Modulus of Rubblized Concrete from Surface Wave Testing

Nenad Gucunski
Center for Advanced Infrastructure and Transportation (CAIT)
Infrastructure Condition Monitoring Program (ICMP)

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Rehabilitation of PCCP

- Prevailing strategy in NJ has been hot mix (HMA) overlays => Reflective cracking
- Alternatives to HMA overlays
  - Crack and seat and overlay
  - Break and seat and overlay
  - Rubblization with overlay
Outline

• Objectives and benefits of rubblization
• Typically used rubblization procedures
  – Multi-head breaker (MHB)
  – Resonant-frequency breaker (RFB)
• Previous information about RPCC modulus
• Seismic (surface wave) evaluation of RPPC modulus
• Moduli comparisons for RPCC and other base materials
• Conclusions
Objective of Rubblization

- Eliminate reflective cracking in the HMA overlay by the total destruction of the existing slab action
- Slab is reduced to small pieces and diminished to a high-strength granular base
- Restoration of structural capacity is accomplished with an HMA overlay
Why Rubblization?

- Rubblization is a viable, rapid, and cost-effective rehabilitation method for deteriorated PCC pavements.
- Rubblization is cost effective when the amount of patching exceeds approximately 10 percent of the project area (NJ).
- Lower Risk to Owner and Contractor:
  - Reduced subgrade exposure to moisture damage.
Why Rubblization?

• Rubblization Saves Time
  – Typical rubblization process recycles one lane mile per day, with no material hauling
  – 4X faster than breaking, excavating, hauling and placing DGA using traditional methods

• Rubblization Saves Money
  – Approximately 50% cost savings compared to reconstruction with PCCP
  – Approximately 33% cost saving compared to reconstruction with HMA
Why Rubblization?

• Environmental Benefits
  – Water Consumption: 41% Reduction
  – Energy Consumption: 44% Reduction
  – CO$_2$ Emissions: 43% Reduction
  – NO$_x$ Emissions: 26% Reduction
  – PM$_{10}$ Emissions: 48% Reduction
  – SO$_2$ Emissions: 40% Reduction
  – CO Emissions: 38% Reduction

source: RMRC case study of a NHDOT project
When Rubblization?

- Wisconsin DOT considers rubblization when one or more of the following conditions are met:
  - Greater than 20% of the concrete pavement joints are in need of repair;
  - Greater than 20% of the concrete surface has been patched;
  - Greater than 20% of the concrete slabs exhibit slab breakup distress; and
  - Greater than 20% of the project length exhibits longitudinal joint distress greater than 4-in. wide.
Rubbllization Procedures (Equipment)

Two types of equipment typically used:

1. Multi-head breaker (MHB)
   - Rubbllization through drops of multiple hammers on the slab

2. Resonant frequency breaker (RFB)
   - Rubbllization through application of high (resonant) frequency energy to the slab through a shoe
Multi-Head Breaker (MHB)

- MHB is a self-propelled unit with multiple drop-hammers mounted at the rear of the machine.
- Hammers are set in two rows, and strike the pavement approximately every 4.5 in.
- 1,200 lb - 1,500 lb hammers have variable drop heights and variable cycling speeds.
- Can break pavement up to 13 ft wide in a single pass.
Multi-Head Breaker (MHB)

- Production level is approximately 1.0 lane-mile per day.
- Z-pattern steel grid roller, a vibratory roller with a grid pattern, must be used in conjunction with the MHB to complete the breaking process.
Rubblized PCCP – I-78
Rubblized PCCP - Route I-78
Rubblized and Z-Roller Compacted PCCP – I-78
Rubblized and Compacted
PCCP – I-78
Cross Section of Rubblized PCCP I-78
Cross Section of Rubblized PCCP – I-78
Resonant Pavement Breaker (RPB)

• High frequency vibrations induce high tension in the top of the slab causing the slab to fracture along a number of shear planes.

• Breaking pattern is approximately 8 inches wide, and requires 18 to 20 passes to break a 12-foot lane width.

• Resonant breaker hinders traffic flow because the machine encroaches 3 to 5 feet on the adjacent lane when rubblizing the centerline.

• 20,000 lb wheel load and 60,000-70,000 lb weight can damage rubblized pavement.
Illustration of PCC Fracturing Resulting from Resonant Rubblization

- High Frequency (44Hz)
- Low Amplitude (3/4"")
- Interlocked rubble distributes loads
- Slab fractured
- Base integrity maintained
- Flat Bottom maintains load-bearing capacity of rubble
- No displacement into base
RPB Rubblized PCC Pavement
Some of the Questions

• What value of the RPCC modulus should be used in the (mechanistic-empirical) pavement design?

• How the modulus of RPCC compares to moduli of traditional base materials? (Especially dense graded aggregate base.)

• What are the means to measure it?
What Do We Know About RPCC Modulus?

- Rubblized modulus appears to be influenced by the slab thickness; thicker slabs tend to provide higher modulus.
- Rubblized modulus related to the pre-rubblized PCC modulus, retained modulus.
- No differences in RPCC moduli between the two types of rubblization equipment (MHB and RPB).
What Do We Know About RPCC Modulus?

- AASHTO M-E Design Guide for Highways: 150 ksi for PCCP 8 to 12 inches thick
- Asphalt Institute Airfield Project 2007
  - Slabs 6 to 8 in. thick: Moduli from 100 to 135 ksi
  - Slabs 8 to 14 in. thick: Moduli from 135 to 235 ksi
  - Slabs >14 in. thick: Moduli from 235 to 400 ksi
What Do We Know About RPCC Modulus?

- For thicker slabs, rubblized particles tend to be larger and interlocked stronger, leading to a higher modulus.
- For thinner slabs on subgrade, reduced support results in poor particle interlock leading to a lower modulus.
Why Seismic Testing?

WAVE VELOCITY  MODULUS

Shear Wave Velocity  Shear Modulus
Compression Wave Velocity  Young’s Modulus
Rayleigh Wave Velocity  Shear Modulus
Surface (Guided) Wave Velocity  Shear Modulus of Layered Systems
Why Seismic Testing?

- Rapid
- Repeatable
- Nondestructive
- Economical
- Can be applied directly on RPCC
- Field and lab tests the same
Waves in Elastic Half-Space

(from Richart et al., 1970)
Modulus of Rubblized Concrete

H-S WAVE PROPAGATION SIMULATION
(Ryden, 2004)
SASW Method

Coherence
Phase

Wavelength
Phase velocity

Depth
Shear modulus

Impact Source
Receiver Array

Displacement Distribution for a Single Frequency Component

S S 2S 4S
Body of R-wave as a Function of $\nu$
(from Richart et al., 1970)
Ultrasonic Surface Wave Method

- **Coherence**
- **Phase**
- **Wavelength**
- **Dispersion Curve**
- **Phase Velocity**
- **Depth**
- **Shear Modulus Profile**
- **Impact Source**
- **Receivers**

Wavelength considered less than layer thickness
Portable Seismic Property Analyzer (PSPA)

- Main pavement and bridge deck applications
  - Evaluation of layer elastic moduli and thickness
  - Detection of overlay delamination
  - Detection of concrete bridge deck delamination

- Seismic methods used
  - Ultrasonic surface waves (USW)
  - Ultrasonic body wave (UBW)
  - Impact echo (IE)
PSPA
PSPA Evaluation of RPCC on I-78
Surface Wave Arrivals

![Graph showing surface wave arrivals with two receivers labeled as Receiver 1 and Receiver 2. The graph plots amplitude against time. A time difference \( \Delta t \) is indicated between the arrivals.]
USW – Cross Power Spectrum Phase

![Graph showing phase vs. frequency with measured and fitted data]
Calculation of Phase Velocity from Phase

\[
\frac{X}{\lambda_{ph}} = \frac{\beta}{360^0}
\]

Phase velocity \( V_{ph} = f \lambda_{ph} \)

Wavelength \( \lambda_{ph} = \frac{360 X f}{V_{ph}} \)

\( X \) \hspace{1cm}  \( \lambda_{ph} \)
USW – Unwrapped Cross Power Spectrum Phase

\[ m = 360 \frac{D}{V} \]
USW – Average Surface Wave Velocity

![Dispersion Curve](image)

- **Wavelength, m**
- **Phase Velocity, m/s**
  - 2500
  - 2000
  - 1000
  - 1500
  - 500
  - 0

**Dispersion Curve**

**Average Surface Wave Velocity**
PSPA Waveforms
Dispersion Curve and Modulus
PSPA Reanalysis (RPCC)
PSPA Reanalysis (RPCC)
RPCC’s Modulus – I-78

The image shows a scatter plot with the x-axis labeled as "Station" ranging from 5442 to 5462, and the y-axis labeled as "Modulus (MPa)" ranging from 0 to 3000. The scatter plot includes data points represented by blue dots, with horizontal lines indicating modulus values of 1000, 1500, 2000, 2500, 2750, and 3000 MPa. There are also dotted lines at 780, 1300, and 1500 MPa, possibly indicating significant or reference values.
Cross Section of Rubblized PCCP
RPCC’s Modulus – I-295

- Lane 1
- Lane 3
## Modulus of Various Base Materials

<table>
<thead>
<tr>
<th>Type of Base</th>
<th>Modulus of Elasticity in MPa (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granular base</td>
<td>220-950 (32-138)</td>
</tr>
<tr>
<td>Sandy gravel base</td>
<td>170-230 (25-33)</td>
</tr>
<tr>
<td>Limestone base</td>
<td>210-3450 (30-500)</td>
</tr>
<tr>
<td>Lime stabilized limestone base</td>
<td>8250-9250 (1200-1340)</td>
</tr>
<tr>
<td>Cement stabilized limestone base</td>
<td>17200-23400 (2500-3400)</td>
</tr>
<tr>
<td>Rubblized PCC – surface waves (this study)</td>
<td>550-2800 (80-400)</td>
</tr>
<tr>
<td>Rubblized PCC – FWD (5)</td>
<td>390-1450 (57-209)</td>
</tr>
<tr>
<td>Rubblized PCC – FWD (6)</td>
<td>620-2400 (90-350)</td>
</tr>
<tr>
<td>Rubblized PCC – FWD (2)</td>
<td>480 (70)</td>
</tr>
<tr>
<td>Rubblized PCC – FWD (10)</td>
<td>830-11450 (120-1660)</td>
</tr>
<tr>
<td>Rubblized PCC – FWD (11)</td>
<td>1380 (200)</td>
</tr>
<tr>
<td>Rubblized PCC – FWD (12)</td>
<td>240-820 (35-120)</td>
</tr>
<tr>
<td>Sandy base</td>
<td>28-48 (4-7)</td>
</tr>
</tbody>
</table>
Conclusions

• Elastic modulus of rubblized PCCP can be efficiently evaluated using seismic testing.
• Modulus is evaluated from the average velocity of surface waves (USW method).
• Seismic modulus is a low strain modulus, reductions should be made to describe it as resilient modulus.
Conclusions

• Seismic modulus varied between 550 and 2800 MPa (80 and 400 ksi), with an average value between 1030 and 1500 MPa (150 and 217 ksi) for all sections tested.

• Other studies based on FWD evaluation of paved RPCC suggest a modulus between 240 and 11500 kPa (35-1660 ksi).

• Modulus of RPCC is higher than modulus of typical granular bases, but lower than modulus of lime or cement stabilized bases.
Thank You!!