STRUCTURAL DESIGN METHODOLOGY FOR SPRAY APPLIED PIPE LINERS IN GRAVITY STORM WATER CONVEYANCE CONDUITS TPF-5(356)

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PRESENTATION OUTLINE

- Main Research Objectives
- Introduction
- Research Approach
- Results
- Conclusions
- Recommendation
- Implementation
- Question/Answer
RESEARCH OBJECTIVES
To develop **Design Equations** for structural renewal of gravity storm water conveyance culverts using spray-applied pipe linings (SAPL) for both cementitious and resin-based materials and for circular and arch shapes.

To develop **Performance Specifications** allowing contractor innovation and utilization of the most current products and techniques.
INTRODUCTION

Trenchless Technology Methods Applicable to Culvert Renewal

Spray Applied Pipe Lining (SAPL)
INTRODUCTION (CONT’D)

Trenchless Renewal Solutions

Sliplining

Cured-in-Place-Pipe

Modified Sliplining

Spiral Wound Lining

Spray Applied Pipe Lining

Spiral Wound Lining

CIPP

Cementitious

Cement mortar
Geopolymers
Epoxies
Polyurethane
Polyurea

Polymeric

Polymeric

Epoxies

Polyurethane

Polyurea
**INTRODUCTION (CONT’D)**

**Scope**
- Large diameter CMP culverts between 36 - 120 in.
- Cementitious and Polymeric SAPLs
- Structural renewal

**What is SAPL?**
- A structurally spray applied pipe lining (SAPL) is a renewal methodology and an application that inhibits further deterioration and can structurally support severely damaged culverts and drainage structures.
- SAPL Installation:
  - Pumping and troweling (old fashion)
  - Hand Spray
  - Centrifugally casting through spin caster machine
## RESEARCH TASKS

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Survey of US DOT’s and Canadian Agencies</td>
</tr>
<tr>
<td>2</td>
<td>Literature Search/Participation Material Vendors</td>
</tr>
<tr>
<td>3</td>
<td>Additional Reinforcement</td>
</tr>
<tr>
<td>4</td>
<td>Evaluation if Corrugations Needed to be Completely Filled by the Spray Applied Liner as Part of the Structural Design</td>
</tr>
<tr>
<td>5</td>
<td>Comparison of Construction and Environmental costs for SAPL, Sliplining and CIPP</td>
</tr>
<tr>
<td>6</td>
<td>Review the Cured in Place (CIPP) Design Equations</td>
</tr>
<tr>
<td>7</td>
<td>Field Data Collection and Assistance from DOT Partners</td>
</tr>
<tr>
<td>8</td>
<td>Preparation of Structural Design Equations</td>
</tr>
<tr>
<td>9</td>
<td>Preparation of Performance Construction Specifications</td>
</tr>
<tr>
<td>10</td>
<td>Computational Modeling</td>
</tr>
<tr>
<td>11</td>
<td>Soil Box Testing</td>
</tr>
</tbody>
</table>
### Results

#### Task 1 - DOT Survey

<table>
<thead>
<tr>
<th>Issues Before SAPL installation:</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Decision Making Priorities</strong></td>
<td></td>
</tr>
<tr>
<td>Durability</td>
<td>1</td>
</tr>
<tr>
<td>Hydraulic Capacity Due to Liner</td>
<td>2</td>
</tr>
<tr>
<td>Impact to Travelling Public</td>
<td>3</td>
</tr>
<tr>
<td>Project Economics</td>
<td>4</td>
</tr>
<tr>
<td>Minimum Thickness</td>
<td>5</td>
</tr>
<tr>
<td>Contractor Experience</td>
<td>6</td>
</tr>
<tr>
<td>Project Schedule</td>
<td>7</td>
</tr>
<tr>
<td><strong>Others:</strong></td>
<td>8</td>
</tr>
<tr>
<td>Fish Passage, Host Pipe Condition, Feasibility, and Benefit/Cost Ratio</td>
<td></td>
</tr>
</tbody>
</table>

#### Issues During SAPL Installation:

<table>
<thead>
<tr>
<th>Protocol for QA/QC</th>
</tr>
</thead>
<tbody>
<tr>
<td>No official direction</td>
</tr>
<tr>
<td>Testing requirements are included in new contract</td>
</tr>
<tr>
<td>No QA/QC. Standards are under development</td>
</tr>
<tr>
<td>No additional safety protocols for SAPL projects</td>
</tr>
</tbody>
</table>

#### Issues After SAPL Installation:

<table>
<thead>
<tr>
<th>Problems faced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal and circumferential cracking</td>
</tr>
<tr>
<td>Hairline cracking with rust bleeding through cracks</td>
</tr>
<tr>
<td>Cracking at joints</td>
</tr>
<tr>
<td>Spalling</td>
</tr>
<tr>
<td>Delamination</td>
</tr>
<tr>
<td>Rust-through</td>
</tr>
<tr>
<td>Slumping from crown</td>
</tr>
</tbody>
</table>
Ward, D.C. (2018): Recommended additional research and synthesis of structural testing and analysis of SAPL

Moore and García (2013): Deteriorated CMPs with SAPLs survived H-20 and HL-93 loads.

Royer and Allouche (2016): Recommended a minimum thickness of 1-in. for pipes smaller than 54-in. and a minimum of 1.5-in. for larger pipes

Mai et al. (2013): Higher deflection occurred at lower cover with single axle loading configuration

Sargand et al. (2015): Under service load, there is no difference between paved and original CMP
The use of fiber reinforcements has many advantages, most importantly crack control and post-cracking behavior.

- Fiber reinforcements may substantially increase the cementitious SAPL matrix tensile strength.
- Fiber reinforcement can enhance the bond strength between the old substrate (host culvert) and SAPL.
It is difficult to get the required thickness of the liner.

Crests of the corrugations provide the reference points for thickness.

Production of a smooth interior surface profile liner, is the best long-term design solution for SAPLs.

When filling corrugations, the thrust (compression) in the SAPL becomes the dominant stress at the interior wall surface of the SAPLs.
Compared with CIPP and Sliplining, SAPL has least overall environmental costs.

After 60-in. diameter, the difference between CIPP environmental costs and SAPL will increase by more than 50%.

For 78 in. to 108 in. diameters, the environmental costs of CIPP and Sliplining are almost the same. For the same range, the environmental costs of both CIPP and Sliplining are twice than SAPL application.

SAPL, CIPP, and Sliplining have the highest to lowest construction costs in culvert with diameter range of 30 in. to 108 in., respectively.
RESULTS (CONT’D)

Task 5 - Environmental & Construction Costs

Sample Construction Costs:

Cementitious (Geopolymer)

<table>
<thead>
<tr>
<th>Bid Item</th>
<th>Item Description</th>
<th>Pay Unit</th>
<th>Unit Qty</th>
<th>Unit Price</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66&quot; CMP Corrugated Metal Pipe, ½&quot; Interior Cement Liner; Includes Labor, Equipment for the installation of an interior cementitious liner, SCM GeoCast cementitious mortar materials provided by GC; surface clean &amp; prep by the GC</td>
<td>LF</td>
<td>1046</td>
<td>$245.00/LF</td>
<td>$256,270.00</td>
</tr>
</tbody>
</table>

Polymeric (Polyurethane)

<table>
<thead>
<tr>
<th>Size</th>
<th>250 mil</th>
<th>500 mil</th>
<th>1000 mil</th>
</tr>
</thead>
<tbody>
<tr>
<td>48&quot;</td>
<td>$275/ft</td>
<td>$440/ft</td>
<td>$880/ft</td>
</tr>
<tr>
<td>54&quot;</td>
<td>300</td>
<td>520</td>
<td>1040</td>
</tr>
<tr>
<td>60&quot;</td>
<td>360</td>
<td>600</td>
<td>1200</td>
</tr>
<tr>
<td>66&quot;</td>
<td>400</td>
<td>660</td>
<td>1320</td>
</tr>
<tr>
<td>72&quot;</td>
<td>450</td>
<td>740</td>
<td>1480</td>
</tr>
<tr>
<td>84&quot;</td>
<td>500</td>
<td>840</td>
<td>1680</td>
</tr>
<tr>
<td>96&quot;</td>
<td>$550/ft</td>
<td>$950/ft</td>
<td>$1800/ft</td>
</tr>
</tbody>
</table>
Task 6 - CIPP Design Equations

- ASTM F1216 design procedure has been found as being unrealistic for designing flexible conduits and it is over-conservative.
- Knowledge of the current performance properties of the surrounding soil are critical to the performance of the rehabilitated soil-structure interaction system.
- Any design procedure used for CIPP must recognize the differences in how rigid pipe structures versus flexible pipe structures will transfer loads to consider the stresses and strains created in the CIPP liner itself.

Partially Deteriorated

\[ P_w = \frac{2K E_L}{(1-v^2)} \times \frac{1}{(DR-1)^3} \times \frac{C}{N} \]

Fully Deteriorated

\[ q_t = \frac{1}{N} \left[ 32R_w B' E'_s \cdot C(E_L I/D^3) \right]^{1/2} \]
RESULTS (CONT’D)

Task 7 - Field Inspection

- SAPLs have potentials to provide structural solutions
- Common Cementitious SAPL issues:
  - Circumferential crack
  - Fracture
  - Infiltration weeper
  - Efflorescence
  - Rust staining
  - Non-uniform thickness
RESULTS (CONT’D)

Task 7 - Field Inspection

Visible Bolt Heads
Iron Oxidation
Circumferential Fracture
Infiltration Dripper
Circumferential Crack Efflorescence
Delamination at the Crown
RESULTS (CONT’D)

Task 7 - Field Inspection

- Disturbed SAPL Surface
- Bare CMP Invert
- Multiple Cracks
- Circumferential Crack Iron Oxidation
Cementitious SAPLs:

- Diameter or Span less than 120 inches
- Bonding between the host pipe and the SAPL required
- Semi-rigid design approach is taken
- Circular Pipes: Use of modified Iowa equation
- Arch Pipes: Use of mechanical analysis of a thin-walled ring structure
- Design loading as per AASHTO's Load and Resistance Factor Design (LRFD) Bridge Design Specifications was used
RESULTS (CONT’D)

Task 8 - SAPL Design Equations

Polymeric SAPLs:

- Diameter or Span less than 120 inches
- No bonding between the host pipe and the SAPL considered
- Need to evaluate the effects of creep under long-term loading conditions
- Modified AASHTO Bride Design Specifications was used which included AWWA M45 design method for thermoset flexible materials.
- Analytical calculations were verified with experimental results
- Design loading as per AASHTO’s Load and Resistance Factor Design (LRFD) Bridge Design Specifications was used
RESULTS (CONT’D)

Task 8 - SAPL Design Equations - Cementitious Arch Example

Live and Dead Loads Calculation:

Select Standard Pipe Arch Sizes

<table>
<thead>
<tr>
<th>Size</th>
<th>71 x 47</th>
</tr>
</thead>
</table>

Pipe Arch - Top Radius

| Value  | 35.750 in. |

Pipe Arch - Bottom Radius

| Value  | 110.250 in. |

Pipe Arch - Span

| Value  | 71.00 in. |

Pipe Arch - Rise

| Value  | 47.00 in. |

Mp Multiple Presence Factor, typically equal to 1.2

| Value  | 1.2 |

P Design Wheel Load

Refer to AASHTO Bridge Design Specifications, 8th Ed., Section 3.6.1.2.6a.
P Load is the weight an AASHTO design truck imposes on a single wheel (or pair of wheels in the case of dual wheels).
Typical HL-93 Design Truck has 3 axles, front axle load of 8 kips, and two rear axles with a load of 32 kips each (rear wheel load of 16 kips each)

| Value  | 16,000.00 lb |

h Depth of Cover over Culvert

Distance from top of the pipe to top of the soil

| Value  | 24.00 in. |

LLDF Live Load Distribution Factor

Refer to AASHTO Bridge Design Specifications, 8th Ed., Table 3.6.1.2.6a-1

| Value  | 1.15 |

Figure 8-1
RESULTS (CONT’D)

Task 8 - SAPL Design Equations - Cementitious Arch Example

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire Patch Length</td>
<td>10.00</td>
<td>in.</td>
</tr>
<tr>
<td>Tire Patch Width</td>
<td>20.00</td>
<td>in.</td>
</tr>
<tr>
<td>Spacing between the Wheel Pairs on the Axle</td>
<td>72.00</td>
<td>in.</td>
</tr>
<tr>
<td>Axle Spacing</td>
<td>48.00</td>
<td>in.</td>
</tr>
<tr>
<td>Soil Unit Weight</td>
<td>120.00</td>
<td>pcf</td>
</tr>
<tr>
<td>Soil Cohesion</td>
<td>0.00</td>
<td>psf</td>
</tr>
<tr>
<td>Select k_p' - Refer to Figure 9-13 in ASCE MOP 60</td>
<td>0.1924</td>
<td></td>
</tr>
<tr>
<td>Height of the Groundwater above the Top of the Pipe</td>
<td>0.00</td>
<td>ft</td>
</tr>
</tbody>
</table>

Figure 8-2

Figure 8-3

Select if it is a Single Span culvert or Multiple Span culverts? Single Span
RESULTS (CONT’D)

Task 8 - SAPL Design Equations - Cementitious Arch Example

Design Assumptions (Cementitious Liner):

- Wall Thickness of the Liner - See figure 8-3
  - Yes/No: Yes
- Assumed and the Liner above the corrugation crests - Yes/No: No
- Distance from the Centroid of the Liner Pipe Wall Profile to the Interior Wall Surface - See figure 8-3
  - Yes/No: No
- SAPL Area Moment of Inertia of the Liner Wall Section
  - Yes/No: Yes

- Compressive Stress Strength of the Liner Material
  - Compressive strength value to be provided by manufacturer in accordance with Pipe Liner Special Provision
  - Yes/No: Yes

- Flexural Stress Strength (Modulus of Rupture) of the Liner Material
  - Flexural strength value to be provided by manufacturer in accordance with Pipe Liner Special Provision
  - Yes/No: Yes

Load Factors:

- Load Factor for Soil Prism Load - Service, 1.0
- Load Factor for Soil Prism Load - Strength, 1.30
- Load Factor for Groundwater Load, 1.0
- Load Factor for Live Load - Service, 1.0
- Load Factor for Live Load - Strength, 1.75
- Load Modifier for Redundancy, 1.0 for Strength Limit State under Earth Loads
- Load Modifier for Redundancy, 1.0 for Strength Limit State under Live Loads
- Load Modifier for Redundancy, 1.0 for Strength Limit State under Live Loads
- Load Modifier, use 1.0 per Article 1.3.2 of the BDS

- Load Modifier for Soil Prism Load, use 1.0 per Article 1.3.2 of the BDS
- Load Modifier for Redundancy, 1.05 for Strength Limit State under Earth Loads
- Load Modifier for Redundancy, 1.0 for Strength Limit State under Live Loads
- Load Modifier for Live Load, use 1.0 per Article 1.3.2 of the BDS
RESULTS (CONT’D)

Task 8 - SAPL Design Equations - Cementitious Arch Example

**Live and Dead Loads Results:**

- $C_1$ Coefficient: 0.32
  
  (Figure 9-13 in ASCE MOP 60)
- $P_L$: Live Load on Pipe: 12.28 psi
- $P_E$: Earth Load acting on the Horizontal Soil Plane at the Top of the Pipe: 0.53 psi
- $P_x$: External Hydrostatic Pressure acting on the Pipe: 0.00 psi

**Results (Cementitious Liner)**

### Service

**Top Radius**

- $T_{service}$ Thrust in Liner: 209.27 lb/in.
- Area of the Cross-Section of the proposed Liner per linear inch: 1.00 in.$^2$/in.
- $M_{service}$ Moment: 51.55 in.-lbf/in.
- $\sigma_{crown}$ Normal Stress (Service): -28.27 psi

Stress within limits. The 1-in. thick liner is sufficient.

### Bottom Radius

- $T_{service}$ Thrust in Liner: 67.39 lb/in.
- Area of the Cross-Section of the proposed Liner per linear inch: 1.00 in.$^2$/in.
- $M_{service}$ Moment: 16.48 in.-lbf/in.
- $\sigma_{crown}$ Normal Stress (Service): -9.51 psi

Stress within limits. The 1-in. thick liner is sufficient.
## RESULTS (CONT’D)

### Task 9 - Performance Construction Specifications

#### Cementitious Based Structural SAPL Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Duration</th>
<th>Minimum Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength</td>
<td>ASTM C109</td>
<td>28 day (min)</td>
<td>Declared Value, but not less than 8,000 psi</td>
</tr>
<tr>
<td>(2.0-inch cubes)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexural Strength (Modulus of Rupture)</td>
<td>ASTM C 1609</td>
<td>28 days (min)</td>
<td>Declared Value, but not less than 1,000 psi</td>
</tr>
<tr>
<td>Compressive Modulus of Elasticity</td>
<td>ASTM C 469</td>
<td>28 days (min)</td>
<td>Declared Value, but not less than 3,500,000 psi</td>
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</tbody>
</table>
### Polymeric Based Structural SAPL Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Minimum Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural Strength</td>
<td>ASTM D790-17</td>
<td>Declared Value, but not less than 10,000 psi</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>ASTM D790-17</td>
<td>Declared Value, but not less than 250,000 psi</td>
</tr>
<tr>
<td>Flexural Creep</td>
<td>ASTM D2990-17</td>
<td>Declared Value - Qualification Test by 3(^{rd}) Party</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>ASTM D695-15</td>
<td>Declared Value, but not less than 8,000 psi</td>
</tr>
<tr>
<td>Compressive Modulus</td>
<td>ASTM D695-15</td>
<td>Declared Value, but not less than 300,000 psi</td>
</tr>
<tr>
<td>Compressive Creep</td>
<td>ASTM D2990-17</td>
<td>Declared Value - Qualification Test by 3(^{rd}) Party</td>
</tr>
</tbody>
</table>
Task 9 - Performance Construction Specifications

• The polymer and cementitious specifications are structured product and installation differences where required because of product and installation variabilities

• Specifications allow for contractor innovation and utilization of the most current products and techniques
RESULTS (CONT’D)

Task 10 - FEM Modeling

Methodology of FEM Modelling

- Modelling the Intact CMP
  - Model intact CMP under soil box loading conditions

- Modeling the invert cut CMP
  - Model "cut" bare CMP under soil box loading conditions

- Update the Model to lined CMP (Polymeric and Cementitious)
  - Add SAPL to "cut" bare CMP

- Check Model Accuracy
  - Calibrate the model of cut-CMP with SAPLs with soil box testing

- Parametric Analysis
Model Steps:

- Abaqus standard with the static analysis was implied to obtain the result.
  - Step 1: Geo-static step for soil load.
  - Step 2: CMP load activated and establishment of the Soil-CMP interaction.
  - Step 3: Removal of invert (not used for intact pipe)
    - Activation of the liner and establishment of the liner CMP interaction (for CMPs with liners).
  - Step 4: Application of the load (displacement-controlled loading)
### RESULTS (CONT’D)

**Task 10 - FEM Modeling**

#### CMP and Soil Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>CMP</th>
<th>Sand</th>
<th>RCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasticity Model</td>
<td>Elastic-Plastic</td>
<td>Drucker Prager</td>
<td>Drucker Prager</td>
</tr>
<tr>
<td>Density (lb./in³)</td>
<td>0.284</td>
<td>0.057</td>
<td>0.069</td>
</tr>
<tr>
<td>Elastic Modulus (psi)</td>
<td>29,000,000</td>
<td>510</td>
<td>1,200</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.3</td>
<td>0.3</td>
<td>0.28</td>
</tr>
<tr>
<td>Yield Stress (psi)</td>
<td>33,000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ultimate Stress (psi)</td>
<td>45,000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Friction Angle (°)</td>
<td>-</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td>Dilation Angle (°)</td>
<td>-</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
SAPL Properties:

- SAPL properties was modified based on the iterative process done on the FEM to best match the given experimental condition and results.
  - Simple elastic-plastic model was used to model the liner.
  - The material test results showed very small plastic region before cracking.
  - An assumption of the occurrence of the 1st plastic strain is considered as the 1st crack in the model.

<table>
<thead>
<tr>
<th>Test Item</th>
<th>FINAL -TRIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (psi)</td>
<td>8,821</td>
</tr>
<tr>
<td>Tensile break Strain (%)</td>
<td>1.61</td>
</tr>
<tr>
<td>Young’s Modulus (psi)</td>
<td>850,000</td>
</tr>
</tbody>
</table>
Boundary Conditions:

- Vertical movement restrained at the bottom.
- Normal horizontal movement restrained at the sides.
- Symmetric boundary along YZ plane.
- The size of the load pad was changed from 10x20 in$^2$ to 20x40 in$^2$ to prevent the failure of the soil before the pipe failure.
RESULTS (CONT’D)

Task 10 - FEM Modeling

Comparison of Plastic Deformation in Experiment and FEM
Comparison of the pressure above the crown

- Test@ Crown
- FEM @CROWN

Crown reading
FEM model of circular (left) and arch CMP (right) with removed invert

RESULTS (CONT’D)
FEM Results for Circular SAPL (Polymeric)

1st plastic strain

Ultimate plastic strain
FEM Results for Circular SAPL (Polymeric)

Load-displacement Curve for 0.25-in. Circular SAPL
FEM Results for Circular SAPL (Polymeric)

Comparison between Experiment and FEM results for 0.25-in. thick Circular SAPL

<table>
<thead>
<tr>
<th>Description</th>
<th>1st plastic strain</th>
<th>1st Crack</th>
<th>Discrepancy Test vs. FEM (%)</th>
<th>Ultimate Load (FEM)</th>
<th>Ultimate Load (Test)</th>
<th>Discrepancy Test vs. FEM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crown Displacement (in.)</td>
<td>3.13</td>
<td>2.92</td>
<td>6.7</td>
<td>4.98</td>
<td>5.23</td>
<td>5.0</td>
</tr>
<tr>
<td>Soil Displacement (in.)</td>
<td>4.79</td>
<td>4.64</td>
<td>3.1</td>
<td>6.48</td>
<td>6.49</td>
<td>0.5</td>
</tr>
<tr>
<td>Load (kips)</td>
<td>44.40</td>
<td>41.3</td>
<td>6.9</td>
<td>46.37</td>
<td>45.78</td>
<td>1.2</td>
</tr>
</tbody>
</table>
RESULTS (CONT’D)

Task 10 - FEM Modeling

Arch CMP results: 0.25-in. thick polymeric SAPL

Load Displacement plot at the crown of the liner and load pad
Conclusions for Circular SAPL (Polymeric)

- The experimental and FEM results compared fairly within the discrepancy of less than 10% for the circular SAPL for most of the comparison.

- The rigidity of the CMP increases with the increase in the thickness of the SAPL. This leads to the sudden crack in the SAPL for higher thickness SAPL with small deformation in the CMP.

- The SAPL with more than 0.5-in. thick is successful in re-establishing the lost capacity of CMP due to the complete loss of the invert.
Arch CMP results: 0.25-in. thick polymeric SAPL

Load Displacement plot at the crown of the liner and load pad
EXPERIMENTAL PROGRAM

Task 11 - Soil Box Testing

- Control tests
  - Intact CMP
  - Circular invert-cut CMP
  - Arch invert-cut CMP
- Circular & Arch Cementitious
  Thicknesses 1, 2 and 3 in.
- Circular & Arch Polymeric
  Thicknesses 0.25, 0.5 and 1 in.
Task 11 - Soil Box Testing
RESULTS (CONT’D)

Task 11 - Material Properties & Soil Box Testing Results

- Polymeric SAPL flexural modulus of 850,000 psi, the averaged tensile stress of 8,600 psi, and the elastic modulus of 329,000 psi

- Average Cementitious SAPL compressive strength was 2,700 psi after 24 hours of curing, 4,400 psi after 7 days

- The polymeric circular SAPL renewed CMPs with the thicknesses of 0.25 in., 0.5 in., and 1 in. increased the ultimate load bearing capacity for 16.2%, 31.4%, and 80.8%, respectively.

- The cementitious circular SAPL with the thicknesses of 1 in., 2 in., and 3 in. increased the ultimate load bearing capacity for 79.7%, 113.9%, and 174.7% respectively.
RESULT (CONT’D)

Task 11 - Soil Box Testing

Cementitious - Arch Shape

Before Load

After Load

➢ 3 in. Cementitious arch SAPL
➢ Maximum Load: 67.84 kips

➢ 2 in. Cementitious arch SAPL
➢ Maximum Load: 55.16 kips
RESULTS (CONT’D)

Task 11 - Soil Box Testing

Cementitious - Arch Shape

- 1 in. Cementitious arch SAPL
- Maximum Load: 46.5 kips
RESULTS (CONT’D)

Task 11 - Soil Box Testing

Cementitious - Arch Shape

Invert-cut Pipe Arch CMP - Renewed with Cementitious SAPL
RESULTS (CONT’D)

Task 11 - Soil Box Testing

Cementitious - Circular Shape

Before Load  

After Load

➢ 3 in. Cementitious circular SAPL 
➢ Maximum Load: 109.7 kips

➢ 2 in. Cementitious circular SAPL 
➢ Maximum Load: 85.42 kips
Task 11 - Soil Box Testing

Cementitious - Circular Shape

Before Load  After Load

- 1 in. Cementitious circular SAPL
- Maximum Load: 71.76 kips
RESULTS (CONT’D)

Task 11 - Soil Box Testing

Cementitious - Circular Shape

Invert-cut Circular CMP - Renewed with Cementitious SAPL
RESULTS (CONT’D)

Task 11 - Soil Box Testing

Cementitious Circular

Circular CMP with 3 in. Cementitious SAPL
RESULTS (CONT’D)

Task 11 - Soil Box Testing

Polymeric - Arch Shape

After Load

- 0.25 in. Polymeric SAPL
  Maximum Load: 32.2 kips

- 0.5 in. Polymeric SAPL
  Maximum Load: 35.5 kips

- 1 in. Polymeric SAPL
  Maximum Load: 54.0 kips
RESULTS (CONT’D)

Task 11 - Soil Box Testing

Polymeric - Arch Shape

Invert-cut Pipe Arch CMP - Renewed with Polymeric SAPL
RESULTS (CONT’D)

Task 11 - Soil Box Testing

Polymeric - Circular Shape

After Load

- 0.25 in. Polymeric SAPL
  - Maximum Load: 38 kips

- 0.5 in. Polymeric SAPL
  - Maximum Load: 44 kips

- 1 in. Polymeric SAPL
  - Maximum Load: 66 kips
RESULTS (CONT’D)

Task 11 - Soil Box Testing

Polymeric - Circular Shape

Invert-cut Circular CMP - Renewed with Polymeric SAPL
RESULTS (CONT’D)

Task 11 - Soil Box Testing

Polymeric Circular

Circular CMP with 1 in. Polymeric SAPL
CONCLUSIONS AND RECOMMENDATIONS
CONCLUSIONS AND RECOMMENDATIONS

- SAPL surface preparation, environmental conditions, bonding and quality of installation are very important.
- Both polymeric and cementitious SAPLs were able to increase the structural capacity of the fully invert deteriorated CMPs.
- Design equations were verified with experimental testing results.
- FE model showed reasonable accuracy for polymeric circular and arch shapes. The FE model for cementitious circular and arch may need more work.
- More studies are recommended to refine design equations (considering effects of CMP’s length, culvert diameter or span of above 120 in., hydrostatic pressure, etc.).
- More advanced FEM simulations are needed to improve the analysis of post-failure behaviors.
- This research can be extended for different culvert shapes, depths and loading conditions.
- Testing is needed to assess reduced strength of field aged SAPLs after 5 and 10 years of service.
SUBSTRATE PREPARATION IS THE KEY!
IMPLEMENTATION

- Results of this project to be implemented and monitored under active traffic with lining a deteriorated CMP culvert divided in two or more sections
- Each section lined with different polymeric and cementitious/geopolymer SAPL
- Developed design equations and performance specifications presented in Chapters 8 and 9 of this report should be used by the contractor
- Strategies to overcome potential risks and obstacles will be identified during this implementation
- Improvement in the quality of installation should be compared with recently installed SAPLs
- Soil movement around the culvert should be monitored at least for one year
- Surface settlement, infiltration, and condition of invert should be monitored and documented
- Additional numerical methods using FEM can expand results of field evaluation to other scenarios
QUESTIONS

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To download full report, fact sheet, and design spreadsheet, visit Ohio DOT website:

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