Boral Resources
Fly Ash Utilization, Applications & Supply Logistics

You need it. We get it.

Boral / Lab Introduction
Ash Definitions & Durability
Concrete Performance & Durability
Micron 3 UFFA
CLSM (Controlled Low Strength Material)
Supply Update & Alternate SCM

National Footprint

We partner with utilities to service their needs and to supply customers with quality products.

105 power plant sources and service in 45 states

Material Testing and Research Facility
Boral’s Central Laboratory

Committed to the advancement of CCP utilization and the enhancement of their values by deploying beneficiation and new application technologies.

Special Projects (1800 SF)
Laboratory (8400 SF)
Pilot Plant (3700 SF)

- Sample Retention/Storage Buildings
- Major features to support pilot testing:
  - High voltage electrical service
  - Rail spur (siting for 5 cars)
  - Silos with truck loadout
  - Material handling equipment
  - Shop space

You need it. We get it.
Ash Definition & Characteristics

**What is a Pozzolan (Fly Ash)?**

A pozzolan is a finely-divided siliceous or siliceous and aluminous material that will not react chemically with water, but will react with calcium hydroxide and water at ordinary temperatures to form compounds possessing cementitious properties.

DISCUSSION—Some supplementary cementitious materials are weak hydraulic cements but their cementitious properties are enhanced in the presence of calcium hydroxide and water. Such materials possess the characteristics of a hydraulic cement and a pozzolan.
What makes Fly Ash Work? Pozzolanic Reaction

If you only remember one thing...what's Pozzolanic mean?

Why should Fly Ash be used? Pozzolanic Reaction

Through Pozzolanic Activity, Fly Ash combines with Free Lime to Produce the Same Cementitious Compounds Formed by the Hydration of Portland Cement

C-618 Results
Class F Ash

<table>
<thead>
<tr>
<th>Sample F Ash</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>SO₃</th>
<th>Available Alkal %</th>
<th>Moisture Content %</th>
<th>LOI %</th>
<th>Fineness %</th>
<th>Density gm/cm³</th>
<th>SAI 7 d %</th>
<th>SAI 28 d %</th>
<th>Water Req’ %</th>
<th>Foam Index*</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM CS68</td>
<td>85.3</td>
<td>0.9</td>
<td>0.9</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
<td></td>
<td>2.46</td>
<td>87</td>
<td>99</td>
<td>97</td>
<td>4</td>
</tr>
<tr>
<td>Class F</td>
<td>70% min</td>
<td>5% max</td>
<td>**</td>
<td>3% max</td>
<td>6% max</td>
<td>34% max</td>
<td>**</td>
<td>75% min</td>
<td>75% min</td>
<td>105% max</td>
<td>HW SOP</td>
<td>&lt;=18%</td>
<td></td>
</tr>
</tbody>
</table>

* Foam Index Conducted with Boral SOP 40g ash / 200g water / MBVR concentrate
** No specification under ASTM C-618

Particle Size Distribution (Horiba Particle Size Analyzer)

Color: Light Brown (Munsell)
S.P. Area: 9958.4 (cm²/cm³)
Median: 15.583 (μm)
Mean: 28.560 (μm)
Ash in Concrete
Performance & Durability

Why should Fly Ash be used?
Compressive Strength Improvement

Note the Cement Control higher early
Note the Ash / Cement mix higher later 28-56 days

Effects of fly ash on fresh
and hardened concrete

STRENGTH

ASR

TEMPERATURE RISE

Water Demand / RHEOLOGY

PERMEABILITY

https://www.galvanizeit.org

http://www.cement.org/designaids/mass-concrete

Flyash.com
Why should Fly Ash be used?
ASR Mitigation

- The alkali–silica reaction (ASR), is a deleterious reaction that can cause expansion and eventually cracking in concrete.
- The reaction is between alkalis in cement paste and the reactive amorphous (i.e., non-crystalline) silica found in many aggregates, given sufficient moisture.
- Use of pozzolan like Fly Ash provide confidence and reliability for ASR Mitigation.

ASTM C441
ASR Testing (Pyrex Glass)

<table>
<thead>
<tr>
<th>Test Data</th>
<th>Cement Control</th>
<th>Class F ash 20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set Date</td>
<td>Bar 1  Bar 2  Bar 3</td>
<td>Bar 1  Bar 2  Bar 3</td>
</tr>
<tr>
<td>Initial</td>
<td>0.0049 0.1711 0.1516</td>
<td>0.0377 0.0432 0.0381</td>
</tr>
<tr>
<td>14d read</td>
<td>0.0331 0.0268 0.0184</td>
<td>0.0531 0.0586 0.0548</td>
</tr>
<tr>
<td>diff.</td>
<td>0.0331 0.0315 0.0331</td>
<td>0.0154 0.0154 0.0167</td>
</tr>
<tr>
<td>Avg.</td>
<td>0.0326 0.0158 0.0158</td>
<td>0.0158 0.0158 0.0167</td>
</tr>
</tbody>
</table>

% Reduction of Mortar Expansion: 51.38%

The specimens were prepared in accordance with the procedures described in ASTM C441. Three mortar bars were prepared for both the control mix and the test mix using the modified proportions specified by ASTM C-441.

The specimens were cured in the moist room for 24 hours and then stored in the moist container specified in ASTM C227-10 Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method) at 38°C for 14 days. Results of the testing are reported in Table above.

ASTM C-1567
Accelerated Mortar Bar (ASR)

Effects of fly ash on fresh and hardened concrete

Control Aggregate Expansion 0.19% @ 14 days
Test mixtures at 20 and 25% replacement of cement
Why should Fly Ash be used?
Reduction in Heat of Hydration

Variation of temperature with time at the center of 15 cubic meter concrete blocks (Samarin, Munn, and Ashby, 1983)

Effects of fly ash on fresh and hardened concrete

Water Demand / Rheology
Flyash.com

Reduction in Heat of Hydration

Fly ash reduces water demand by approx. 4% for every 10% replacement according to ACI 232

Similar effect by C and F fly ash

The spherical nature of Fly Ash produces a ball bearing effect in concrete making it easier to place

Provides slump reduction without additional water reducing admixtures

Improves rheology for ease of pumpability and finish

Reduction in water decreases drying shrinkage
Effects of fly ash on fresh and hardened concrete

Fly Ash Performance
Decreased Permeability

A resistivity probe measures the concrete’s interference in the transmission of an electric field
- Higher resistivity relates to decreased permeability
- This test is often used to estimate resistance to chloride ion penetration

Fly Ash Performance
Decreased Permeability

ASTM C1012
Sulfate Expansion Testing

<table>
<thead>
<tr>
<th>Expansion %</th>
<th>1 wk</th>
<th>2 wk</th>
<th>3 wk</th>
<th>4 wk</th>
<th>8 wk</th>
<th>13 wk</th>
<th>15 wk</th>
<th>4 mth</th>
<th>6 mth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.007</td>
<td>0.013</td>
<td>0.020</td>
<td>0.022</td>
<td>0.027</td>
<td>0.040</td>
<td>0.049</td>
<td>0.053</td>
<td>0.088</td>
</tr>
</tbody>
</table>

Conducted at 20% replacement

The specimens were prepared in accordance with the procedures described in ASTM C1012 as modified by ASTM C311 / Procedure A. Prairie States ash was substituted for 20% of the cement. A complete chemical analysis of the fly ash is provided in Table 1.

The specimens were cured according to C1012 until the strength of the cubes reached a minimum of 2,850 psi. The specimens were then stored in sulfate solution at 72°F for six months.
Kirkland Natural Pozzolan (KNP)
ASTM C618 Summary

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>KNP</th>
<th>ASTM C618, min/max (lb/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ (%)</td>
<td>72</td>
<td>75</td>
</tr>
<tr>
<td>Al₂O₃ (%)</td>
<td>13–15</td>
<td></td>
</tr>
<tr>
<td>Fe₂O₃ (%)</td>
<td>1–3</td>
<td>123–150</td>
</tr>
<tr>
<td>Sum of Oxides (SiO₂+Al₂O₃+Fe₂O₃) (%)</td>
<td>88–95</td>
<td>50%</td>
</tr>
<tr>
<td>SO₃ (%)</td>
<td>&lt;1</td>
<td>5% Max</td>
</tr>
<tr>
<td>CaO (%)</td>
<td>1–3</td>
<td>50% Min</td>
</tr>
<tr>
<td>Na₂O (%)</td>
<td>2–3</td>
<td>50% Min</td>
</tr>
<tr>
<td>MgO (%)</td>
<td>1–2</td>
<td>50% Min</td>
</tr>
<tr>
<td>K₂O (%)</td>
<td>2–4</td>
<td>50% Min</td>
</tr>
<tr>
<td>Sodium Oxide Equivalent (Na₂O+0.658K₂O) (%)</td>
<td>4–6</td>
<td>50% Max</td>
</tr>
<tr>
<td>LOI (%)</td>
<td>3–5</td>
<td>10% Max</td>
</tr>
</tbody>
</table>

Fineness (% retained on 45 micron sieve)  
7 day SAI (% of control) 85–95 75% Min  
28 day SAI (% of control) 90–105 75% Min  
Water Requirement (% of control) 105–107 115% Max  

Background Micron³

- How is Micron³ produced?  
  - Micron³ is made by air classifying an ordinary production fly ash and separating a portion of the fines

- What is Micron³?  
  - Ultrafine fly ash that has a median particle size between 2 and 4 μm

- What is the goal for the final product?  
  - To provide a high-performance pozzolan for use in concrete
You need it. We get it.

Background – What is Micron³ UFFA

How is it produced?

- Air classification?
  
  Air classifier is an industrial machine which separates materials by a combination of size, shape, and density. It works by injecting the material stream to be sorted into a chamber which contains a column of rising air.

You need it. We get it.

Background – Particle distribution of Micron³

- Run of Plant ash has 44% passing 10µm
- Micron 3 Product has 100% passing 10µm

You need it. We get it.

Performance – Micron³

ASTM C-618 Comparison

<table>
<thead>
<tr>
<th>Micron³</th>
<th>As-Produced Fly Ash</th>
<th>ASTM Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of the Oxides (SiO₂+Al₂O₃+Fe₂O₃) (%)</td>
<td>74.91</td>
<td>73.13</td>
</tr>
<tr>
<td>CaO (%)</td>
<td>9.65</td>
<td>13.72</td>
</tr>
<tr>
<td>SO₃ (%)</td>
<td>1.59</td>
<td>0.76</td>
</tr>
<tr>
<td>Moisture (%)</td>
<td>0.09</td>
<td>0.05</td>
</tr>
<tr>
<td>LOI (%)</td>
<td>0.52</td>
<td>0.27</td>
</tr>
<tr>
<td>Fineness (% retained on 45 micron sieve)</td>
<td>0</td>
<td>21.32</td>
</tr>
<tr>
<td>7 Day SAI (% of control)</td>
<td>111</td>
<td>84</td>
</tr>
<tr>
<td>28 Day SAI (% of control)</td>
<td>125</td>
<td>91</td>
</tr>
<tr>
<td>Water Requirements (% of control)</td>
<td>91</td>
<td>94</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.69</td>
<td>2.59</td>
</tr>
</tbody>
</table>

Note Increase in Strength activity
Index and reduction in water demand

You need it. We get it.

Micron³ Performance

Strength Development Comparison to class F and C fly ash

- 5% replacement values of PC with UFFA exceed ash mixes at 7, 28 and 90 day
- UFFA improves concrete strength at all testing ages

You need it. We get it.
Micron³ Performance
ASR Mitigation, C1567 Comparison to class F and C fly ash

![Graph showing expansion due to ASR compared to Micron³](image)

- Expansion due to ASR is greatly reduced by Micron3

CLSM
Controlled Low Strength Material

A self compacting low to moderate strength material with flowable consistency which cures and hardens over time. It is used as backfill material instead of compacted granular material. CLSM can also include sand or fine aggregates.

**Primary Ingredients**

- **Fly Ash**
  - Residual material after the combustion of coal. Primarily composed of silica, alumina, iron oxide and calcium oxide.

- **Portland Cement**
  - Primarily composed of calcium oxide, silica and alumina.

- **Water**

Compared to compacted soil, CLSM:

- Provides more versatility and durability
- Fills voids or empty spaces more effectively
- Consistently achieves 100% compaction
- Reduces total project expenditures
- Provides a safer working environment
Flowability

- Flowability is a significant advantage of using CLSM instead of granular or native fill material.
- Free flowing thus self-leveling. It’s also easy to pump.
- It fills small voids, so no compaction required.
- Fast and inexpensive to place.

*ASTM D6103

Density & Thermal Insulation

- CLSM mixtures can be designed to provide insulating performance. The thermal insulation can be enhanced with foaming agents
  - The in-situ unit weight of CLSM may range from 40 to 145 lb/ft$^3$
  - The use of air entraining admixtures can typically reduce the unit weight to 90 ~ 100 lb/ft$^3$
  - Foamed cell systems can reduce the unit weight to as low as 40 lb/ft$^3$

Foaming agent added to flowable fill mixture to reduce unit weight and improve flow

Decreasing compressive strength of foamed flowable fill mix designs as density decreases. (Vipulanandan, 2000)

Supply and Alternate SCM

Overview – Initiatives and Technologies
- Logistics
- Harvesting Ash
- Carbon Burn-Out
- Ground Bottom Ash
- Beneficiation

Initiatives and Technologies to Supply the Concrete Market

- Regional Disparity
- Seasonal Disparity
- Grade Disparity
- Quality Disparity
- Rail
- Screen/Dry
- Legacy Ash Deposits
- CBO
- Hi LOI Ash
- Bottom Ash
- Storage
- Blending
- Grind/Blend
- Concrete Market (where’s the ash?)
- RestoreAir
Logistics
Rail Movement & Storage Options

- Rail large volumes of ash to manage supply deficits
- Use of high-volume domes and flat storage
- Versatility in transfer options
  - Conveyed pneumatically or auger
  - Portable Baghouse

Logistics
Iowa Locations

- Examples of some of the storage location in Iowa
- Storage during low demand winter to offset higher demand season

Harvesting Ash
Harvesting Ash for Pozzolan Use
Driven by regional shortage of quality ash

Closed landfill with 2 ft of soil cap
On 30 acres with 2 million tons of
Consistent quality meeting DOT specs
To be reclaimed in less than 10 years

A technology solution for harvesting pre-Lo-NOx burners fly ash from a utility owned deposit.

Harvesting Operation
Started in August 2018

Drying System
Site Photo

Reclaimed vs Current Generation Ash

<table>
<thead>
<tr>
<th></th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>SO₃</th>
<th>Fe₂O₃</th>
<th>Moisture</th>
<th>LOI</th>
<th>Fineness 7 d</th>
<th>SA1 28 d</th>
<th>Water Req'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Generation</td>
<td>81.99</td>
<td>9.55</td>
<td>0.38</td>
<td>0.21</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reclaimed</td>
<td>90.84</td>
<td>8.19</td>
<td>2.21</td>
<td>0.16</td>
<td>3.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ASTM C618 Class F

Which is Which?

Ground Bottom Ash
Ground Bottom Ash (GBA)

- Same source as fly ash
- Slower cooling
- Lower amorphous content
- Angular and spherical
- Requires milling

Ground Bottom Ash (GBA)

C 618 Testing of Ground Bottom Ash

<table>
<thead>
<tr>
<th></th>
<th>Sum of Main Oxides</th>
<th>SO₃ (%)</th>
<th>LOI (%)</th>
<th>Fineness (% retained on 325 mesh)</th>
<th>7D (% of cement control)</th>
<th>28D (% of cement control)</th>
<th>Water Req. (% of cement control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly ash</td>
<td>87.58</td>
<td>0.43</td>
<td>0.66</td>
<td>17.67</td>
<td>87</td>
<td>91</td>
<td>95</td>
</tr>
<tr>
<td>Ground Bottom Ash</td>
<td>89.98</td>
<td>0.39</td>
<td>3.12</td>
<td>17.07</td>
<td>82</td>
<td>84</td>
<td>101</td>
</tr>
<tr>
<td>C 618 Criteria</td>
<td>70% min for F</td>
<td>3% Max.</td>
<td>6% Max.</td>
<td>14% Max.</td>
<td>75% Min.</td>
<td>75% Min.</td>
<td>105% Max.</td>
</tr>
</tbody>
</table>

Class F

<table>
<thead>
<tr>
<th></th>
<th>Sum of Main Oxides</th>
<th>SO₃ (%)</th>
<th>LOI (%)</th>
<th>Fineness (% retained on 325 mesh)</th>
<th>7D (% of cement control)</th>
<th>28D (% of cement control)</th>
<th>Water Req. (% of cement control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fly Ash</td>
<td>63.76</td>
<td>1.66</td>
<td>0.48</td>
<td>13.63</td>
<td>96</td>
<td>104</td>
<td>94</td>
</tr>
<tr>
<td>Ground Bottom Ash</td>
<td>72.08</td>
<td>0.32</td>
<td>2.2</td>
<td>1.00</td>
<td>83</td>
<td>87</td>
<td>101</td>
</tr>
<tr>
<td>C 618 Criteria</td>
<td>50% min for class F</td>
<td>3% Max.</td>
<td>6% Max.</td>
<td>14% Max.</td>
<td>75% Min.</td>
<td>75% Min.</td>
<td>105% Max.</td>
</tr>
</tbody>
</table>

Blended Pozzolans

Regional Options

Performance Pozzolan (P²)

Driven by DOT durability specs and demand for F-ash

- Sum of oxides optimized between 72% and 75%.
- Sulfate resistance (F-ash)
- Mitigates ASR (F-ash)
- Early strength development (C-ash).
- Conforms to ASTM C1697 uniformity of ±5.0%.
- F-ash LOI is typically lowered (<2.0%).
- C-ash available alkalies are tempered as well.

F-Ash  

P² (Gaston/ Miller) approved in 7 states

Other P² supplies/markets are being used Midwest, TX and GA
Ash Beneficiation

You need it. We get it.

RestoreAir®

Carbon Treatment

RestoreAir® Technology Highlights

- New formulated reagent for improved dispersion
- Accurate PLC controlled reagent delivery system
- Robust QA/QC program
- 20 systems installed
- Combined capacity of 2 million tpy
- Very suitable for reclaimed ash that meets DOT LOI specifications

A COST EFFECTIVE OPTION FOR PAC AND LOW LOI ASH

Carbon Burn Out (CBO)

Technology to beneficiate high carbon ash

- Developed by Progress Energy with support from EPRI and other utility partners.
- The technology was spun off through PMI to deploy at other utilities.
- Boral acquired all patents and know-how related to the CBO from PMI.
- 4 CBO plants were built at powerplant sites with a combined operating history of more than 40 years processing more than 7 mm tons of ash.
- Improvements and other design features have been developed to allow its operation without power plant support to reclaim ash from landfills and ponds.
Technical solutions to meet supply challenges

**Fly Ash**
- Blending to augment supply
- Beneficiation for utilization
  - Chemical Treatment
  - CBO
  - Seasonal Storage

**Ground Bottom Ash**
- Milling to fly ash fineness
- Meet C-618 Requirements
- Durability
  - Effective mitigating ASR
  - Reduces Sulphate Expansion

**Harvesting**
- Excavation / Dredging
- Drying
- Crushing
- Sieving or Classifying

Additional Resources

Bill Sutton / Doug Rhodes
Boral Resources

Federal Highway Administration
Fly Ash Facts for Highway Engineers

Thank you.
www.flyash.com