Coal Combustion Products in Geotechnical Applications

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CCPs in Geotechnical Applications

Fly ash is a product of the combustion of pulverized coal in power plants removed by collection systems as a fine powder from the combustion gas stream.

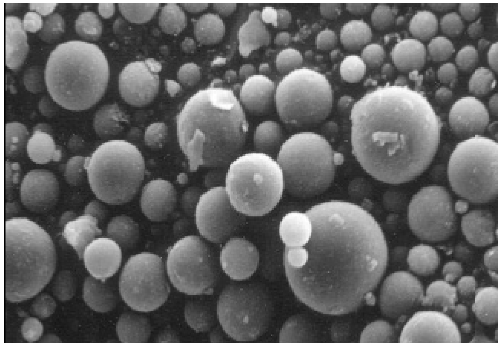
- **Self-cementing: Class C and Off-specification including high carbon**
- **Pozzolanic: Class F)**

CCPs in Geotechnical Applications

Bottom Ash is agglomerated ash particles, formed in pulverized coal furnaces, that are too large to be carried in the flue gases and impinge on the furnace walls or fall through open grates to an ash hopper at the bottom of the furnace. Physically, bottom ash is typically grey to black in color, is quite angular, and has a porous surface structure.

What is Fly Ash ?

- Pozzolanic material
- Fine and glassy particles
- Spherical in shape
- Silt-sized particle, ranging from 0.01 to 100 micron



Fly ash particles at 2000x magnification (ACAA, 2003)

- ~ 95% of the ash is composed of inert mineral oxides: oxide of silicon, aluminum, iron and calcium
- Other elements: As, B, Ba, Be, Cd, Cu, Hg, K, Mg, Mo, Mn, Na, Ni, P, Pb, Sb, Se, Sr, Ti, V and Zn

Fly Ash Classification (ASTM C 618)

Class C fly ash

- produced from burning lignite and sub-bituminous coals; abundant in calcium (CaO); self-cementing characteristics
- ASTM C 618 compliant (cement replacement & soil/base stabilization)
- ASTM 618 non-compliant (high carbon; soil/base course stabilization)

Class F fly ash

- derived from burning bituminous and anthracite coals; possesses little/no self-cementing characteristics

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CCP Production & Use (2007)

Amount of CCPs Produced

- Fly Ash (FA): 71.7 million tons
- Bottom Ash (BA): 18.1 million tons
- FGD Gypsum: 12.3 million tons (used as gypsum source)

❖Amount of CCPs Used in Major Areas

	Area	Quantity (million tons)*
Fly Ash	Concrete	13.7
	Structural Fill	7.7
	Soil Stabilization	0.4
Bottom Ash	Structural Fill	2.6
	Soil Stabilization	0.8
FGD	Wallboard	8.3

* Data source: ACAA 2007 Survey

Recap Poll # 1 – True or False

- The largest quantity of CCPs produced is fly ash: T/F
- Nearly all of fly ash is beneficially used: T/F
- Fly ash particles are spherical silt-size glassy particles: T/F
- High carbon fly ash cannot be used in stabilization: T/F

Application - Structural Fill

❖ Assumptions

- Fly ash and bottom ash replace sand & gravel at a 1:1 substitution ratio
- Fly ash replaces a 50:50 sand/gravel mixture
- Bottom ash replaces sand at a 1:1 ratio

❖ Unquantified Benefits in this Analysis

- Conservation of domestic earth materials

Application - Soil Stabilization

- Assumptions
  - Fly ash and bottom ash replace gravel & crushed rock
  - 10% fly ash stabilized subgrade replaces crushed rock
  - Bottom ash replaces gravel at a 1:1 substitution ratio

- Unquantified Benefits
  - Reduction of construction time
  - Enhanced life of construction projects
  - Conservation of domestic earth materials

CCP Utilization: Summary of Benefits-1

CCP Utilization: Summary of Benefits-2

* U.S. Census Bureau 2006

Laboratory Materials Characterization Tests

- **Soil Index properties:** Atterberg Limits (LL, PI), grain size distribution, organic content, free swell, natural water content, Unified Soil Classification
- **Fly Ash properties:** Chemical composition (%CaO, CaO/SiO_2 ratio), classification
- **Mixture Tests:** Compaction (performed 1 to 2 hr after mixing to simulate field) and CBR and/or unconfined compression strength (UCS) to determine optimum moisture and fly ash content in mix design also for the design of working platforms (typically fine-grained soft soils, organic soils, expansive soils) and modulus for the pavement layer structural (thickness) design, i.e., stabilized subgrade (i.e., subbase) or granular base course (resilient modulus, M_r or static modulus, E_{50}. Durability tests (loss of modulus after freeze-thaw and wet-dry cycles.

Unconfined Compressive Strength (UCS)

- ASTM D 5102 – 96.
- No confining pressure.
- Compress the soil sample at a rate of 0.21% strain per minute
- Can also be performed on resilient modulus specimens after the resilient modulus test.

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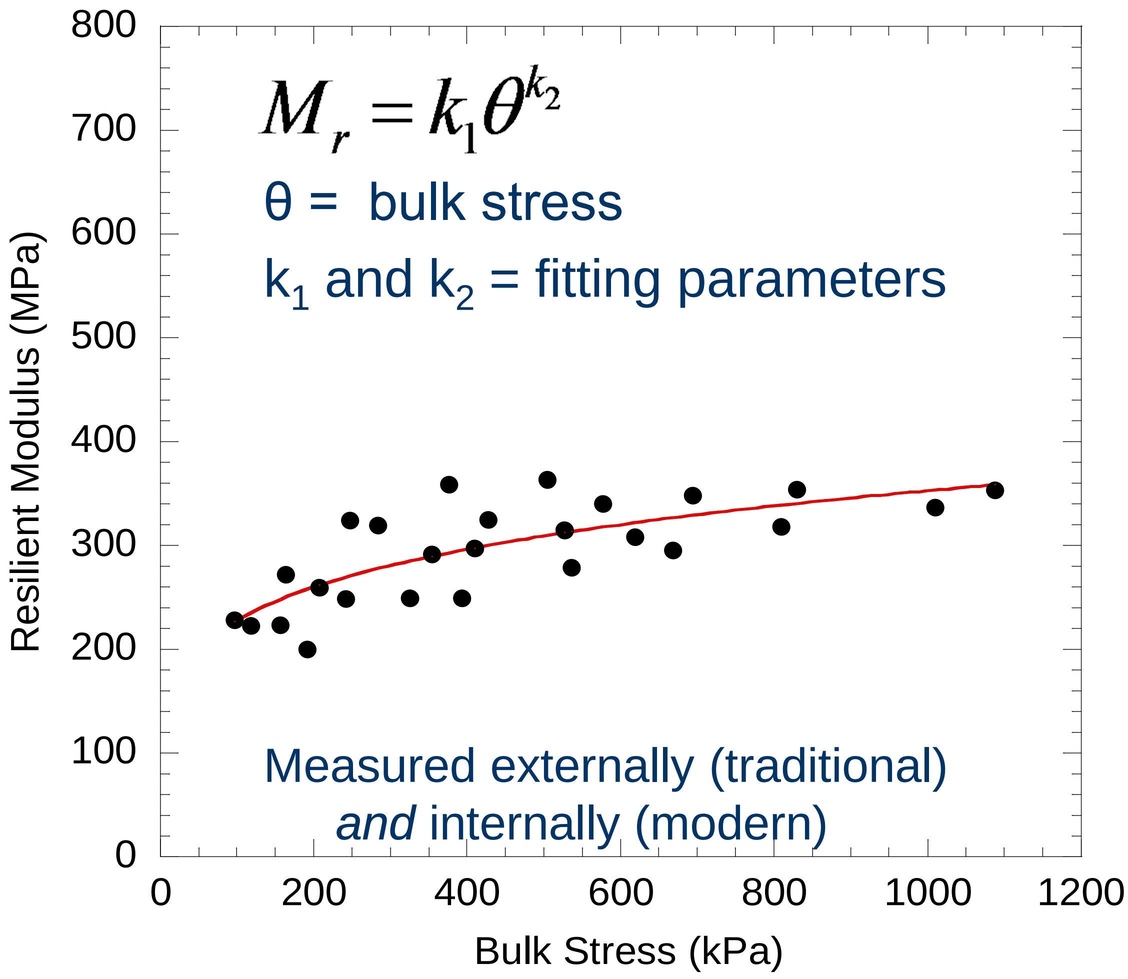
California Bearing Ratio Test

- **ASTM D 1883**
- **After 7 d of curing for fly ash stabilized material (unsoaked)**
- **Strain rate of 1.3 mm/min**

Method

Resilient Modulus



$$M_r = k_1 \theta^{k_2}$$

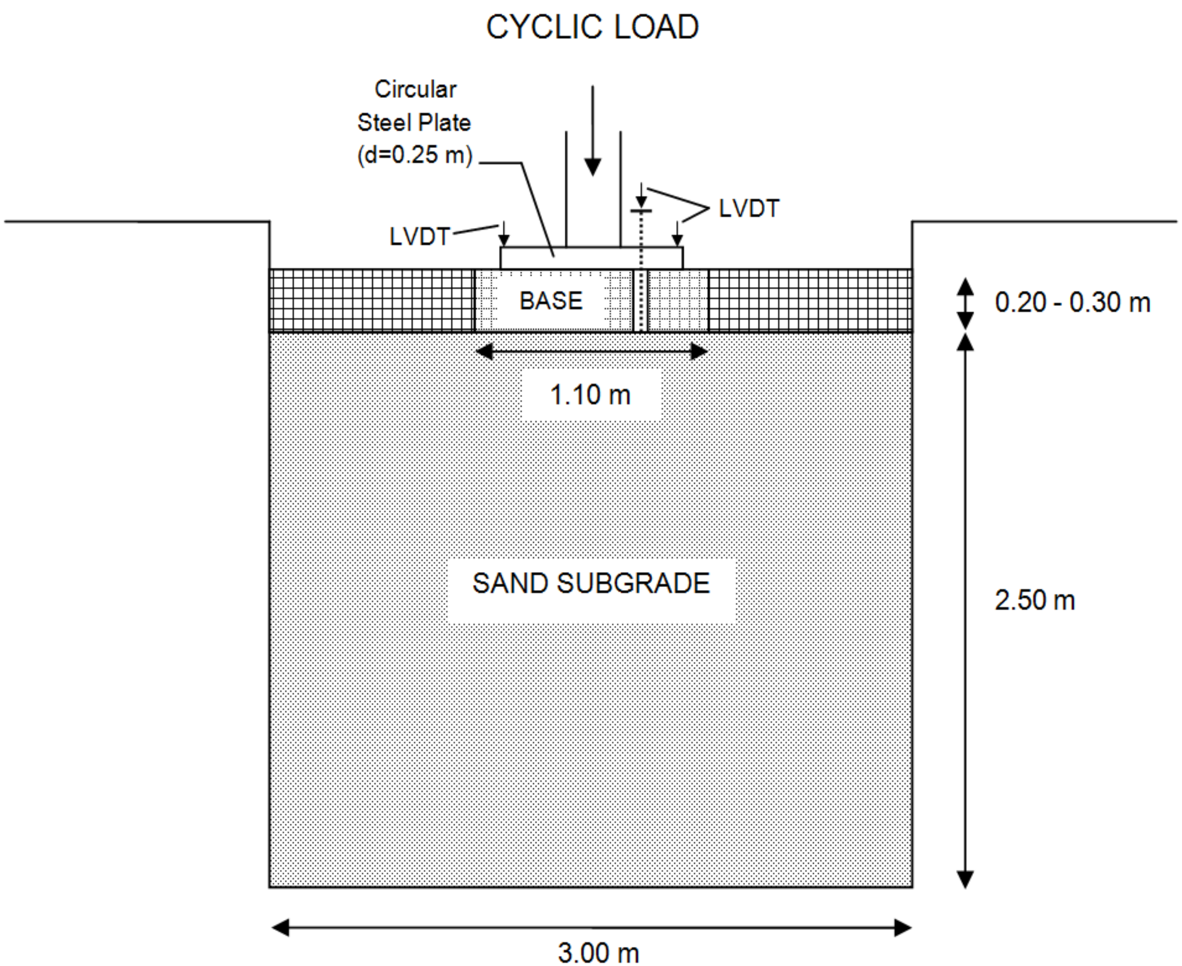
θ = bulk stress

k_1 and k_2 = fitting parameters

Measured externally (traditional) *and* internally (modern)

Summary resilient modulus (SMR) at bulk stress = 208 kPa.

Prototype Testing in LSME



- Prototype cycling loading apparatus to evaluate near full-scale pavement structures.
- Evaluate elastic and plastic deflections.

Subgrade Stabilization

Objectives:

1. To create a working platform for road construction over very soft and wet subgrade, which can be treated as a subbase layer for its contribution to pavement structure in pavement design
2. To treat expansive subgrade or organic subgrade or simply stiffen subgrade to reduce in turn base course thickness
3. To stabilize deep fills below buildings to limit settlement (does not require high strength).

Mechanisms:

- Due to solid fly ash particles reducing water content as a drying agent
- Due to chemical binding of soil particles by end-products of chemical reactions

Main Advantage: Allows rapid construction in adverse climates and over wet soils that can't be dried to optimum moisture content.


RS-6502
B. Fly Ash Mixing


C. Grading


D. Compaction

Recap Poll # 2 – True or False

- Reduction in CO_2 emissions due to beneficial use of CCPs is equal to removing nearly 2 million cars from traffic annually: T/F
- To find the optimum fly ash content, a mix design is conducted in which strength gain is measured: T/F
- The only mechanism for fly stabilization of wet soils is chemical cementation: T/F
- Modulus or resilient modulus is a property needed for pavement design: T/F

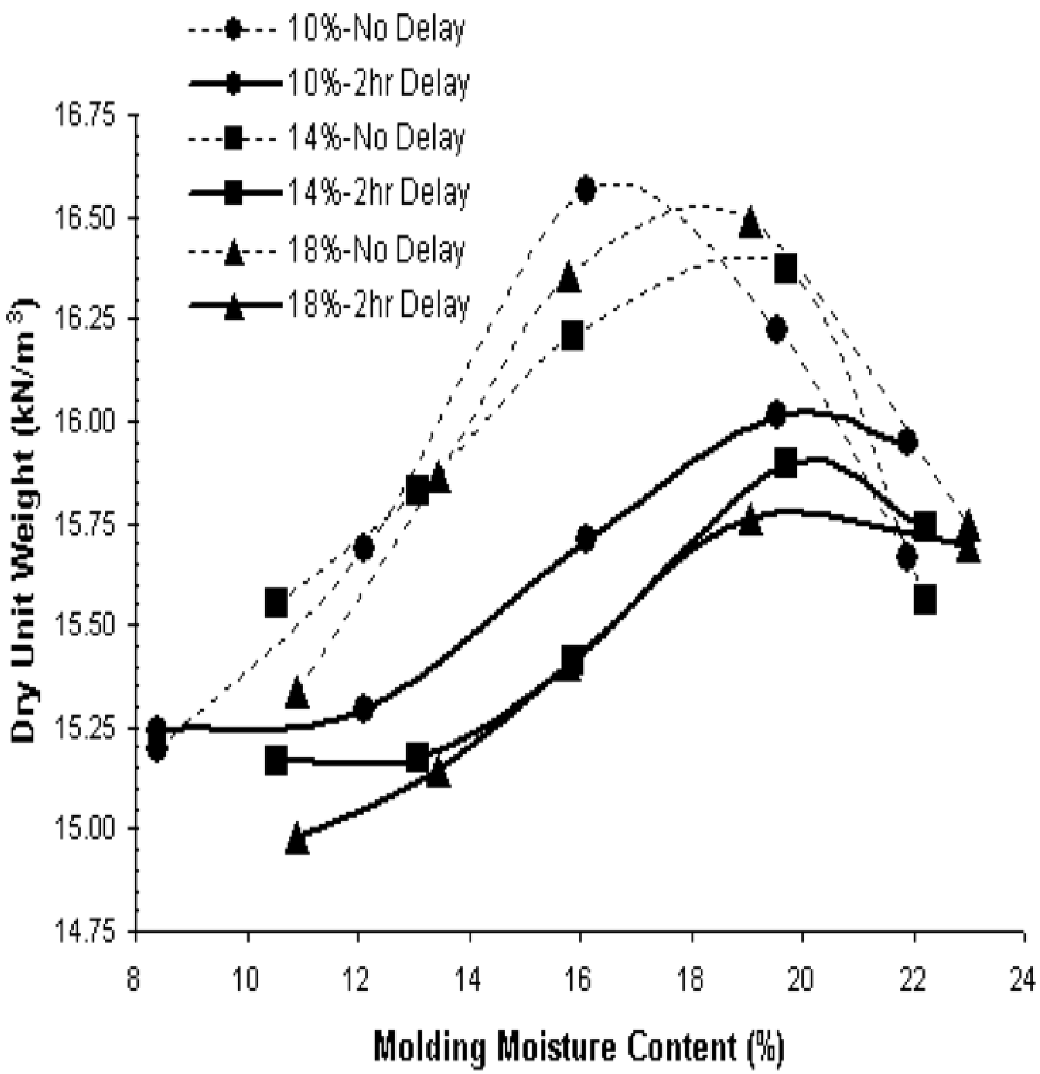
Working Platform Design with Self-Cementing Fly Ash

- Strength is the governing property for working platforms
- Need UCS or un-soaked CBR
- Typical mixing depth 20-30 cm (8-12 in)
- Typical dosage 10-14% for self-cementing fly ashes
- Field properties are lower than laboratory-developed properties (up to 50%)
- Typical soils: Fine-grained subgrades (USCS designations of CL, ML, CL-ML, SM, SC), soils containing organic matter (may require higher fly ash content)
- Since the subgrade soils and binders are not standard, there is a huge range of possibilities. So the specifications are based on mixed design optimizing strength (UCS or CBR rather than thickness).

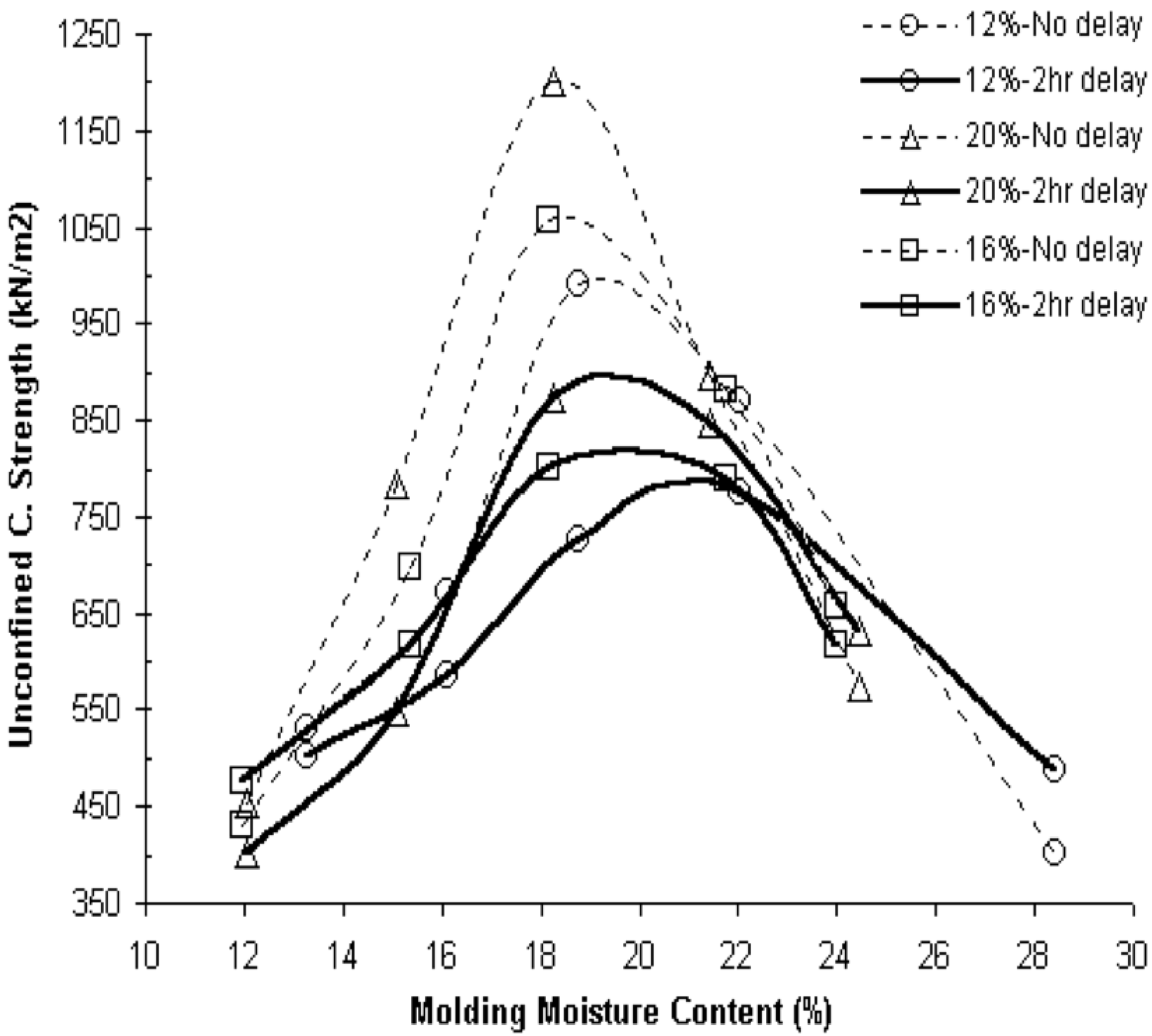
General Behavioral Observations

- Two-hour compaction delay after mixing water results in considerably lower dry unit weights and higher optimum water contents compared to no-delay compaction.
- A compaction delay simulating field conditions, such as 1-2 hr, is recommended in all laboratory tests in order to simulate the field conditions. Optimum compaction moisture content can be used as the approximate optimum strength gain moisture content for delayed compaction.
- Swell potential can be expected to be reduced 5 to 10 times.
- Unconfined strength gain and CBR gain of specimens compacted with two-hour delay can be expected to be 3 to 5 times greater than untreated specimens.
- Typically wet conditions (i.e., in situ moisture contents of up to 7% wetter than the optimum moisture content) may exist and require fly ash treatment at existing moisture content.

Compaction Curves of a Low Plasticity Silt (ML)



UCS of a Low Plasticity Silt (ML)



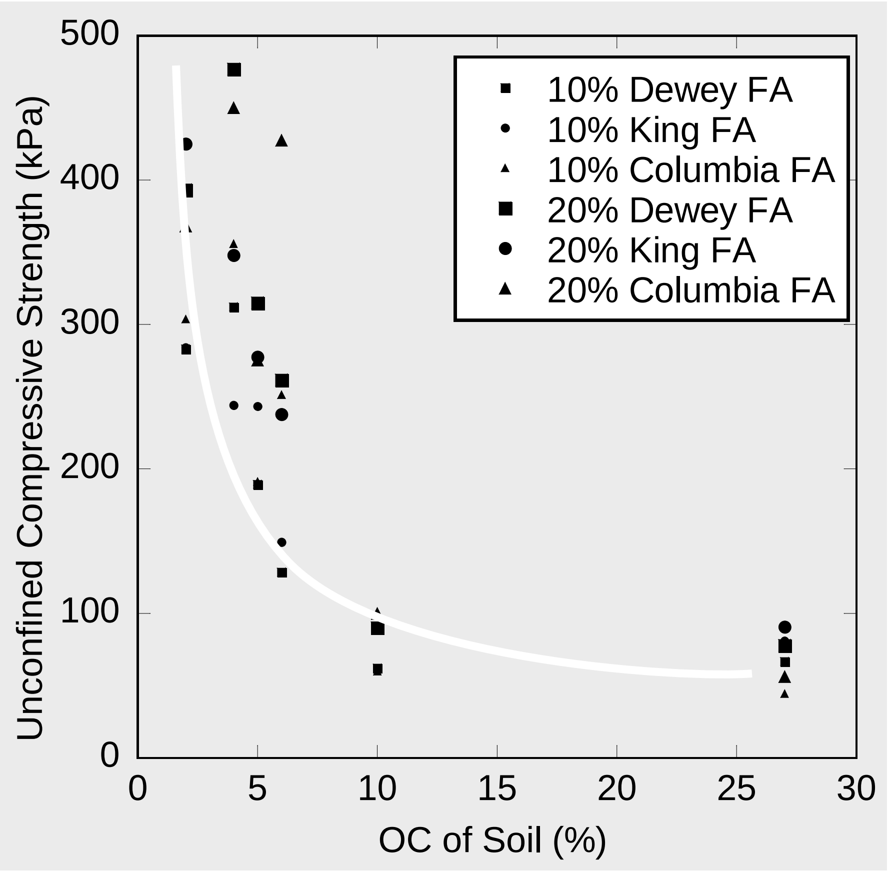
General Behavioral Observations – con't

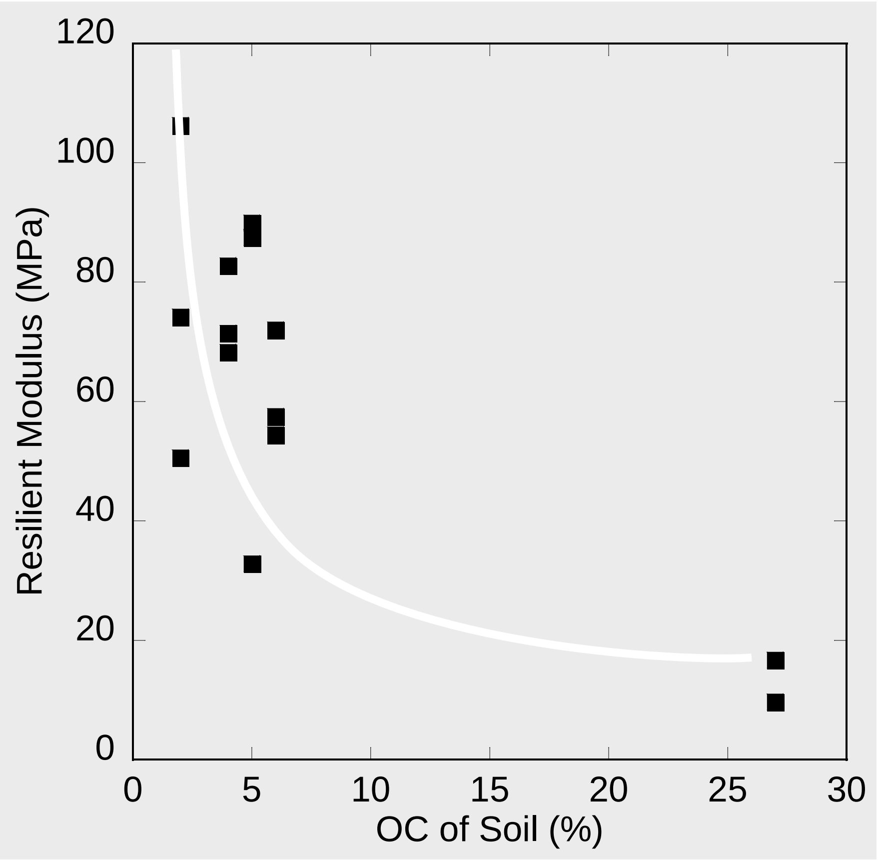
- A CBR of 10 or more is achievable with 10% Class C fly ash in 7 days in wet fine-grained inorganic subgrades (e.g., at 7% wet of optimum).
- The significant characteristics of fly ash affecting the increase in q_u and M_r include CaO content and CaO/SiO_2 ratio (or $CaO/(SiO_2 + Al_2O_3)$ ratio). The highest UCS and M_r were obtained when the CaO content was greater than **10%** and the CaO/SiO_2 ratio was between **0.5-0.8.**
- Comparable increases in UCS and M_r were obtained with the Class C ashes, normally used in concrete applications, and the off-specification fly ashes meeting the aforementioned criteria for CaO content and CaO/SiO_2 ratio.
- Unconfined compressive strength of organic soils can be increased using fly ash, but the amount of increase depends on the type of soil and characteristics of the fly ash.

Chemical Composition of Fly Ashes

	Dewey	King	Presque Isle	Coal Creek	Columbia	Stanton
CaO (%)	9.2	25.8	3.2	13.3	23.3	21.3
SiO2 (%)	8.0	24.0	35.6	50.4	31.1	40.2
Al2O3 (%)	7.0	15.0	18.0	16.4	18.3	14.7
Fe2O3 (%)	2.6	6.0	3.5	7.2	6.1	8.7
CaO/SiO2	1.2	1.1	0.1	0.3	0.8	0.5
$CaO/(SiO_2+Al_2O_3)$	0.9	0.9	0.1	0.2	0.4	0.6
Fineness	27	41	25	28	12	23
pH	9.9	10.9	11.3	11.9	12.8	11.7
LOI	42.0	12.0	34.0	0.5	0.7	0.8
Classification	Off-spec	Off-spec	Off-spec	Class F	Class C	Class C

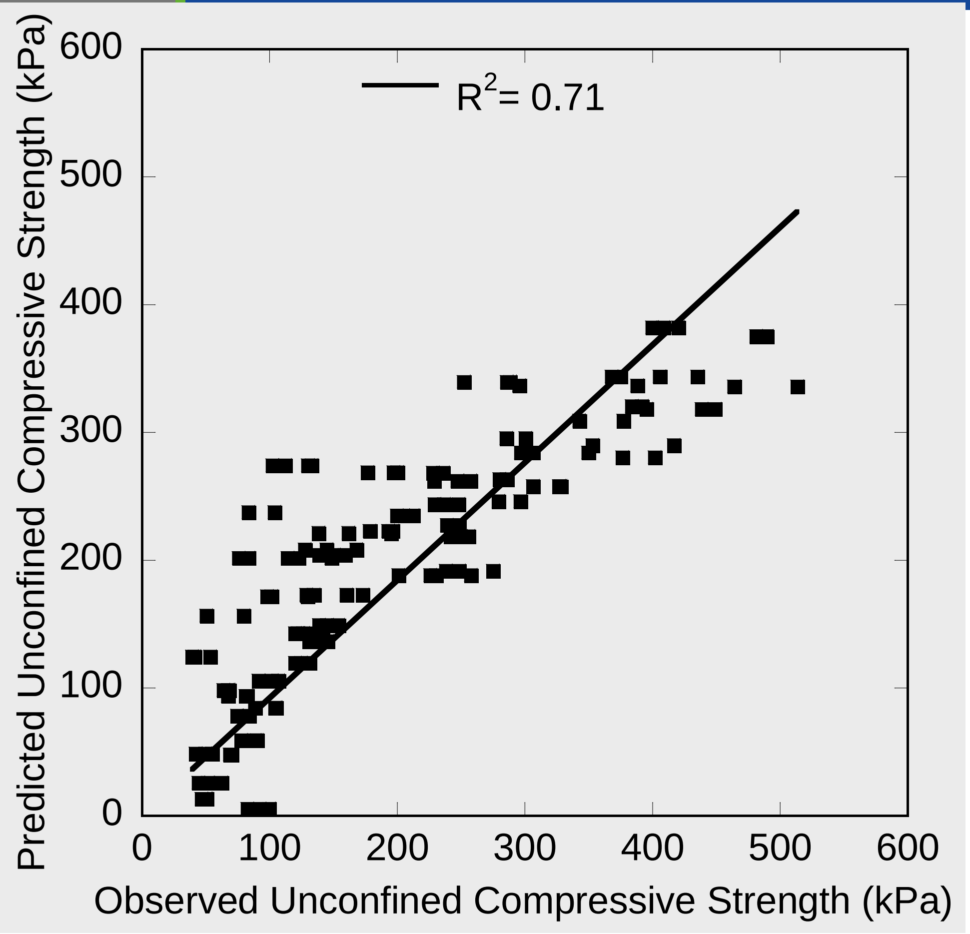
Effect of Organic Content of Soil





Expontential decay in strength and stiffness

Linear Model to Reproduce Mixture Unconfined Compressive Strength



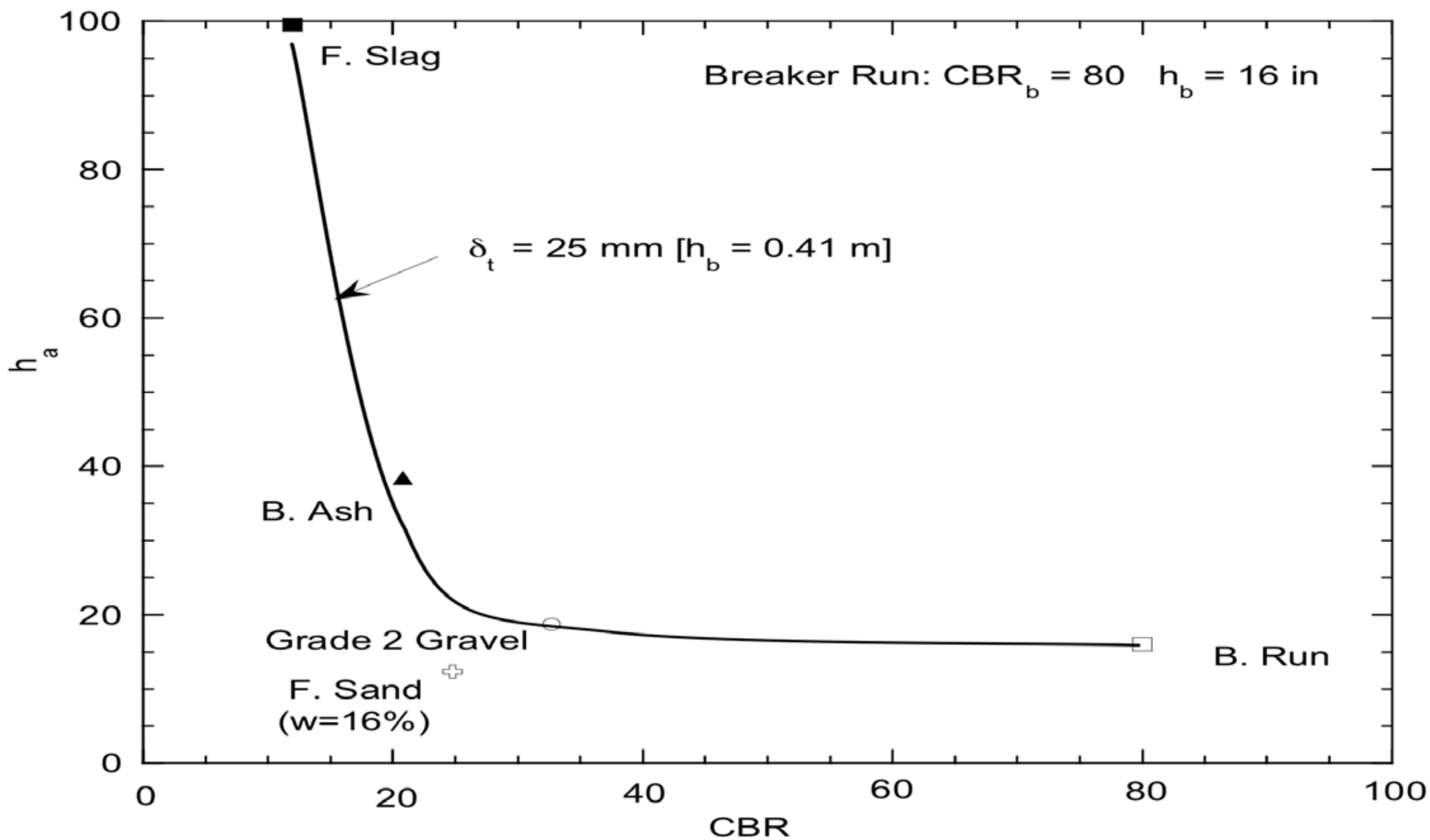
$$UCS_{treated} = -320 + 795(CaO/SiO_2) - 573(CaO/SiO_2)^2$$
$$-125673(e^{-OC}) + 6(FA_{percent}) + 25(UCS_{untreated}) - 33(pH_{mixture})$$

Working Platform Design with Bottom Ash

- Bottom ash is a granular replacement material for crushed large aggregate (often referred as “breaker run”). Traditional working platform for construction over wet and soft subgrade requires removal of about 0.4 m (16 in) of subgrade and placement with breaker run.
- Strength is the governing property for working platforms
- Need un-soaked CBR
- Required thickness for breaker run equivalency of bottom ash can be determined from CBR and typically equivalent bottom ash thickness is 1 m (38 in).

Working Platform Thickness Design with Bottom Ash

h_a = equivalent thickness of granular industrial byproducts such as bottom ash alternative to breaker run for a maximum total deflection of 25 mm (1 inch) during typical construction traffic based on the measured CBR_a obtained at the specified field compaction conditions



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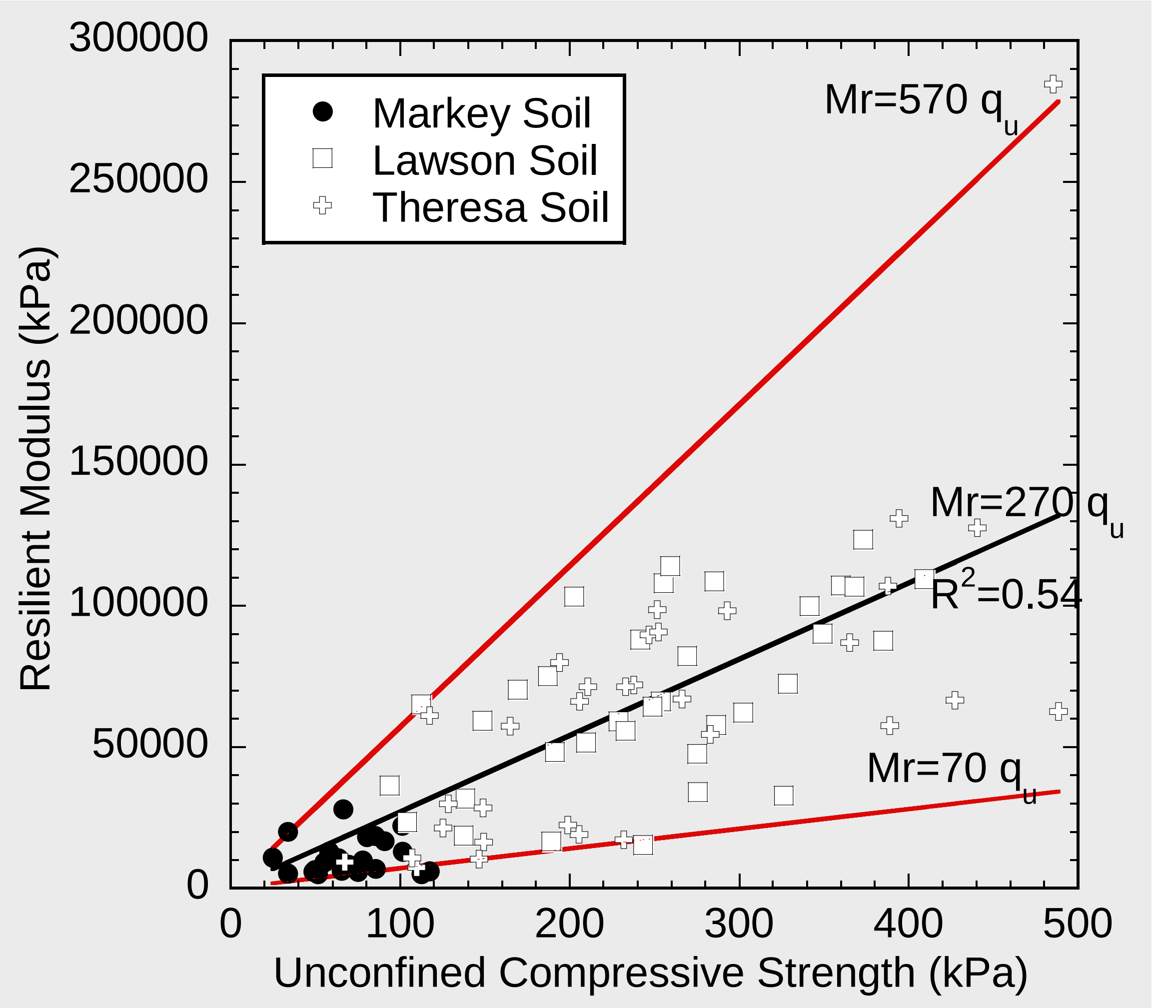
Recap Poll # 3 – True or False

- The main property needed for working platform design is modulus: T/F
- The important fly ash properties are CaO content and CaO/SiO_2 ratio for strength gain: T/F
- Organic soils can not be stabilized with fly ash: T/F
- Required bottom ash thickness for working platform is based on CBR ratio: T/F

Working Platform Layer Structural Contribution to Pavement

- Modulus is the governing property for fly ash stabilized subgrade or bottom ash granular working platforms. Need resilient or static modulus
- Typical mixing thickness 30 cm (12 in) for fly ash stabilized subgrade and 100 cm (38 in) for bottom ash for working platform
- Typical dosage 10-14% for self-cementing fly ashes
- Field properties are lower than laboratory-developed properties (up to 50%) for fly ash stabilized layers.
- AASHTO 1993 pavement design requires layer coefficient (a_3 for subbase) multiplied with layer thickness giving structural number (i.e., the structural contribution of the layer). a_3 can be calculated from $a_3 = 0.227\times(\log \text{Modulus}) - 0.839)$
  - Typical fly ash stabilized subgrade working platform layer coefficient: 0.13 with typical modulus of 200 MPa (28612 psi).
  - Typical bottom ash working platform layer coefficient: 0.06 with typical modulus 100 MPa (14306 psi)

Modulus vs Unconfined Compressive Strength for Fly Ash Stabilized Subgrade



Resilient Modulus (kPa) = 270 x Unconfined Compresssive Strength (kPa).
(Multiplier varies 70 and 570 with best fit being 270)

Fly Ash Stabilized Base Course Layer Structural Contribution to Pavement

- Fly ash stabilized granular base include crushed rock aggregate, recycled pavement material or recycled asphalt pavement (RPM or RAP), recycled road surface gravel (RSG)

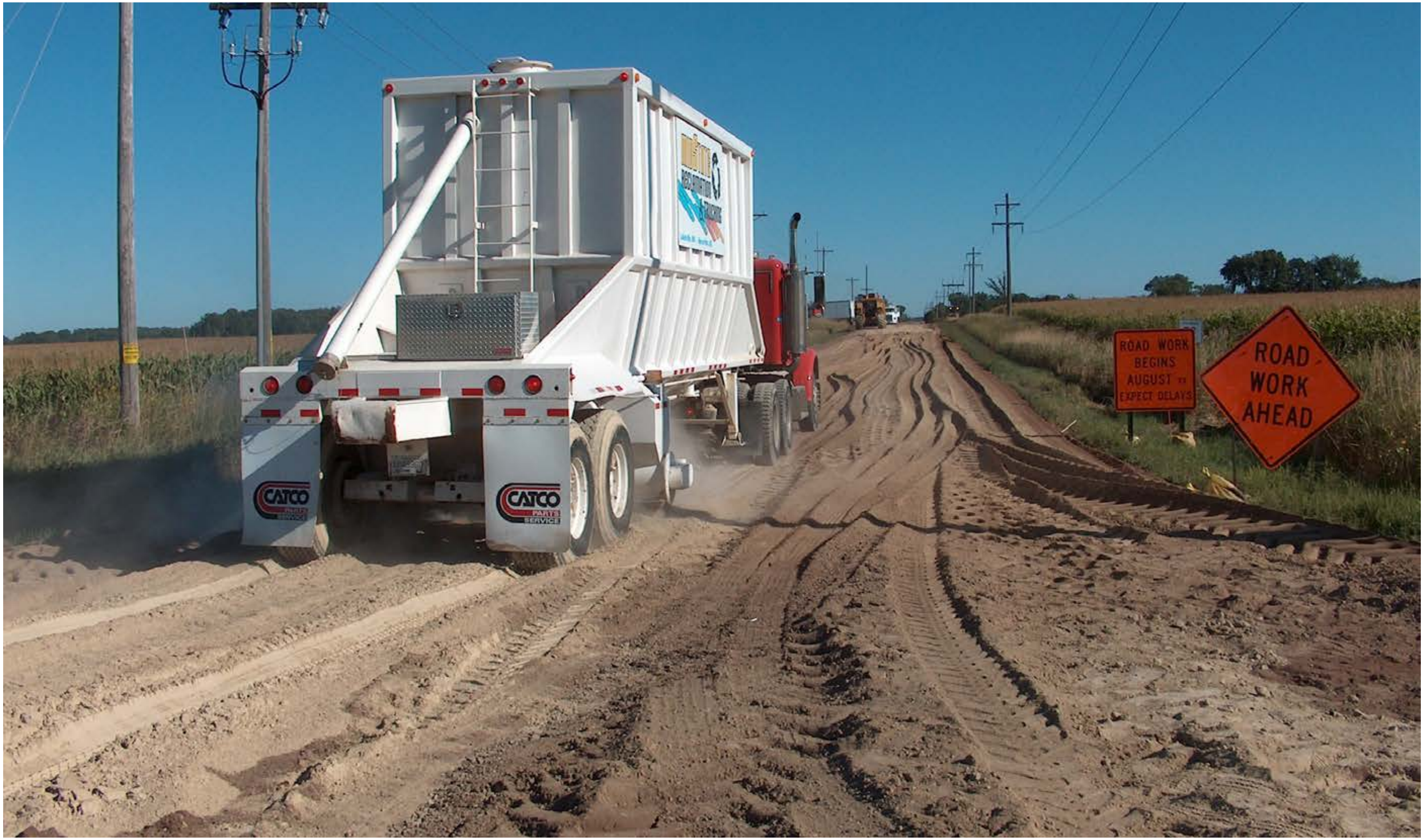
- AASHTO 1993 pavement design requires layer coefficient (a_2 for base) multiplied with base thickness giving structural number (i.e., the structural contribution of the layer). a_3 can be calculated from a_3 = 0.249×(log Modulus) −0.977)

- Typical fly ash stabilized granular base course material layer coefficient: 0.3 with typical modulus 850 MPa (121,600 psi)

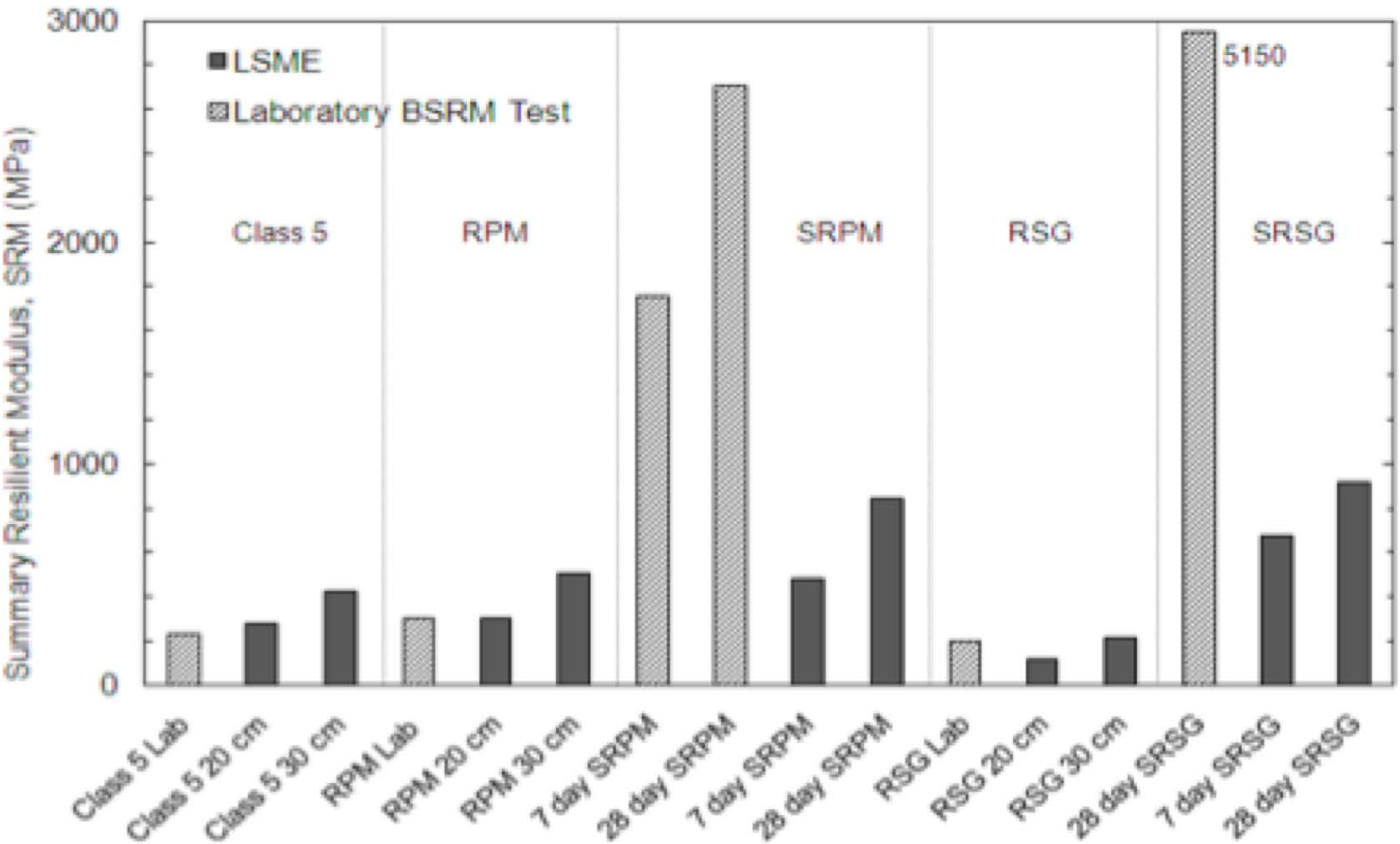
- Alternatively Mechanistic-Empirical Pavement Design Guideline (2006) can be used with modulus. Typical increase in service life of 4 years can be expected for fly ash stabilized granular base materials compared to untreated base course (21 versus 17 yr).

RPM/Fly Ash Compaction for Base

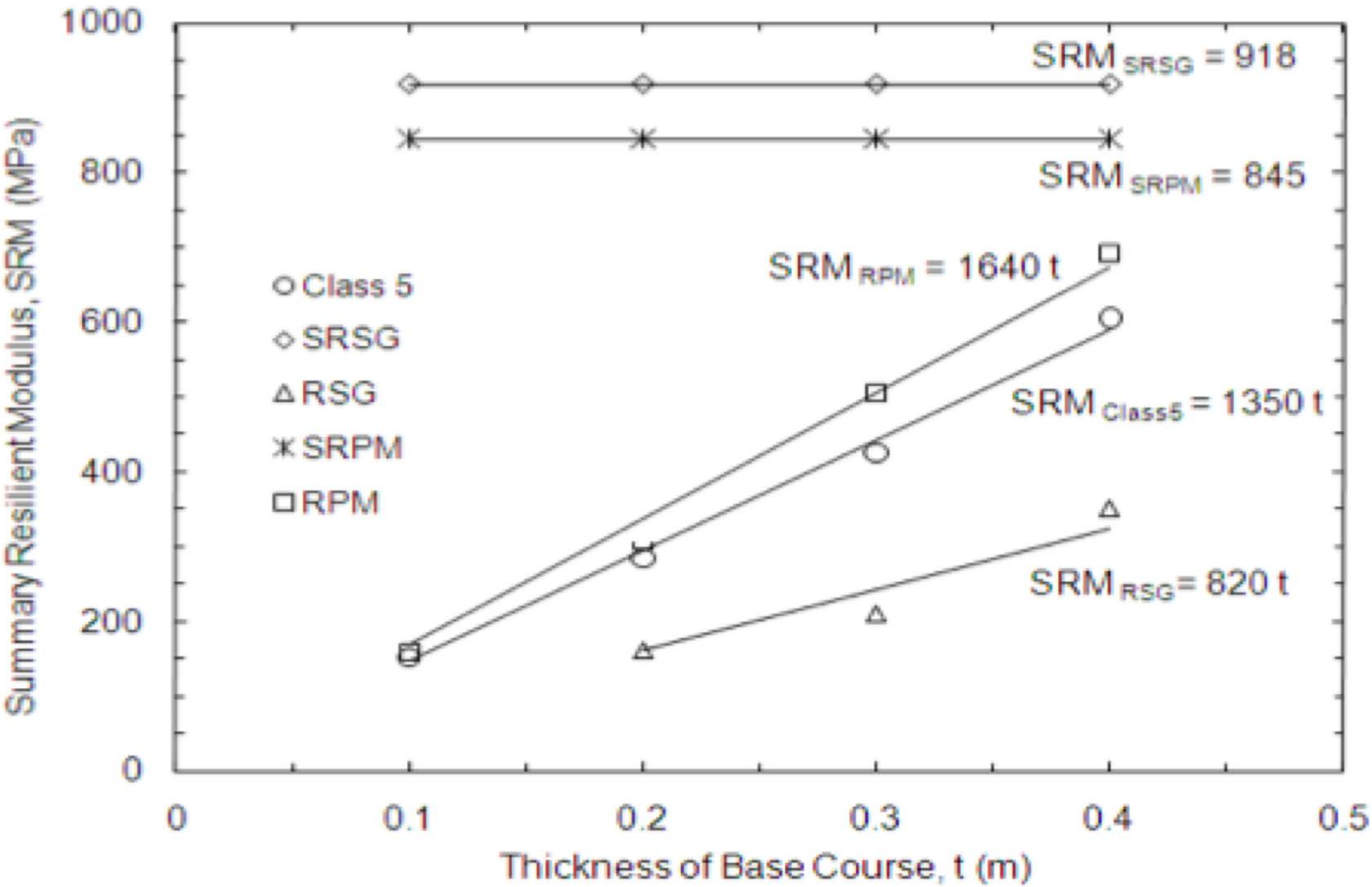
Spreading Fly Ash over RSG for Base



Stabilized Base Layer Properties



Stabilized Base Layer Modulus



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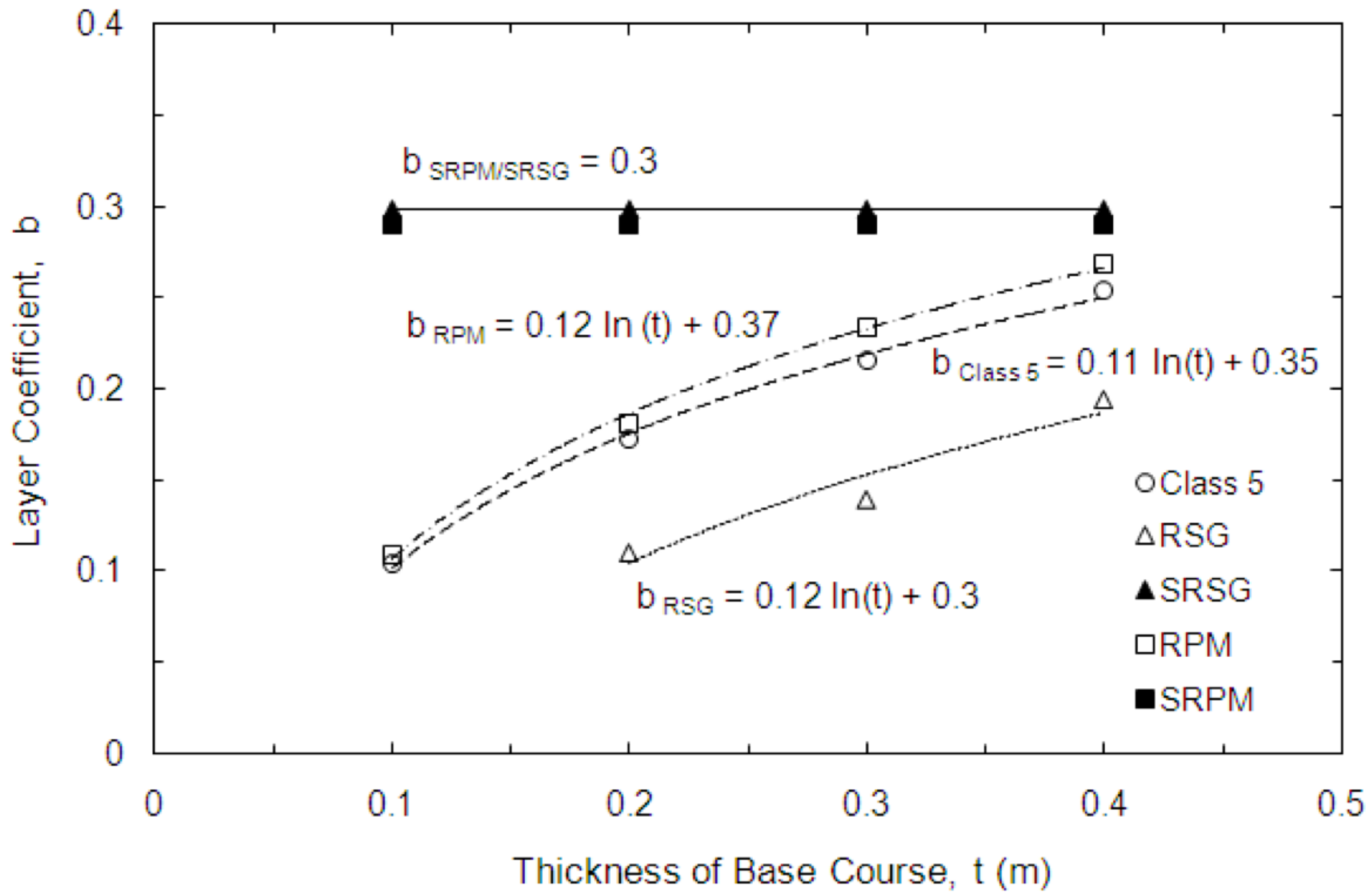
Stabilized Base Layer Coefficients



Structural Fill with Bottom Ash or Fly Ash

Relevant Properties for Design of Fly Ash and Bottom Ash Structural Fills:

- Very steep side slopes can be achieved with self-cementing fly ashes based on UCS; expected to have low compressibility alone or in mixtures
- Pozzolonic fly ashes (Class F) angle of internal friction: 26^0-42^0 (typical 30^0). A silt-sized fill material.
- Bottom ash angle of internal friction: 38^0-53^0; $C_c/1+e_o$) = 0.09 (slightly compressible). A gravel-sand size granular fill material.

Recap Poll # 4 – True or False

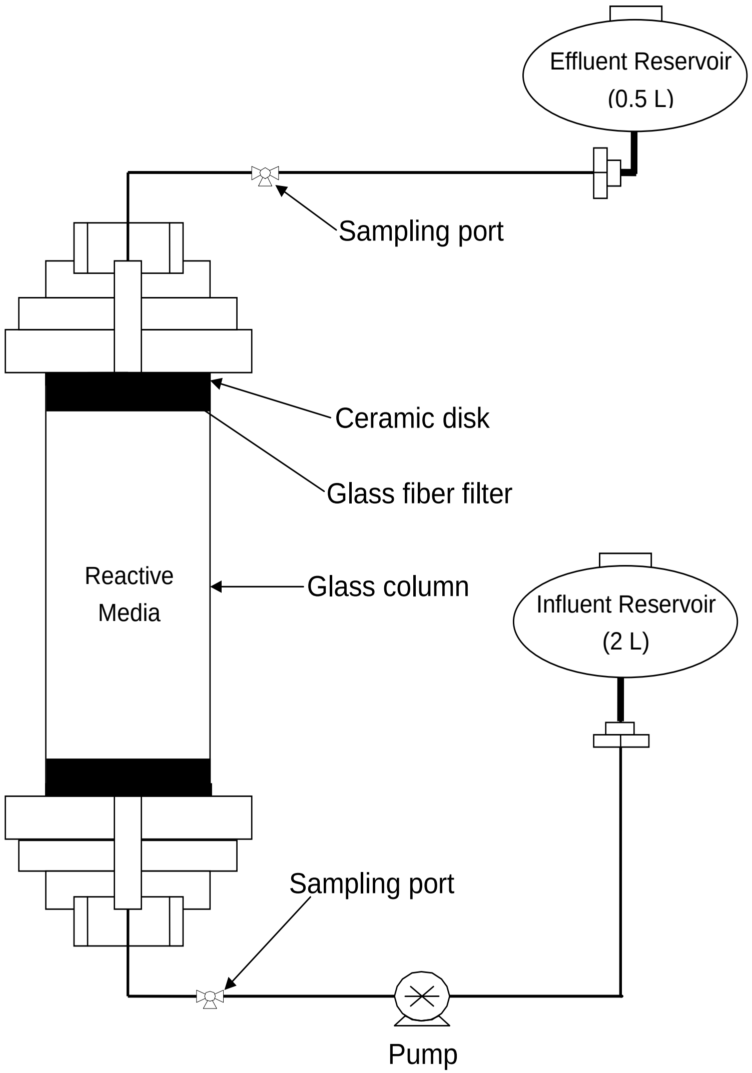
- Structural contribution of fly ash stabilized layers and bottom ash to pavement structure are estimated from their modulus: T/F

- Modulus of fly ash stabilized layers is essentially constant and not sensitive to in situ stresses or layer thickness: T/F

- Layer coefficient multiplied with layer thickness gives structural number, i.e., structural contribution of a layer in pavement design: T/F

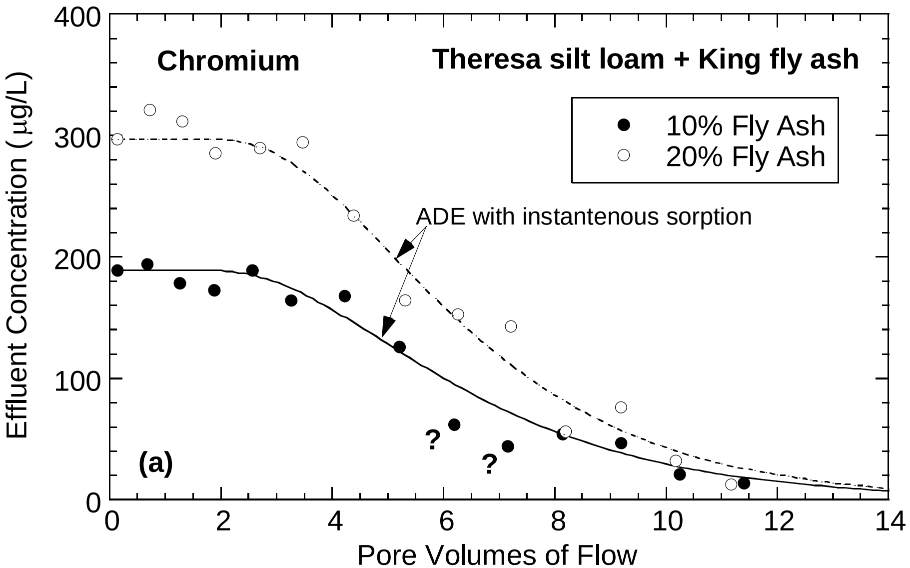
- We have no experience regarding layer coefficients of CCPs to be used in design: T/F

Leaching - Lab

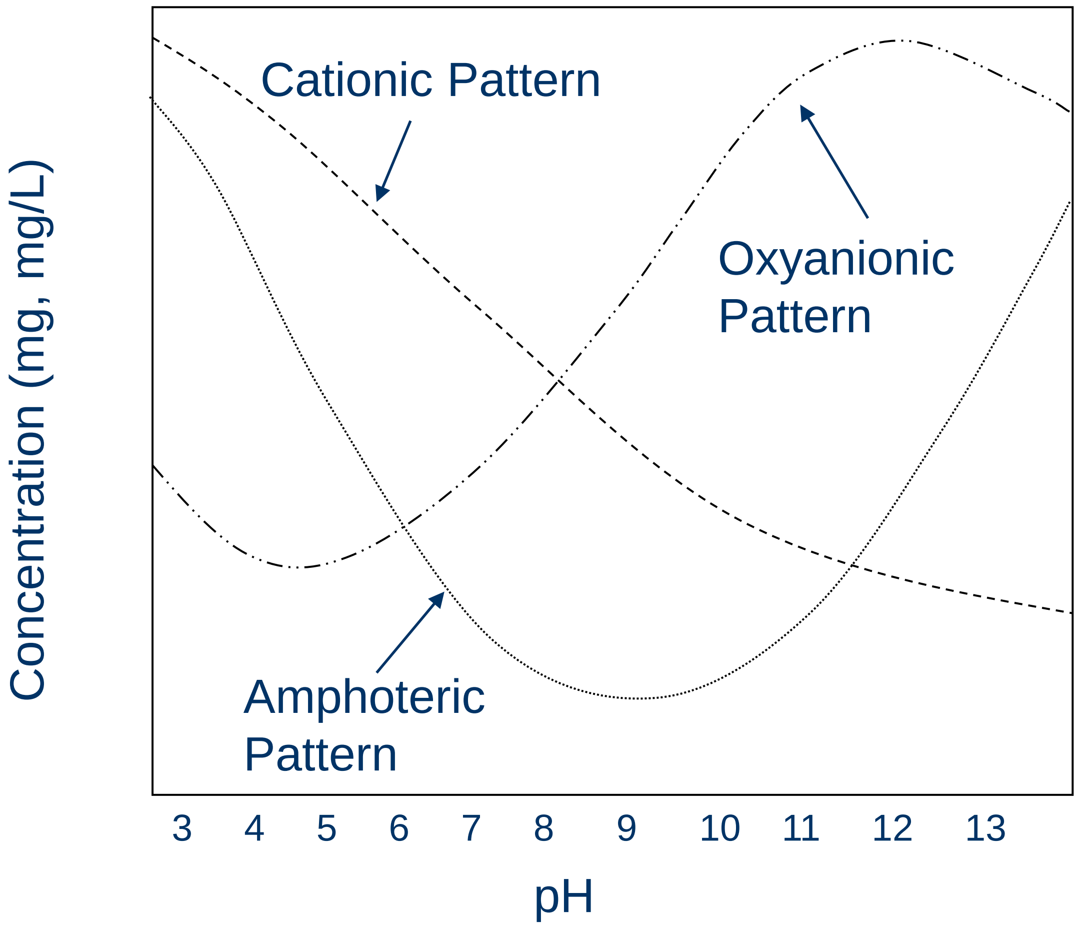


Column test example

Effluent concentrations



Leaching Patterns as a Function of pH



Leaching Patterns and Mechanisms

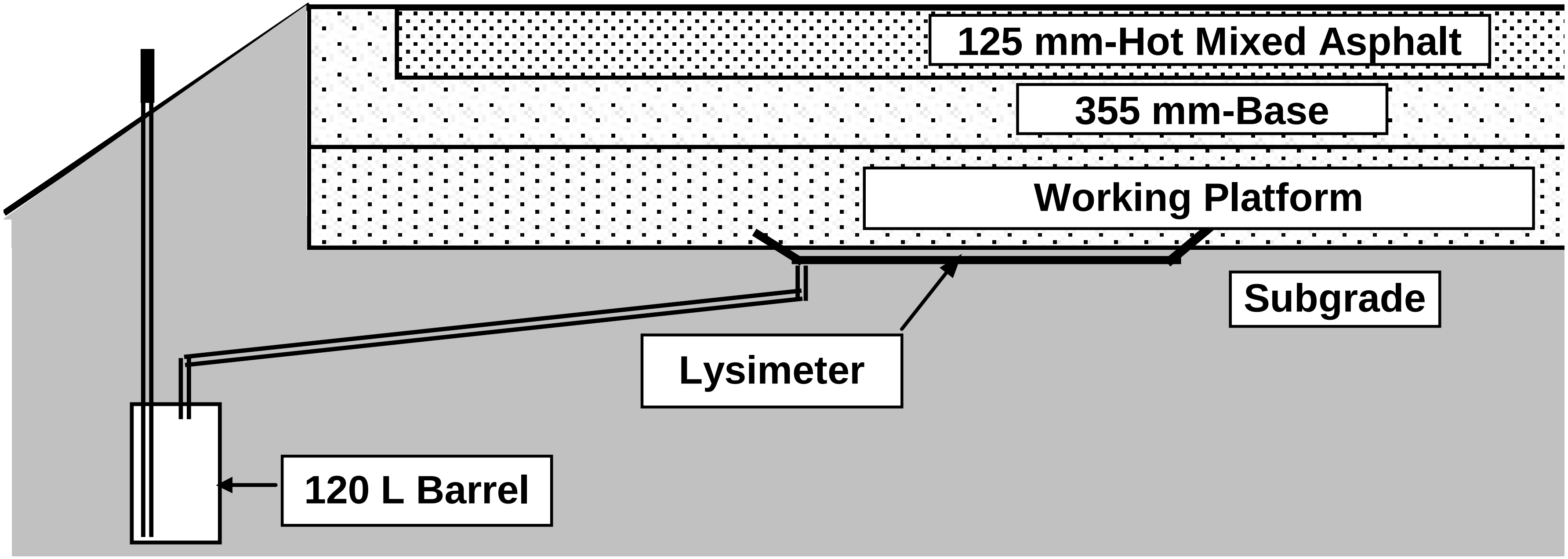
PATTERNS

- Cationic: Ca, Cd, Mg, and Sr
- Amphoteric: Al, Fe, Cr, Cu, and Zn
- Oxyanionic: As and Se

MECHANISMS

- Dissolution-Precipitation (Solubility Control)
  - Al, Ca, Fe, Mg, Ba, Cd, Cu, Cr, Sr, and Zn
  - As and Se?
- Solubility Controlling Solids
  - Oxide & hydroxide minerals: Al, Fe, Cr and Zn
  - Carbonate minerals: Mg and Cd
  - Oxides and/or carbonate minerals: Cu
  - Sulfate and carbonate minerals: Ca, Ba, and Sr

Leaching – Field Lysimeters

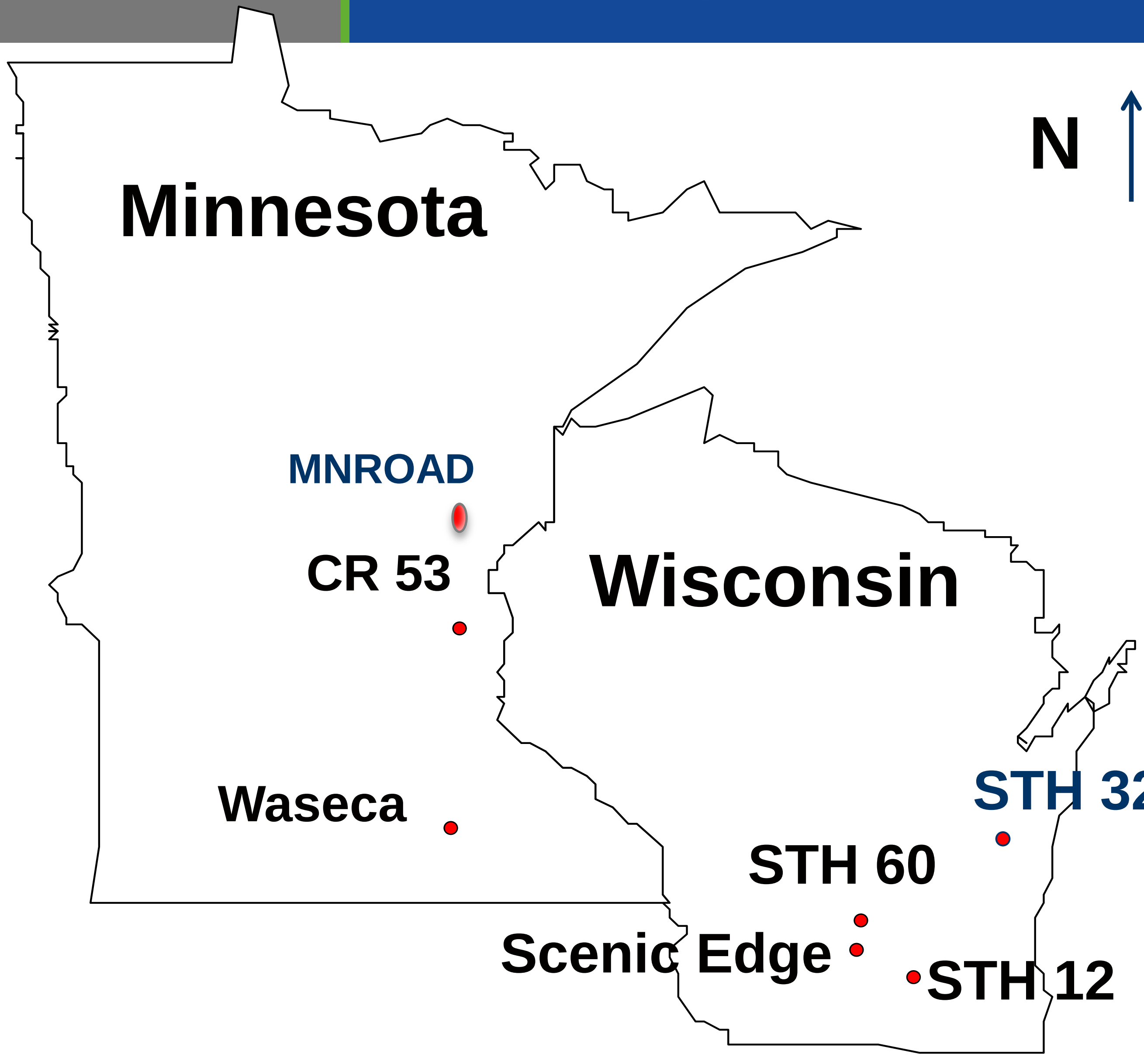


Leachate collected in drum & pumped periodically to determine percolation rate.

Samples analyzed for pH & metals concentrations.


Geomembrane installation
Sump welding
Drainage layer installation
Collection tank installation

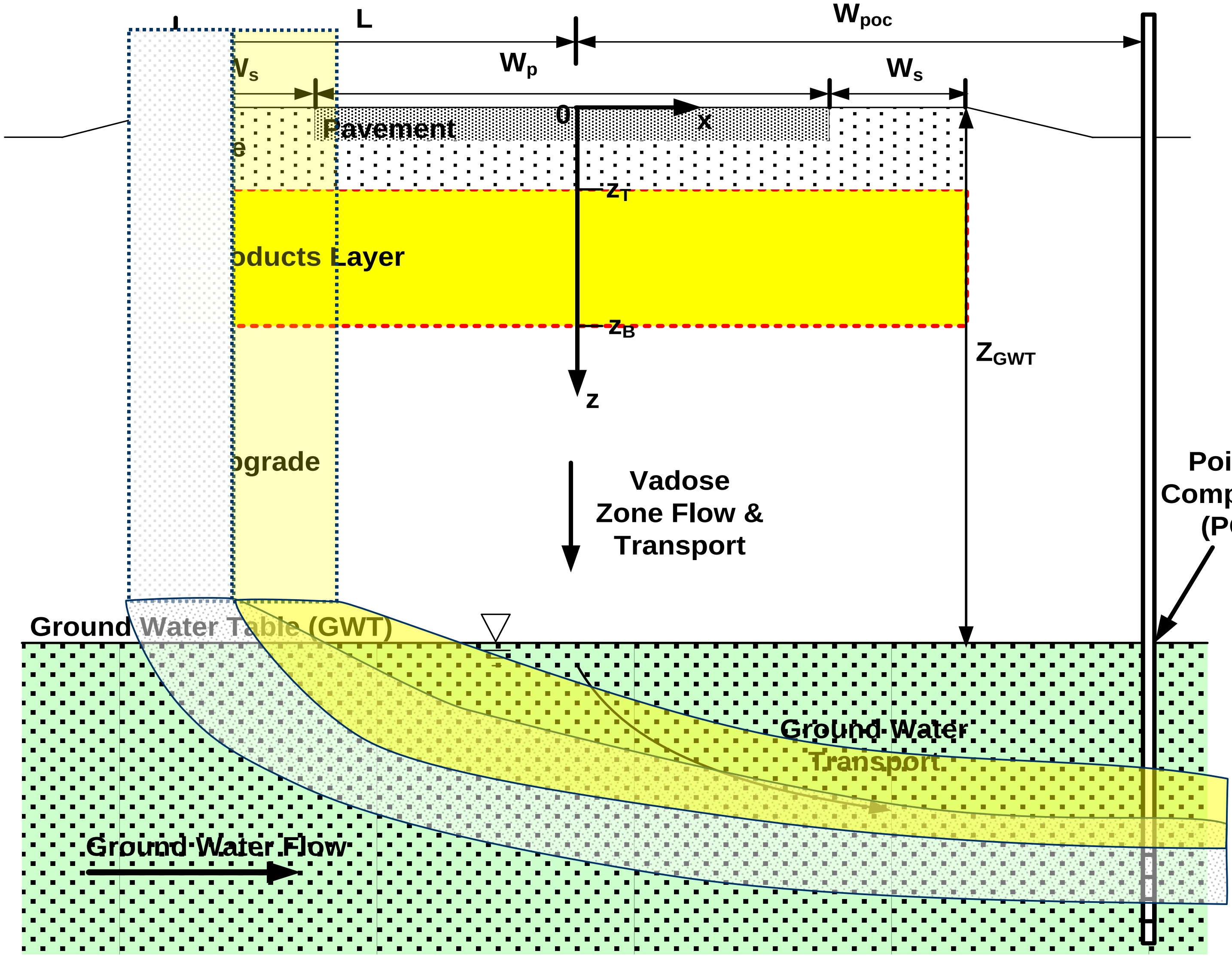
Field Lysimeter Sites



Leaching Results - Field

- Percolation rates typically range between 0.1-0.5 mm/d, with the average percolation rate falling between 0.1-0.2 mm/d depending on site conditions.
- For many elements, concentrations below US water drinking water quality standards are attained at the bottom of the pavement profile within 2-4 pore volumes of flow.
- Concentrations of four elements from fly-ash-stabilized materials were elevated relative to the control sections at all sites (As, B, Mo, Cr, and Cd) and also exceeded MCLs.
- Concentrations of Cd and Cr only exceeded MCLs in the first samples collected (PVF < 0.25), and then remained well below the MCL in all subsequent samples unlike B and Mo.
- As and Pb from stabilized materials are only slightly elevated relative to control concentrations.

WiscLeach Model



Regulation of CCPs

- No federal regulations or guidance. Some states have rules or ‘beneficial use determinations’ (BUDs).
- Wisconsin NR538•
  - Evaluate byproducts based on total elemental analysis and water leach tests.
  - Define byproduct categories based on test data.
  - Define suitable application based on category.
  - Lower category number provides more stringent limits on leaching characteristics.
  - Contaminants of concern depend on byproduct being considered.
  - Category 1 has the most test requirements.

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NR 538 (Wisconsin Administrative Code)

Beneficial Use Methods	Industrial Byproduct Category				
	5	4	3	2	1
(1) Raw material for manufacturing a product	x	x	x	x	x
(2) Waste Stabilization/ Solidification	x	x	x	x	x
(3) Supplemental Fuel Source/Energy Recovery	x	x	x	x	x
(4) Landfill Daily Cover/ Internal Structure	x	x	x	x	x
(5) Confined Geotechnical Fill a. Commercial, industrial or institutional building subbse b. Paved lot base, subbase and subgrade fill c. Paved roadway base, subbase and subgrade fill d. Utility trench backfill e. Bridge abutment backfill f. Tank vault or tunnel abandonment g. Slabjacking material		x	x	x	x
(6) Encapsulated Transport Facility Embankment		x	x	x	x
(7) Capped Transport Facility Embankment			x	x	x
(8) Unconfined Geotechnical Fill			x	x	x
(9) Unbonded Surface Course				x	x
(10) Bonded Surface Course				x	x
(11) Decorative Stone				x	x
(12) Cold Weather Road Abrasive				x	x
Note: General beneficial use in accordance with s. NR 538.12 (3)					x

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NR 538 (Wisconsin Administrative Code)

Parameter	Standards (ppm)		
	Category-1	Category-2 & 3	Category-4
Aluminum	1.5	15	
Antimony	0.0012	0.012	
Arsenic	0.005	0.05	
Barium	0.4	4	
Beryllium	0.0004	0.004	
Cadmium	0.0005	0.005	0.025
Chloride	125		
Chromium(T)	0.01	0.1	0.5
Copper	0.13		
Iron	0.15		
Lead	0.0015	0.015	
Manganese	0.025	0.25	
Mercury	0.0002	0.002	
Molybdenum	0.05		
Nickel	0.02		
Nitrite & Nitrate	2		
Selenium	0.01	0.1	0.25
Silver	0.01	0.1	0.25
Sulfate	125	1250	2500
Thallium	0.0004	0.004	
Zinc	2.5		

Recap Poll # 5 – True or False

- Federal regulations govern the use of CCPs in geotechnical construction: T/F
- States have regulations to follow regarding using CCPs in construction: T/F
- Batch tests are the most common tests to evaluate leaching from CCPs: T/F
- Control tests are un-necessary and provide extraneous data: T/F

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