Reducing Clinker Content and Carbon Footprint of Concrete Using SCMs, Limestone Cement, and Optimized Aggregate Gradations

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Portland cement is the primary binder in Concrete

- Portland Cement is manufactured from limestone and shale rocks that have been fired at 1450 C to form a synthetic rock called clinker. This clinker is then crushed to a powder.
- When limestone is heated,
  it gives off CO_2.
  - $CaCO_3 \rightarrow CaO + CO_2 \uparrow$

- This reaction is unavoidable in the manufacture of cement clinker
- So to reduce CO_2 the clinker fraction of cement has to be reduced.

Manufacture of Portland Cement

- Contributes up to 5% of global CO_2 emissions
- Contributes up to 2% of global energy use
- For every tonne of cement produced:
  - 0.8 – 1.0 t of CO_2 produced
  - 1,700 kWh of energy consumed/t
  - 1.5 t of raw material required
  - 3,300,000 t cement produced globally in 2010
- Cement is the most expensive concrete material component and can account for up to 60% of the total materials cost even though it is only approx. 10 – 15 % by mass
- The cement paste fraction usually is 25% to 30% of the total volume of concrete

But cement is only one component of concrete

- ~90% of carbon footprint of concrete is from portland cement clinker (assuming portland cement is used as the sole cementing material)

There is no single right answer to reducing clinker content of concrete

- Optimization of combined aggregate gradations.
- Use of water reducing admixtures.
- Use of portland-limestone cements (PLC)
- Use of SCMs

- All can be done simultaneously

Optimizing Concrete Mixtures by Use of Supplementary Cementitious Materials (SCMs) and Portland-Limestone Cements (PLCs)

SCMs →

PLC →

Portland cement type	Portland-Limestone cement type	Blended hydraulic cement type
Type I (GU)	Type IL (GUL)	Type IT (GULb)

Two approaches for reducing the carbon footprint of concrete

1. Reduce the clinker content of the cementitious binder
2. Reduce the total binder content of concrete mixtures.

For the first, combinations of supplementary cementitious materials can be combined with Type IL cements while still attaining early-age strength development with at least a 40% reduction in clinker content.

For the second, optimizing aggregate gradations with at least three size fractions can result in savings of up to 15% of the required cementitious materials content while also reducing concrete permeability and shrinkage.

More Cement is Not Always Better!

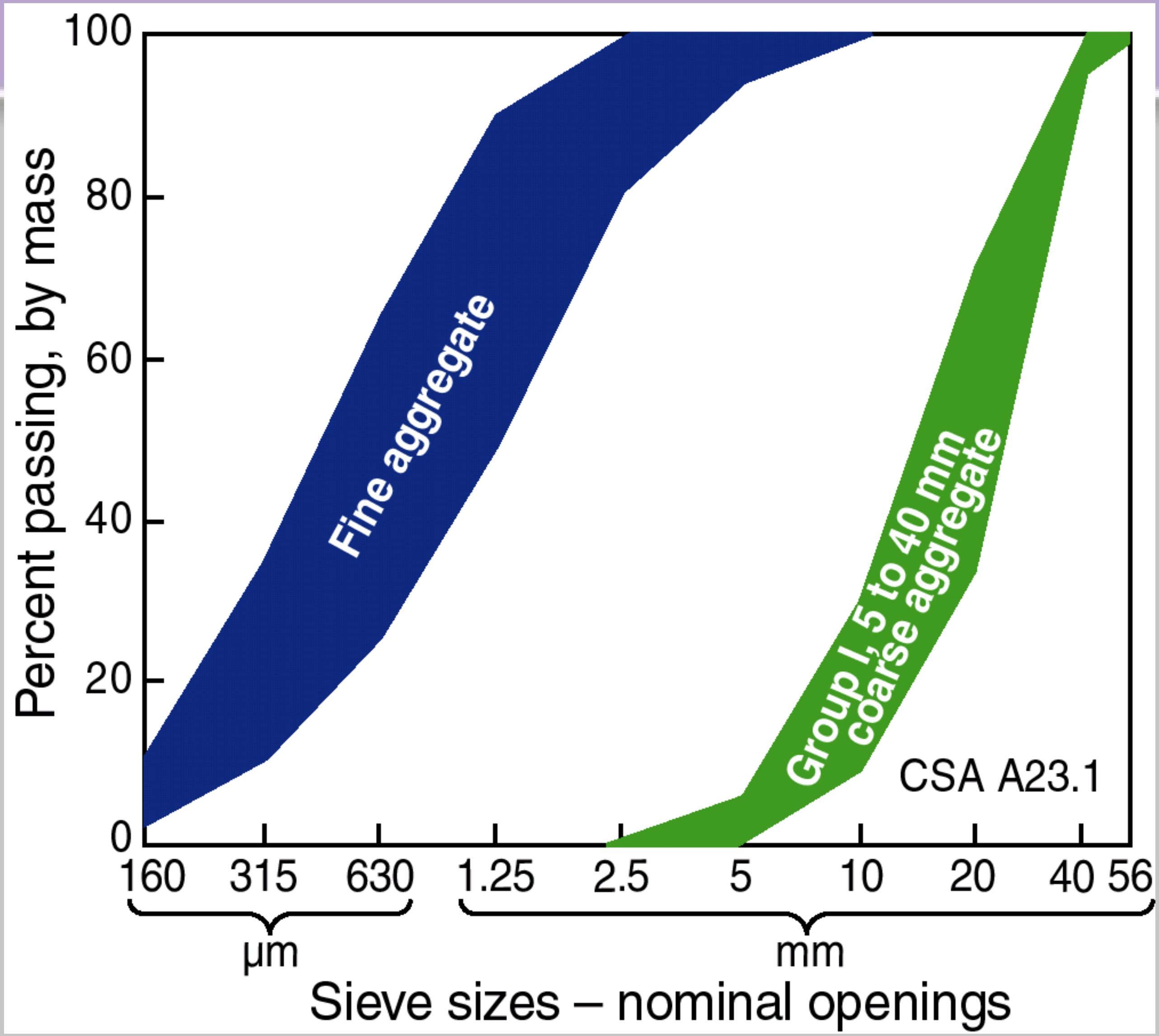
- At a fixed W/CM, more cement raises the unit water content of the mix and makes it more porous and more permeable.
- High cement contents can also lead to higher thermal stresses and increased shrinkage, making the concrete more vulnerable to cracking.
- Chemical admixtures can be used to obtain workable concretes at lower water (and cement) contents.
- Optimized aggregate gradations will also reduce water demand.

1. Increasing Aggregate Content

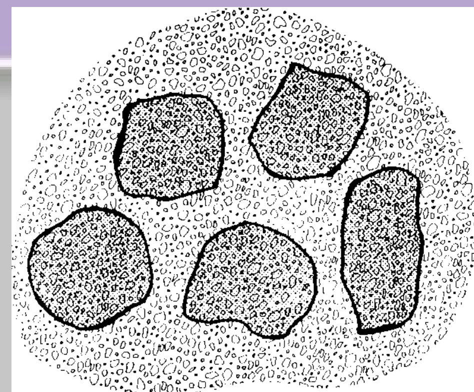
- Having to meet current ASTM, CSA and DOT specifications for meeting separate fine and coarse aggregate gradations can result in large portions of quarried and crushed stone being wasted only due to sieve sizes.

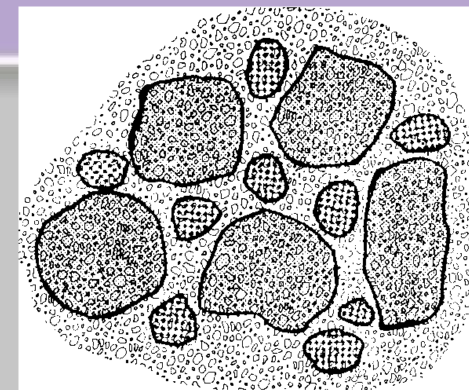
Fine and Coarse Grading Limits

There is typically a gap when individual fine & coarse aggregates meet their individual grading envelopes



Optimizing Combined Aggregate Gradation and using Microfine Fillers





Typical Mix
Gap-graded

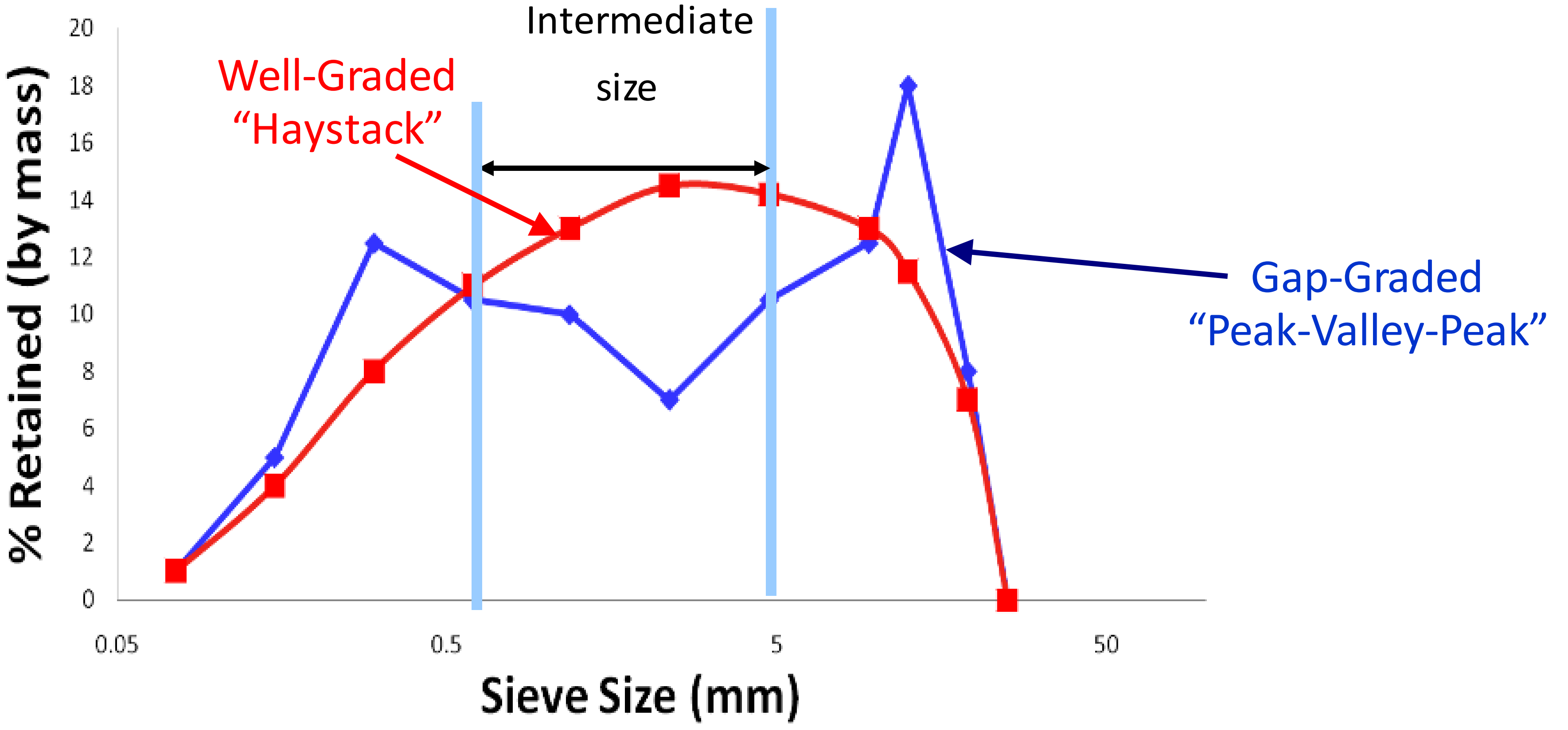
- Gap-graded; lack of intermediate particles
- No microfine fillers; lack of <75μm particles
- ↑ void content
- ↑ paste fraction required

Optimal Mix
Well-graded

- Well-graded; plenty of intermediate particles
- Microfine fillers; plenty of <75μm particles
- ↓ void content
- ↓ paste fraction required

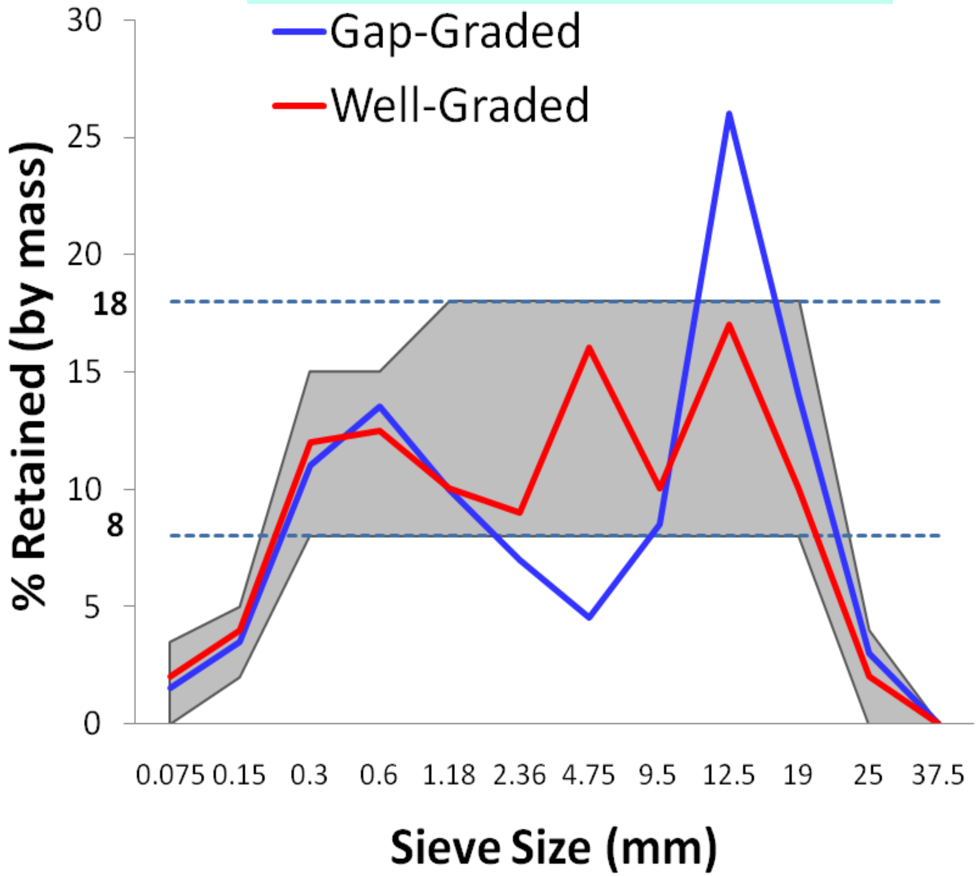
Optimizing Combined Aggregate Gradation

- A well-graded combined aggregate blend can be achieved by using optimization techniques, or by adding low value or wasted coarse aggregate material of finer sieve sizes (1-5 mm)

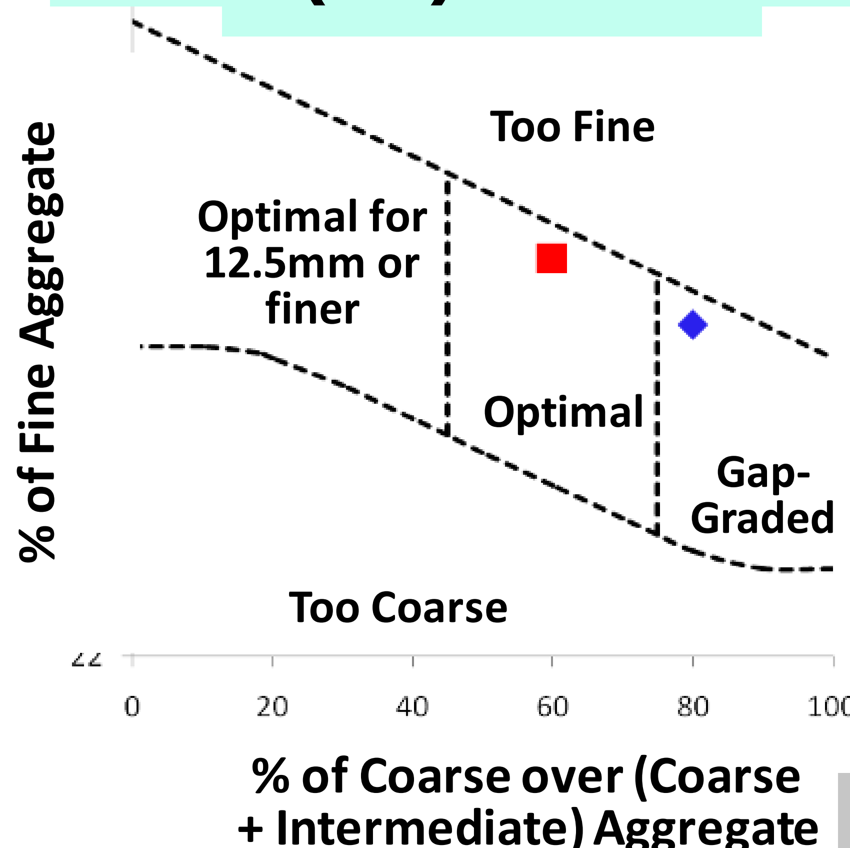


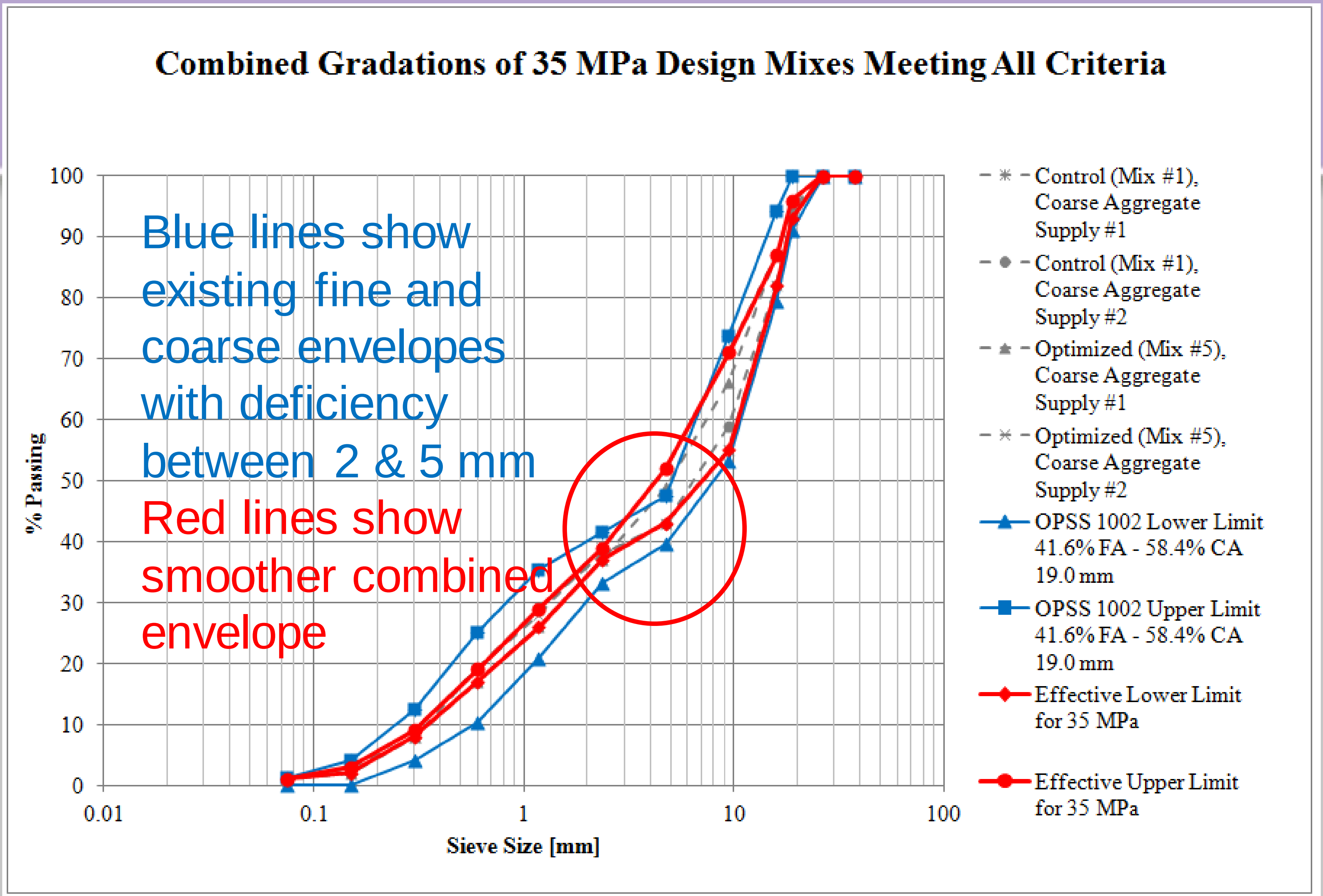
Existing Optimization Techniques: Sieve Analysis

8-18 Distribution



Coarseness Factor (CF) Chart





Combined Gradations of 35 MPa Design Mixes Meeting All Criteria
Blue lines show existing fine and coarse envelopes with deficiency between 2 & 5 mm
Red lines show smoother combined envelope
% Passing
Sieve Size [mm]
0
10
20
30
40
50
60
70
80
90
100
0.01
0.1
1
10
100
Control (Mix #1), Coarse Aggregate Supply #1
Control (Mix #1), Coarse Aggregate Supply #2
Optimized (Mix #5), Coarse Aggregate Supply #1
Optimized (Mix #5), Coarse Aggregate Supply #2
OPSS 1002 Lower Limit 41.6% FA - 58.4% CA 19.0 mm
OPSS 1002 Upper Limit 41.6% FA - 58.4% CA 19.0 mm
Effective Lower Limit for 35 MPa
Effective Upper Limit for 35 MPa

Combined Aggregate Gradations in CSA A23.1-14

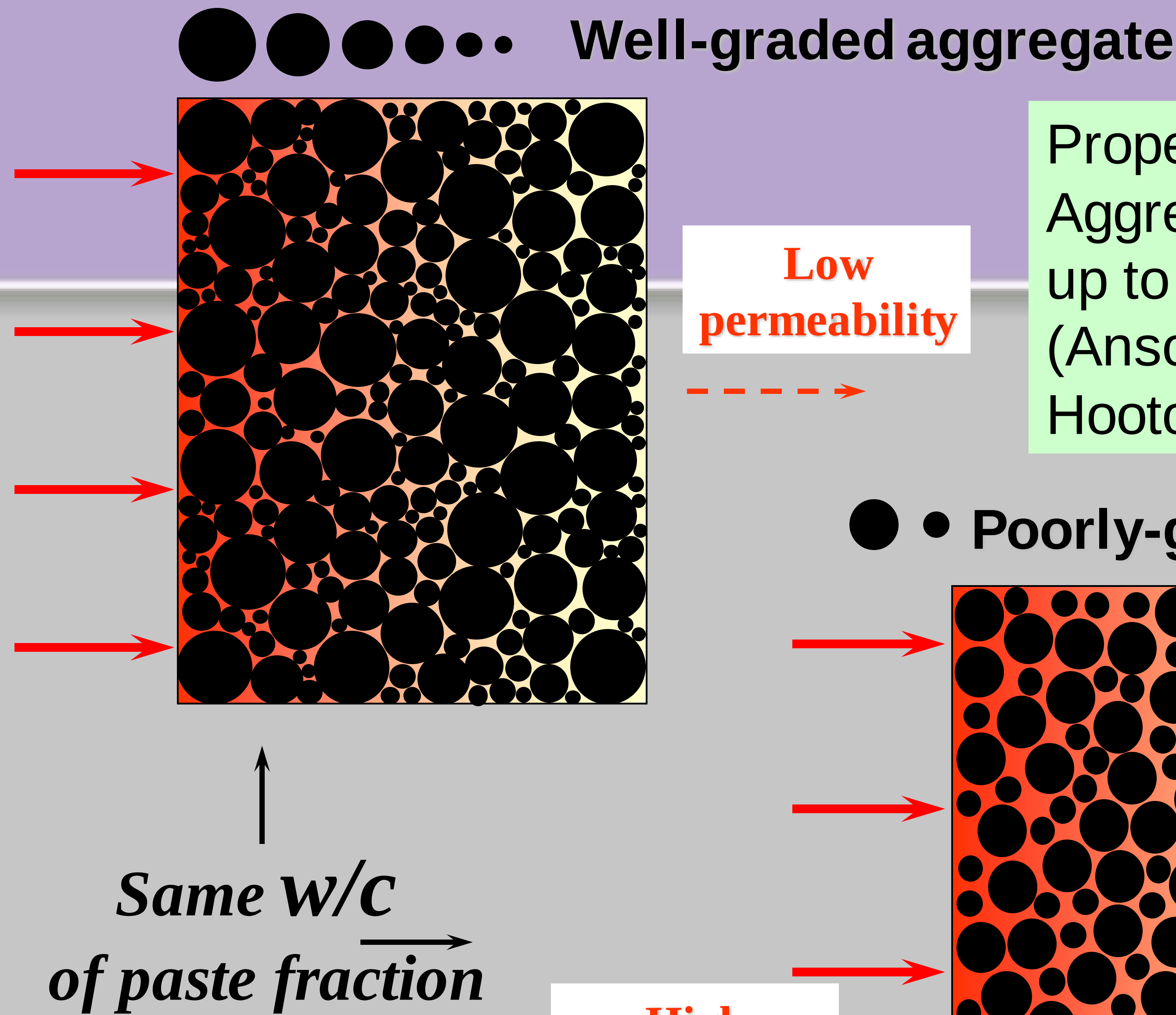
- Optimized total aggregate gradation is now allowed to provide the opportunity to improve concrete performance, sustainability and economy by optimizing the aggregate envelope for the whole mix and not the individual components.
- Combination must include 3 or more separate components
- Material from all aggregate sources passing the 5 mm sieve shall be tested in the proportions to be used in the concrete mixture and the blend tested as a fine aggregate to show compliance with requirements.
- Material retained on the 5 mm sieve shall be tested to show compliance with coarse aggregate requirements.

Workability of optimized gradation mixes also needs to be evaluated

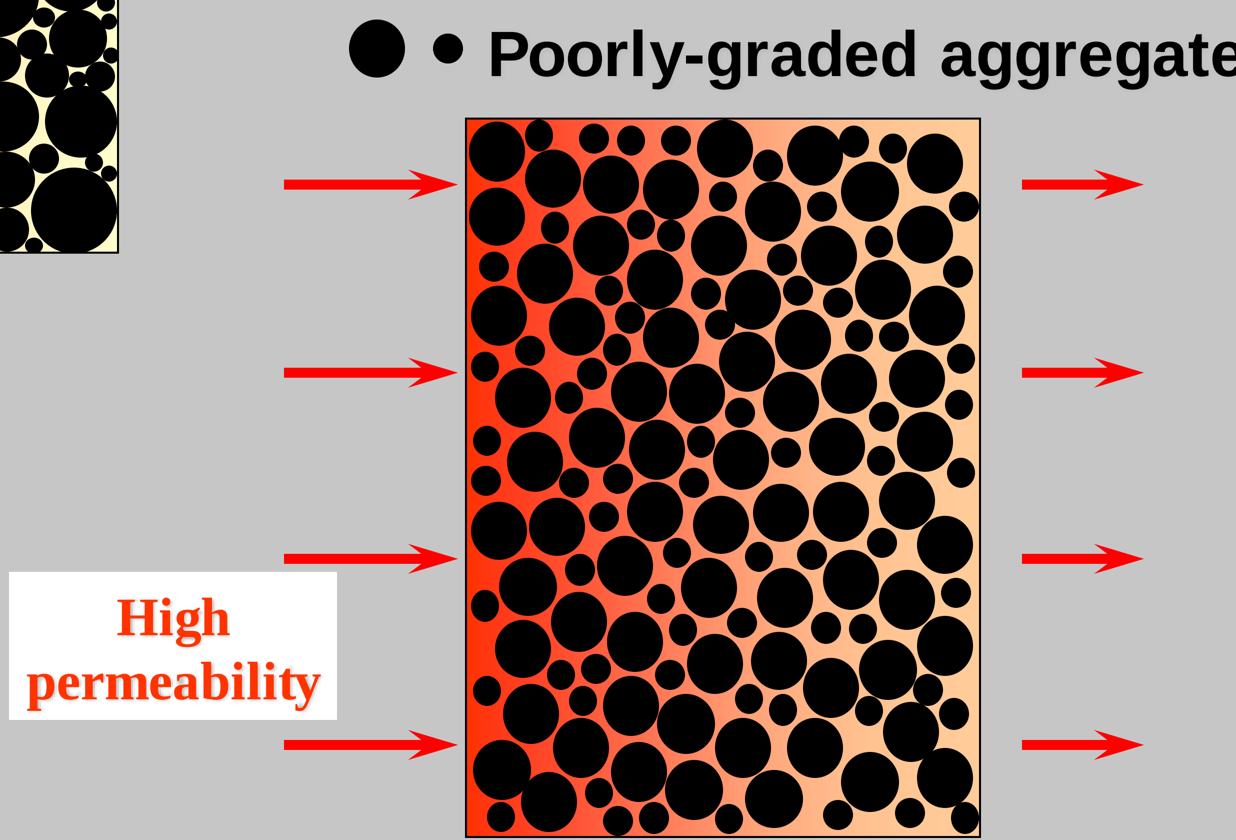
Adapted from: http://offthemark.com/search-results/key/goldilocks+and+the+three+bears/

Comparison of concretes with and without 31% (0.3 to 5 mm) limestone screenings: w/cm = 0.39, normal water reducer and air entrained to 5-8% air. (Anson-Cartwright, PhD)

Total Cementitious Content (kg/m³)	360	330
Cement Type	Type I +25%Slag	Type I + 25%Slag
Limestone Screenings	No	Yes
MRWR Dose for 80-120 mm slump (mL/100 kg)	935	950
28 day Strength (MPa)	57.8	69.2
28 day drying shrinkage	0.033%	0.025%
ASTM C1202 (coulombs @ 56 days)	900	640



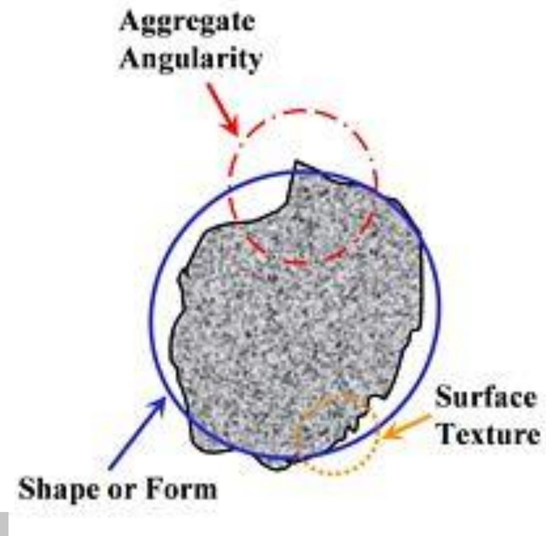
Proper Gradation of Aggregates can save up to 15% of cement (Anson-Cartwright & Hooton 2011)



Influences on Particle Packing

For individual and combined aggregate materials:

- Gradation (including nominal maximum size and size distribution)
  - ➢ The more gap-graded and coarser the combined aggregate gradation, the higher the cement paste content required
- Shape (spherical, cubical, flat, or elongated)
  - ➢ The more cubical / spherical the particles, less cement paste is required
  - ➢ Cubical is best for packing and spherical best for workability
- Angularity (angular or rounded)
  - ➢ The more rounded the particles, less cement paste is required
- Surface Texture (rough or smooth)
  - ➢ The smoother the particles, the less cement paste (effectively less water demand) required



Cementitious contents can be reduced

- 16% reductions in 50 MPa (7250 psi) bridge deck mixes were obtained (465 to 390 kg/m^3) while meeting 1000 coulomb limit @56d. (775 → 650 pcy)
- 8% reductions in 35MPa mixes were obtained (360 to 330 kg/m^3) while still meeting a 1500 coulomb limit @ 56d. (600 → 550 pcy)
- This was with use of an intermediate size C. Agg. to fill the gap between fine and coarse agg. fractions

2. Portland-Limestone Cement

- While supplementary cementitious materials (SCMs) such as slag and fly ash can be used to reduce the clinker content of concrete, another initiative is to intergrind the cement clinker with raw limestone.
- SCMs and limestone also work well when used together, so limestone cements do not require reducing SCM levels.
- This directly reduces point-source CO_2 emissions at cement plants by ~10%.
- ASTM C595 Type IL allows up to 15% limestone as does CSA Type GUL

Sustainable Development

Use of portland-limestone cements

- Reduces CO_2 emissions (by 10% over current portland cements)
- Reduces impact on natural resources, since 46% less limestone isused than when it is processed into clinker
- Reduces energy consumption (coal)

Performance Requirements

- In ASTM C595 and CSA A3000, the setting times and strength development limits are the same for Type IL (GUL in Canada) as for portland cements.
- Type IL cements typically perform better with SCMs than Type I in terms of strength and permeability. This is due to formation of calcium carbo-aluminates.

Strengths of Air-entrained Concretes cured at 23 °C with limestone and SCMs

Mix Identification (all 400 kg/m^3 (666 pcy mixes)	% clinker in binder	w/cm	Compressive Strength (MPa)			
			7 day	**28 day**	**56 day**	**182 day**
Type I (GU) Control	**89***	0.40	**39.3**	**45.5**	**50.7**	**52.6**
GU + 40% Slag	**53**	0.40	**32.8**	**46.2**	**49.2**	**51.2**
Type IL (9%L) + 40% Slag	**50**	0.40	**36.1**	**50.9**	**53.6**	**50.7**
Type IL (9%L) + 50% Slag	**41**	0.40	**34.6**	**49.0**	**53.0**	**51.0**
Type IL (15%L) + 40% Slag	**46**	0.40	**37.1**	**52.3**	**57.5**	**59.2**
Type IL (15%L) + 50% Slag	**38**	0.40	**36.3**	**55.3**	**60.1**	**65.6**
Type IL (15%L) + 6% Silica Fume + 25% Slag	**53**	0.40	**46.0**	**65.0**	**70.1**	**76.0**

* 3.5% limestone and 8% gypsum

U of Toronto Field site mixes

RCPT of Air-entrained Concretes cured at 23 ^{o}C with limestone and SCMs

Mix Identification (all 400 kg/m^3 (666 pcy mixes)	% clinker in binder	w/cm	Rapid Chloride Permeability (Coulombs)		
			28 day	**56 day**	**182 day**
Type I Control	**89**	0.40	**2384**	**2042**	**1192**
Type I + 40% Slag	**53**	0.40	**800**	**766**	**510**
Type IL 9% + 40% Slag	**50**	0.40	**867**	**693**	**499**
Type IL 9% + 50% Slag	**41**	0.40	**625**	**553**	**419**
Type IL 15% + 40% Slag	**46**	0.40	**749**	**581**	**441**
Type IL15% + 50% Slag	**38**	0.40	**525**	**438**	**347**
Type IL 15% + 6% Silica Fume + 25% Slag	**53**	0.40	**357**	**296**	**300**

Example of MTO Highway Field Trials a) Nov. 4, 2009

- Dufferin Construction Barrier Wall Test sections 23m^3 of PLC+15% Slag vs GU+15% Slag (CM = 355 kg/m^3)
- QEW in Burlington
- First MTO trial of PLC
- Testing performed by Dufferin and University of Toronto, with scaling slabs also tested by MTO.

PLC Barrier Walls on QEW
Nov. 4, 2009

GU Cement + 25% Slag

GUL Cement + 25% Slag

23 m^3 of each mix placed, 30 MPa, 60-100 mm (2.5-4 in.) slump

Nov. 2009 Barrier Wall

2009 Barrier Wall	PC +25% SLAG	PLC + 25% SLAG
Shrinkage (28d)	**0.038%**	**0.038%**
Strength (MPa)		
1	**9.5**	**10.3**
3	**19.3**	**19.4**
7	**25.6**	**26.8**
28	**36.9**	**37.9**
56	**38.9**	**38.0**
91	**40.7**	**40.2**
Freeze/Thaw Durability	**94%**	**94%**
MTO LS-412 Scaling	**0.24 kg/m^2**	**0.24 kg/m^2**
RCP (Coulombs)		
28 days	**2070**	**1490**
56 days	**1930**	**1340**

Nov. 2009 Barrier Wall Scaling Tests

2009 Barrier Wall	PC +25% SLAG	PLC + 25% SLAG
MTO LS-412 Scaling	**0.35 kg/m^2**	**0.51 kg/m^2**
UofT LS-412 Scaling	**0.24 kg/m^2**	**0.24 kg/m^2**

MTO scaling limit is 0.8 kg/m^2

Since 2009

- Several more MTO field trials in 2010-2012 showed benefit of using PLC
- Increasing use of Portland-limestone cements with SCMs in pavements and industrial / commercial applications

Concrete Optimization

Cause

Reduced paste fraction by:

- Optimization of Combined Aggregate Gradation
- Use of water reducing admixtures

Reduced Portland cement content by:

- Addition of Interground Limestone
- Addition of Supplementary Cementitious Materials

Effect

Performance:

↑ Strength

Durability:

↓ Permeability

↓ Shrinkage

Sustainability and Cost:

↓ Cement content

Possible Cumulative Reduction in Cement Contents (from 12% to 3% by volume)

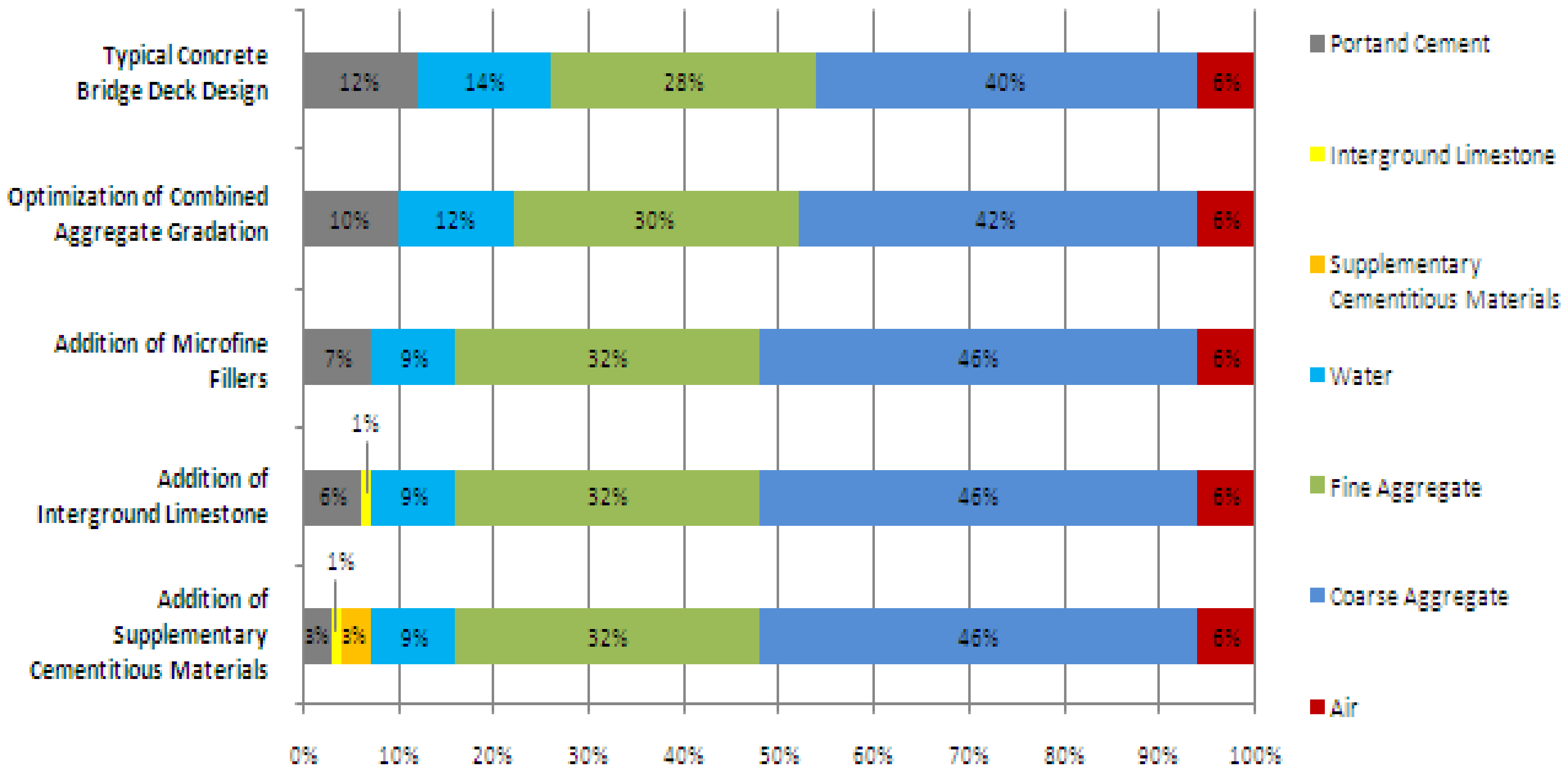


Chart: *% by Volume*

Anson-Cartwright & Hooton 2011

From 380 kg/m³ to 95 kg/m³ (633pcf to 158 pcf)

Summary

Two approaches for reducing the carbon footprint of concrete are to,

1. Reduce the clinker content of the cementitious binder:

   Combinations of supplementary cementitious materials can be combined with Type IL cements while still attaining early-age strength development with at least a 40% reduction in clinker content.

2. Reduce the total binder content:

   (a)Optimizing aggregate gradations with at least three components can result in savings of up to 15% of the required cementitious materials content while also reducing concrete permeability and shrinkage.

   (b) Use water-reducing admixtures.

Summary

- The carbon footprint of concrete can be reduced by fairly simple changes to materials and mix proportions.
- When aggregate gradations are optimized, and the binder contains both SCMs and limestone, the clinker content of concrete can be reduced by a factor of up to 60%.
- Since 90% of the carbon footprint of concrete is from cement, these measures would reduce the footprint concrete by as much as 60%.