Lining the HATS Sewage Tunnel with High-performance Concrete in Hong Kong

Gammon Construction Ltd. (Ir. Dr. Herbert Zheng, Ir. Martin Ho)
AECOM Asia Co. Ltd (Ir. Benny Chan)
Drainage Services Department, the Government of the Hong Kong Special Administration Region (Ir. P. F. Ma)
“Failure is success in progress.”

On 20 March, 2014
“There is always a gift in any challenge.”

On 28 March, 2014
Where? - Harbour Area Treatment Scheme (HATS)
The Stage 2A Sewage Conveyance System (SCS)
Contents

A. HATS Stage 2A Sewage Conveyance System
B. Mix characterization and risk prevention framework
C. Long time transportation and crack control
D. High-performance concretes at HATS
E. Conclusions
A  HATS Stage 2A

Sewage Conveyance System
HATS Stage 2A SCS alignment

- Sandy Bay
- Cyberport
- Ap Lei Chau
- Aberdeen
- North Point
- Stonecutters Island
- Wan Chai East
- Kent Point
- Central
- East Point
- Kowloon
- Hong Kong Island

Stage 1 (by others – completed)
Stage 2A Sewage Conveyance System
A total of 21km deep tunnels with depth varying up to 160m below sea level, and unreinforced concrete lining diameters ranging from 900mm to 3,050mm.
Quality assurance and the Swiss Cheese

Some viable solutions due to proper actions

Other viable solutions due to beneficial latent conditions

Challenges in successive layers

B Mix Characterization and Risk Prevention Framework
### Prescribed requirements for structural design

<table>
<thead>
<tr>
<th>Category</th>
<th>GS (2006) Sections 16 &amp; 21 - Marine Concrete (Grade 45/20D)</th>
<th>DSD HATS (Plain marine concrete Grade 45/20D)</th>
</tr>
</thead>
</table>

#### A Concrete mix

- **(1)** Min grade: 45 MPa
- **(2)** Max 0.38 w/cm ratio
- **(3)** Mix design: from 375 to 450 kg/m$^3$ cementitious materials (cm), with 25-40% PFA with 5-10% condensed silica fume

- PC, SRPC, PFAC, PBFC, GGBS, CSF
- SRPC (Sulphate resisting Portland cement) or equivalent

#### B Concrete Performance

| Temperature | Placing temperature < 30 °C | (1) Placing temperature < 32 °C  
(2) Peak ≤ 70 °C  
(3) Max difference ≤ 20 °C |
|-------------|-----------------------------|-------------------------------------------------|
| Strength    | Same as normal concrete     | Extra requirements on any consecutive 40 results of 28-day cube strength:  
- Coefficient of variation ≤ 8%  
- Average strength ≥ Grade strength + 2 x Standard Deviation |
| Durability  | Not specified               | 28-day AASHTO chloride diffusion (6 hour test) \(\leq 1,000\) coulombs  
28-day Water sorptivity \(\leq 0.07\) mm/min$^{0.5}$ |
Logistic requirements

- 200,000m$^3$ Grade 45 and 60 unreinforced high performance concrete, up to Grade 80
- Typical 300m$^3$ (max. 370m$^3$) single pour volume (max. length = 22.5m for Tunnel K, 60m for Tunnel L)
Construction requirements for workability & strength

Leave batching plant after mixing

Arrive to site and queuing

Vertical Discharge (over 160m deep)

Placed in final position

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 ~ 1 hr</td>
<td>queuing for vertical discharge</td>
</tr>
<tr>
<td>0.5 ~ 2 hrs</td>
<td>tunnel concrete conveyance by train mixer / pumping</td>
</tr>
<tr>
<td>1.5 hrs</td>
<td>contingency</td>
</tr>
</tbody>
</table>

Earliest 2 hours

Latest 4.5 hours

Slump ≤ 240mm at 2.5 hrs after mixing with water
(For special concreting works ≥ 680mm slump flow)

Early Strength ≥ 3MPa in 8 hrs for Tunnel L

Early Strength ≥ 1MPa in 6 hrs for Tunnel J & K

Slump ≥ 200mm at 6 hrs after mixing with water
High-performance concrete (HPC)

“Concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices.”

- American Concrete Institute, January 2013
Revelation to Construction Industry

The use of high-performance concrete integrates flexibility and control of various time-dependent concrete properties to suit different construction methods so that the overall performance of construction projects and concrete structures is improved significantly.

A Vision for Future

- The market needs for, and the use of HPC will increase.
- There will be following changes in the industry:
  - Application of performance-based concrete specification;
  - Small changes in concrete construction methods;
  - Improvements in QM/QC of concrete mix design, production, supply and application;
  - Wider acceptance to slightly higher materials cost of construction projects.

The Concrete for Future Hong Kong

- The shelf life of ready-mixed concrete could be tailor-made, either as soon as after mixing or as long as needed.
- The grade strength is achieved in one day after concreting.

Conclusions at SCCT

Annual Concrete Seminar 2007
Concrete: known and unknown

Paste
- fine aggregate
- hydrated & unhydrated cementitious material particles
- water
- air

Transition zone (air)

Entrapped air void

Coarse aggregates

Free water

Entrained air void

By volume: 68% Aggregate + 32% Cement & Water & Air
By weight: 26% Cement & Water + 74% Aggregates
Concrete properties: time-dependent

- Workability / consistency
- Volume change:
  - Temperature rise
  - Shrinkage
  - Resistance to environmental loadings
- Mechanical properties: strengths and modulus
- Durability: absorption, permeability and abrasion resistance
- Others: ductility and fire resistance
Mix design and optimal packing

At optimal state:
- denser micro structure
- higher workability
- less segregation
- higher density
- higher strength

Normal concrete

High-performance concrete
Characteristic curve for concrete performance

- Slump (mm)
- Cube Strength (MPa)

- Designed slump
- 6-hr retention
- Target curve, by accelerator
- 2.5-hr retention
- Demoulding

Logistic for 2.5-hr retention
Logistic for 6-hr retention
Framework of quality management

Viable solutions due to proper actions and latent conditions in production and supply of quality concrete

Inputs made by concrete producer

Challenges (i.e. difficulties, barriers or limitations)

Mix and Process Design

Constituent materials

Method and equipment

Procedures

People

Targets (i.e. durable concrete)

Latent condition pathways

Proper decision and implementation

Local construction project circumstances (i.e. contract requirements, site conditions)

Organizational factors (i.e. existing setup of concrete producers, clients and contractors)

Legend:

↑ Contribution factors
C Long Time Transportation and Crack Control
Logistic plan for production, transportation & placing

- Transportation: 4.5 hrs.
- Contingency: 1.5 hrs.
- Total: 6 hrs.

1. Call Batching Plant to start delivery
2. Batching Plant production
3. Pre-delivery QC testing
4. Concrete transportation by mixer truck
5. Mixer truck arrival and on site concrete testing
6. Concrete discharged to Agitator
7. Concrete transported by mixer truck and mixer train trolley
8. Concrete transported by placing pump
9. Concrete placement
Long distance pumping & train mixer

Max 1.2km single pumping

Concrete discharged from train mixer to pump receiving hopper
Advantages of long-distance pumping

- Rapid transportation and placement of concrete at a rate of more than 35m³/hour/pump
- Perform concreting where traffic condition is restricted, or access is difficult such as in underground construction
- Maintain concrete supply in line with concrete placement rate to enhance concrete crews’ efficiency
Common problems encountered in long distance pumping

- Loss of workability and temperature control
- Insufficient headroom for pump of proper capacity
- Pump or pump line blockage
  - Mix design deficiencies
  - Pipeline and joint deficiencies
  - Operating error
  - Slow reaction in locating and cleaning pipe blockage
  - Lack of contingency plan
- Insufficient risk prevention measures in place
Unexpected loss of workability

Concrete tested after pumping does not achieve designed performance criteria

Pump pipe line blocked during pumping, causing delays in concrete construction
Pumpline blockages

Causes of pumping system blockage

- Mix design deficiencies
- Pipeline and joint deficiencies
- Failure to response properly
- Organizational accident
Nature of concrete cracking

Before hardening
- Construction Movement
  - Formwork movement
  - Subgrade movement
- Plastic
  - Plastic shrinkage
- Environmental damage
  - Premature freezing
  - Scaling, crazing, pattern

After hardening
- Volume change
  - Drying shrinkage
  - Thermal expansion and contraction
  - Creep
- Structural design
  - Design load / Overload
  - Design / subgrade
  - Fatigue
- Concrete Shell
  - AAR/DEF (Delayed ettringite formation)
  - Corrosion of reinforcement
  - Freeze-thaw cycling

Autogeneous shrinkage
Early-age dimension stability

Dimension stability (or volume change): an increase or decrease in volume due to any cause.
Thermal expansion and contraction

- Factors affecting concrete thermal movement:
  - Cement hydration
  - Ambient temperature
  - Sunlight & wind exposure
  - Heat dissipation

"In Search of Crack-Free Concrete", David A. Lange, 2005
Dimension stability: shrinkage by design

“In Search of Crack-Free Concrete”, David A. Lange, 2005
Cracking control by material’s approach

**Management**
- Quality control
- Programming
- Sequencing
- Communications

**Construction**
- Method
- Placing
- Curing
- Finishing
- Maintenance

**Environment**
- Environmental loadings
- Exposure conditions
- External/internal restraints
- Early age loading

**Structural design**
- Reinforcement
- Loading
- Deflection
- Ductility

**Material design**
- Temperature rise
- Shrinkage
- Creep
- Strength development
- Buildability
D High-performance Concretes at HATS
## List of concrete mixes

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Mix Type</th>
<th>Designation</th>
<th>Workability</th>
<th>cm (kg/m³)</th>
<th>PFA Content</th>
<th>CSF Content</th>
<th>w/cm</th>
<th>Coarse Agg. (kg/m³)</th>
<th>Fine Agg. (kg/m³)</th>
<th>Admixtures (L/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Self-compacting</td>
<td>15/10D</td>
<td>680mm SF</td>
<td>440</td>
<td>58%</td>
<td>0%</td>
<td>0.42</td>
<td>830</td>
<td>820</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>45/10D</td>
<td>700mm SF</td>
<td>435</td>
<td>31%</td>
<td>6%</td>
<td>0.37</td>
<td>950</td>
<td>780</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>High-performance</td>
<td>45/20D</td>
<td>200mm slump</td>
<td>435</td>
<td>31%</td>
<td>6%</td>
<td>0.38</td>
<td>1000</td>
<td>730</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>45/20D</td>
<td>200mm slump</td>
<td>435</td>
<td>31%</td>
<td>6%</td>
<td>0.37</td>
<td>1000</td>
<td>750</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>60/20D</td>
<td>200mm slump</td>
<td>450</td>
<td>30%</td>
<td>6%</td>
<td>0.35</td>
<td>1000</td>
<td>765</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>60/20D</td>
<td>225mm slump</td>
<td>450</td>
<td>30%</td>
<td>6%</td>
<td>0.35</td>
<td>1000</td>
<td>765</td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>80/20D</td>
<td>225mm slump</td>
<td>450</td>
<td>25%</td>
<td>5%</td>
<td>0.31</td>
<td>1020</td>
<td>770</td>
<td>11</td>
</tr>
<tr>
<td>8</td>
<td>Very early strength</td>
<td>45/20D</td>
<td>225mm slump</td>
<td>435</td>
<td>31%</td>
<td>6%</td>
<td>0.38</td>
<td>950</td>
<td>780</td>
<td>17</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>60/20D</td>
<td>225mm slump</td>
<td>450</td>
<td>28%</td>
<td>6%</td>
<td>0.34</td>
<td>940</td>
<td>810</td>
<td>17</td>
</tr>
</tbody>
</table>

Remarks:
1. cm – Cementitious materials; PFA – Pulverized fly ash; CSF – Condensed silica fume; w/cm – Water to cementitious materials ratio; SF – Slump flow.
2. Mix 1 is used for backfilling at Sai Ying Pun Junction Shaft. Mix 2 is used for Stonecutter adit.
3. Mix 3-7 is used for tunnel lining, while mix 8 and 9 are prepared for contingency use.
Portion of Stage 2A SCS tunnel and shaft network

Mix 1
Sai Yin Pun Junction Shaft

Mix 2, 3, 4
Tunnel L (4.55km)

Mix 5, 6, 7
Tunnel J & K (7.5km)

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Placing of lining concrete at Tunnel J, K (Invert)
Placing of lining concrete at Tunnel J, K (Crown)
Lining concrete at Tunnel L
In-situ trial of low strength self-compacting concrete
Conclusions
Conclusions

1. Various high-performance concretes have brought substantial benefits to HATS Stage 2A Sewage Conveyance System project by proper planning and implementation of:
   - Risk prevention based quality management strategy;
   - Technological advancement in design, production, supply and application of HPC.

2. High-performance concrete has significantly facilitated the design and construction of HATS Stage 2A Sewage tunnel lining in aspects of buildability, construction programme and durability.

3. Project applications also show that the potentials of HPC durability, i.e. acid resistance, can be enhanced so that longer design life of sewage concrete structures can be achieved.
Thank You