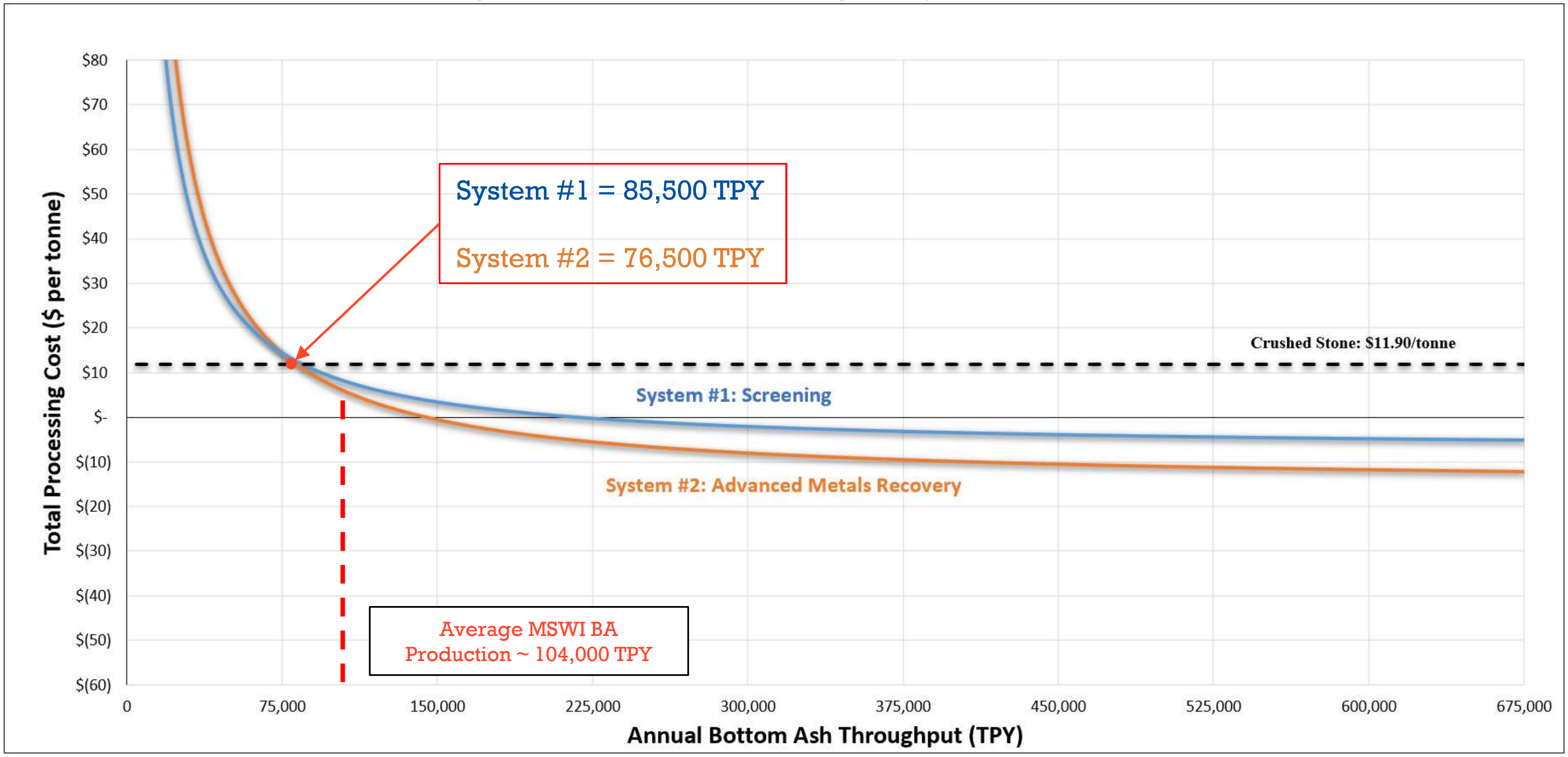


# Annual Cost Breakdown

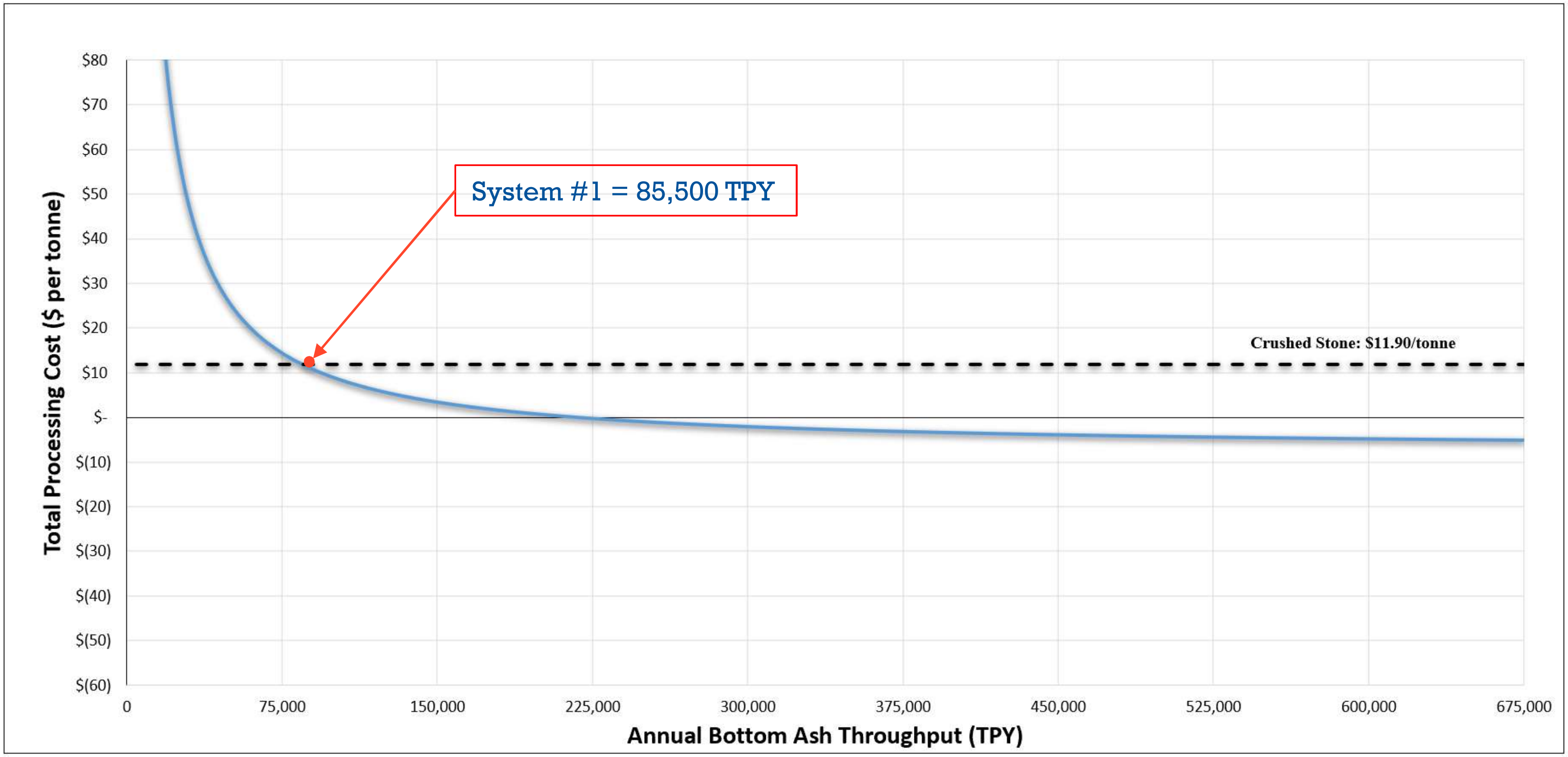
- Based on 4,500 TPY to 675,000 TPY throughput, 4,500 HPY operation time
- Equipment (10-yr lifespan)
- Key Difference: Advanced
- Building (30-year lifespan)
- Land (30-year lifespan)

| Categories | System #1 Costs ($) | System #2 Costs ($) |
|---|---|---|
| **Fixed Capital** | | |
| Purchased Equipment | 101,334 | 219,112 |
| Building (30,000 ft$^2$) | 72,650 | 72,650 |
| Land (9 acres), 6% purchased equipment | 30,000 | 30,000 |
| Property Insurance, 1.0% total fixed capital | 2,040 | 3,218 |
| Property Taxes, 1.5% total fixed capital | 3,060 | 4,826 |
| **Total Annual Fixed Capital Costs** | 209,083 | 329,806 |
| Operating | | |
| Equipment | 779,781 | 996,270 |
| Building | 53,754 | 53,754 |
| **Total Annual Operating Costs** | 833,535 | 1,050,024 |
| Maintenance | | |
| Building, $3/h (4500 HPY) | 13,500 | 13,500 |
| Equipment, $1.37/t processed | 6,165 - 924,750 | 6,165 - 924,750 |
| **Total Annual Maintenance Costs** | 19,665 - 938,250 | 19,665 - 938,250 |
| **Labor** | | |
| Operating Labor | 202,500 | 337,500 |
| Supervision, 15% operating labor | 30,375 | 50,625 |
| Plant Overhead, 60% operating labor + supervision + equipment maintenance | 143,424 - 694,575 | 234,574 - 787,725 |
| General Administration, 25% operating labor | 50,625 | 84,375 |
| **Total Annual Labor Costs** | 426,924 - 978,075 | 707,074 - 1,260,225 |
| **Total Annual Costs** | 1,489,207 – 2,958,943 | 2,106,569 – 3,578,305 |

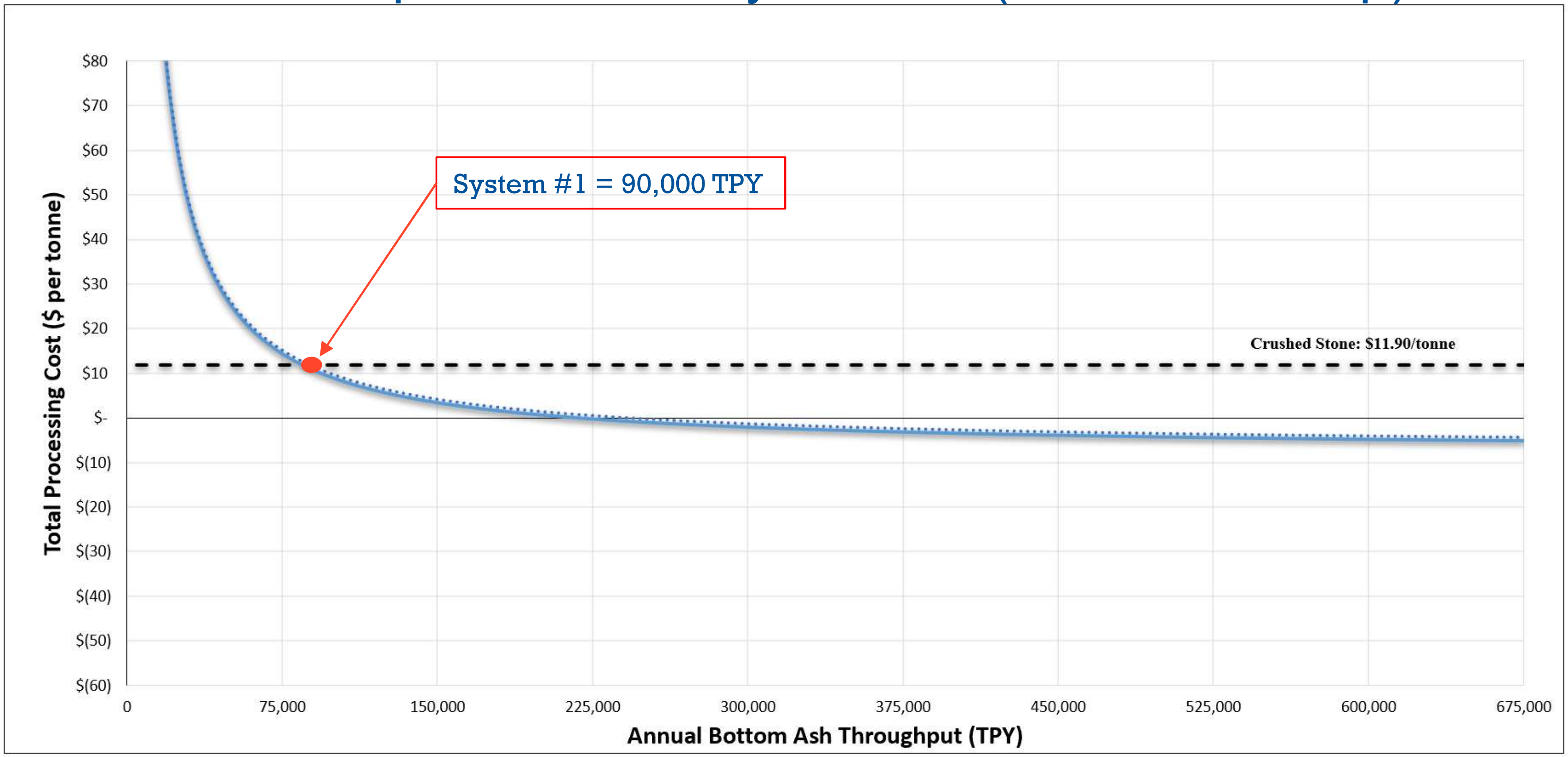
# Baseline Costs (no transport) Systems #1 and #2



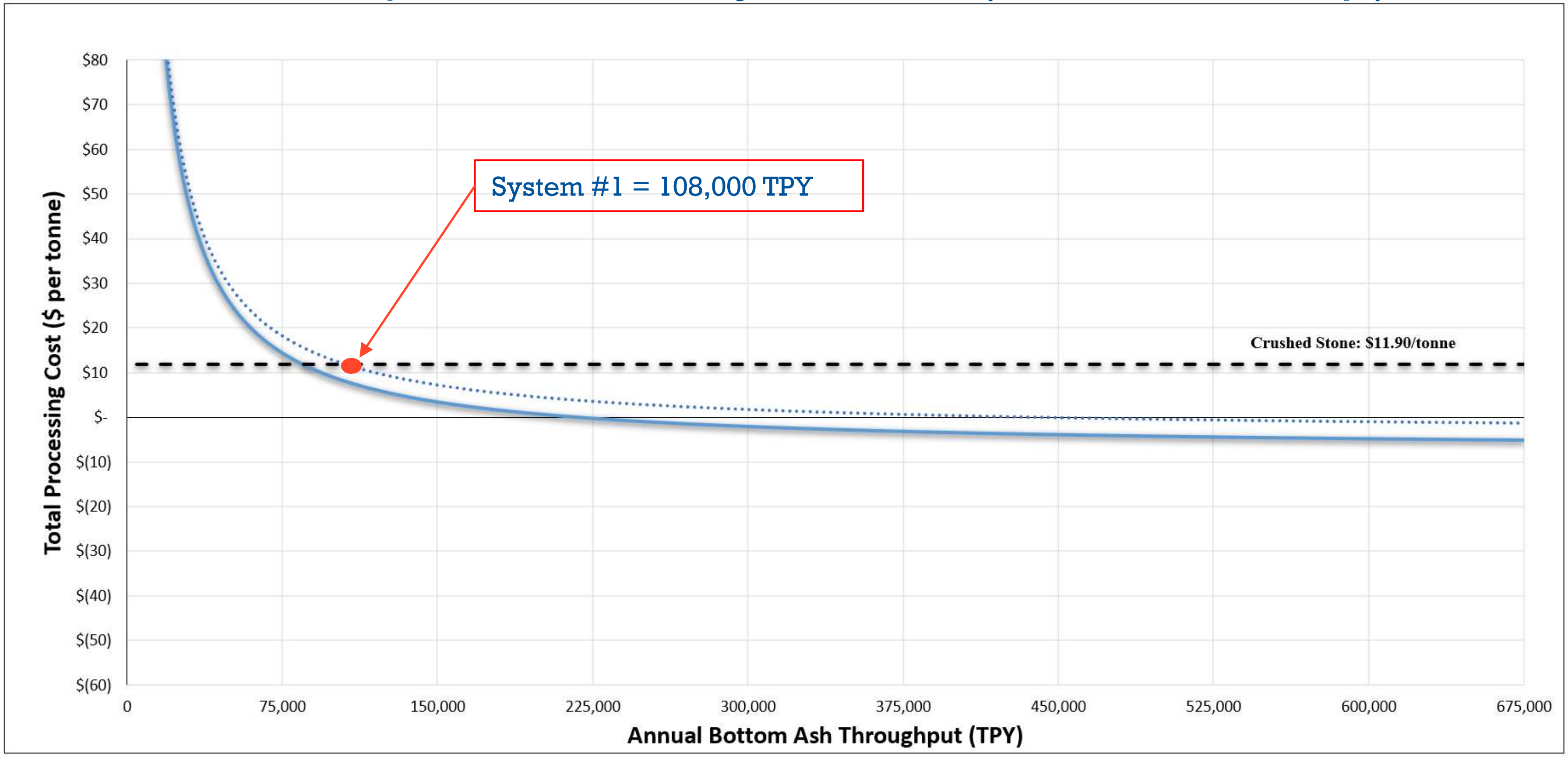
# Effects of Transportation on System #1 (0-mi roundtrip)



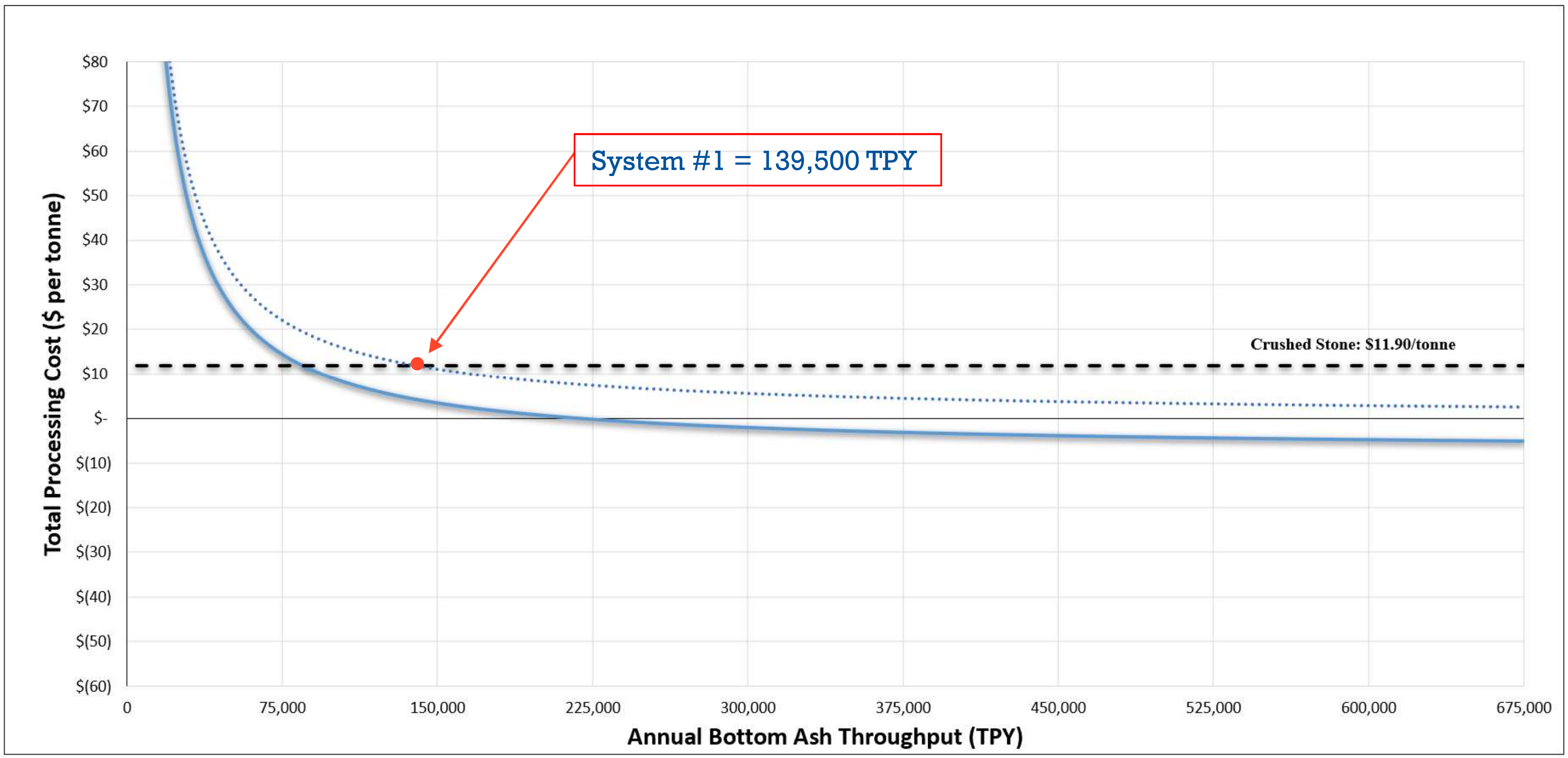
# Effects of Transportation on System #1 (10-mi roundtrip)



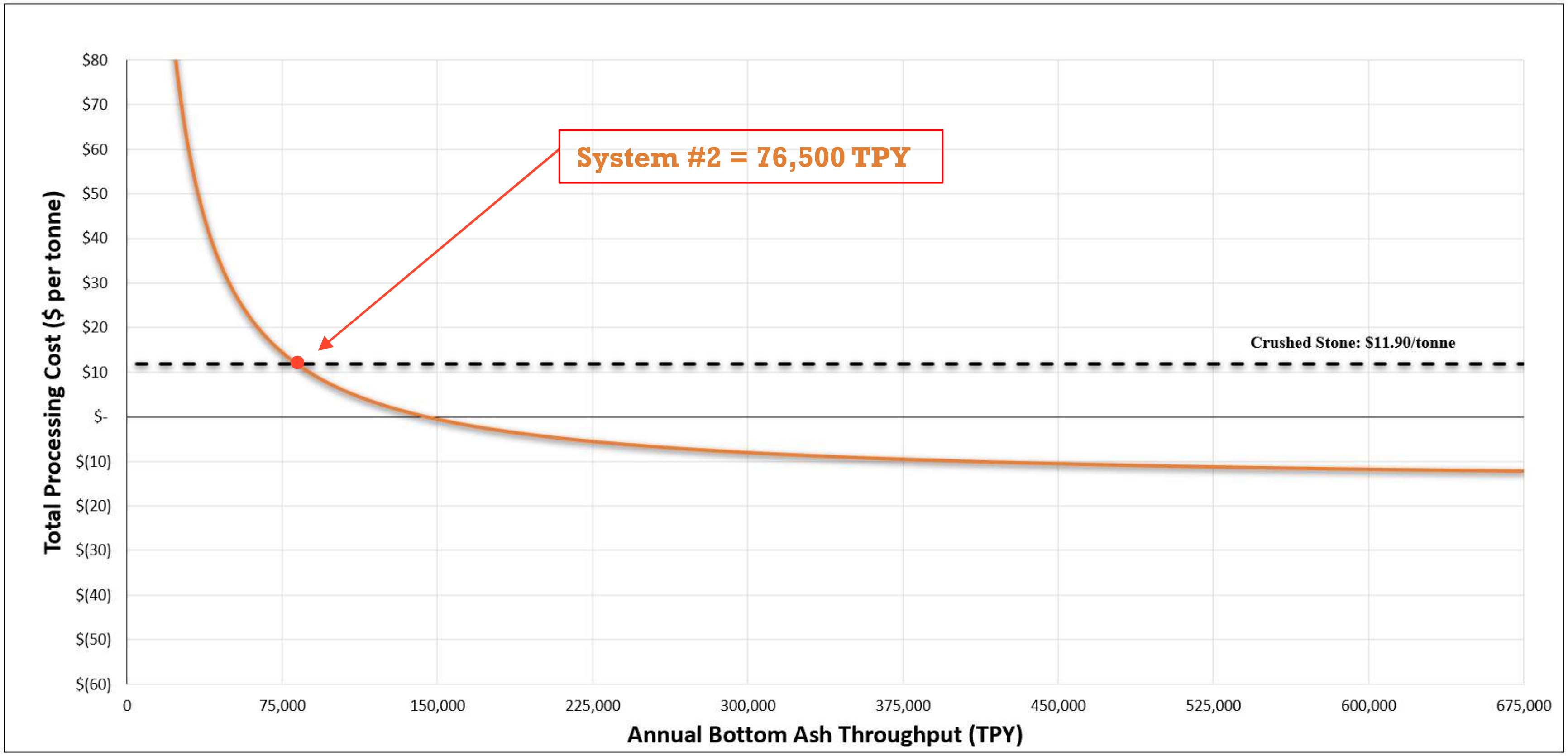
# Effects of Transportation on System #1 (50-mi roundtrip)



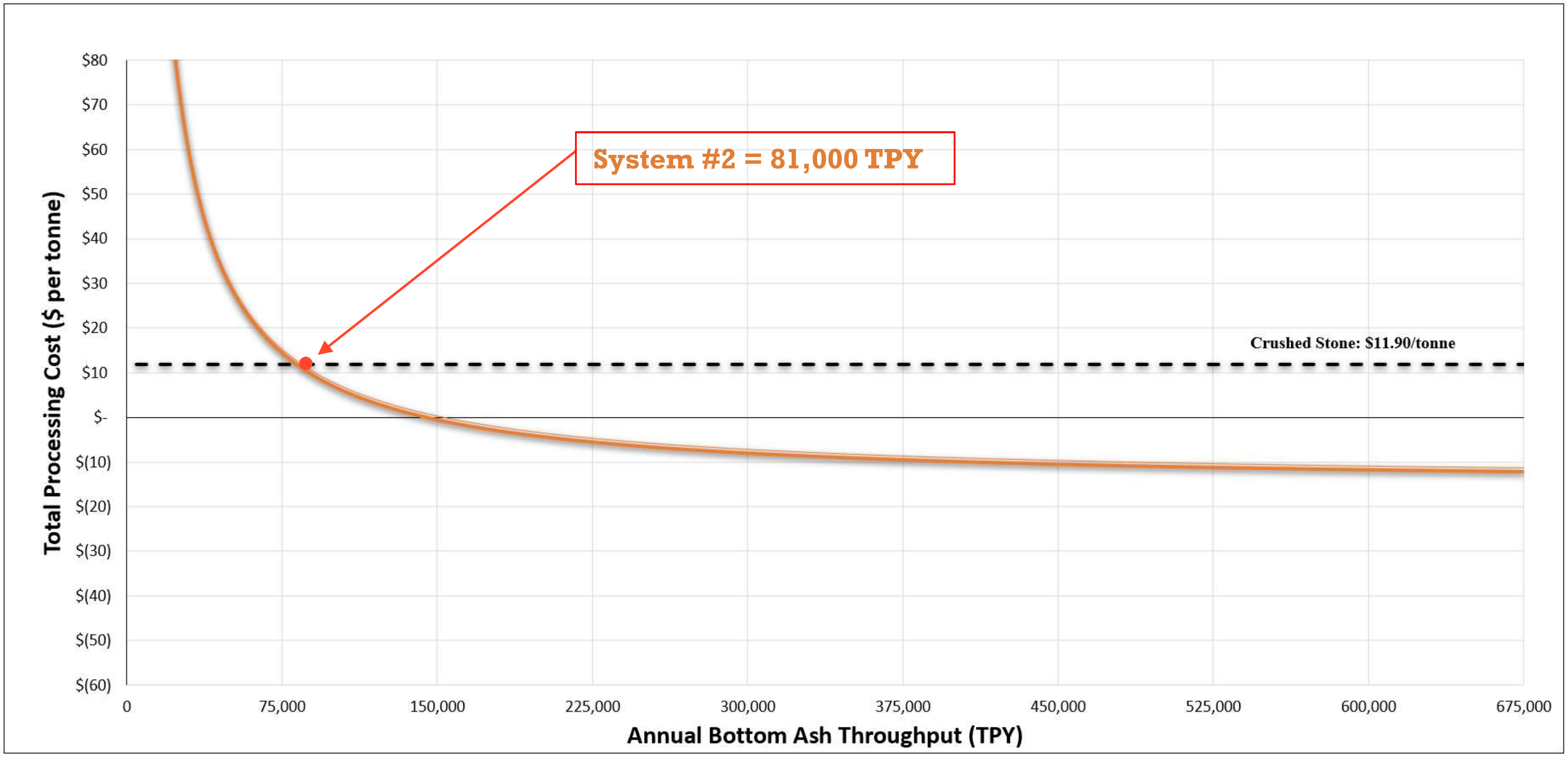
# Effects of Transportation on System #1 (100-mi roundtrip)



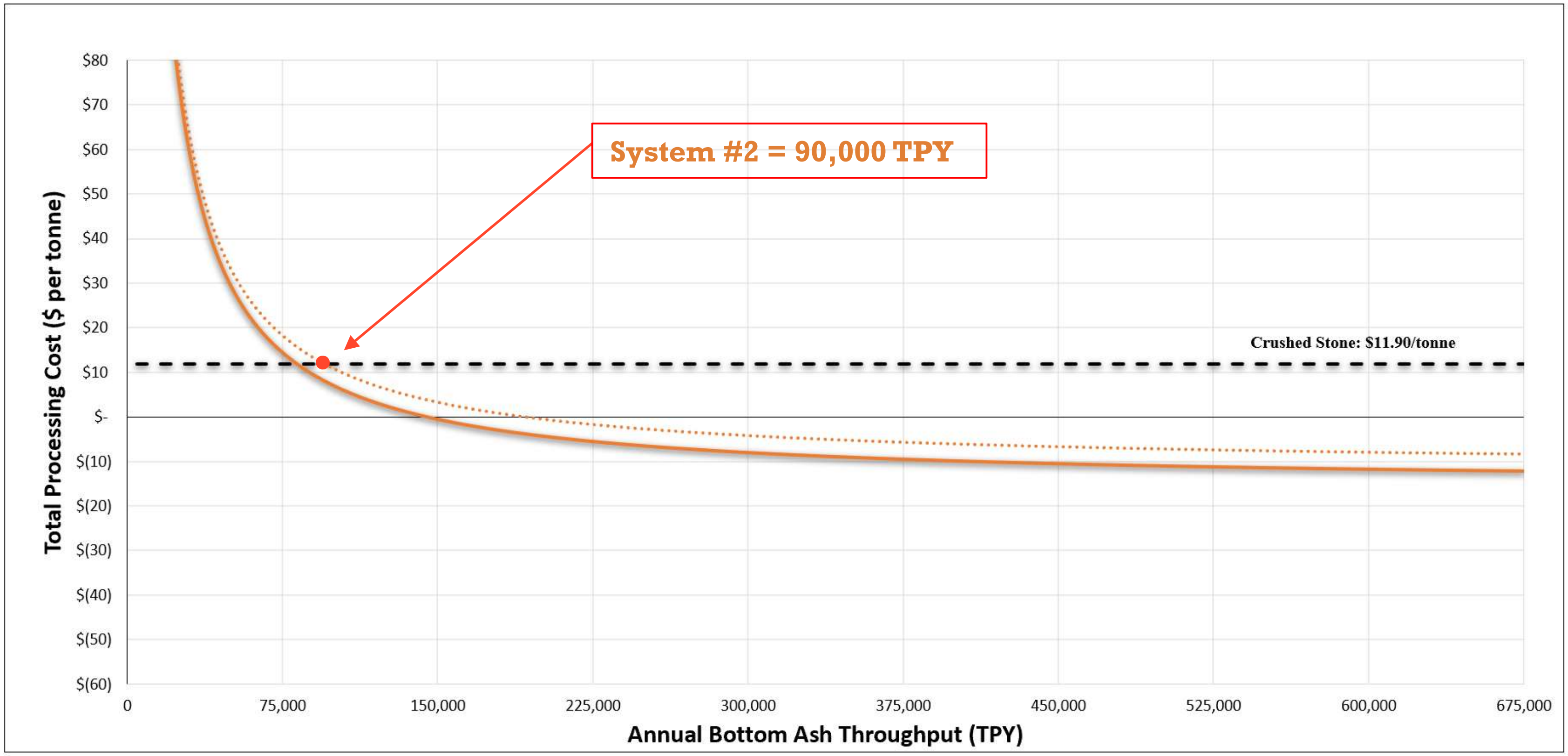
# Effects of Transportation on System #2 (0-mi roundtrip)



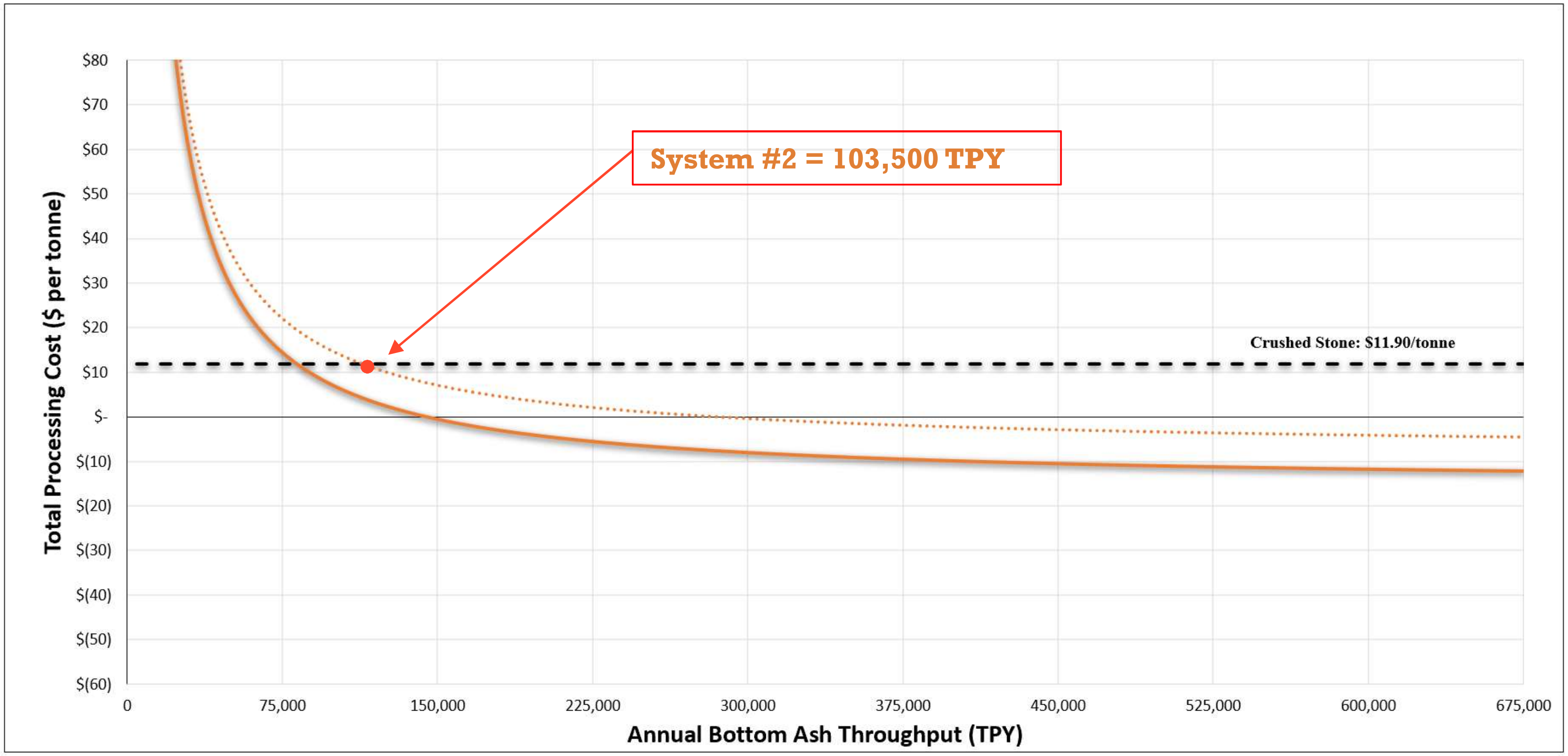
# Effects of Transportation on System #2 (10-mi roundtrip)



# Effects of Transportation on System #2 (50-mi roundtrip)



# Effects of Transportation on System #2 (100-mi roundtrip)



# Feasibility – Metals Sensitivity Analysis for System #2

| System #2 – Sensitivity Analysis for Throughputs Necessary for Breakeven | | | | | |
|---|---|---|---|---|---|
| **Distance to Aggregate Yard (miles, roundtrip)** | Original (TPY) | % Change in Metals Yield | | % Change in Market Value of Metals | |
| | | 20% Increase | 20% Decrease | 20% Increase | 20% Decrease |
| **0** | 76,500 | 72,000 | 85,500 | 72,000 | 90,000 |
| **10** | 81,000 | 76,500 | 85,500 | 76,500 | 90,000 |
| **50** | 90,000 | 85,500 | 99,000 | 85,500 | 103,500 |
| **100** | 103,500 | 94,500 | 117,000 | 94,500 | 117,000 |

*How would washing affect this?*

# Big Picture and Next Steps

- Similar to waste glass, WTE ash feasibility is strongly influenced by throughput
  - Advanced metals recovery incurs higher capital costs but these can be offset by profits from metals resale
- For ash recycling:
  - Metals type and quality (grade) can impact profits from recovery
  - Transportation distance can be a major driver of costs
- Washing WTE ash is likely a necessary step for increasing its reuse in concrete and asphalt applications
  - Higher cost to operate, but also higher quality (more profitable) product
  - What to do with wash water/filter cake?

# *Future Areas of Work*

# Specifications for Waste Materials

- Lack of dedicated specifications for utilizing WTE ash as aggregate in road base, asphalt and portland cement concrete
  - UF is working with FDOT to begin to develop such specifications specifically considering WTE ash
- Specifications are also needed for waste glass as a pozzolan
  - Contamination limits, fineness requirements, etc.

# Understanding Metals Content and Quality

- Advanced metals recovery is of growing interest in North America
- Recovering of metals such as aluminum, copper and lead should make better aggregates
- Metals recovery can also make recycling more feasible economically
- Profits from metals influenced by amount and quality of metals
- Current practices of waste processing (e.g., quenching) and landfilling can affect metals quality
  - Ferrous/aluminum corrosion results in "lost" resources


# *Discussion*

UF Herbert Wertheim College of Engineering
UNIVERSITY *of* FLORIDA

# Research Advances on the Use of Solid Wastes in Concrete and Asphalt

The Hinkley Center for Solid and Hazardous Waste Management

Technical Advisory Group Meeting

May 13, 2019

POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE