Changing Needs In Sulfur Capacity For In-Ground Reinforced Concrete Sulfur Pits

April 13-16, 2010
League City, Texas, USA
Concrete Problems

- Defects
  - Design, materials, construction

- Damage
  - Overload, fire, impact, chemical spill

- Deterioration
  - Metal corrosion, erosion, freeze/thaw, sulfate attack
Disintegration

Chemical Exposure

Attack matrix – sulfurous acid erosion exposing resistant large coarse aggregate

Matrix modification – sulfur contact alters Portland cement paste matrix into a semi-gelatinous state
Typically the sulfur pit concrete is exposed to operating temperatures of molten sulfur ranging between 285°F to 315°F.

Temperature gradient exists within the wall mass extending from pit interior molten sulfur contact of 300°F to pit exterior earth contact of 57 °F. Actual exterior soil temperatures stabilized during operation reach elevated temperatures ranging between 120°F to 130°F.
Operating Conditions

Operating Parameters

- Water Table
- Roof Slab
- Grade
- Ground Pressure
- Base Slab
- Steam Coils
Operating Conditions

Operating Parameters

Exterior Earth (Actual Ranges 120°F to 130°F)

Molten Sulfur (Actual Ranges 285°F To 315°F)
Operating Conditions

Operating Parameters

Small Pit
Fluctuating Levels

Deterioration

Large Pit
Constant Level
Sulfur Pit Structural Issues

- An irresistible force (i.e., thermal growth) meeting an immovable object (i.e., densely compacted soils and rock).

Sulfur Pit Interior

Compacted Back Fill

Cracking
Concrete Material Alterations

Sulfate & Calcium Ions form Gypsum
(CaSO$_4$•32 H$_2$O) - expands 124% in volume

Sulfate & Calcium Aluminate form Calcium Sulfoaluminate (ettringite) (3CaO•Al$_2$O$_3$•3CaSO$_4$•3H$_2$O) - expands 227% in volume

To remedy and reduce the effects of these chemical reactions - Use cements with low C$_3$A
- Type V Sulfate resisting Portland cement
- Blends of Hydraulic/Portland cements
- Cement replacements with supplemental Cementitious materials (Flyash, Microsilica, etc.)
Operating Conditions

Type V

3 - 5,000 psi >>> 10 - 13,000 psi

Sulfur
Sulfur impurities and by-products form "Carsul"

"Carsul" settles along crevices and base regions

May be mistaken for concrete
Operating Conditions

Deterioration Mechanisms

- “Desiccatio”n of the concrete mass (i.e., removal of excess moisture by high service temperatures) causing cracks
- Sulfurous acid attack – “acid” generated by water leakage into the pit from cracks, failed penetration seals or jacketed pipe/coils leaks
- Corrosion of reinforcing steel bar above molten sulfur levels in the Vapor Zone
- Scouring effect of fluctuating molten sulfur levels in daily “working pits”
Operating Conditions

Deterioration Mechanisms
Sulfur Pit Repair Failures
Concrete Repair Is A Process!

Cause & Effect
- Defect, damage or deterioration
  - Leakage
  - Settlement
  - Deflection
  - Wear
  - Spall
  - Disintegration
  - Crack

Repair required?
- Safety
- Structural catastrophe
- Use disfunction
- Leakage
- Effects on environment
- Aesthetics
- Preventive maintenance

Condition Survey
- Evaluate
- Quantify
- Document
- Prioritize

Repair Analysis
- Owner Criteria
  - Urgency
  - Cost
  - Expectations
  - Useful life
  - Aesthetics
- Engineering & contractor Issues
  - Structural req.
  - Effect
  - Constructability
  - Environment
  - Safety

Repair Strategy
- Contractor Methods
  - Surface repair
  - Stabilization
  - Strengthening
  - Waterproofing
  - Protection
- Techniques
- Materials

Repair
Condition Survey

- Visual Inspection and Site Survey
- Acoustic Impact Testing
- Mapping of Significant Features
Repair Process

Condition Survey

- Ferroscan & Standard Rebar Pachometer Survey

Field Investigation
Repair Process

Condition Survey

Field Investigation

Ground Penetrating Radar Line Scan

Concrete Surface

Reinforcement

Concrete Surface
Repair Process

**Condition Survey**
- Sample Extraction

**Field Investigation**
- Core Extraction
- Chloride Sampling
Sulfur Pit Repair Scenarios

- **Leaking Cracks**
  - Cementitious grouting
  - “Chinking”
  - Well-points

- **Surface Erosion**
  - Partial and full-depth removal and replacement
  - Installation of a “new skin” (i.e., durability liner)
  - Installation of a new structural liner

- **Corroding Reinforcing**
  - New rebar replacement & integration with repair couplers
  - Incorporation of corrosion inhibiting admixtures into repair materials
Each Sulfur Pit is a unique structure and should be engineered as such.

- Soil sampling and analysis
- Structural modeling and analysis
- Partnering between contracting and engineering
Surface Repair

Material Selection Criteria

- Repair material similar to original substrate...
  - Modulus of elasticity (loads)
  - Thermal expansion (Δ temp)
  - Low drying shrinkage (crack-free)
  - Chemically resistant to service environment

- Repair like with like!
  - So the repair will behave compositely ("as-one") with the substrate under load
Placement Techniques

Roof Slab Soffit – Form & Pump

- Shoring required to support roof slab as flexural steel lacks bond with concrete
- Excavation requiring undercutting of rebar & new bars added as necessary due to corrosion losses
- Soffit forms installed and concrete placed under pressure into formwork cavity
Full-Depth Repair

- Remove deteriorated roof slab
- Formwork at base of roof slab and dowel walls to roof reinforcing
Placement Techniques

Form & Pour Wall Repairs

- Form & pour partial-depth wall repairs via “birds-mouth” ports employing external form vibrators to assemble formwork and internal vibrators to address concrete consolidation within formwork cavity
Placement Techniques

Precast Roof Slab Panels

Predrilled Core Holes on a Grid Pattern
Sulfur Pit Repair Construction Environment – Innovative Techniques To Accelerate Repair Construction Schedule

- Use of site-built modular formwork adjusts to as-built Sulfur Pit site conditions with roof in-place (atypical Pits)
- Port locations & spacing assure “port-to-port communication” during repair material placement & adequate consolidation
Sulfur Pit Repair Construction Environment – Innovative Techniques To Accelerate Repair Construction Schedule

- Use of panelized modular formwork adjusts to Sulfur Pit metrics (typical Sulfur Pits)
- Panelized forms are externally braced (i.e., form-ties not required) works best with roof slab removed allowing internal & external consolidation
Implementing an SPIP (Sulfur Pit Inspection Program) provide owner & contractor a verifiable audit trail of accountability with designated milestones & hold points - assuring no important details “fall-through-the-cracks”

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Attribute / Activity Description</th>
<th>Acceptance Criteria Codes (Ref. Spec.)</th>
<th>Applicable</th>
<th>Test</th>
<th>Submittals</th>
<th>Review</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Remove Loose Concrete Materials from Sulfur Pit Wall Areas</td>
<td>ASTM, ACI, P. Emmons Rep./Maint. as Appl.</td>
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<td>2</td>
<td>Verify existing Concrete Wall at repair areas is free of Sulfur Cake deposits</td>
<td>ASTM, ACI, P. Emmons Rep./Maint. as Appl.</td>
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<td>3</td>
<td>Verify reinforcing steel is routed on as-built construction drawings</td>
<td>ASTM, ACI, P. Emmons Rep./Maint. as Appl.</td>
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<td>4</td>
<td>Verify existing reinforcing steel has been cleaned on all sides and augmented if necessary</td>
<td>ASTM, ACI, P. Emmons Rep./Maint. as Appl.</td>
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<td>5</td>
<td>Install Reinforcing Steel bars as specified and verify rebar cover</td>
<td>ASTM, ACI, P. Emmons Rep./Maint. as Appl.</td>
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<td>6</td>
<td>Verify dowel holes are 2” in Dia. 12” deep and Clear</td>
<td>ASTM, ACI, P. Emmons Rep./Maint. as Appl.</td>
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<td>7</td>
<td>Verify S-80 Grade is mixed and consolidated according to manufacturer’s recommendations</td>
<td>ASTM, ACI, P. Emmons Rep./Maint. as Appl.</td>
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<tr>
<td>8</td>
<td>Verify forms are built and secured to withstand the concrete pour pressure</td>
<td>ASTM, ACI, P. Emmons Rep./Maint. as Appl.</td>
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<td>9</td>
<td>Verify mix water is appropriate for Emacre S-64 product being used and maintaining a consistent slump for placement and testing</td>
<td>ASTM, ACI, P. Emmons Rep./Maint. as Appl.</td>
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<td>10</td>
<td>Verify placement procedures are in accordance with ACI 304.2R &amp; 304R-89</td>
<td>ASTM, ACI, P. Emmons Rep./Maint. as Appl.</td>
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Conclusion

- “Devil-is-in-the-Details”
- Even small amounts of deterioration require specific detailing so things aren’t made worse while in-service
- Each Sulfur Pit is unique and requires a thoughtful enlightened approach in order to implement an enduring repair