Multi-Layer Pavement Design Approach for Effective Utilization of Off-Spec Coal Combustion Products

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ABSTRACT

This research introduces an approach for a multi-layer pavement system based on the use of roller-compacted concrete (RCC) and asphalt with high-volume off-spec fly ash including harvested bituminous coal ash. Typically, coal combustion products (CCP) are evaluated as a portland cement or bitumen replacement components and are often disqualified for use in projects due to not meeting corresponding ASTM and AASHTO specifications. Inconsistencies leading to disqualification include high concentrations of calcium sulfates and elevated LOI. A proposed system that can address effective use of off-spec CCP and performance concerns consists of the replacement of a hot mix asphalt (HMA) surface layer in a composite with an alternative RCC (ARCC). The ARCC binder system utilizes 50 percent replacement of portland cement with off-spec CCP.

Multi-layer design requires an integrated assessment of each layer’s elastic properties. The empirical design methods such as the California Bearing Ratio (CBR) and AASHTO Mechanistic-Empirical Design Guidelines (MEPDG) lack the data and inputs for components that use off-spec CCP and do not specifically address the use of ARCC in layered systems. Based on the laboratory measured elastic properties for ARCC mixes, a finite element model was developed to evaluate the alternatives compared to conventional designs. This evaluation of a composite system demonstrates compliance with EPA CCP Rule conditions for the Beneficial Use of CCP. Proposed equivalent pavement systems performance is shown using thickness–modulus ratios for various alternative cross sections and estimation of the equivalent single axles loads (ESAL) for the service life and economics.
INTRODUCTION

Currently, there is limited use of “off-spec” coal combustion products (CCP) in concrete applications that do not meet ASTM standards and include millions of tons of potentially beneficially usable landfilled or impounded CCP materials. An ideation for broader utilization consists of combining two major off-spec materials consisting of harvested fly ash (e.g., landfilled or impoundment ash) and spray dryer absorber ash (SDA) in flexible proportions and volumes of greater than 50 percent with portland cement and supplementary admixtures to create highly durable, sulfate resistant and dimensionally stable binder systems for a variety of large-volume applications.

Addition of a pozzolanic additive (harvested fly ash) increases reactions with calcium hydroxide (reaction by-product of the cement hydration process) that reduces inter-porewater pH and inhibits production of crystalline structures consisting of ettringite and thaumasite at later stages. The use of SDA alone as a binder with portland cement concrete, which contains higher amounts of sulfate than other types of fly ash, leads to the continued formation of these two crystalline structures that eventually degrades the cement matrix causing loss of structural stability and long-term durability. The addition of a pozzolan densifies the cement matrix, reduces porewater pH and reduces the permeability that exhibits comparable performance characteristics to conventional portland cement binders or portland cement binders combined with other pozzolans (i.e., blended cements) meeting current ASTM standards. See WOCA paper titled Innovative Green Cementitious Systems Using Fly Ash by Marina Kozhukhova for further details [1].

Bench and pilot scale studies are underway to demonstrate the performance of a SDA/fly ash/portland cement binder in an alternative roller compacted concrete (ARCC) multi-layer pavement system with a flexible hot mixed asphalt (HMA). See paper titled Demonstration Project: Roller Compacted Concrete Pavement with High Volumes of Harvested Coal Ash by Tomas Jansen for further details [2]. A comparative assessment of the design and performance parameters for the alternative multi-layer pavement system with respect to both conventional single layer systems are presented to highlight the potential benefits for expanded use of off-spec materials in low volume road (LVR) applications. The proposed alternative pavement system could also address a major hurdle with higher than acceptable levels of unburned carbon typically found in older CCP materials due to incomplete combustion of coal for power generation. The presence of unburned carbon in percentages greater than 3 to 4 percent mitigate the effectiveness of air entrainment additives to prevent freeze/thaw degradation.

MULTI-LAYER PAVEMENT APPROACH

A multi-layer pavement system typically consists of a structure that incorporates two or more layers of materials with different strength characteristics that can provide superior performance as compared to each of the materials individually. A typical section for a multi-layer system is illustrated in Figure 1:
As illustrated, the multi-layer pavement system consists of four primary components: i) a subbase consisting of compacted natural existing soils or a treated subbase such as a lime, fly ash or cement stabilized material (not always required), ii) a base consisting of a layer of compacted material such as recycled concrete, crushed stone or sand and gravel, iii) an intermediate or binder layer of RCC, and iii) a top layer of hot mixed HMA that serves as a wearing course to provide a smooth durable surface for traffic. This definition is not all inclusive as there are a variety of composite systems that include different layering of materials such as jointed plain concrete pavement (JPCP) over HMA or HMA directly over a cement treated base. The focus of this paper will be on a three-layer system consisting from top to bottom of HMA, RCC and a base.

The use of multi-layer systems dates to the 1950’s by various states, countries and transportation agencies. These systems have been popular in urban areas such as the City of New York that has been using multi-layer systems since the 1990s due to anticipated benefits associated with greater ease of maintenance for the HMA wearing surface and higher durability of the portland cement concrete (PCC) base. Extensive studies have been performed in the City of New York to better address the potential for reflective cracking which is one the of the primary failure mechanisms for HMA/PCC composites due to underlying fatigue cracking of the PCC layer. The results of these studies indicated that saw cutting and sealing of control joints for fresh PCC was most effective in limiting reflective cracking [3].

In general, the use of multi-layer systems is gaining greater acceptance as a potentially more durable and cost-effective approach in comparison with flexible HMA systems. General benefits include the following [4]:

- Greater strength characteristics for long term durability and support of the flexible HMA layer
- Enhanced levels for driver comfort due to a smooth and quite driving surface in comparison with a single layer rigid PCC pavement
- Extended design life of the rigid layer due to the protection provided by the flexible layer from infiltration of moisture and deicing salts and other deleterious materials
• Reduced maintenance for the rigid layer because the flexible layer can be periodically replaced to maintain an adequate protective cover
• Reduced potential for thermal damage and scaling to the rigid layer due the insulating effect of the flexible layer

The use of a RCC rigid layer provides an excellent opportunity for massive use of off-spec fly ash in a composite system because of its inherent performance characteristics. For example, RCC does not require reinforcement that reduces the need for the addition of air entrainment that would be adversely affected by fly ash with high LOI levels. RCC is also known as a dry lean concrete that is prepared with a low water to cement ratio (low to zero slump) and compacted using the same type of equipment used for high density HMA. The compaction can provide a durable surface within a short timeframe with compressive strengths exceeding HMA or JCPC using conventional binders.

A significant difference between the performance of a rigid versus a flexible system is the load distribution and locations for the development of tensile strains in the pavement system that must be considered in the design. Differences in the load distributions between the two types are illustrated in the following figures:

![Figure 2: Multi-Layer HMA and Rigid PCC Base](Internet Source: Steve Muench, 2003)

![Figure 3: Flexible HMA Only with Base and Subbase](Internet Source: Steve Muench, 2003)

Considering the base as a rigid PCC layer, the load distribution is more elongated and evenly distributed than the load distribution for a flexible HMA layer shown in Figure 3 that indicates a more localized, deeper distribution through the base and subbase materials. The difference in these load distributions, reflect the tendency of the rigid layer to act as a bridge over the subbase materials that prevents translation of the load to deeper materials. In a flexible system the stiffness of the pavement structure relies primarily on the HMA which would need to be thicker than the rigid system due to its lower strength characteristics in comparison with PCC. The localized and deeper stresses from a flexible pavement into the subgrade can lead to pumping of softer soils especially during seasons with high precipitation and thawing of frozen soils.
For a flexible HMA layer, tensile strains develop at the bottom of the HMA layer, which is a primary design factor for mitigating the risk of fatigue cracking (i.e. flexural fatigue due to repeated loading). The key design parameter in this case is the Resilient Modulus ($M_r$) that reflects the strength of an HMA layer subjected to repeated loadings that do not exceed the elastic limit of the material. For a multi-layer system with a rigid base, tensile strains are translated to the bottom of the rigid layer and strains in the HMA layer remain primarily compressive. The key design parameter in this case is the Modulus of Rupture (MR) that reflects the tensile strength of the rigid layer.

**TESTING PROGRAM FOR ALTERNATIVE RCC MIX DESIGNS USING OFF-SPEC CCP MATERIALS**

Bench scale testing was performed on several ARCC mix designs. Selected mix designs are summarized in the following table:

**Table 1: ARCC 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>Spray Dryer Absorber Ash (%)</td>
<td>30</td>
<td>30</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Fly Ash (%)</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Fresh compacted density, (kg/m²)</td>
<td>2668</td>
<td>2603</td>
<td>2623</td>
<td>2632</td>
<td>2701</td>
</tr>
</tbody>
</table>

Aggregate blends were established based on mix designs developed for the Wisconsin Department of Transportation (WisDOT) by the University of Wisconsin Milwaukee (UWM) that were optimized to meet WisDOT requirements for use in rigid pavement systems [5]. As indicated in Table 1, each of the mixes reflect replacement of portland cement with 50 percent off-spec CCP materials consisting of harvested fly ash (with Class F characteristics) and spray dryer absorber ash (SDA) with Class C characteristics and high sulfate levels provided by We Energies, Milwaukee, Wisconsin. Mix design CCP proportions were varied between mix designs to evaluate differences in performance. Trial Mixes 1 and 2 are the same with the exception that a higher water to cement ratio was used for mix design 1. All other mixes used a water to cement ratio of 0.46. Trial Mix 3 reverses the percentages of SDA and Fly ash from Trial Mix 2 for comparison of performance characteristics. Mix design 4 was prepared using lower amounts of admixtures for comparative assessment of workability and slump. Trial Mix 5 contains 40 percent SDA with only 10 percent fly ash to further assess the limits for replacement of PC using SDA.

Admixtures were added to the mixes in optimized proportions to maximize workability and setting times that would most closely align with conventional RCC. Early optimization testing indicated that some mix proportions would require unacceptably long hydration periods for full scale construction using existing field construction methods.
techniques and equipment. A key objective was to develop mixes that could be seamlessly introduced using established construction practices.

Vibratory equipment (i.e., VEE BEE Consistometer™) was used to prepare the bench scale trial mixes that would model the use of vibratory roller compaction equipment in the field. Both cylinders and cubes were prepared for testing at various time intervals. The testing program included compressive strength (1, 3, 7, 28 and 90 days) flexural strength and stress/strain testing for Modulus of Elasticity and Poisson’s Ratio. Only Trial Mixes 2 and 4 were tested for strength at 90 days.

Key questions for the bench scale testing included the following:

- How do the strength results compare with conventional portland cement mixes?
- Will the mixes meet minimum performance requirements for RCC pavement applications?
- How much portland cement can be replaced without compromising performance characteristics?

Compressive strength testing results are provided in the following figure:

**Figure 4: Compressive Strength for Various Mix Designs**

The results of the testing program indicate the following:

- Except for Trial Mix 1 (50PC:30SDA:20FA) all the mixes indicate continued strength development. Trial mix 1 with a 0.50 water to cementitious ratio testing was discontinued after 7 days.
- At 90 days, Trial Mix 2 (50PC:30SDA:20FA) exhibits the highest strength.
• Reducing the amount of SDA and increasing the amount of fly ash generally reduced strengths in comparison with the other mixes as indicated in Trial Mix 3 (50PC:20SDA:30FA).

For comparison, the strength data for each of the trial mixes through 28 days are plotted in Figure 5 with high-performance concrete (HPC) using 100 percent PC, HPC using 70 percent PC/30 percent fly ash, concrete using 70 percent PC/30 percent fly ash and concrete using 100 percent PC (WisDOT specification [5]).

![Figure 5: Comparison of Strength Versus Time for each of the Trial Mixes and Reference Mixes](image)

The results provided in Figure 5 indicate that all the ARCC trial mixes would meet or exceed minimum WisDOT specifications at 28 days. In addition, the RCC mixes perform well in comparison to mixes using PC and fly ash only. It is also interesting to note the strength for Trial Mix 5 (50PC:40SDA:10FA) converges with the HPC strength using 100 percent PC at 28 days.

Provided in Figure 6 are the results of several stress-strength testing performed on Trial Mix 2 and Trial Mix 5. A minimum of two stress-strain tests were performed for each mix for comparison. Testing frequencies consisted of the following:

- Trial Mix 2 (50PC: 30SDA:20FA) tested at 7 and 35 days
- Trial Mix 5 (50PC:40SDA:10FA) tested at 7 and 28 days
The results of the testing were plotted against the American Concrete Institute (ACI) correlation for the modulus of elasticity ($E$ vs $f'$c curve) that is expressed as:

- $E = 57000 \times \sqrt{f'}c$ (ACI 8.5.1 formula) (multiply by 0.00689476 to convert to mPa)

As indicated, measured moduli of elasticity for the trial mixes exceed the ACI criteria at 35 days for Trial Mix 2 and 7, and 28 days for Trial Mix 5. Poisson’s ratio was also measured during stress strain testing for Trial Mix 2 that yielded a value of 0.15

DESIGN APPROACH FOR ASSESSING SINGLE AND MULTILAYER PAVEMENT SYSTEMS

Design data obtained during the bench scale testing were used to develop comparative design scenarios that included the following pavement systems:

- Flexible HMA
- Single layer RCC and ARCC
- Multi-Layer HMA with conventional RCC
- Multi-Layer HMA with ARCC using off-spec CCP materials

The design approach for this paper used to develop each of the design scenarios consisted of the following:

**Single Layer Systems:**

- Used the mechanistic-empirical approaches based on equivalent single axle loadings (ESALs)
• Key design parameters included the Modulus of Rupture (MR) for rigid pavements and the Resilient Modulus (M_r) for flexible pavements

**Composite Systems:**

• Used a mechanistic-empirical approach to provide a base line for finite element modeling
• Modeled an elastic multilayer system under a circularly loaded area.
• Addressed different material properties through finite element modeling of each layer based on their respective moduli of elasticity and Poisson ratio
• Evaluated critical strain in each pavement layer

For the single layer rigid pavement, a software platform (StreetPave 12™) developed by the American Concrete Pavement Association (ACPA) was used for estimating rigid pavement sections [6]. It allows for the design of JPCP, with or without doweling, and RCC. The design methodology is based on an approach modeled by the Portland Cement Association (PCA). It is tailored for streets and roads and is focused on failure modes for cracking or faulting of concrete pavement. Design thicknesses are based on stress ratios (i.e., stress divided by the concrete strength) that are low enough to achieve target design traffic load repetitions. Accordingly, pavement is made thicker until the model predicts that the pavement will not fail through the designated design life. This design approach is considered more conservative than the American Association of State Highway and Transportation Officials (AASHTO) 1993 Mechanistic – Empirical (ME) design guidance [7]. The latest version of the ME design guidance is offered as DARWin-ME Pavement Design Software [8] that supports AASHTO's 2008 Mechanistic Empirical Pavement Design Guidance (MEPDG) [9].

For the single layer flexible pavement, AASHTO's MEPDG was used to develop an equivalent section for comparison with the rigid sections based on the estimated equivalent single axle loadings (ESALs) obtained from the StreetPave12™ calculations. Development of the AASHTO methodology was originally based on extensive testing conducted by the American Association of State Highway Officials (AASHO) during the 1950s and 1960s in Ottawa, Illinois, known as the AASHO Road Test. Empirical performance equations developed for flexible pavement design continue to serve as the basic model but have been significantly modified to address other regions of the country. For the purposes of this design exercise, a software platform (Pavexpress™), was accessed through the Transportation Research Integrated Database (TRID) [10]. The software, which was issued in 2017, follows 1993 AASHTO design guidance for flexible pavement and a 1998 AASHTO supplement for rigid pavements [11]. Future development of this software will include composite design features.

Multi-layer sections were developed using the AASHTO 1993 design guidance for estimating HMA overlays over existing PCC pavement. The estimation requires the following equation:

\[ D_{OL} = A (D_t - D_{eff}) \]
Where,

- $D_{OL}$ represents the required thickness of the HMA overlay
- $D_f$ represents the required pavement thickness to carry future traffic
- $D_{eff}$ represents the effective thickness of the existing slab based on the degree of distress ($D_{eff} = F_{jc} \times F_{dur} \times F_{fat} \times D$, where $D$ is the existing slab thickness and empirical distress coefficients are represented by various $F$ factors)

Estimation of the factor $A$, which is considered a factor for the deficiency of the existing pavement, is based on the following equation:

$$A = 2.2233 + 0.0099(D_f - D_{eff})^2 - 0.1534(D_f - D_{eff})$$

To estimate the amount of HMA overlay for a new rigid pavement, $D_f$ would be set to the new rigid single layer design thickness and $D_{eff}$ would be set to given reduction in the design rigid pavement thickness. For example, using this procedure, reduction in one inch of rigid pavement would require a corresponding HMA overlay of 2 inches, which is consistent with AASHTO guidance.

For the finite element analysis of composite pavement sections, a 3-dimensional model was developed that is illustrated in the following figure:

**Figure 7: Multi-Layer Finite Element Model**

Key design aspects and assumptions for the multi-layer model consist of the following:

- The overall dimensions are 40 feet (12.19 m) by 24 feet (7.32 m) that reflect two 12-foot-wide lanes.
- Three layers are included to reflect from top to bottom an HMA overlay, binder layer consisting of either HMA, RCC or ARCC and base consisting of a compacted sand and gravel.
- A linear elastic isotropic model is assumed for all layers that ignores some potential anisotropic and visco-elastic properties for the base material,
- Each of the layers is assumed to be bound to the other,

Loading conditions are based on a Federal Highway Administration (FHWA) Class 7 quad axle dump truck with the following loading characteristics:
The contact area represents the tire pavement pressure distribution of 100 psi (0.69 mPa) that translates to 4500 pounds (20 kN) per tire for the quad axles. Maximum ESALs for the quad axles are limited to 18,000 pounds (80 kN) per axle. Contact areas for each tire are indicated on Figure 7 that include two quad axles and the single front axle. The load per tire on the single axle is 6000 pounds (27 kN) for a total of 12,000 pounds (53.4 kN). The location for the tires was set close to the edge of the composite pavement structure to evaluate stress and strain edge affects where fatigue cracking and distress often occurs.

Finite element analysis was performed using a software platform called ANSYS™ [12]. This software provides 3-dimensional modeling capabilities for a variety engineering design and modeling applications. It is particularly applicable for evaluating performance characteristics for multi-layer pavement systems because it can easily integrate materials with different performance properties.

**DESIGN PARAMETERS AND ASSUMPTIONS**

Provided in Tables 2 and 3 are the design parameters that were used to develop the single and multi-layer pavement sections for analysis. Table 2 summarizes strength and baseline subbase design parameters for the HMA, conventional RCC using 100 percent PC, and ARCC that replaces 50 percent of the PC with CCPs. Published values were used for the HMA and RCC whereas the values for the ARCC are based on average test results obtained during bench scale testing of the various mix designs previously discussed. Table 3 summarizes the baseline data for the design of a rural arterial road traffic for a 4-lane road with 12-foot (3.65 m) wide lanes. Data were obtained using published ranges provided by ACPA and AASHTO for arterial roads. A rural arterial roadway scenario was select to model as what might be expected for a low-volume road (LVR) where high PC replacement using off-spec CCPs could be most applicable. Each of the pavement sections was designed for approximately 13,000,000 ESALs over a period of 30 years (the generally accepted life cycle for concrete pavement).
Table 2: Pavement Design Strength and Performance Parameters for HMA, RCC and ARCC

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Units</th>
<th>HMAC</th>
<th>Conventional RCC (100% portland cement)</th>
<th>ARCC (50% portland cement/50% CCP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subbase Modulus of Elasticity (unstabilized)</td>
<td>mPa/psi</td>
<td>207.85/30,000</td>
<td>207.85/30,000</td>
<td>207.85/30,000</td>
</tr>
<tr>
<td>Subgrade Thickness</td>
<td>cm/in</td>
<td>30.48/12</td>
<td>15.24/6</td>
<td>15.24/6</td>
</tr>
<tr>
<td>Modulus of Subgrade Reaction (k-value)</td>
<td>mPa/psi</td>
<td>33.11/451</td>
<td>33.11/451</td>
<td>33.11/451</td>
</tr>
<tr>
<td>28-Day Compressive Strength</td>
<td>mPa/psi</td>
<td>Not Applicable</td>
<td>27.58/4,000</td>
<td>41.37/6,000</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>mPa/psi</td>
<td>Not Applicable</td>
<td>27,924/4,050,000</td>
<td>41,368/6,000,000</td>
</tr>
<tr>
<td>Modulus of Rupture (MR)</td>
<td>mPa/psi</td>
<td>Not Applicable</td>
<td>4.58/665</td>
<td>5.16/749</td>
</tr>
<tr>
<td>Mean Annual Air Temperature</td>
<td>deg C/deg F</td>
<td>7.22/45</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>Subgrade Modulus Coefficient of Variation</td>
<td>%</td>
<td>38</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>Resilient Modulus (M_r)</td>
<td>mPa/psi</td>
<td>33.68/4,885</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>

Table 3: Traffic Design Parameters for an Arterial Road Scenario

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Units</th>
<th>HMAC</th>
<th>Single Layer Conventional RCC (100% portland cement)</th>
<th>Single Layer Alternate RCC (50% portland cement/50% CCP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Growth Rate</td>
<td>%</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Design Life</td>
<td>years</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Number of lanes</td>
<td># lanes</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Directional Distribution</td>
<td>%</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Design Lane Distribution</td>
<td>%</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

SINGLE LAYER AND MULTILAYER PAVEMENT SECTIONS

Single Layer Pavement Sections

Design single layer pavement sections for HMA, RCC and ARCC are provided in Figures 9 and 10. The HMA section provided in Figure 9 indicates a wearing course followed by a binder layer of HMA although this could be constructed as a single full depth layer. Based on the performance data in Table 2, the results for the design calculations, yielded equivalent thicknesses for the RCC and ARCC although the ARCC bench test data indicate higher strengths and moduli of elasticity then what would be expected for 100 percent PC. The design sections presented below represent one set of outcomes. Other design configurations with different thicknesses are possible and selected designs for construction would require factoring local availability of materials.
In addition, AASHTO guidance recommends a minimum of six inches of base material for designs ESALs exceeding 500,000. For rigid pavement sections, ACPA does not recommend increasing the base thickness with the intent of reducing the rigid layer thickness as it has little design effect in changing rigid layer thickness due to the differences in moduli of elasticity and is considered uneconomical.

**Figure 9:** Flexible HMA (7.62 cm HMA wearing: 15.64 cm binder: 30.48 cm base)

**Figure 10:** Rigid RCC or ARCC (17.78 cm RCC/ARCC: 15.24 cm base)

**Multi-Layer Pavement Section**

Using the single layer rigid pavement section as a starting point and AASHTO overlay design guidance, one possible multi-layer section configuration is provided in Figure 11. (alternatively, another equally possible section could consist of 5.08 cm (2-in.) HMA overlay with a 15.24 cm (6-in.) RCC or ARCC layer).

**Figure 11:** Multi-Layer HMA with either RCC or ARCC using 50% CCP (10.16 cm HMA: 12.7 cm RCC/ARCC: 15.64 cm base)
Finite Element Analysis of Flexible HMA and ARCC Composite Sections

Finite element analysis was performed on the single layer HMA and multi-layer HMA and ARCC sections. Provided in Figure 12 is the initial model setup highlighting the pavement section, meshing for the modeling, constraints and loading. Constraints were initially set to prevent movement in the z direction (i.e., vertically) assuming it has a rigid subgrade beneath the base but was also modeled to compare relative deformation between the flexible and rigid pavement sections for further analysis of potential pavement performance. As indicated by the red arrows, vehicle loading was situated at the edge of the pavement where high stress conditions often lead to initial failure due to fatigue cracking.

**FIGURE 12: Model Framework Indicating Meshing, Constraints and Loading Distribution**

Provided in figure 13 are comparisons for lateral strain for the HMA single layer ARCC and multi-layer HMA and ARCC pavement sections. Viewpoints are shown from the edge of the pavement to highlight strain through the layers. Lateral strain conditions are considered important design considerations for fatigue cracking. As previously discussed, the tensile strain (positive) leads to fatigue cracking from the bottom of the HMA layer for a flexible system and from the bottom of the concrete layer for a rigid system. For the purposes of this analysis, static loading conditions were used for comparison of strain conditions.
Figure 13: Single Layer HMA, Single Layer ARCC and Multi-Layer HMA and ARCC Lateral Strains

The results for the single layer pavement section indicate development of positive lateral strains (tensile) directly beneath the loading area for the quad axles. Red indicates higher lateral strains. For the multi-layer pavement section, the rigidity of the ARCC layer is preventing development of tensile strains in the upper HMA layer and tensile strains beneath the ARCC are lower than the tensile strains in the single layer systems.

Given reduced lateral strain development in the multi-layer system, the AASHTO overlay design approach modified for HMA over new PCC pavement may be conservative and a reduced HMA overlay thickness could potentially be considered. In this regard, the HMA layer could be considered as a wearing course to improve driver comfort and reduce road noise. It would also serve as a protective layer to the ARCC layer for surface water infiltration or weathering due to salt scaling. Essentially, the HMA
could serve as a sacrificial layer that may be milled and refurbished on a regular maintenance schedule.

**COMPARATIVE CONSTRUCTION COSTS FOR SINGLE AND MULTI-LAYER PAVEMENT SECTIONS**

Estimated unit pricing and parameters for assessing total construction costs using ACPA published default values for each pavement scenario include the following:

- Project Length – 1.61 kilometers (1.0 mile)
- Lane Width – 3.65 meters (12.0 feet)
- RCC Pavement (material delivered) – $98.10/m³ ($75.00/yd³)
- ARCC Pavement (material delivered) – $91.23/m³ ($69.75/yd³)
- Concrete Placement (cure, saw, seal) - $6.00/m² ($5.00/yd²)
- Aggregate Subbase - $13.23/tonne ($12.00/ton)
- Asphalt Surface Course - $66.14/tonne ($60.00/ton)
- Asphalt Base – $63.93/tonne ($58.00/ton)

Total estimated construction costs for each pavement section are summarized in the following table:

<table>
<thead>
<tr>
<th>Material</th>
<th>HMA</th>
<th>RCC (100 % PC)</th>
<th>ARCC (50%PC:50%CCP)</th>
<th>Multi-Layer RCC w/ HMA surface</th>
<th>Multi-Layer ARCC w/ HMA surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(22.86 cm (9 in.) HMA over 30.48 cm (12 in.) base)</td>
<td>(17.78 cm (7 in.) RCC over 15.24 cm (6 in.) base)</td>
<td>(17.78 cm (7 in.) ARCC over 15.24 cm (6 in.) base)</td>
<td>(10.16 cm (4 in.) HMA over 12.7 cm (5 in.) ARCC over 15.24 cm (6 in.) base)</td>
<td>(10.16 cm (4 in.) HMA over 12.7 cm (5 in.) ARCC over 15.24 cm (6 in.) base)</td>
</tr>
<tr>
<td>Asphalt</td>
<td>$124,476</td>
<td>-----</td>
<td>-----</td>
<td>$55,217</td>
<td>$55,217</td>
</tr>
<tr>
<td>Concrete</td>
<td>$85,564</td>
<td>$81,105</td>
<td>$61,117</td>
<td>$57,932</td>
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<td>Aggregate Base</td>
<td>$28,293</td>
<td>$14,146</td>
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<tr>
<td>Total</td>
<td>$152,769</td>
<td>$99,710</td>
<td>$95,251</td>
<td>$130,480</td>
<td>$127,295</td>
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</table>

A comparison of these costs indicates the use of a single layer or multi-layer system using either RCC or ARCC has the potential for significant savings in comparison with a single layer HMA system. In addition, the costs for a single layer system using either RCC or ARCC are lower than the associated multi-layer costs. However, if the upper HMA layer were reduced to a 2-inch (5.08 cm) layer with a corresponding increase in the RCC or ARCC layer to 6 inches (15.24 cm) comparative cost differentials to the single layer RCC or ARCC pavement section would reduce. These costs do not consider life-cycle maintenance or repair cost over the design period of 30 years where a multi-layer system may be more cost effective because only the HMA surface would potentially require periodic maintenance or replacement and the RCC or ARCC layer would be significantly more protected than the single layer section.
The cost differential between a multi-layer RCC versus a multi-layer ARCC is $3,185 per lane kilometer. To put this into perspective, for a 10-kilometer section of 4-lane arterial the potential cost savings would be in the range of $127,400. This could represent a significant cost savings for county or municipal budgets to support other transportation roadway or infrastructure construction.

SUMMARY

The initial results presented herein for the replacement of portland cement with CCP materials show promise with respect to several important performance characteristics for use in low volume road (LVR) applications. However, on-going bench and pilot scale testing is being conducted to further evaluate several critical parameters for long term durability that include:

- Reduction in pH to confirm prevention of ettringite formation
- Effects of carbonation and formation of thaumasite
- Freeze/thaw resistance for single and multi-layer roller compacted concrete pavement systems
- Effects of elevated levels of unburned carbon in harvested fly ash

Efforts are also underway to develop a model for assessing different sources of SDA with varying sulfate and sulfite levels with harvested fly ash that can be used to develop optimized concrete mix designs. In addition, some sources of SDA may contain ash with either Class C or Class F characteristics. This model could then be used to assist stakeholders with expanding and enhancing beneficial use programs in other geographical locations using off-spec materials.

Transportation applications in LVRs are an opportunity for maximizing beneficial use of these materials in high volumes. High volume applications are essential to creating the economic incentives necessary for investing in these technologies and gaining industry and regulatory acceptance for effective use of off-spec CCPs. For example, replacement of PC with 50 percent CCPs would yield beneficial use of approximately 360 tonnes per kilometer (580 tons per mile) of 4-lane arterial roadway based on the single layer ARCC pavement section. Demonstration of long term durability for these innovative binder systems through pavement pilot testing could also expand opportunities for beneficial use of off-spec materials in other areas such as concrete building blocks, shoreline restoration/stabilization, levees and environmental applications for solidification/stabilization.

REFERENCES


