OPTIMIZED GRADATION FOR CONCRETE PAVING MIXTURES

BEST PRACTICES
WORKSHOP

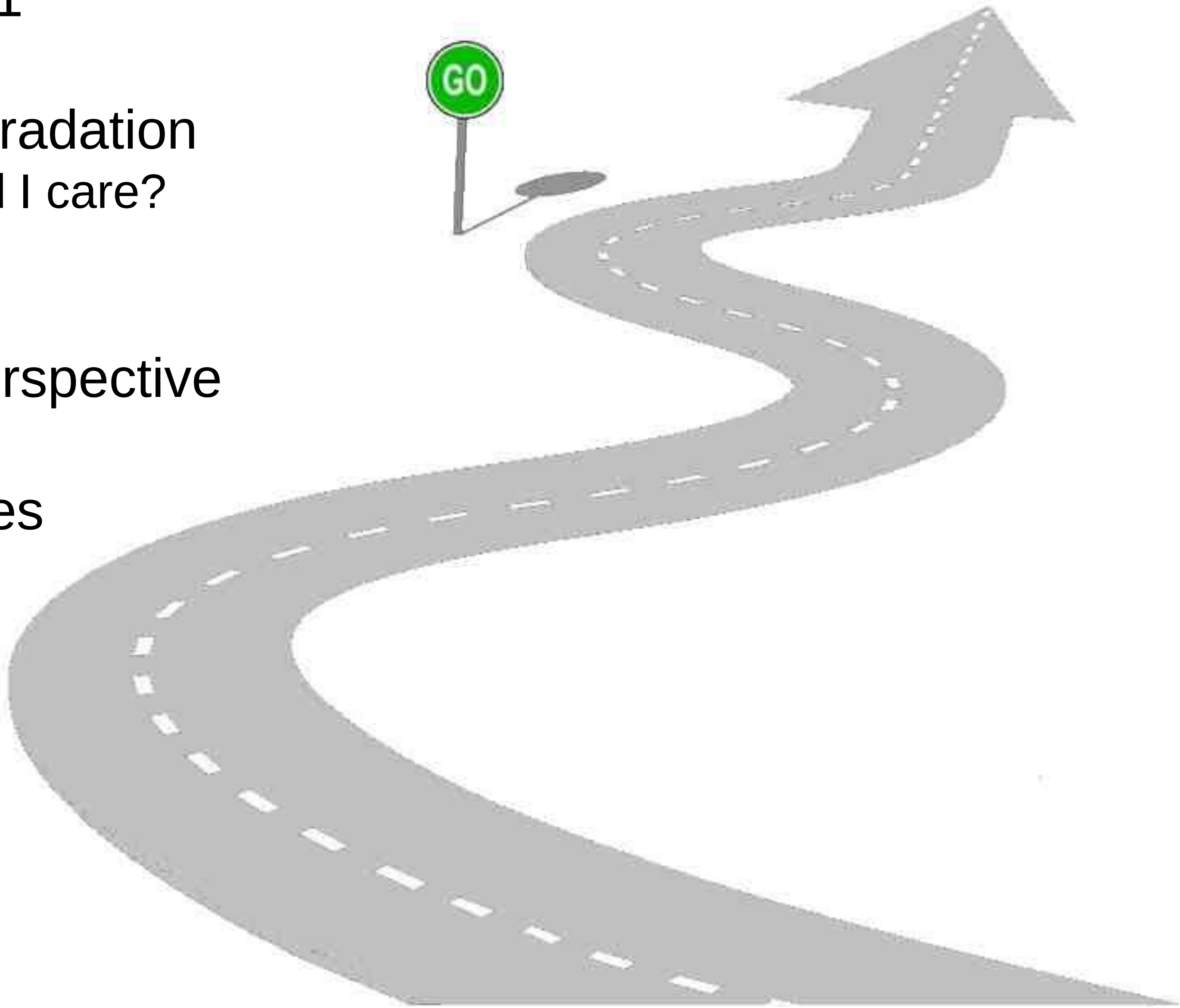
U.S. Department of Transportation
Federal Highway Administration

National Concrete Pavement Technology Center
Tech Center

Iowa State University
Institute for Transportation

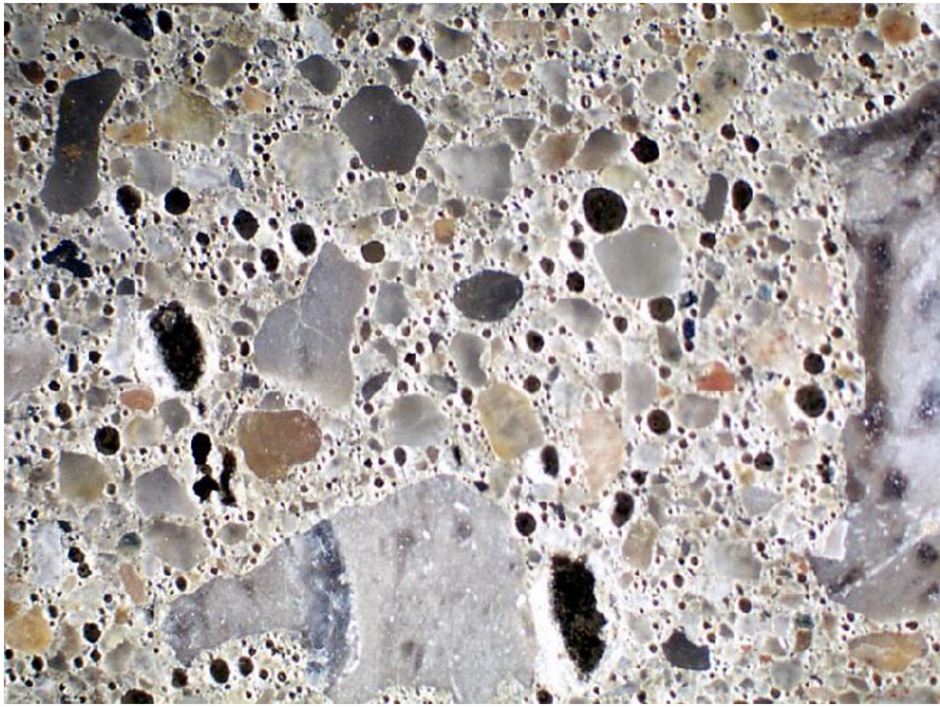
Outline

- Concrete 101
- Optimized Gradation
  - ➢ Why should I care?
  - ➢ What is it?
- Historical Perspective
- Best Practices
- Conclusions



Concrete 101

- Portland Cement Concrete
  - A hard strong building material made by mixing a cementing material (as portland cement) and a mineral aggregate (as sand and gravel) with sufficient water to cause the cement to set and bind the entire mass (Merriam-Webster.com).



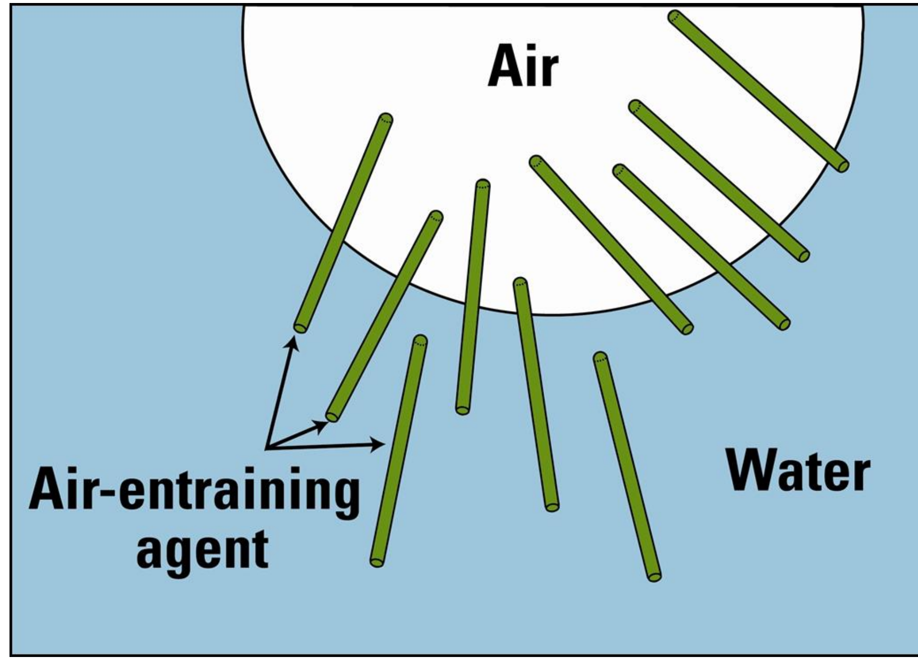
Concrete 101

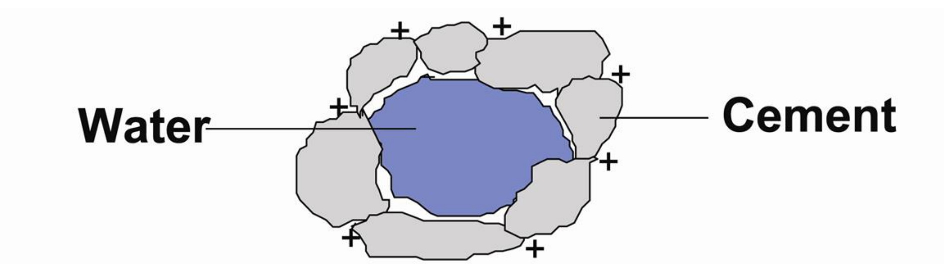
- Materials used in portland cement concrete (PCC)
  - Hydraulic cement – reacts with water

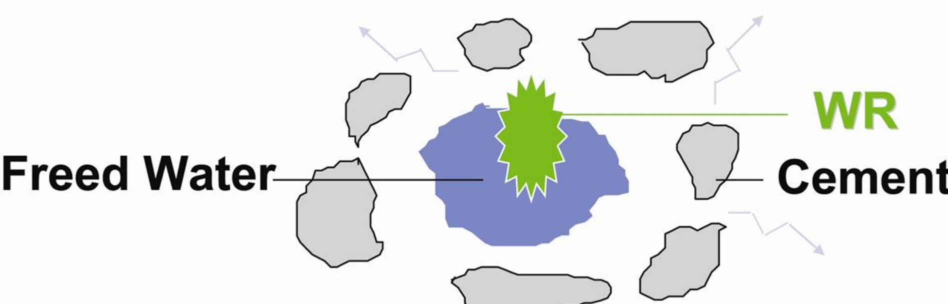
- Materials used in portland cement concrete (PCC)
  - Supplementary cementitious materials
    - Fly ash
      - –Class C
      - –Class F
    - Slag cement
    - Natural pozzolan

Concrete 101

- Materials used in portland cement concrete (PCC)
  - Admixtures
    - Air entrainers
    - Water reducers
    - Retarders
    - Accelerators







Concrete 101

- Materials used in portland cement concrete (PCC)
  - Water

Concrete 101

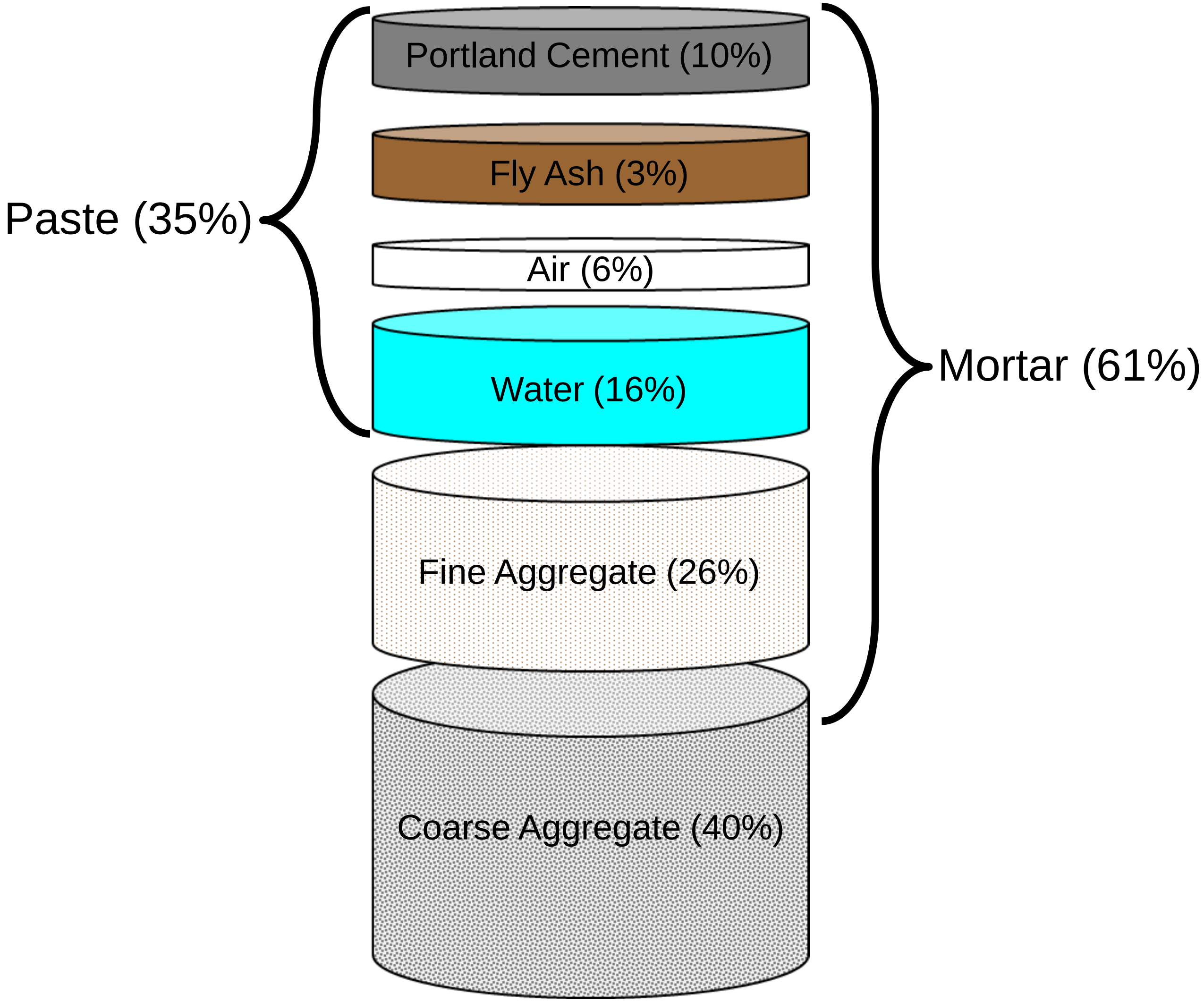
- Materials used in portland cement concrete (PCC)
  - Aggregates – coarse and fine
  - Can influence the following concrete properties:
    - Durability
    - Workability
    - Dimensional changes
    - Strength

Concrete 101

- Typical concrete proportions (**non-optimized**)
  - 6.5 sacks of cementitious materials (611 lb/yd^3)
  - 6% air
  - 0.45 water:cementitious materials ratio (275 lb/yd^3)(33 gal)
  - 60% coarse aggregate (1,800 lb/yd^3)
  - 40% fine aggregate (1,200 lb/yd^3)

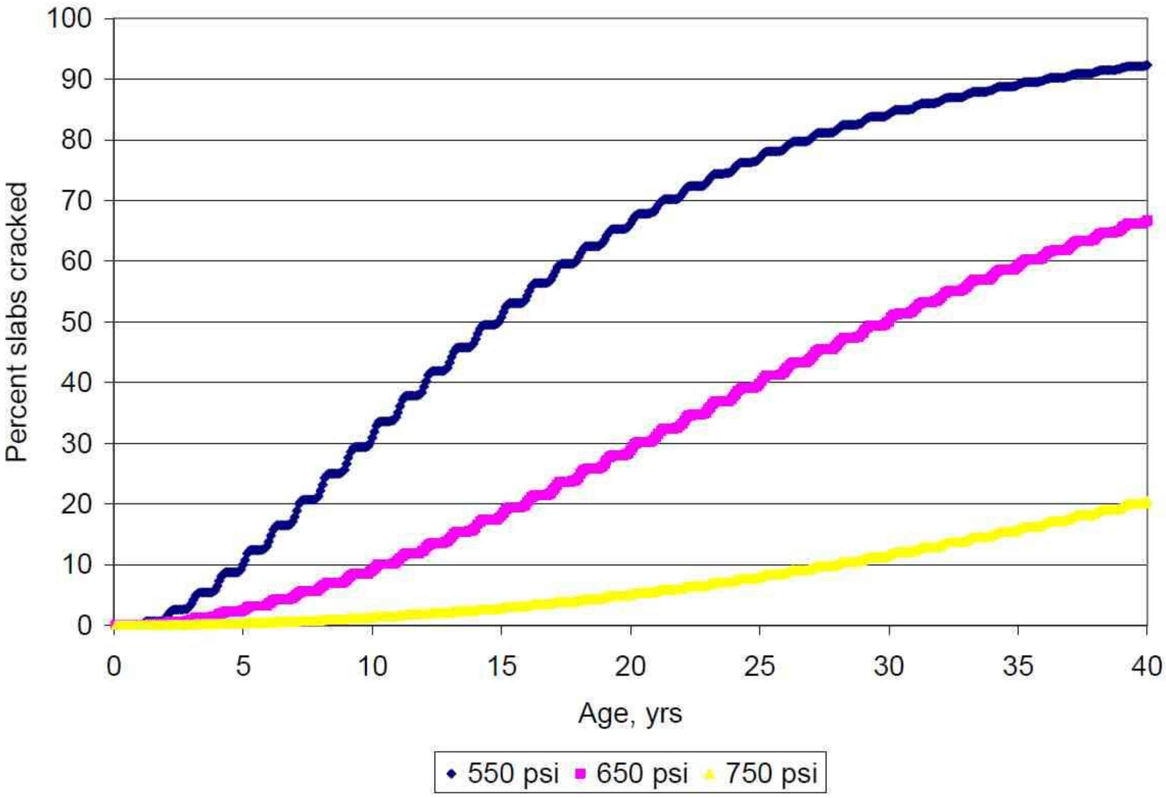
Concrete 101

- Typical concrete proportions (by volume)(**non-optimized**)



Concrete 101

- Quality measurements related to optimized gradation
  - Strength
  - Thickness
- Achieving average specified flexural strength is important for a given thickness



Darter, M. I., Titus-Glover, and Von Quintus, H. L. 2009. *Draft User's Guide for UDOT Mechanistic-Empirical Pavement Design*. Utah Department of Transportation Research Division, Salt Lake City, UT.

- Quality measurements related to optimized gradation
  - ➢ Air content – freeze-thaw resistance

- Quality measurements related to optimized gradation
  - Permeability - the ease with which fluids can penetrate concrete

- **Most durability damage is governed by permeability of the paste**
  - Optimize paste volume
  - Use low w/cm
  - Use SCMs
  - Cure
  - Minimize cracking

Optimized Gradation

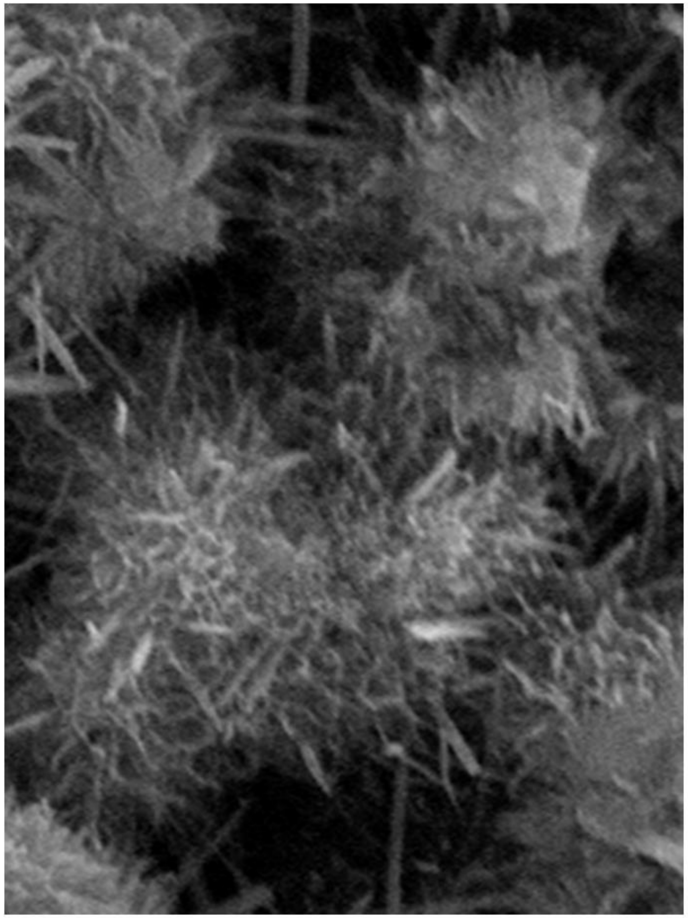
- What is it?
  - ➢ Economically combining aggregate particles to achieve the desired objectives of:
    - ➢ Appropriate workability
    - ➢ Reduced paste content
    - ➢ Required hardened properties

Optimized Gradation

- Why should I care?
  - ➢ Durability – long life pavements have high quality and optimized paste contents, which is partially achieved through an optimized gradation approach

Optimized Gradation

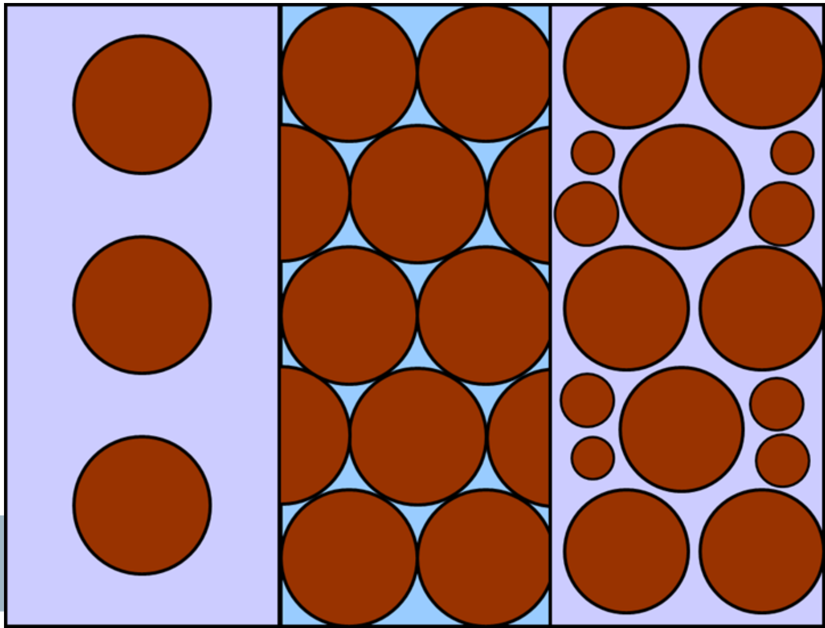
- Why should I care?
- Paste quality
  - Low permeability
    - W/CM less than or equal to 0.42
    - Use of SCMs
  - Air entrained – Minimum of 5% behind the paver



Optimized Gradation

- Why should I care?
  - ➢ Durability – long life pavements have high quality and optimized paste contents, which is partially achieved through an optimized gradation approach

- Paste quantity
  - ➢ Low permeability
    - ➢ Optimized gradation requires less paste for a given workability target



Optimized Gradation

- Why should I care?
  - ➢Workable mixture
    - ➢Responds to vibration without segregation
    - ➢Holds an edge
    - ➢Minimal surface voids

Optimized Gradation

- Why should I care?
  - Smoothness
    - Reduced hand finishing
    - Stable edge
    - Uniform response to vibration

Optimized Gradation

- Why should I care?
  - ➢Economics?
    - ➢Lowest material cost?
      - –Cementitious content should be reduced, this can offset increased aggregate costs
    - ➢Reduced labor – finishing, re-work and grinding
    - ➢Life-cycle cost

Optimized Gradation

- Why should I care?
  - Sustainability
    - Reduced paste content (cement)
    - Longer life

Optimized Gradation – Historical Perspective

“We frankly doubt that concrete of the same 28-day strength made with modern materials will always perform as well (as concrete made 15 years ago).”

Powers, PCA SN 1099, 1934

Optimized Gradation – Historical Perspective

- 1960s interstate era – PCC was the predominant paving material
  - Two aggregate system (coarse and fine) - for the most part, uniformly graded
  - Mixed on grade

Optimized Gradation – Historical Perspective

- Post interstate era
  - ➢Intermediate particles (3/8” to #8) scalped for use in other products
  - ➢“Gap graded” mixtures were common
    - ➢Highly responsive to vibration
    - ➢Increased risk of segregation
    - ➢Increased risk of vibrator trails
  - ➢Slipform paving with high energy vibrators became common

1968

Optimized Gradation – Historical Perspective

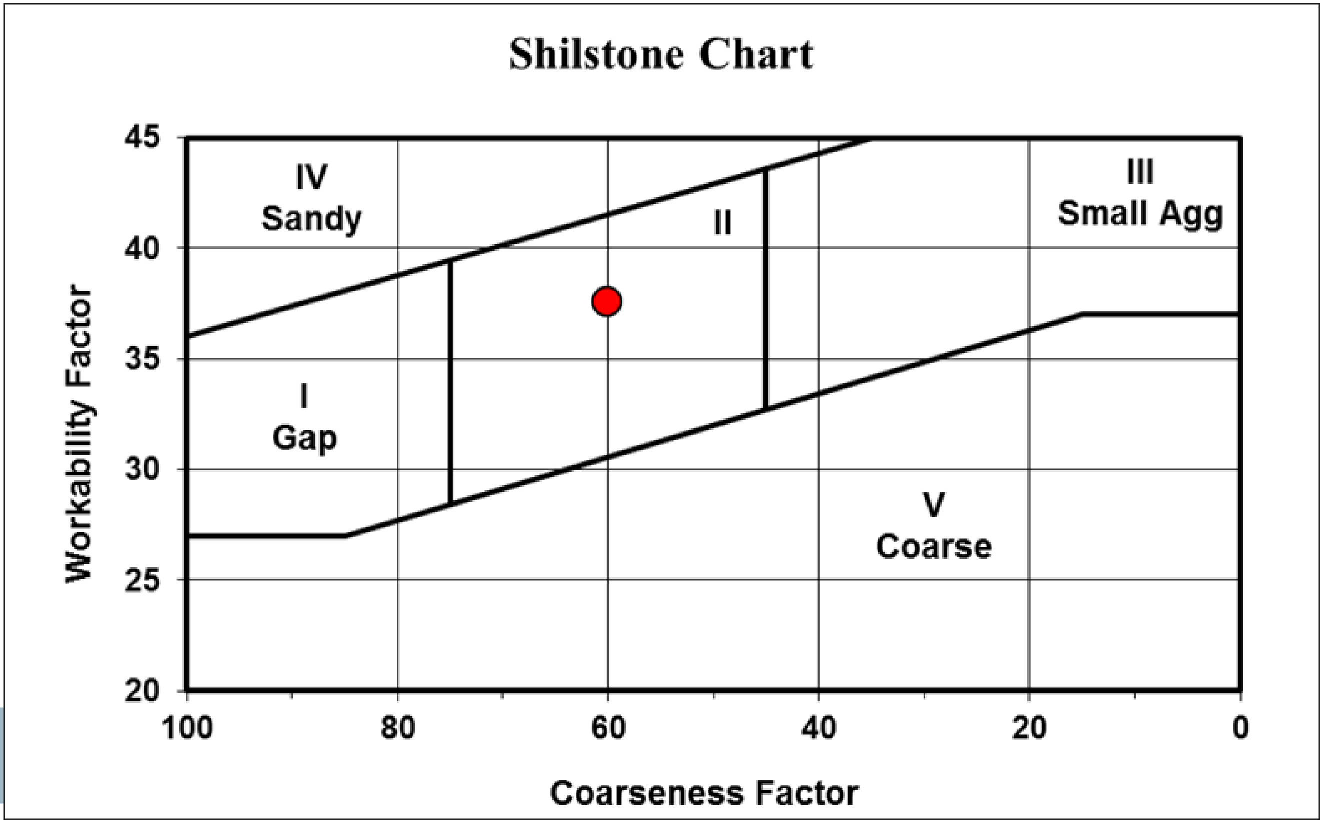
- Fast forward to late 1980s
  - The PCC paving industry began listening to Jim Shilstone's approach to combined gradation
    - Coarseness and workability factor
    - Percent retained
    - 0.45 power chart

Optimized Gradation – Historical Perspective

- Coarseness and workability factors

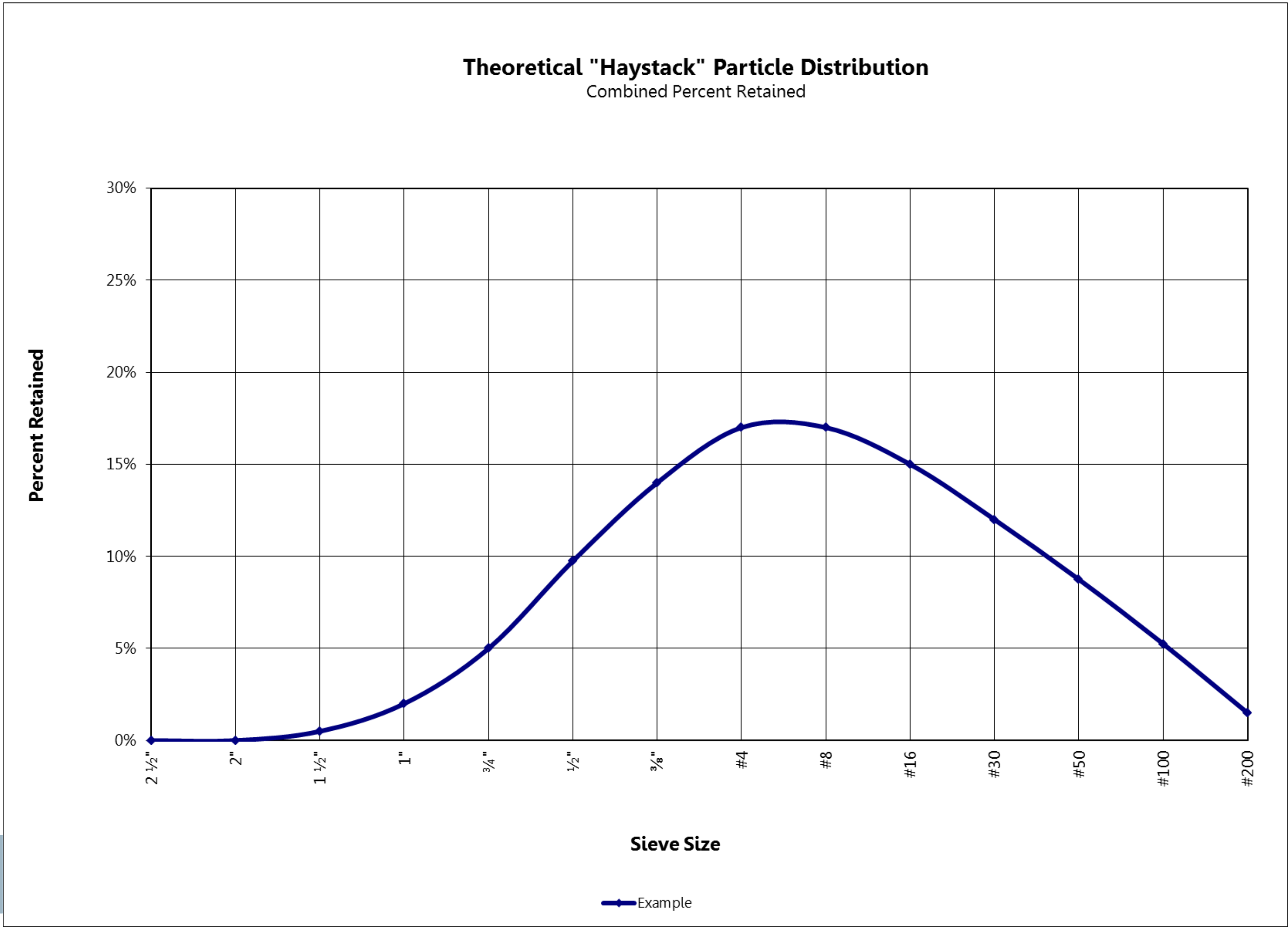
$$\text{Coarseness Factor} = \frac{\%\ Retained\ Above\ 3/8"\ Sieve}{\%\ Retained\ Above\ \#8\ Sieve} \times 100$$

Workability Factor = % Passing #8 (+2.5% for every 94 lb/yd^3 over 564 lb/yd^3)



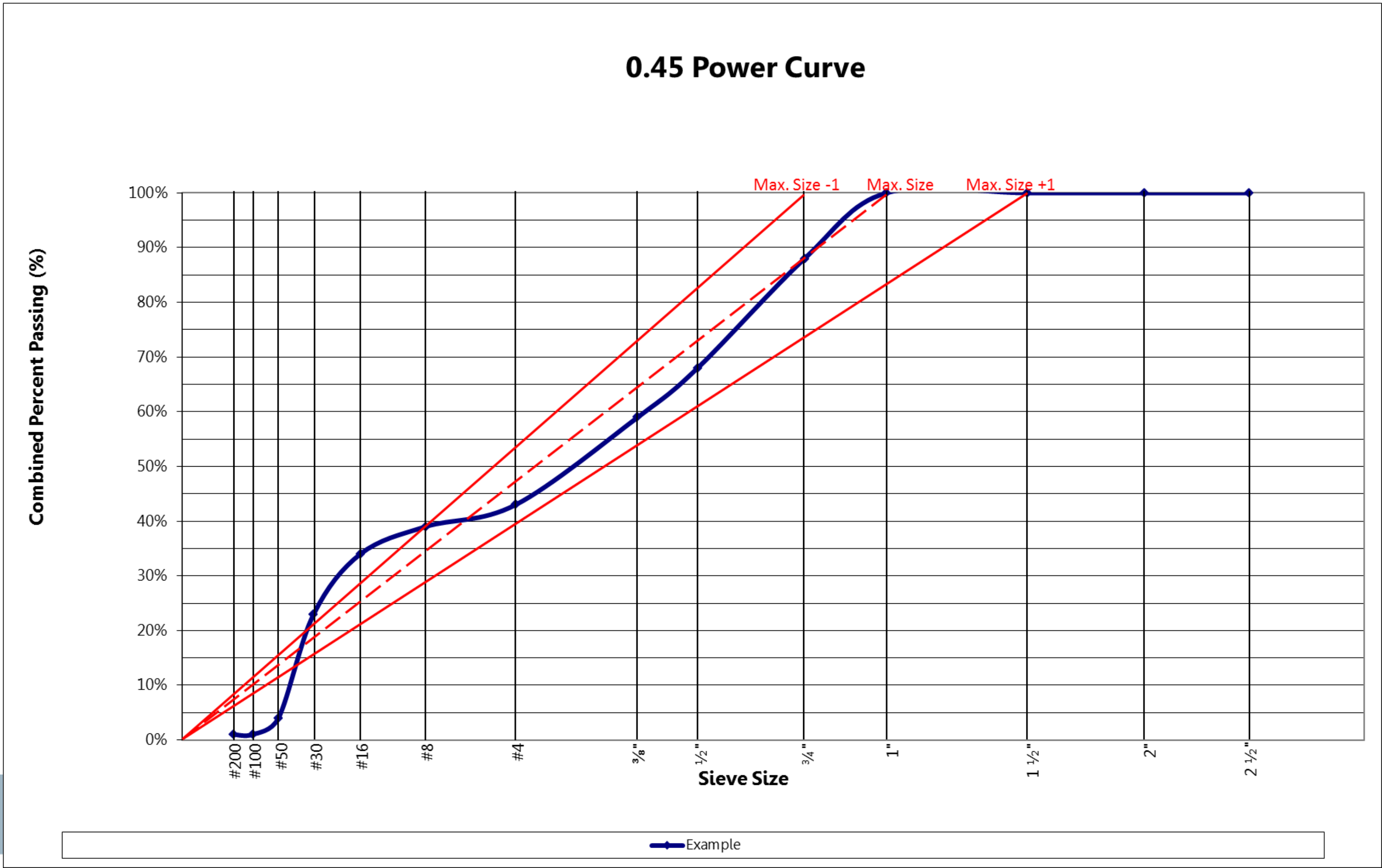
Optimized Gradation – Historical Perspective

- Percent retained on individual sieves



Optimized Gradation – Historical Perspective

- 0.45 power chart

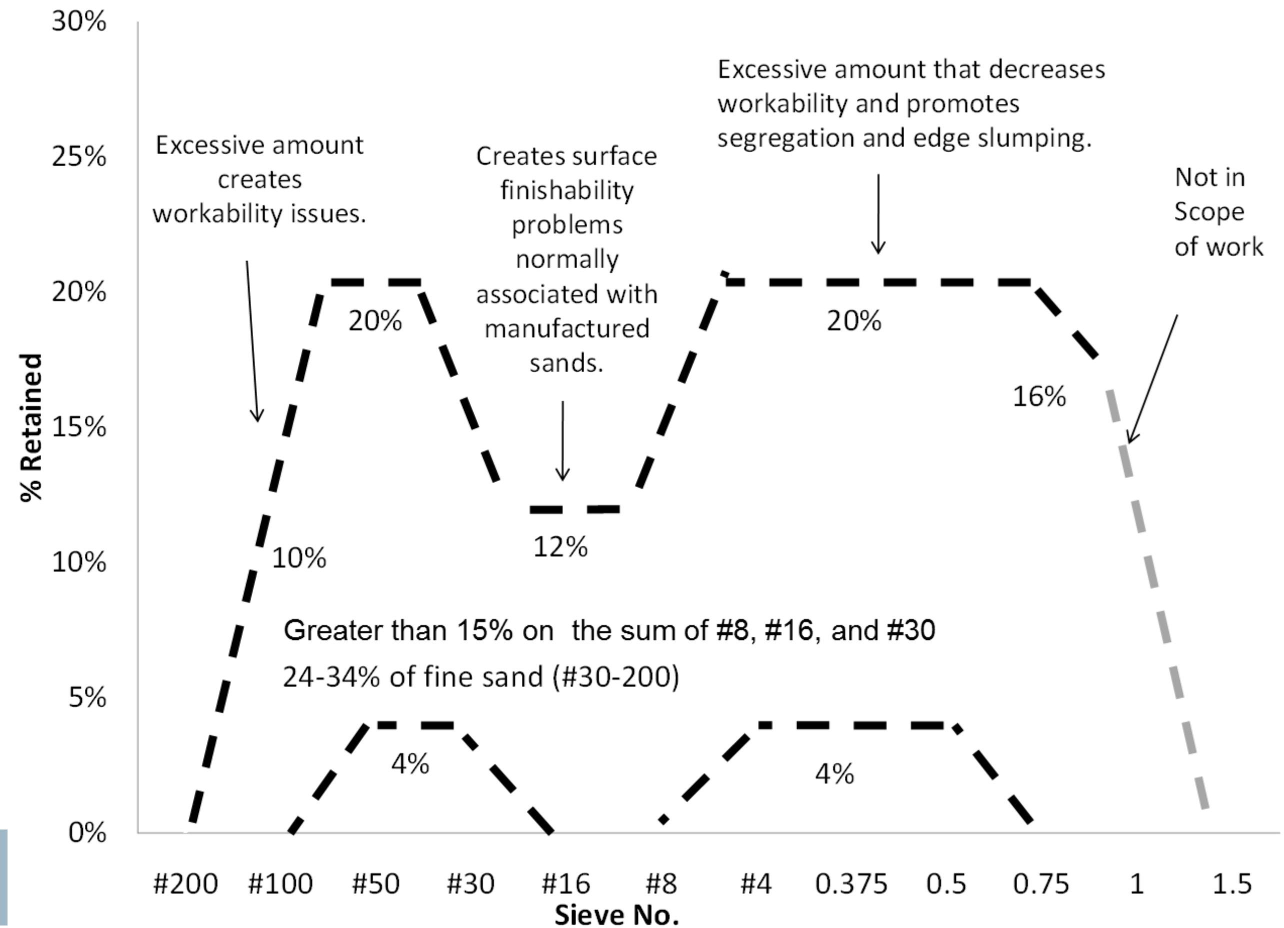


Optimized Gradation – Historical Perspective

- Shilstone's approach has been an improvement, but …
  - Focuses on 3/8" to #8
  - Aimed at preventing segregation
  - Lack of definitive rules for interpreting the graphical output
  - Some mixtures that plot in zone 2 have still been problematic

Optimized Gradation – Best Practices

- The "Tarantula" curve, the latest development in optimized grading for slipformed concrete pavements
- Developed by Dr. Tyler Ley and others



Cook, Ghaeezadah, Ley
FHWA-OK-13-12. 2013.

Optimized Gradation – Best Practices

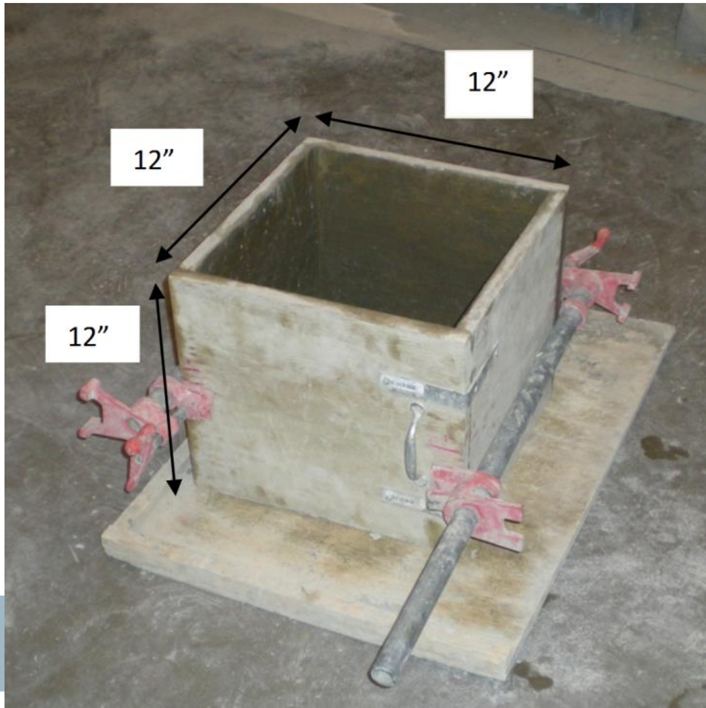
- Remember the purpose of optimized gradation:
  - Economically combining aggregate particles to achieve the desired objectives of:
    - Reduced paste content
    - Desired workability
    - Required hardened properties
- The Tarantula curve was developed concurrently with a lab test that evaluates a concrete mixture’s response to vibration

Following slides from Tyler Ley, Oklahoma State University

Optimized Gradation – Best Practices

- Needed a test that is <u>simple</u> and can examine:
  - Response to vibration
  - Filling ability of the grout (avoid internal voids)
  - Ability of the slip formed concrete to hold an edge (cohesiveness)
- The box test was born out of this need

Images: Cook, D., N. Seader, A. Ghaeezadah, B. Russell, T. Ley. 2014. Aggregate Proportioning and Gradation for Slip Formed Pavements. Fall 2014 TTCC-National Concrete Consortium Meeting, September 9–11, Omaha, NE. www.cptechcenter.org/ncc/TTCC-NCC-documents/F2014%20NC2%20Omaha/11F2014%20Ley%20Optimized%20Graded%20Concrete2.pdf



Optimized Gradation – Best Practices

- Add 9.5” of unconsolidated concrete to the box

Optimized Gradation – Best Practices

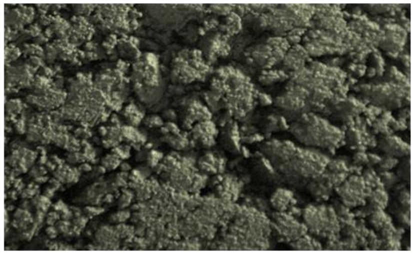
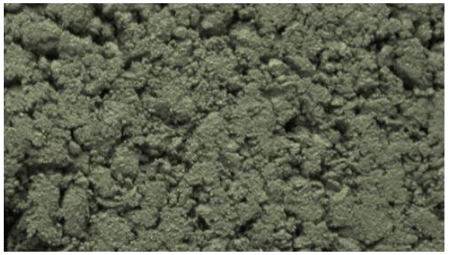
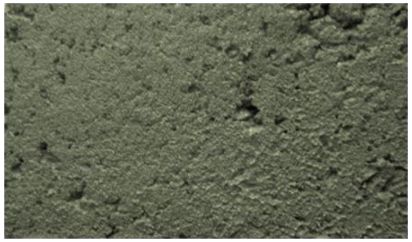
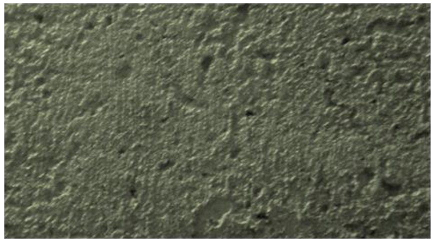
- A 1” diameter stinger vibrator is inserted into the center of the box over a three count and then removed over a three count

Optimized Gradation – Best Practices

- The sides of the box are then removed and inspected for honey combing or edge slumping

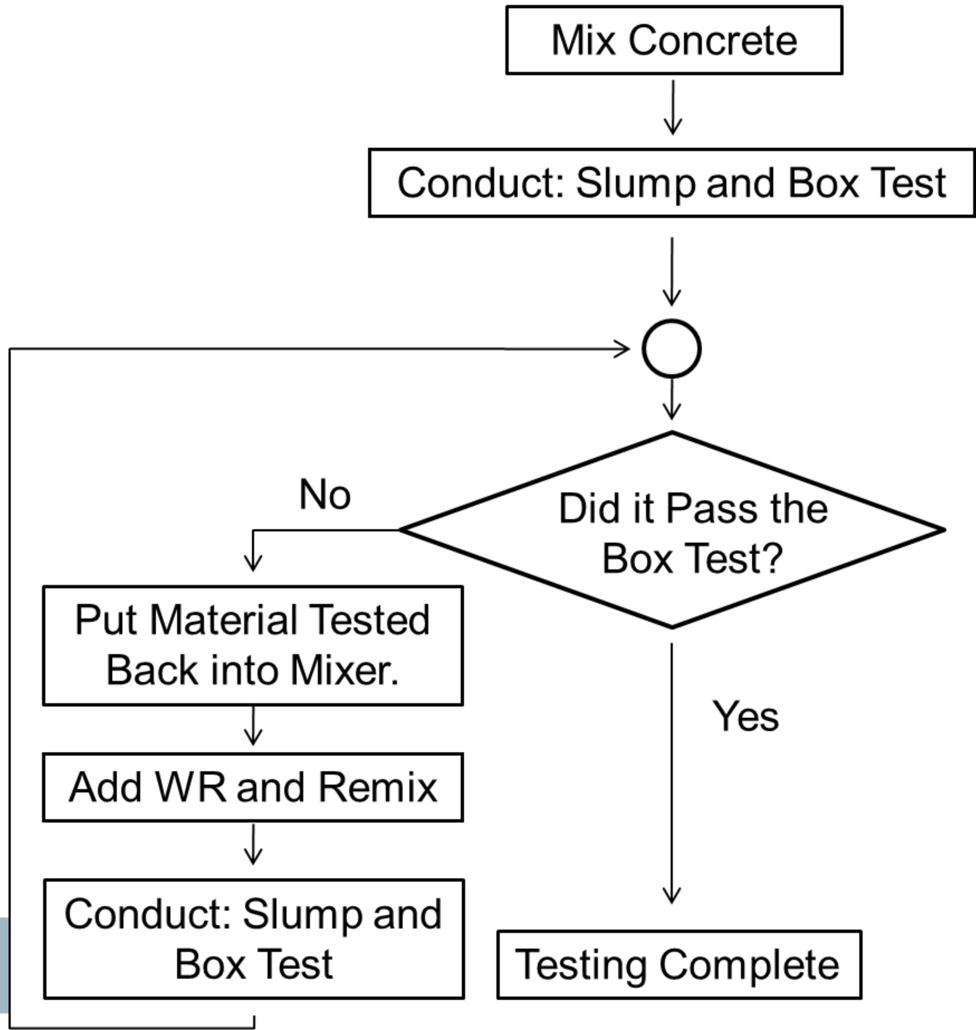
Optimized Gradation – Best Practices

- Visual rating of surface voids and edge slumping
  - A rating of 3 or 4 is considered undesirable
  - Excessive edge slumping with any rating is considered undesirable
  - The box test evaluates the response of a concrete mixture to vibration and its ability to hold an edge
  - It has compared well with field performance

	
4	**3**
Over 50% overall surface voids.	30-50% overall surface voids.
	
2	**1**
10-30% overall surface voids.	Less than 10% overall surface voids.

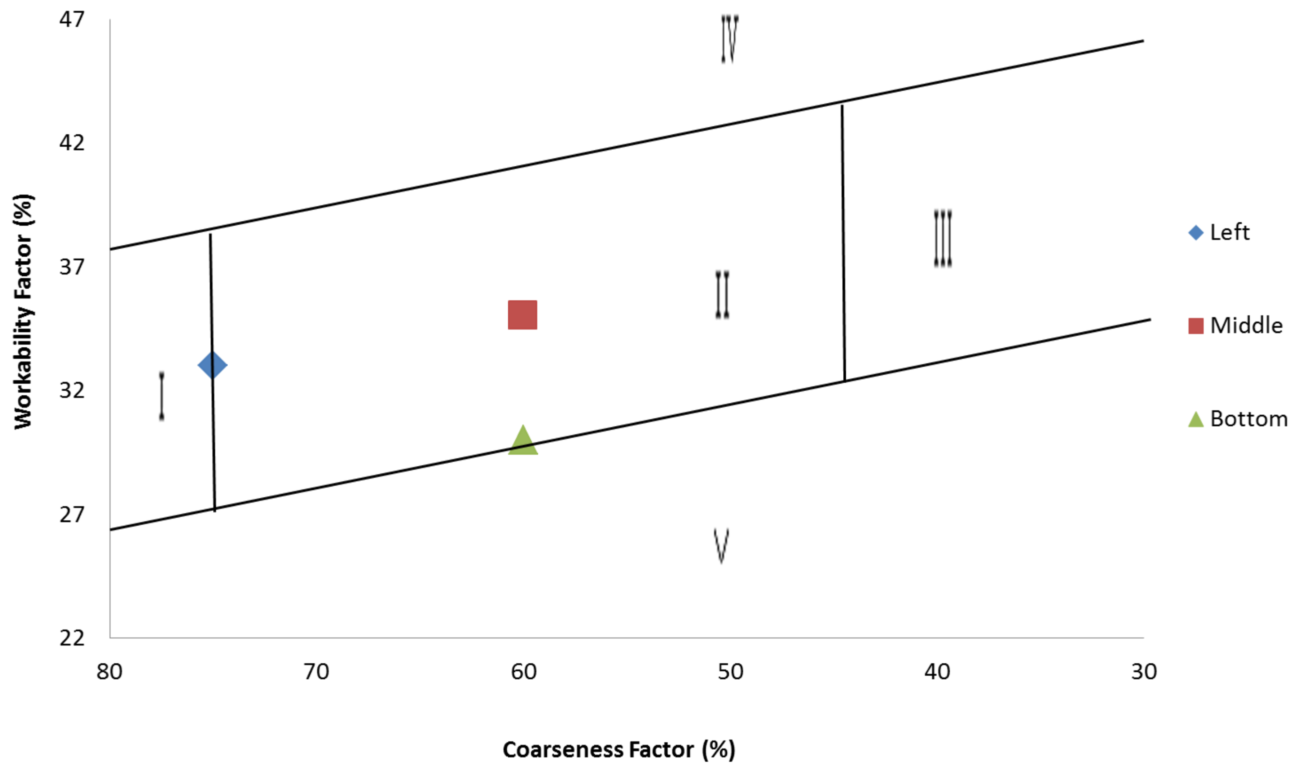
Optimized Gradation – Best Practices

- Low amounts of water reducer indicate a good mixture
- High amounts indicate an undesirable combined gradation
- Quantify how WRA dosage demand varies with changes in the combined gradation



Optimized Gradation – Best Practices

- In the beginning, …
  - Lab evaluation of multiple mixtures
  - Focused first on Zone II of the coarseness factor chart

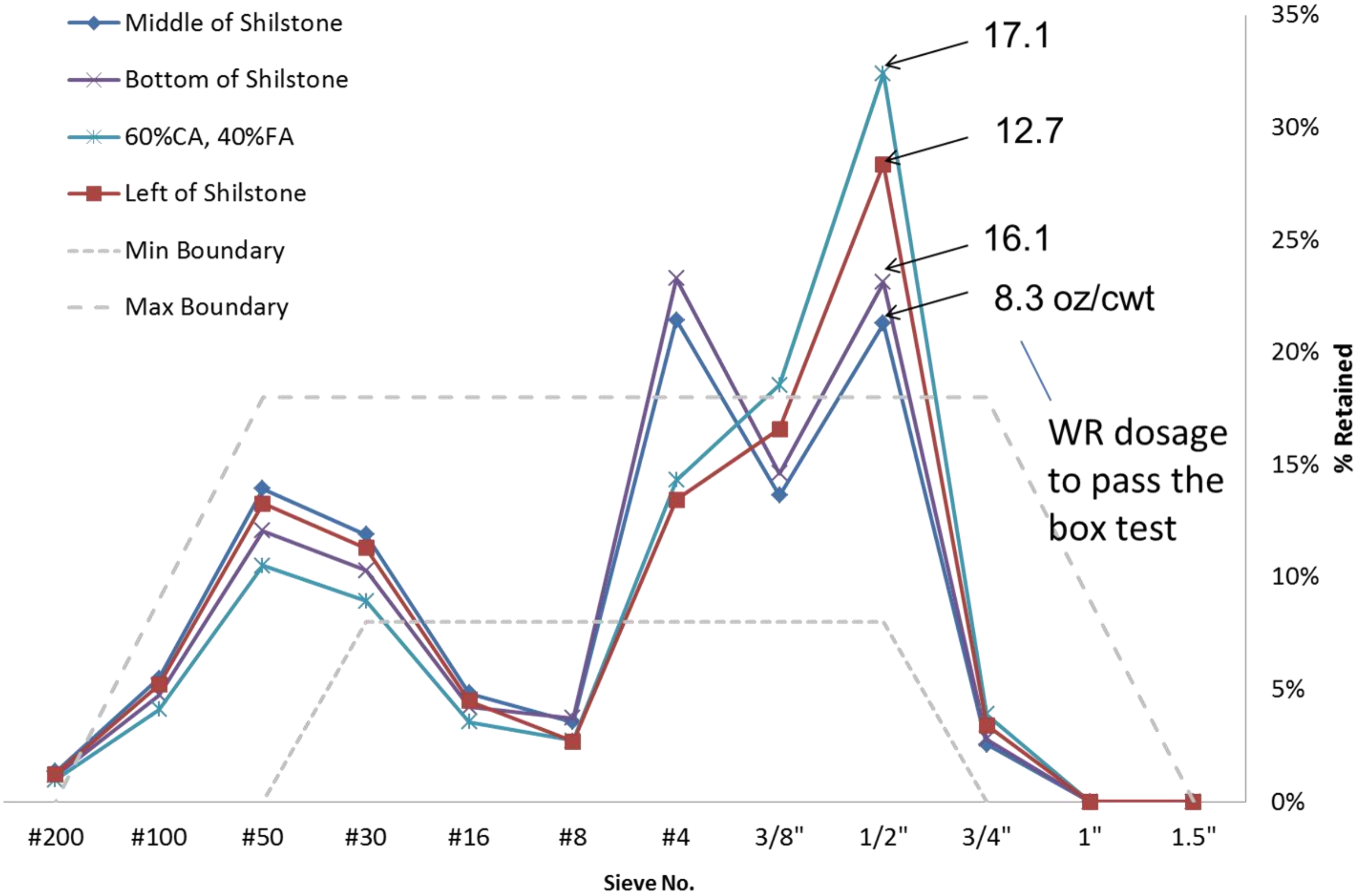


Optimized Gradation – Best Practices

- Typical mixture used in the laboratory studies
  - 0.45 w/cm
  - 5 sacks total cementitious
  - 20% fly ash
  - Single sand source
  - 3 crushed limestones
    - Limestone A
    - Limestone B
    - Limestone C

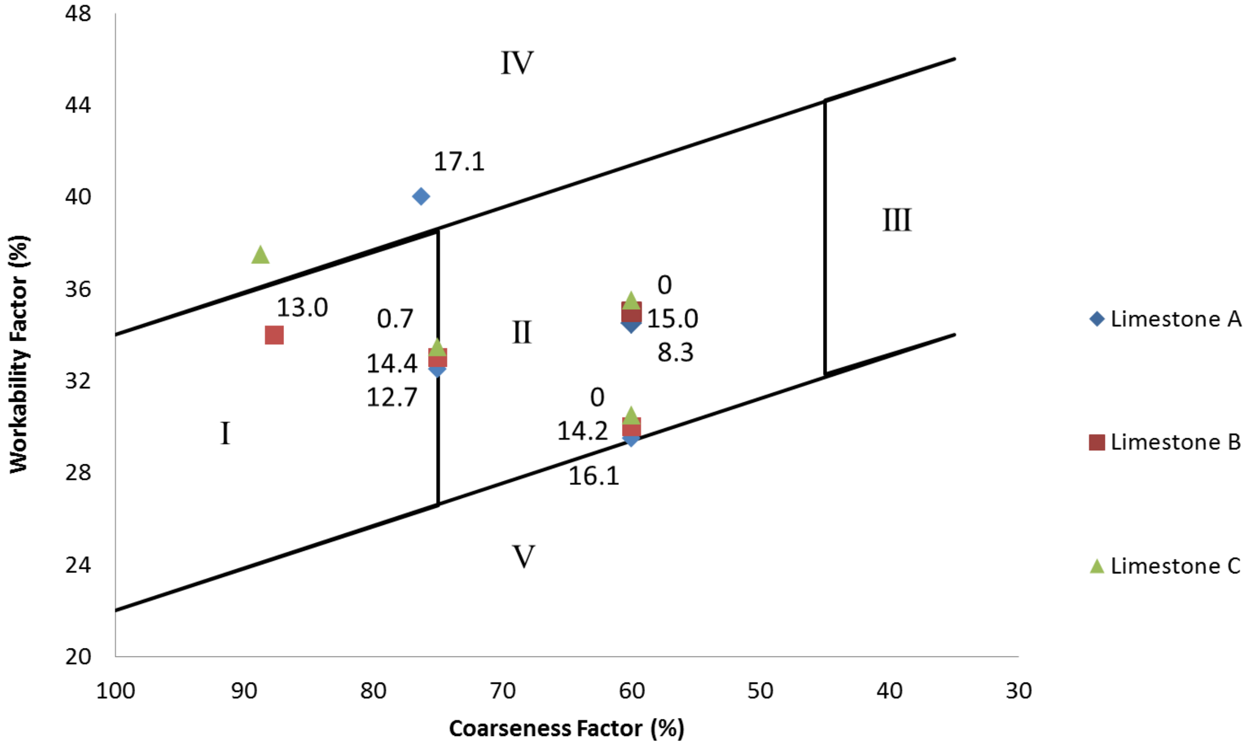
Optimized Gradation – Best Practices

- Limestone A



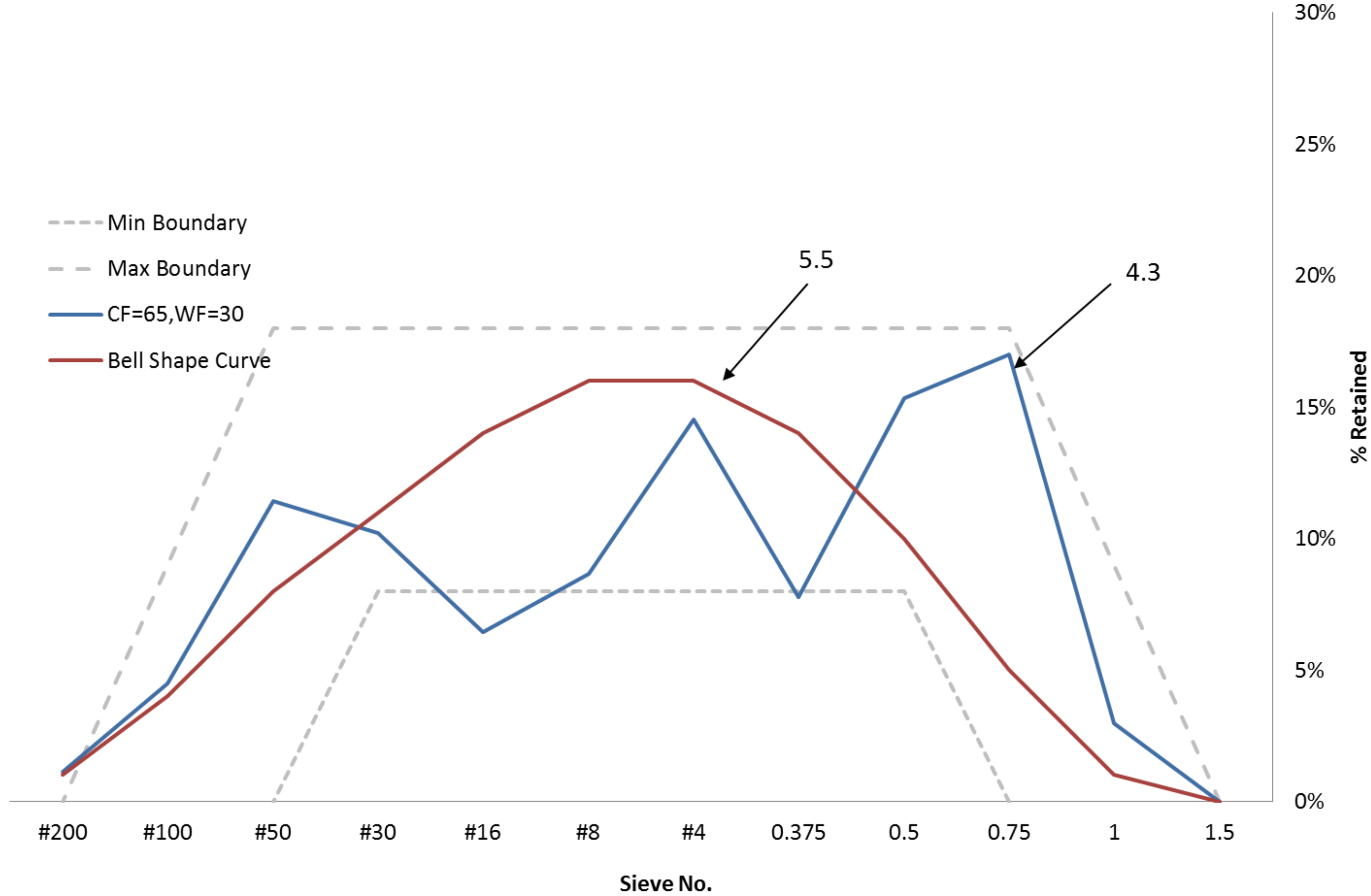
Optimized Gradation – Best Practices

- Box test results vary significantly for mixtures that plot in the same area of the coarseness factor chart
- The coarseness factor chart is not a reliable indicator of response to vibration and ability to hold an edge



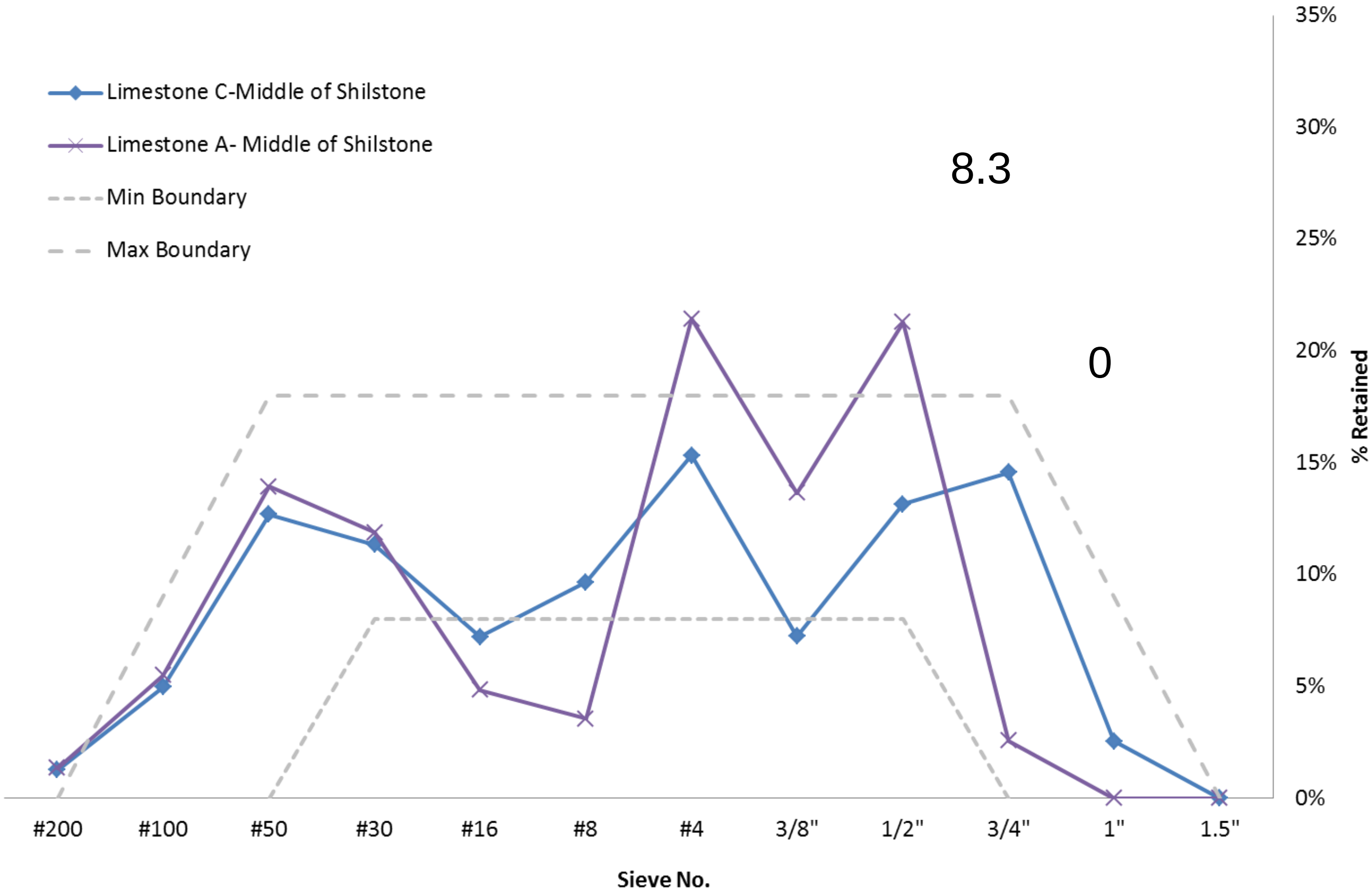
Optimized Gradation – Best Practices

- What about the Haystack?
- Box test results are no better than for a typical mixture



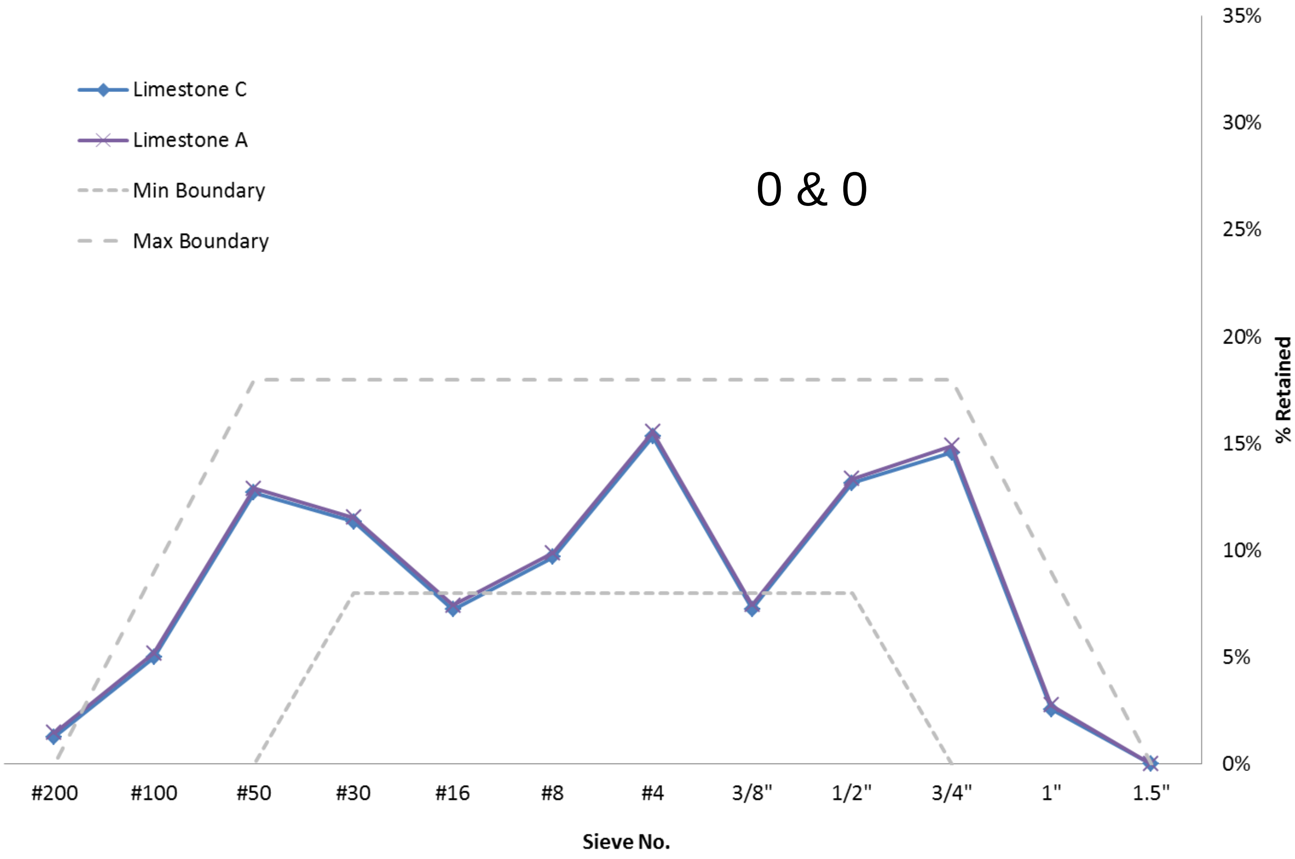
Optimized Gradation – Best Practices

- Focus on the combined percent retained chart



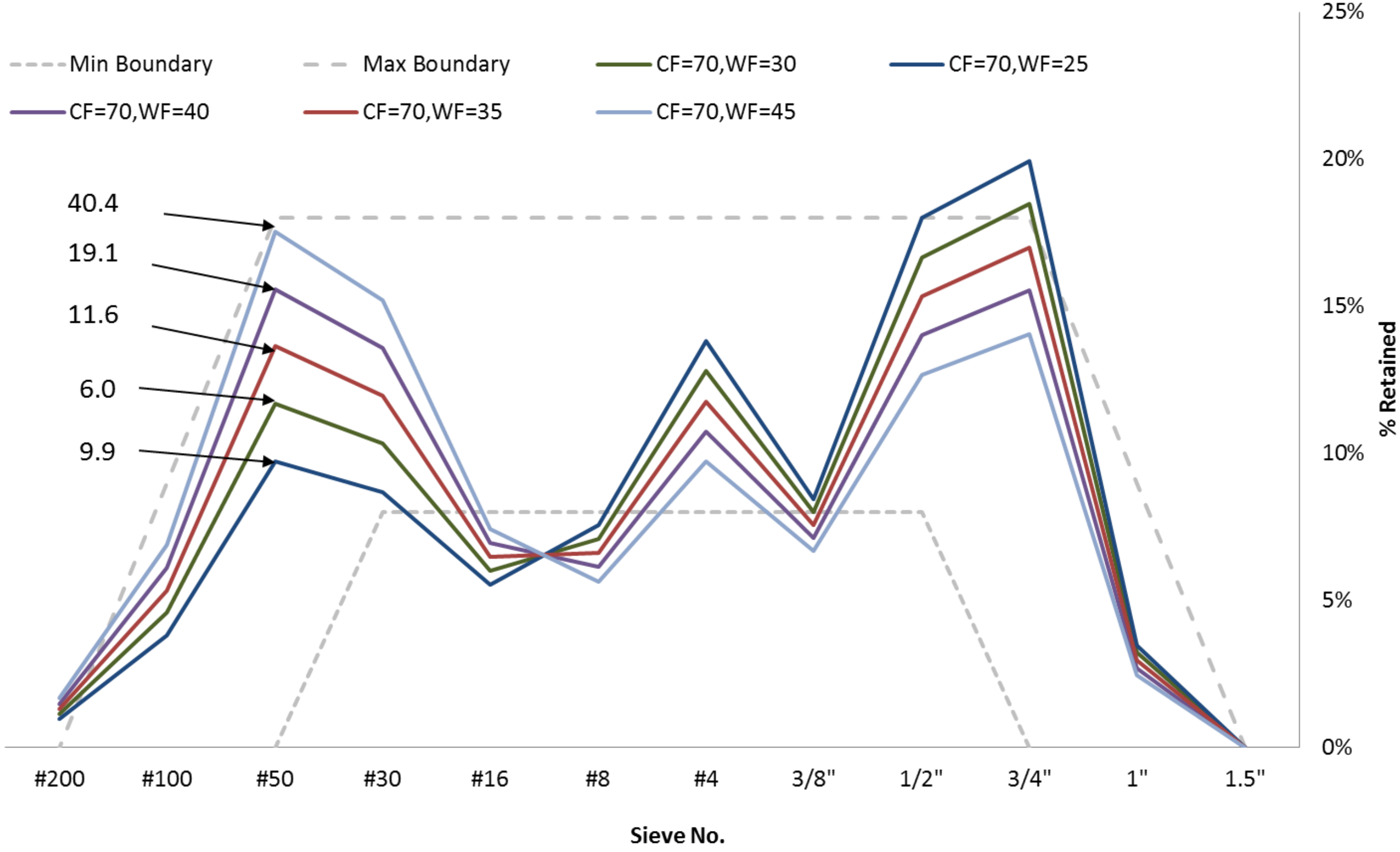
Optimized Gradation – Best Practices

- Sieve limestone A to match the gradation of limestone C
- The percent retained on each sieve chart provides improved feedback over the coarseness factor chart



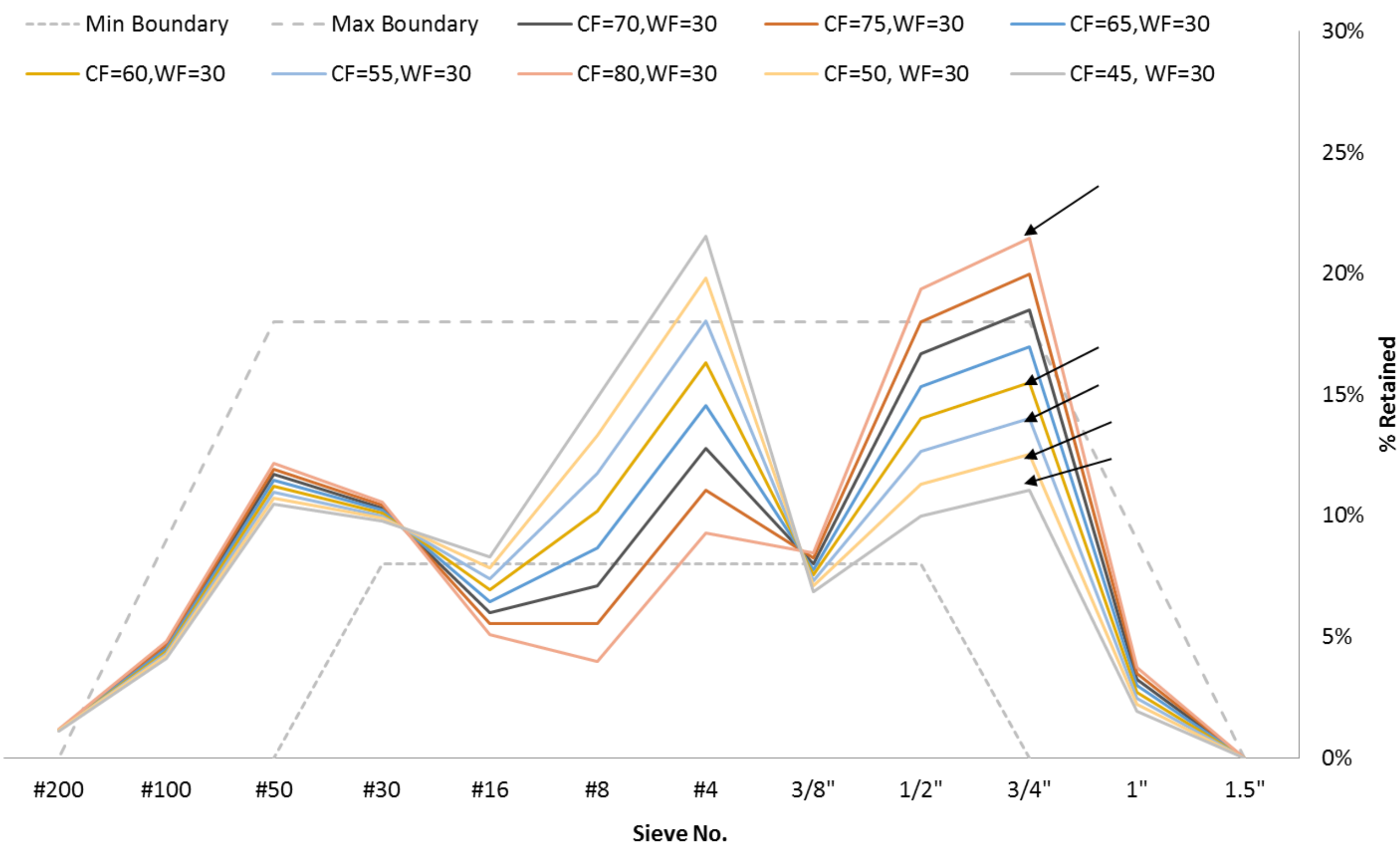
Optimized Gradation – Best Practices

- What about fine aggregate?



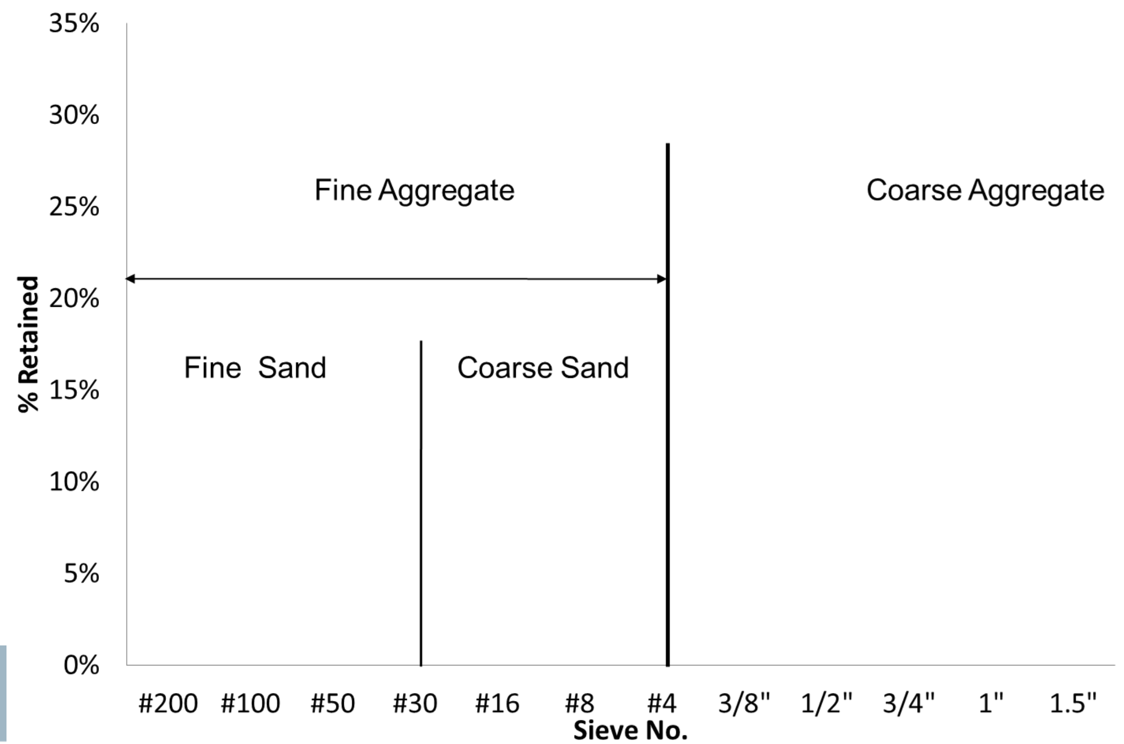
Optimized Gradation – Best Practices

- And coarse aggregate?



Optimized Gradation – Best Practices

- Defining coarse sand (between the #4 and #30) and fine sand (finer than the #30)
- ACI 302.1R-04 recommends the sum of material retained on the #8 and #16 sieves should be a minimum of 13% to avoid edge slumping

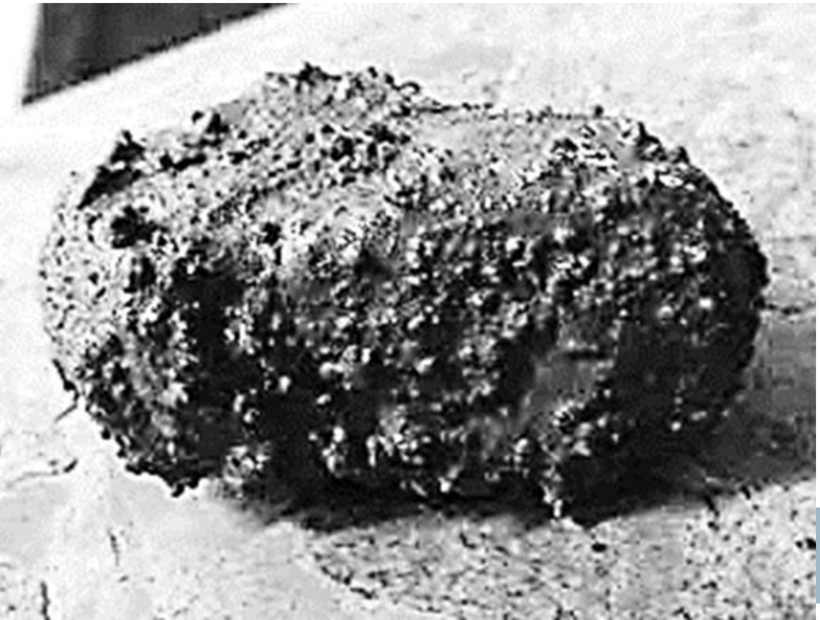


Optimized Gradation – Best Practices

- Determine how fine aggregate gradation impacts the box test:
  - Remove all coarse sand (#30 to #4)
  - Test multiple mixtures
    - All fine sand
    - Multiple mixtures with slowly increasing amounts of coarse sand

Optimized Gradation – Best Practices

- Fine aggregate impacts
  - #8 and #16 tend to cling to coarse aggregate particles, improving cohesion and stability of the mixture
    - Reduced edge slumping
    - Improved response to vibration

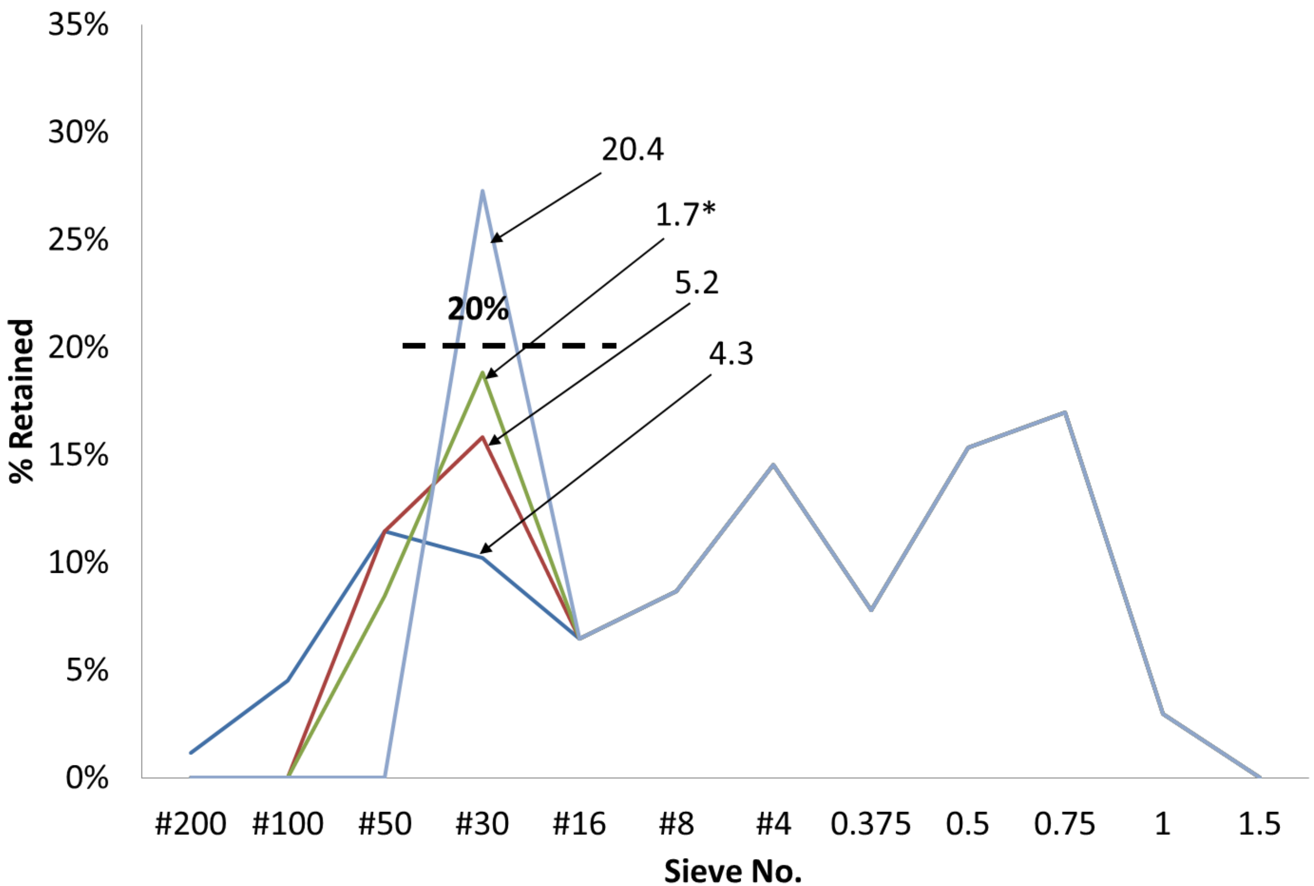


Optimized Gradation – Best Practices

- Given that coarse sand (#30 to #4) improves the mixture, how much is enough?
  - A minimum of 15% cumulative retained on the #8-#30 sieve sizes is suggested
  - The #8 and #16 should be limited to 12% to minimize finishing issues

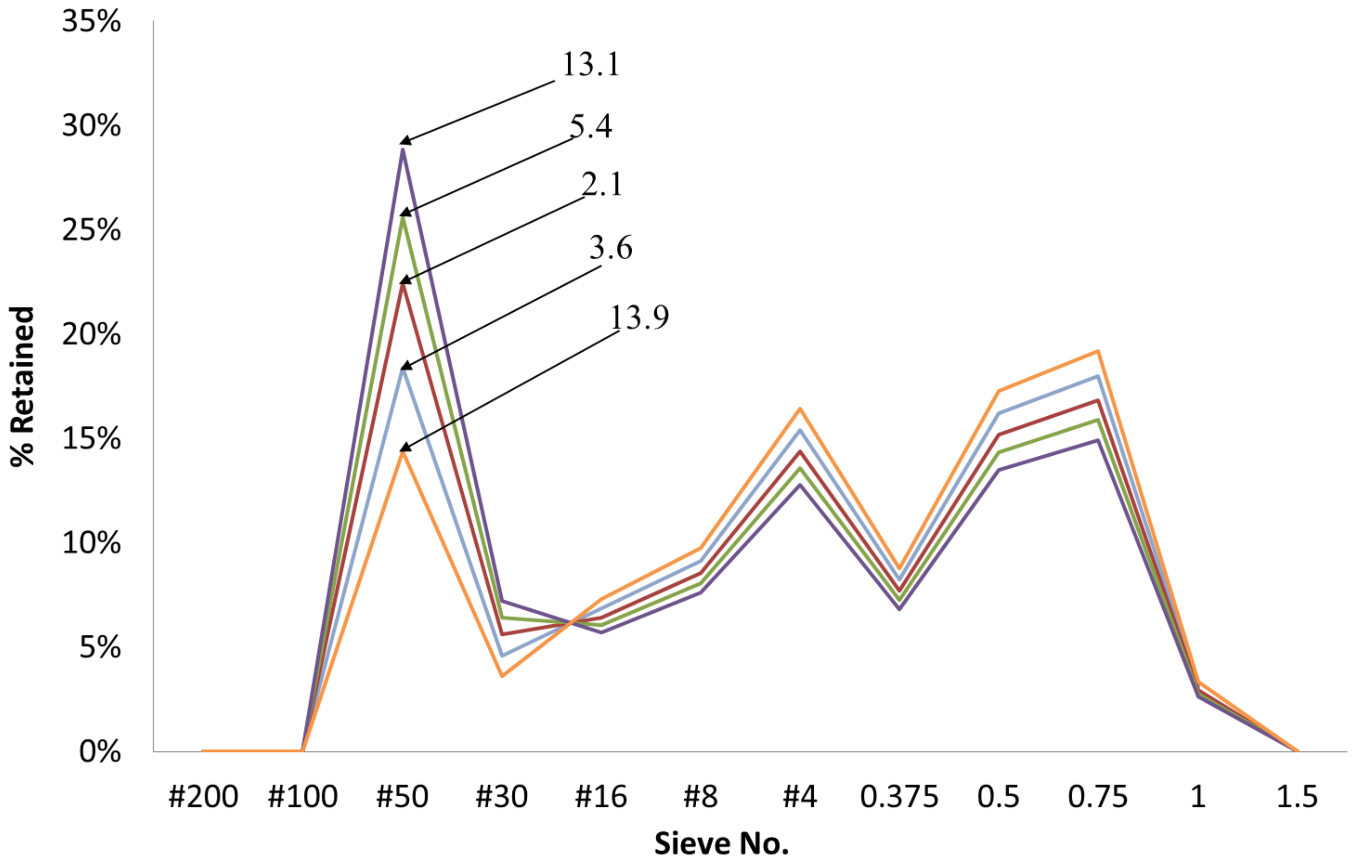
Optimized Gradation – Best Practices

- Determine how fine aggregate gradation impacts the box test:
  - ➢Keep the ratio of coarse and fine sand constant
  - ➢Vary the gradation of the fine sand



Optimized Gradation – Best Practices

- Determine how fine aggregate gradation impacts the box test:
  - Vary the fine sand (#30 to #200) while holding the #16 through 1" constant



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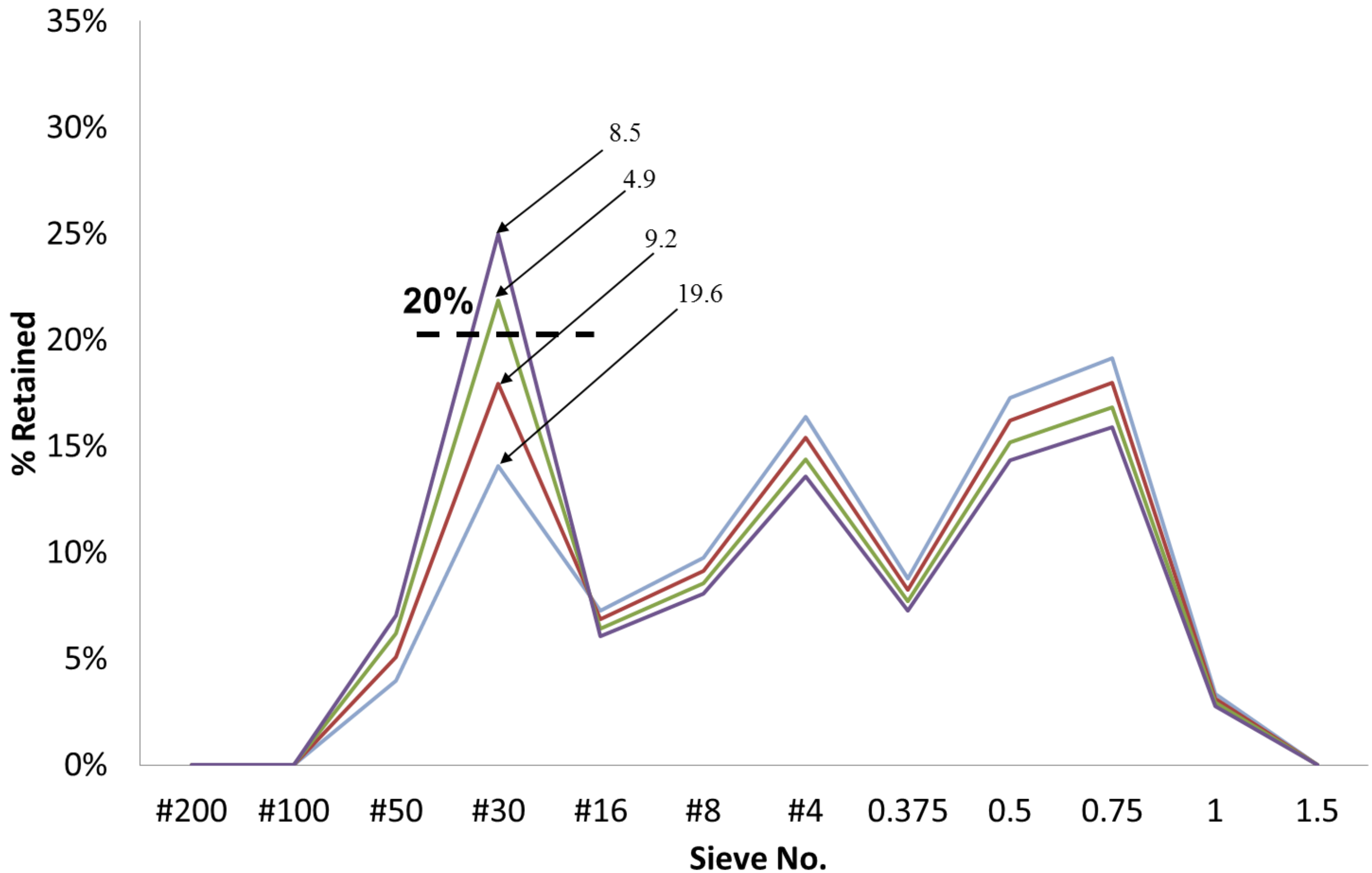

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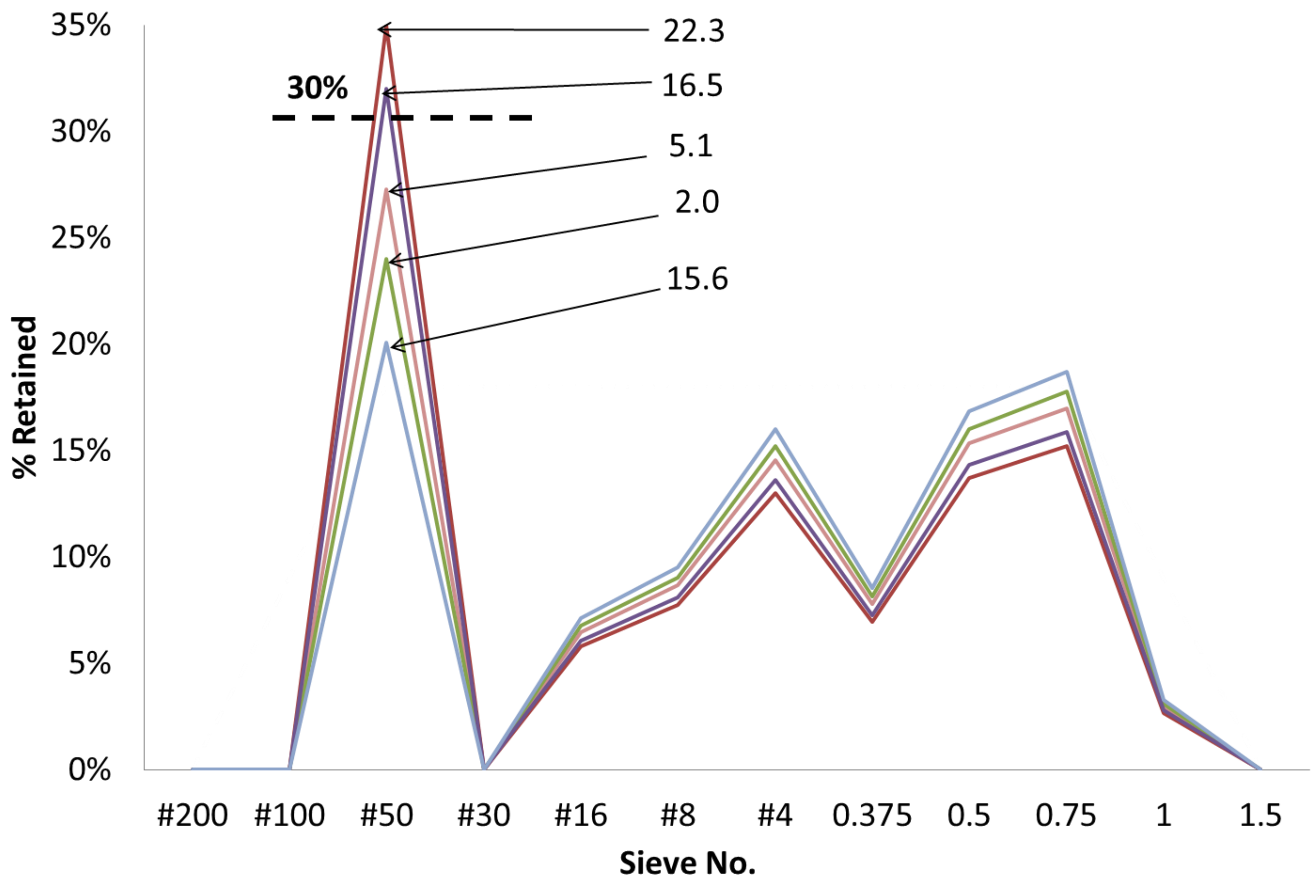

Optimized Gradation – Best Practices

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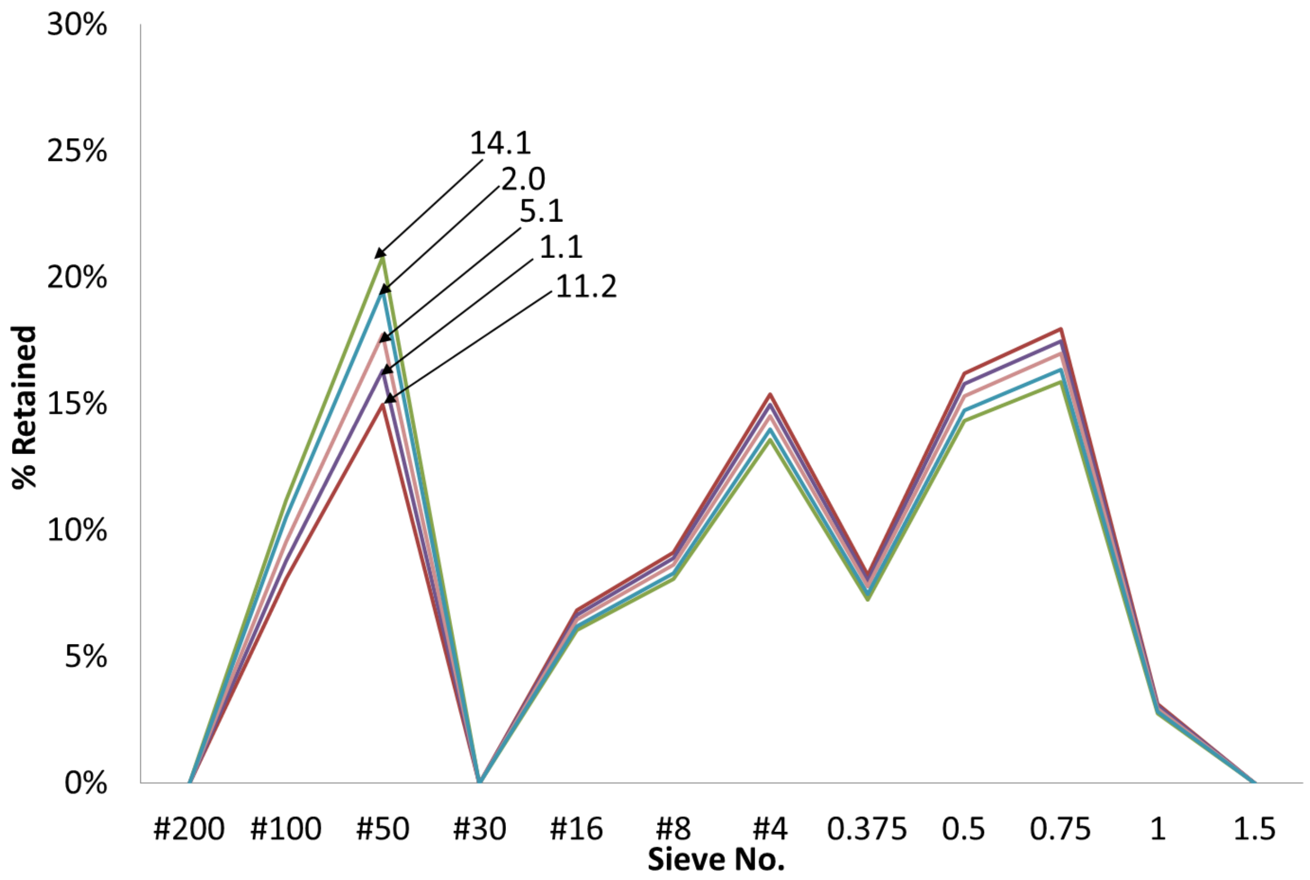
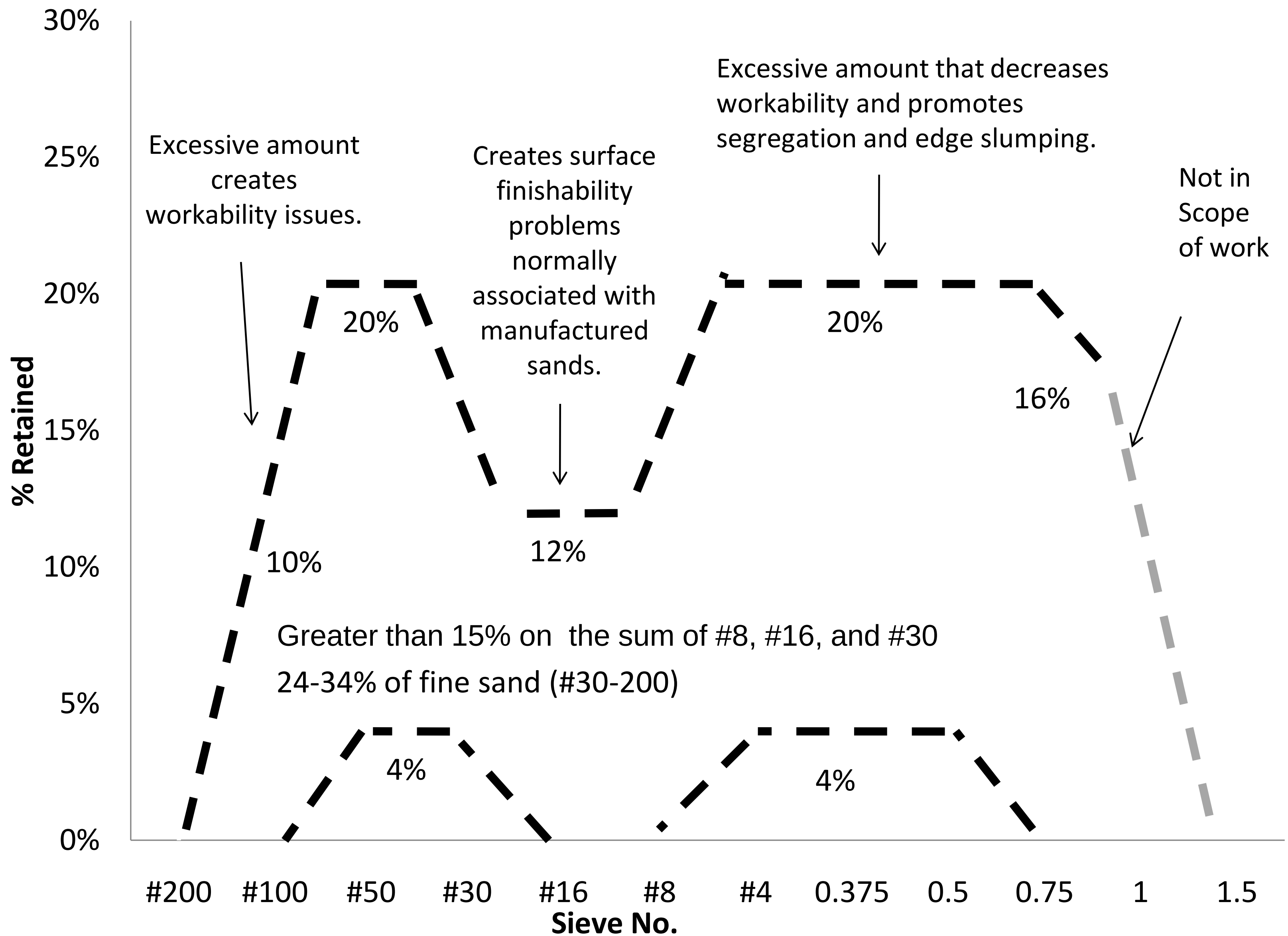


Optimized Gradation – Best Practices

- The distribution of fine sand can vary largely without affecting the workability.
- An aggregate volume between 24% to 34% is recommended for #30 - #200.
- This range was similar for multiple gradations and aggregate sources
- More than 20% retained on the #30 sieve size created finishing issues

Optimized Gradation – Best Practices

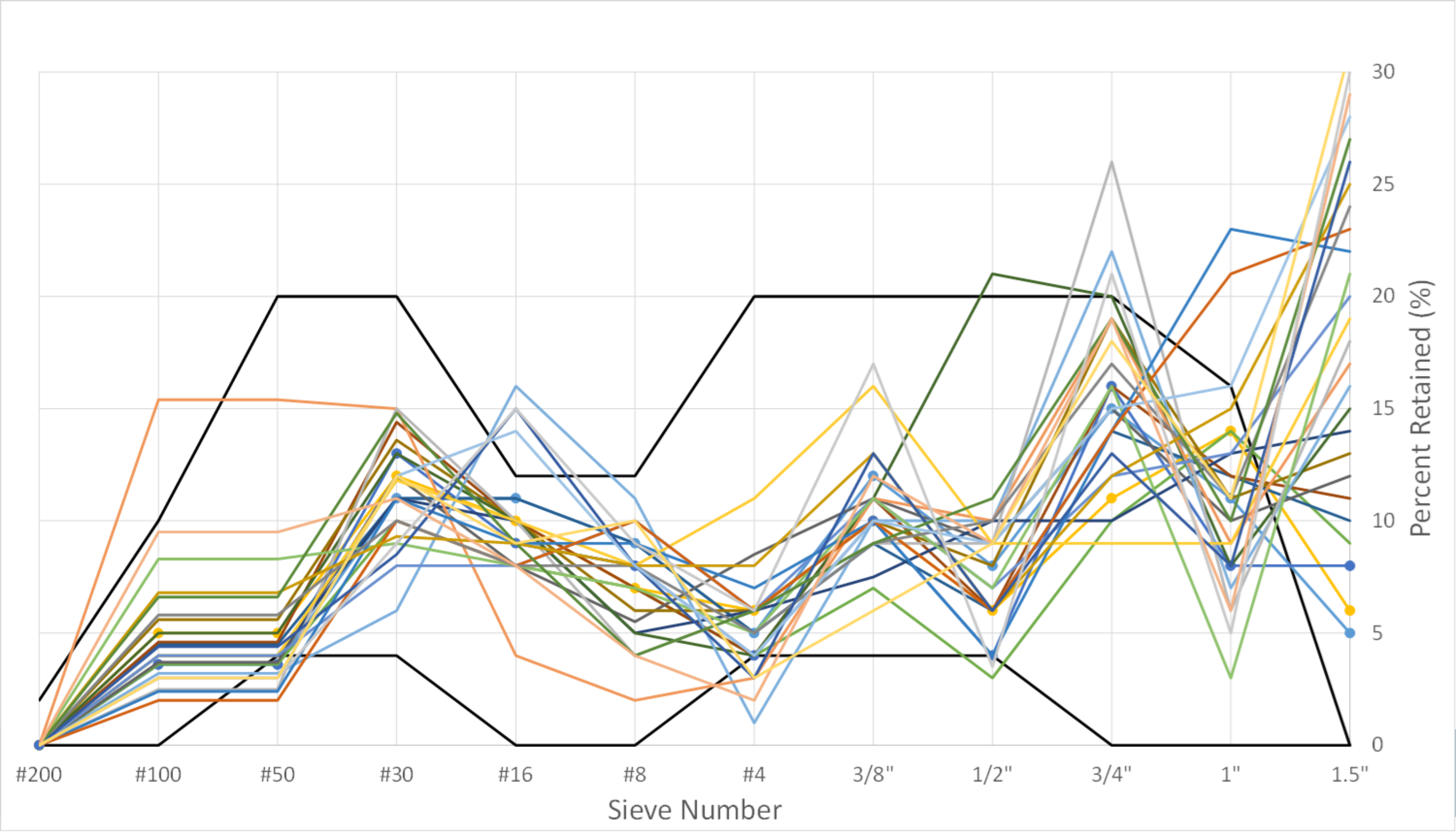
- The Tarantula curve



Optimized Gradation – Best Practices

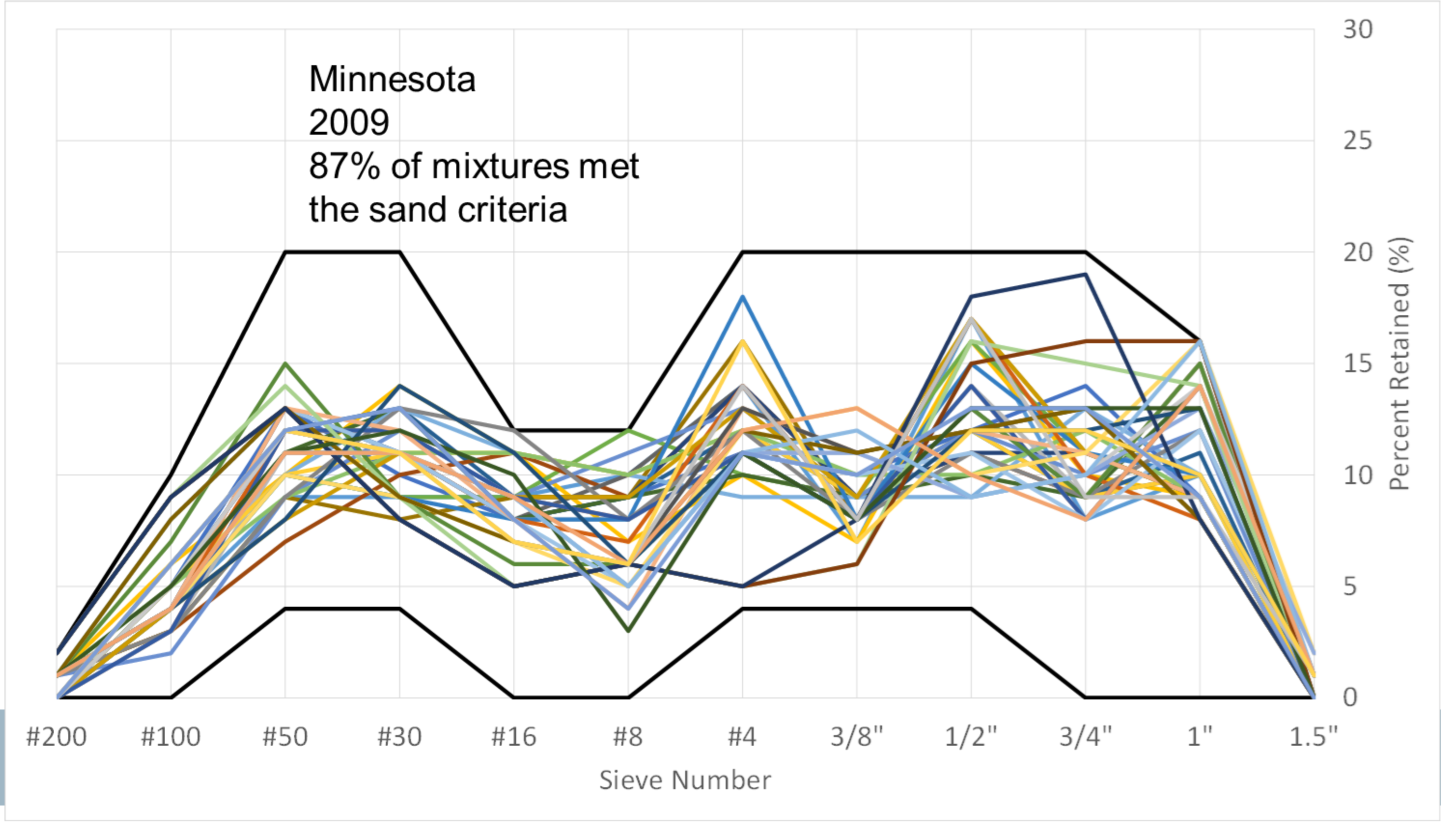
- Tarantula Curve validation
  - ➢ MNDOT implements a combined gradation specification in the late 1990s (incentive for Zone II)(data from Maria Masten)

1996-1998



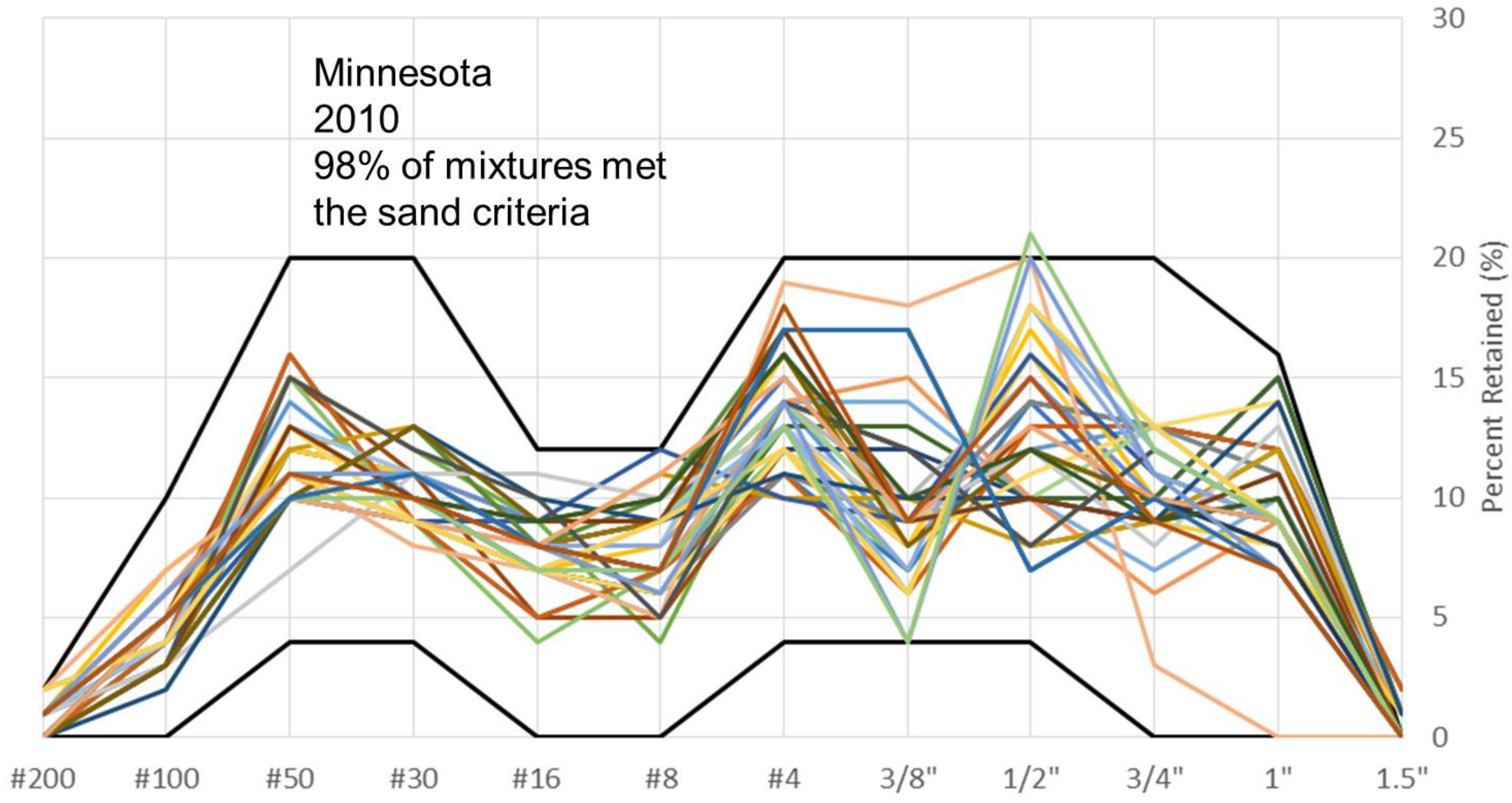
Optimized Gradation – Best Practices

- Tarantula Curve validation
  - Through trial and error, contractors independently validated the Tarantula curve by honing in on mixtures that fit within the recommended limits (data from Maria Masten)



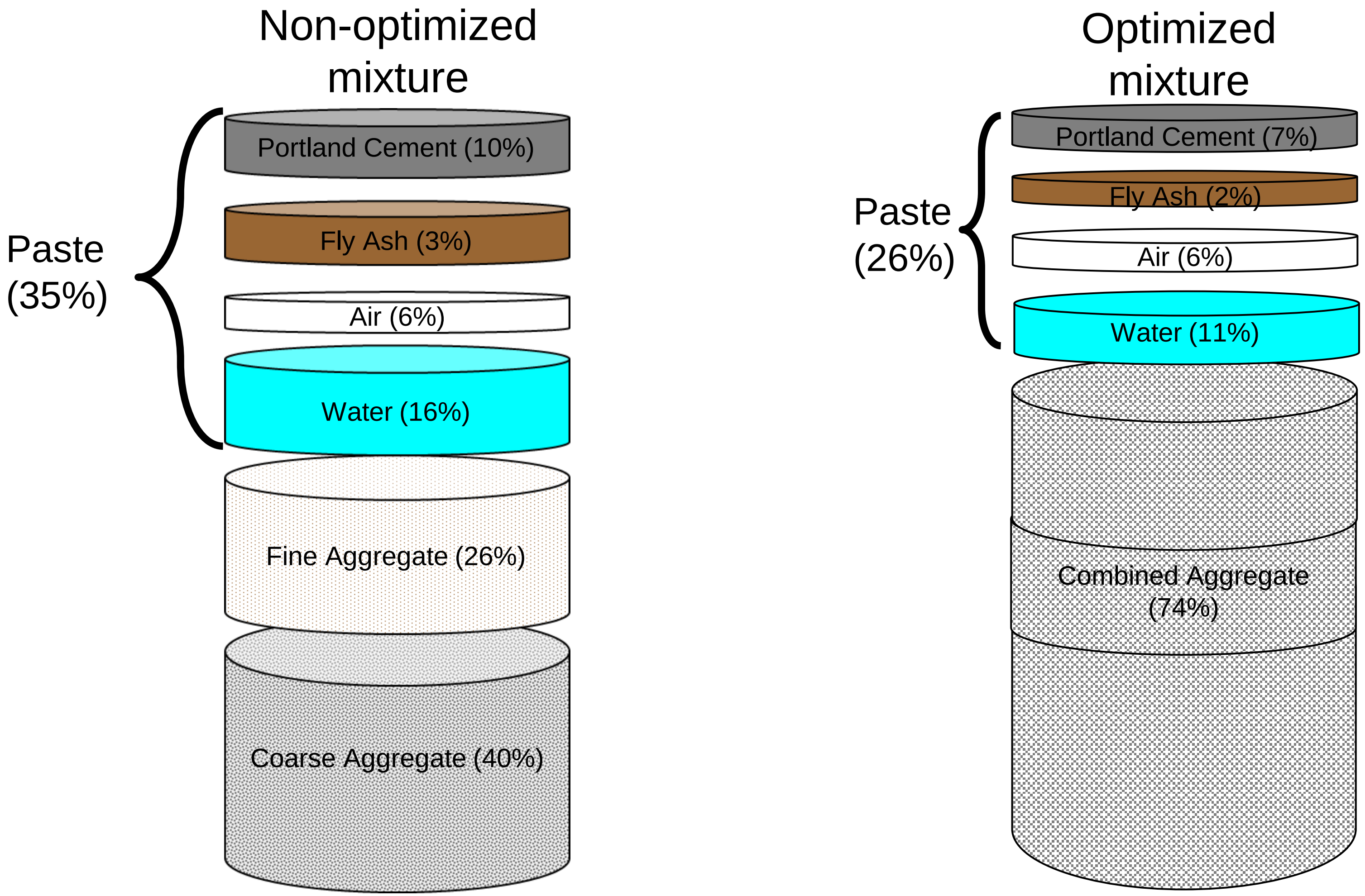
Optimized Gradation – Best Practices

- With added experience, the field mixtures continue to be refined and further reflect the Tarantula curve recommendations



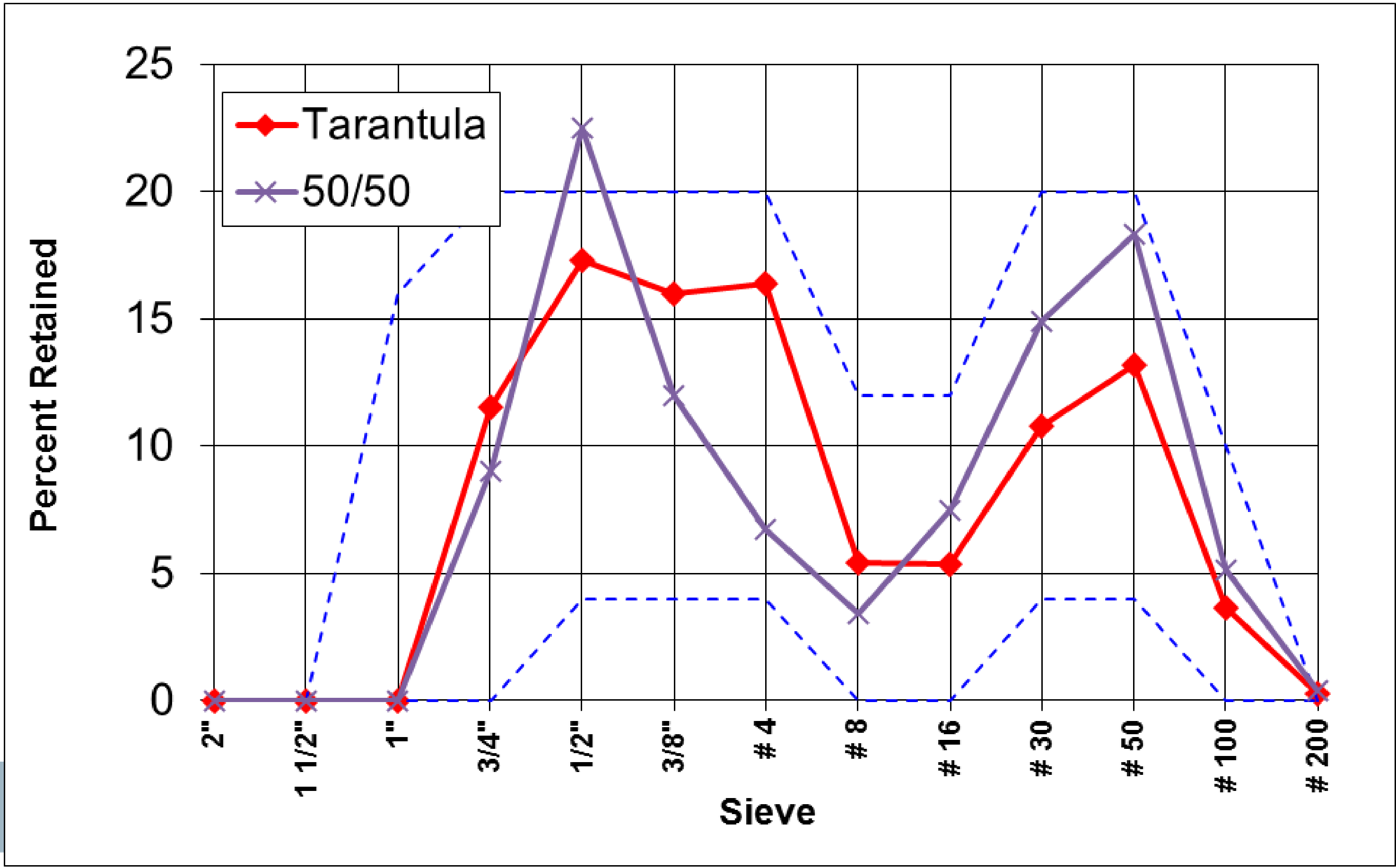
Concrete 101

- Typical concrete proportions (by volume)



Aggregate System

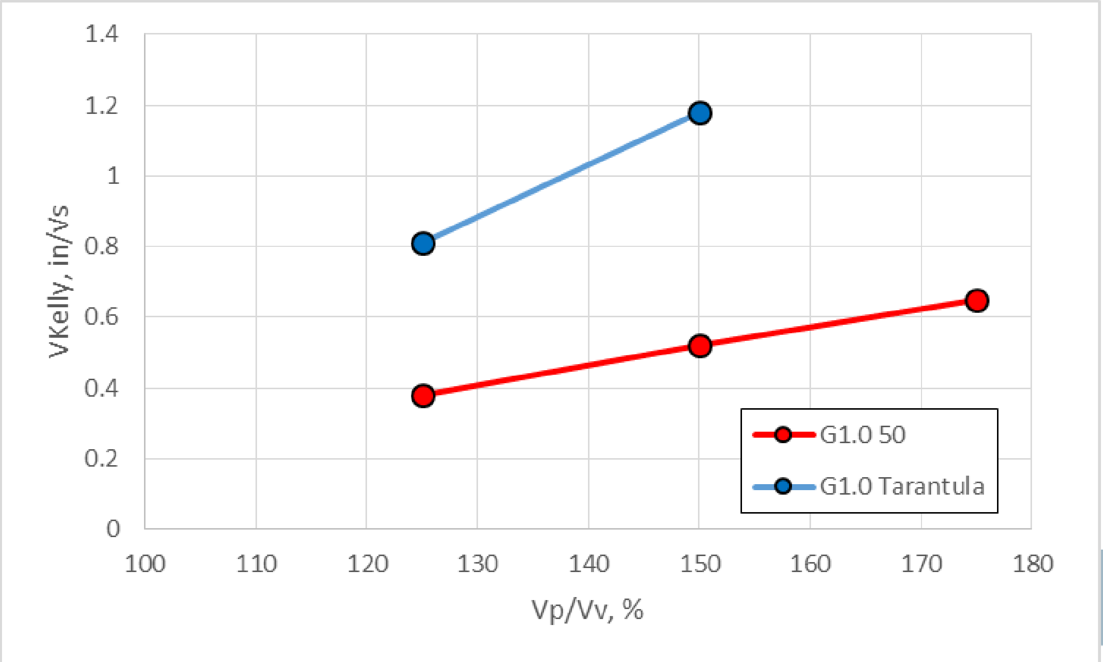
- 50/50 – void ratio 27.1%
- Tarantula – void ratio 25.3%



Proposed Mixture Proportioning Procedure

<u>Put it all together</u>

	Tarantula		50/50		
Void ratio	125	150	125	150	175
Cementitious	427	505	424	500	543



Optimized Gradation – Best Practices

- Strength will not be adversely affected
  - 338 lb/yd^3 of portland cement
  - 85 lb/yd^3 of fly ash

- Still have to do trial batches

	7 Day Strength		28 Day Strength	
Source	Min-Max (psi)	Average (psi)	Min-Max (psi)	Average (psi)
Limestone A	4000-6320	5180	5330-8890	6940
Limestone B	4990-5270	5130	6220-7940	7450
River Rock	3990-4850	4440	5760-7050	6410

Optimized Gradation – Best Practices

- Putting optimized gradation into practice
  - Specifications
    - Aggregate grading – modify as needed to allow use of the Tarantula curve
    - Control paste volume
      - –Cementitious content
      - –Maximum w/cm = 0.42

Optimized Gradation – Best Practices

- Putting this into practice
  - ➢Plant production
    - ➢Stockpile management – minimize segregation
    - ➢Aggregate stockpile moisture content
    - ➢Multiple aggregate bins
    - ➢Thorough mixing

Optimized Gradation – Best Practices

- Conclusions
  - ➢ Optimized gradation is one tool helping to produce durable concrete
    - ➢ Reduced paste content
    - ➢ Improved workability
  - ➢ The box test evaluates a mixtures response to vibration and ability to hold an edge
  - ➢ The Tarantula curve was developed in parallel with the box test
  - ➢ The Tarantula curve has been independently validated by contractors who have been developing optimized mixtures since the late 1990s

Questions and Discussion