Concretes for pavements and bridge decks: A Primer

Narayanan Neithalath
Associate Professor
School of Sustainable Engineering and the Built Environment
Arizona State University, Tempe AZ
Structural Concretes
What is CONCRETE?

• From the Latin word “Concretus”
• Means: To hold together or grow together
• It is a “Formable Rock”
• A composite material – Binder(s) + Filler(s)
Scale of concrete use

- Present consumption of concrete of the order of 12 billion tons every year
- Humans consume no material except water in such tremendous quantities
Raw material usage in concrete

- Normal concrete: 12-15 percent cement, 8-10 percent mixing water, 70-80 percent aggregate by mass.
  - 1.5-2 billion tonnes of cement, 9-12 billion tonnes of sand and rock together with one billion tonne of mixing water

- 12 billion tonne concrete industry is the largest user of natural resources
Size scales in concrete

**Macroscale**

**Mesoscale**

**Microscale**
Bridges – Large concrete consumers
Concrete Pavements
Early Concrete Uses

• 1 mile long Michigan rural concrete road - 1909
Roman Use of Concrete

- Romans - arches

Designs placed ‘Concrete’ Mainly in Compression (Coliseum, Pantheon)
Precast, Prestressed Concrete
Proportions - Range

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix 1</td>
<td>15%</td>
<td>18%</td>
<td>8%</td>
<td>28%</td>
<td>31%</td>
</tr>
<tr>
<td>Mix 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7%</td>
<td>14%</td>
<td>4%</td>
<td>24%</td>
<td>51%</td>
</tr>
<tr>
<td>Mix 3</td>
<td>15%</td>
<td>21%</td>
<td>3%</td>
<td>30%</td>
<td>31%</td>
</tr>
<tr>
<td>Mix 4</td>
<td>7%</td>
<td>16%</td>
<td>1%</td>
<td>25%</td>
<td>51%</td>
</tr>
</tbody>
</table>

Air-entrained concrete

Non-air-entrained concrete
Particle Packing
Significance of the material on performance?
Slump Testing

Slump Test

slump cone

rod

concrete

4 in

12 in

8 in
Slump Testing

Slump test

Measured to the nearest 1/4 in (5 mm)
Uses of slump test

- Check on the day to day or hour to hour variation in materials
- Increased slump may indicate increased moisture states of aggregates
- Changes in slump indicate changes in aggregate gradation
- Indicates the relative amount of coarse to fine aggregates
Factors affecting slump-paste content

Low paste content
Harsh mix

High paste content
Rich mix
Ball bearing effect-start

starting height
Ball bearing effect-end

\[ \text{slump} \]
Fly ash benefit
Aggregate size / surface area

volume = 1 cubic in
surface area = 6 square inches

volume = 1 cubic in
surface area = 1.5*8 = 12 square inches
Admixtures

- set retarding admixtures
- set accelerating admixtures
- water reducing admixtures
- superplasticizers
- air entraining admixtures
Unit Weight and Yield (ASTM C 138)

• Unit weight or fresh density
• **Yield** – volumetric quantity of concrete produced per batch
• Proper consolidation needed before determining yield and density
• Expressed in kg/m$^3$ or lb/ft$^3$
Air Content

- To ensure sufficient freezing and thawing resistance
  - Pressure Method
    - ASTM C 231
  - Volume method
    - ASTM C 173
  - Gravimetric Method
    - ASTM C 173
  - Air Indicator Method
    - AASHTO T 199
Pressure Method (ASTM C 231)

• Based on Boyle’s law
• Relates pressure to volume
• Calibrated to read air contents directly
Volumetric Method (ASTM C 173)
Heat evolution curve

Stage 1 – Initial dissolution

Denotes Initial set

Denotes final set

Stage 2

Stage 3

Stage 4

Stage 5

Rate of heat evolution (cal/g.h)

Time (h)
Temperature

Fresh concrete

Aggregates

Paste
Bleeding
Interaction between bleeding and evaporation

Evaporation

Bleed water = evaporation
Too much evaporation

Evaporation

no surface water

drying

Bleed water < Evaporation
Free Shrinkage

before shrinkage

After Shrinkage
Restrained Shrinkage
Curing of Concrete

• Three most important aspects in curing
  • TIME
    – Cure for as long as it is required
  • TEMPERATURE
    – Cure at the right temperature for strength gain
  • MOISTURE
    – Enough (or more) moisture
Importance of Curing

• Stronger concrete
• Impermeable concrete
• More resistant to stress, abrasion
• Resistance to freezing and thawing
Method-I – maintaining the presence of water

- Water supplied from external source
- Evaporation from water surface
- Saturated
- Concrete

Images show the application of water to concrete using a hose sprayer.
Method-II – Reduce loss of mixing water from the surface

Membrane curing compounds
Hydration product - C-S-H
Hydration product - C-H
Hydration product - C-A-S-H
Paste Microstructure

What is revealing in these pictures?
High Strength (Performance) Concrete Buildings
Interplay of strength determinants
Reducing the friction results in a more uniform state of stress.
Size Effect

Test results

Strength

100%

85%

6”

36”

structures

N. Neithalath; Presented at the AZ Pavement Conference, ASU, November 2013
Loading Rate

- Stress
- Dynamic
- Static
- Elastic
- Strain Softening

N. Neithalath; Presented at the AZ Pavement Conference, ASU, November 2013
Flexural test
Flexural Test

![Graph showing the relationship between load (N) and deflection (mm) for a flexural test. The graph includes a line labeled 'Control'.]
City At Peace New York
Proudly Presents
CRACKS IN THE CONCRETE CANVAS
An original musical drama
Written and performed by
a diverse group of teenagers from
the five boroughs of New York City

THURSDAY APRIL 24TH, 2003
FRIDAY APRIL 25TH, 2003
SATURDAY APRIL 26TH, 2003
SUNDAY APRIL 27TH, 2003
AT 8PM

AT
Lucille Lortel Theatre
121 Christopher Street
New York, NY 10014

Between Bleeker and Hudson Streets, West of Seventh Avenue South
Subways: 1 or 9 to Christopher Street/Sheridan Square or A,C,E,F,V to West Fourth Street

N. Neithalath; Presented at the AZ Pavement Conference, ASU, November 2013
Aesthetically unpleasing
Why is Shrinkage important?

- Transverse cracking observed in 100,000+ bridges in the US
- Early age cracking an important issue for state DoTs
- Cracks enhance the risk for further durability problems like corrosion, sulfate attack etc.
- Increased maintenance costs, reduced life
Influence of SRAs

![Graph showing bulk shrinkage strain and residual stress over time with different percentages of SRAs.]

\[ \gamma = 2 \sqrt{D_m t} \]

\( \gamma \) = f (time, Diffusion coefficient)

Neithalath et al. 2005
Concerns with Durability

Bridge deck
Concerns with Structural integrity
Freezing and thawing damage

In northern climates, concrete’s most persistent problem is deterioration caused by freezing and thawing.
Fig. 8-3. Effect of weathering on boxes and slabs on ground at the Long-Time Study outdoor test plot, Project 10, PCA, Skokie, Illinois. Specimens at top are air-entrained, specimens at bottom exhibiting severe crumbling and scaling are non-air-entrained. All concretes were made with 335 kg of Type 10 (Type I) portland cement per cubic metre. Periodically, calcium chloride deicer was applied to the slabs. Specimens were 40 years old when photographed (see Klieger 1963 for concrete mixture information). (69977, 69853, 69978, 69854)
Concrete subjected to F-T
Frost / F-T Action in Concrete

Volume of Ice > Volume of water

$C_2 > C_1$

As water freezes, it expands by 9% - Hydraulic Pressure

Pore water in concrete is ionic - Osmotic Pressure

Hydraulic Pressure

Osmotic Pressure

Stresses

Cracking and Spalling
Air void size and distribution

- Hardened concrete analysis – polished section
- Air void content in the hardened state may be different from that in the fresh state – field changes
- Air void size, spacing also important to achieve good F-T resistance
ASTM C 457 – Point Count or Linear Traverse
Scaling of Concrete
Alkali-Silica Reaction (ASR)

Damages in California Highway system

Thomas E. Stanton

Map cracks

Vertical cracks

California, 1936

Mehta and Monteiro 2005

Mehta and Monteiro 2005

N. Neithalath; Presented at the AZ Pavement Conference, ASU, November 2013
Alkali-Silica Reaction (ASR)

- Visual Symptoms
  - Network of cracks
  - Closed or spalled joints
  - Relative displacements
  - Fragments breaking out of the surface (pop-outs)

Mechanism

1. Alkali hydroxide + reactive silica gel $\Rightarrow$ reaction product (alkali-silica gel)
2. Gel reaction product + moisture $\Rightarrow$ expansion
ASR Gel

ASR reaction with quartzite particle

PCA

N. Neithalath; Presented at the AZ Pavement Conference, ASU, November 2013
Reaction products
Backscattered SEM image
Reinforcing Steel Corrosion 101

Ingress of corrosive species (into porous concrete)

Cracking and spalling of the concrete cover

Build up of voluminous corrosion products

Corroding reinforcing steel

Porous concrete

Corrosive species may already be present in concrete from "contaminated" mix ingredients
Factors needed for corrosion

\[ \text{H}_2\text{O} \rightarrow \text{O}_2 \rightarrow \text{H}_2\text{O} \rightarrow \text{O}_2 \rightarrow \text{H}_2\text{O} \]

+ humidity

Corrosion of the rebar
Effects of Corrosion
Corrosion of Steel
Delamination due to corrosion
Pop outs and Corrosion spalling
Chloride Penetration into Concrete

Rapid Chloride Permeability Test

• Slices 2” thick from cores used for RCPT
• ASTM C 1202
• Allowing chloride ions to pass through concrete under a concentration gradient
• Measuring the chloride ion passage in terms of electrical charge passed (Coulombs)
Chloride Penetration into Concrete

- Ponding the surface of concrete with solution rich in chlorides
- Represented as lbs/cy absorbed after a certain amount of time

Chloride Ponding Test
Tips for good bridge and pavement concretes

• Workability
  – Aggregate gradation
  – Cement replacement materials
  – Admixtures

• Hydration
  – Right amount of cement (cracking because of heat)
  – Cement replacement materials / secondary reaction
  – Fillers
  – Temperature
  – Curing
Tips for good bridge and pavement concretes

• Strength
  – Cement content, packing of particles, water content
  – Curing
  – Cement replacement materials/fillers

• Volume changes (Shrinkage)
  – Cement and water contents
  – Paste properties
  – Admixtures

• Durability
  – Cement and water contents
  – Replacement materials