What Aggregate Packing is Optimal?

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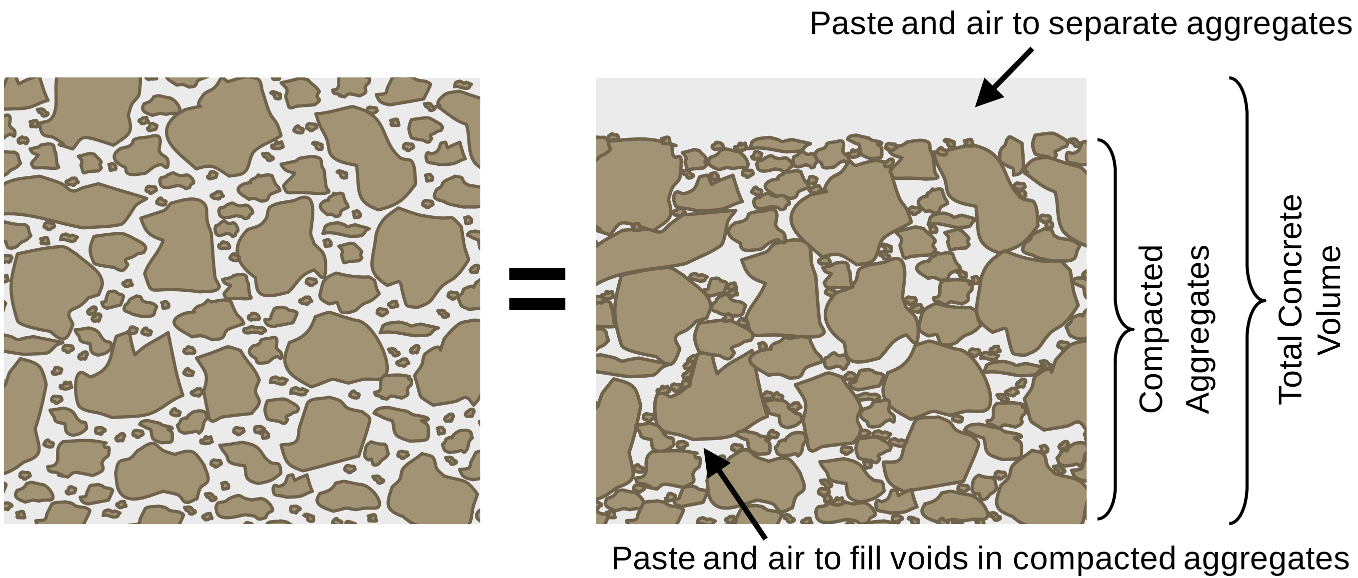
Packing of Aggregate in Concrete

Concrete is a suspension of aggregates in paste.



Minimum Particle Size

It is best to consider combined solid particles due to interaction between particles.
In reality, minimum size approaches zero.
For analysis, need to consider a specific size.

1 µm
colloidal particles (strong contributor to strength, viscosity, HRWR performance)

75 µm
maximum powder size

Recommended

5 mm
minimum coarse aggregate

Least Accurate

Why Consider Packing Density?

Packing provides an indication of voids content, which must be filled with paste and air.

Higher aggregate volume results in improvements in strength, stiffness, creep, drying shrinkage, and permeability.

$$\text{Packing \& Workability} = f\left(\begin{array}{l}\text{Shape}\\ \text{Angularity}\\ \text{Texture}\\ \text{Particle Size Distribution}\\ \text{Minimum Size}\\ \text{Maximum Size}\end{array}\right)$$

…but not the same function

Aggregate should be as dense as possible, but not more.

Constraints

Maximum size
Workability, finishability and pumpability
Segregation resistance
Strength and stiffness
Cementitious materials requirements
Local material availability
Bin space in concrete plant

Constraints

Maximum size

Increasing maximum size results in higher packing and lower viscosity.

Decreasing maximum size results in better passing ability and segregation resistance.

Workability

Grading for best workability is typically finer than for maximum packing.

For a given packing density, a well-shaped aggregate will have result in better workability.

A finer combined grading may be required for pumpability.

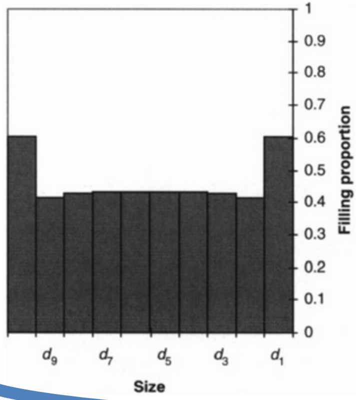
Strength and stiffness

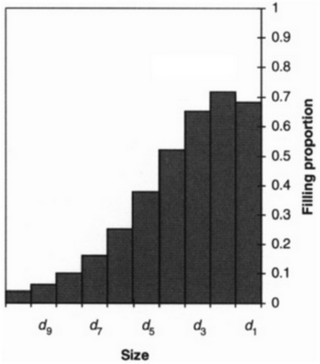
Crushed aggregates typically result in higher strength, but lower workability.

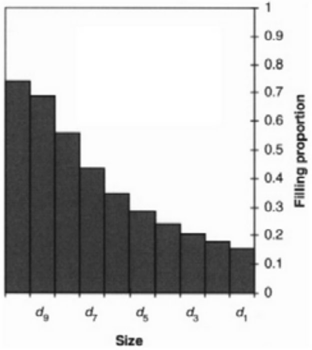
Concrete modulus of elasticity highly dependent on aggregate stiffness.

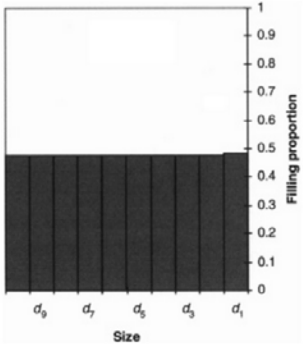
Segregation Resistance

Particle Size Distribution	Packing Density	Segregation Potential
Maximum Density	0.929	0.59
Fuller	0.869	0.96
Faury	0.927	0.59
Dreux	0.914	0.80
Uniform (log scale)	0.891	0.85
Gap Graded	0.928	1.00
Minimum Segregation	0.926	0.53









Credit: de Larrad, F. (1999). “Concrete Mixture Proportioning”. Notation added.

Cementitious Materials

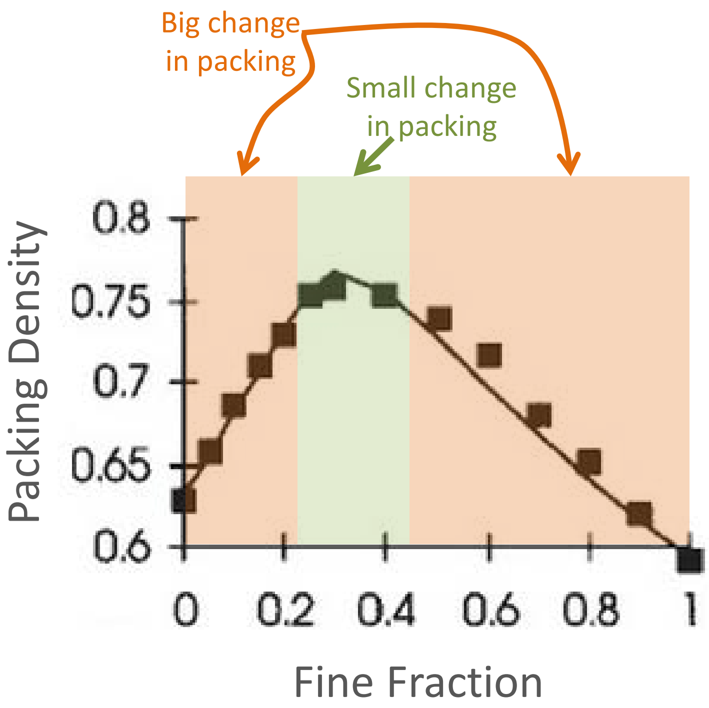
Cementitious materials affect the packing of fine and coarse aggregate.
(Particles must differ in size by 10x to avoid interaction.)

Strength and durability requirements significantly affect the amount of cementitious materials required.

Amount of cementitious materials needed for optimal dry powder packing may not be sufficient for strength and durability.

High cementitious materials content enables a reduction in the amount and fineness of fine aggregate.

Packing Near Optimal



Near maximum packing, changing the ratio of coarse and fine aggregate does not affect packing density much.

The amount of fine material is less than in a typical concrete mixture, as other considerations influence selection of aggregate blend in concrete.

Image Credit: de Larrad, F. (1999). “Concrete Mixture Proportioning”. Notation added.

Idealized Particle Size Distributions

Fuller and Thompson (1907)

$$p_t = \left(\frac{d}{D}\right)^{1/2}$$

Generalized power curve

$$p_t = \left(\frac{d}{D}\right)^{q}$$

Faury suggests q=0.20
Kennedy suggests q=0.45

Balomey

$$p_t = f + (1 - f)\left(\frac{d}{D}\right)^{1/2}$$

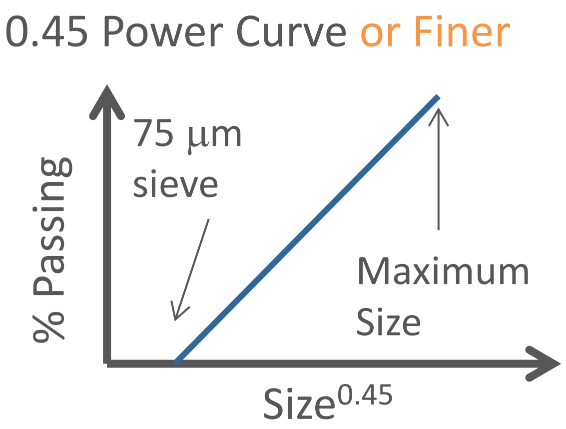
Many more…

…the hypothesis that there is an ideal size grading for concrete aggregate, or for all solid material in concrete, has now become almost if not entirely abandoned.

--T.C. Powers, 1968

The Properties of Fresh Concrete

Power 0.45 Curve



Exponents less than 0.45 are preferred: they result in finer gradings and potentially higher packing.

Curve should pass through minimum particle size considered, **not zero**.

Can use separately on power and aggregate.

An effective starting point for optimizing aggregates provided other relevant factors are considered.

Models for Calculating Packing Density

Two purposes:

1) Determine predicted packing density
2) Determine optimal blend

Consider:

1) What purpose you need
2) Accuracy with respect to these purposes
3) Data input needed for accurate results: particle size distribution and shape

Examples:

Furnas
Aim and Goff
Toufar, Klose, and Born
Compressible Packing Model, de Larrard
Many more…

Rheology Models for Suspensions

Einstein (1906) for low concentrations

$$\eta = \eta_s (1 + 2.5\phi)$$

For concentrated suspensions

$$\eta \approx \eta_s (1 + [\eta]\phi + K_H \phi^2 + \ldots)$$

Krieger-Daugherty (1959)

$$\eta = \eta_s \left(1 - \frac{\phi}{\phi_m}\right)^{-[\eta]\phi_m}$$

η = viscosity of suspension
η_s = viscosity of suspending medium
ϕ = concentration of solid materials
ϕ_m = max concentration of solid materials = f (particle shape, size distribution, and flocculation)
$[\eta]$ = intrinsic viscosity = f(particle shape)
K_H = Huggins coefficient

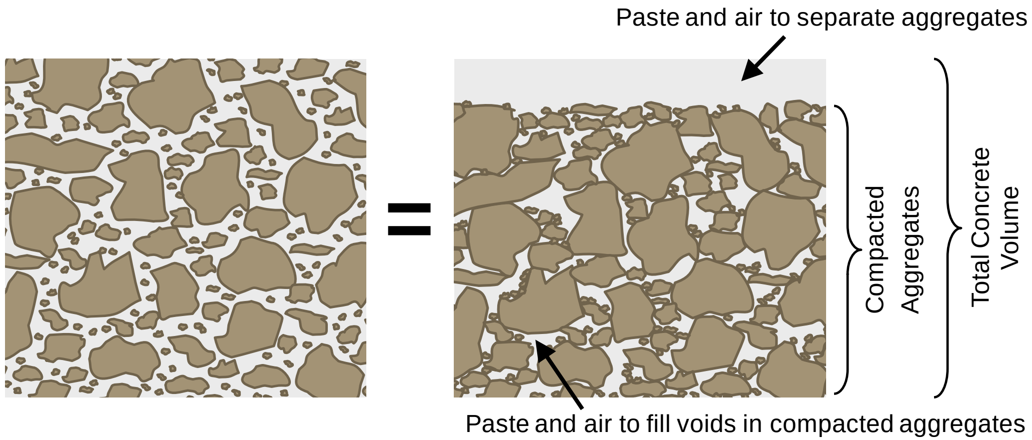
ϕ_m is not packing packing density, but applies to solid particles in suspension.
Intrinsic viscosity affects viscosity beyond the influence of ϕ_m

Aggregate Suspension Proportioning Method

ORIGINALLY
Koehler and Fowler
2007

NEW – Coming Soon
Revised and Updated
ACI 211.6T

Concrete is considered a suspension of aggregates in paste.



Select combined aggregates ❯ **Fill voids with paste + air** ❯ **Adjust composition of paste**

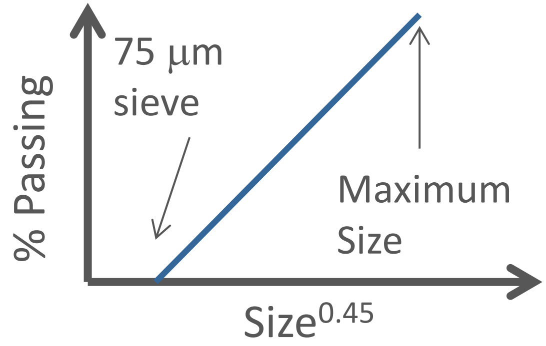
Aggregate Suspension Proportioning Method

1. Select maximum aggregate size
2. Select combined aggregates
3. Determine combined aggregate voids content and shape/angularity factor
4. Calculate paste and air volume
5. Select maximum w/cm and blend of powders for hardened properties
6. Select air content for freeze-thaw durability
7. Select w/p and admixture doses for workability
8. Calculate volumes and weights of individual constituents
9. Evaluate trial mixtures and make adjustments

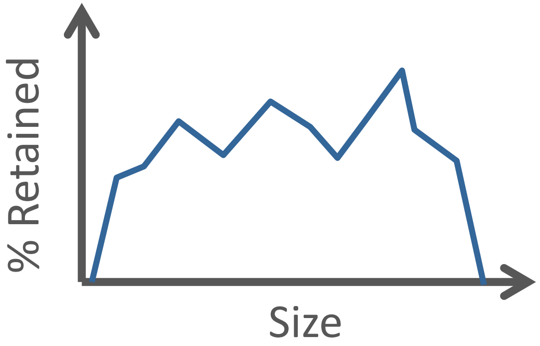
Aggregate Selection

Grading | There is no universally optimal grading.

0.45 Power Curve or Finer



Percent Retained Chart



Two consecutive sieves
>10% retained
<35% retained

Gap grading:
↓viscosity
↑packing
↑segregation

Shape, Angularity, Texture | Balance water demand and strength.

Equi-dimensional **Shape**
Well Rounded **Angularity**

↓water
↓admixture
↓paste + air volume

Angular
Rough **Texture**

↑strength

Paste Volume (As Influenced by Aggregates)

Voids Content

Measure dry-rodded bulk density with ASTM C29, but use combined aggregate (fine+coarse).

Calculate the voids content from the DRBD.

$$\%voids_{compacted\_agg} = \left(1 - \frac{DRBD}{\left(62.4\ {}^{lb}/_{ft^3}\right)\sum_{i=1}^{n}\left(p_i\left(SG_{OD}\right)_i\right)}\right) * 100\%$$

Shape-Angularity Factor

Shape-Angularity Factor	1 (well shaped, well rounded)	2	3	4	5 (poorly shaped, highly angular)
Description	natural river/glacial gravels and sands	partially crushed river/glacial gravels	well-shaped crushed coarse aggregate or manufactured sand with most corners > 90°	crushed coarse aggregate or manufactured sand with some corners ≤90°	crushed coarse aggregate or manufactured sand with many corners ≤90°

Paste Volume (As Influenced by Aggregates)

Paste to fill voids in aggregate

$$V_{\text{minimum paste+air}} = 100 - \frac{(100 - V_{\text{minimum spacing paste+air}})(100 - \%voids_{\text{compacted\_agg}})}{100}$$

Paste to separate aggregates

Shape-Angularity Factor		1 (well shaped, well rounded)	2	3	4	5 (poorly shaped, highly angular)
Minimum Spacing Paste and Air Volume	<8 in. slump	2%	4%	6%	8%	10%
	SCC	8%	12%	14%	16%	18%

Paste Composition

Select paste composition to achieve desired strength, durability, and other hardened properties.

Adjust water/powder and admixtures to achieve workability.

Typical relationships apply.

Summary

Aggregate packing is one of several factors to consider in selecting aggregates.

Aggregate gradings finer than maximum packing density are often preferred.

The packing density, along with shape, is useful in determining amount of paste required.

Consider the combined solid particle size distribution.

Aggregate Suspension Mixture Proportioning Method (ACI 211.6T) considers packing density.

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