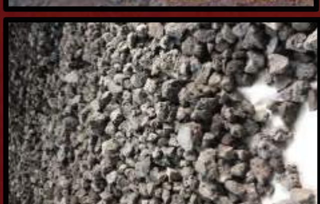
Civil and Environmental Engineering Department

# *Steel Slag as a Paving Aggregate: Properties, Applications, and Comparison to Alternatives*

**Summary of a Technology Transfer Event Developed, Organized, and Conducted By:**


Isaac L. Howard – Mississippi State University
Travis Zimber – Edward C. Levy
Kelly Cook – Edward C. Levy
John J. Yzenas Jr. – Edward C. Levy
Taylor Cagle – Mississippi State University
Leigh E.W. Ayers – Mississippi State University


**Spring 2019**



Mississippi State University
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Construction Materials Research Center
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## Technical Report Documentation Page

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16. Abstract

This workshop was held on February 27, 2019 and was tailored to a regional market, generally several dozen miles from Starkville, MS. The workshop's focus was steel slag and how steel slag can be beneficially used for paving applications. The workshop began with a discussion of fundamental properties of steel slag and transitioned to aggregate needs for shoulder applications. Thereafter, aggregate needs for unsurfaced roads and parking lots were discussed, prior to ending the workshop with the role of aggregates in pavement design.

| | | | |
|---|---|---|---|
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# Table of Contents

## Disclaimer

The contents of this workshop report were provided for knowledge transfer and general information. This document was written in the interest of information exchange. The organizers assume no liability for the contents or use of this document.

## Acknowledgements

Thanks are due to many for the successful completion of this technology transfer activity. This project was funded by the Edw. C. Levy company; Michael Lockwood is owed thanks. The Mississippi Department of Transportation (MDOT) provided a considerable amount of information related to their shoulder aggregates practices. MDOT contributors included: District 1 – Nan Mitchell, Mark Holley; District 2 – Mitch Turner; District 3 – Kevin Magee; District 5 – Graham Clarke, Neil Patterson, Brian Ratliff; District 6 – Kelly Castleberry; District 7 – Albert White; Research Division – Alex Middleton, Marta Charria; Materials Division – Griffin Sullivan. Several others also provided content from activities occurring outside Mississippi: Zack Smith (Noble County Highway Department – Indiana); Jennifer Sharkey and Emmett Heller (Steuben County Highway Department – Indiana); Michael Barton (Whitely County Highway Department – Indiana); Pennsylvania DOT.

# Program Description and Overview of Steel Slag Applications

## Program Description

The Mississippi State University (MSU) Construction Materials Research Center (CMRC) has been evaluating steel slag for use in the regional market since the summer of 2017. This evaluation has led some in the market to inquire about applications for steel slag (paving applications in particular). During this time frame, CMRC was collecting data with steel slag available in the regional market and reviewing practices/findings from other markets. The inquiries and data being collected ultimately led to the decision to hold a workshop in the spring of 2019 that is summarized in this document; Figure 1 provides photos taken during the workshop.

Late in the 2018 calendar year, a flyer was generated related to registration, and this flyer was sent to several groups in Mississippi and surrounding states (Figure 2). Over the next several weeks, registration and workshop planning took place. The event was held at The Mill Conference Center adjacent to the MSU campus on February 27, 2019 to a total attendance of 75. Attendees represented nine groups: consultants or design firms; material suppliers or manufacturers; Mississippi Department of Transportation; MSU faculty/staff (planning, design, construction); MSU students; contractors; State Aid Roads representatives; county supervisors representatives; and the National Slag Association. Attendees were given a certificate worth 4 Professional Development Hours (PDH's) for attendance at all activities.

## Technical Content and Presentations

Figure 3 is the agenda handed out to attendees. The schedule in Figure 3 was generally followed. After opening remarks, there were four presentations given, and each of them are briefly summarized in the remainder of this section. In a few cases, the summaries shown have additional content beyond what was given in the workshop. This summary report also contains the slides as used by presenters that are provided in the order given at the workshop. These slides have identical technical content relative to the actual slides used by the speakers, but there have been a few non-technical modifications for efficiency and ease of use.

Attendees were given an optional and anonymous questionnaire related to their experience at the workshop where responses were 1 (disappointing) to 5 (exceptional). Attendees were asked to rate their overall experience at the workshop including format, venue, and similar (54% - 5; 43% - 4; 3% - 3). Attendees were also asked to rate the technical content (57% - 5; 43% - 4). Overall, feedback suggests attendees were pleased.

### *Slag 101: Origin, Types & Fundamental Properties*

This presentation provided a fairly comprehensive overview of slag (not just steel slag), and reinforced the notion that "slag" can refer to many different products. Methods in which slag is produced were covered, as were chemical compositions and characteristics of a variety of types of slag. The presentation spent more time covering fundamental properties of steel slag that are pertinent to paving because of the subsequent applications driven presentations. This presentation did, however, also highlight the vast number of other applications where steel slag can be suitable. One family of applications for steel slag are environmental in nature. While only discussed for a few moments in the workshop, special attention was given in the following paragraphs because they might be of interest to the regional market. The remaining content in this sub-section was not directly presented during the workshop.

Steel slag can serve several environmental needs such as armor for streambank stabilization, or a filter for absorbing phosphorous and raising the pH of acidic surface water. Steel slag is more than a byproduct of the steel manufacturing process; it has been used in environmental applications such as constructed wetlands. While some of these applications were covered during the workshop, it is important to note that the breadth of environmental applications with steel slag is further reaching. Since the subject of the workshop was the use of steel slag in road construction, this was the filter in which the environmental impacts are assessed.

The utilization of steel slag in road construction can have meaningful implications. When steel slag is used in place of other aggregates, natural resources are conserved (additional reading on this subject can be found at https://doi.org/10.1016/j.conbuildmat.2014.02.025). Steel is one of the world's most recycled materials (hundreds of millions of tons are recycled), capable of being reused numerous times.

Physical, chemical and mineralogical properties of steel slag differ depending on the steel type and slag handling after the separation from the steel melt (additional reading on this subject can be found at https://doi.org/10.1177/0734242X10365095). One environmental concern with using steel is the potential leaching of different elements within the slag such as chromium and vanadium and its tendency to increase the alkalinity of surrounding water. However, current research has shown that the amount of leaching from steel slag (LFS and EAFS) utilized in road construction is in accordance with acceptable limits of EPA's drinking water standards (additional reading on this study can be found at doi:10.1007/s10098-016-1289-6). Another study (available at doi:10.1016/s0956-053x(00)00098-2) also found no significant impact from steel slag (ferrochrome) on the soil, plants, or groundwater at their test sites. The conclusions of this research were 1) there was low transfer of particles from the slag to the surrounding soil; 2) leaching from the steel slag to the groundwater was low for all elements analyzed; 3) uptake by plants and spreading of dust seems to have been the biggest impact on the environment; 4) there is a need for further research on the bioaccumulation of trace metals, namely chromium, by plants.

*Aggregate Needs for Shoulder Applications*

Generally speaking, this presentation can be described in two parts: 1) MDOT practices were discussed relative to shoulder aggregates; and 2) descriptions from the Federal Highway Administration (FHWA) about steel slag use for shoulder applications where overall quality control, design, material handling and similar guidance was also provided. The workshop organizer reached out to each of MDOT's six districts a few days prior to the workshop asking for overall information related to their shoulder aggregates practices. Five of the districts responded in time for the workshop and their content was included in the slides presented. The remaining district (District 7) responded just after the workshop, and their content has been included in this summary but was not presented at the workshop. The list below summarizes the shoulder rock information from the MDOT districts – note that additional information is included in the presentation slides for districts 1, 2, 3, 5, and 6.

- *District 1:* Typically use clay gravel (Class 3-Group C or Class 5-Group D). Performance depends on location and amount of traffic that gets onto the shoulders.
- *District 2:* Typically use clay gravel (Class 3-Group D). Performance varies depending on plasticity. In recent years, low plasticity values have been common and as such they have begun to use limestone (610) in higher traffic areas and it has worked far better.
- *District 3:* Their perspective that clay gravel is probably the worst material to use for shoulders (short or long term). They do not get adequate plasticity out of their clay gravel materials. Reclaimed Asphalt Pavement (RAP) and crushed limestone are used for some shoulder applications – both are favored over clay gravel for withstanding traffic.
- *District 5:* Has used clay gravel (Class 5-Group C) for years with shoulders of adequate width. For narrow shoulders, the typical material is Class 5-Group E, which is becoming harder to find. Crushed stone has started to be allowed in the district, and they have used RAP on some routes. Crushed concrete was used on a narrow shoulder but did not work well (slope was steep). Gravels with a plasticity index (PI) less than 4 are not comfortable to District 5.
- *District 6:* Has exclusively used 610 or 825 crushed limestone or concrete for the past nine years, and its performance has been unmatched with previous shoulder material applications. Clay gravel washing away was reported as a concern.
- *District 7:* Use clay gravel almost exclusively – materials with adequate clay seem to work well. Typically, however, materials are being provided at the low end of the plasticity specification. Clay gravel is readily available and more economical on an initial cost basis. More restrictive specifications for clay gravel was suggested as a possible solution. District 7 has used crushed concrete or crushed limestone on larger re-construction projects with great success, and over the past year more limestone has been used by maintenance crews.

*Aggregate Needs for Unsurfaced Roads or Parking Areas*

This presentation was applications driven and began with a summary of steel slag products available in the regional market. Thereafter, several photos were shown as case studies in the regional market where steel slag was serving customers in an adequate manner. One specific example was Glenn Road where gravel only and steel slag only portions are present and where steel slag seems to be performing the best based on user discussions at the workshop. Data was presented that was collected at MSU by CMRC where California Bearing Ratio (CBR) testing showed Dura-berm when blended with modest amounts of sand could produce soaked CBR readings well in excess of 100. The data collected recently at MSU was supported by work presented in other states where lightweight deflectometer measurements showed meaningful modulus improvements for unpaved roads that had been reclaimed and used steel slag as part of the project.

*Pavement Design 101: The Role of Aggregates*

The Plastic Mold compaction device (PM Device) developed in Mississippi and contained within AASHTO PP92 protocols was first described. Thereafter, unconfined compressive strength to elastic modulus relationships were shown for one of the most typical pavement bases in Mississippi (soil-cement). These relationships were shown from roadway cores and also PM Device prepared specimens. The soil-cement relationships were compared to those for cold-in-place recycling (CIR) materials mixed and compacted in the laboratory with and without the use of steel slag. Without steel slag, cement stabilized CIR had a lower strength to modulus relationship than soil-cement (undesirable), but addition of steel slag was shown to bring this relationship more in line with typical values observed with soil-cement in Mississippi.

The second part of this presentation focused on incorporating steel slag into plant mixed asphalt. Design fundamentals were covered prior to transitioning to several successful uses of steel slag in asphalt in states such as Indiana, Illinois, and Washington. Successful uses included the Indianapolis Motor Speedway, I-55 in Indiana, very high traffic intersections such as Williams Street in Thornton, Illinois, and I-65 in Illinois. Some of these projects used steel slag in high volumes. Another case study was presented from the Washington Department of Transportation. Overall, it was shown that steel slag can be an effective material within a pavement structure with proper design and material selection practices.

*a) Registration* *b) Opening Remarks* *c) Edw C. Levy Speakers*

*d) Presenters John J. Yzenas Jr., Kelly Cook, Isaac L. Howard, and Travis Zimber*

*e) Overall view of audience from front of room*

*f) Overall view of audience from back of room*

**Figure 1. Photos from the February 27, 2019 Steel Slag Workshop**

**FIGURE 2. WORKSHOP ANNOUNCEMENT**

# *Steel Slag as a Paving Aggregate: Properties, Applications, and Comparison to Alternatives*

**WHEN:** February 27, 2019 from 10 AM to 3 PM

**WHERE:** The Mill Conference Center, 600 Russell Street, Starkville, MS, 39759

**FREE REGISTRATION:** There are no registration fees, but to attend you must register by sending an email to Isaac L. Howard at ILHoward@cee.MsState.edu that contains the name, affiliation, phone number, and email address of each individual being registered. If you register multiple people with one email, please make it clear who is being registered and provide the information for each registrant separately. Each registrant will receive a registration number via email, and you are not registered until you receive this number. Total attendance for this event is limited to 80, and registration is first come, first serve.

**PARKING AND DIRECTIONS:** The Mill has free outdoor parking in front of the venue accessible from Russell Street, and there is also a parking garage associated with the adjacent hotel (Courtyard Starkville, at 100 Mercantile St, Starkville, MS 39759, phone 855-516-1090). No room block has been reserved for this event.

**REASONS TO ATTEND:** Earn up to 4 professional development hours (PDHs). This one day workshop focuses on use of steel slag in several manners that might be of interest to the regional construction market.

**TENTATIVE SCHEDULE**

| | |
|---|---|
| 10:00 AM to 10:05 AM: | Opening remarks (Isaac L. Howard) |
| 10:05 AM to 11:00 AM: | Slag 101: Origin, Types, & Fundamental Properties (Kelly Cook, Isaac L. Howard) |
| 11:00 AM to 11:05 AM: | Break |
| 11:05 AM to 12:00 PM: | Aggregate Needs for Shoulder Applications (John Yzenas, Isaac L. Howard) |
| 12:00 PM to 1:00 PM: | Lunch - Provided on Site as Part of Registration |
| 1:00 PM to 1:55 PM: | Aggregate Needs for Unsurfaced Roads or Parking Areas (Travis Zimber, Kelly Cook) |
| 1:55 PM to 2:00 PM: | Break |
| 2:00 PM to 2:55 PM: | Pavement Design 101: The Role of Aggregates (John Yzenas, Isaac L. Howard) |
| 2:55 PM to 3:00 PM: | Closing remarks (Isaac L. Howard) |

**ABOUT THE SPONSOR**

Edw C. Levy - The Levy Group of Companies transforms our products into lightweight aggregates, asphalt, cement, concrete, agricultural products, and more. We provide services that include construction materials, road building, flame cutting and treatment, steel mill services, logistics, and laboratory testing.

**ABOUT THE ORGANIZER AND PRESENTERS**

*Organizer-Presenter:* **Isaac L. Howard** is the CMRC Director and a Professor in the Civil & Env. Engineering Dept. at Mississippi State University. 662-325-7193 http://www.cee.msstate.edu/cmrc/

*Presenter:* **Kelly Cook** is the Technical Laboratories Supervisor for Edw C. Levy. She is an eight-year veteran in the laboratory testing field with experience in wet chemistry, metals based testing and aggregate and construction materials testing, including asphalt mix design.

*Presenter:* **John J. Yzenas Jr.** is the Director of Technical Services for the Edw. C. Levy Company. He has been engaged in the construction and construction materials industry for over 30 years: working in operations, quality, engineering services and new product development.

*Presenter:* **Travis Zimber** is the slag sales coordinator for Columbus, MS, Memphis Mill and Charleston Mill Service for Edw C. Levy.

**FIGURE 3. AGENDA**
**CMRC WS 19-1**

# *Steel Slag as a Paving Aggregate: Properties, Applications, and Comparison to Alternatives*

**WHEN:** February 27, 2019 from 10 AM to 3 PM

**WHERE:** The Mill Conference Center, 600 Russell Street, Starkville, MS, 39759

**SUMMARY:** One-day workshop on use of steel slag in several manners of interest to the regional construction market - four professional development hours (PDHs).

**ABOUT THE SPONSOR:** Edw C. Levy - The Levy Group of Companies transforms our products into lightweight aggregates, asphalt, cement, concrete, agricultural products, and more. We provide services that include construction materials, road building, flame cutting and treatment, steel mill services, logistics, and laboratory testing.

**ABOUT THE ORGANIZER:** The Construction Materials Research Center (CMRC) is a part of the Civil & Environmental Engineering Department at Mississippi State University. CMRC's website is http://www.cee.msstate.edu/cmrc/. CMRC has an email list to keep people up to date on the happenings within the program, announcements for workshops, and meeting dates, and so forth. Anyone can receive the emails by notifying Isaac L. Howard (ilhoward@cee.msstate.edu) or (662-325-7193) of your desire to be on the CMRC email list.

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## APPROXIMATE SCHEDULE

*This program is intended to be informative, and to answer questions related to use of steel slag. Feel free to ask questions at any time as we welcome attendee participation. The schedule below is approximate – we intend to cover the topics listed, but the amount of time on any given topic can fluctuate depending on attendee interest.*

| | |
|---|---|
| 10:00 AM to 10:05 AM: | Opening remarks |
| 10:05 AM to 11:00 AM: | Slag 101: Origin, Types, & Fundamental Properties |
| 11:00 AM to 11:05 AM: | Break |
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# Steel Slag as a Paving Aggregate: Properties, Applications, and Comparison to Alternatives
## *Topic: Opening Remarks*

*February 27, 2019*

*Starkville, MS*

Mississippi State University

CMRC

Construction Materials Research Center

An Industry, Agency & University Partnership

**Presenters:**


Kelly Cook

Isaac L. Howard

John J. Yzenas, Jr.

Travis Zimber


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# Construction Materials Research Center (CMRC) Overview

- CMRC aims to be an "industry, agency, and university partnership," and a "sound program at all levels that couples discovery and education." **Applied Focus**
- CMRC's basic composition
  - Agencies (MDOT, USACE)
  - Board Members (**15** members)
  - Contributors (**41** financial contributors to endowment)
  - Affiliates (**76** entities)

# CMRC Overview

- CMRC is always looking involve new people
  - A great way to get plugged in is to get on the email list (just let me know and I will add you – over 100 entities get these emails)
  - Another great way is to come to our bi-annual meetings or visit our website (https://www.cee.msstate.edu/cmrc/)
  - Thanks to all of the current students, alumni, practitioners…that make CMRC work!!!!!!!

# CMRC Board

James Williams - Chair

Baxter Burns

Joel Waters

Kyle LaPorte

Les Howell

Eustace Conway

Dwayne Boyd

# CMRC Board

Judge Brown

Pepper Beckman

Brett VanderMeeden

Michael Arnemann

Wayne Wilson

Kyle Beckman

Paul McPhail

Joe Lauderdale

# Additional Contributors

BURNS COOLEY DENNIS, INC.
GEOTECHNICAL AND MATERIALS ENGINEERING CONSULTANTS

- Atwood Fence Company
- Bill Waters
- Tone Garrett
- W.R. Fairchild Construction Co.

Harry H. Bush & Jeanne C. Bush Foundation
Hope Christian Community Foundation
Tubb Equipment & Rental Co.
Randy and Malinda Battey

# Today is About Steel Slag (Not all slag is the same)

Video of steel slag pot dumping shown here

Steel Slag – produces aggregate and is the focus of today's workshop


Iron Blast Furnace Slag – can produce a cement and is not the focus of today's workshop

# Thank you for coming!

## Presenters:


Kelly Cook - KCOOK@edwclevy.net - 219-462-2924

Isaac L. Howard - ilhoward@cee.msstate.edu - 662-325-7193

John J. Yzenas, Jr. - JYZENAS@levyco.net - 219-462-2924

Travis Zimber - tzimber@edwclevy.net - 662-242-7704

# Steel Slag as a Paving Aggregate: Properties, Applications, and Comparison to Alternatives

***<u>Topic:</u>***

## *Slag 101: Origin, Types & Fundamental Properties*

*February 27, 2019*

*Starkville, MS*

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**Presenters:**


Kelly Cook

Isaac L. Howard

John J. Yzenas, Jr.

Travis Zimber


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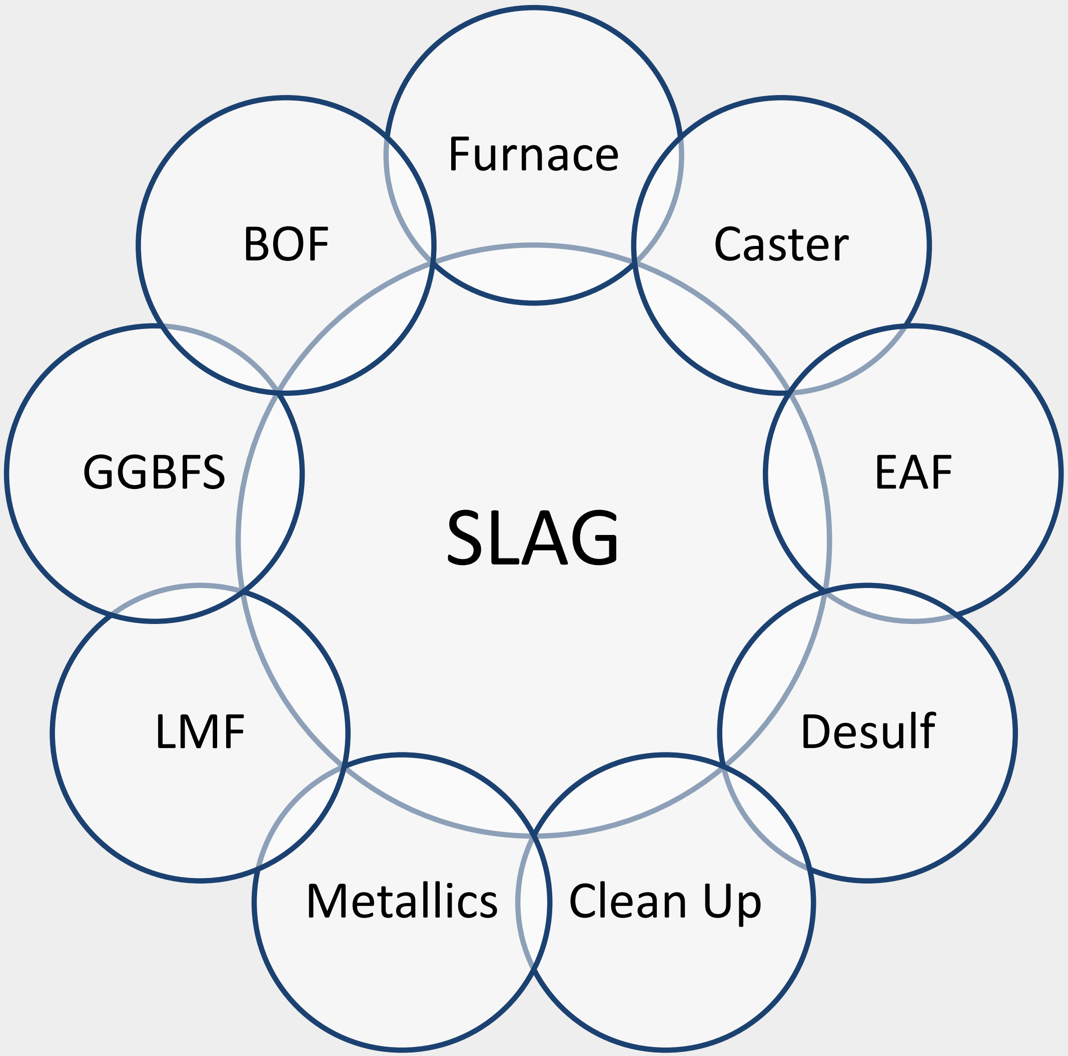
# Outline

- Define Slag
- Overview of the Slag Making Process
- Key Characterization Testing
- Chemical composition / characteristics
- BF Slag
  - Types
  - Applications
- Steel Slag
  - Types
  - Applications
- Environmental Remediation
- Mineralogy

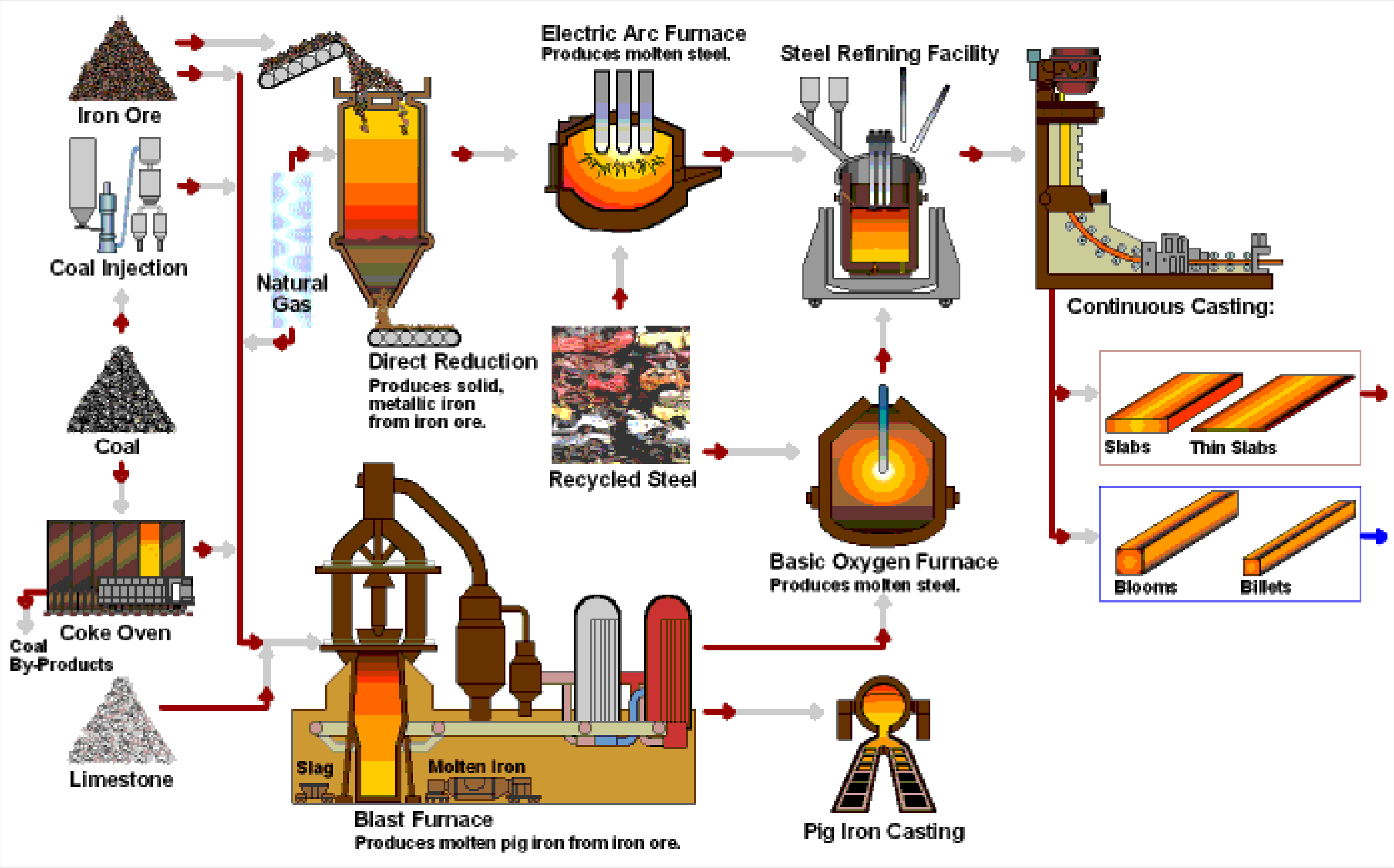
# What’s in a name?



# Definitions

- **blast-furnace slag, *n***—the nonmetallic product, consisting essentially of silicates and alumino-silicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace.
- **steel slag, *n***—the nonmetallic product consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium and magnesium, that is developed simultaneously with steel in basic oxygen, electric, or open hearth furnaces.

# Iron and Steel Making



# Slag Pot

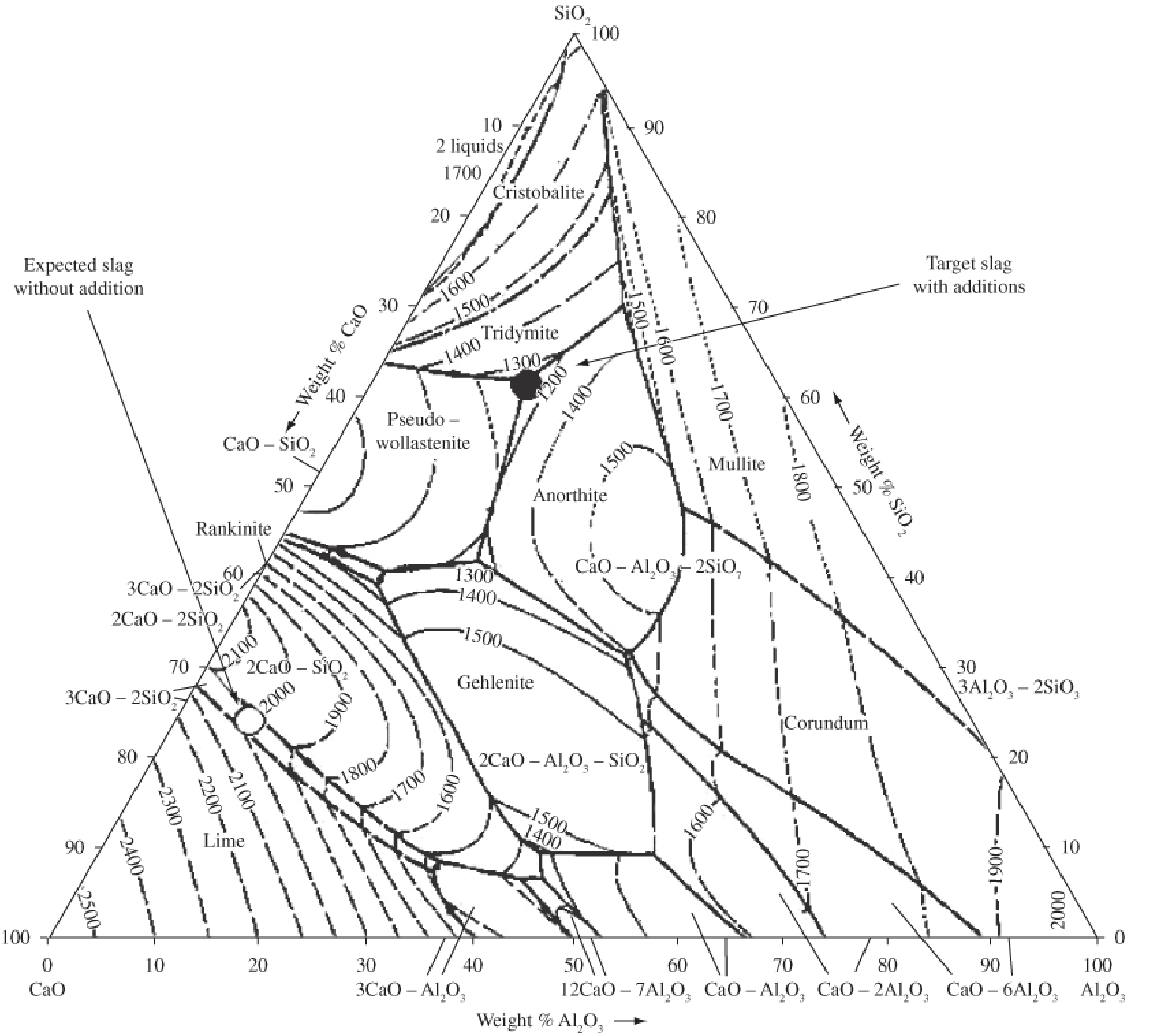



**Figure 1.** Liquidus temperatures of the CaO-SiO2-Al2O3 system and the expected slags without and with additions[9].

# Cooling

**Crystalline > Amorphous**

**Slow > Fast**

---

**Particle Size / Density**

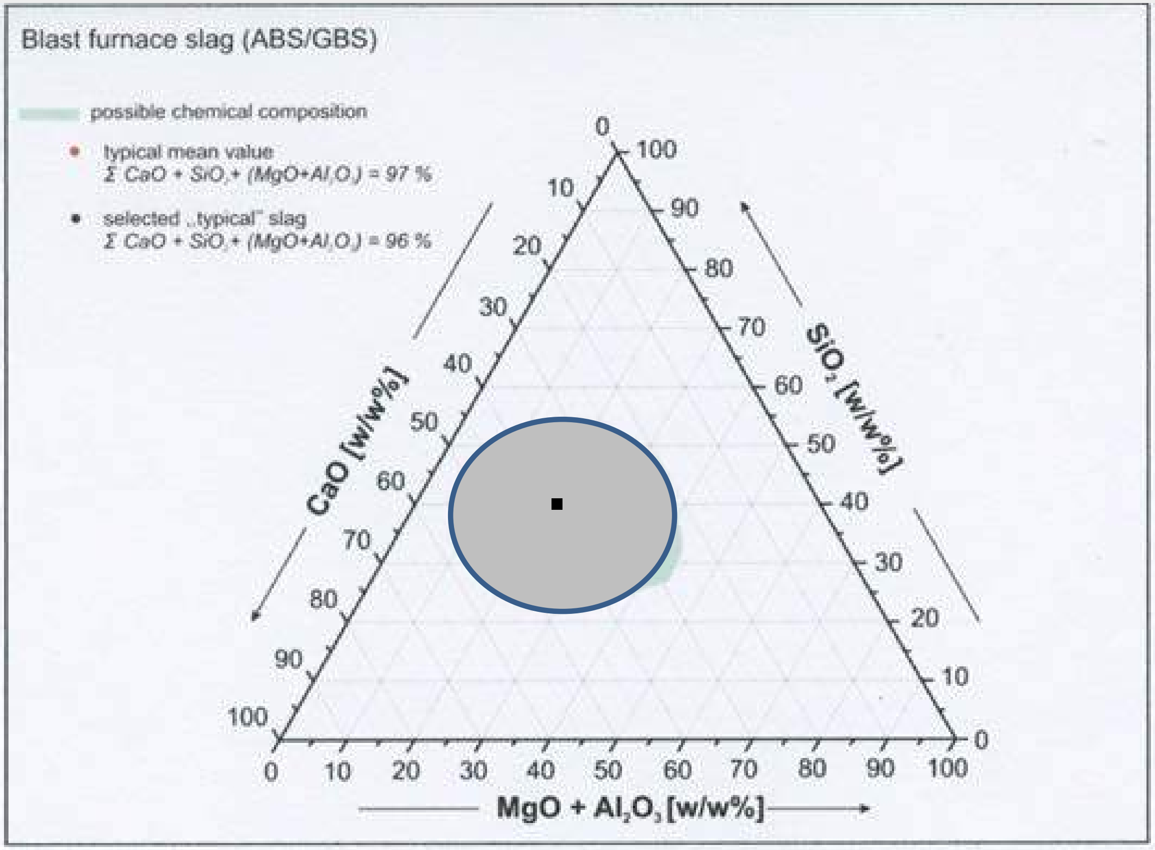

2 cm

# Slag Types

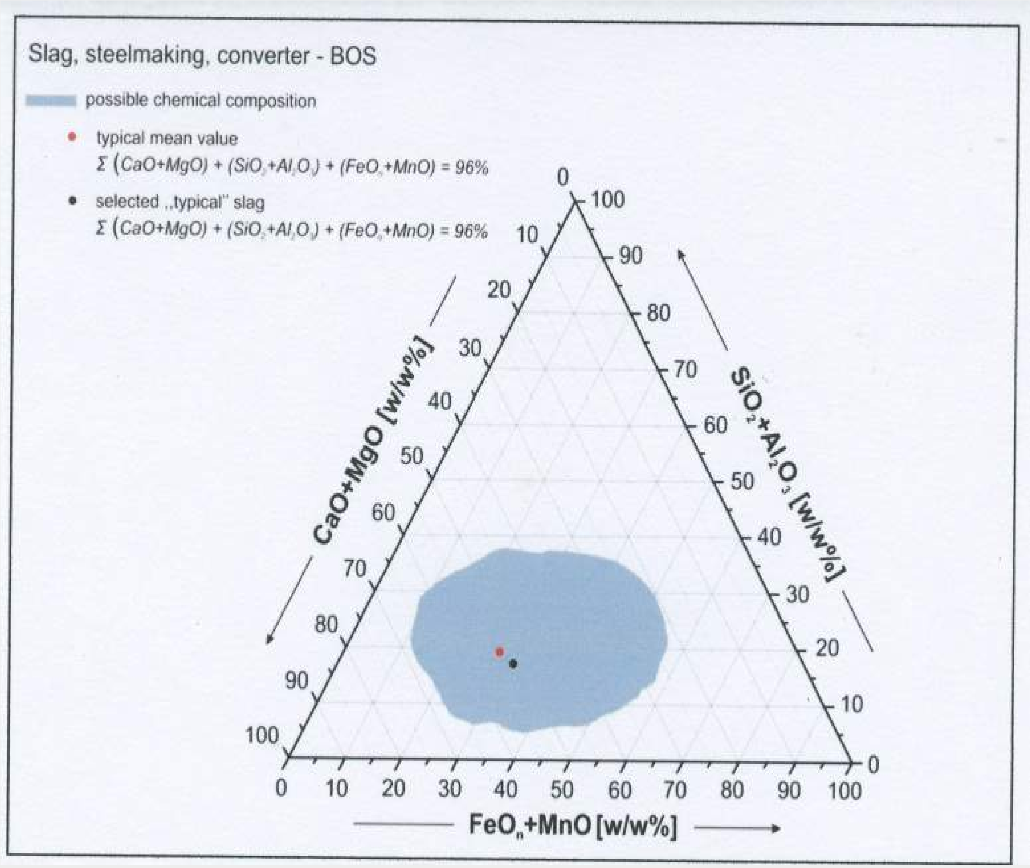
- Blast Furnace (BF)
  - Air-Cooled (ACBF)
  - Expanded Slag
  - Pelletized
  - Granulated (GBF)
- Desulf

- Steel Furnace (SF)
  - Basic Oxygen (BOF / BOS)
  - Electric Arc (EAF)
  - Open-Hearth (OH)
  - Stainless (AOD)
  - Ladle Modification
    - Ladle (LD) / Caster (CSP)

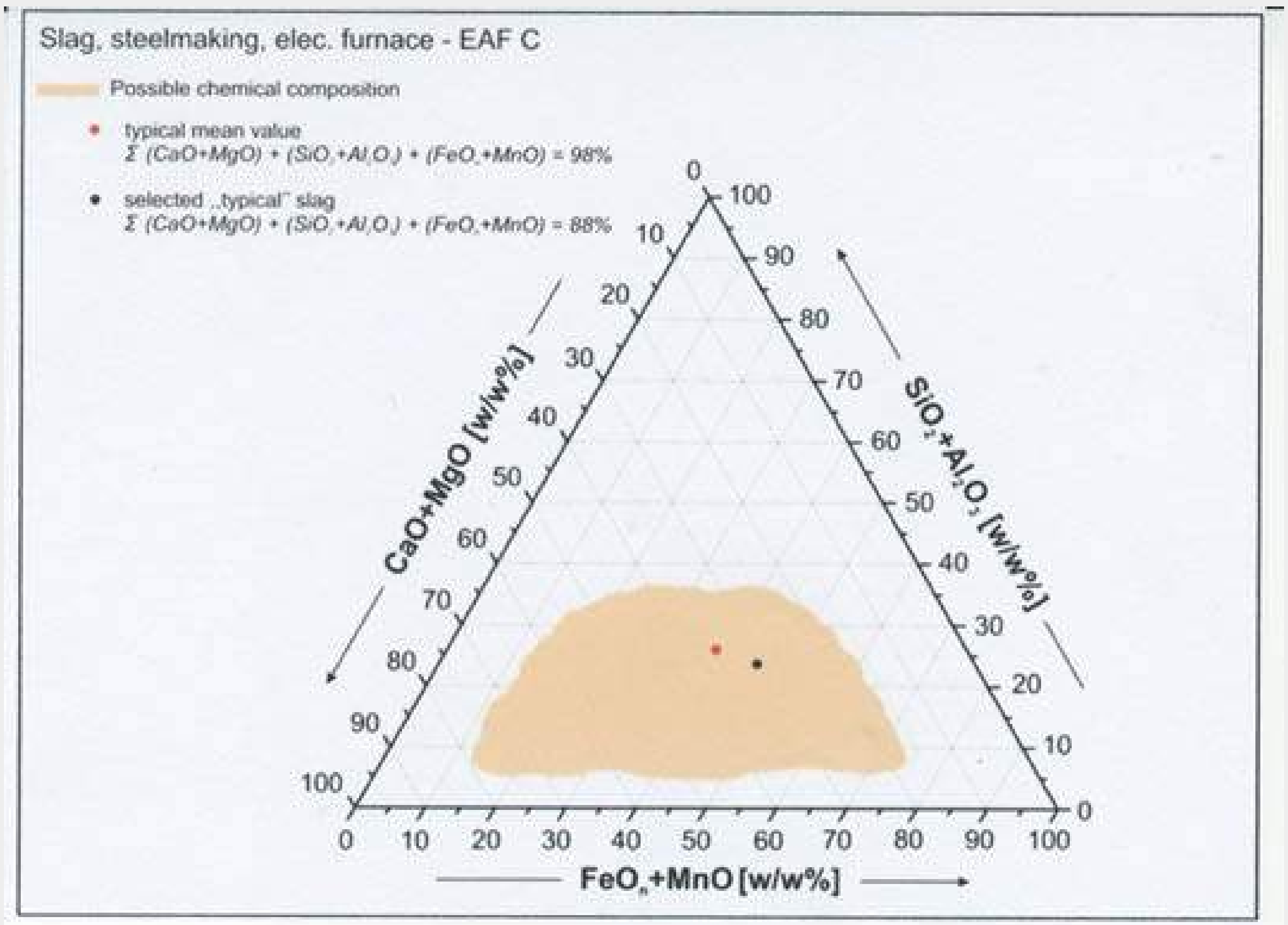
# Slag, ferrous metal: Blast Furnace



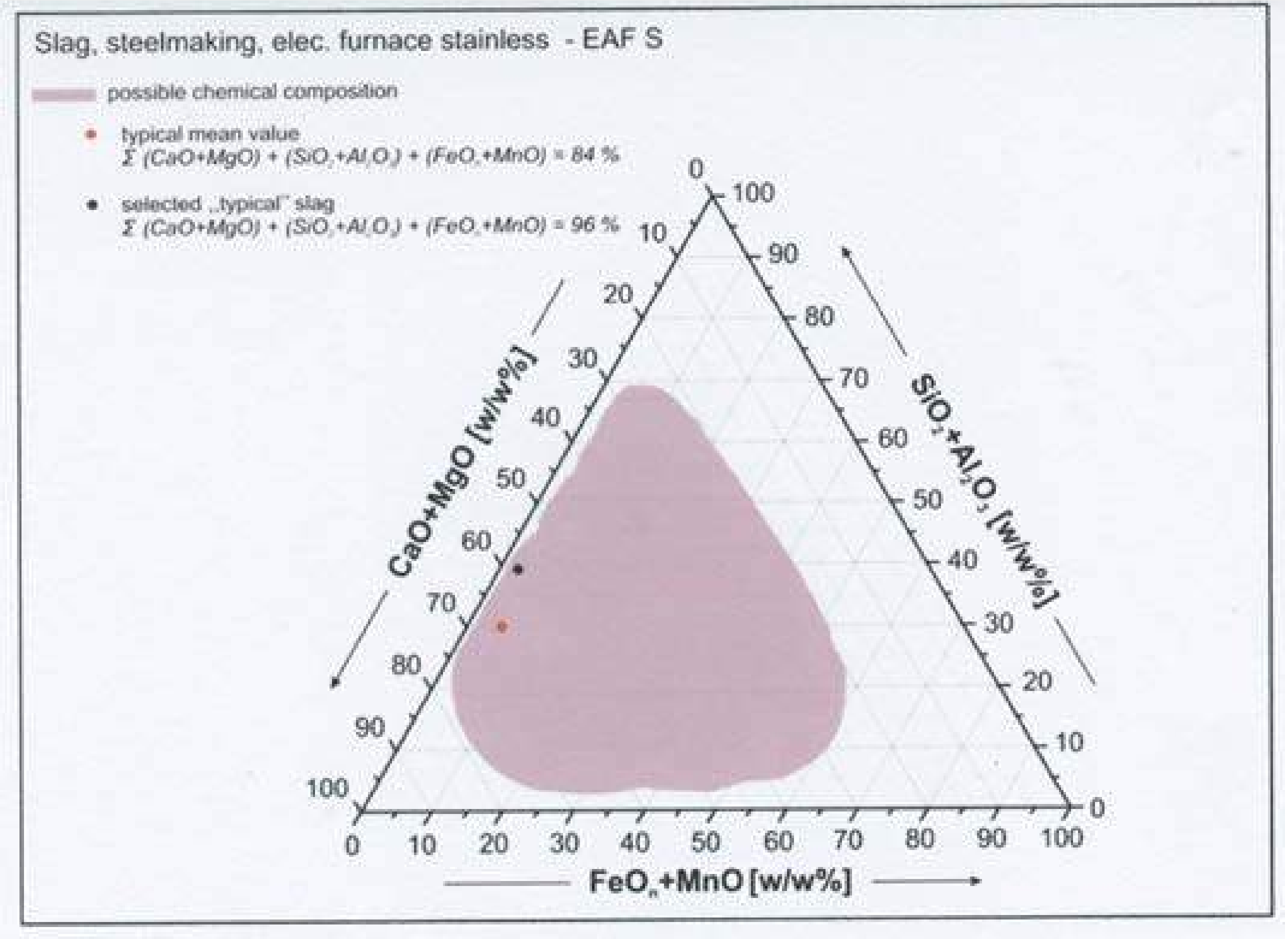
# Slag, steelmaking / converter:BOF



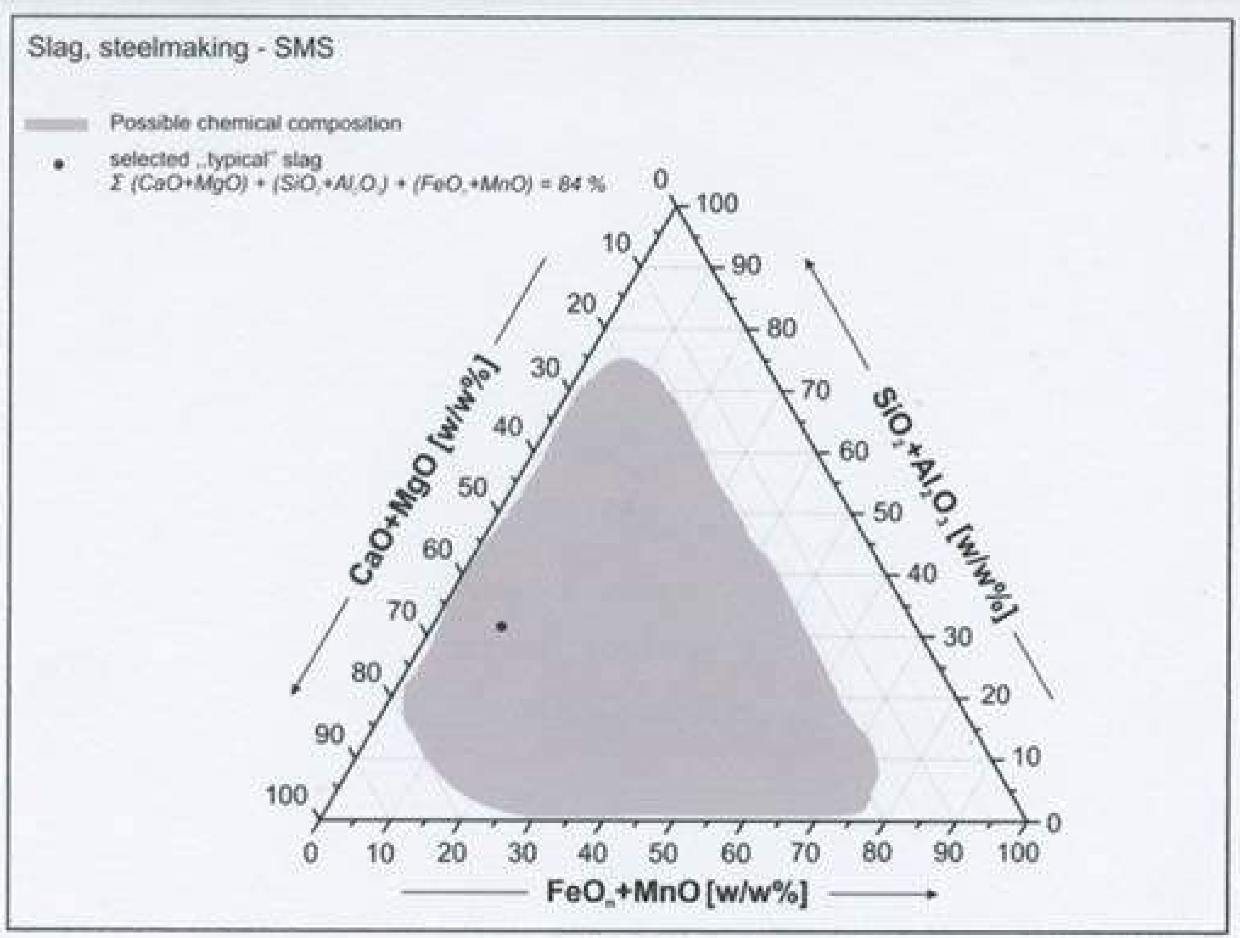
# Slag, steelmaking: EAF C



# Slag, steelmaking: EAF S



# Slag, steelmaking: SMS



# Key Characterization Testing

- Chemical Properties
  - pH
  - Chemical Analysis
    - XRF
    - ICP
    - TCLP
  - Calcium Carbonate Equivalency (CCE)
  - Free Lime
  - Mineralogy
- Physical Properties
  - Gradation
  - Moisture
  - Specific Gravity and Absorption
  - Unit Weight
  - Expansion / Disruption

# Blast Furnace (BF) Slag

# BF Slag

- **Blast furnace slag is chemically and mineralogically as consistent as naturally occurring aggregates, comprising primarily the silicates and aluminosilicates of calcium and magnesium together with other compounds of sulfur, iron, manganese and other trace elements.**
- **n—the <u>nonmetallic product</u>, consisting essentially of silicates and alumino-silicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace.**

# Chemistry vs Mineralogy (BF)

- Chemistry
- Minerology
  - Melilite
    - Gehlenite, $2CaO.Al_2O_3.SiO_2$
    - Akermanite, $2CaO.MgO.2SiO_2$
    - Calcium sulphide (oldhamite) <1%
  - Occasionally
    - Merwinite  $3CaO.MgO.2SiO_2$
    - Dicalcium silicate $2CaO.SiO_2$

| Average | |
|---|---|
| CaO | 41 |
| SiO2 | 35 |
| MgO | 7.0 |
| Al2O3 | 14 |
| SO3 | 1.0 |

# Air-Cooled Blast Furnace Slag (ACBF)

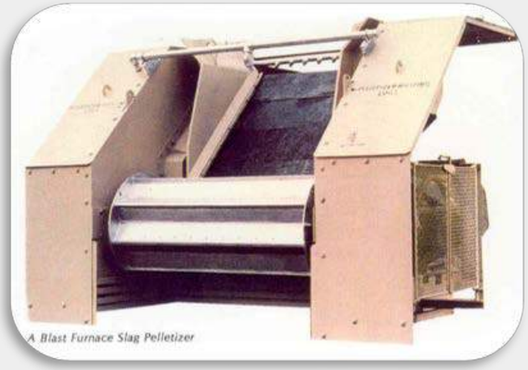
- Characteristics
  - Hard Mohs – 7
  - Angular / Irregular
  - Mid – Weight (80+ pcf))
  - Leachate (Calcium Sulfate)
- Natural Aggregates
  - Weight Advantage
- Chemical
  - Quasi Wollastenite
  - Cement

# Expanded BF Slag

- Lightweight
- Angular / Cubical
- Markets
  - LW Masonry
  - LW Embankment
  - Medium to Lightweight Concrete

# Pelletized BF Slag

- Unique Structure
  - Cellular
  - Spherical
  - Low Density
- Markets
  - Raw Material – Cement
  - Medium to LW Masonry
  - Structural Concrete
  - LW Fill



A Blast Furnace Slag Pelletizer

# Granulated BF Slag (GBFS)

- Glassy, granular material formed when slag is rapidly chilled, as by immersion in water.
- Hydraulic Cement
- ASTM C 989:
  - Grade 80 (SAI @ 28days = 75%)
  - Grade 100 (SAI @ 7days = 75% & 28days = 95%)
  - Grade 120 (SAI @ 7days = 95% & 28days = 115%)

(SAI: Strength Activity Index)

# Steel (SF) Slag

# SF Slag

- **SF Slag consists primarily of calcium silicates together with oxides and compounds of iron, manganese, alumina and other trace elements. <u>The chemical composition of each batch of SF slag varies dependent on the type of steel being produced (i.e. high, ordinary or low sulfur steel) which is largely influenced by the flux used (i.e. lime or dolomitic lime).</u>**
- ***n*—the <u>nonmetallic product</u> consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium and magnesium, that is developed simultaneously with steel in basic oxygen, electric, or open hearth furnaces.**
-

# Co-Mingled

# Chemistry vs Mineralogy (SF)

- Chemistry
- Mineralogy
  - Dicalcium silicate (bredigite) ($2CaO.SiO_2$)
  - Tricalcium silicate ($3CaO.SiO_2$)
  - Free lime (CaO)
  - Wustite (FeO)
  - Calcium ferrite
    - (also dicalcium ferrite and calcium aluminoferrite)
  - Minor amounts:
    - Periclase (MgO)
    - Magnesiowustite (solid solution of FeO and MgO)
    - Usually around 1% free metal in fine globules is present.

| BOF Typical | |
|---|---|
| CaO | 42-44 |
| SiO2 | 10-12 |
| MgO | 5-6 |
| Al2O3 | 1-2 |
| TiO2 | 0.5 |
| Fe2O3 | 27-31 |
| MnO4 | 3-4 |
| P2O5 | 1-2 |

The proportions of each phase vary mainly with the CaO and $SiO_2$ proportions of the slag. Tricalcium silicate only appears at high lime/silica ratios (>>3.0). Wustite and ferrites are major phases in iron-rich BOS slags.

# Reactivity

**(Available Lime)**

- $CaCO_3$ > Burning (1000 deg C) > CaO
  - Quicklime = Highly Reactive
  - 100% Available
- Hydrated Lime (CaO + Moisture )
  - $Ca(OH)_2$
  - ~75% Available
- Steel Slag
  - 0 – 10+% Available
    - Expansion
      - Base / Stability
    - Stabilization

# Basic Oxygen Furnace (BOF)

# Electric Arc Furnace (EAF)

# Open Hearth Steel Slag

- Open Hearth Furnaces producing Open Hearth Steel Slag as a co-product of the steel making process were closed in the late 1970's due to technological advances in the production of steel. However, Open Hearth Steel Slags are typically non-expansive and reserves are still being processed into aggregates and have been used successfully in base applications.

# Air-Cooled Steel Furnace Slag BOF/EAF

- Characteristics
  - Expansion / Instability
  - Irregular Shape
  - Heavy (120+ pcf) / Dense
  - Tufa

- Markets
  - Asphalt
  - Cement
  - Fill
  - Base

# Stainless Steel Slag

- AOD
  - Argon Oxygen Decarburization
- Characteristics
  - Falling Slag
  - Unstable

| Average | |
|---|---|
| CaO | 52.12 |
| SiO2 | 12.71 |
| MgO | 8.97 |
| Al2O3 | 19.64 |
| TiO2 | 0.33 |
| FeO | 5.52 |
| MnO | 0.73 |
| P2O5 | 0.17 |
| CrO3 | 0.12 |
| SO3 | 0.42 |

# AOD Characteristics

- Falling Slag
- Instability



# AOD Applications

- Agriculture
- Chemical
  - Cement (When Blended)
- Boron Stabilization
  - SFS Applications
    - Asphalt

# Ladle Slag

- Ladle / Caster
- Characteristics
  - Unstable / Expansion
  - Limey
- Markets
  - Agriculture - Liming
  - Base (Duraberm)
  - Calcium Aluminate
  - Cement
  - Stabilization

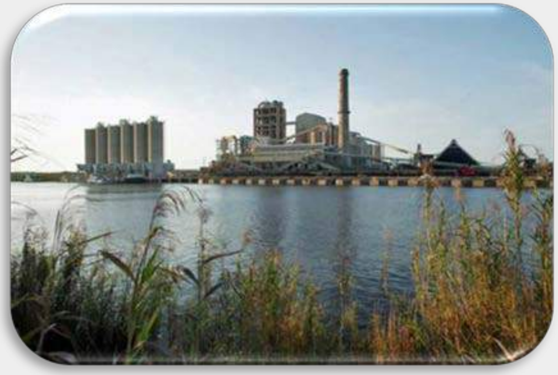
| Typical LMF | |
|---|---|
| CaO | 51.0 |
| SiO2 | 4.7 |
| MgO | 8.2 |
| Al2O3 | 33.1 |
| TiO2 | 0.3 |
| FeO | 4.2 |
| MnO | 0.7 |
| P2O5 | 0.2 |
| Cr2O3 | 0.5 |

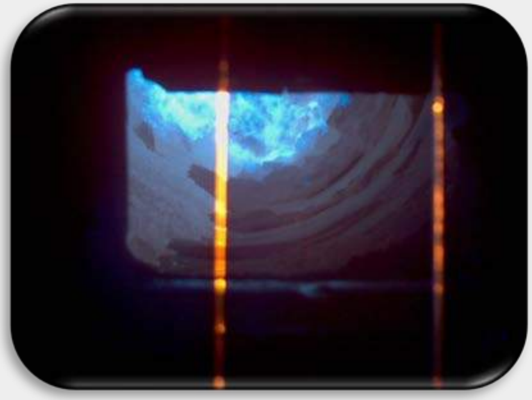
# Steel Furnace Slag Applications

- Asphalt
- Concrete / Cement
- Slag Cement
- Secondary / Low Volume Roads
- Stabilization
- Geotechnical
- Environmental
- Misc. – Fill, Counter Weights, Shot Blasting

# Asphalt - Highway


# Concrete / Cement - Highway





# Slag Cement

# Secondary / Low Volume Roads

# Stabilization

- Physical Modification
  - Steam Box
- Chemical Modification
  - Silica
  - Liquid Spray
    - Stabilization & pH


# Geotechnical

- Ballast
- Embankments
- Stabilization
- Reclamation



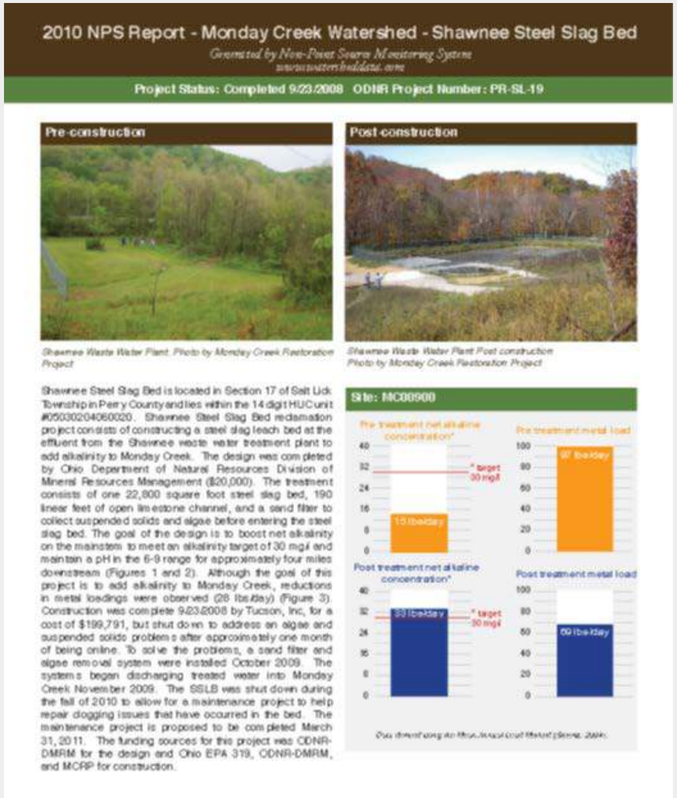

# Environmental

- Acid Mine Drainage
- Permeable Reactive Barriers
- Phosphorous Remediation

# Acid Mine Drainage (AMD)

- During Mining, pyrite is exposed to oxygen.
- Ground water seeps into the mine.
- Oxygen, water and pyrite react to form sulfuric acid and in turn dissolve metals from the rocks.
- Water drains out of the mine.
- Dissolved metals react with oxygen and fall out of solution into the stream water, turning a bright color.
- Aquatic animals and plants are killed by the drainage.

# AMD Remediation



2010 NPS Report - Monday Creek Watershed - Shawnee Steel Slag Bed

*Generated by Non-Point Source Monitoring System*

*www.watersheddata.com*

Project Status: Completed 9/23/2008 ODNR Project Number: PR-SL-19



*Shawnee Waste Water Plant. Photo by Monday Creek Restoration Project*

*Shawnee Waste Water Plant Post construction Photo by Monday Creek Restoration Project*

Shawnee Steel Slag Bed is located in Section 17 of Salt Lick Township in Perry County and lies within the 14 digit HUC unit #05030204060020. Shawnee Steel Slag Bed reclamation project consists of constructing a steel slag leach bed at the effluent from the Shawnee waste water treatment plant to add alkalinity to Monday Creek. The design was completed by Ohio Department of Natural Resources Division of Mineral Resources Management ($20,000). The treatment consists of one 22,800 square foot steel slag bed, 190 linear feet of open limestone channel, and a sand filter to collect suspended solids and algae before entering the steel slag bed. The goal of the design is to boost net alkalinity on the mainstem to meet an alkalinity target of 30 mg/l and maintain a pH in the 6-9 range for approximately four miles downstream (Figures 1 and 2). Although the goal of this project is to add alkalinity to Monday Creek, reductions in metal loadings were observed (28 lbs/day) (Figure 3). Construction was complete 9/23/2008 by Tucson, Inc, for a cost of $199,791, but shut down to address an algae and suspended solids problems after approximately one month of being online. To solve the problems, a sand filter and algae removal system were installed October 2009. The systems began discharging treated water into Monday Creek November 2009. The SSLB was shut down during the fall of 2010 to allow for a maintenance project to help repair clogging issues that have occurred in the bed. The maintenance project is proposed to be completed March 31, 2011. The funding sources for this project was ODNR-DMRM for the design and Ohio EPA 319, ODNR-DMRM, and MCRP for construction.

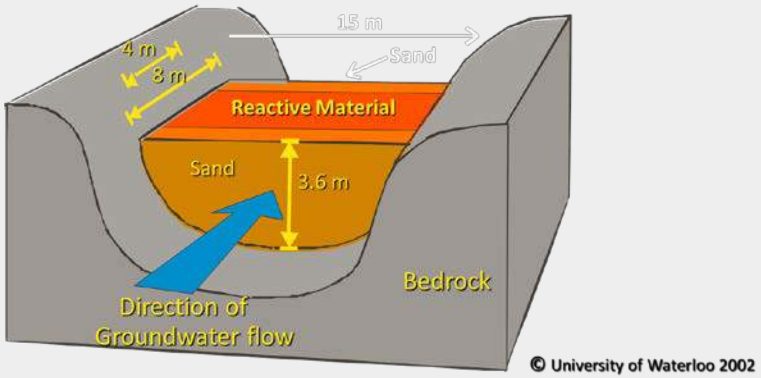
Site: MC00900

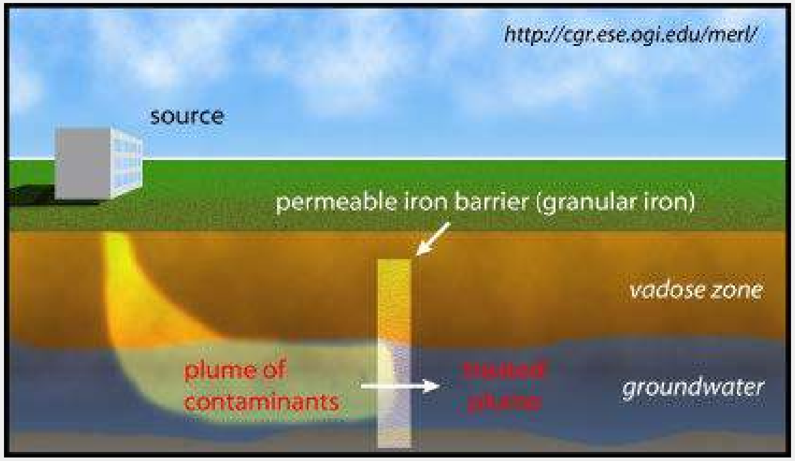


- Active Treatment-Neutralization by Addition of Lime/Limestone
- Install Treatment Plant (High Cost)
- Passive Treatment - Utilize Naturally Occurring Biological and Geochemical Processes
- Steel Slag Utilization
  - High Calcium Content
  - Slag’s pH is very high (>11%)
  - Produces a High Alkaline Environment to Balance the acidic drainage. (pH > 7)

# Permeable Reactive Barrier (PRB)

- PRB’s consist of a trench filled with reactive materials placed in the pathway of contaminated groundwater.

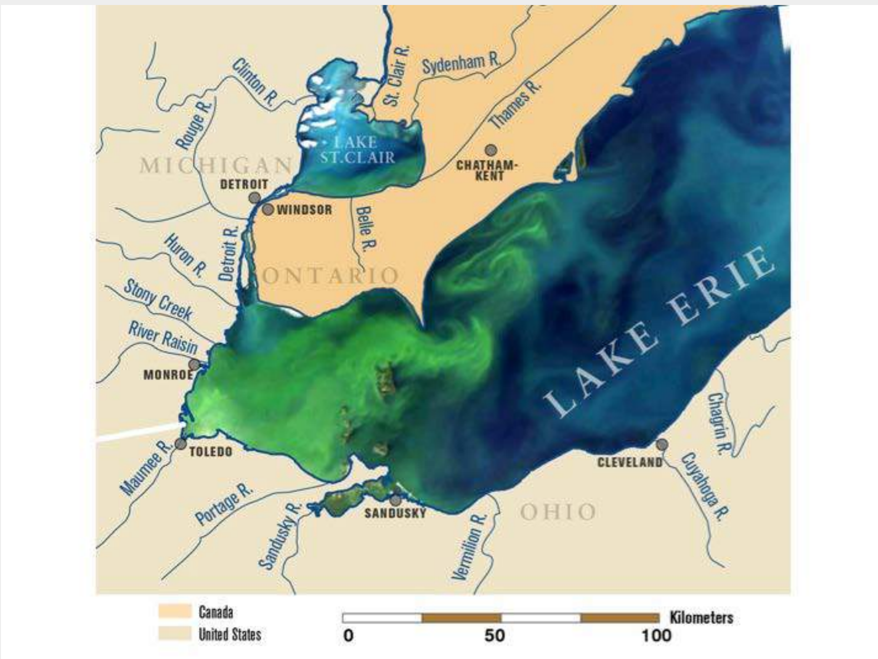


# University of Waterloo

- East Chicago, In 2002
  - 1 – 3 mg/l As plume with neutral pH.
  - Mainly As III
  - 2 Parallel Barriers (3 meters apart)
  - 500 meters long
  - 11 meters deep
  - 0.6m wide
- @ 5- years
  - Removed Arsenic to <0.01 mg/l
  - Slag pH reduced <13 to <12

# Lake Erie

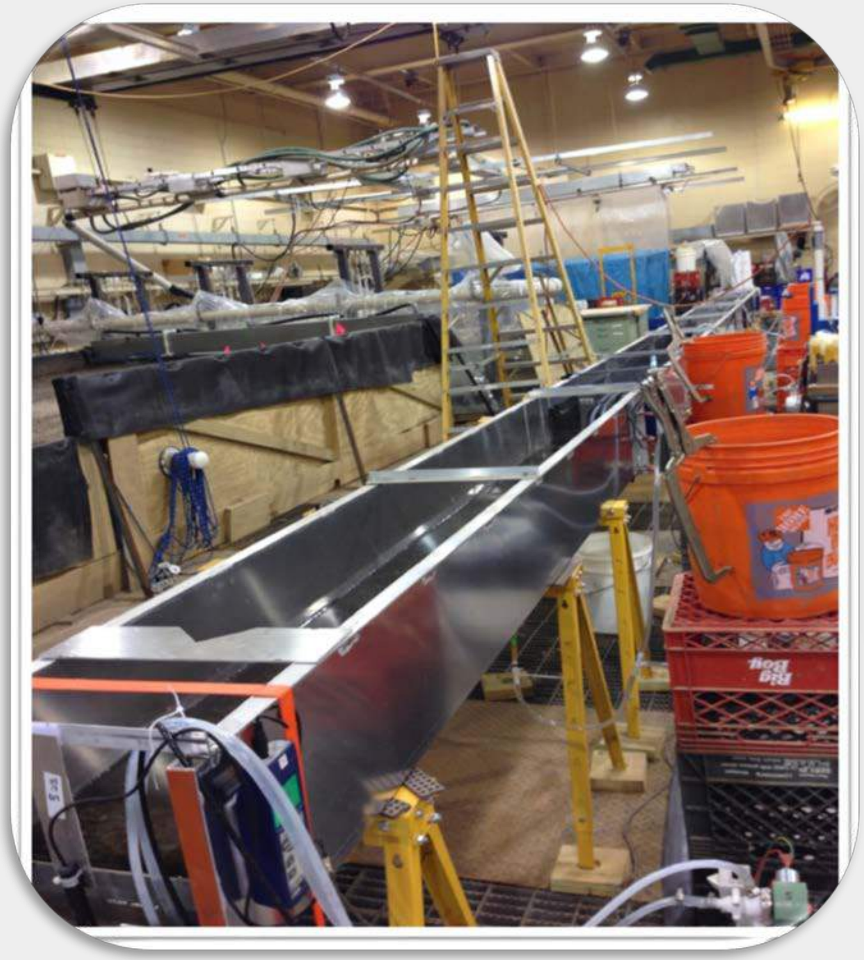



- A satellite image of Lake Erie overlaid on a map of the lake and its tributaries. This image shows a bloom about six weeks after its initiation in the lake's western basin. Map by Michigan Sea Grant.
- Loading is ~2000 tons/year of "p"

# Phosphorous Run-Off

- Leading Cause
  - Waste Water / Agriculture / Animal Lots
    - Non-Point Run-off: Agricultural, urban/residential
    - Point Run-off: Waste Water
- 37% of Large River Delta, Coastal Waters are in Poor overall Condition (US EPA)
- Reducing P loads from soils to surface waters is necessary for resolving  Eutrophication.

# Research (USDA)



# Waste Water

- New Zealand
  - Township of Waiuku
    - Installed in 1993 and handles up to 3000m³ a day of treated effluent from the settling ponds.
  - Department of Conservation Headquarters in the Waipoua Forest
    - Septic Systems

# Storm Sewers / Run-Off

- Storm Sewers
- Urban / Residential


# Agricultural

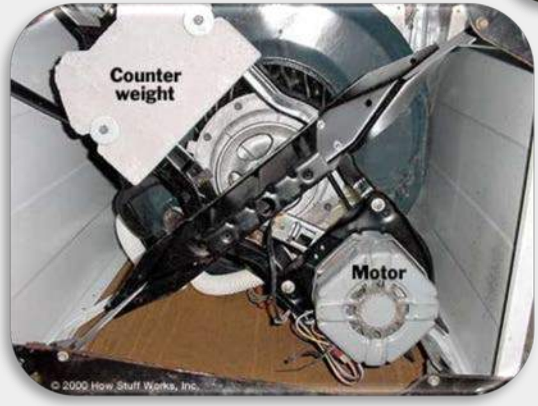
- Fertilizer Run-Off
  - Surface
  - Drain Tile

# Animal Lots

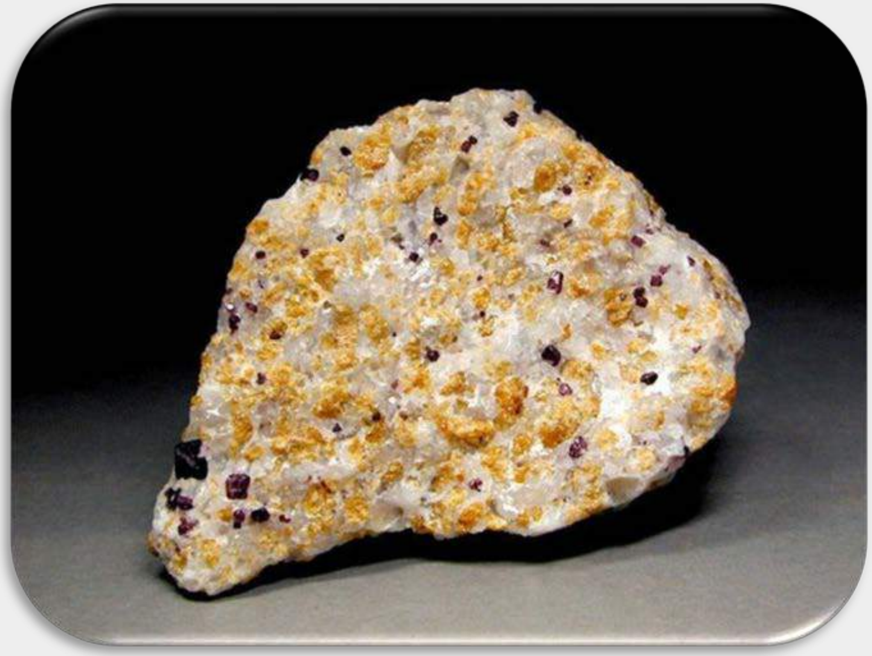
- Manure
  - Cows
  - Chicken
  - Pigs
- Processing / Handling is costly
  - Ship to treatment
- Spread on Field
  - Excess Nutrients
    - (Phosphorous, etc.)
  - Artificial Wetlands
    - Spread on Field

# Miscellaneous

- Fill
- Counter Weights
- Shot Blasting




# “Mineralogy not Oxides: The next step in Slag Characterization”



Spinel

# What is Mineralogy?

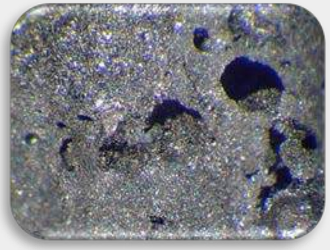

Marcasite -- Selma Chalk Formation,
Starkville, Oktibbeha Co.

Mellite

# Calcite / $CaCO_3$

- **Chalk** is a soft, white, porous, sedimentary carbonate rock, a form of limestone composed of the mineral calcite.

# Oxides versus Mineralogy



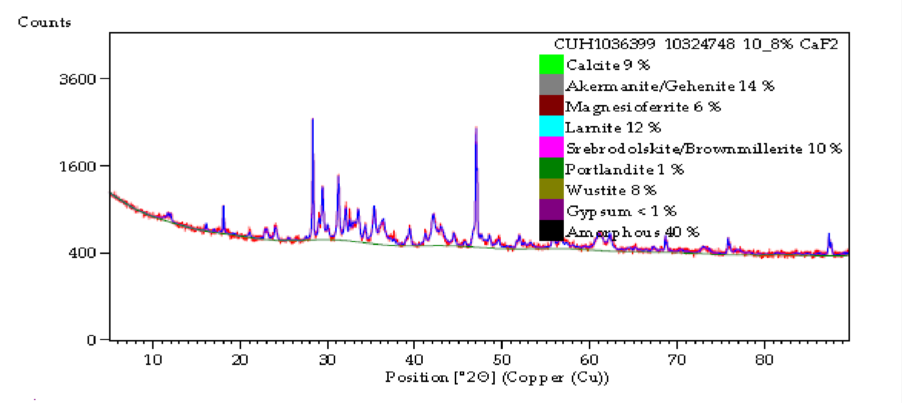
| Typical Oxide Analysis | |
|---|---|
| $SiO_2$ | 10-15% |
| $Al_2O_3$ | 3-15% |
| CaO | 20-50% |
| MgO | 5-20% |
| MnO | 0-8% |
| FeO | 10-40% |
| S | 0-1% |

| Major primary mineral constituents | Molecular and structural formula |
|---|---|
| larnite, beta-dicalcium-silicate | beta-Ca2SiO4 |
| srebrodolskite, calcium-iron-oxide | Ca2Fe2O5 |
| brownmillerite, calcium-aluminium-ironoxide | $Ca_2AlFeO5$ |
| spinel | Me2+Me3+2O4 |
| wuestite, solid solution of iron(II)-oxide with MgO and MnO | (Fe1-x-y,Mgx,Mny)Oz |
| gehlenite, calcium-aluminium-silicate | $Ca_2Al_2SiO_7$ |
| bredigite, calcium-magnesium-silicate | $Ca_{14}Mg_2Si_8O_{32}$ |

# CaO

- CALCIUM OXIDE is an odorless, white or gray-white solid in the form of hard lumps. A strong irritant to skin, eyes and mucous membranes. (pubchem.ncbi.nlm.nih.gov)
- Where?

| Client Sample No.: | 83150298-01 |
|---|---|
| RJ Lee Group No.: | 10324748 |
| Oxide | (weight%) |
| $Na_2O$ | 0.24 |
| MgO | 6.17 |
| $Al_2O_3$ | 3.94 |
| $SiO_2$ | 16.05 |
| $P_2O_5$ | 0.63 |
| $SO_3$ | 0.67 |
| Cl | 0.08 |
| $K_2O$ | 0.10 |
| CaO | 46.07 |
| $TiO_2$ | 0.48 |
| $Cr_2O_3$ | 0.32 |
| MnO | 2.74 |
| $Fe_2O_3$ | 22.19 |
| NiO | 0.01 |
| CuO | 0.01 |
| ZnO | 0.04 |
| SrO | 0.03 |
| ZrO | 0.03 |
| $Nb_2O_5$ | 0.05 |
| | |
| Total | 99.85 |



# $SiO_2$

- Quartz?
- Cristobalite?
- Glass?

mineralseducationcoalition.org

# Slag, steelmaking, converter – BOF
## EINECS no.: 294-409-3 CAS no.: 91722-09-7

## Major primary constituents / Molecular and structural formula

- larnite, beta-dicalcium-silicate beta- / $Ca_2SiO_4$
- srebrodolskite, calcium-iron-oxide / $Ca_2Fe_2O_5$
- hatrurite, tricalcium-silicate / $Ca_3SiO_5$
- spinel / $Me^{2+}Me^{3+}_2O_4$
- wuestite, solid solution of iron (II)-oxide with MgO and MnO / $(Fe_{1-x-y},Mg_x,Mn_y)O_z$
- free lime, calcium oxide / CaO

Magnetite-Spinel

# Slag, ferrous metal, blast furnace (air-cooled) - ACBF
## EINECS no.: 266-002-0 / CAS no.: 65996-69-2

- Major primary constituents / Molecular and structural formula
  - melilite (solid solution between Akermanite and gehlenite) / $Ca_2MgSi_2O_7$
  - calcium-aluminum/magnesium- silicate / $Ca_2Al_2SiO_7$
  - merwinite, calcium-magnesium-silicate / $Ca_3MgSi_2O_8$
  - pseudo wollastonite, calcium-silicate / $CaSiO_3$
  - Monticellite / $CaMgSiO_4$

**Wollastonite**

# Slag, steelmaking, elec. furnace - EAF C
# EINECS no.: 294-410-9 / CAS no.: 91722-10-0

- larnite, beta-dicalcium-silicate beta — $Ca_2SiO_4$
- srebrodolskite, calcium-iron-oxide — $Ca_2Fe_2O_5$
- brownmillerite, calcium-aluminum-iron oxide — $Ca_2AlFeO_5$
- spinel — $Me^{2+}Me^{3+}_2O_4$
- wuestite, solid solution of iron (II)-oxide with MgO and MnO
  $(Fe_{1-x-y},Mg_x,Mn_y)O_z$

- gehlenite, calcium-aluminum-silicate — $Ca_2Al_2SiO_7$
- bredigite, calcium-magnesium-silicate — $Ca_{14}Mg_2Si_8O$

# Questions?

## Presenters:


Kelly Cook - KCOOK@edwclevy.net - 219-462-2924

Isaac L. Howard - ilhoward@cee.msstate.edu - 662-325-7193

John J. Yzenas, Jr. - JYZENAS@levyco.net - 219-462-2924

Travis Zimber - tzimber@edwclevy.net - 662-242-7704

# Steel Slag as a Paving Aggregate: Properties, Applications, and Comparison to Alternatives

## *Topic:*

## *Aggregate Needs for Shoulder Applications*

*February 27, 2019*

*Starkville, MS*


**Presenters:**

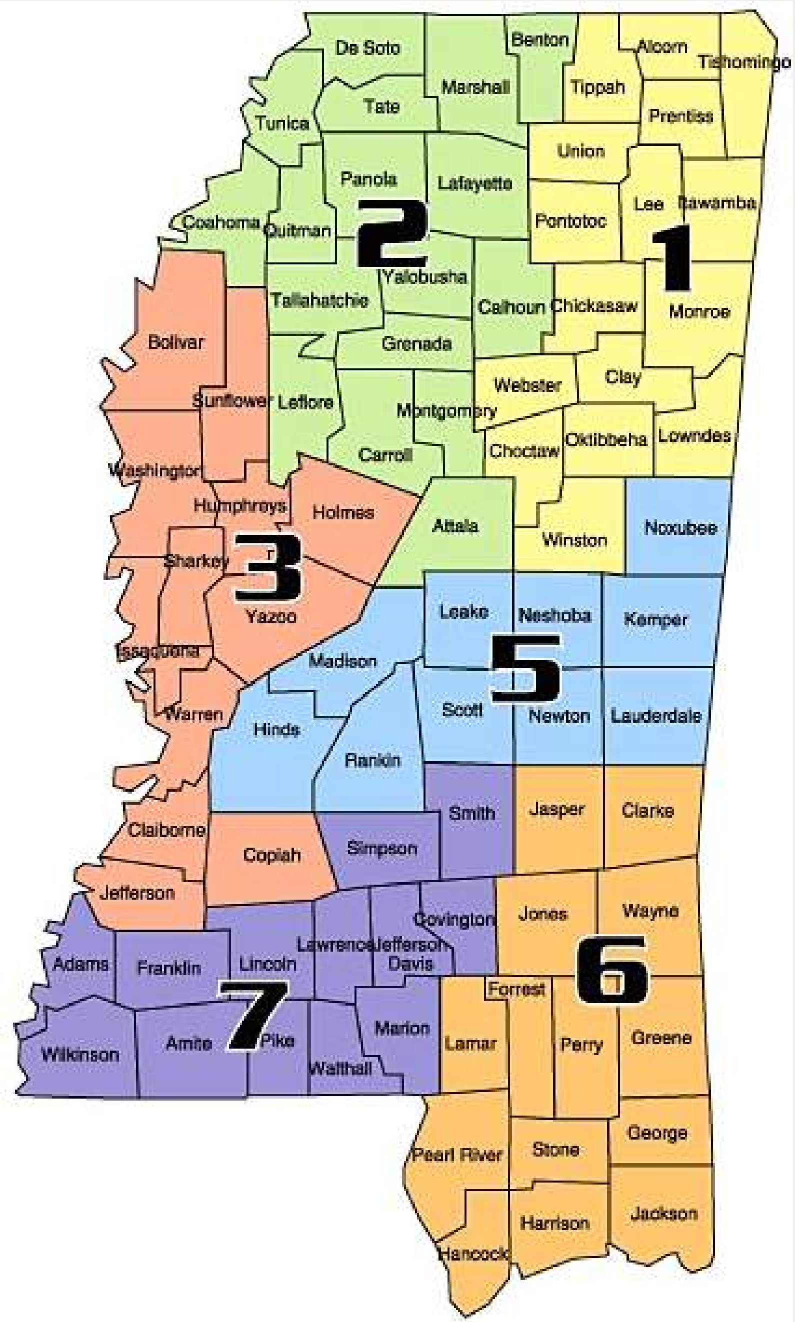
Kelly Cook

Isaac L. Howard

John J. Yzenas, Jr.

Travis Zimber

# MDOT Shoulder Practices




The following slides either come from Red Book, or from information provided through communication with MDOT

# MDOT Centerline Mile Summary as of February 2019

| Road Type | Total Miles | Paved Shoulders |
|---|---|---|
| Interstate | 1,606 | 1,606 |
| 4 lane | 3,906 | 867 |
| 2 lane (80,000) | 4,833 | 61 |
| 2 lane (57,650) | 3,069 | 7 |
| **Total** | **13,414** | ***2,480*** |

- Roughly 82% of network has unpaved shoulders

# Pavement Management

- Shoulders are not evaluated through semi-annual condition surveys.
- MDOT looks at mainline pavements only.
- MDOT’s Interstate Rating Committee considers shoulder condition when they prioritize interstate projects annually.

# Red Book – Shoulders – Section 320

**320.02 Materials**

Meet Division 700.

**320.03.2 Construction Details**

Typically refer to “controlling requirements for bases constructed of like material”.

Determination of acceptance of compaction of shoulders for required density will be performed on a lot to lot basis (max 10,000 linear feet – 5 sublots – average all for lot density to compare to spec).

The required density (94 to 98%) for the shoulder portion of any layer or course shall be the same as for the adjacent (internal) portion of the layer or course when constructed of the same material.

# 703.04 Aggregate for Crushed Stone Courses

## 703.04.3 Gradation

Aggregates for crushed stone shall be well-graded from coarse to fine, and shall conform to the following:

**TABLE OF SIZES AND GRADATION OF CRUSHED STONE AGGREGATE**

| Sieve Size | Percent Passing by Weight | | |
|---|---|---|---|
| | Size ¾ inch and Down | Size No. 610 | Size No. 825 B |
| 2 inch | | | 100 |
| 1 1/2 inch | | 100 | 90 - 100 |
| 1 inch | 100 | 90 - 100 | 75 - 100 |
| 3/4 inch | | 70 - 100 | |
| 1/2 inch | | 62 - 90 | 60 - 85 |
| 3/8 inch | 50 - 85 | 50 - 80 | |
| No. 4 | 35 - 65 | 40 - 65 | 40 - 70 |
| No. 8 | | | 28 - 54 |
| No. 10 | 25 - 50 | | |
| No. 16 | | | 19 - 42 |
| No. 40 | 15 - 30 | 12 - 26 | |
| No. 50 | | | 9 - 32 |
| No. 200 | 5 - 15 | 5 - 12 | 4 - 18 |

If crushed concrete is used, the crushed material shall meet the gradation requirements of Size No. 825 B with the exception that the percent passing by weight of the No. 200 sieve shall be 2 – 18.

# 703.07—Granular Materials

- Class ___, Group ___ (e.g. Class 5, Group C or 5C)

Class 5 Requirements (Commonly Specified on Shoulders)

| Sieve | Gradation Range |
|---|---|
| 3 in | 100 |
| 1.5 in | 85 to 100 |
| 1 in | 65 to 100 |
| 0.5 in | 35 to 100 |
| No. 4 | 30 to 85 |
| No. 10 | 25 to 65 |

| Sieve | -No. 10 Gradation Range |
|---|---|
| No. 10 | 100 |
| No. 40 | 20 to 100 |
| No. 60 | 15 to 80 |
| No. 200 | 8 to 40 |

## Gravels

| Group Symbol | LL Max | Min PI | Max PI |
|---|---|---|---|
| A | 25 | --- | 6 |
| B | 25 | --- | 8 |
| C | 30 | --- | 10 |
| D | 35 | --- | 15 |
| E | 35 | 6 | 15 |

# Begin Information From MDOT (Not Necessarily in Red Book)

- Densities are only required for new routes or 4-lane routes, because they have a full lift (6 in or more) at a consistent width. Shoulder material on overlays is put in at variable depths and widths so densities are not required.

# MDOT District 1 (D1)

- D1 typically uses clay gravel
- Class 3 Group C (3C) or sometimes 5D depending on location
- Performance depends on location and amount of traffic that tends to get onto the shoulders

# MDOT District 2 (D2)

- D2 typically uses clay gravel (3D) for shoulder material.
- Performance seems to depend in large part on plasticity index (PI).
- In recent years (more than in the past), D2 has ended up with gravel with low PI’s (low side of spec) and they behave near non-plastically.
- These non-plastic materials do not stay on shoulders well and are often unstable when cars and trucks pull off the road
- D2 has begun to use more limestone (610) in areas were more shoulder traffic is anticipated – 610 has seemed to work far better.

# MDOT District 3 (D3)

- Feels the type of material selected is biggest factor to success.
- Feels maintenance practices could be improved; e.g. use of crushed limestone can result in an easier to maintain shoulder.
- Clay Gravel (Class _ Group _) is probably the worst material to use for shoulder gravel, long term and short term.
- Generally, you don’t get adequate plasticity out of gravel pits. It is mostly red sand and rock – any plasticity is usually lost fairly quickly.

# District 3 – Problem Areas
## (Frequent Truck Traffic Across White Line)

- Crushed Limestone Use: D3 maintenance forces heel out about 3 foot wide by 6 in deep trench of the clay gravel adjacent to the travel lane and spread it on the remainder of the shoulder and put dense graded limestone in its place. Purpose is to provide a better recovery area.
- RAP: Sometimes they use asphalt milling (RAP) – limestone is favored over RAP (can be hard to blade and re-shape), both are favored over clay gravel in terms of withstanding traffic.

# MDOT District 5 (D5)

- D5 used 5C for years, but in recent times they have performed some lane widening (multiple projects), which narrowed their shoulders. They reported 5C performed well with an adequate shoulder. Narrow shoulders don’t keep material in place very long – gravels wash away. Inaquedate shoulder width is one of D5’s biggest issues/concerns and they need a material that will stay in place on narrow shoulders.
- 5E does better with washing on narrow shoulders but is getting harder to find.
- D5 has started allowing crushed stone
- D5 imports all their shoulder material

# District 5

- Unless the project is 4 lane or higher priority, minimal density checks are performed on shoulder aggregates, unless project is new construction with wide shoulders
- Overlays on older two-lane routes are a mixed bag – usually just shoring up what is there because shoulder widths vary from 1 to 4 ft
- 2 ft paved shoulders have greatly helped with maintenance as most shoulder drop offs develop where vehicles run off the edge of the pavement
- Have used RAP on some routes (via Maintenance forces – half cold milling is kept by MDOT) – since fine milling started, RAP has been noted to be less effective – RAP isn't mentioned as an "official" Red Book source

# District 5

- Over past few years, D5 hasn't performed shoulder work through special provisions (SP's), though they have allowed crushed stone (typically 610 was used) or 5E (min PI of 6) as alternatives.
- One contractor requested use of crushed concrete a few years ago because they had a stockpile from pulverizing concrete pavement on I-20 in Scott County, but it didn't work on the route that they tried it on…..shoulders were really narrow (or almost non-existent) and the slope was very steep.
- Don't feel comfortable with gravel with PI less than 4

# MDOT District 6 (D6)

- Materials: exclusively used 610 or 825 crushed limestone or concrete for the last 9 years as a shoulder material. Its performance has been unmatched with previous shoulder material applications.
- Placement of material – Material should be placed very wet (close to pumping in compacted mode). Water will then drain out of material causing aggregate to lock into place. Most material is placed with shoulder widening machine, but may be placed with motor grader as well.
- Vegetation – D6 does not grass the rock. Eventually, underlying seed and vegetation permeates through the material but it takes a while. The color differential of asphalt and limestone does provide a safety factor to let motorists observe the proper roadway.

# District 6

- **Previous Problem** – This shoulder was primarily clay/gravel and contractor would place material as new pavement - increased shoulder drop-off. The material was compacted, however first rainfall would cause material to soften, erode, and present new drop-offs. Contractor would then be required to pull material back into place or provide additional new material. Once project was closed out, material would continue to wash and shoulder drop-offs would occur. Maintenance forces are especially busy during mowing season (currently April – December in District 6) and thus motorist would leave roadway and encounter drop-off. This can lead to lawsuits.

# District 6

- **<u>Solution as of 2010 (to problem on previous slide)</u>** – District 6 began exclusively specifying 825 or 610 crushed limestone or concrete for all shoulder applications. Contractors like the material as they place it and do not have to come back to project after rain event and pull back up. Erosion is very limited after rainfall event. Vehicle can leave roadway and not sink into soft shoulder. No further drop-off occurring on these sections that require maintenance to address. One additional benefit occurs when widening highway with 2 foot trench widening (with limited or no shoulder remaining); the rock interlocks allowing a shoulder to be constructed with limited material on older no right of way routes. Material does cost more initially, however no re-mobilization of contractor or maintenance forces is required and lawsuits have been substantially reduced for this cause.

# Trial Project – SR 388 Noxubee County – Contractor: Falcon – Project Let Jan 2019

- Looking at overall shoulder rock specs of MDOT, and also looking for alternatives to gravel.
- Mill and overly (2 inch) around 8.8 miles – fairly wide shoulders
- Project is planned to have 13± shoulder test sections to be monitored during construction and over time
  - Gravel (5C, 5E)
  - Limestone (3/4 down, 610, 825B)
  - RAP (Fine Milled, Cold Milled)
  - Crushed Concrete (details TBD)
  - Steel Slag (multiple gradations)

# Why Steel Slag Shoulders?

- FHWA User Guide
  - Steel slag can be used as aggregate in granular base applications.
  - It is considered by many specifying agencies to be a conventional aggregate and can normally exceed the aggregate requirements for granular aggregate base applications.
  - The high bearing capacity of steel slag aggregates can be used advantageously on weak subgrades and in heavy traffic applications.
  - Good interlock between steel slag aggregate particles provides good load transfer to weaker subgrades.

# PERFORMANCE RECORD

- Experience in the United States, Belgium, Japan, The Netherlands, and Germany has shown that steel slag, properly selected, processed, aged, and tested, can be used as granular base for roads in above-grade applications. Steel slag aggregates exhibit a number of very favorable mechanical properties for use in granular base, including very high stability and good soundness.

# MATERIAL PROCESSING REQUIREMENTS

- **Crushing and Screening:** Prior to use as a granular base material, ferrous components of the steel slag are magnetically separated. Steel slag must be crushed and screened to produce a suitable granular aggregate gradation using processing equipment similar to that for conventional aggregates.

# Quality Control

- The same field test procedures used for conventional aggregate are recommended for granular base applications when using steel slag. Standard laboratory and field test methods for compacted density are given by AASHTO T191, T205, T238, and T239.
- In addition procedures such as the autoclave expansion (Modified C-151) are performed to confirm stability.

# ENGINEERING PROPERTIES

- When steel slag is used as an aggregate in granular base important properties include gradation, specific gravity, stability, durability, volumetric stability, and drainage.
- *Gradation*: Steel slag can be processed to satisfy the gradation requirements for granular aggregates.
  - Balanced Gradation, “Not Gap Graded”
- *Specific Gravity*: Due to the high specific gravity (3.2-3.6) of steel slag, steel slag aggregate can be expected to yield a higher density product compared with conventional mixes (2.5-2.7).
- *Stability*: Steel slag aggregates have high angle of internal friction (40° to 45° ) that contribute to high stability and California Bearing Ratio (CBR) values up to or exceeding 150 percent.
- *Durability*: Steel slag aggregates display good durability with resistance to freezing, weathering and erosion.
- *Drainage Characteristics*: Steel slag aggregates are free draining and are not susceptible to frost.

# DESIGN CONSIDERATIONS

- Properly processed steel slag aggregates can readily satisfy gradation requirements and the physical requirements for granular shoulder aggregates.
- It is recommended that steel slag be tested for volumetric stability. Some steel slags can be potentially expansive. Volume changes typically occur during the hydration of calcium and magnesium oxides.
- Granular base containing steel slag should be designed so that it is well drained (no standing water) and adequately separated from water courses to prevent immersion.
- Conventional AASHTO pavement structural design procedures can be employed for granular base containing steel slag aggregates.

# CONSTRUCTION PROCEDURES

- **Material Handling and Storage**
- The same general methods and equipment used to handle conventional aggregates are applicable for steel slag.

- **Placing and Compacting**
- The same methods and equipment used to place and compact conventional aggregate can be used to place and compact steel slag. A good groundwater drainage system is recommended when steel slag aggregate is used to allow free drainage and to prevent ponding within or against the steel slag.

# Questions?

## Presenters:

Kelly Cook - KCOOK@edwclevy.net - 219-462-2924

Isaac L. Howard - ilhoward@cee.msstate.edu - 662-325-7193

John J. Yzenas, Jr. - JYZENAS@levyco.net - 219-462-2924

Travis Zimber - tzimber@edwclevy.net - 662-242-7704

# Steel Slag as a Paving Aggregate: Properties, Applications, and Comparison to Alternatives

## ***Topic:***

## *Aggregate Needs for Unsurfaced Roads or Parking Areas*

*February 27, 2019*

*Starkville, MS*

Mississippi State University
CMRC
Construction Materials Research Center
An Industry, Agency & University Partnership


**Presenters:**

Kelly Cook

Isaac L. Howard

John J. Yzenas, Jr.

Travis Zimber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# Overview

- Steel slag is being used for several unsurfaced applications in the regional market (and other markets)
- These slides highlight:
  - Products available in this market and recent usage patterns
  - Visual case studies of unsurfaced roads in this market
  - CBR testing of unsurfaced combination and applications
  - Case studies of steel slag in service based on light weight deflectometer measurements

# ¾ x 0 Commercial Slag

- 80% driveway and walkways
- 20% heavy use pads

Expansion Rate

<2%

Tons per Cu. Yard

1.83

| Sieve | % Passing | Unit |
|---|---|---|
| 3/4 In | 100.0 | % |
| 1/2 In | 85.4 | % |
| 3/8 In | 63.0 | % |
| No. 4 | 24.6 | % |
| No. 8 | 11.1 | % |
| No. 16 | 5.2 | % |
| No. 30 | 3.3 | % |
| No. 50 | 2.4 | % |
| No. 100 | 1.8 | % |
| No. 200 | 1.3 | % |

# 1 ½ x 0 Duraberm

- 50% Driveway and Low Volume Roads
- 40% Parking Lots and Laydown Yards
- 10% Shoulder Gravel

Expansion Rate

<2%

Tons per Cu. Yard

1.87

| Sieve | % Passing | Unit |
|---|---|---|
| 1 1/2 In | 100.0 | % |
| 1 In | 87.5 | % |
| 3/4 In | 57.6 | % |
| 1/2 In | 23.0 | % |
| 3/8 In | 14.2 | % |
| No. 4 | 10.1 | % |

# 2 x ¾ Railroad Ballast

- 50% Base Material
- 30% Heavy Haul Rd.
- 20% Chicken Houses

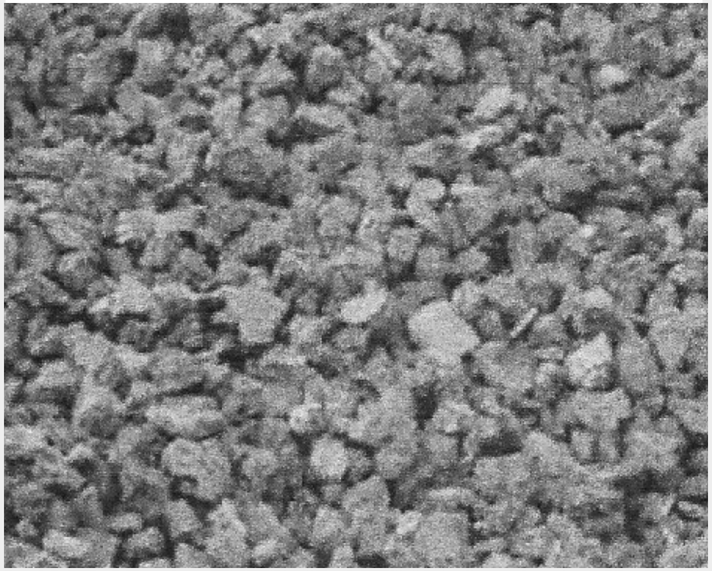
Expansion Rate

<2%

Tons per Cu. Yard

1.66

| Sieve | % Passing | Unit |
|---|---|---|
| 2 In | 100.0 | % |
| 1 1/2 In | 94.3 | % |
| 1 In | 51.2 | % |
| 3/4 In | 27.2 | % |
| 1/2 In | 3.0 | % |
| 3/8 In | 1.7 | % |
| 1/4 In | 1.7 | % |
| No. 4 | 1.2 | % |



# 4 x 1 ½ Commercial Slag

- 40% Base Material
- 30% Logging Roads
- 30% Erosion and Wash out Control

Expansion Rate

<2%

Tons per Cu. Yard

1.51

| Sieve | 4” | 3 1/2” | 3” | 2 1/2” | 2” | 1 1/2” | 1” |
|---|---|---|---|---|---|---|---|
| % | 100.0 | 84.6 | 61.5 | 53.4 | 45.8 | 28.7 | 5.4 |


STOP

Glenn Road

Early Stages

2 years Old

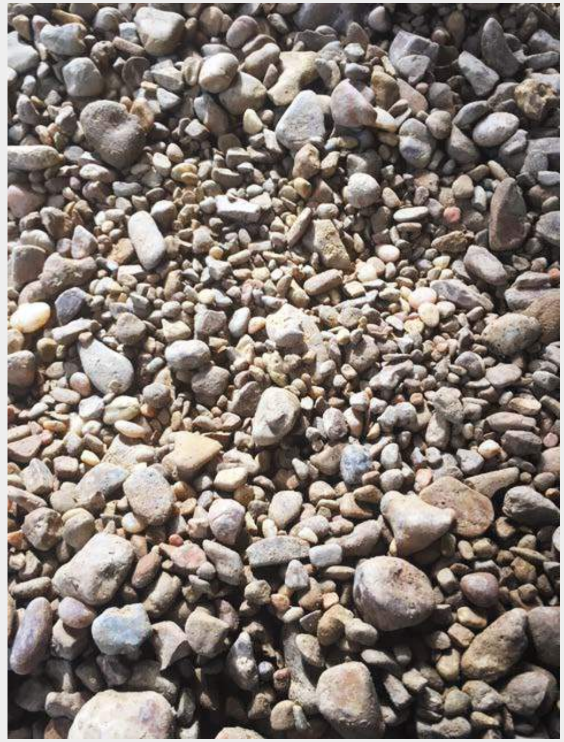


# Unpaved Road Testing at MSU

- Over the past couple of years, several California Bearing Ratio (CBR) tests have been performed to assess unpaved road applications
- Summary data is provided in the following slides

# Materials: Dura-Berm/Gravel/Sand

- Dura-Berm
- From Golden Triangle Mill Service
- Material above 3/4” discarded

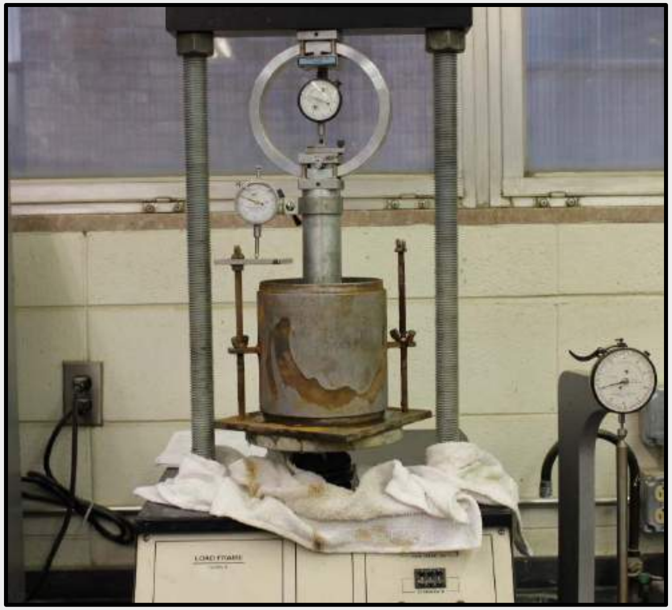


- Gravel
- From Glenn Road
- Material above 3/4” discarded

- SM, A-2-4, 9B, 9C level sands from north Mississippi

# Batching/Mixing/Compaction


# Leveling/Submerged/Draining/Testing

# Dura-Berm/Gravel Blends

0% Dura-Berm

25% Dura-Berm

50% Dura-Berm

75% Dura-Berm

100% Dura-Berm

# Dura-Berm/Sand Blends

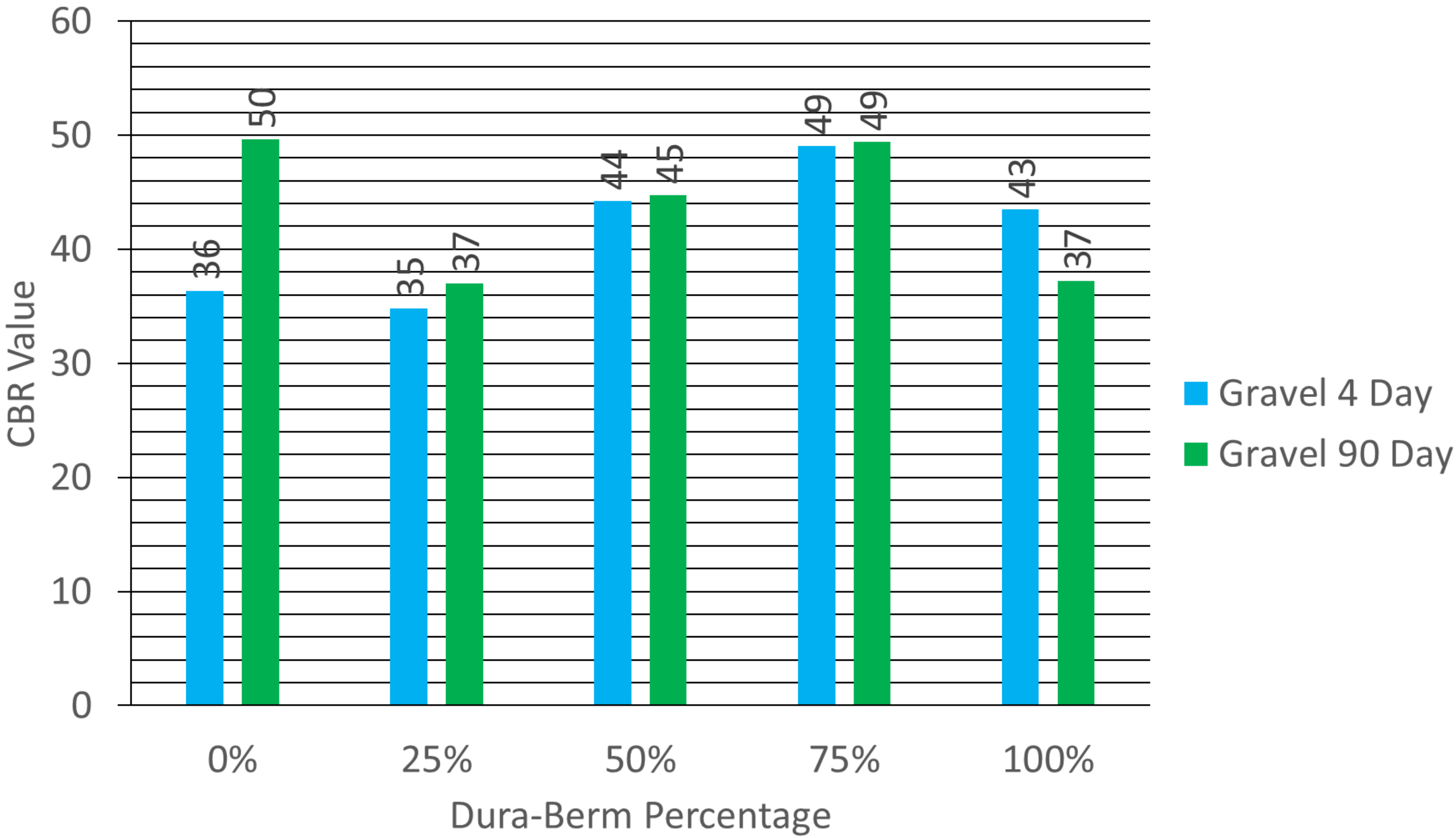
75% Dura-Berm

50% Dura-Berm

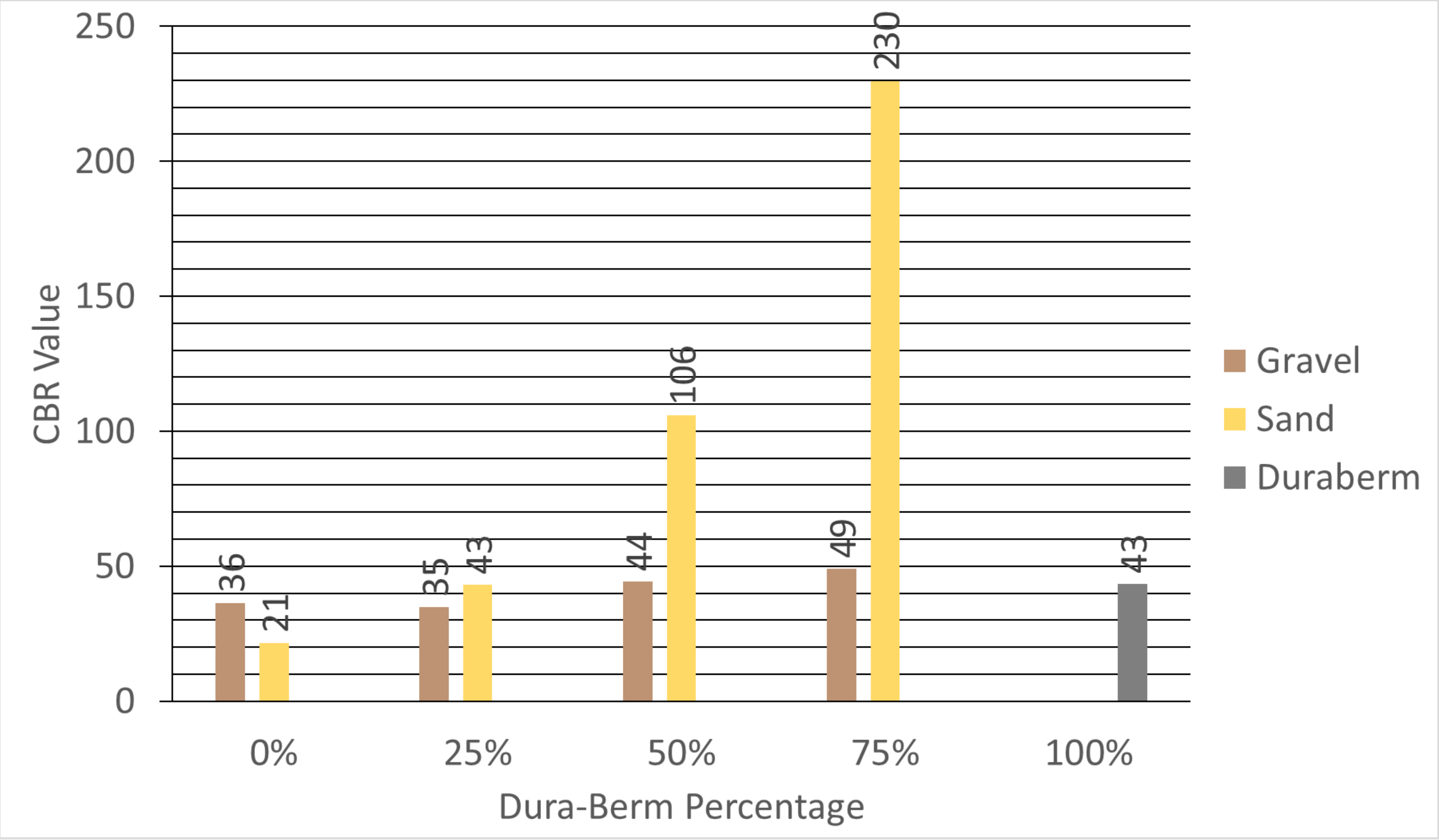
25% Dura-Berm

0% Dura-Berm

# 4 Day v 90 Day Testing



# 4 Day Testing

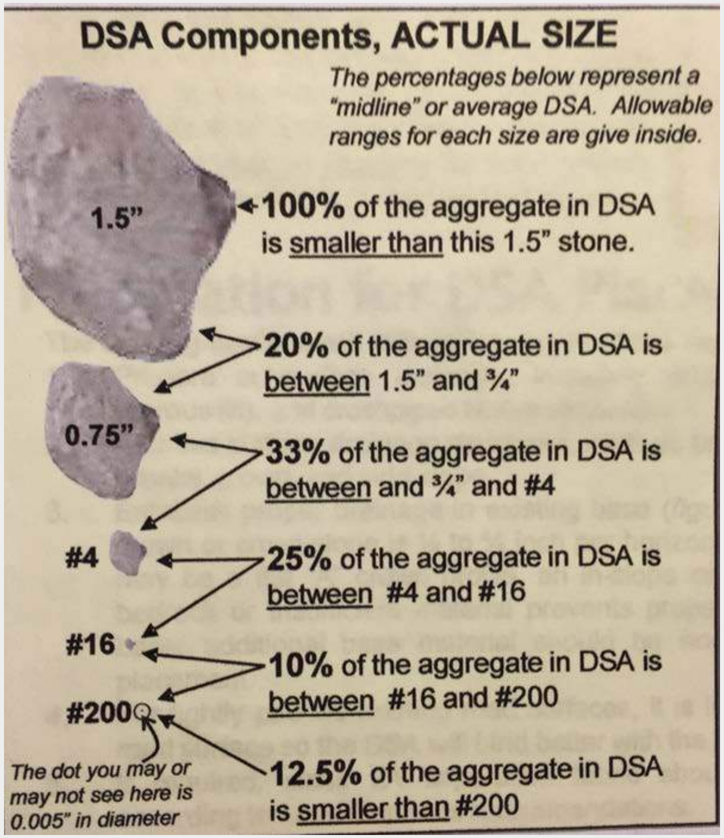


# County Roads: Doing more than designed for

# Aggregate Additions

DSA: Driving Surface Aggregate (PSU)

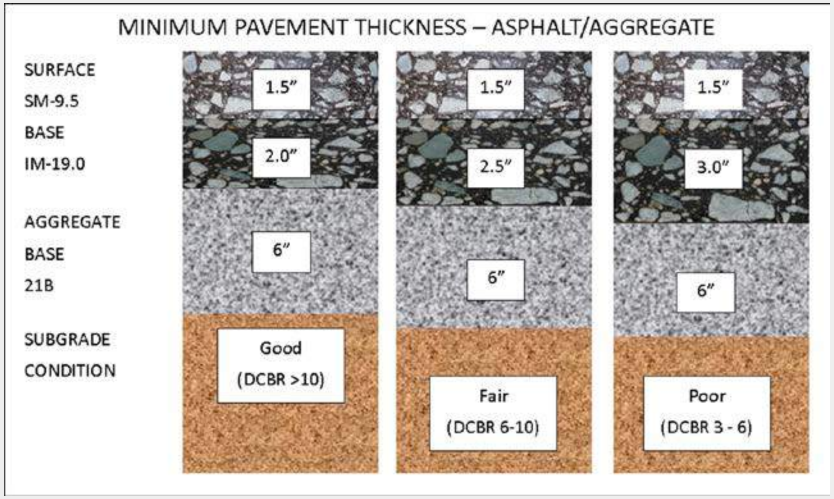
- Surface Wearing Course developed specifically for Unpaved Roads.
- Unique particle size distribution
  - Maximize packing density
  - Durable road surface
  - 1 ½ '' X 0
- PENNDOT approved as of 2006 (publication 447)



# Pavements

Typically comprised of several layers with each layer having it's own function and purpose. The most important part of a roadway is the subgrade / sub-base condition. If this layer is good a smaller asphalt cross-section is required to provide a stable pavement section. If this supporting layer is poor a thicker asphalt section is required.

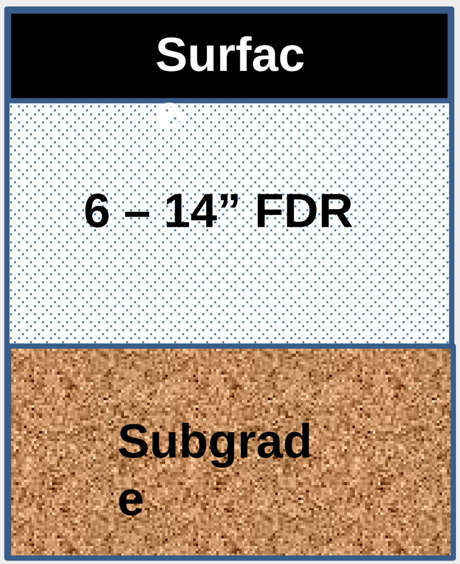
Noble County



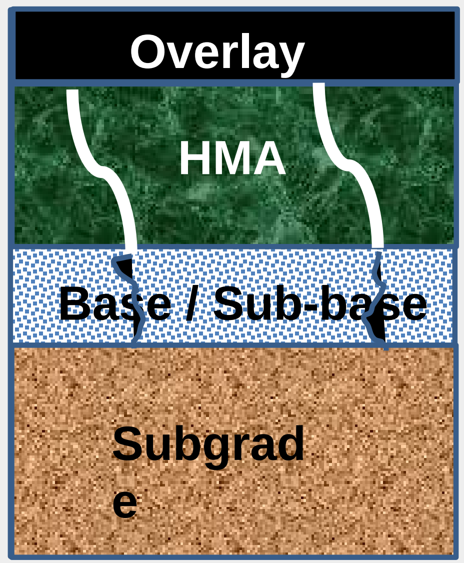

Steuben County

# Improved Foundation = Added Strength / Life

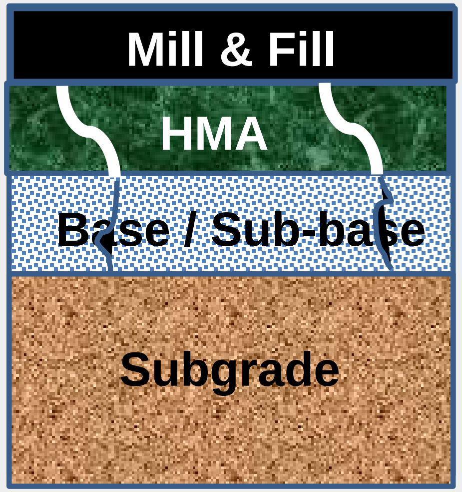
## Reclamation




## Overlay




## Mill & Fill



# What is secondary road stabilization?

- Removes deep pavement cracks
- Allows for adjustments to the road profile
- Road can be opened to traffic prior to placement of final road surface
- Equivalent to traditionally reconstructed roadway in terms of expectancy, wear and load bearing characteristics (Better Road 2001)
- Less traffic interruption
- Environmentally Friendly
- Reduced cost of construction

# Reclamation Benefits

- Reduced Costs of Construction
- Conservation of Aggregates and Binders
- Preservation of Existing Pavement Geometrics
- Preservation of the Environment
- Conservation of Energy
- Less User Delay
- No need to remove materials

Kandhal and Mallick 1997

# Full Depth Stabilization

# CIR/Partial Depth Stabilization

# Why Use Steel Slag?

- Europe
  - The use of steel slag in pavement structure courses would be acceptable from both economic and environmental standpoints: (Građevinar; 1/2012)
  - The main aim of the work was to determine whether a weathered BOF slag could be used as a main constituent in hydraulic road binder. (Mahieux, Aubert, and Escadeillas; 9/2009)
- Australia
  - The material has been blended at a rate of about 40% with existing base materials to rehabilitate existing pavements where the EAFS increased the wet/dry strength value, decreased the Plasticity Index and modified the pavement materials such that it now conforms to a DGB20 specification in accordance with RMS Specification 3051.
- Stabilization
  - Mechanical / Chemical
    - Purdue

# Steel Slag Characterization

- Non-Liquid / Non-Plastic
- LA Abrasion: 18 to 30
- Sodium Sulfate Soundness: <12%
- Crush Count: Highly Irregular (80+ Two Face)
- Gradation: Meets ASTM (D1241) and FHWA (Type 1 or 2) Requirements
- Binding Potential:  Free Lime in Excess of 6%*
  - There are various types of Steel Slag.
  - Not all have the ability to act as a binder in these applications.
  - Proper characterization is essential.

# Steel Slag Characterization

- Chemical Properties
  - pH
  - Chemical Analysis by various methods
  - Calcium Carbonate Equivalency (CCE)
  - Free Lime
- Physical Properties
  - Gradation
  - Moisture
  - Specific Gravity and Absorption
  - Unit Weight
  - Expansion / Disruption

# Gravel Roads Maintenance and Design Manual

| Gradation for Aggregate Surface Course | | | | |
|---|---|---|---|---|
| Percent Passing | | | | |
| Sieve | No.1 | No.2 | IN-53 | IN-73 |
| 1 ½” | | | 100 | |
| 1" | 100 | 100 | 80-100 | 100 |
| ¾” | | | 70-90 | 90-100 |
| ½” | | | 55-80 | 60-90 |
| 3/8" | 50-85 | 60-100 | | |
| #4 | 35-65 | 50-85 | 35-60 | 35-60 |
| #8 | 25-50 | 40-70 | 25-50 | |
| #30 | 15-30 | 24-45 | 12-30 | 12-30 |
| #200 | 8-15 | 8-15 | 5.0-10.0 | 5.0-12.0 |

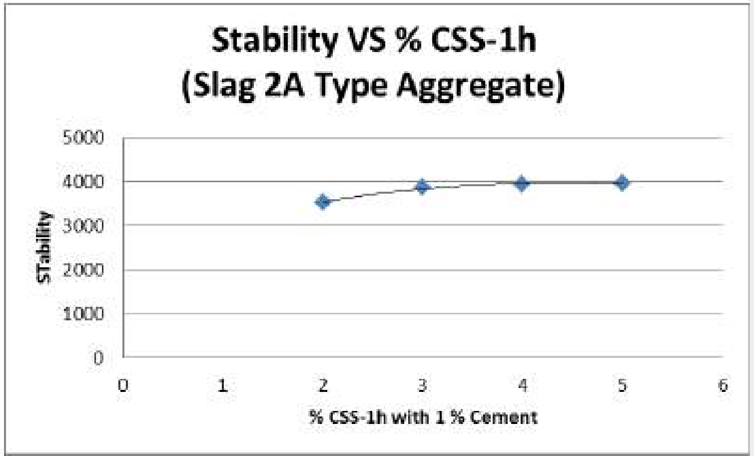
# Purdue / I-65; 2010 > 2016

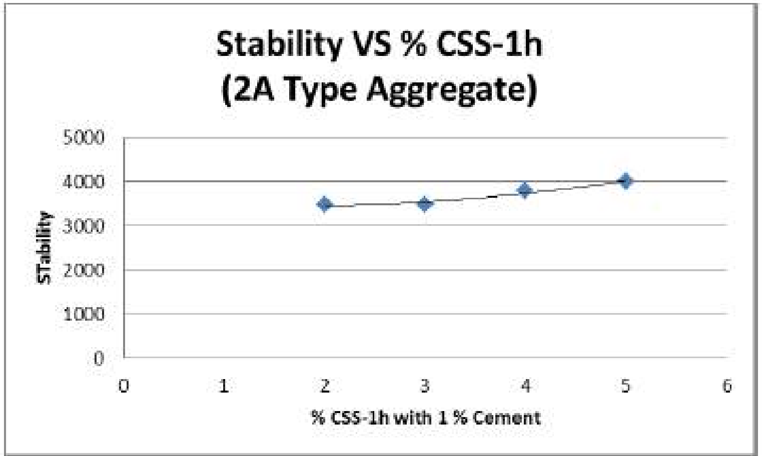
# PennDOT Project: FDR/SLAG 2016/2017

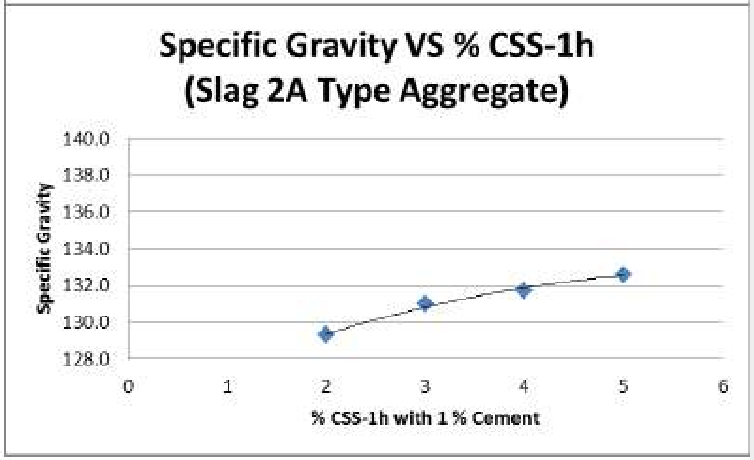
**PBE FDR / SLAG Project FY: 2016 / 2017**

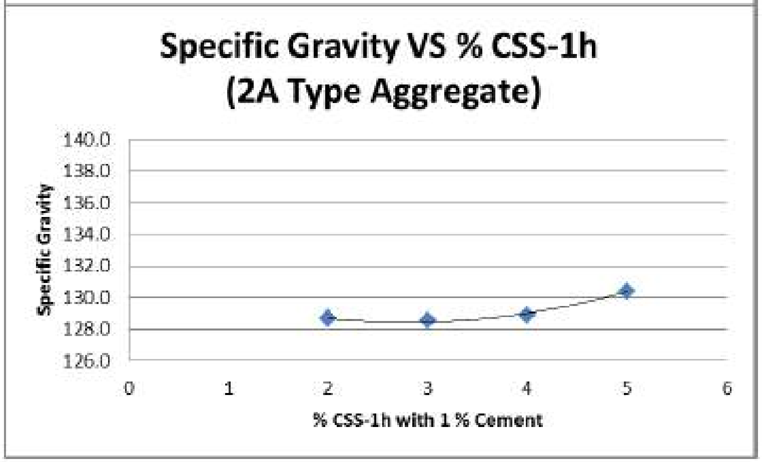
| | |
|---|---|
| **County** | **McKean Co.** |
| **Project Length** | 4.65 Miles |
| **Estimated Project Cost/ Cost per mile** | |
| **Average Daily Truck Traffic** | 1,035 |
| **Average Daily Truck Traffic** | 376 |
| **Estimated Project starting Date** | Fall 2016 |
| **Scope of repairs proposed:** | 12” Full-depth reclamation (FDR) to widen the base from 20’ to 24’. Approximately 100,000 Cubic feet / **6,500 ton of slag** is to be used as the aggregate to obtain the necessary structure for widening. Overlay with 3” Binder & 1.5” Wearing course at 22’. Guiderail safety upgrade, tree trimming and some drainage will be addressed. |

# PennDOT – Material Characterizations

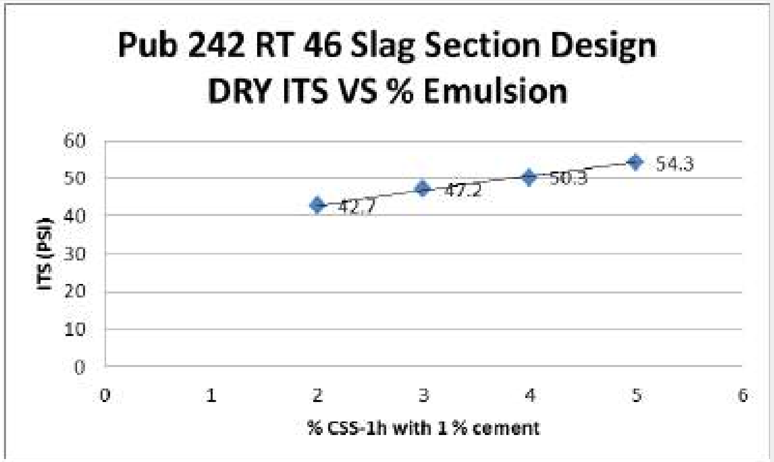


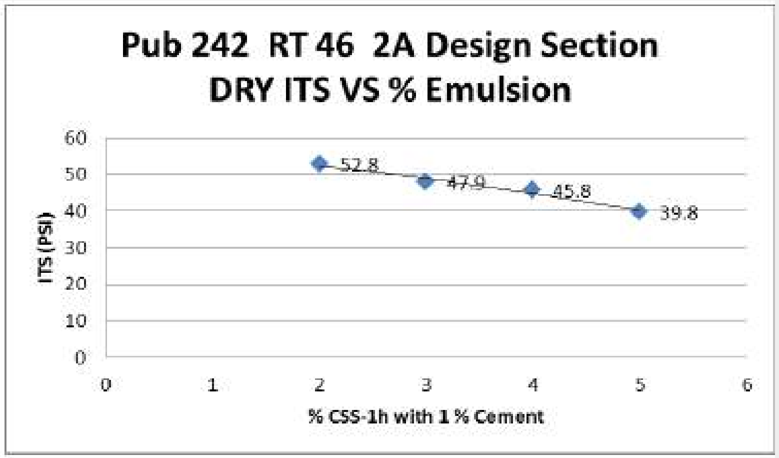



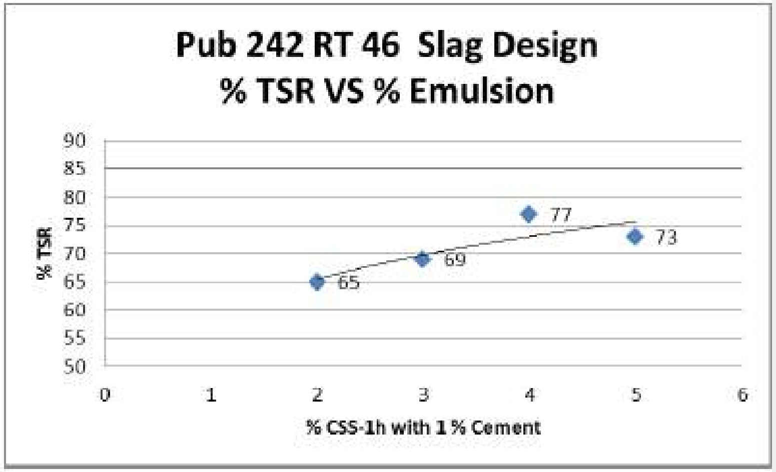



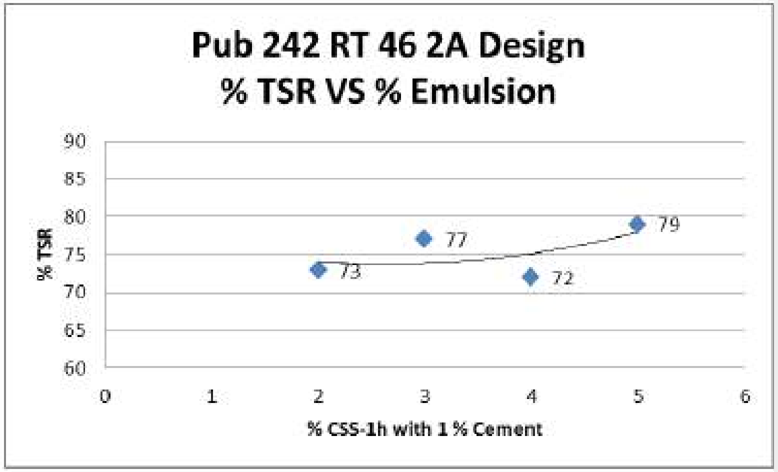



# PennDOT – Material Characterizations, cont.



# PennDOT - Construction

# PennDOT - Construction

# PennDOT - Construction

# PennDOT – Finished Reclamation/Stabilization

# PennDOT – Highway 46

# Indirect Tensile Strength

- Noble County 2016
- Results
  - 4.59 PSI # 3% Binder
  - Inconclusive

# California Bearing Ratio

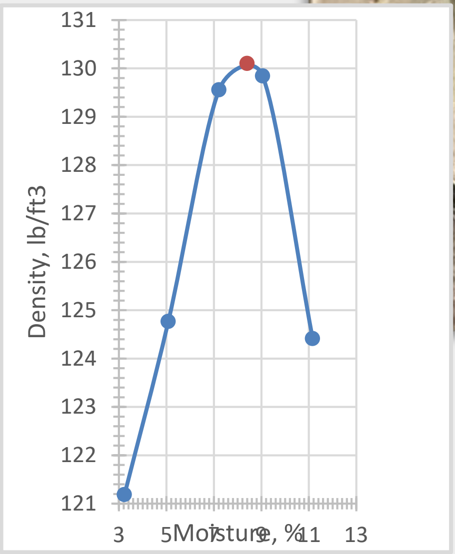
- Noble County  2016
- Results

| | 0.1 Penetration | 0.2 Penetration |
|---|---|---|
| Initial | 25.1 PSI | 33.3 PSI |
| Final | 60.8 PSI | 81.1 PSI |

# Proctor

- Noble County 2016
- Results

| | Moisture | Density |
|---|---|---|
| Initial | 6.55 % | 132.9 PCF |
| Final | 7.10 % | 138.4 PCF |




# Unconfined Compression

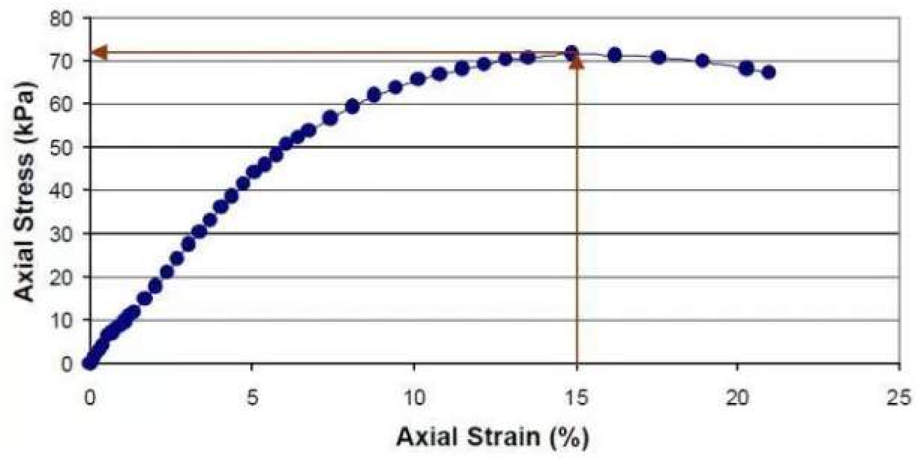




Fig-3

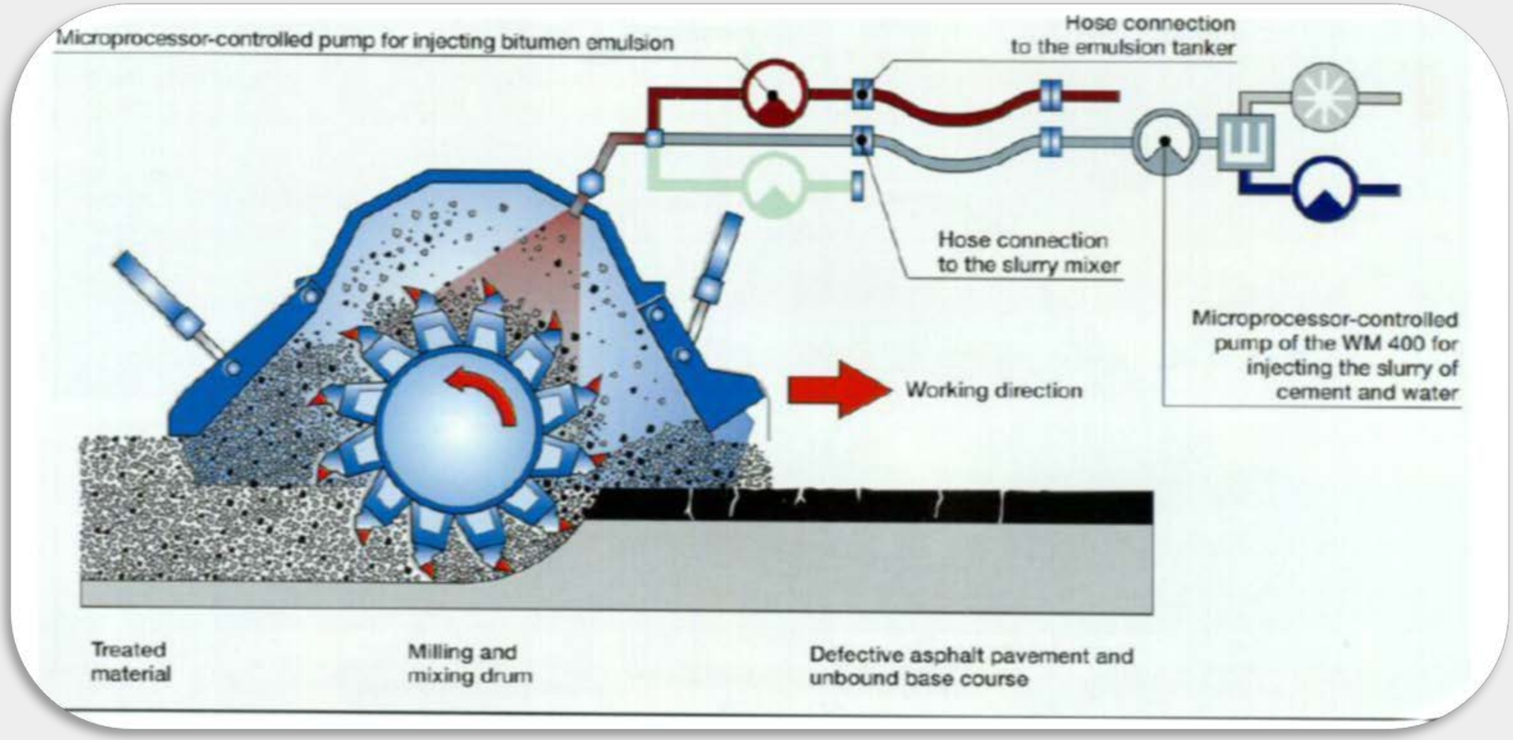
# Triaxial Data

| | Unconfined Compression | |
|---|---|---|
| | **No Aging** | **28 Day** |
| **Existing Roadway** | 23.0 psi | 46.5 psi |
| **W/ 30% Blend** | 26.4 psi | 80.9 psi |
| **W/ 40% Blend*** | 39.5 psi | 85.3 psi |
| **W/ 50% Blend** | 57.5 psi | 90.3 psi |
| **W/ 60% Blend** | 61.8 psi | 96.0 psi |

# Noble County, IN Secondary Stabilization in Action

# Secondary Stabilization in Action

# Secondary Stabilization in Action




New York DOT 2015

# Secondary Stabilization in Action

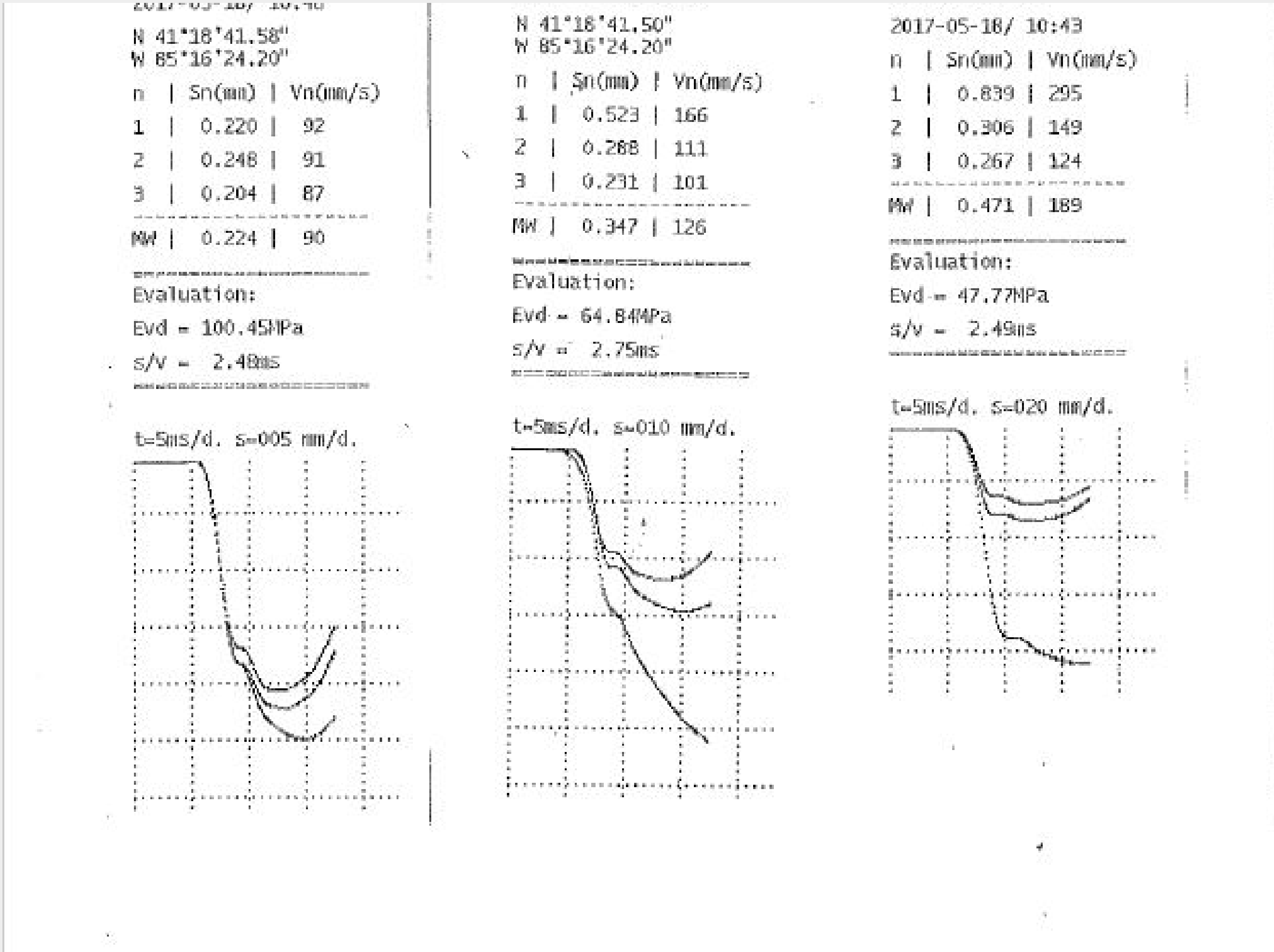
# Secondary Stabilization in Action

# How do you know you’ve done a good job?

# Lightweight Deflectometer (LWD)

- Hand portable falling weight device
- Measures deflection and compaction
- Modulus – measure of stiffness
  - Optimize performance
  - Increase life span of pavement
  - Predict performance of recycled materials
- Cost Effective
  - Inexpensive
  - Efficient – short testing time (~2 minutes per test)
- **Correlate Deflection to Modulus**
- **QA / QC for Quick Field Determination of compaction**

# Example LWD Data



N 41°18'41.58"
W 85°16'24.20"

| n | Sn(mm) | Vn(mm/s) |
|---|---|---|
| 1 | 0.220 | 92 |
| 2 | 0.248 | 91 |
| 3 | 0.204 | 87 |
| MW | 0.224 | 90 |

Evaluation:
Evd = 100.45MPa
s/v = 2.48ms

t=5ms/d. s=005 mm/d.

N 41°18'41.50"
W 85°16'24.20"

| n | Sn(mm) | Vn(mm/s) |
|---|---|---|
| 1 | 0.523 | 166 |
| 2 | 0.288 | 111 |
| 3 | 0.231 | 101 |
| MW | 0.347 | 126 |

Evaluation:
Evd = 64.84MPa
s/v = 2.75ms

t=5ms/d. s=010 mm/d.

2017-05-18/ 10:43

| n | Sn(mm) | Vn(mm/s) |
|---|---|---|
| 1 | 0.839 | 295 |
| 2 | 0.306 | 149 |
| 3 | 0.267 | 124 |
| MW | 0.471 | 189 |

Evaluation:
Evd = 47.77MPa
s/v = 2.49ms

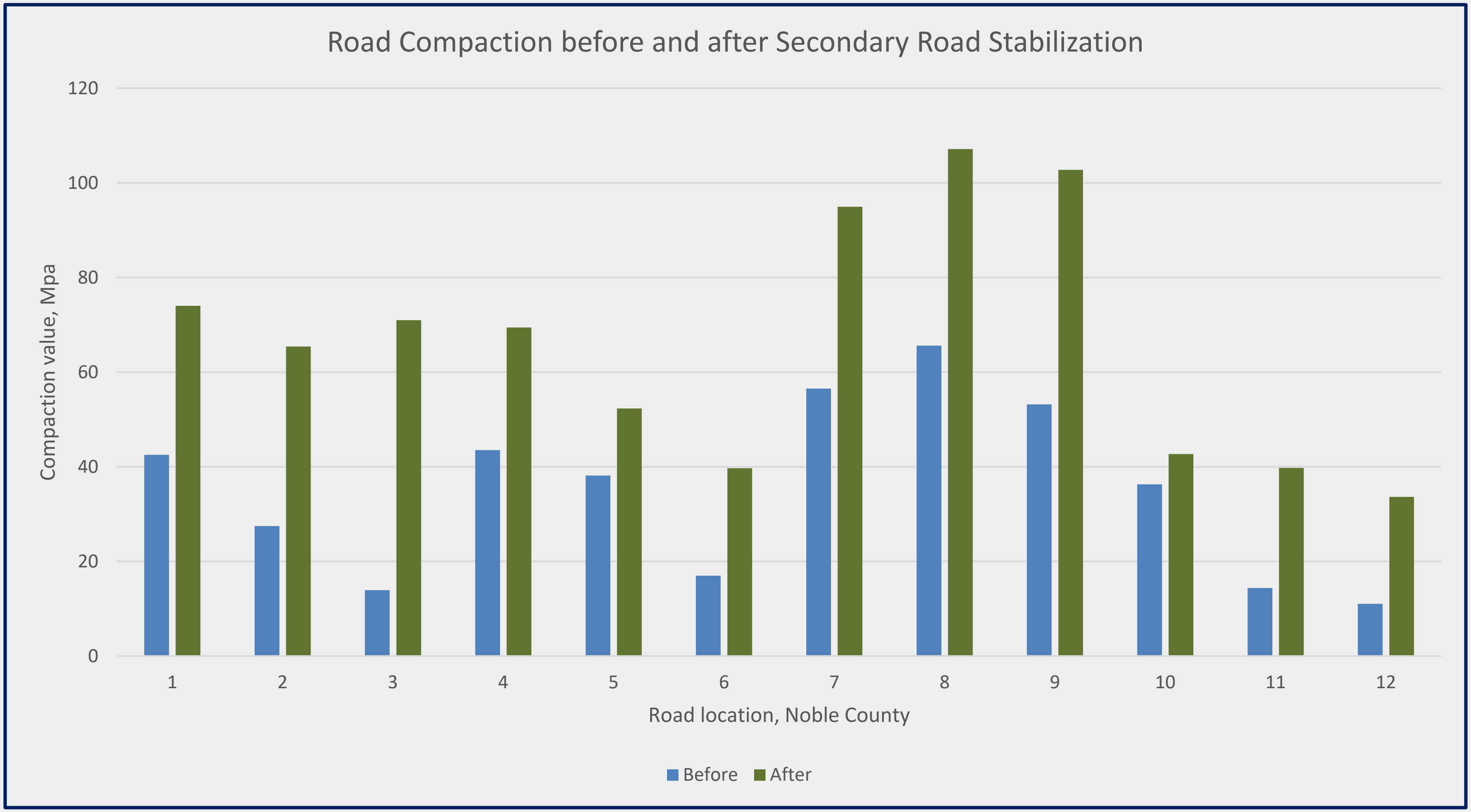
t=5ms/d. s=020 mm/d.

# Benefit of LWD

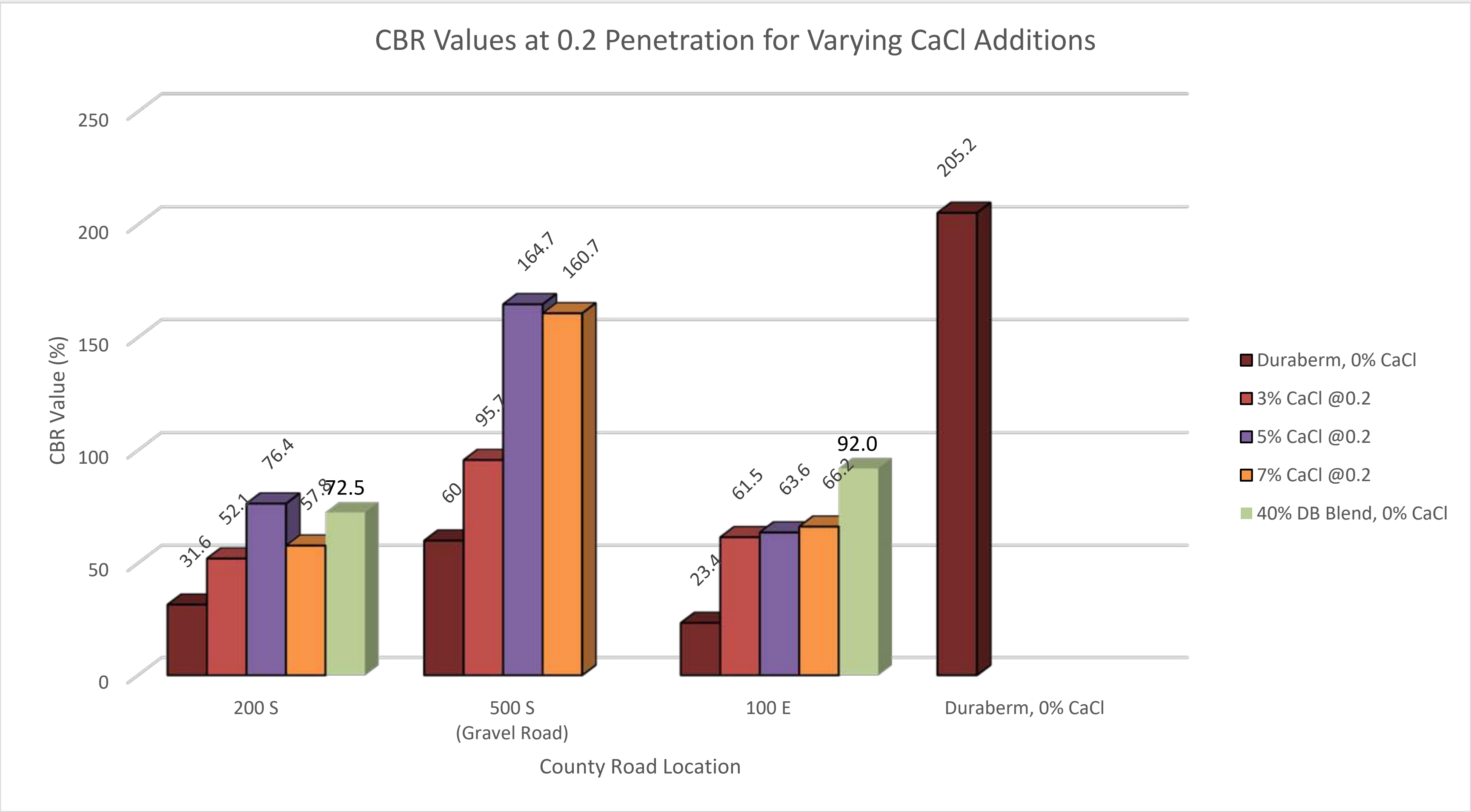
- Cost Effective
  - Inexpensive
  - Efficient – short testing time (~2 minutes per test)
- Hand Portable
- In Field – Real Time data

# In Field, Real Time

# Noble County Improvements



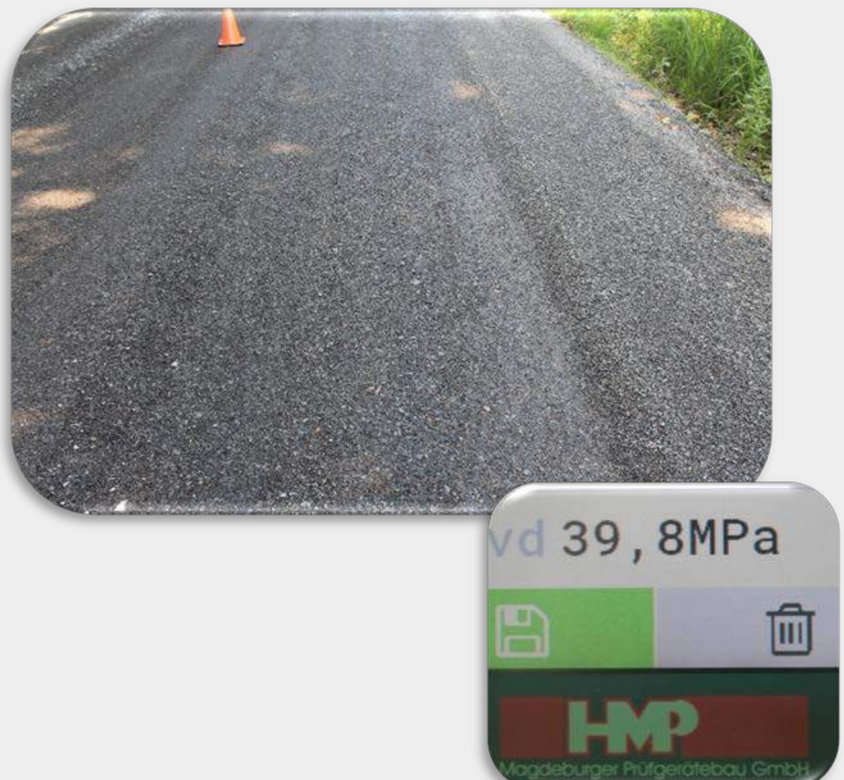
# Duraberm Blend Trials



# County Improvements

**Before Stabilization**

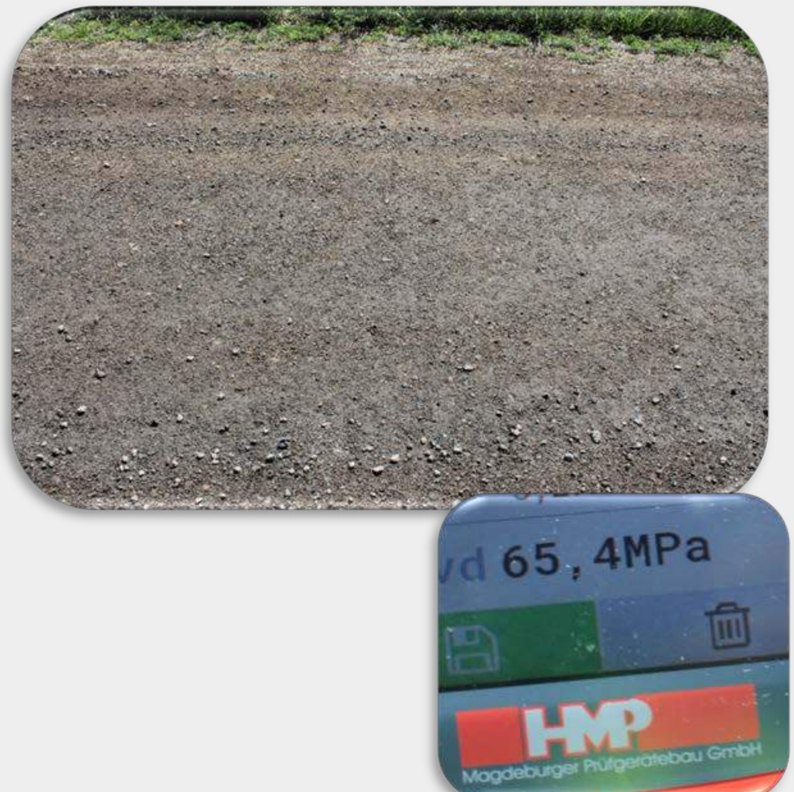

**After Stabilization**



# County Improvements

**Before Stabilization**


**After Stabilization**



# County Improvements

**Before Stabilization**


**After Stabilization**

# Measuring Success

# Identifying Potential Failures

# References


- FHWA: Gravel Roads Maintenance & Design Manual
- FHWA –HIF-036, Full Depth Reclamation
- USDA Forest Service: Stabilization Selection Guide for Aggregate & Native-Surfaced Roads
- USACE: UFGS Section 32 15 00 – Aggregate Surface Course
- Minnesota DOT: Design Guide for Low-Volume Aggregate Surfaced Roads
- ASTM: D1241 – Specification for Materials for Soil-Aggregate Subbase, Base and Surface.
- New York DOT GEM-27, "Full Depth Reclamation of Asphalt Pavement"
- NCHRP Project 10-84: Modulus-Based Construction Specification for Compaction of Earthwork and Unbound Aggregate
- Comparative Studies of Lightweight Deflectometer and Benkelman Beam Deflectometer in Low Volume Roads – Guzzarlapudi et al.
- The Use of Light Weight Deflectometer for In Situ Evaluation of Sand Degree of Compaction – Elhakim et al.
- INDOT Specification Handbook

# Questions?

## Presenters:


Kelly Cook - KCOOK@edwclevy.net - 219-462-2924

Isaac L. Howard - ilhoward@cee.msstate.edu - 662-325-7193

John J. Yzenas, Jr. - JYZENAS@levyco.net - 219-462-2924

Travis Zimber - tzimber@edwclevy.net - 662-242-7704

# Steel Slag as a Paving Aggregate: Properties, Applications, and Comparison to Alternatives

## *Topic:*

## *Pavement Design 101: The Role of Aggregates*

*February 27, 2019*

*Starkville, MS*

Mississippi State University
CMRC
Construction Materials Research Center
An Industry, Agency & University Partnership


**Presenters:**

Kelly Cook

Isaac L. Howard

John J. Yzenas, Jr.

Travis Zimber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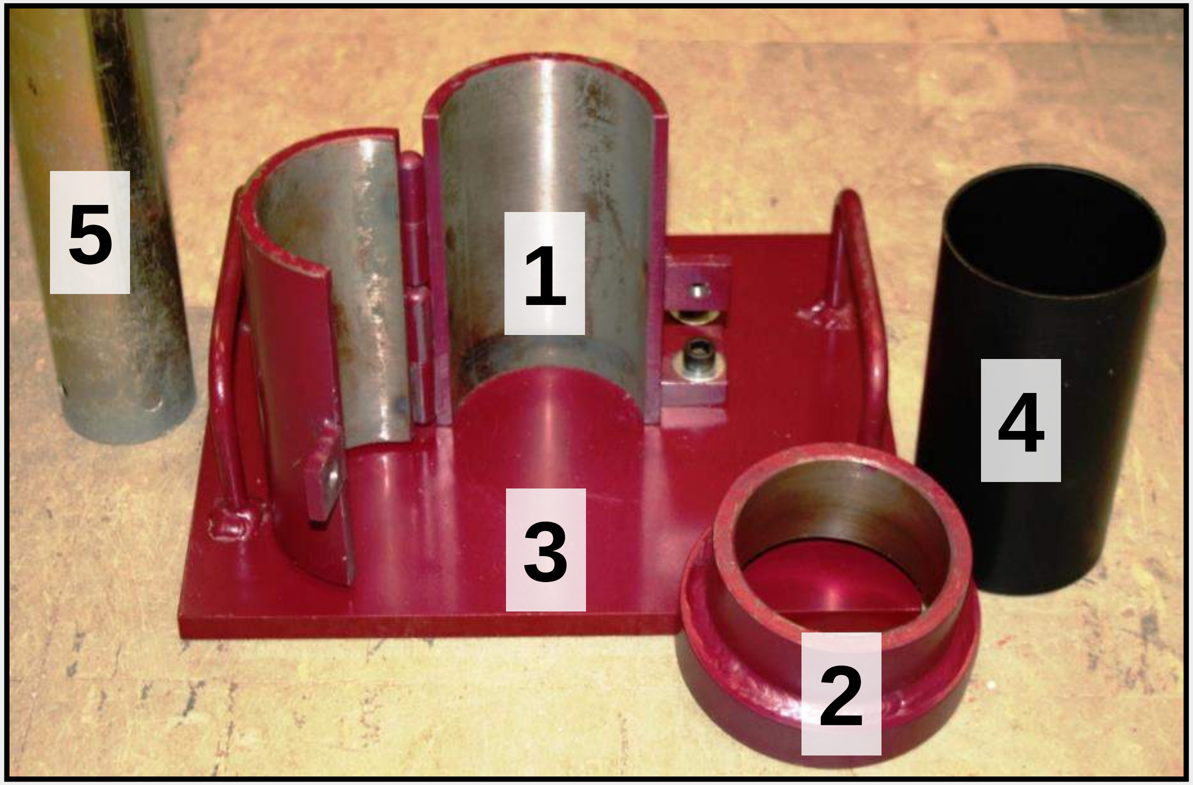
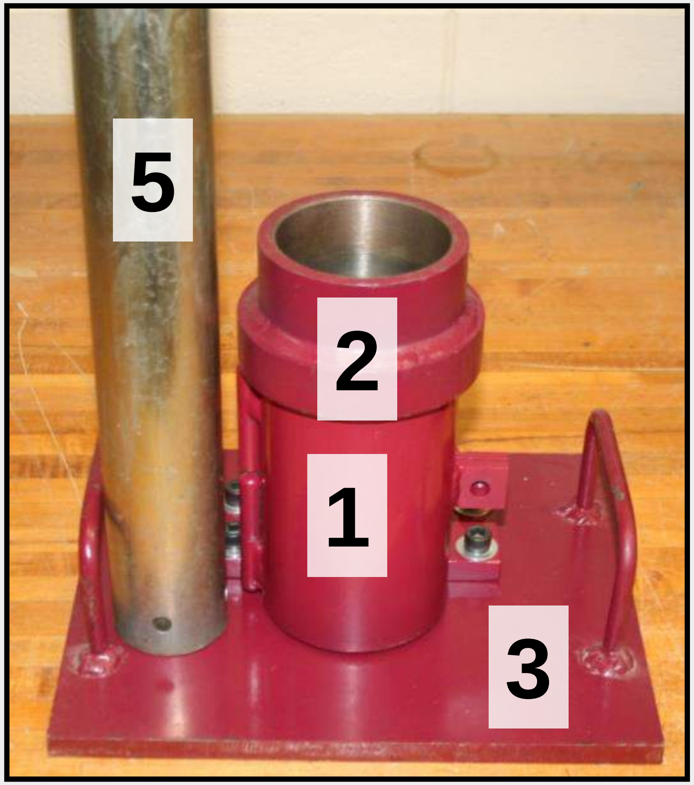
# PM Device Concept & Design

- The PM Device allows a wide range of chemically stabilized soils to be compacted inside a plastic mold

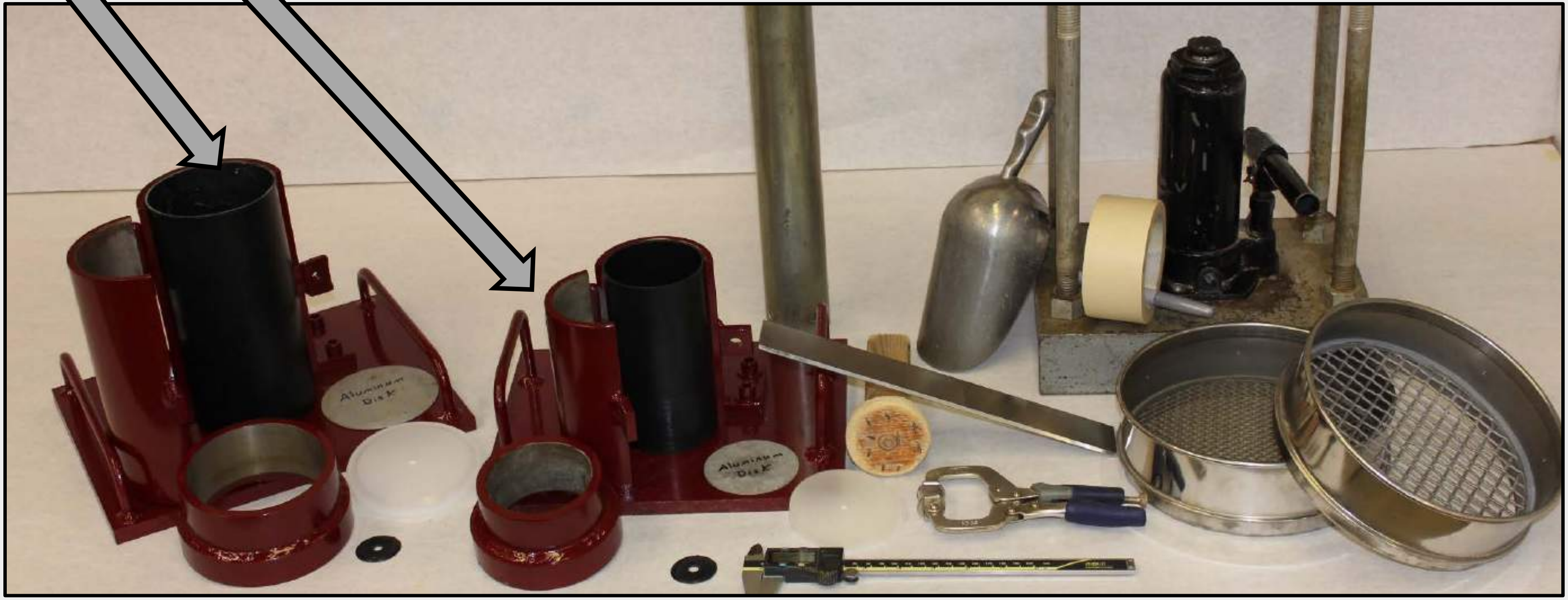
Video of operation is available at
https://www.youtube.com/watch?v=F-iYEpzBHko



# Two PM Device Sizes

| Specimen Size (in) | Approximate Dimensions (in) | Weight w/ Aluminum Base (lb) | Terminology i = number of blows per lift |
|---|---|---|---|
| 3x6 | 11x10x9 tall | 17 | 3x6[i] i = 5 is default |
| 4x8 | 11x10x11 tall | 22 | 4x8[i] i = 9 is default |



# AASHTO PP92

Standard Practice for

## Preparation of Test Specimens Using the Plastic Mold Compaction Device

AASHTO Designation: PP 92-18[1]

AASHTO

Technical Section: 1b, Geotechnical Exploration, Instrumentation, Stabilization, and Field Testing

Release: Group 3 (August)

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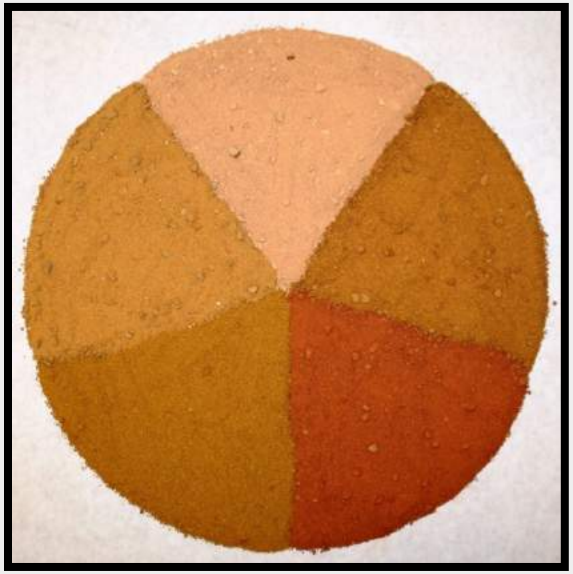
### 1. SCOPE

1.1. This standard practice covers the use of the plastic mold compaction device (PM device) to prepare cylindrical test specimens with an approximate 2:1 height-to-diameter aspect ratio for use in a variety of mechanical property testing (e.g. compressive strength, elastic modulus, tensile strength). This practice is intended for chemically stabilized soil materials (e.g. soil–cement). This standard practice can be performed in a laboratory, or, if performed at a construction site, may produce comparable properties.

# PM Device's Role in MDOT Soil-Cement Manual of Practice

- MDOT currently has a Manual of Practice (MOP) under development, scheduled for completion in next couple of years
- One key feature:
  - ***PM Device compacted specimens used as MEPDG inputs for layer thickness design, for design cement content selection, <u>and</u> for construction quality control***



<u>Materials:</u> Mainly M145 A-2-4 or USCS SM (Near 100% passing No 10 sieve), MDOT Designated 9C (or a few others)

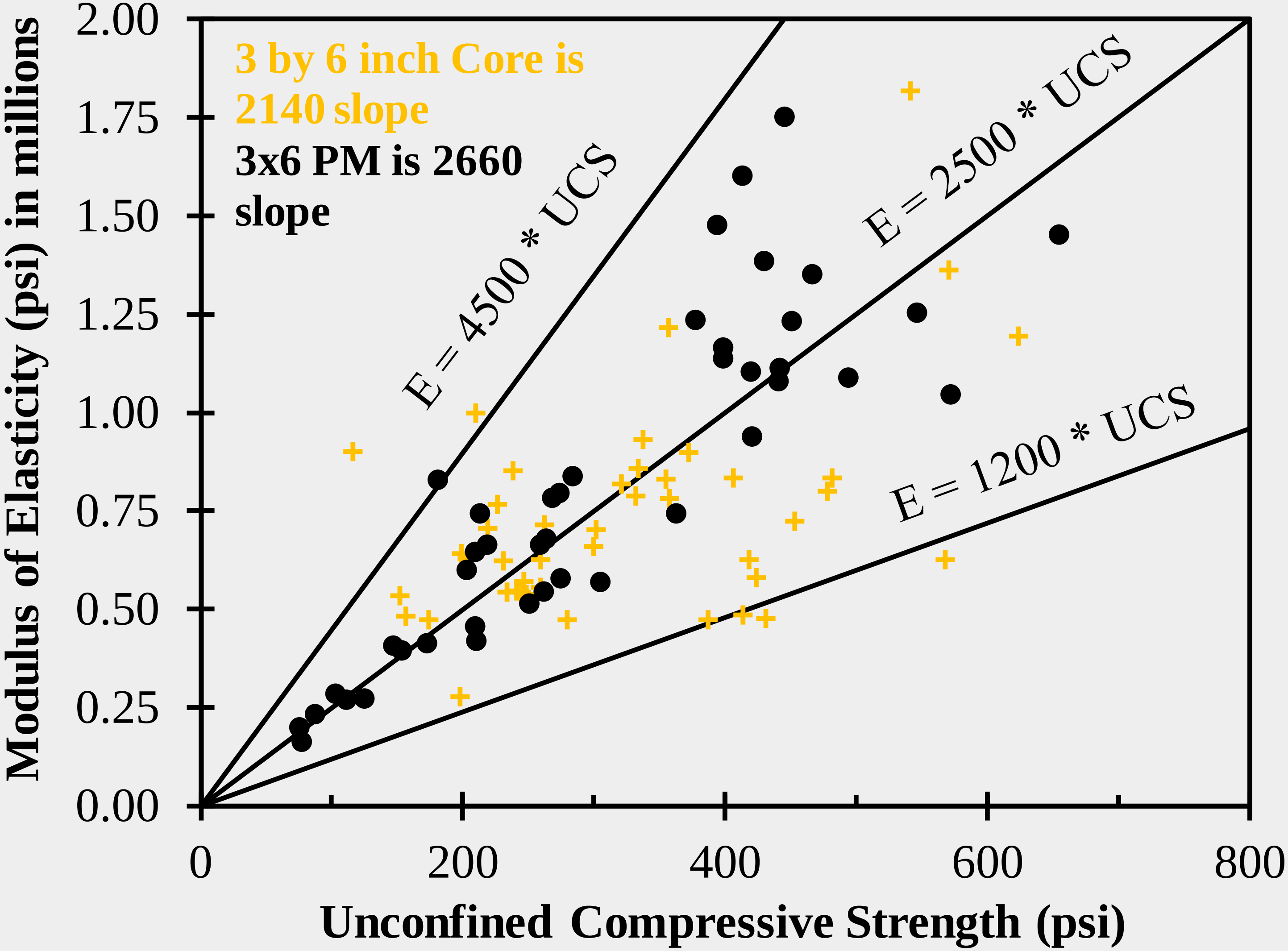
# Mixed In Place Soil-Cement (Routinely Used in MS Instead of Aggregate Bases)

- What is designed isn't always what is built – for reference MDOT averaged 43 million $yd^2$ of soil-cement annually Jan 2005 through June of 2016
- The ability to assess cement content and mixing uniformity in field is important, especially when mixing in place
- High variability leads to lowered reliability of design or artificially high design strength criteria to avoid strengths below minimum specification levels – **all the while pavement performance is usually more driven by modulus than strength**

# What is a good target strength level?

- The maximum vertical stress in the base will never exceed the contact pressure on the pavement surface.
- Average contact pressures for highway applications are 100-120 psi in service
- Average vertical stress at top of subgrade for adequate design < 30 psi, in most cases < 20 psi
- Using stress ratio of 0.40, adequate strength = 30/0.4=75 psi (don’t fall in love with this number – point is it isn’t 300 to 700 psi during service)
- During construction, might need more strength, but not for pavement design/performance – it is important to understand this fundamental concept

# Soil-Cement Elastic Modulus to Strength Benchmarking (I-269)



# CIR w/ Cement Testing at MSU

- MUST use steel slag with little to no expansion in stabilized base – DO NOT use materials with considerable expansion potential in applications like this
- Idea is to improve strength to modulus relationships with aggregates instead of binders (e.g. cement) - binders play very important role, but modulus increases with gradation/aggregate properties are more durable over time

# PM Device Testing of Steel Slag/CIR/Base Soil

- 2 3/4 " Commercial Steel Slag
- From Golden Triangle Mill Service
- Material above 1.25" discarded

- Cold In Place (CIR) Recycling
- From Highway 45 near Tupelo
- Material above 1.25" discarded

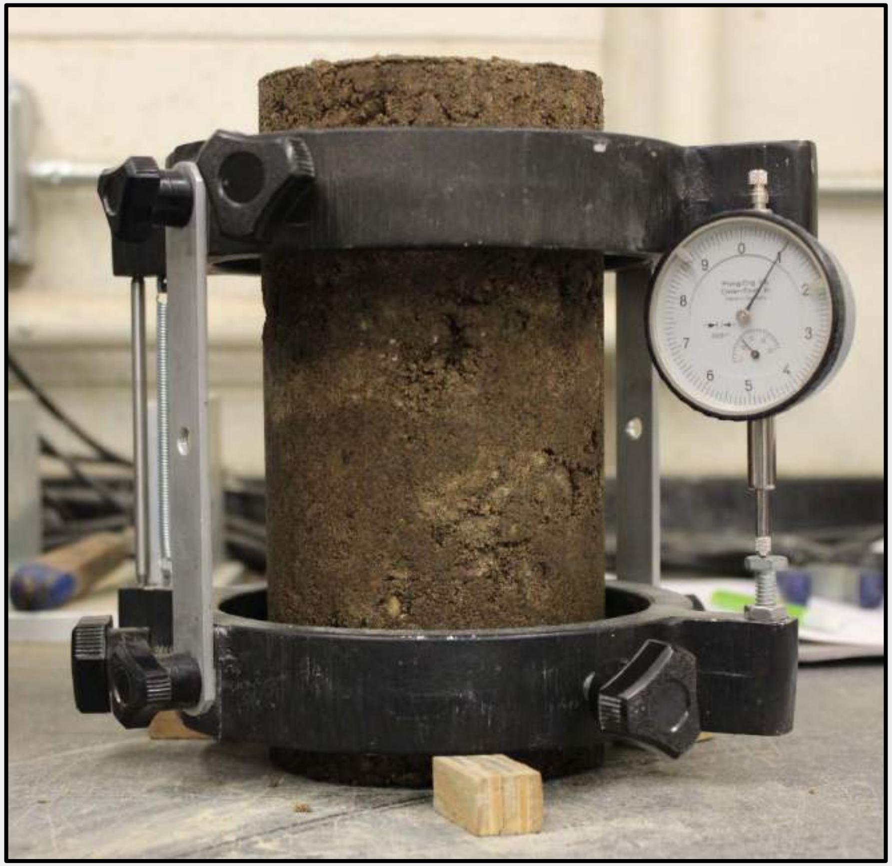
- Roadway Base Material
- From Highway 45 near Tupelo
- Material above No. 4 Sieve discarded

# Mixing, Compaction, and Extraction






# CIR Steel Slag Elastic Modulus Testing




Fitting in Collar


On Loading Frame

# CIR w/ Steel Slag UCS Testing

Before

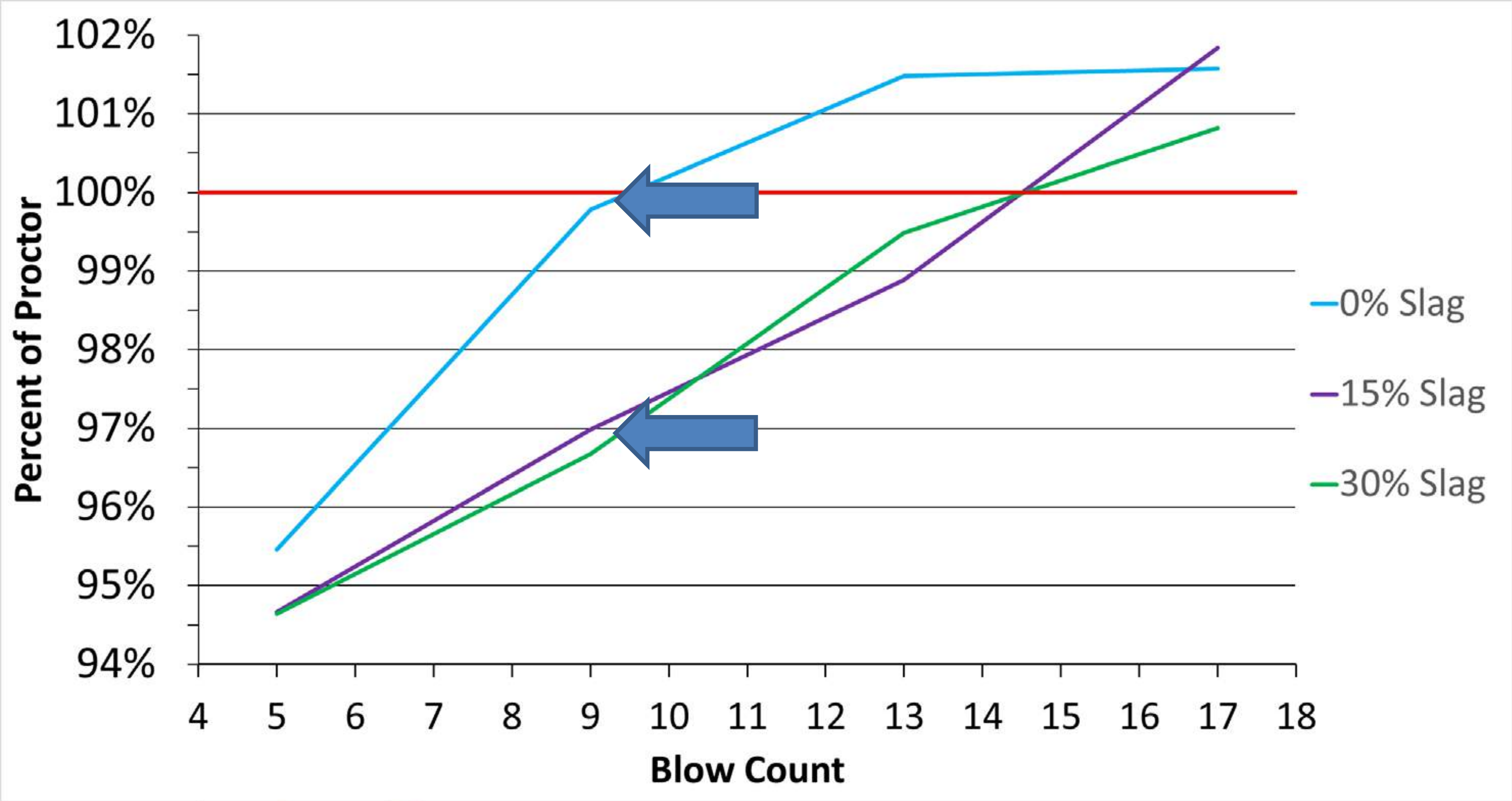

After

# CIR w/ Steel Slag and Cement

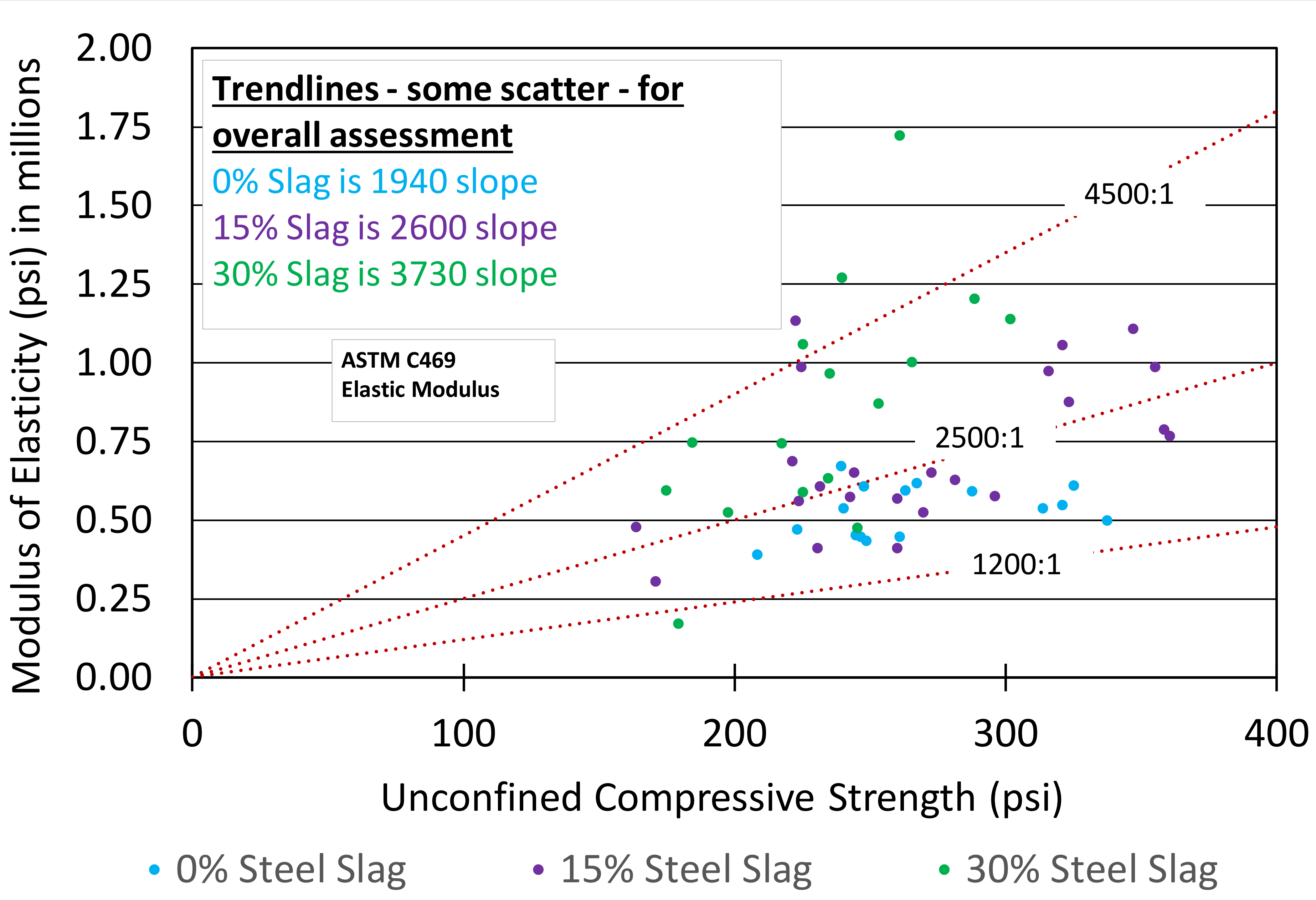
- 3 materials on previous slide mixed at 0, 15, 30% slag – lab testing only
- Steel Slag
  - 88% passing 1.25 in, 64% passing 1 in, 27% passing ¾")
- CIR
  - 99% passing 1.25 in, 94% passing 3/4 in, 44% passing No. 4, 33% passing No. 8, .5% passing No. 200)
- 4 to 5% Type I Portland Cement


Note: 0% and 30% steel slag Specimens are visually similar

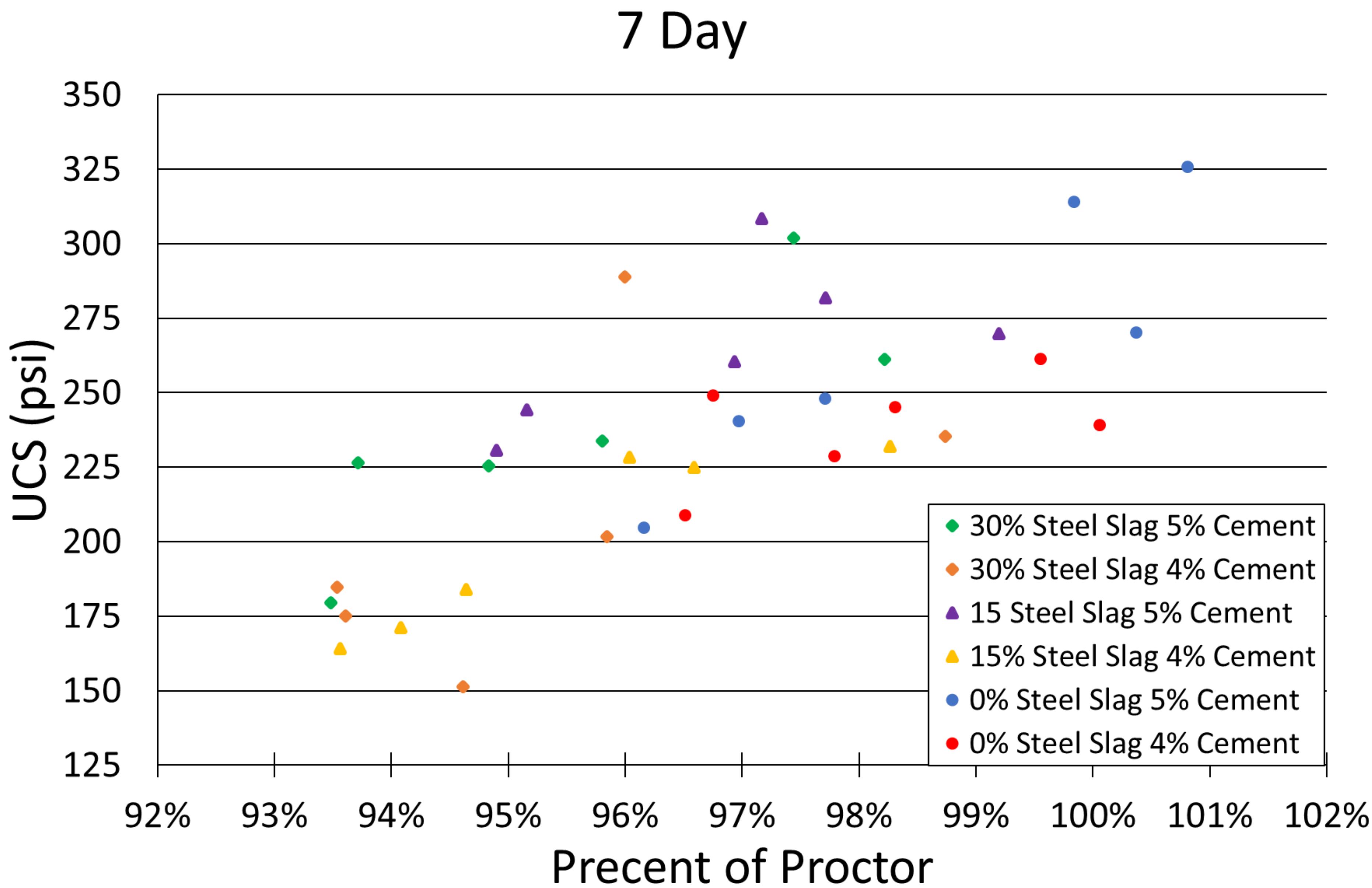
# CIR w/ Steel Slag Density vs. Blow Count
# 4x8 PM Device



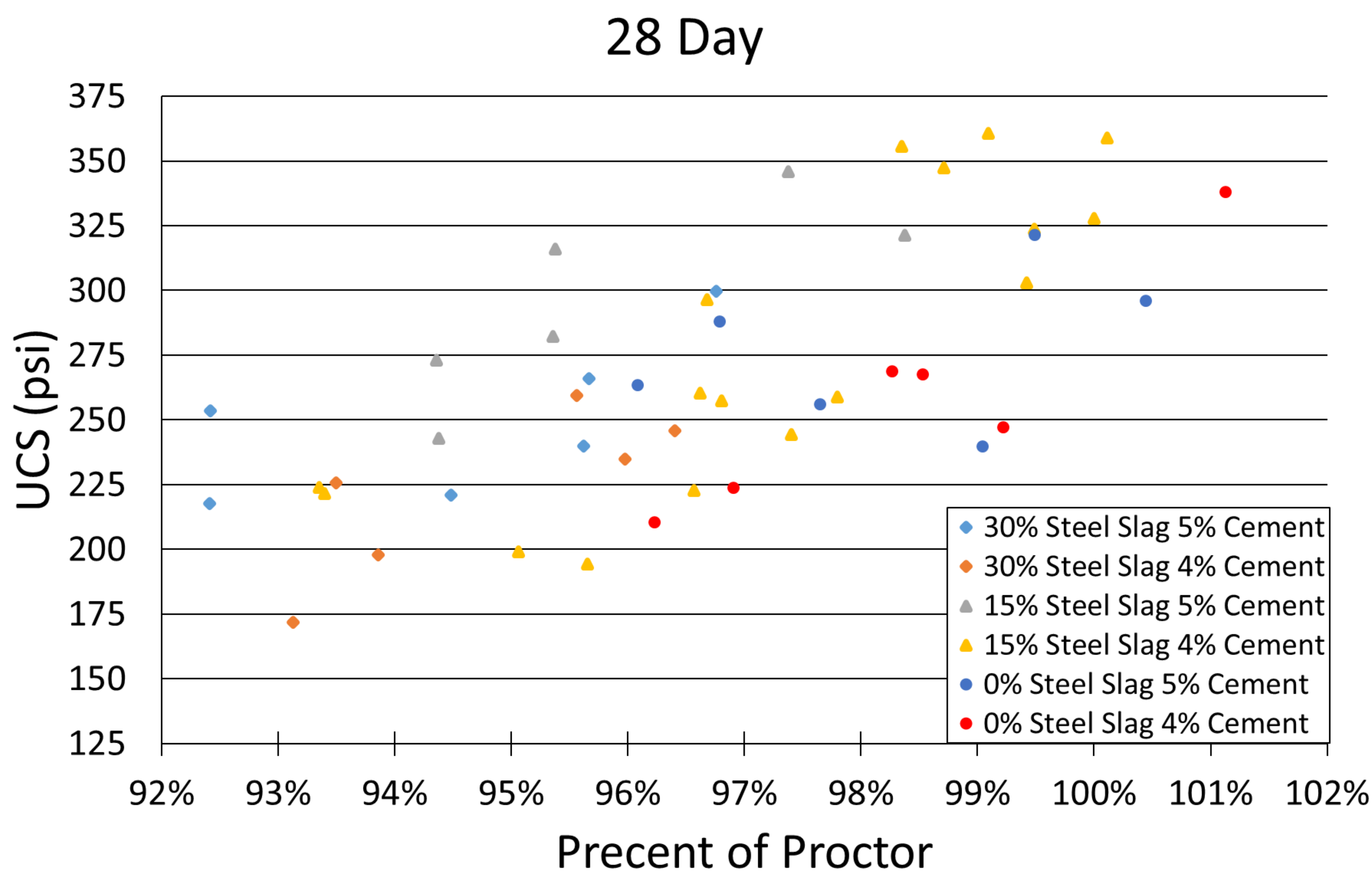
# CIR Steel Slag Modulus Effects



# 7 Day - UCS vs Percent of Proctor



# 28 Day - UCS vs Percent of Proctor

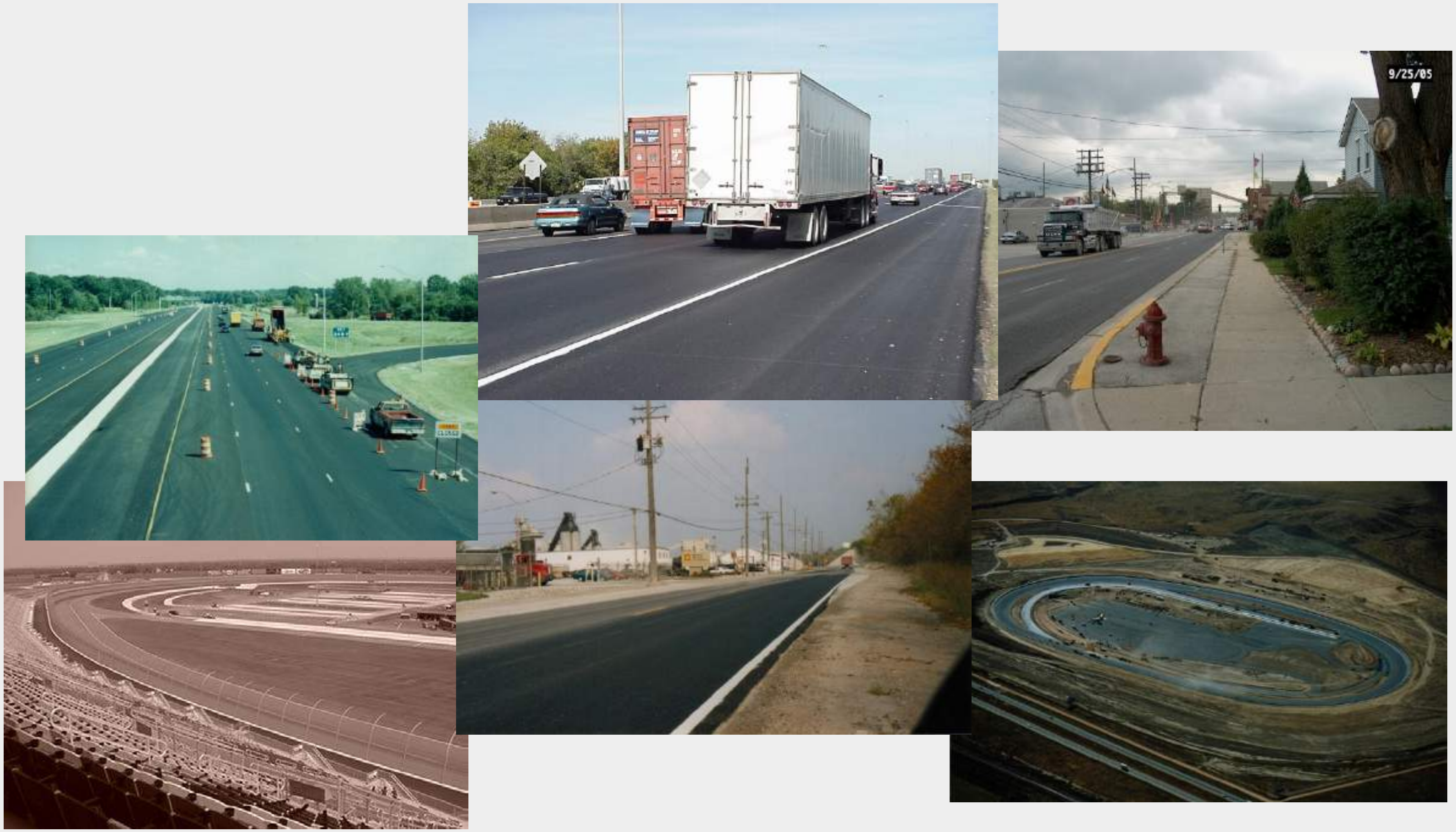


# Strength Comparisons

- Trend lines from previous slides used to calculate UCS at 97% Proctor. Values in psi

| Steel Slag Percentage | 7 Day | | 28 Day | |
|---|---|---|---|---|
| | 4% | 5% | 4% | 5% |
| 0% Slag | 231 | 232 | 226 | 269 |
| 15% Slag | 225 | 268 | 272 | 318 |
| 30% Slag | 230 | 263 | 265 | 276 |

# Hot Mix Asphalt (HMA)



# Physical Properties

- Angularity
- Density
- Gradation
- Durability
  - Freeze Thaw / Soundness
- Strength
  - LA Abrasion
  - Micro Deval

# Friction


PORTABLE 'SKID-RESISTANCE' TESTER
STANLEY LONDON
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

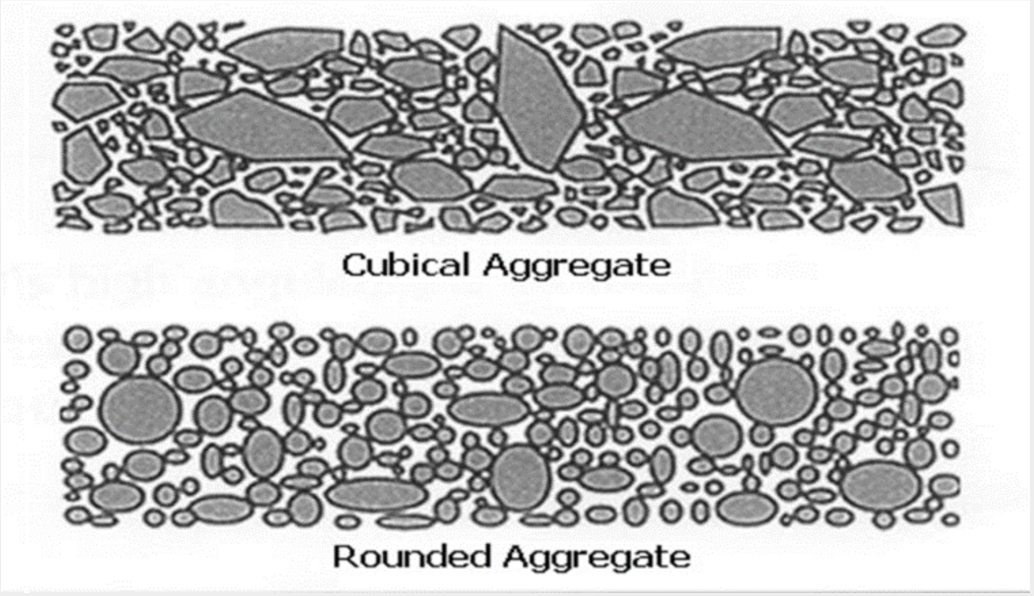
# Volumetric Stability

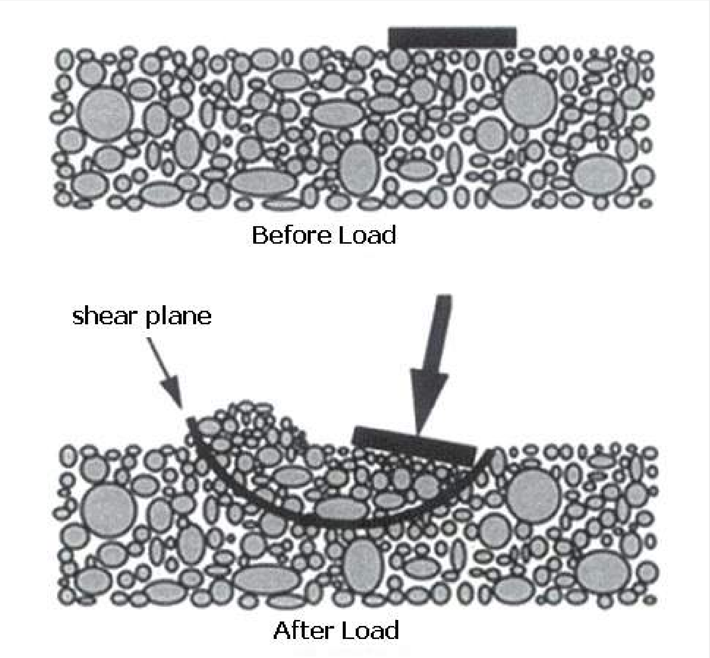
- Expansive Items
  - CaO (Lime): Early
  - MgO (Periclase): Delayed
- Free Lime
  - <u>Doesn't</u> Correlate to Expansion
    - Doesn't Indicate MgO
    - Variable procedures
- Autoclave Expansion
  - Quality Control

# SUPERPAVE

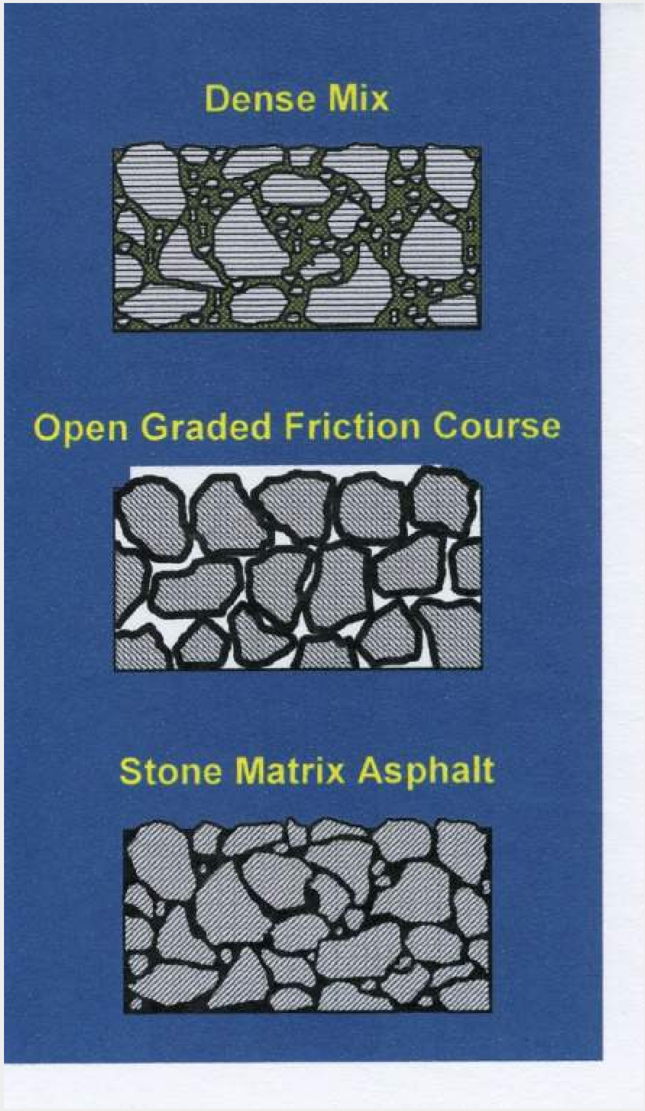
**Superior Performing Pavement**

# Shape – Stability - Strength



# Mixture Types



# Typical Mix Designs

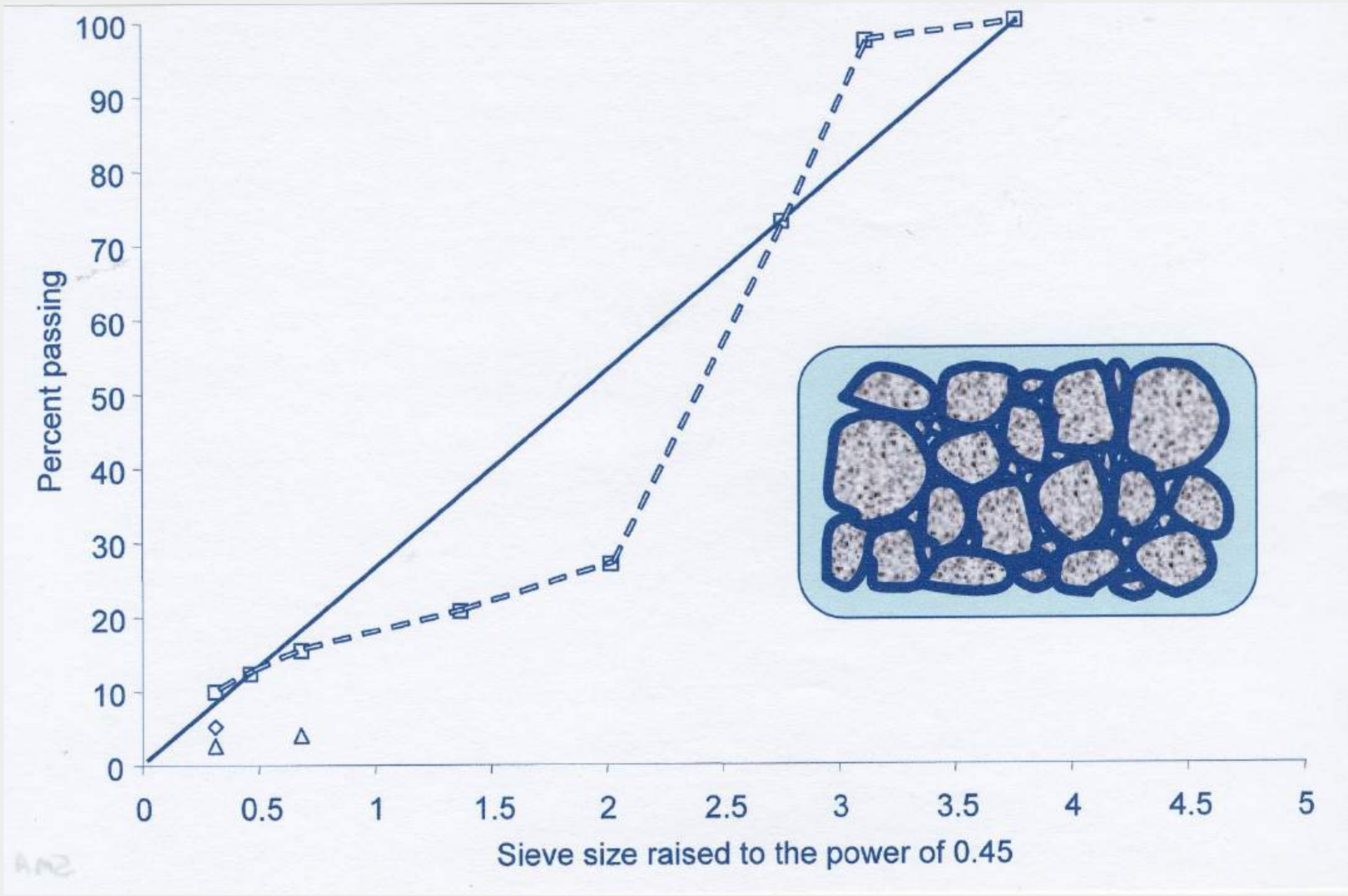
| Parameter | PFC | SMA | HMA |
|---|---|---|---|
| **12.5mm** | 100 | 100 | 100 |
| **9.5mm** | 83.0 | 84.7 | 94.0 |
| **4.75mm** | 27.9 | 39.1 | 64.3 |
| **2.36mm** | 12.5 | 26.9 | 46.0 |
| **1.18mm** | 8.6 | 21.0 | -- |
| **0.600mm** | 6.0 | 17.7 | 17.0 |
| **0.300mm** | 4.6 | 15.0 | -- |
| **0.150mm** | 3.3 | 13.3 | -- |
| **0.075mm** | 2.4 | 10.1 | 5.5 |
| **PG Grade** | 76-22 | 76-22 | 76-22 |
| **Pb, %** | 5.7 | 5.5 | 5.7 |
| **Air Voids, %** | 23.1 | 4.0 | 4.0 |
| **VMA, %** | -- | 17.7 | 15.5 |
| **Other** | 0.3% fiber | 0.1% fiber | -- |

# Liquids

- PG Graded
  - PG 58-28 / 64-22
    - Dense Graded
  - PG 70-22 / 70-28 / 76-22
    - SMA
    - Mix Temperature
    - Placement

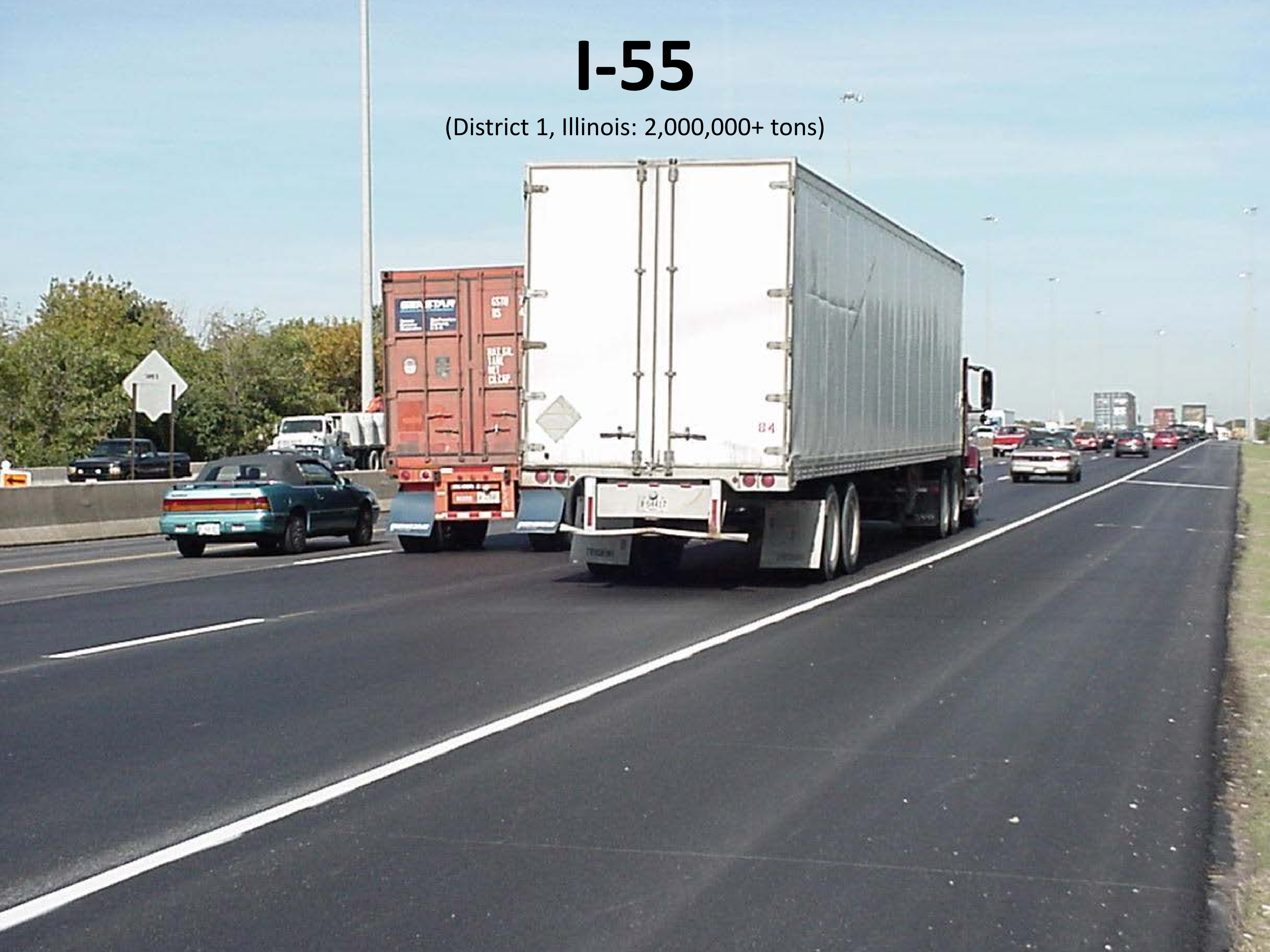
# Indianapolis Motor Speedway

# Stone Mastic Asphalt



# Williams Street

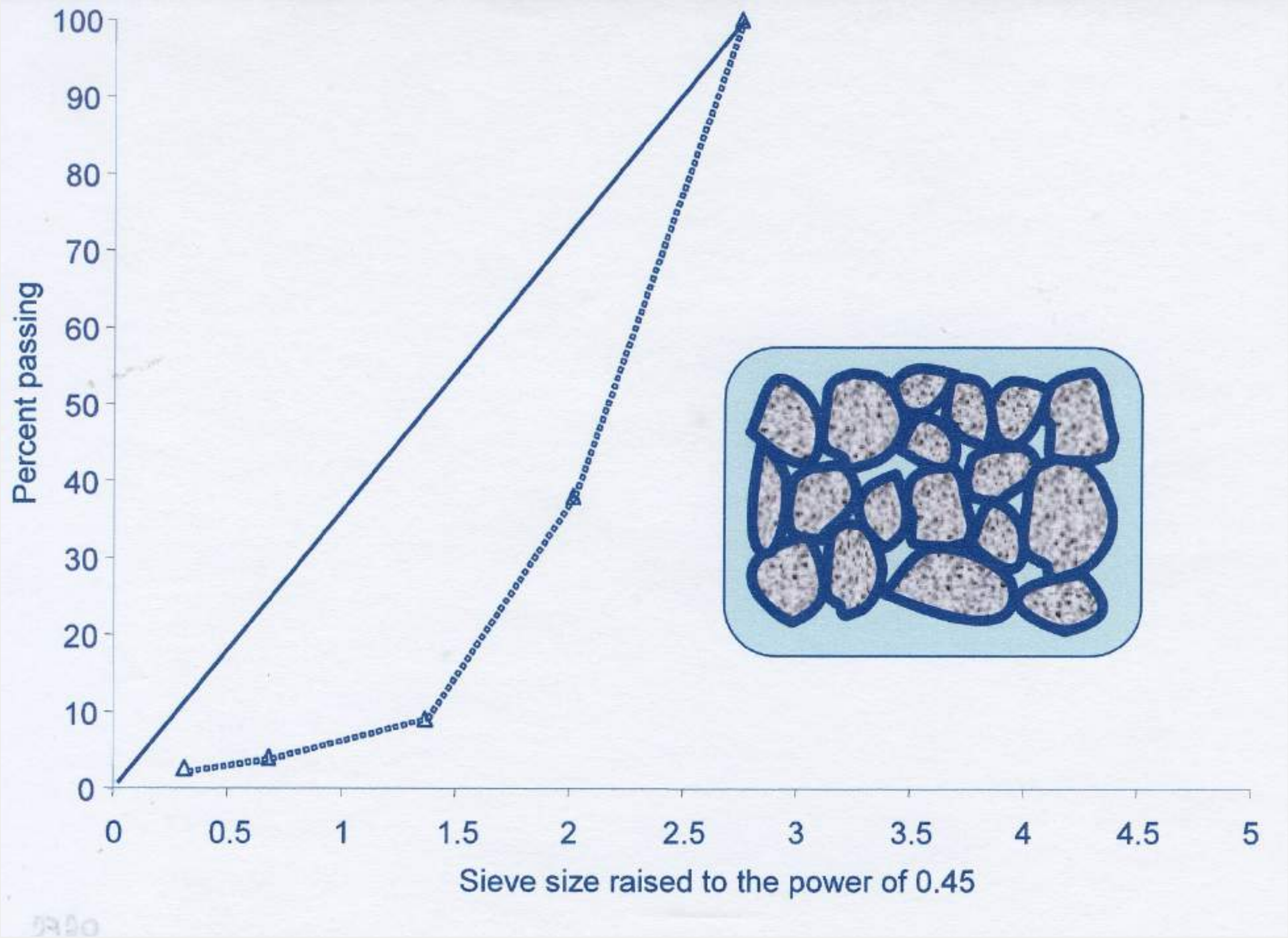
(Worlds Strongest Intersection)


I-55
(District 1, Illinois: 2,000,000+ tons)

# I-65

(Indiana: Cat 4 & 5 – Dense / OGFC / SMA)

# OGFC



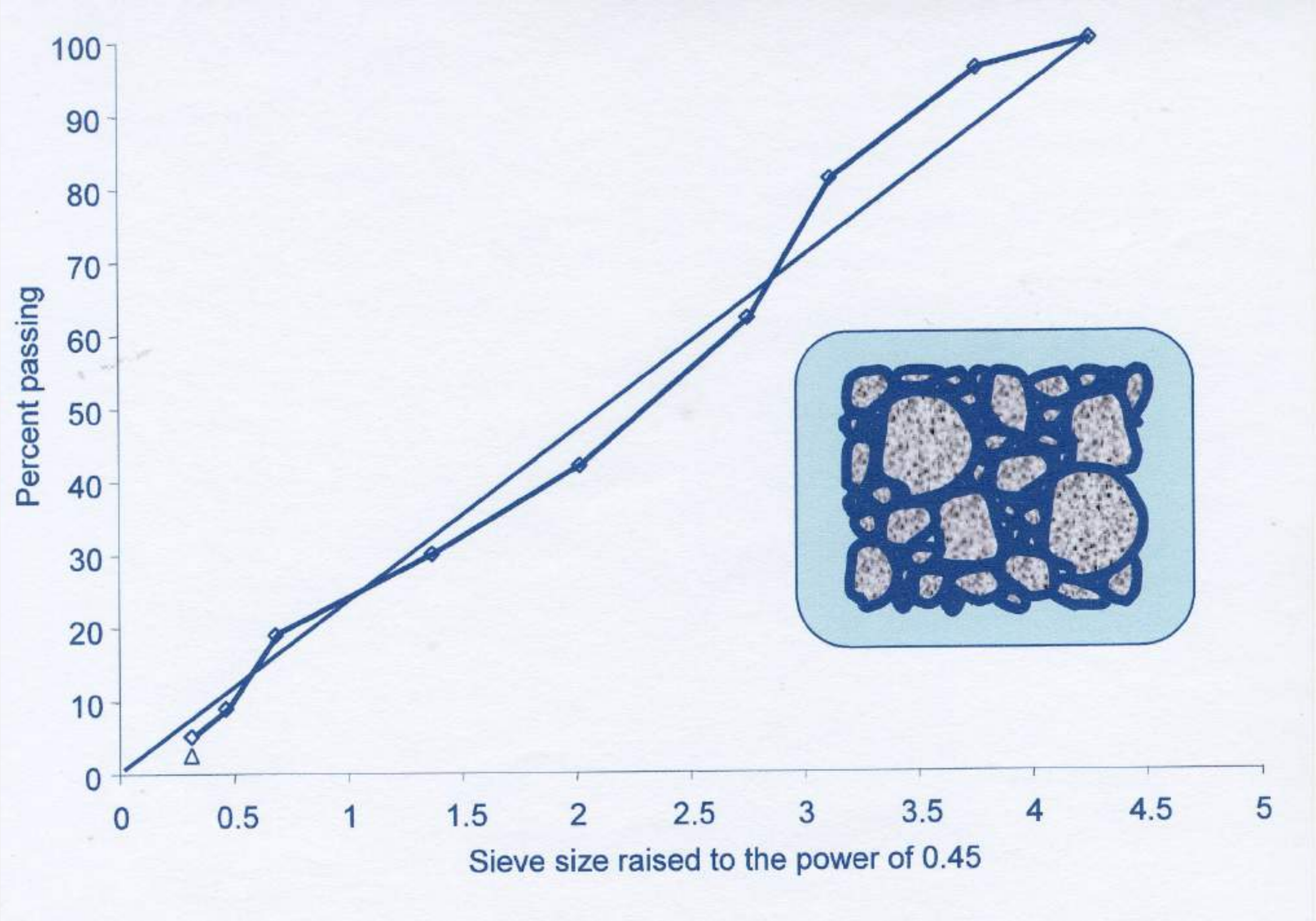
100
90
80
70
60
50
40
30
20
10
0
Percent passing
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Sieve size raised to the power of 0.45

# OGFC:

North Central Superpave Center: Durable and Quiet


Surface Treatments

# Dense Graded



# Bituminous Base

# Utilization of Steel Furnace Slag in WsDOT Project 8866

**Edw. C. Levy Co.**

**Kelly Cook / John J. Yzenas Jr.**

kcook@levyco.net

jyzenas@edwclevy.net

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edwclevy.com

**ADC – 60 Spokane, Washington: 15-17 July 2018**

# Applications

- Hot Mix Asphalt (HMA)
  - Surface
    - SMA / OGFC / Dense Graded
  - Intermediate
- Aggregate Shoulders
- Soil Stabilization
- Secondary Road Stabilization
- Environmental Remediation

# Project

**Washington State Department of Transportation**

**Material: HMA ½” – 9-03.8 - 2016 Work Order No.:008866**

**Date Sampled: 09/15/2016 Sample ID: 0000011e935**

**Date Rec’vd: 09/19/2016 Mix ID No.: MD160070**

**SR No.: 202 Contractor: Watson Asphalt**

# SR 202 and SR 203/NE 124th St Vic to Tolt River Bridge – Paving & ADA - Map

# Contractor Mix Design Data

| | Gyrations | 1 | 2 | 3 | Specification |
|---|---|---|---|---|---|
| **Pb** | | 5.1 | 5.6 | 6.1 | |
| **% Gmm @ $N_{initial}$** | 8 | 85.7 | 86.8 | 87.8 | ≤89.0 |
| **%Va @ $N_{Design}$** | 100 | 5.8 | 4.2 | 2.7 | ~4.0 |
| **%VMA @ $N_{Design}$** | 100 | 15.1 | 14.6 | 15.0 | ≥14.0 |
| **%VFA @ $N_{Design}$** | 100 | 61 | 71 | 82 | 65 - 75 |
| **% Gmm @ $N_{max}$** | 160 | | 97.4 | | ≤98.0 |
| **Dust to Asphalt Ratio (D/A)** | | 1.0 | 0.9 | 0.8 | 0.6 - 1.6 |
| **$Pb_e$** | | 3.9 | 4.3 | 5.1 | |
| **Gmm** | | 2.603 | 2.589 | 2.550 | |
| **Gmb** | | 2.451 | 2.479 | 2.482 | |
| **Gb** | | 1.028 | 1.028 | 1.028 | |
| **Gse** | | 2.837 | 2.845 | 2.821 | |

# Mix Verification

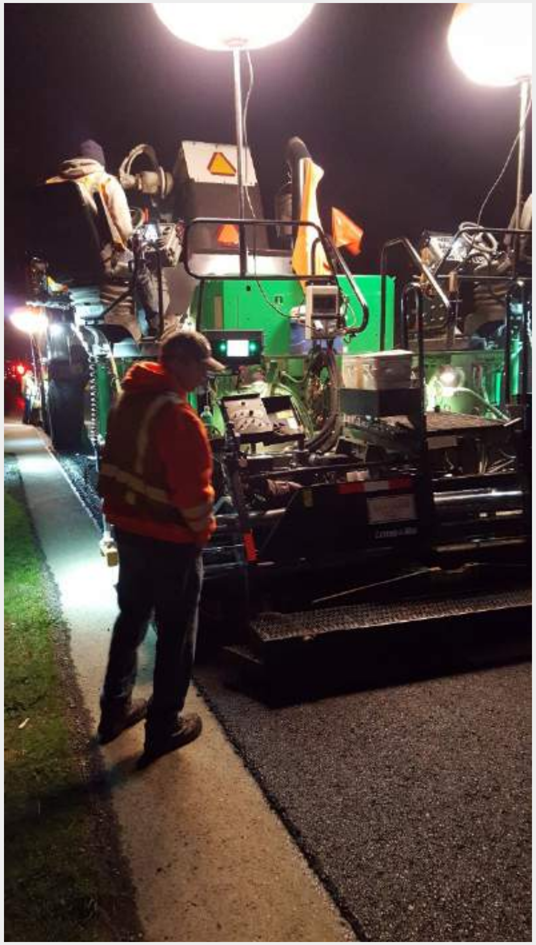
| | Gyrations | 1 | 2 | 3 | Specification |
|---|---|---|---|---|---|
| **Pb** | | 5.1 | 5.6 | 6.1 | |
| **% Gmm @ $N_{initial}$** | 8 | 85.6 | 87.0 | 88.1 | ≤89.0 |
| **%Va @ $N_{Design}$** | 100 | 6.4 | 4.1 | 2.8 | ~4.0 |
| **%VMA @ $N_{Design}$** | 100 | 16.2 | 15.2 | 15.0 | ≥14.0 |
| **%VFA @ $N_{Design}$** | 100 | 61 | 73 | 82 | 65 - 75 |
| **% Gmm @ $N_{max}$** | 160 | | 97.1 | | ≤98.0 |
| **Dust to Asphalt Ratio (D/A)** | | 0.9 | 0.8 | 0.8 | 0.6 - 1.6 |
| **$Pb_e$** | | 4.2 | 4.7 | 5.1 | |
| **Gmm** | | 2.596 | 2.576 | 2.561 | |
| **Gmb** | | 2.431 | 2.473 | 2.491 | |
| **Gb** | | 1.028 | 1.028 | 1.028 | |
| **Gse** | | 2.828 | 2.829 | 2.835 | |
| **Hamburg Wheel (mm)** | | | 3.9 | | ≤10.0 |
| **Stripping Inflection Point** | | | Pass | | None @ 15,000 |
| **Indirect Tensile Strength (psi)** | | | 93 | | ≤175 |

# Aggregate

| Material | 5/8" - 3/8" | 3/8" - 0 | Fine Aggregate | Slag | Bag House Dust | Combined | Spec | Tolerance |
|---|---|---|---|---|---|---|---|---|
| **Source:** | A309 | A309 | A309 | UNCL | UNCL | | | |
| **Ratio:** | 21.0% | 31.0% | 27.0% | 20.0% | 1.0% | | | |
| **3/4"** | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100 | 99 - 100 | 99 - 100 |
| **1/2"** | 79.1 | 100.0 | 100.0 | 81.7 | 100.0 | 92 | 90 - 100 | 90 - 98 |
| **3/8"** | 34.6 | 98.4 | 100.0 | 63.5 | 100.0 | 78 | 90 Max | 72 - 84 |
| **No. 4** | 2.7 | 61.6 | 100.0 | 33.3 | 100.0 | 54 | | 48 - 60 |
| **No.8** | 1.7 | 38.8 | 75.0 | 18.2 | 100.0 | 37 | 28 - 58 | 31 - 43 |
| **No.16** | 1.5 | 25.5 | 48.2 | 11.1 | 100.0 | 24 | | |
| **No.30** | 1.4 | 19.1 | 24.8 | 7.1 | 100.0 | 15 | | |
| **No.50** | 1.3 | 10.5 | 10.5 | 4.8 | 100.0 | 8 | | |
| **No.100** | 1.1 | 9.5 | 2.8 | 3.1 | 95.0 | 6 | | |
| **No.200** | 0.8 | 6.7 | 1.0 | 2.0 | 90.0 | 3.8 | 2.0 - 7.0 | 2.0 - 5.8 |
| | | | | | | | | |
| **Gsb Coarse** | 2.699 | 2.656 | | 3.249 | | | | |
| **Gsb Fine** | | 2.605 | 2.617 | 3.152 | | | | |
| **Gsb Blend** | 2.699 | 2.631 | 2.617 | 3.209 | | 2.758 | | |
| **Sand Equivalent (SE)** | | 72 | 95 | | | 77 | 45 Min | |
| **% Uncompacted Voids** | | | | | | 44 | 44 Min | |
| **% Fracture** | 95 | 100 | | 100 | | 99 | | |
| | | | | | | | | |

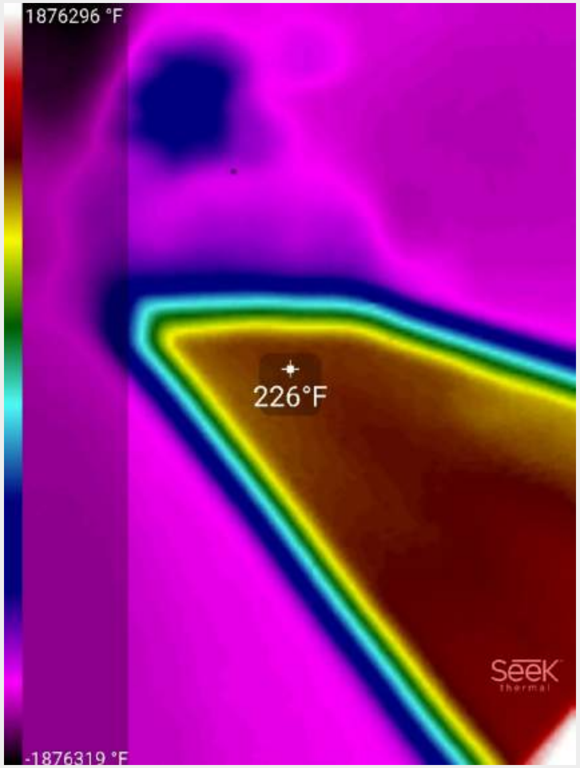
# Blend Verification

| Material | 5/8" - 3/8" | 3/8" - 0 | Fine Aggregate | Slag | Combined | Spec |
|---|---|---|---|---|---|---|
| | | | | | | |
| **Gsb Coarse** | 2.692 | 2.633 | | 3.309 | | |
| **Gsb Fine** | | 2.625 | 2.609 | 3.242 | 2.681 | |
| **Gsb Blend** | 2.692 | 2.639 | 2.609 | 3.286 | 2.751 | |
| **Sand Equivalent (SE)** | | 73 | 88 | 93 | 82 | 45 Min |
| **% Uncompacted Voids** | | | | | 45 | 44 Min |
| **% Fracture** | 99 | 99 | | 100 | 99 | 90 Min (2 Face) |

# Finished Surface

# Thermal




# Questions?

Mississippi State University

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## Presenters:


Kelly Cook - KCOOK@edwclevy.net - 219-462-2924

Isaac L. Howard - ilhoward@cee.msstate.edu - 662-325-7193

John J. Yzenas, Jr. - JYZENAS@levyco.net - 219-462-2924

Travis Zimber - tzimber@edwclevy.net - 662-242-7704