Demonstration Project: Roller Compacted Concrete Pavement with High Volumes of Harvested Coal Ash

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KEYWORDS: roller-compacted concrete (RCC), harvested coal ash, coal combustion products, CCP, spray dryer absorber ash, SDAM, fly ash

INTRODUCTION

There are over 20 million metric tons of coal combustion fly ash produced annually¹ that do not meet ASTM C618 Standard Specifications for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. Generally these “off-spec fly ashes may not meet some of the ASTM C618 criteria for either the physical requirements (such as fineness and strength activity index) or chemical requirement limits (such as loss-on-ignition, sum of oxides and SO3). The fly ash that is not beneficially used is disposed at high costs. There is also an increasing need to find uses for recovered coal ash that is harvested from landfills and impoundments that are not likely to meet ASTM C618. It is estimated that over 1.5 billion metric tons of fly ash was deposited in landfills and impoundments since 1970². Construction project specifications may impose prescriptive limits on the chemistry of construction materials in order to assure certain performance criteria such as compressive strength development, set time, air entrainment and dimensional stability. Despite the institutional and commercial barriers that limit the use of off-spec fly ash, there are multiple means to overcome the compromised performance of a particular fly ash in concrete by blending with other cementitious materials and pozzolans; using of admixtures; allowing longer time periods for strength development; adjusting curing temperature; or alternative placement and finishing methods.

A demonstration project evaluated the performance of roller-compacted concrete (RCC) pavement that used various mix proportions of spray dryer absorber fly ash (SDAM) and harvested bituminous coal ash (HBCA) from a landfill that were combined to substitute 50% of the cementitious binder mass in the RCC. The concrete mixes and construction practices were modified to mitigate the compromising chemical and physical properties
that these two off-spec materials may otherwise have on the performance of concrete pavement. The demonstration pavement is located at an industrial facility that has high pressure point loading and heavy equipment traffic. The RCC mixes were developed in a laboratory and tested for compressive strength, flexural strength, modulus of elasticity, freeze-thaw durability and dimensional stability. The demonstration evaluated appropriate practices for material handling, batching, mixing, placement and compaction of an RCC using the alternative binder materials.

PROJECT OBJECTIVES

The objective of the demonstration project was to mix, deliver and place a pavement system that is less expensive than conventional asphalt or concrete pavement with the use of byproducts that would otherwise be disposed in a landfilled or used at a high subsidized cost.

The use of RCC was selected based on a literature review and prior experience with pavements made with in-situ mixing of RCC that had cementitious binder with 50% fly ash. Preliminary estimates indicated that pavement costs could be reduced by the use of RCC that had a cementitious binder that used locally available SDA ash and HBCA. Portland cement is not produced in Wisconsin and is shipped from other Midwestern states. The field test results of the demonstration will be used to refine the mix design and construction process, and then to incorporate the lessons learned into a road pavement. The test results will also provide data that can be used to design future pavement sections using RRC single layer systems and RCC/hot mix asphalt composite systems (see WOCA Paper #159 Multi-Layer Pavement Design Approach for Effective Utilization of Off-Spec Coal Combustion Products).

The benefits of using RCC compared to conventional reinforced/screed finished concrete include:

- Reduce costs
- Quick placement of high volumes of concrete
- Low slump concrete that facilitates low water to cementitious ratios
- Attain higher strengths with lower amount of cementitious binder
- Reduce labor costs of concrete placement via the use of conventional construction grading equipment (dozers, graders and drum roller compactors)
- The placement could be performed by either a concrete paving contractor, an earth mover/grading contractor, or an asphalt pavement contractor thus creating a more competitive bidding of pavement projects
- Steel reinforcement is not necessary
- Less shrinkage
- Fewer control joints
- Allows delayed set times of the concrete due to structural stability of the fresh low slump concrete
- Compactible and potentially synergistic for use in a composite system with asphaltic concrete wearing surfaces

**MATERIALS**

**SDA ASH CHEMICAL AND PHYSICAL PROPERTIES**

SDA ash are byproducts of a specific flue gas desulfurization (FGD) air quality control system, often referred to as SDA scrubbers, that typically use aqueous solutions of calcium or sodium-based reagents as sorbents to reduce the sulfur dioxide (SO$_2$) emissions from the flue gasses at coal-fired power plants. Depending on where the sorbents are injected in the process, the SDA system byproducts may be removed from the flue gas and captured with the coal fly ash (the combined material is called SDA ash) or downstream after the main fly ash removal device.$^3$

The SDA ash for this demonstration project was produced at Wisconsin Public Service Weston Power Plant Unit 4 (W4) near Wausau, WI. W4 feeds limestone slurry after the combustion of a 8800 BTU Powder River Basin Coal. The SDA material is comingled with the fly ash and pneumatically conveyed and stored dry in a silo. W4 SDA ash generally does not meet the SO3 limits prescribed by ASTM C618. The W4 SDA ash is either used for sludge stabilization; used as an anti-aging agent in asphalt pavement, used in agriculture as a liming material for adjusting the soil pH; or the material is disposed in a landfill. Currently the ash is not used commercially in concrete.

The X-Ray Diffraction (XRD) was used to evaluate dry SDA ash from the Weston Power Plant Unit 4 (W4) scrubber that used a calcium based reagent. XRD analysis indicated that the samples had a high concentration of amorphous glass phases. Quartz is the dominant phase for the dry SDA ash.$^3$ The calcium compounds are generally in the form of calcium sulfite and as the material is exposed to air it will increasingly oxidize to calcium sulfate over an extended period of time.$^4$ The loss on ignition (LOI) test method (ASTM 311) was modified by ramping the temperature to adjust for the possible loss of mass from the release of hydrates and sulfate compounds at temperatures above 600 degrees C. ASTM C311 specifies a temperature of 750 degrees C to determine the LOI. For example using the modified method calculated the mass loss for the trial sample of W4 SDA fly ash was 2.8% below 550 degrees C and a total mass loss of 3.4% below 750 degrees C. If the objective of obtaining LOI test results is to estimate the amount of carbon in the ash then there should be consideration for the loss of sulfur and sulfites. In the case of the W4 SDA ash it would be more accurate to state that the carbon content is closer to 2.8%. In practice the foam index test would be a better indicator of the SDA fly ash performance in concrete and its compatibility with air entrainment admixtures.
The W4 SDA fly ash was evaluated to determine compliance with ASTM C618 criteria. See Table 1 for test results. As indicated by the test results, W4 SDA fly ash attains the specified strength activity (SAI) requirements and is similar to a Class C fly ash. The total available alkalis (Na2O% + .658 x K2O%) averaged 1.5% for 27 samples over a period of one year.

TABLE 1: W4 SDA Fly Ash ASTM C618 Test Results

<table>
<thead>
<tr>
<th>Data Set</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>Fe2O3</th>
<th>SUM</th>
<th>CaO</th>
<th>SO3</th>
<th>Moisture</th>
<th>LOI</th>
<th>Fineness</th>
<th>7 day SAI</th>
<th>28 day SAI</th>
<th>WaterReq</th>
<th>Autoclave</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>27.88</td>
<td>15.08</td>
<td>4.57</td>
<td>47.53</td>
<td>27.78</td>
<td>12.42</td>
<td>1.56</td>
<td>1.94</td>
<td>10.48</td>
<td>97.77</td>
<td>99.56</td>
<td>100.83</td>
<td>-0.01</td>
<td>2.68</td>
</tr>
<tr>
<td>Min.</td>
<td>24.48</td>
<td>14.46</td>
<td>4.25</td>
<td>43.53</td>
<td>26.85</td>
<td>10.68</td>
<td>0.18</td>
<td>0.22</td>
<td>7.40</td>
<td>83.98</td>
<td>92.00</td>
<td>99.17</td>
<td>-0.02</td>
<td>2.66</td>
</tr>
<tr>
<td>Max.</td>
<td>30.82</td>
<td>15.78</td>
<td>4.80</td>
<td>51.01</td>
<td>29.18</td>
<td>14.25</td>
<td>3.51</td>
<td>3.38</td>
<td>12.50</td>
<td>102.70</td>
<td>107.00</td>
<td>103.31</td>
<td>0.00</td>
<td>2.72</td>
</tr>
</tbody>
</table>

ASTM C618 Limits

<table>
<thead>
<tr>
<th>SAI</th>
<th>Water Req</th>
<th>Autoclave</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0 Min</td>
<td>75 Min</td>
<td>105 Max</td>
<td>0.8 Max</td>
</tr>
<tr>
<td>5.0 Max</td>
<td>34 Max</td>
<td>3.0 Max</td>
<td>6.0 Max</td>
</tr>
</tbody>
</table>

Notes:
1. Chemical properties calculated from 27 samples from the year 2018
2. Physical test results are from 5 samples from the year 2018
3. SAI refers to Strength Activity Index

Generally the fine fraction of fly ash is the most reactive due to the higher surface area for reactions to occur. A size distribution was determined using a MicroTrac S3500 laser analyzer set with a reflective index of 1.76 and isopropyl alcohol as the suspension fluid. The results determined that 80% of the volume of W4 SDA fly ash particles are less than 45 microns (see Figure 1).

Figure 1: W4 SDA Fly Ash Particle Size Distribution
HARVESTED ASH CHEMICAL AND PHYSICAL PROPERTIES

The HBCA was from the combustion of bituminous coal that was placed and stored in a coal ash monofill landfill and segregated to facilitate future use. Size distribution was determined using the MicroTrac laser analyzer set with a reflective index of 1.76 and isopropyl alcohol as the suspension fluid. The results from a sample used in the mortar cube mixes determined that 75% of the volume of HBCA particles is less than 45 microns (#325 sieve). See Figure 2 for the size distribution.

![Figure 2: HCBA Particle Size Distribution](image)

Additional particle size analysis of samples from the HCBA stockpile indicated that the HCBA may have significant variability in size distribution throughout the pile from 42% particle volume less than 42% of the volume in one sample to 75% of the volume less than 45 microns in a sample from another area of the stockpile. ASTM C618 has a fineness limit of 34% of the sample mass retained on 45 micron sieve (in other words, must have more than 66% passing the 45 microns sieve) therefore is not likely that each load of HCBA will meet the ASTM fineness requirement. The laser analyzer provides a quick test result (takes less than 15 minutes from preparation to test result) and does not require elaborate sample preparation using the wet sieve method specified in ASTM C311, though the laser analyzer provides a result in % volume rather the % mass. It would be advisable to use a similar test method to assess individual loads for future demonstrations commercial projects. For instance, the HCBA for the mortar cube testing had 75% less than 45 microns. A base line for the amount of HCBA used in a concrete mix can be established and then adjusted based on the increase or decrease in the amount of fly ash passing 45 microns, and then adjusted for the increase or decrease in the LOI.
The HBCA has a relatively high fraction of coarse particles due to the ash collection system of the former generating unit. For the trial concrete mixes the coarse fraction of the HBCA was considered to be sand fines and the sand proportion of the concrete was adjusted accordingly.

The HBCA ash for this demonstration project had a loss-on-ignition (LOI) of approximately 26% and did not meet the LOI limit imposed by ASTM C618. It should be noted that the HBCA for this project was normally used as fuel in an ash reburn system to recover its residual fuel value. The HCBA has unburned residual coal particles therefore there are varying amounts of sulfur and volatiles in the ash, and the LOI does not represent the amount of carbon within a sample.

The HBCA generally had moisture contents exceeding 20%. The use of HCBA in the trial mixes and demonstration project was in a moist as-is condition as it was introduced to the concrete mix. Mix proportions for the trial mixes and field concrete used the dry mass of the HCBA and then the water content of the mixes were adjusted to account for the moisture of the HBCA.

For the lab trial mixes and the filed concrete mix, the particle fraction less than 45 microns and decreased to adjust for the LOI was considered to part of the cementitious binder component of the concrete mix and to serve as a pozzolan to mitigate the sulfate reactions that may otherwise occur due to sulfate and sulfite compounds in the SDA ash. The demonstration RCC pavement will be evaluated to determine the extent of the pozzolanic fraction of HBCA and whether it sufficiently reacts with available unreacted calcium hydroxide within the RCC and reduces the inter-porewater pH to inhibit production of crystalline structures of ettringite and thaumasite at later stages of curing. Earlier lab testing of trial concrete mixes indicated that the sole use of SDA fly ash with SO3 content above 10% used as a cement replacement in concrete could lead to the continued formation of these two crystalline structures. There is the possibility that within certain environmental conditions of and eventually degrading the cement matrix causing loss of dimensional instability and loss of long-term durability. The addition of a HBCA pozzolan densifies the cement matrix and reduces the permeability. Other pozzolans such as silica fume or commercially available Class F fly ash could mitigate the sulfate compound reactions more effectively but it would be contrary to the objectives of this research to determine the effectiveness of using a harvested off-spec fly ash.

A sample of the HBCA used in the trial concrete mix was analyzed in accordance with the Ultimate Analysis ASTM D6721 for coal due to the high residual coal content in the ash, therefore the mineral analysis in Table 2 is on an ignited basis that excludes the mass of volatiles, sulfur and carbon.
TABLE 2: Chemical Properties of Harvested Bituminous Coal Ash Material

<table>
<thead>
<tr>
<th>MINERAL ANALYSIS D8349</th>
<th>% Ignited Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phos. Pentoxide, P2O5</td>
<td>0.54</td>
</tr>
<tr>
<td>Silica, SiO2</td>
<td>51.79</td>
</tr>
<tr>
<td>Ferric Oxide, Fe2O3</td>
<td>7.12</td>
</tr>
<tr>
<td>Alumina, Al2O3</td>
<td>23.96</td>
</tr>
<tr>
<td>Titania, TiO2</td>
<td>0.95</td>
</tr>
<tr>
<td>Lime, CaO</td>
<td>4.87</td>
</tr>
<tr>
<td>Magnesia, MgO</td>
<td>1.93</td>
</tr>
<tr>
<td>Sulfur Trioxide, SO3</td>
<td>2.68</td>
</tr>
<tr>
<td>Potassium Oxide, K2O</td>
<td>1.07</td>
</tr>
<tr>
<td>Sodium Oxide, Na2O</td>
<td>1.50</td>
</tr>
<tr>
<td>Barium Oxide, BaO</td>
<td>0.29</td>
</tr>
<tr>
<td>Strontium Oxide, SrO</td>
<td>0.23</td>
</tr>
<tr>
<td>Manganese Dioxide, MnO2</td>
<td>0.03</td>
</tr>
<tr>
<td>Undetermined</td>
<td>3.04</td>
</tr>
</tbody>
</table>

PORTLAND CEMENT

A Type I/II cement was used in the concrete mix. The proportion of cement was targeted to be no more than 50% in order to reduce the cost of the trial RCC mix and optimize the use of SDA ash and HBCA.

AGGREGATES

The lab trial mixes used a ¾" coarse aggregate. The concrete mix for the field demonstration uses a 1 ½ inch coarse aggregate. The top size of the coarse aggregate should be no more the 1/3 the thickness of the concrete pavement to assure a uniform distribution of aggregate and cementitious paste throughout the depth of the concrete pavement. The larger aggregate reduces water demand and provides structural stability as the fresh concrete is placed and spread with conventional grading equipment and vibratory roller compactors. Typical concrete uses around 55% - 60% coarse aggregate and 40% to 45% sand. The coarse fraction of HBCA had a relatively high coarse particle fraction and some of its fine fraction is non-reactive, therefore the sand component of the trial mix was reduced to 38% to 40% and the stone coarse aggregate was targeted at 60%.

LAB TRIAL MIX TEST RESULTS

See WOCA Paper #157 *Innovative Green Cementitious Systems Using Off-Spec Fly Ash* for the details of the lab trial mixes. The results of the research in Paper #157 were used to establish the concrete mix design for the field demonstration project. The following is a summary of the trial mixes from that research.
The proportions of the cementitious materials were determined by varying the amount of portland cement, W4 SDA fly ash, and HBCA in mortar cubes cast and cured in accordance with ASTM C109 and C305. Comprehensive strength and set times were evaluated for each mix to determine optimum proportions based on performance and economics. The 50/30/20 and the 50/40/10 mixes were selected to use in the lab trial concrete mixes.

**Figure 3: Compressive Strength of Mortar Cubes**

![Figure 3: Compressive Strength of Mortar Cubes](image)

It was assumed that the calcium sulfate/sulfite fraction of the SDA fly ash would not act as a pozzolan or cementitious material. Likewise the coarse fraction of the HBCA and the carbon component (estimated to be the LOI) would not be pozzolanic. The lab trial mixes had a total cementitious binder content of 280 kg/m$^3$ (470 lb/yd$^3$) and water-to-cementitious ratios equal to .46 were targeted.

**Table 3: RCC Lab Trial Mix Designs**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Mix 1</th>
<th>Mix 2</th>
<th>Mix 3</th>
<th>Mix 4</th>
<th>Mix 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Cement (%)</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>SDA Fly Ash (%)</td>
<td>30</td>
<td>30</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>HBCA (%)</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Water/Cementitious Ratio</td>
<td>0.50</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
</tr>
</tbody>
</table>
RCC MIXING

The sequence of adding and mixing the materials was determined in the lab through trial and error in order to evaluate the best process to introduce the moist condition of HBCA into the field mix. The following is the step-by-step procedure used for concrete mixing in the lab and will be used for the large scale batching for the demonstration project to verify or refine the process.

1. Add ½ portion of coarse aggregate plus 2/3 portion of water and mix
2. Pre-mix the rest of water with chemical admixtures until completely dissolved. Add the pre-mixed solution to the mixer and continue mixing
3. Add all Portland cement
4. Add all harvested ash and continue mixing
5. Add all SDA ash and continue mixing
6. Add the rest ½ portion of coarse aggregates and mix
7. Add all sand and mix
8. The total duration of mixing should be about 6 minutes.

Compressive strengths were determined by averaging the average test results of two samples at 1 day, 3 days, 7 days, 28 days and 90 days.

Figure 4: RCC Lab Mix Test Results
CONSTRUCTION

SITE CONDITIONS AND PAVEMENT DESIGN

The location for the first demonstration was within an unheated sprung enclosure. The concrete pavement will be used for the storage and maintenance of heavy construction equipment weighing up to 55,000 kg (120,000 pounds). The pavement will be 25 cm (10 inches) thick and unreinforced. Pavement will placed in three 20 foot wide strips. The total pavement area will be 49 meters long by 18 meters wide (130 feet x 60 feet).

Figure 5: Demonstration Site Prior to Construction

The RCC will be tested for compressive strength, flexural strength, modulus of elasticity, freeze thaw durability and dimensional stability. The demonstration will evaluate appropriate practices for material handling, batching, mixing, placement and compaction of the RCC.

The field demonstration will commence in April 2019. The field results will be presented at the WOCA 2019 Conference. This paper will be amended to include the additional information.

REFERENCES

and cement categories did not meet ASTM C618 and disposed ash did not meet the specification.  https://www.acaa-usa.org/Portals/9/Files/PDFs/2017-Survey-Results.pdf

