Research on Concrete Applications for Sustainable Transportation

RE-CAST

# Particle Packing and Mixture Design Approach for Eco-SCC

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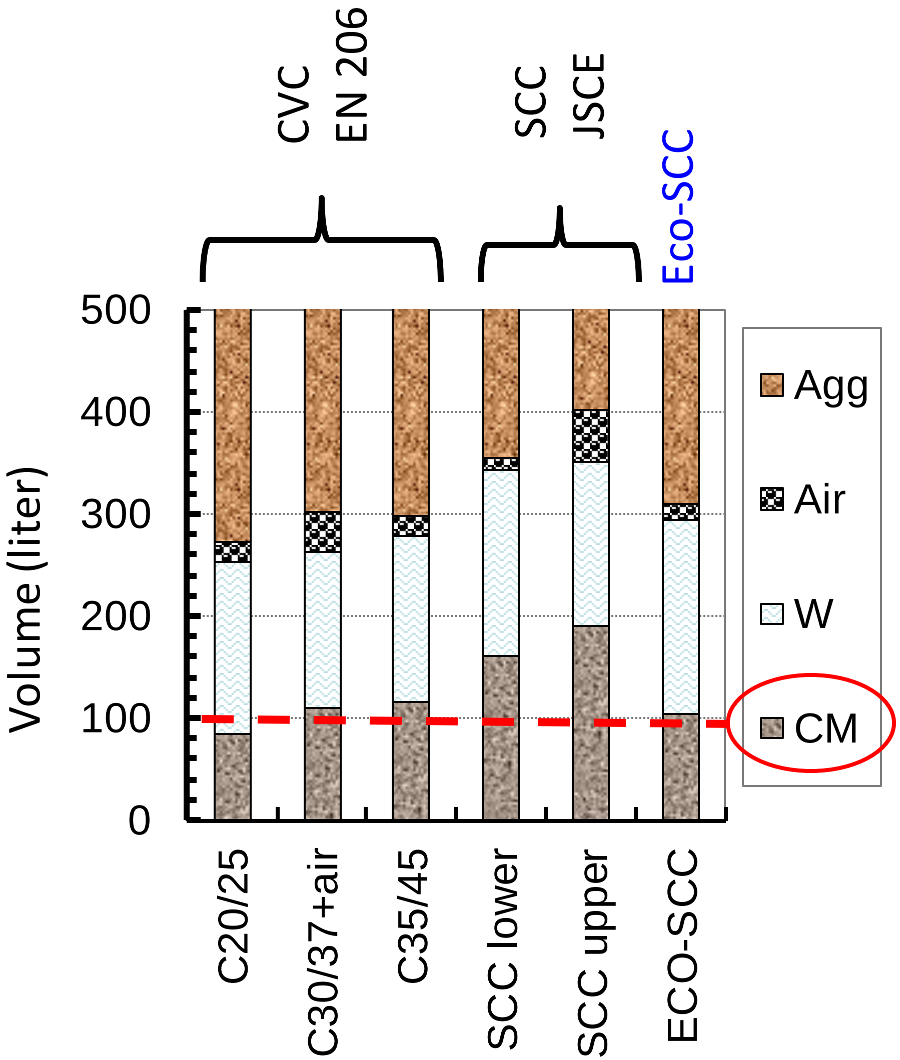
**ACI 2018 Fall Convention, Las Vegas**

# Towards Eco-SCC and Eco-Crete …

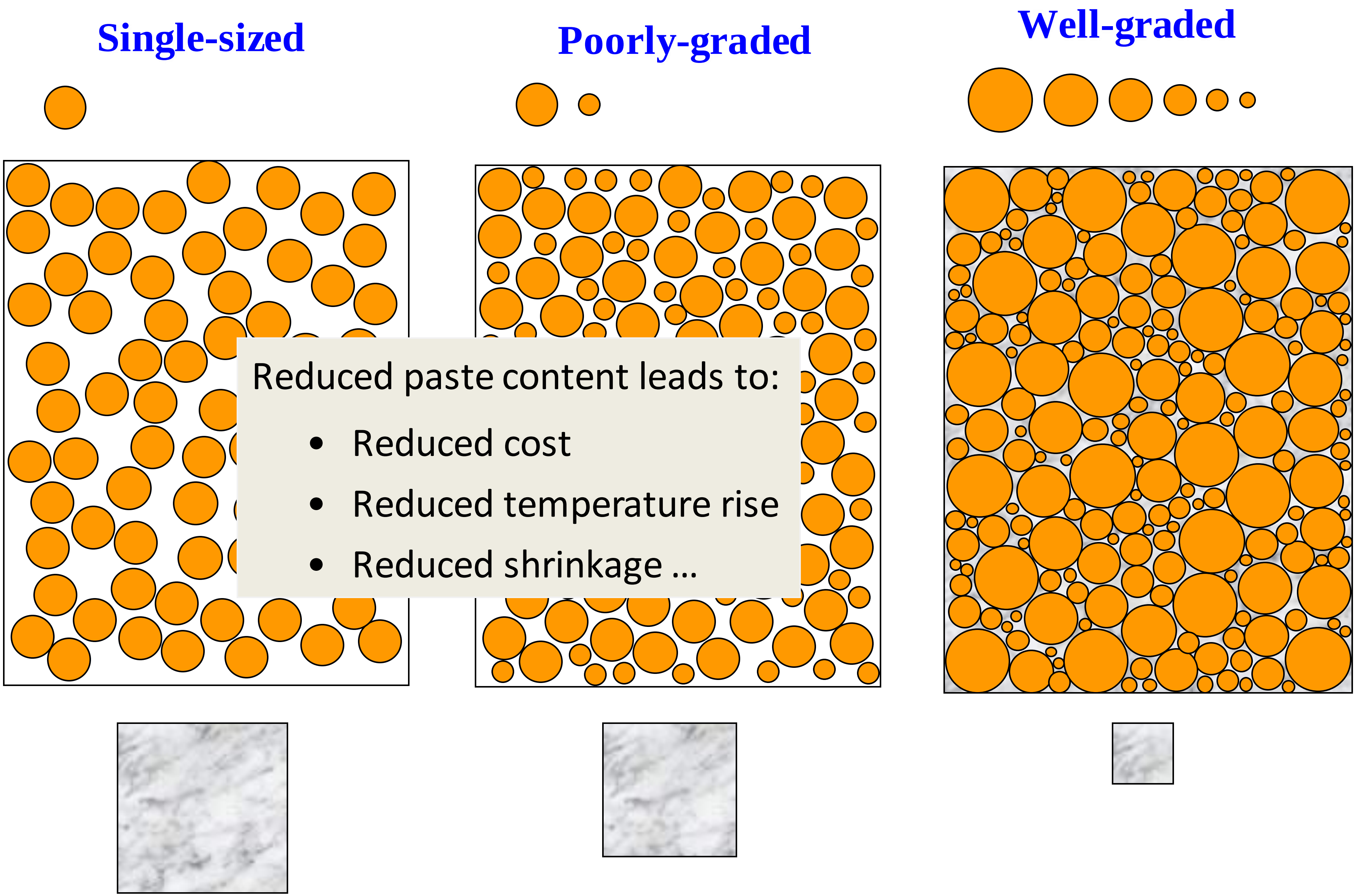
| SCC type | Powder content |
|---|---|
| Rich | ≥ 550 kg/m$^3$ |
| Regular powder content | 500 ± 50 kg/m$^3$ |
| Lean | 415 ± 35 kg/m$^3$ |
| Green | 350 ± 35 kg/m$^3$ |
| Eco-SCC | ≤ 315 kg/m$^3$ |

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



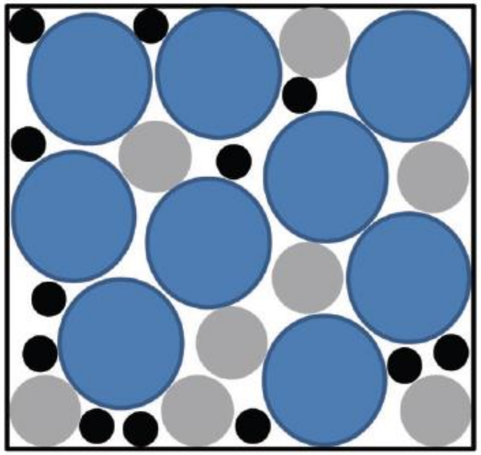

Reduced paste content leads to:

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

# Outline

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

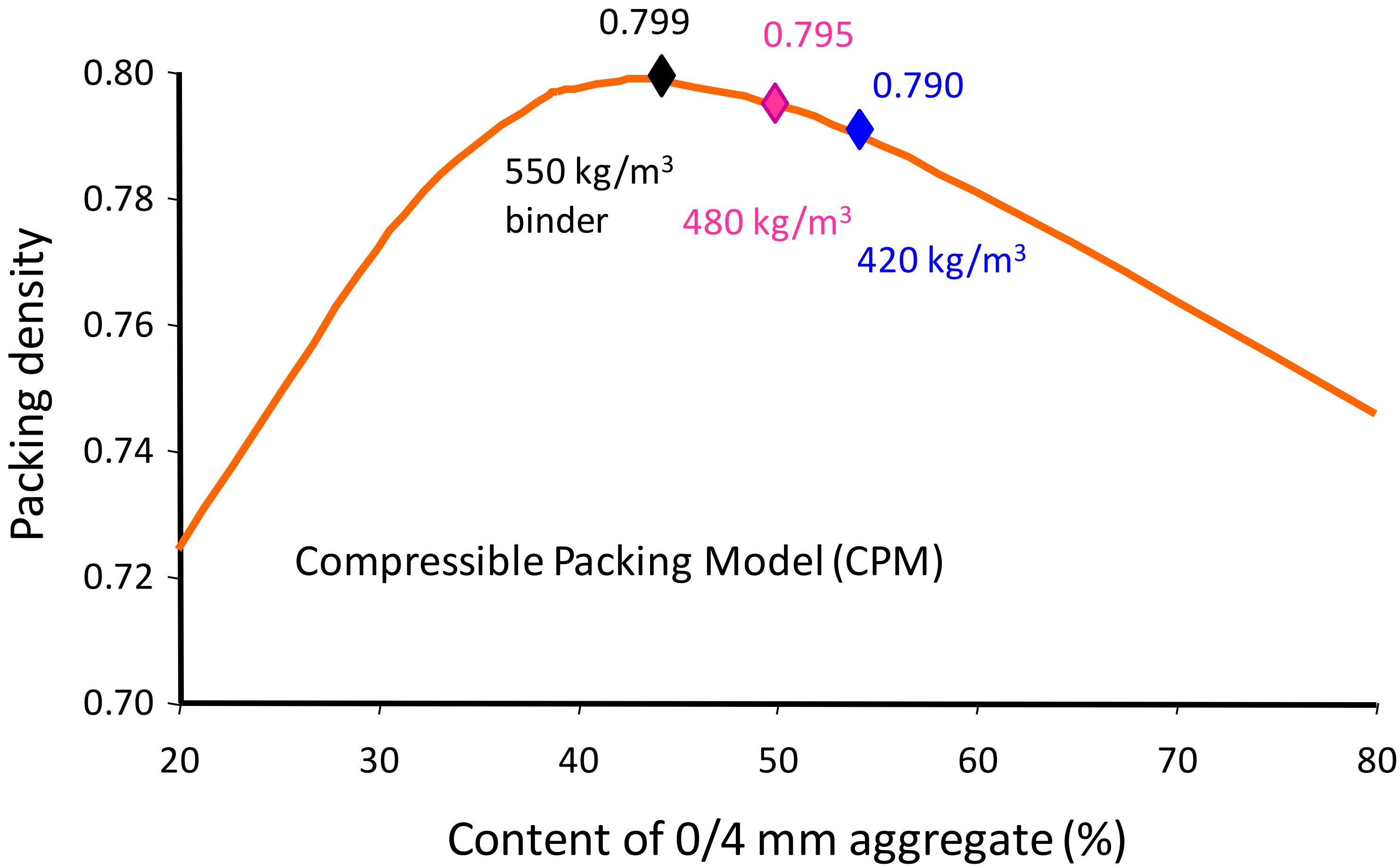
# Higher packing density (PD) of aggregate minimizes paste (binder) content




$$\Phi = \frac{\rho_{bulk}}{\rho_{grain}} = \frac{\frac{M_S}{V_T}}{\frac{M_S}{V_S}} = \frac{M_S}{V_T} \cdot \frac{V_S}{M_S} = \frac{V_S}{V_T}$$

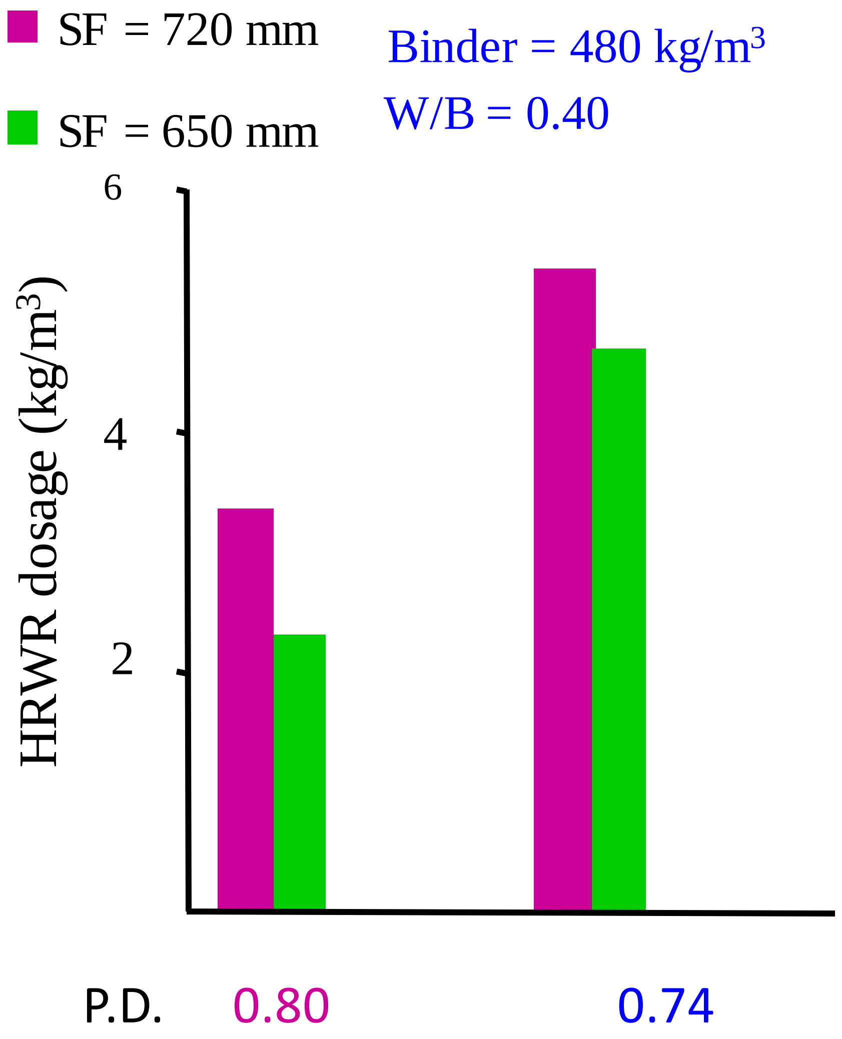
$$\phi = \frac{Vs}{Vt} = \frac{Vs}{Vs + Vv} = 1 - e$$

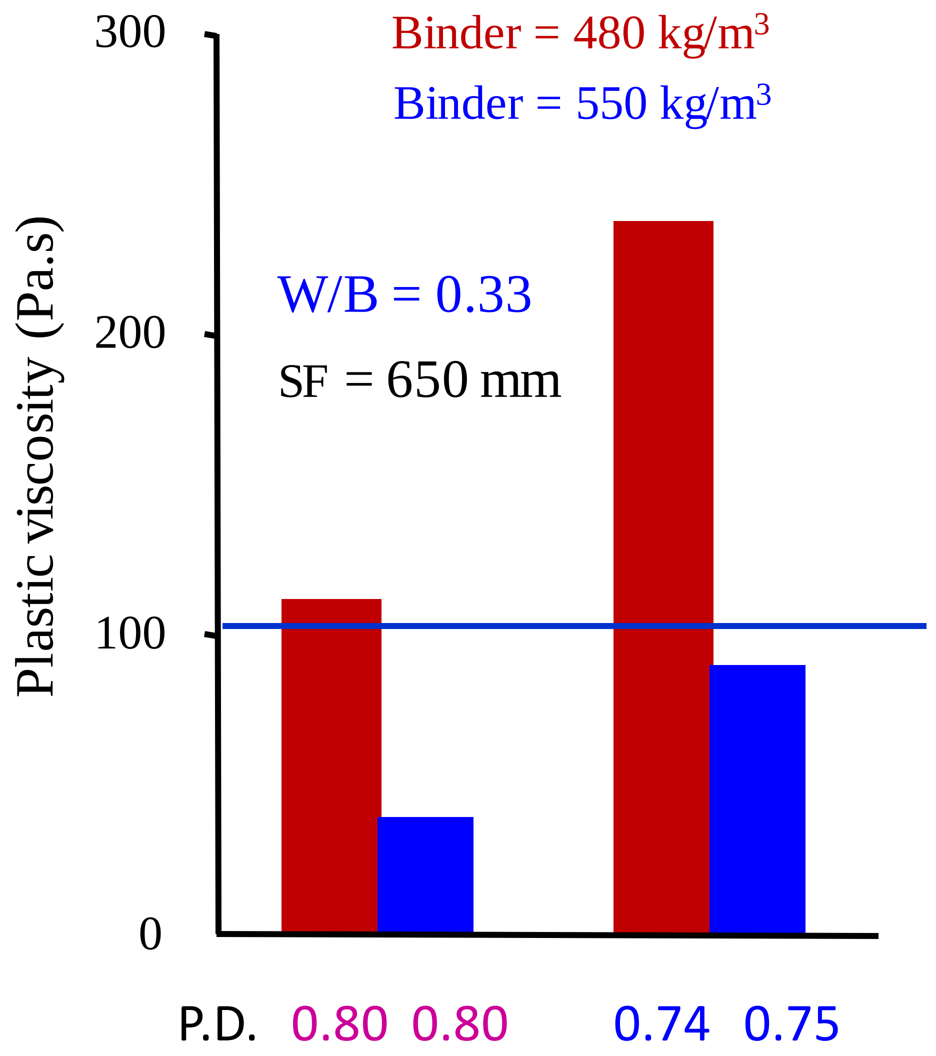
# Effect of Packing Density on Rheology of SCC




*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

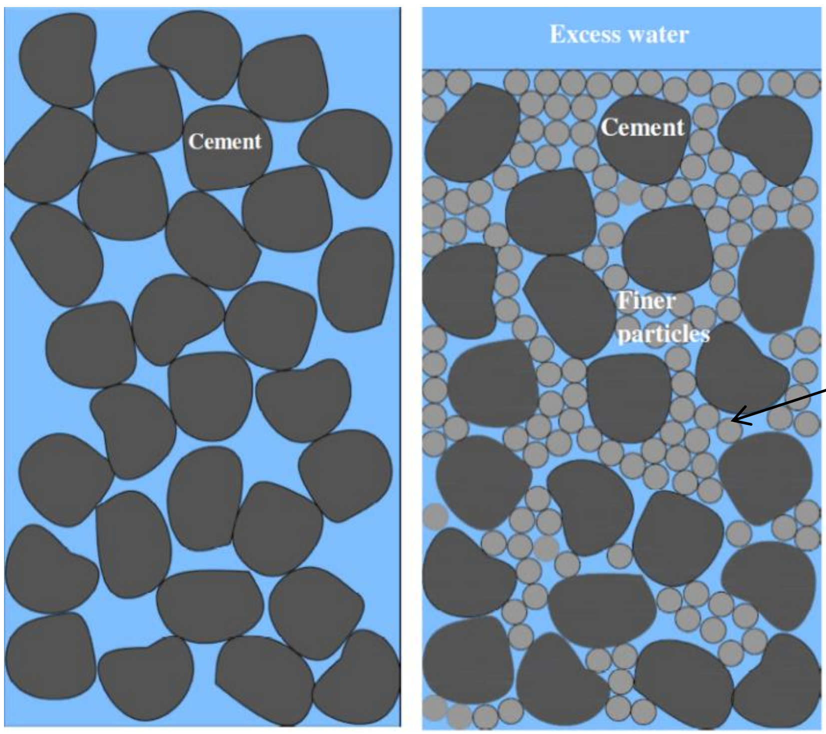


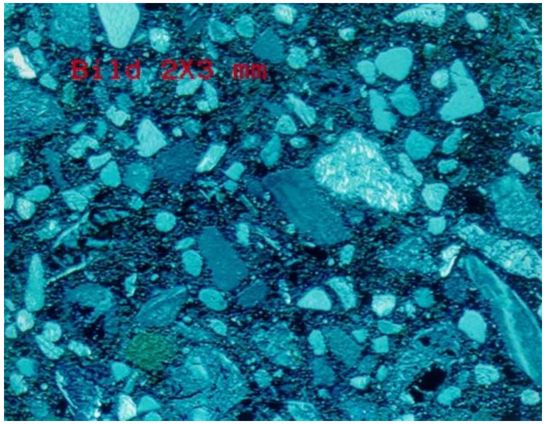
# Particle Packing of Binder

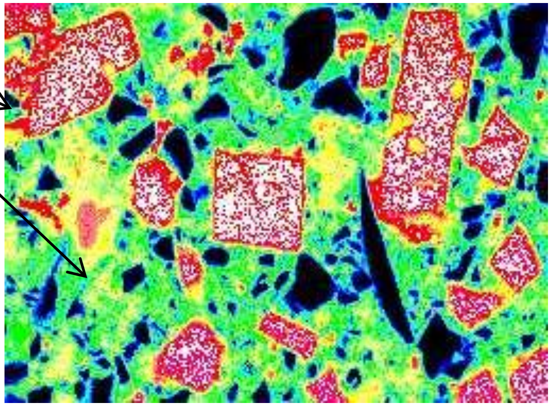
- Enhanced packing characteristics of binder reduces cement content, water content, HRWRA demand, and viscosity

**Lower voids and higher excess water**



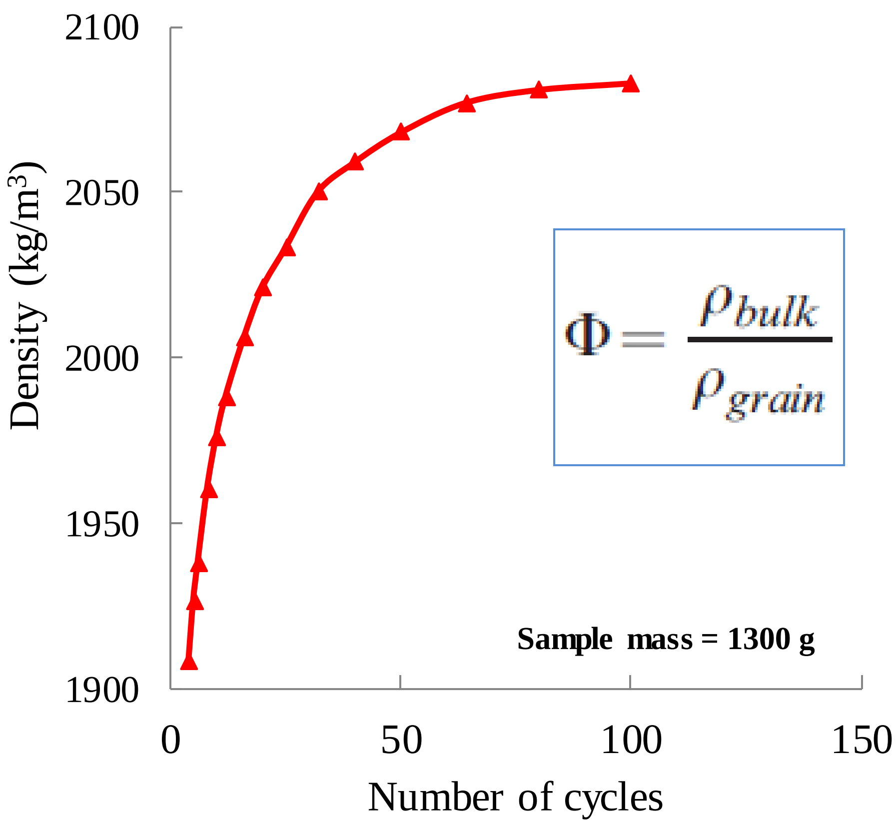

**Different particle shapes**



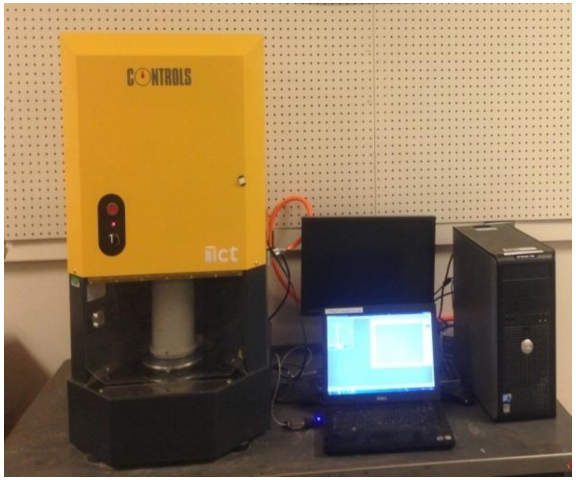



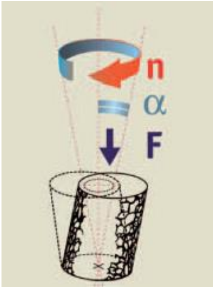
# Evaluation of PD Density of Aggregates

- Intensive compaction tester (ICT)




$$\Phi = \frac{\rho_{bulk}}{\rho_{grain}}$$



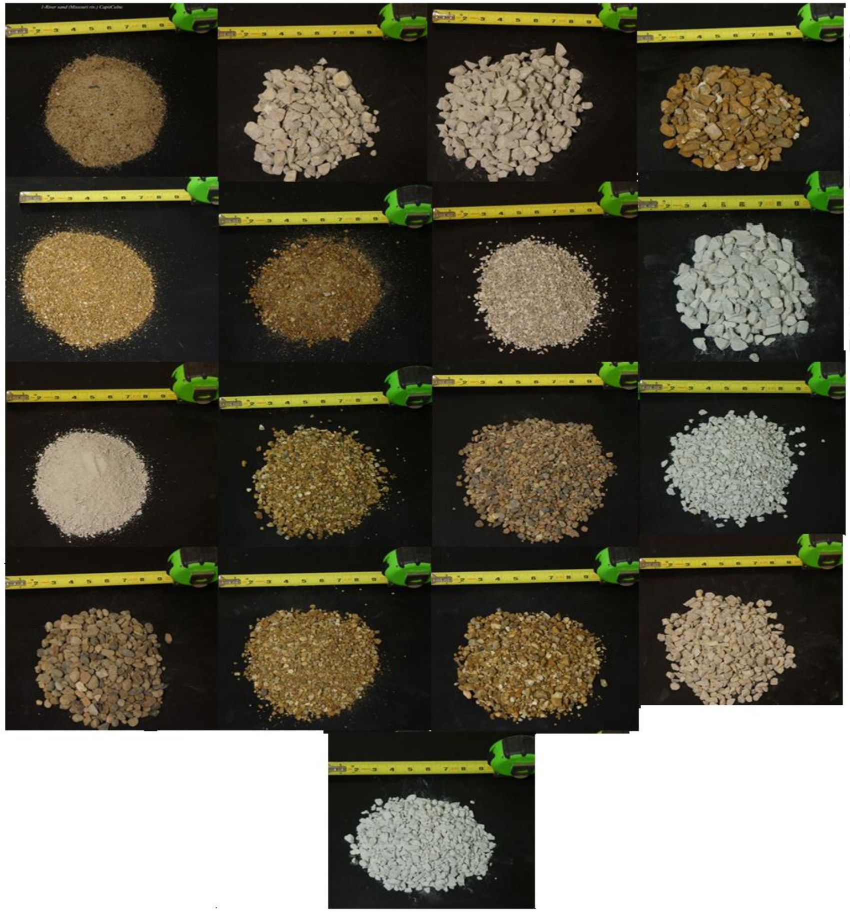



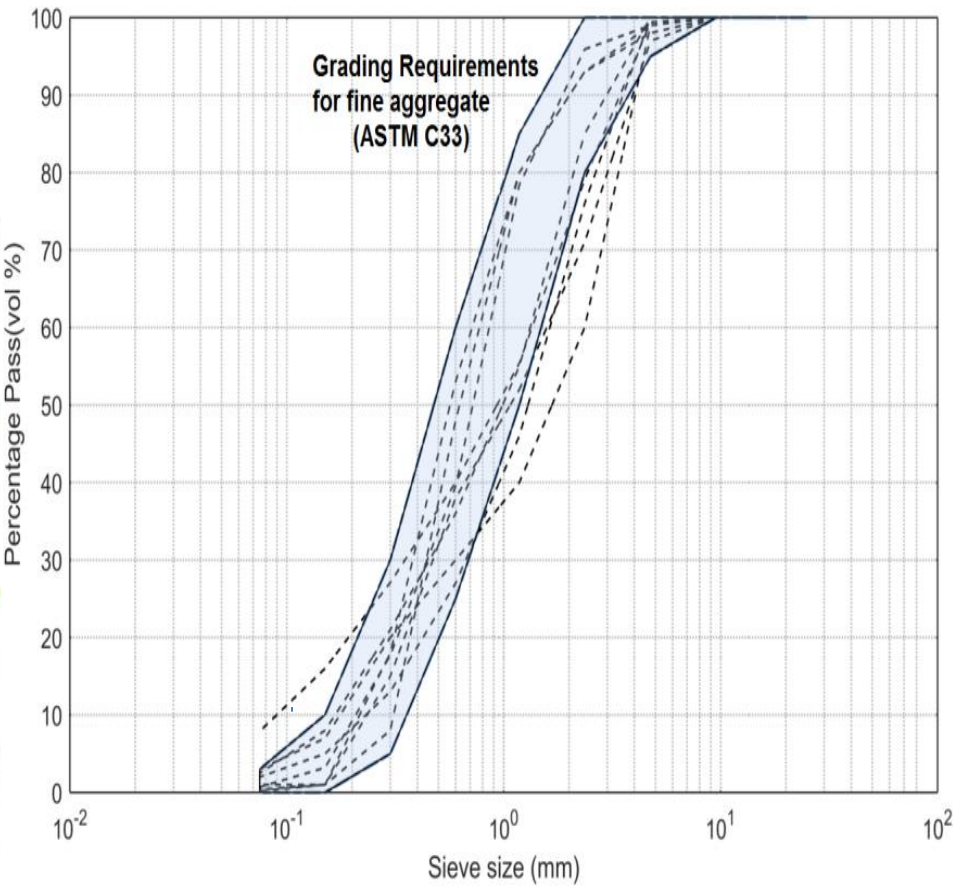

| Parameter | Unit | Available range | Selected |
|---|---|---|---|
| Vertical pressure | bar | 0.5-10 | 2 |
| Number of cycles | | 2-512 | 256 |
| Velocity | rpm | 0-60 | 60 |
| Gyratory angle | mrad | 0-50 | 40 |

*Mehdipour, I., Khayat, K.H., Understanding the Role of Particle Packing Characteristics in Rheo-Physical Properties of Cementitious Suspensions: A Literature Review, Construction and Building Materials,* ***161****, 2018, 340-353.*

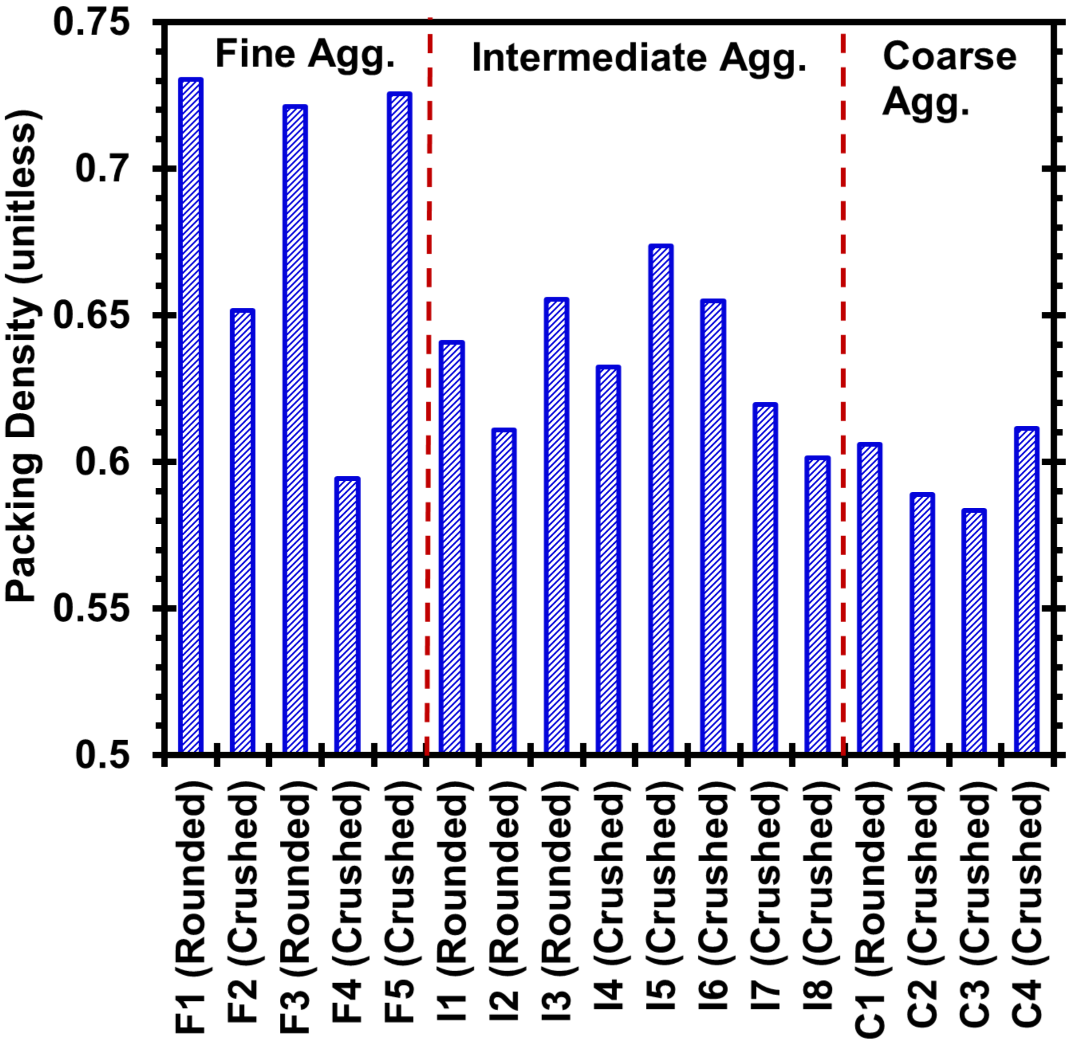
# Selected Aggregates

- 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:

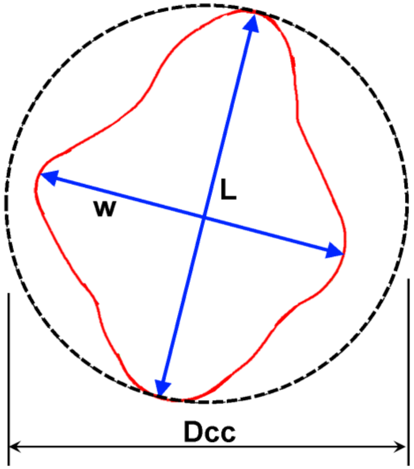
- ✓ Particle size distribution
- ✓ Minimum size
- ✓ Maximum size
- ✓ Shape
- ✓ Angularity
- ✓ Texture

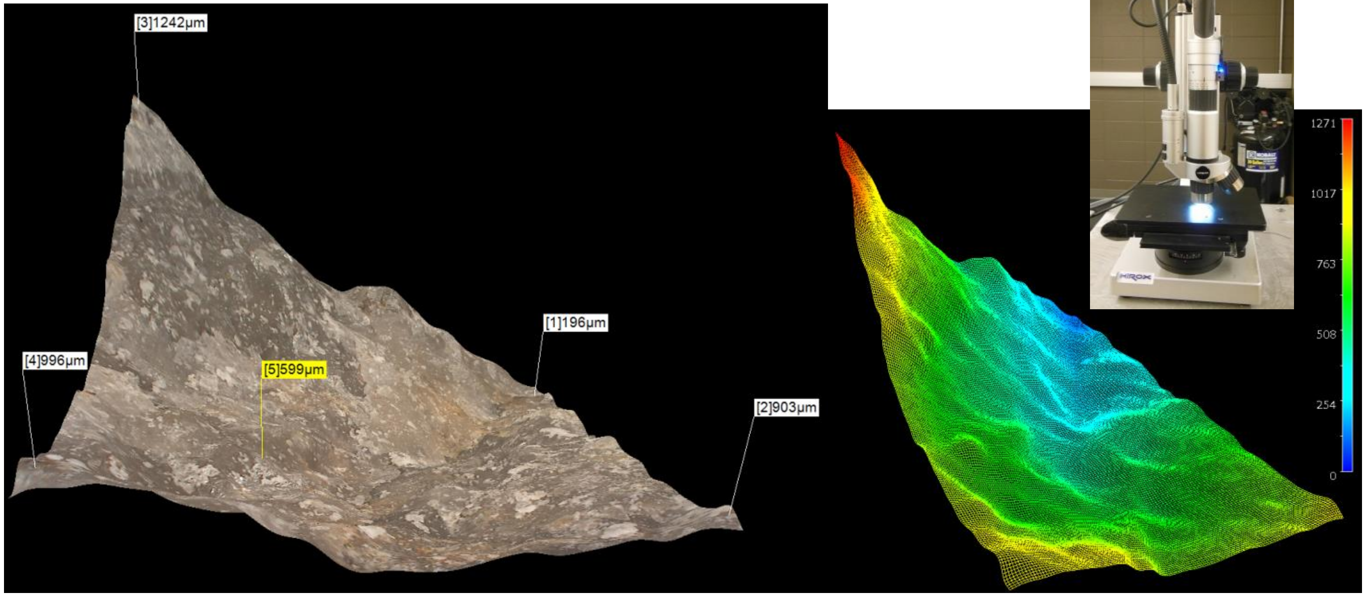
# Particle Morphological Characteristics

$$Aspect\ ratio = \frac{L}{W} = \frac{D_{\max}}{D_{\min}} \geq 1$$

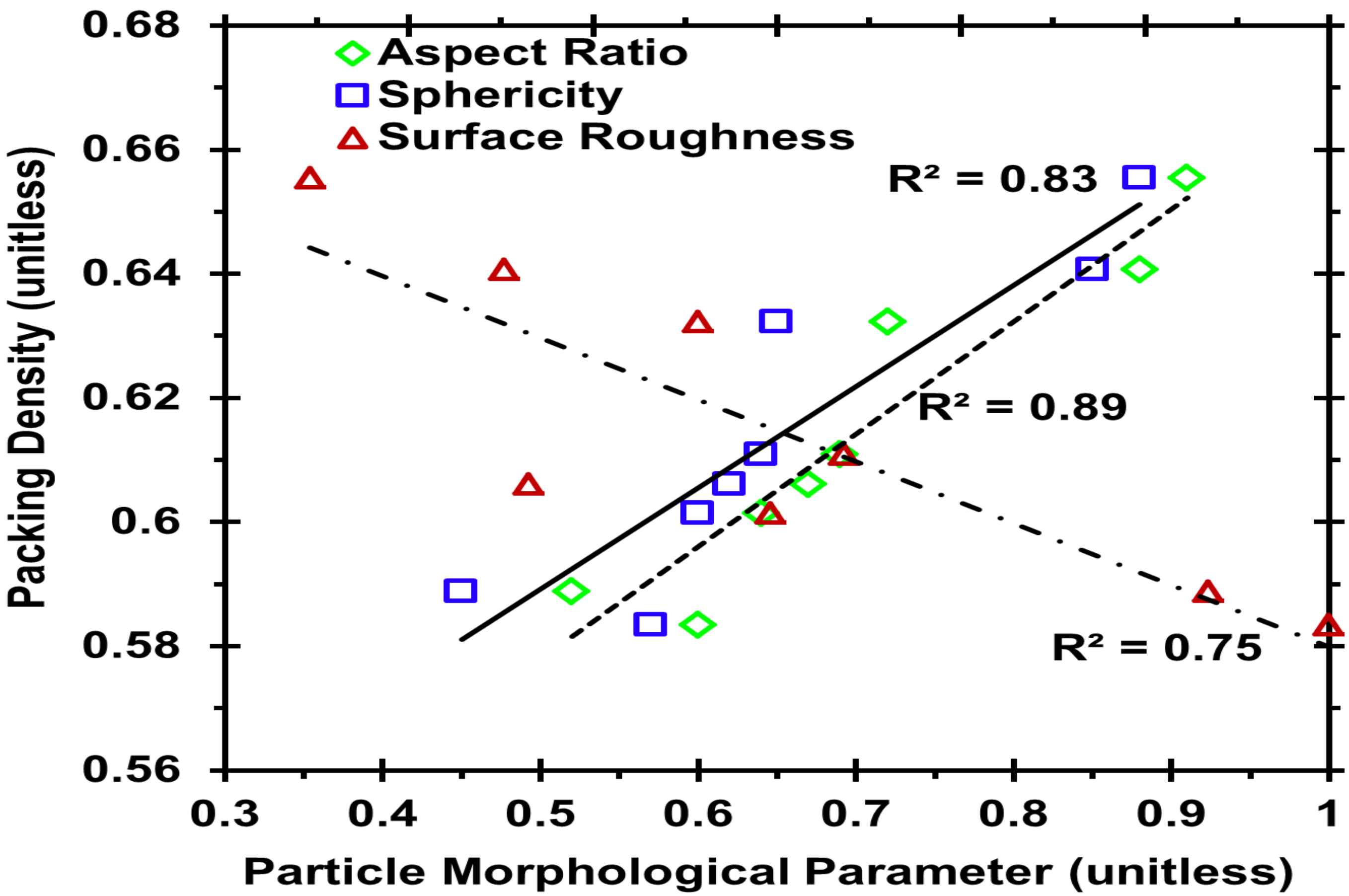
$$Sphericity = \frac{area\ of\ particle \overset{elliptical\ shape}{\approx} \pi LW/4}{area\ of\ circumscribed\ circle = \pi D_{cc}^2/4} \leq 1$$

$$Surface\ roughness = \frac{1}{mn}\sum_{i=1}^{m}\sum_{j=1}^{n}\left|Z_{ij}\right|$$



# Effect of Aggregate Characteristics on PD




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

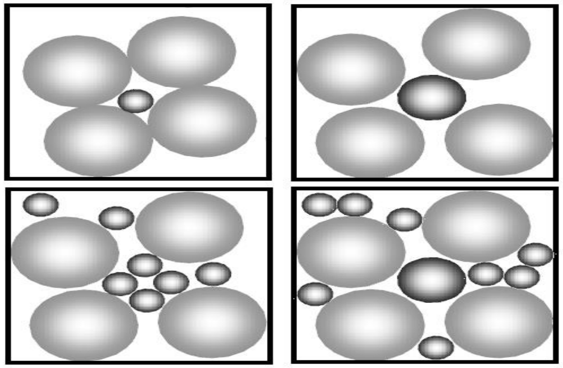
*Mehdipour, I., Khayat, K.H., Understanding the Role of Particle Packing Characteristics in Rheo-Physical Properties of Cementitious Suspensions: A Literature Review, Construction and Building Materials,* ***161****, 2018, 340-353.*

# Outline

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

# Packing Models for Solids

- 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

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

K: compaction index (assumed based on consolidation effort)

ϕ: PD of combined aggregates (unknown)

β: PD of each aggregate

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

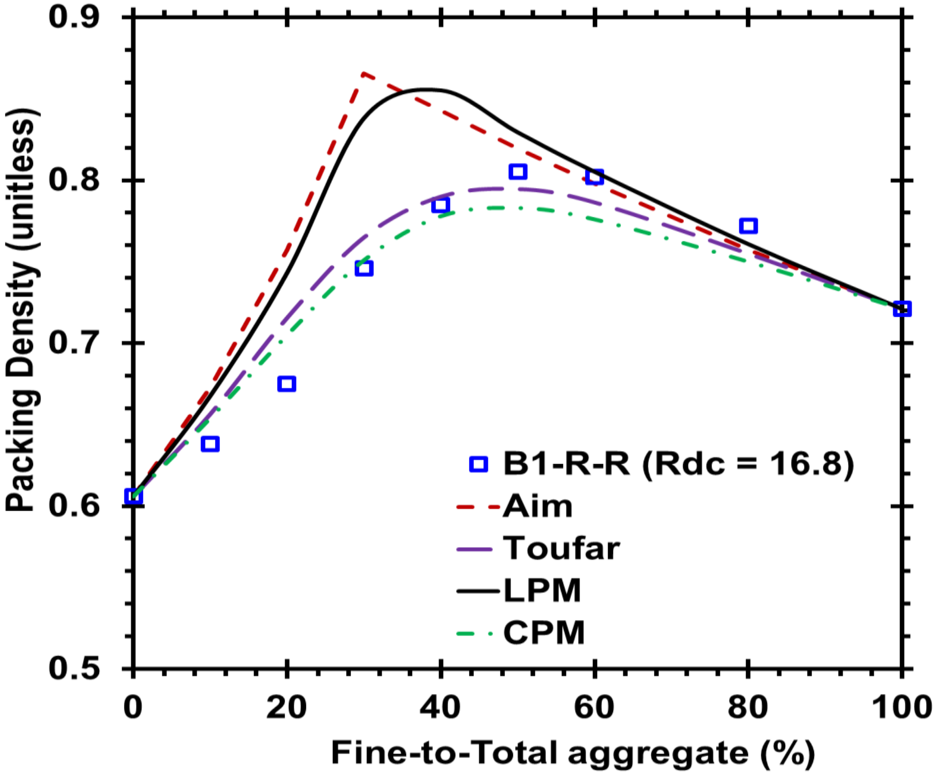
$$a_{ij} = \sqrt{1 - \left(1 - d_j/d_i\right)^{1.02}}$$ Wall effect

$$b_{ij} = 1 - \left(1 - d_j/d_i\right)^{1.50}$$ Loosening effect

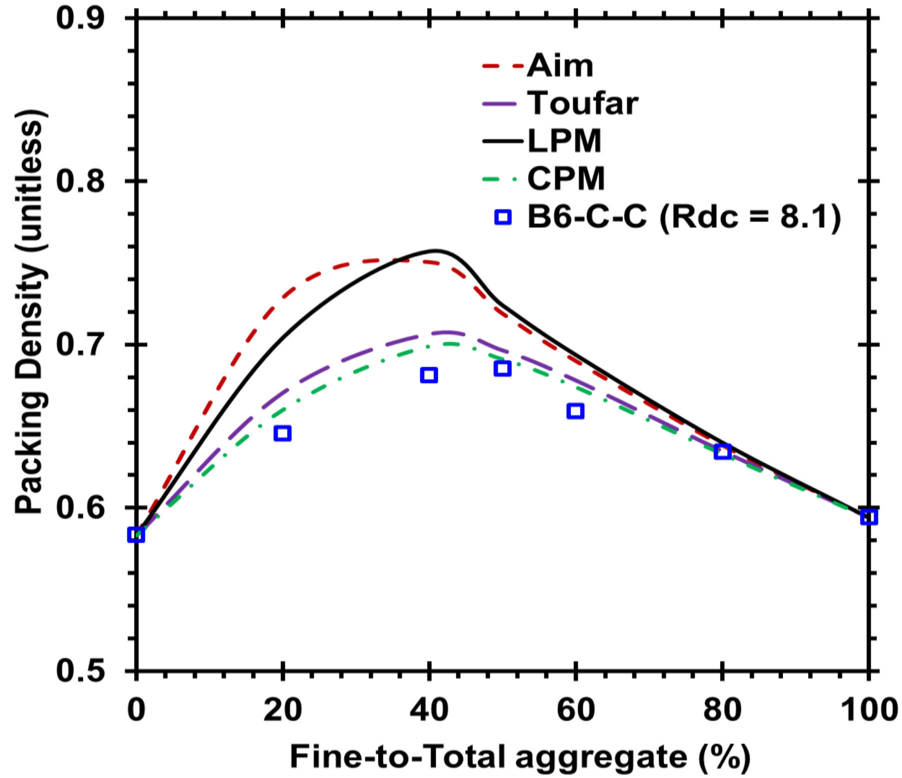
d: Characteristic diameter (67% passing diameter); $d_i$ , $d_j$

# Packing Density of Binary Aggregate Systems

Rounded aggregate

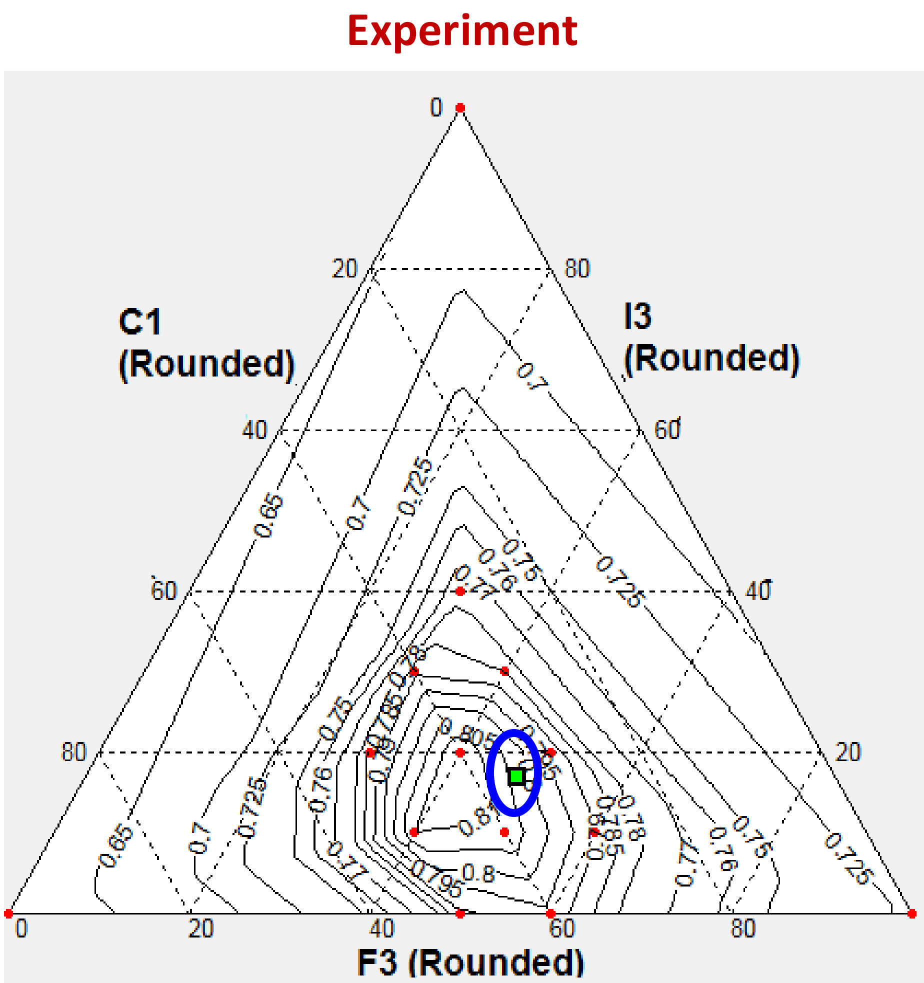


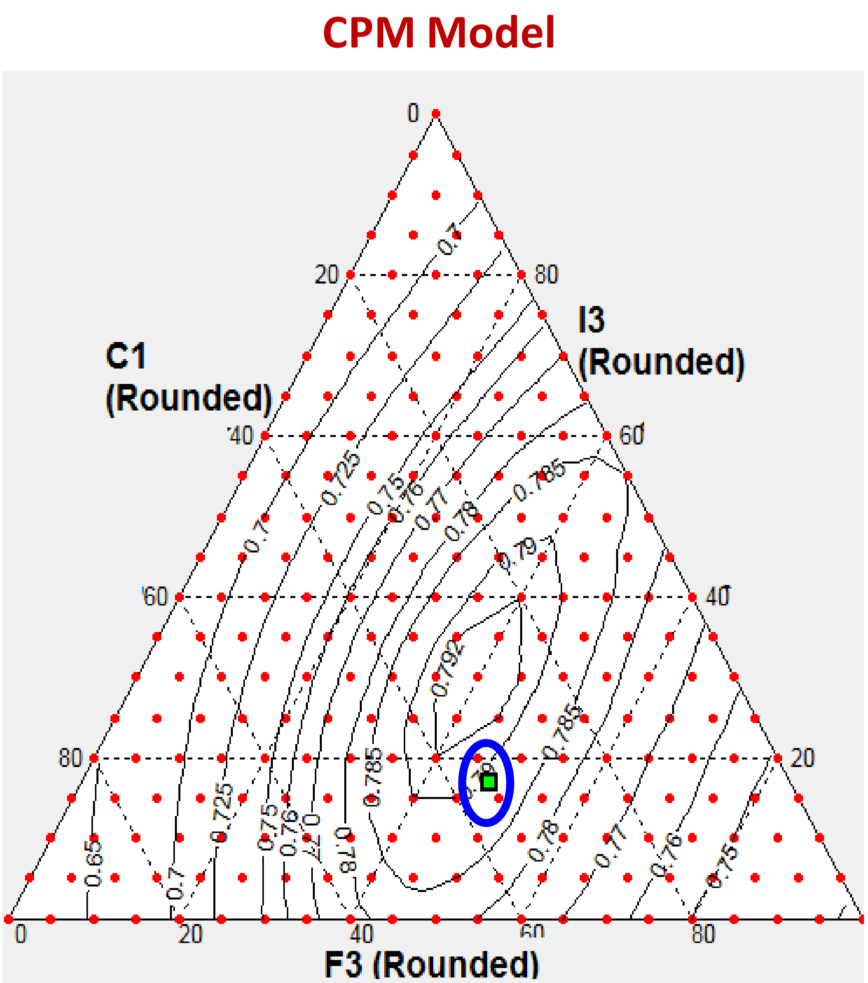

Crushed aggregate




- 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

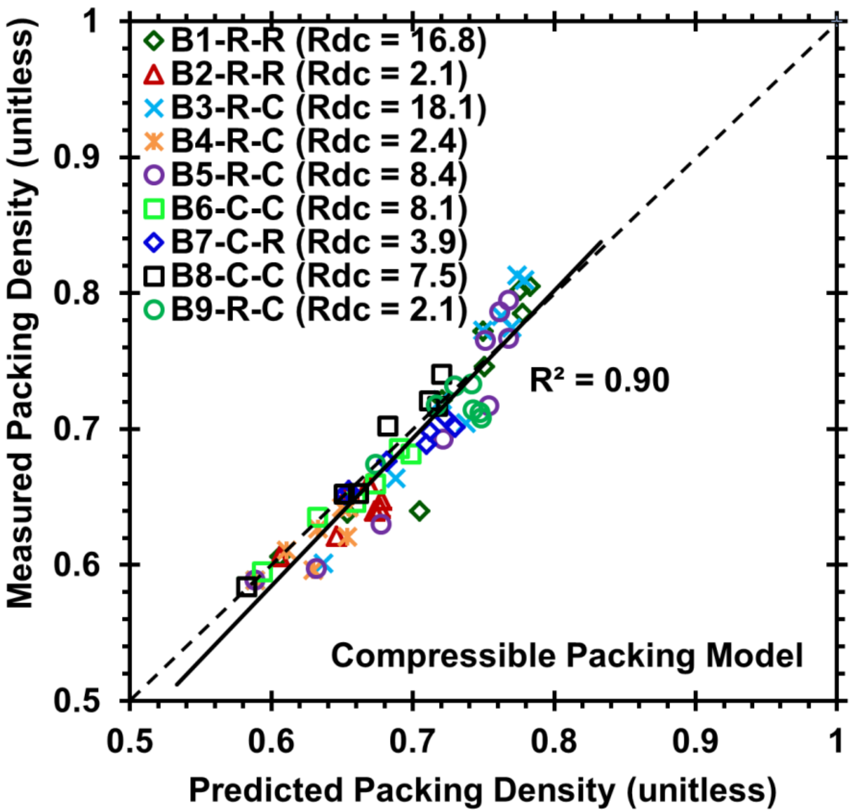
# Packing Density of Ternary Aggregate Systems (F-I-C)

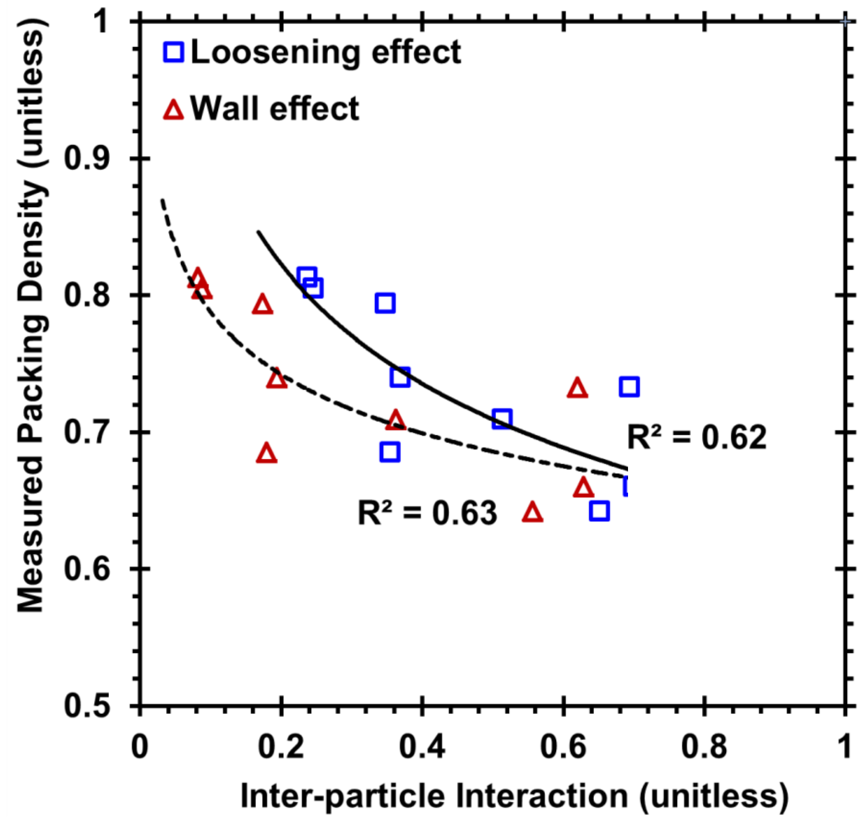



Optimum proportioning of **Fine, Intermediate, and Coarse aggregates** increases PD from 0.65 to 0.82

# Predicted PD from CPM vs. Measured PD from ICT



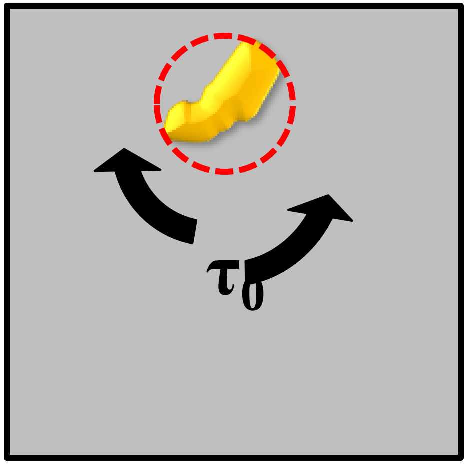




- CPM exhibits good accuracy in predicting PD of aggregates
- PD decreases with increasing Loosening and wall effects (accounted for in CPM)

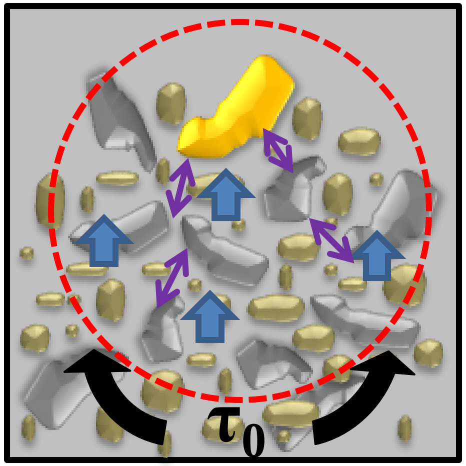
*Mehdipour, I., Khayat, K.H., Understanding the Role of Particle Packing Characteristics in Rheo-Physical Properties of Cementitious Suspensions: A Literature Review, Construction and Building Materials,* ***161****, 2018, 340-353.*

# 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)*

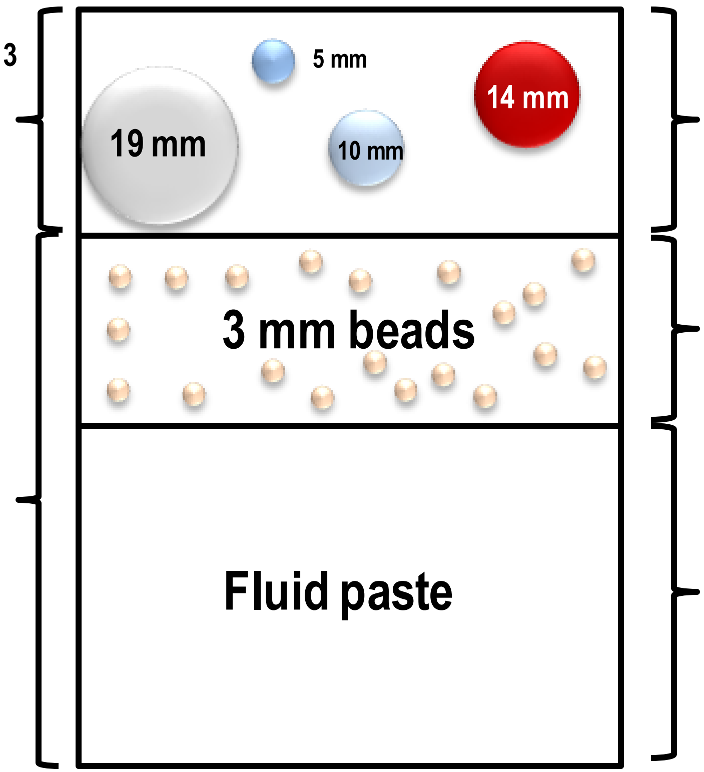
**Greater PLE if:** $V_{\text{finer class}} \geq V_{\text{coarser adjacent class}}$ *(Wallevik, 2009)*

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

**Better stability when volume of stable class ≥ 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




30% of total volume

25% of total volume

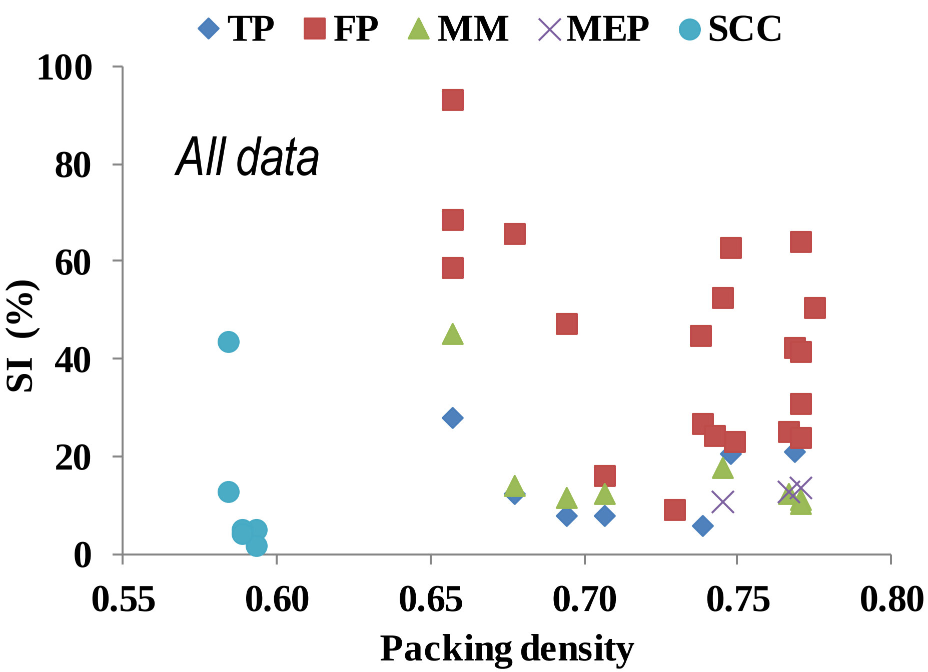
45% of total volume

Model Mortar (MM)

Constant rheological properties over testing time

| | Yield stress, Pa | | Viscosity, Pa.s | Density, kg/m$^3$ |
|---|---|---|---|---|
| | Dynamic | Static | | |
| Model Mortar (MM) | 11.1 ± 0.6 | 13.8 ± 1 | 3.4 ± 0.1 | 2075 ± 10 |
| Mortar Equivalent Paste (MEP) | 11.3 ± 0.6 | 12.0 ± 0.8 | 2.7 ± 0.1 | 2045 ± 10 |

# Relationship between Particle Packing Density and Segregation Index




No clear relationship between packing density and Segregation index

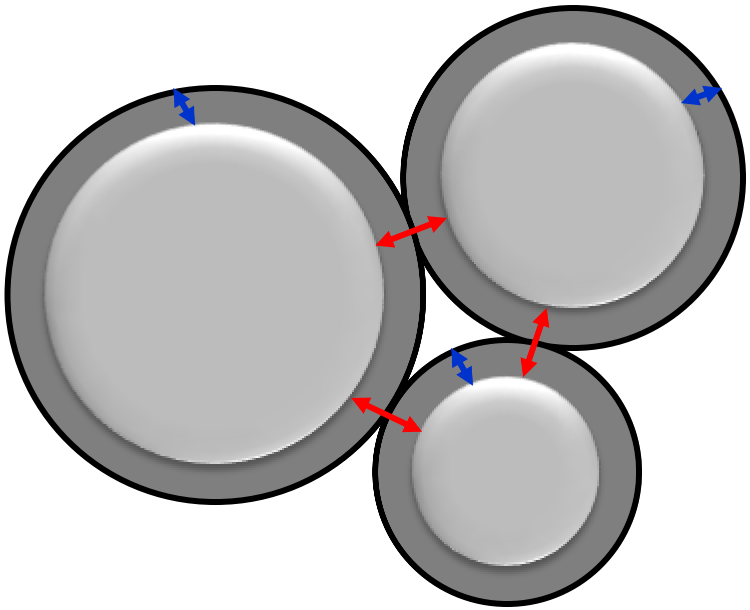
Segregation Index (SI) = C.O.V. of bead mass over 5 sections


*Esmaeilkhanian, B., Diederich, P., Khayat, K.H., Yahia, A., Wallevik, Ó.H., Influence of Particle Lattice Effect on Stability of Suspensions: Application to Self-Consolidating Concrete, Materials and Structures, 50 (39), 2107.*

# Initial Average Distance between Particles

Excess paste theory

Excess paste layer thickness = K



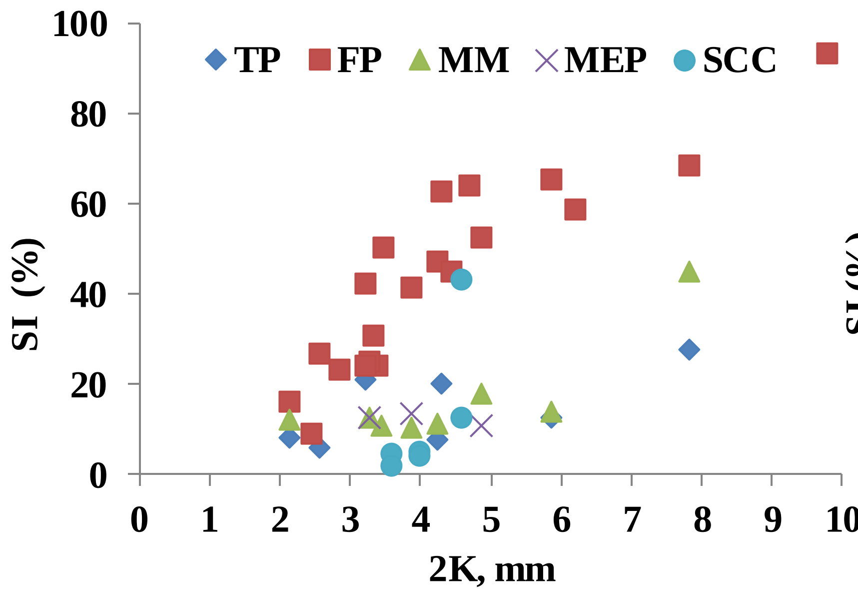
Approximate initial average distance between particles = 2K

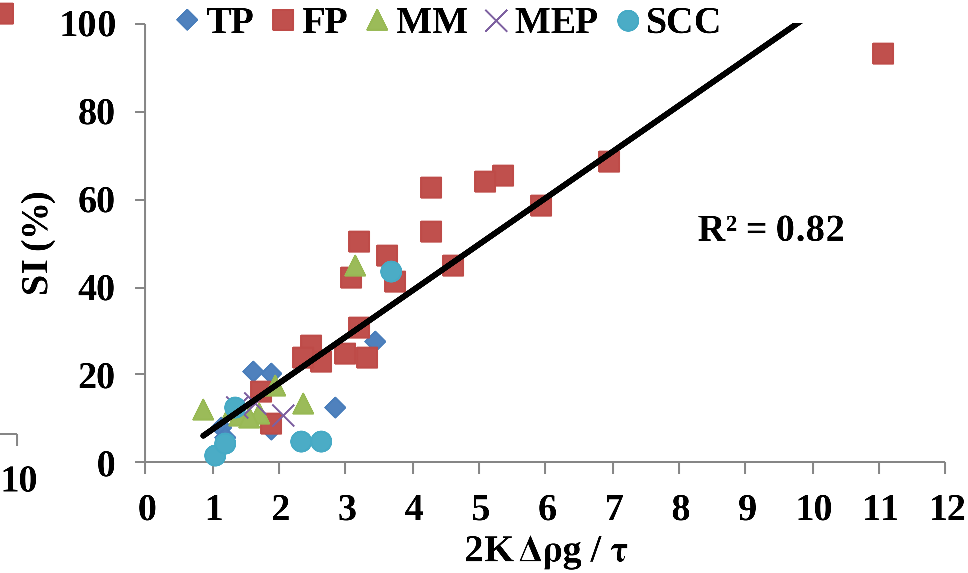
- Assumption: spherical particles positioned at equal distances, no overlap of excess paste

# Segregation vs. 2K (average initial distance between particles)

2K ∝ extent of segregation (Roussel, 2007)

final arrangement of particles (δ) ∝ $\frac{\tau}{\Delta\rho g}$




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

Δρ: difference between densities of particles and fluid
g: gravitational acceleration
τ: suspending medium yield stress

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# Theoretical Packing Models for Solids

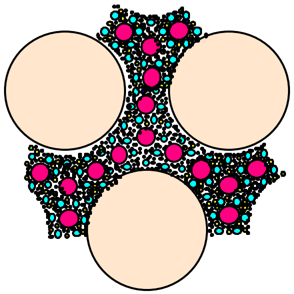
- Aim Model
- Linear Packing Model (LPM)
- Toufar Model
- Compressible Packing Model (CPM)
- **Modified Andreasen & Andersen (A&A model) : Funk & Dinger (1994)**

Cumulative fraction of particle size smaller than $D_i$

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

Squares of residuals

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



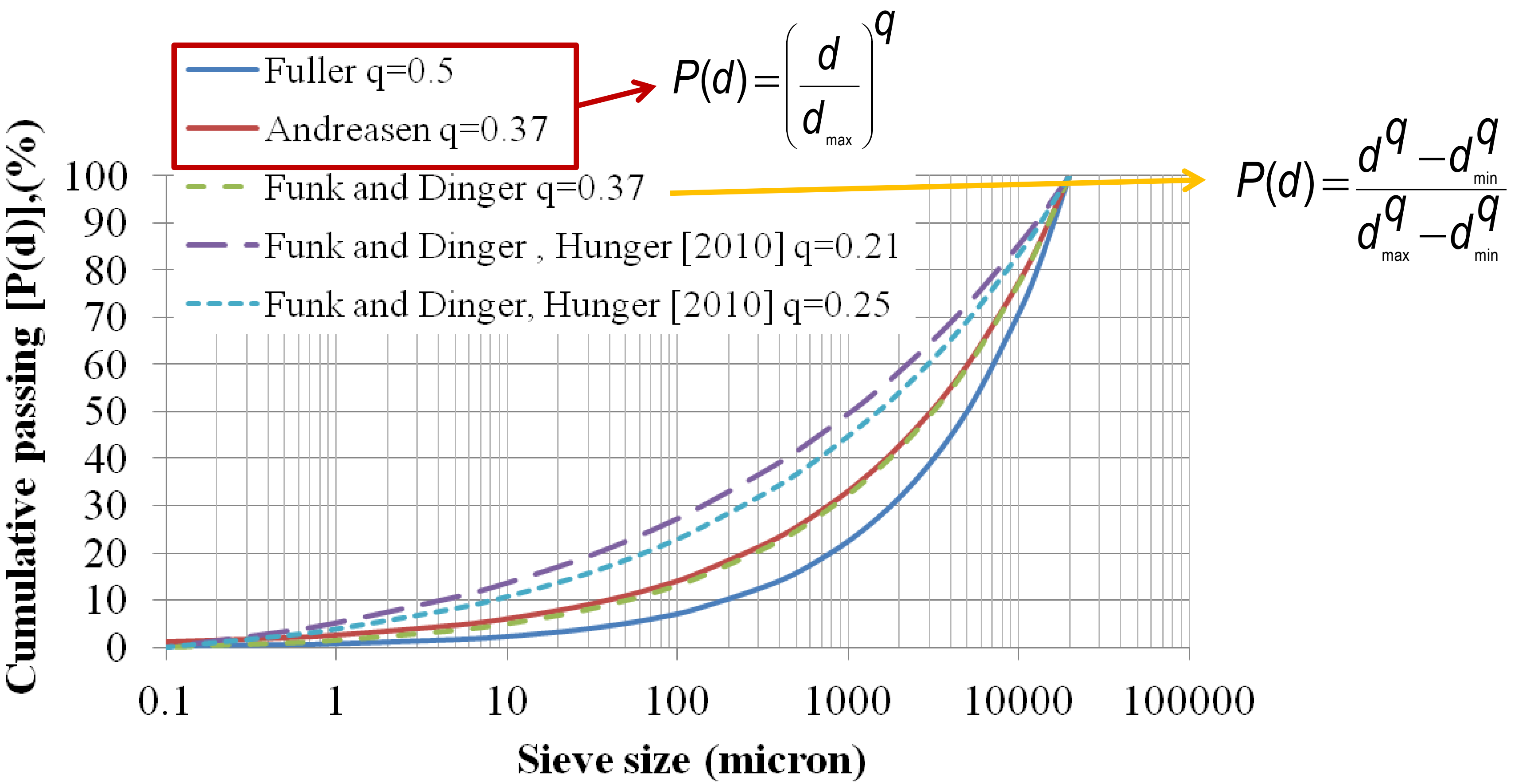
$D_{min}$ and $D_{max}$ : min. and max. particle sizes

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

*q:* A&A distribution modulus

# Ideal Particle-size Distribution of Solid Particles - Background

Optimization of all solid materials ($d_{min}$ = 0.1 micron for silica fume, and $d_{max}$ = 20 mm)

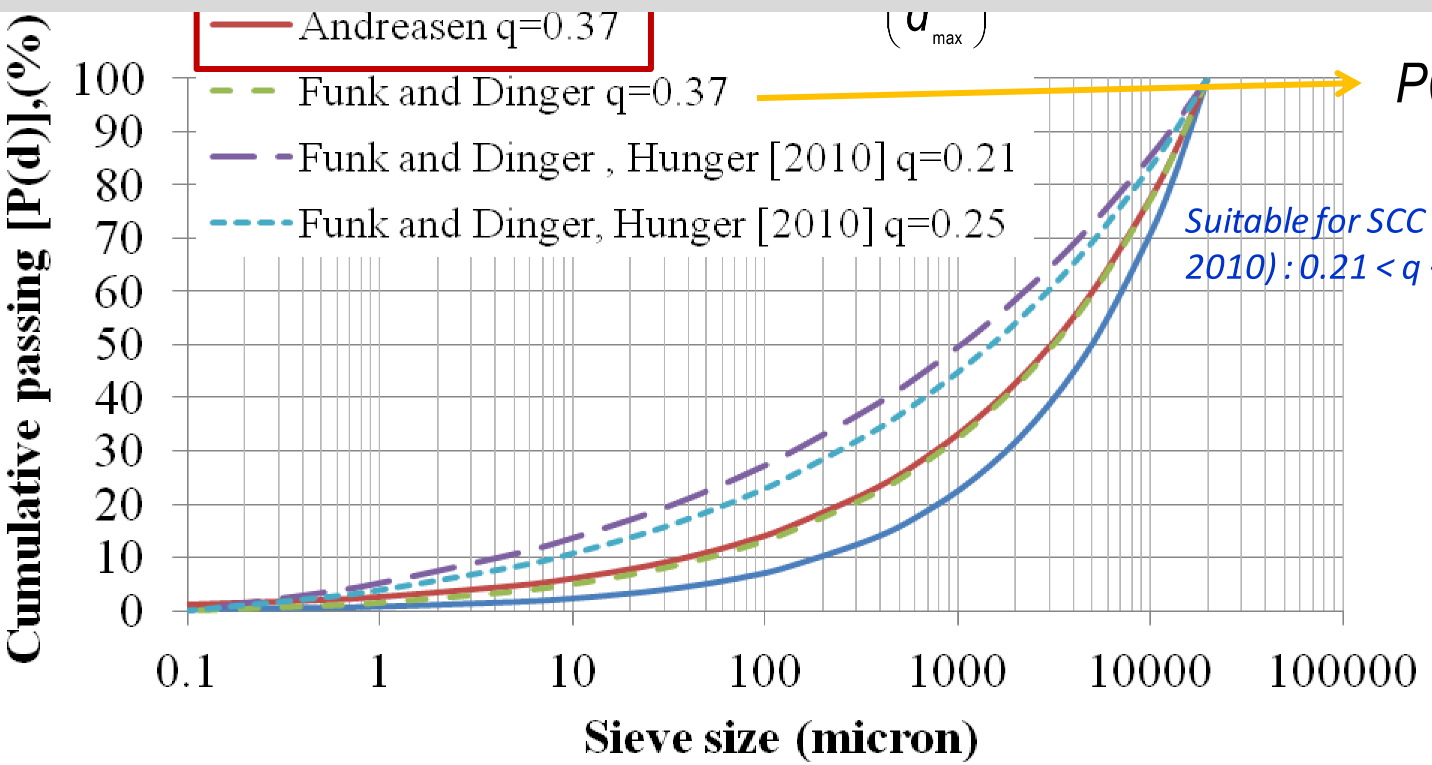


# Ideal Particle-size Distribution of Solid Particles - Background

"q" from $d_{min}$ to $d_{max}$ (entire solid skeleton)

too fine granular skeleton if q < 0.27 and too coarse if q > 0.3

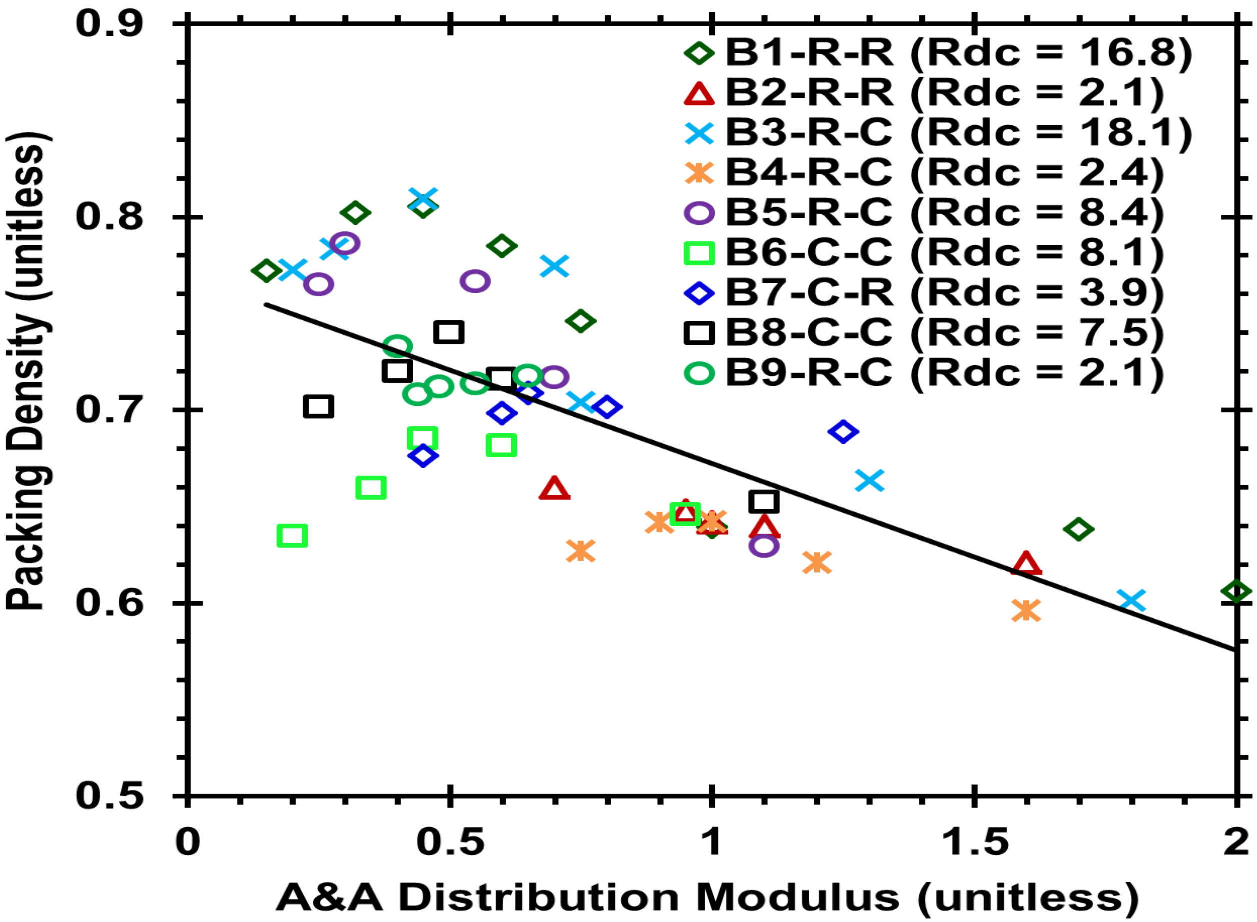
best correlation for q = 0.28 for MSA = 20 mm




$$P(d)=\frac{d^q-d_{min}^q}{d_{max}^q-d_{min}^q}$$

*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

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

*Mehdipour, I., Khayat, K.H., Understanding the Role of Particle Packing Characteristics in Rheo-Physical Properties of Cementitious Suspensions: A Literature Review, Construction and Building Materials,* ***161****, 2018, 340-353.*

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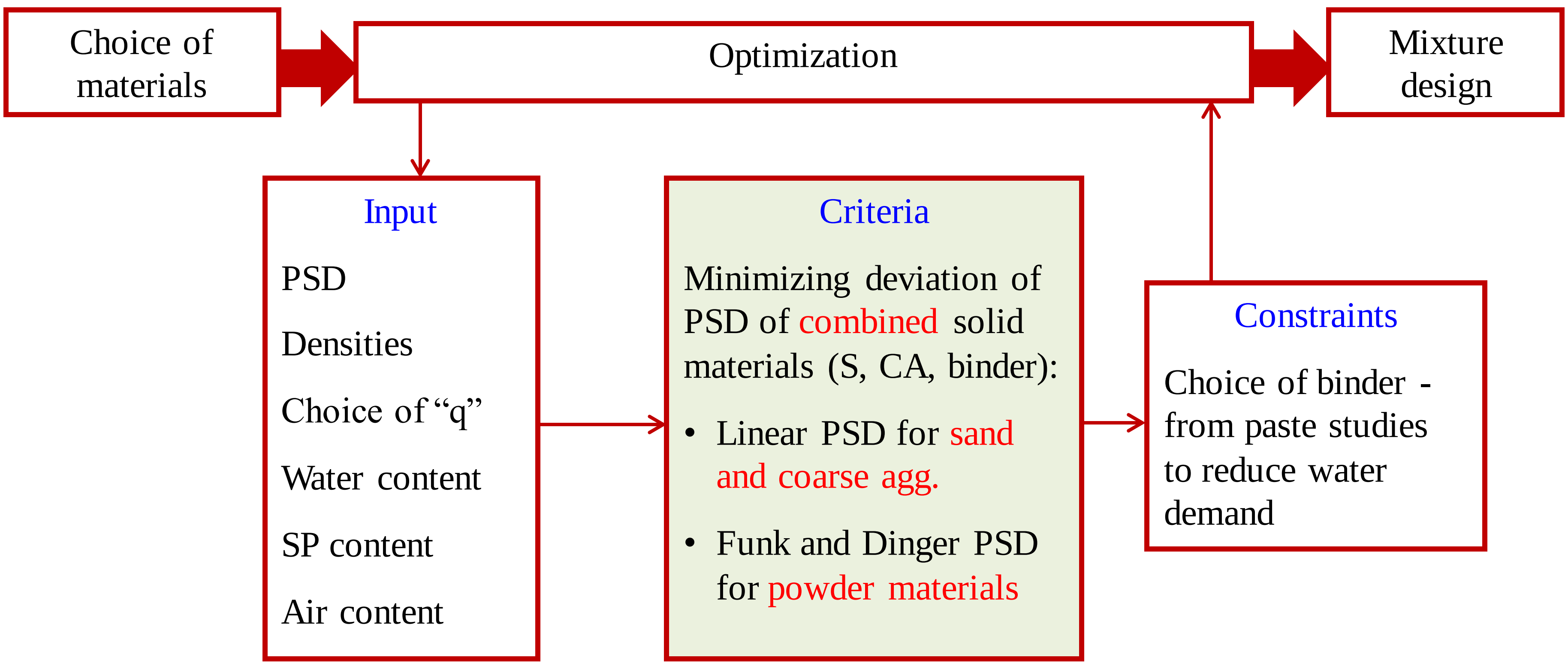
# Mixture Design Methodology for Eco-SCC

Propose design method to reduce efforts to develop Eco-SCC

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




*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

# Mixture Design Methodology

1- Material characterization (PSD and Density)

2- Select binder and water contents

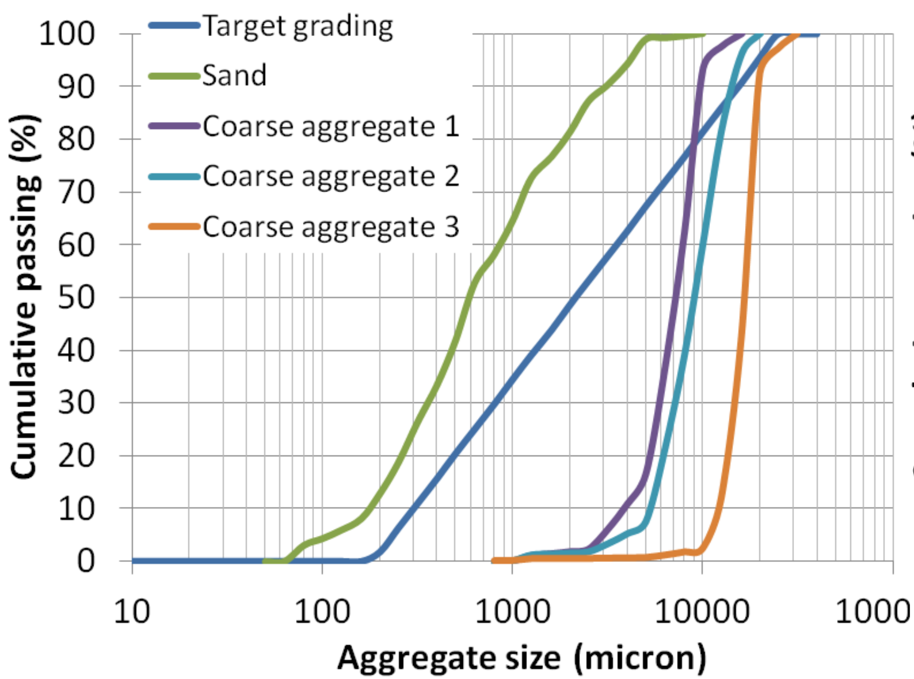
3- Determine saturation point of SP at different W/B values

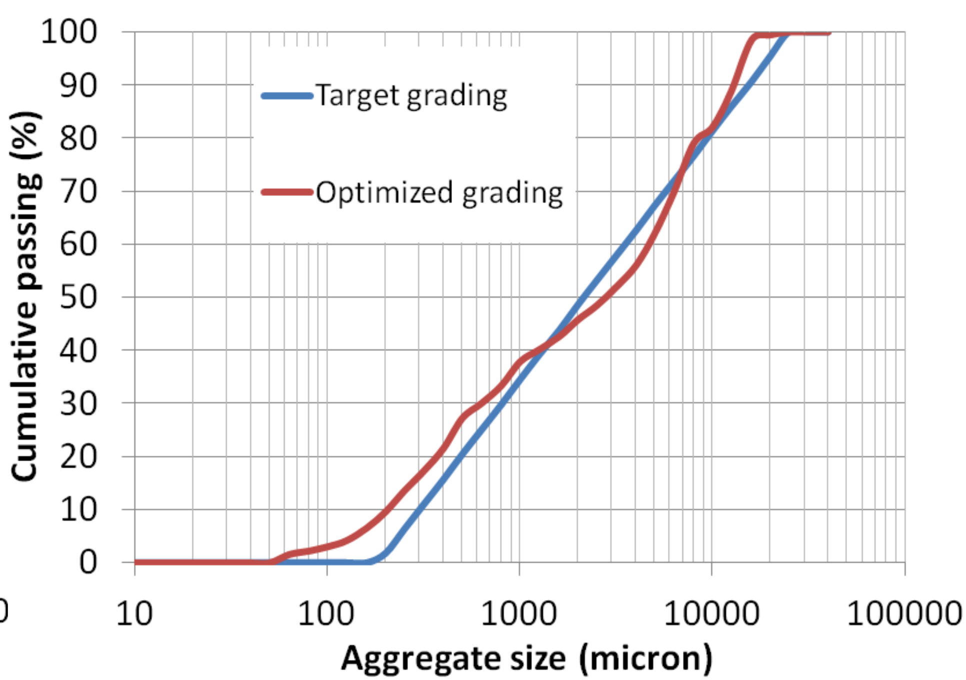
4- Choice of optimum binder composition

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




**Least squares method** → **Optimization**

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

# Known and Unknown Parameters so Far

## Known:

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

**From aggregate optimization:**

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

## Unknown:

- Volumetric proportions of powder materials (Funk and Dinger PSD)

# Mix Design Methodology

1- Material characterization (PSD and Density)

2- Selection of binder and water contents

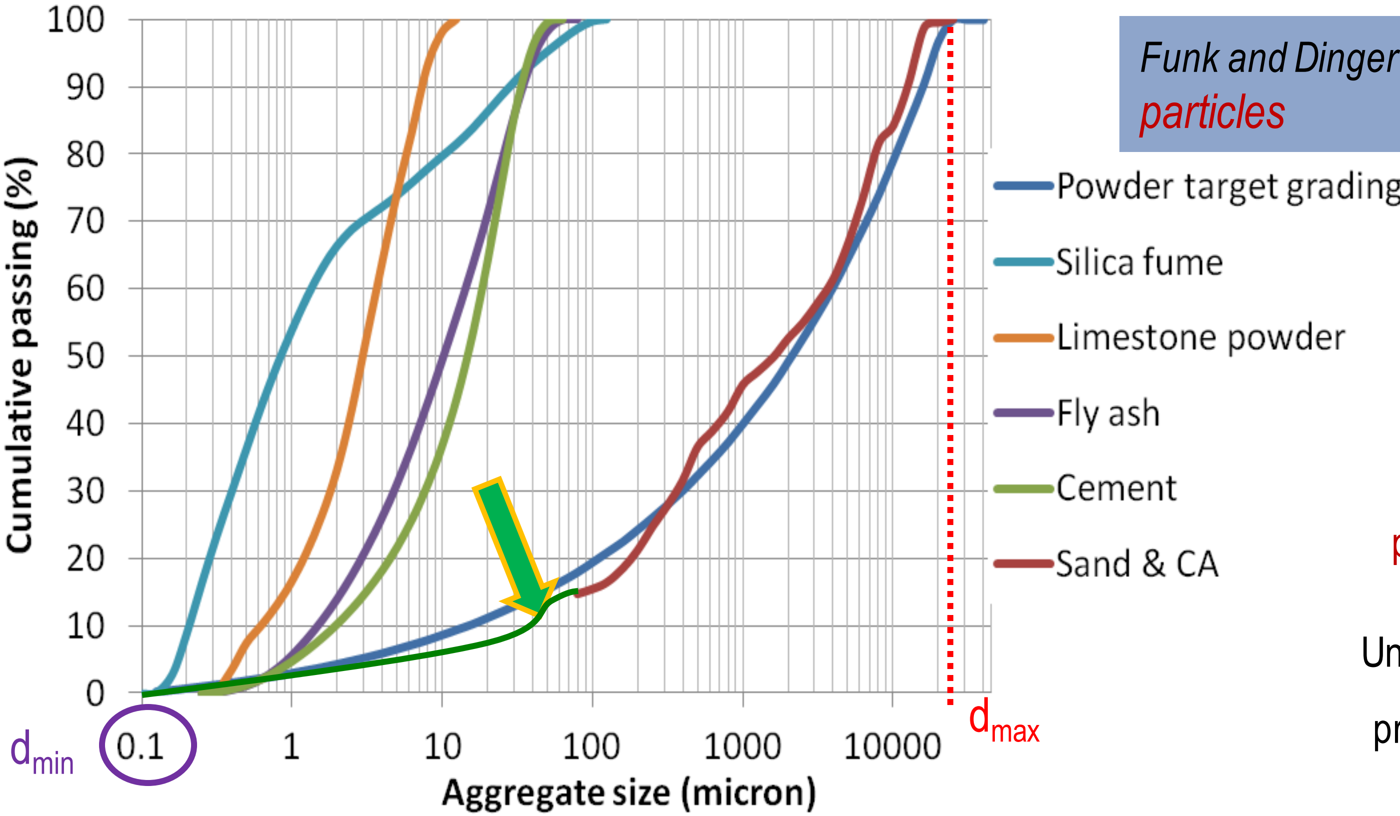
3- Determine saturation point of SP at different W/B values

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 ($C_i$)




*Funk and Dinger – for total solid particles*

$$P(d) = \frac{d^q - d_{min}^q}{d_{max}^q - d_{min}^q}$$

*q : set to 0.28*

Sand and CA volumetric proportions are constant

Unknown : volumetric proportions of binder

Least squares method for PSD of binder materials

Optimization →

Volumetric proportions of each binder material

# Optimized Mix Design

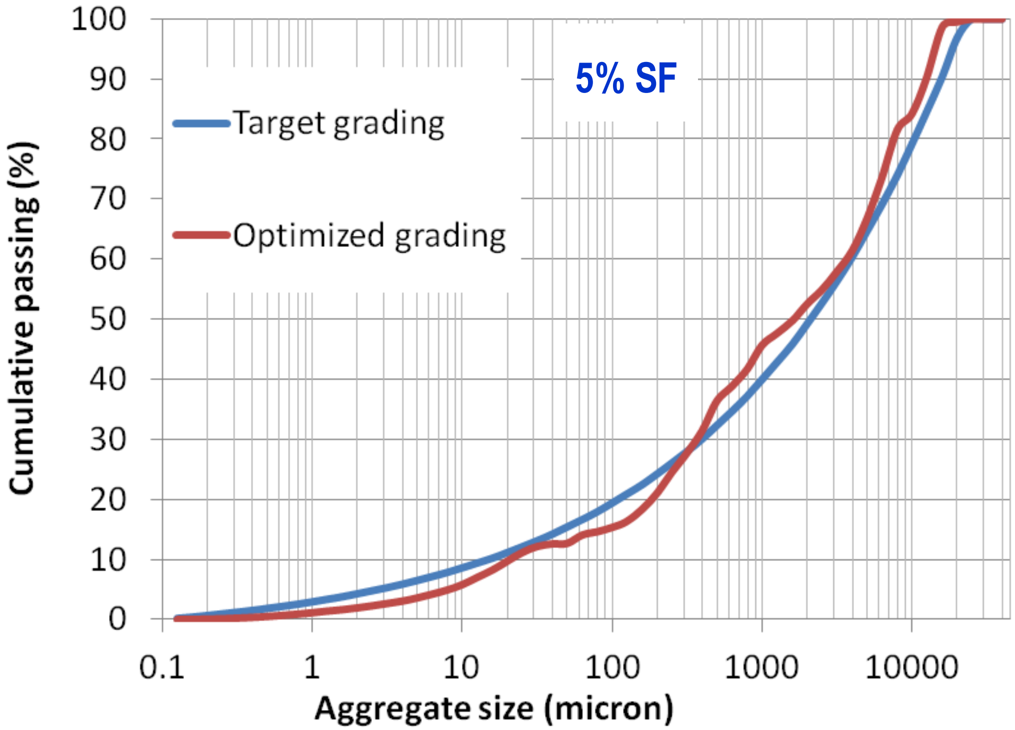
## 3 Optimized Eco-SCC mixtures

**Non air-entrained, $V_{pa}$ = 330 ± 4 l/m³**

***W/P* = 0.65** **$V_{sand}/V_{agg}$ = 0.515**

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

**5% SF**




| Mixture | Cement, kg/m³ | Fly ash (F), kg/m³ | Silica Fume, kg/m³ | Total binder, kg/m³ | Water, kg/m³ | Sand, kg/m³ | CA1, kg/m³ | CA3, kg/m³ | Total SP liq, kg/m³ |
|---|---|---|---|---|---|---|---|---|---|
| 5% SF | 302 | - | 12 | 314 | 203 | 925 | 541 | 368 | 2.25 |

# 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

# Conclusions

- Eco-SCC with powder content of 278 -308 kg/m$^3$ (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%)