Outline

• What are Coal Combustion By-products (CCBs)?

• Accelerated Loading of Newly Constructed Full-Scale Asphalt and Concrete Pavements Utilizing Fly Ash and Bottom Ash

• Full Depth Reclamation (FDR) of Failing Asphalt Pavements Using Lime Activated Class F Fly Ash

• Two-Lift Concrete Paving (2LCP)

What are Coal Combustion Byproducts (CCBs)?

• CCBs are solid minerals that remain after pulverized coal is burned to generate electricity or steam

• Types:
  • Fly Ash
  • Boiler Slag
  • Bottom Ash
  • Flue Gas Desulfurization (FGD) Materials
    • Dry FGD Materials (FBC, CFBC, SD)
    • Wet FGD Materials (sulfite & sulfate)

Fly Ash

• Fine powdery mineral collected by ESP or baghouse

• Consists mainly of non-combustible matter but also some unburned carbon

• Mostly silt size particles (with some fine sand size particles) which are mostly spherical (and sometimes hollow)

• Types:
  • Class F (non self-cementing)
  • Class C (self-cementing)

• Handled dry or wet
**Bottom Ash**

- Fine to coarse heavier material collected at dry bottom boilers
- Consists of dark agglomerated ash particles that fall to bottom of boiler
- Sand size particles which are angular
- Handled dry or wet

**Types of Beneficial Uses of CCBs**

- Concrete & concrete products
- Cement production
- Structural & flowable fills
- Road base
- Mineral fillers
- Gypsum wallboard
- Soil & waste stabilization
- Snow & ice control
- Blasting grit & roofing granules
- Aggregate
- Agricultural
- Mining

**OSU CCB Pavement Investigations**

- **Construction of New Pavements**: Accelerated Loading of Newly Constructed Full-Scale Pavements (2003) – Asphalt and Concrete
- **Rehabilitation of Existing Pavements**: Full Depth Reclamation of Failing Asphalt Pavements (2006) – Asphalt
- **Two-Lift Concrete Paving**: Enhanced utilization of fly ash in lower foundational layer / lift (in progress) - Concrete

**Accelerated Load Testing of Full Scale Asphalt and Concrete Pavements Constructed of CCBs**
**Motivation**

Demonstrate effective use of CCBs (especially fly ash and bottom ash) as alternatives to natural materials currently used in construction and repair of highway pavement wearing surfaces, and bases / subbases. Evaluate the effect of 20+ years of highway traffic on CCB and conventional pavements by accelerated testing of full-scale pavement sections.

**What is APLF?**

- APLF means Accelerated Pavement Loading Facility
- Air temperature: 10 to 130 °F
- Humidity: 0 to 100%

**Pit Dimension**

45 ft long x 38 ft wide x 8 ft deep

- Asphalt and Portland cement concrete pavements can be tested
- Moisture can be added to subgrade through pipes on the pit floor

**APLF – Load Mechanism**

- **Load Range**
  9,000 lbs to 30,000 lbs

- **Tires**
  Standard single and duals

- **Test Speed**
  5mph
  500 repetitions/hr for bidirectional tests

- Evaluation time period can be significantly reduced

**Pavements of interest**

- Asphalt Concrete (flexible) Pavement
- Portland Cement Concrete (rigid) Pavement
Laboratory Testing of Pavement Components

- **Concrete Slab** *(Class F Fly ash)*
  - Unconfined Compressive Strength
  - Flexural Strength
  - Freeze-Thaw Resistance
  - Permeability
  - Leaching Potential

- **Base and Subbase** *(Class F Fly ash & bottom ash)*
  - Unconfined Compressive Strength
  - Permeability
  - Leaching Potential

- **Subgrade** *(Class F Fly ash & lime)*
  - Index Properties
  - Resilient Modulus
  - Unconfined Compressive Strength

Design of the Test Pavements

- Application: Rural State Highway
- Average Daily Traffic: 5,000 vehicles
- Truck Percentage: 6%
- Design Life: 20 years
- AASHTO 1993 Pavement Design Procedure

Plan View of Test Pavements

- Office
- PCC Sections
- AC Sections
- Aggregate Base Mixes
- Bituminous Base Mixes

Longitudinal profile *(A-A’)* of flexible pavement lane

- Bituminous Base: Mix 14
- Aggregate Base: Mix 12
- Stabilized A-6 Soil
- Unstabilized A-6 Soil
- Aggregate: Mix 14

Mixes:
- Mix 14: 30% #57 + 10% Bottom Ash + 15% Fly Ash + 5% Cement + 40% Sand
- Mix 12: 30% #57 + 20% Bottom Ash + 25% Fly Ash + 5% Cement + 20% Sand
- Mix 11: 50% #57 + 20% Bottom Ash + 25% Fly Ash + 5% Cement
- Stabilized A-6 Soil: 100% Soil + 10% Fly Ash + 5% Lime
Longitudinal profile (B-B’) of Rigid Pavement Lane

15’

Plain Concrete
Aggregate Base
Stabilized A-6 Soil
Unstabilized A-6 Soil
Aggregate (#57 crushed stone)

15’
FA Concrete (30%)
Mix 11
6”
18”
24”
34”

15’
FA Concrete (50%)
Mix 11

Finished rigid pavements (8”)

Control
50% FA
30% FA

Pavement Instrumentation

Instrumentation plan of PCC sections
Instrumentation plan of AC sections

Accelerated Load Testing

- State Route 20-Year Traffic Target is 1 Million ESALs
- Standard dual tires with load of 15,000 lbs
- 130,000 number of passes
- 1.35 months of APLF testing for bi-directional testing, 8 hrs/day, 5 days/week
- Two Phases:
  - Phase I: Mechanical loading only (136,000 cycles)
  - Phase II: Mechanical and environmental (moisture, freeze-thaw (-12°C & 54°C), and elevated temperature 54°C maintained) loading:
    - Asphalt: Saturation with freeze-thaw for 34,000 cycles. Then 30,000 cycles with elevated temperature.
    - Concrete: Saturation with freeze-thaw for 34,000 cycles. Then 10,000 cycles with elevated temperature.

Data Monitoring during Accelerated Pavement Loading

- Dynamic response monitoring under wheel loading (monitoring of embedded instrumentation)
- Falling Weight Deflectometer Testing (FWD)
- Performance data monitoring (rutting and cracking)
- Environmental monitoring

Falling Weight Deflectometer (FWD) Testing

(Time from A to C is Variable, Depending on Drop Height)
Asphalt Pavement Data and Analysis

- **Phase I:** Mechanical loading only for 136,000 cycles
- **Phase II:** Saturation with freeze-thaw for 34,000 cycles. Then 30,000 cycles with elevated temperature.
Peak Vertical Stresses on Top of Stabilized and Natural Subgrade vs. Total Number of Load Repetitions

FWD Tests (Backcalculated Resilient Modulus)

Comparison of Rut Development

Concrete Pavement Data and Analysis

• **Phase I**: Mechanical loading only for 136,000 cycles

• **Phase II**: Saturation and then 34,000 cycles with freeze-thaw. Then 10,000 cycles with elevated temperature.
**Peak Longitudinal Strains v. Number of Load Repetitions**

- **Phase I**
- **CCP#2**
- **CCP#1**
- **Control**

- **Phase II**
- **CCP#2**
- **CCP#1**
- **Control**

- **Total Number of Run Repetitions**

**Peak Transverse Strains v. Number of Load Repetitions**

- **Phase I**
- **Phase II**
- **CCP#2**
- **CCP#1**
- **Control**

- **Total Number of Run Repetitions**

**Peak Stresses in Subgrade vs. Number of Load Repetitions**

- **Phase I**
- **Phase II**
- **CCP#2**
- **CCP#1**
- **Control**

- **Total Number of Run Repetitions**

**Fatigue Cracking Analysis Results**

(Calibrated mechanistic design model of Salsilli et al. 1993)

<table>
<thead>
<tr>
<th>Section</th>
<th>CCP#1 (30% FAC)</th>
<th>CCP#2 (50% FAC)</th>
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</thead>
<tbody>
<tr>
<td><strong>Control</strong></td>
<td>Flexural Strength (MPa)</td>
<td>5.56</td>
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<tr>
<td></td>
<td>Tensile Stress (MPa)</td>
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<tr>
<td></td>
<td>Stress Ratio</td>
<td>0.13</td>
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<tr>
<td></td>
<td>Allowable Load Repetition (Nf)</td>
<td>5x10^{24}</td>
</tr>
</tbody>
</table>
APLF Conclusions

- Overall, full-scale CCP pavement sections exhibited similar or better performance than control sections under accelerated traffic loading.
- After 20-year equivalent traffic loading, none test pavement sections failed in terms of rutting or fatigue cracking.
- All three PCC sections demonstrated good performance. Virtually no fatigue damage had occurred in any of the PCC sections by the end of pavement design life. No fatigue cracking was observed in any of the PCC sections even much later, i.e., at the end of the full-scale testing program.
- Both CCP base/subbase mixes out-performed control mix based on collected response, surface rutting, and FWD testing data throughout the full-scale testing program.
- During Phase II, two CCP sections showed better resistance to adverse environmental conditions and exhibited better performance than control section. This effect was most manifest at most intrusive environmental condition at end of the first freeze-thaw cycle which simulates the high ground water table and thawing condition that is a typical experience for spring in Ohio.

Asphalt Pavement Rehabilitation

- In recent decades:
  - increasing traffic demand (loads & volumes)
  - decreasing budgets
  - continuing need for a safe, efficient, cost-effective transportation system
- Roads are experiencing serious distress due to economic development, especially with rapid development of suburbs
- Choices:
  - Replace distressed road with new one (fewer miles can be paved per year)
  - Replace distressed roads by recycling existing pavement and other by-products into a new pavement (more miles can be paved for a given budget)
- Recycling/reclamation of existing pavements must be a priority

Full Depth Reclamation of Asphalt Pavements Using Lime Activated Class F Fly Ash

- FDR is a flexible pavement reclamation process. The full pavement section (wearing surface, base/subbase, and a pre-determined portion of underlying soil) is uniformly pulverized, blended with chemical additives (e.g., cement, fly ash, lime, emulsion) and compacted to construct a new stabilized base. An asphalt overlay can then be placed.
- Short of conventional re-construction, FDR is the only cost-effective pavement rehabilitation procedure that corrects base and subbase problems.
Role of Fly Ash in FDR Work

- Fly ash provides silica and alumina needed for cementious reaction with lime to increase strength, stiffness, and durability of stabilized base layer.

- Fly ash act as mineral filler to fill the voids in the granular pulverized pavement mix, thus reducing permeability of the FDR stabilized layer.

Section Line Road - Delaware County Pavement Sections (6.6 km)

Nine sections were designed and constructed (2006) using the following six mixes:

- Station 1: 2% Cement with 7.2 liters per square meter emulsion, 20 cm stabilization depth (0.48 km)
- Station 2: 5% Cement, 30 cm stabilization depth (1.3 km)
- Station 3: 3% Lime Kiln Dust with 6.3 liters per square meter emulsion, 20 cm stabilization depth (1.1 km)
- Station 4: 13 cm Mill and Fill (Two 0.16 km sections at the north and south ends of the project, and a 1.1 km as well as 0.16 km sections near the middle of the project)
- Station 5: 5% Lime Kiln Dust with 5% Fly Ash, 20 cm stabilization depth (1.1 km)
- Station 6: 4% Lime with 6% Fly Ash, 20 cm stabilization depth (1.1 km)

Long Spurling Road - Warren County Pavement Sections (0.65 km)

Two sections were designed and constructed (2006):

- Station 1: 13 cm Mill and Fill (0.13 km)
- Station 2: 4% Lime with 6% Fly Ash, 30 cm stabilization depth (0.52 km)
FDR Construction

1. Milling of Asphalt Surface (Warren County)
2. Placing of Fly Ash, Lime, & LKD (Warren County)
3. Train of equipment (front to back: water truck, mixer and compactor) Delaware County
4. Teeth of Mixer (Delaware County)
5. Material before mixing (left) and after mixing (right), Delaware County
6. Compaction of FDR base layer (Delaware County)
7. Final FDR base layer ready for asphalt overlay (Warren County)
8. Asphalt overlay (Warren County)

Pavement Instrumentation Plan

Falling Weight Deflectometer (FWD) Testing by Ohio DOT

Delaware site before FDR
Measured Deflections - (Delaware County)

Measured Deflections (Warren County)

Average Backcalculated Moduli of FDR Layer from FWD Testing (Delaware County)

Average Backcalculated Moduli of FDR Layer from FWD Testing (Warren County)
## Structural Layer Coefficients

### Delaware County – Section Line Rd.

<table>
<thead>
<tr>
<th>Date</th>
<th>Cement &amp; Emulsion</th>
<th>Cement</th>
<th>LKD &amp; Emulsion</th>
<th>M &amp; F</th>
<th>LKD &amp; Fly Ash</th>
<th>Mill &amp; Fill</th>
<th>Lime &amp; Fly Ash</th>
<th>M (psi)</th>
<th>a</th>
<th>M (psi)</th>
<th>a</th>
<th>M (psi)</th>
<th>a</th>
<th>M (psi)</th>
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<th>M (psi)</th>
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<td>9,900</td>
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<tr>
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<td>10/07</td>
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<td>494,722</td>
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<td>0.47</td>
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AASHTO: \( a = 0.14 \left( \frac{M_R}{30,000} \right)^{1/3} \)

## Structural Layer Coefficients

### Warren County - Long Spurling Rd.

<table>
<thead>
<tr>
<th>Date</th>
<th>Mill &amp; Fill</th>
<th>Lime &amp; Fly Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/06</td>
<td>7,408</td>
<td>3,124</td>
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<tr>
<td>09/06</td>
<td>4,966</td>
<td>494,545</td>
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<td>10/06</td>
<td>6,331</td>
<td>1,742,470</td>
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<td>01/07</td>
<td>27,104</td>
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<td>07/09</td>
<td>3,340</td>
<td>314,653</td>
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<tr>
<td>03/10</td>
<td>10,147</td>
<td>368,157</td>
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<td>09/10</td>
<td>35,714</td>
<td>1,395,845</td>
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</table>

AASHTO: \( a = 0.14 \left( \frac{M_R}{30,000} \right)^{1/3} \)

### Delaware Pavements – 2012

#### Section 1:
- Cement + Emulsion

#### Section 2:
- Cement

#### Section 3:
- LKD + Emulsion

#### Section 4:
- Control (Mill & Fill)

#### Section 5:
- Fly Ash + LKD

#### Section 6:
- Fly Ash + Lime
FDR Conclusions

- Pavement sections stabilized with fly ash (+LKD/lime) showed comparable stiffness and strength to cement stabilized sections for up to 4 years of monitoring (including four seasons of winter).

- The use of fly ash (with LKD or lime) as substitute for traditional cementitious additives in FDR can result in substantial cost savings as well as additional significant environmental benefits.

- Fly ash can be easily mixed and compacted using standard FDR construction equipment.

Past Demos - Summary

- Study 1: Full-scale asphalt & concrete test pavement sections were constructed using fly ash and bottom ash and subjected to accelerated repeated loading for service life beyond 30 years (including freeze-thaw & pavement base and subgrade saturation).

- Study 2: 4 mile section of a failing asphalt pavement was rehabilitated using full depth reclamation technology using fly ash and sections were monitored for over 4 years.

- In both studies, control sections (which had no coal combustion byproducts) were also constructed side by side and monitored.

- Results show that pavement sections (whether new pavement construction or pavement rehabilitation) amended with fly ash and/or bottom ash performed better than or as good as control sections.

Current OSU Research

- Use of Fly Ash in Two-Lift Concrete Paving (2LCP)

- Reclamation of Ohio Coal Mine Sites Using FGD Byproducts

- Role of Remining in Mitigating Impacts of Legacy Mining in Ohio

- Stability of Fly Ash During Cyclic Loading

- Effectiveness of Geocomposites as Drainage Layer for CCBs

Two-Lift Concrete Paving (2LCP)

- Two layers of concrete placed “wet-on-wet” rather than one homogenous layer:
  - Lower foundational layer (about 80% of total thickness)
  - Upper surface course layer (about 20% of total thickness)

- Lower Layer
  - Lower quality concrete mixture (low cement content, higher w/c ratio)
  - Allows for higher Supplemental Cementitious Materials (SCMs) such as fly ash
  - Can include recycled aggregates or local aggregates not suitable for surface courses

- Upper Surface Layer
  - Higher quality concrete mixture
  - Designed for increased durability, reduced noise, and improved skid resistance
2LCP Developments

- **Historical Point of Interest:** First 2LCP in US was constructed in 1891 in Bellefontaine, Ohio!
  - Bottom layer (4 inch thickness, w/c = 0.60, 1.5” maximum size of aggregate)
  - Top layer (w/c = 0.40, 0.5” maximum size of aggregate)

- In early concrete pavement construction in US, 2LCP was common due to lack of reliable paving equipment
- As modern paving machines developed, 2LCP faded
- Europe – commonly used today in Europe
- Interest in US is again increasing
  - Kansas, Iowa, Illinois, Minnesota, Texas


Use of Fly Ash in 2LCP in US

- **Kansas I-70 Demo Project, 2008**
  - 5-mile section near Salina, Kansas
  - Top lift (1.6”) – 20% replacement of cement with Class F Fly Ash (bottom lift of 11.8” contained no fly ash)
  - $33/sy for standard mix - $41/sy for 2LCP - $48/sy for durable mix

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Bottom Lift</th>
<th>Top Lift (Textured Section)</th>
<th>Top Lift (EAC Section)</th>
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</thead>
<tbody>
<tr>
<td>Portland Cement Type III (pcc)</td>
<td>548</td>
<td>438</td>
<td>526</td>
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<tr>
<td>Class F Fly Ash (pcc)</td>
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<td>132</td>
<td>132</td>
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<tr>
<td>Water (pcc)</td>
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<td>270</td>
<td>270</td>
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<tr>
<td>Course Agg: Fine Agg. Ratio</td>
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<td>50:50</td>
<td>70:30</td>
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<tr>
<td>w/c</td>
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<td>0.43</td>
<td>0.41</td>
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<td>Air Entraining Admixture (as w/y%)</td>
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<td>2.5</td>
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- EAC: Epoxy Asphalt Concrete

- **Kansas I-70 Demo Project, 2008**
  - 5-mile section near Salina, Kansas
  - Top lift (1.6”) – 20% replacement of cement with Class F Fly Ash (bottom lift of 11.8” contained no fly ash)
  - $33/sy for standard mix - $41/sy for 2LCP - $48/sy for durable mix

- **Minnesota I-94, 2010**
  - 2” high quality EAC top lift over a 6” low cost bottom lift
  - Bottom lift – 250lb/cy cement and 60% Class C fly ash replacement
  - Top lift concrete – 550lb/cy cement and 15% Class C fly ash replacement
  - Local ready mix company was not experienced in handling high fly ash concrete
  - $19.94/sy for 2LCP composite concrete - $20.38/sy for conventional mix

<table>
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<td>Mid Range Water Reducer (as w/y%)</td>
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<td>Anti-Blind Anti-Settling Admixture (as w/y%)</td>
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<tr>
<td>Type A Water Reducer (as w/y%)</td>
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</tbody>
</table>

- EAC: Epoxy Asphalt Concrete

- **Illinois Tollway, 2010 onwards**
  - 2010: I-292 ramp composite pavement - bottom layer used 20% fly ash replacement
  - 2012: 0.7 miles of I-88 – bottom layer used 10% fly ash replacement
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<table>
<thead>
<tr>
<th>Material Type</th>
<th>Bottom Lift</th>
<th>Top Lift (Textured Section)</th>
<th>Top Lift (EAC Section)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Cement Type III (pcc)</td>
<td>548</td>
<td>438</td>
<td>526</td>
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<td>Class F Fly Ash (pcc)</td>
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<td>Water (pcc)</td>
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<td>Course Agg: Fine Agg. Ratio</td>
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<td>Air Entraining Admixture (as w/y%)</td>
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<td>Mid Range Water Reducer (as w/y%)</td>
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<td>Anti-Blind Anti-Settling Admixture (as w/y%)</td>
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<td>Type A Water Reducer (as w/y%)</td>
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<td>2.5</td>
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OSU 2LCP Research

**Objective:** Promote sustainable beneficial use of coal fly ash in 2LCP.

**Phase I study underway:**
- Literature Review
- Laboratory testing of trial mixes for field implementation
- Propose potential demo project in partnership with project partners