Particle Packing and Mixture Design Approach for Eco-SCC

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Ólafur H. Wallevik – Innovation Center Iceland

ACI 2018 Fall Convention, Las Vegas
Towards Eco-SCC and Eco-Crete ...

<table>
<thead>
<tr>
<th>SCC type</th>
<th>Powder content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rich</td>
<td>$\geq 550$ kg/m$^3$</td>
</tr>
<tr>
<td>Regular powder content</td>
<td>$500 \pm 50$ kg/m$^3$</td>
</tr>
<tr>
<td>Lean</td>
<td>$415 \pm 35$ kg/m$^3$</td>
</tr>
<tr>
<td>Green</td>
<td>$350 \pm 35$ kg/m$^3$</td>
</tr>
<tr>
<td>Eco-SCC</td>
<td>$\leq 315$ kg/m$^3$</td>
</tr>
</tbody>
</table>

Wallevik - ICI Rheocenter (2010)

*Mueller, Wallevik, Khayat, Considerations for Designing Low-Powder Self-Compacting Concrete, Proceeding of Eco-Crete, Inter. Symp. on Sustainability, Reykjavik, 2014.*
Particle Packing - Vital for Any-Crete

Reduced paste content leads to:

- Reduced cost
- Reduced temperature rise
- Reduced shrinkage ...

Single-sized

Poorly-graded

Well-graded
Outline

➢ Particle Packing Density and Rheology
➢ Models to Predict Packing Density
➢ Ideal PSD of Solid Particles
➢ Methodology for Eco-SCC Mixture Design
➢ Conclusions
Higher packing density (PD) of aggregate minimizes paste (binder) content.
Effect of Packing Density on Rheology of SCC

Khayat, Hu, Laye, Influence of Aggregate Grain-Size Distribution on Workability of Self-Consolidating Concrete (SCC), Proc., Inter. Conf. on High-Performance Concrete, Hong Kong, 2000, 1001-1024.
Effect of Packing Density on HRWR Demand & Viscosity

- **SF = 720 mm**
  - Binder = 480 kg/m³
  - W/B = 0.40

- **SF = 650 mm**
  - Binder = 550 kg/m³
  - W/B = 0.33
  - SF = 650 mm

**HRWR dosage (kg/m³)**
- P.D. 0.80
- P.D. 0.74

**Plastic viscosity (Pa.s)**
- P.D. 0.80 0.80
- P.D. 0.74 0.75
Particle Packing of Binder

➢ Enhanced **packing characteristics of binder** reduces cement content, water content, HRWRA demand, and viscosity

**Lower voids and higher excess water**

Different particle shapes
Evaluation of PD Density of Aggregates

➢ Intensive compaction tester (ICT)

Density (kg/m$^3$)

![Graph showing the relationship between number of cycles and density](image)

- Sample mass = 1300 g

\[ \Phi = \frac{\rho_{\text{bulk}}}{\rho_{\text{grain}}} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Available range</th>
<th>Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical pressure</td>
<td>bar</td>
<td>0.5-10</td>
<td>2</td>
</tr>
<tr>
<td>Number of cycles</td>
<td></td>
<td>2-512</td>
<td>256</td>
</tr>
<tr>
<td>Velocity</td>
<td>rpm</td>
<td>0-60</td>
<td>60</td>
</tr>
<tr>
<td>Gyratory angle</td>
<td>mrad</td>
<td>0-50</td>
<td>40</td>
</tr>
</tbody>
</table>

Selected Aggregates

- 17 Aggregates (fine and coarse)
- 7 Quarries
- 5 Producers
Packing Density of Mono Type Aggregate

➢ Packing density ranges:
  ✓ Fine: 0.58 - 0.73
  ✓ Intermediate: 0.6 - 0.73
  ✓ Coarse: 0.57 - 0.61

Agg. characteristics affecting PD:
  ✓ Particle size distribution
  ✓ Minimum size
  ✓ Maximum size
  ✓ Shape
  ✓ Angularity
  ✓ Texture
Particle Morphological Characteristics

Aspect ratio \( \frac{L}{W} = \frac{D_{\text{max}}}{D_{\text{min}}} \geq 1 \)

Sphericity \( = \frac{\text{area of particle}}{\text{area of circumscribed circle}} \approx \frac{\pi LW}{4} \leq 1 \)

Surface roughness \( = \frac{1}{mn} \sum_{i=1}^{m} \sum_{j=1}^{n} |Z_{ij}| \)
Effect of Aggregate Characteristics on PD

PD is improved with increased aspect ratio and sphericity and decrease in surface roughness.

Outline

- Particle Packing Density and Rheology
- Models to Predict Packing Density
- Ideal PSD of Solid Particles
- Methodology for Eco-SCC Mixture Design
- Conclusions
Aim Model

Linear Packing Model (LPM)

Toufar Model

**Compressible Packing Model (CPM)**

Basic assumptions:

- Knowledge of PD of each aggregate
- Spherical particles
- No friction
- No overlap between fine and coarse aggregates

\[ K = \sum_{i=1}^{n} K_i = \frac{\sum_{i=1}^{n} y_i/\beta_i}{1/\phi - 1/\gamma_i} \]

- **K**: compaction index (assumed based on consolidation effort)
- **\( \phi \)**: PD of combined aggregates (unknown)
- **\( \beta \)**: PD of each aggregate

\[ \gamma_i = \beta_i \left( 1 - \sum_{j=1}^{i-1} \left[ 1 - \beta_j + b_i \beta_j \left( 1 - 1/\beta_j \right) \right] y_j \right) - \sum_{j=i+1}^{n} \left[ 1 - a_{ij} \beta_i/\beta_j \right] y_j \]

- **\( a_{ij} \)**: Wall effect

\[ a_{ij} = \sqrt{1 - \left( 1 - d_j/d_i \right)^{1.02}} \]

\[ b_{ij} = 1 - \left( 1 - d_j/d_i \right)^{1.50} \]

- **\( d \)**: Characteristic diameter (67% passing diameter); \( d_i, d_j \)

Loosening effect
Packing Density of Binary Aggregate Systems

➢ Rounded aggregate blends have higher PD than crushed blends
➢ There is an optimum value of fine-to-total aggregate (F/A) for each blend
➢ CPM and Toufar models provide better estimates of combined PD
Optimum proportioning of **Fine**, **Intermediate**, and **Coarse** aggregates increases PD from **0.65** to **0.82**
Predicted PD from CPM vs. Measured PD from ICT

- CPM exhibits good accuracy in predicting PD of aggregates
- PD decreases with increasing Loosening and wall effects (accounted for in CPM)

Particle Lattice Effect (PLE)

1 unstable aggregate (will segregate)

1 unstable aggregate + other aggregates of different sizes in the same paste may remain in suspension

**Group effect** is positive when stability of concrete is enhanced

**Magnitude** of PLE depends on coarse aggregate volume fraction and paste rheology but not paste composition (Bethmont et al. 2005, 2009)

Greater PLE if: \( V_{\text{finer class}} \geq V_{\text{coarser adjacent class}} \) (Wallevik, 2009)

**PSD** of sand and coarse aggregate is linear (Wallevik, 2010)

Better stability when volume of stable class \( \geq \) unstable class (Esmaeilkhanian et al., 2017)
Particle Lattice Effect – Stability – and PD – Model Systems

- Glass beads with density 2530 kg/m$^3$
- Monodisperse and polydisperse PSDs

Model Mortar (MM)

Constant rheological properties over testing time

<table>
<thead>
<tr>
<th></th>
<th>Yield stress, Pa</th>
<th>Viscosity, Pa.s</th>
<th>Density, kg/m$^3$</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Dynamic</td>
<td>Static</td>
<td></td>
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<tr>
<td>Model Mortar (MM)</td>
<td>11.1 ± 0.6</td>
<td>13.8 ± 1</td>
<td>3.4 ± 0.1</td>
</tr>
<tr>
<td>Mortar Equivalent Paste (MEP)</td>
<td>11.3 ± 0.6</td>
<td>12.0 ± 0.8</td>
<td>2.7 ± 0.1</td>
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</table>

30% of total volume
25% of total volume
45% of total volume

- Glass beads with density 2530 kg/m$^3$
- Monodisperse and polydisperse PSDs

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Relationship between Particle Packing Density and Segregation Index

No clear relationship between packing density and Segregation index

Segregation Index (SI) = C.O.V. of bead mass over 5 sections

Initial Average Distance between Particles

Excess paste theory

Excess paste layer thickness = K

Approximate initial average distance between particles = 2K

- Assumption: spherical particles positioned at equal distances, no overlap of excess paste
Segregation vs. 2K (average initial distance between particles)

- Segregation increases with increase in 2K
- Relationship is not unique since effect of rheology and density difference is not considered

\[ 2K \propto \text{extent of segregation (Roussel, 2007)} \]

**Final arrangement of particles (δ)**

\[ \delta \propto \frac{\tau}{\Delta \rho g} \]

\( \Delta \rho \): difference between densities of particles and fluid

\( g \): gravitational acceleration

\( \tau \): suspending medium yield stress

\( R^2 = 0.82 \)
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Cumulative fraction of particle size smaller than $D_i$

$$P(D_i) = \frac{D_i^q - D_{\text{min}}^q}{D_{\text{max}}^q - D_{\text{min}}^q}$$

Squares of residuals

$$RSS = \sum_{i=1}^{n} \left[ P_{\text{mix}}(D_i) - P_{\text{tar}}(D_i) \right]^2 \rightarrow \min$$

$D_{\text{min}}$ and $D_{\text{max}}$ : min. and max. particle sizes

$P_{\text{tar}}(D_i)$ and $P_{\text{mix}}(D_i)$ : cumulative fraction of particle size smaller than $D_i$ for target grading curve and composed mixture, respectively

$q$: A&A distribution modulus
Optimization of all solid materials ($d_{\text{min}} = 0.1$ micron for silica fume, and $d_{\text{max}} = 20$ mm)

$$P(d) = \left( \frac{d}{d_{\text{max}}} \right)^q$$

$$P(d) = \frac{d^q - d_{\text{min}}^q}{d_{\text{max}}^q - d_{\text{min}}^q}$$
“q” from $d_{\text{min}}$ to $d_{\text{max}}$ (entire solid skeleton) too fine granular skeleton if $q < 0.27$ and too coarse if $q > 0.3$

best correlation for $q = 0.28$ for $\text{MSA} = 20$ mm

Suitable for SCC design (Hunger, 2010): $0.21 < q < 0.25$
Packing Density vs. A&A Distribution Modulus (q)

- Packing density decreases with increase of $q$
- $q < 0.35$ yields higher packing density
## Optimization of PSD Using Modified A&A Model

<table>
<thead>
<tr>
<th>Reference</th>
<th>Concrete type</th>
<th>Binder (kg/m³)</th>
<th>w/cm</th>
<th>Granular materials</th>
<th>q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brouwers and Radix (2005)</td>
<td>SCC</td>
<td>315</td>
<td>0.55</td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>Mueller et al. (2014)</td>
<td>Eco-SCC</td>
<td>317</td>
<td>0.60</td>
<td>Aggregate and powder</td>
<td>0.27</td>
</tr>
<tr>
<td>Wang et al. (2014)</td>
<td>SCC</td>
<td>380–450</td>
<td>0.4</td>
<td>Aggregate and powder</td>
<td>0.23–0.29</td>
</tr>
<tr>
<td>Yu et al. (2014)</td>
<td>UHPC</td>
<td>650</td>
<td>0.33</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Yu et al. (2013)</td>
<td>LWA Concrete</td>
<td>423</td>
<td>0.54</td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>Khayat and Mehdipour (2014)</td>
<td>Eco-SCC</td>
<td>315</td>
<td>0.45</td>
<td>Aggregate</td>
<td>0.29</td>
</tr>
<tr>
<td>Khayat and Libre (2014)</td>
<td>RCC</td>
<td>300</td>
<td>0.39</td>
<td></td>
<td>0.35</td>
</tr>
</tbody>
</table>

Mixture Design Methodology for Eco-SCC

Propose design method to reduce efforts to develop Eco-SCC

Optimization of volumetric proportions of solid materials based on ideal grading curves

**Choice of materials**
- Input
  - PSD
  - Densities
  - Choice of “q”
  - Water content
  - SP content
  - Air content

**Optimization**
- Criteria
  - Minimizing deviation of PSD of combined solid materials (S, CA, binder):
    - Linear PSD for sand and coarse agg.
    - Funk and Dinger PSD for powder materials

**Mixture design**
- Constraints
  - Choice of binder - from paste studies to reduce water demand

*Esmaeilkhanian, Khayat, Wallevik, Mix Design Approach for Low-Powder Self-Consolidating Concrete: Eco-SCC – Content Optimization and Performance, Materials and Structures, 50 (124) 2017.*
Phases II & III: Materials

Portland cement GU (C)
Class F fly ash (FA)
Silica fume (SF)
Medium-sized limestone filler (LF-M)
Coarse-sized limestone filler (LF-C)
Siliceous river-bed sand (0-5 mm)
CA1 : Coarse agg. 5 – 10 mm
CA2 : Coarse agg. 5 – 14 mm
CA3 : Coarse agg. 10 – 20 mm
CA-R: Coarse agg. 5 – 14 mm

PC-based SP
VMA with premixed SP (stabilizer)
Vinsol resin AEA
1- Material characterization (PSD and Density)
2- Select binder and water contents
3- Determine saturation point of SP at different W/B values
4- Choice of optimum binder composition
5- Optimize proportions of aggregate to secure linear PSD of agg. skeleton
6- Optimize proportions of powder materials to secure PSD of total solid content closest to Funk and Dinger ideal curve (q = 0.28)
Optimize proportions of aggregate based on linear PSD

- $V_{CA2} (5-14 \, mm) = 0$
- $\frac{V_{CA1}}{V_{CA3}} = 1.47 \, (5-10 \, mm)/ (10-20 \, mm)$
- $\frac{V_{sand}}{V_{(sand + CA)}} = 0.517$

Least squares method
Known and Unknown Parameters so Far

Known:

- \( V_{\text{powder}} \) and \( V_{\text{water}} \) selected
- \( V_{\text{air}} = 2\% \ V_{\text{total,concrete}} \) (assumed)
- \( V_{\text{SP}} = 0.2\% \ \frac{m_{\text{powder}}}{\rho_{\text{SP}}} / \text{SP dry content} \)
- \( V_{\text{sand} + CA} = 1- (V_{\text{powder}} + V_{\text{water}} + V_{\text{air}} + V_{\text{SP}}) \)

From aggregate optimization:

- \( V_{\text{CA2}} \) (5-14 mm) = 0
- \( V_{\text{CA1}} = 1.47 \times (V_{\text{CA3}}) \) and \( V_{\text{CA,total}} = V_{\text{sand} + CA} - V_{\text{sand}} \)
- \( V_{\text{sand}} = 0.517 \times V_{(\text{sand} + CA)} \)

Unknown:

- Volumetric proportions of powder materials (Funk and Dinger PSD)
1. Material characterization (PSD and Density)
2. Selection of binder and water contents
3. Determine saturation point of SP at different W/B values
4. Determine optimum binder composition
5. Optimize proportions of aggregate based on linear PSD
6. Optimize proportions of powder materials in terms of total solid content (Funk and Dinger PSD)
Volumetric Proportions of Binder \( C_i \)

Least squares method for PSD of binder materials

Optimization

Volumetric proportions of each binder material

Funk and Dinger – for total solid particles

\[
P(d) = \frac{d^q - d_{\text{min}}^q}{d_{\text{max}}^q - d_{\text{min}}^q}
\]

\( q \) : set to 0.28

Sand and CA volumetric proportions are constant

Unknown: volumetric proportions of binder

Cumulative passing (%)

Aggregate size (micron)

0.1

\( d_{\text{min}} \)

\( d_{\text{max}} \)
3 Optimized Eco-SCC mixtures

Non air-entrained, $V_{pa} = 330 \pm 4$ l/m$^3$

$W/P = 0.65$  \hspace{1cm} $V_{\text{sand}}/V_{\text{agg}} = 0.515$

$V_{CA1}/V_{CA3} = 1.46$

5% SF

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Cement, kg/m$^3$</th>
<th>Fly ash (F), kg/m$^3$</th>
<th>Silica Fume, kg/m$^3$</th>
<th>Total binder, kg/m$^3$</th>
<th>Water, kg/m$^3$</th>
<th>Sand, kg/m$^3$</th>
<th>CA1, kg/m$^3$</th>
<th>CA3, kg/m$^3$</th>
<th>Total SP liq, kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% SF</td>
<td>302</td>
<td>-</td>
<td>12</td>
<td>314</td>
<td>203</td>
<td>925</td>
<td>541</td>
<td>368</td>
<td>2.25</td>
</tr>
</tbody>
</table>
Conclusions

- Packing density of aggregate has considerable effect on rheology
- Gyratory ICT is appropriate methodology to evaluate PD of aggregate
- CPM and modified A&A (Funk and Dinger) models can be effectively applied to optimize aggregate combinations
- Mixture optimization based on ideal grading curve of all solid particles can be employed to achieve Eco-SCC
- Funk and Dinger curve with appropriate distribution modulus (q) is an effective optimization criterion for sand and coarse aggregate PSD
Eco-SCC with powder content of 278 - 308 kg/m³ (470-520 pcy) exhibited:

- **sufficient** passing ability (J-Ring difference ≤ 50 mm)
- Slump flow of **600 ± 30 mm**, V-funnel time ≈ **3 s**
- Stability (sieve index < 10%, T-Box PDI ≤ 4 mm)
- 56-d compressive strength of **30 ± 3 MPa**
- Limited drying shrinkage: 350-650 μm/m after 112 d (7 d moist curing)
- Air-entrained Eco-SCC had **excellent** frost durability (durability factors 97%-100%)