Concrete Pavement Mix Selection and Design

Iowa Concrete Lunch & Learn Program
Spring 2023

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IOWA STATE UNIVERSITY
Institute for Transportation

National Concrete Pavement Technology Center
Tech Center

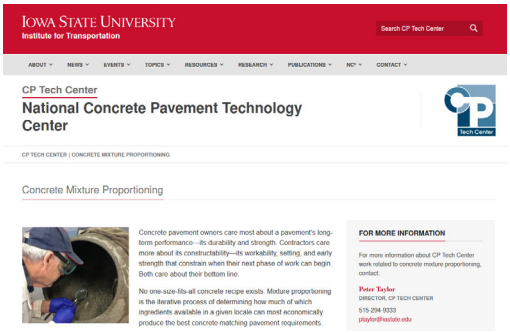
Announcements

- We'd like to hear from you!
  - Interest in future topics
  - Evaluation and thoughts on the lunch & learn program

Acknowledgments

- Thanks to Iowa DOT & ICPA for their support of this program

- Additional resources are available on the CP Tech Center's "Concrete Mixture Proportioning" webpage:
  - https://cptechcenter.org/mix-proportioning/



Today's Presentation

- Basics of concrete mix design and proportioning
- How to choose and design the right Iowa concrete paving mix

Image: ACPA

Special Note

- Mixes in certain parts of Western Iowa (including Council Bluffs) and Nebraska use Class V aggregate
- Iowa DOT's Class C paving mixes look a little bit different when using Class V aggregates (Class C-V47B & CV-SUD mixes)
  - Some comments in this presentation are specific to "standard" Class C mixes, but all of the general principles are applicable to all concrete pavement mixes

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Introduction

- We select materials and design concrete pavement mixes to achieve a variety of construction and performance goals:
  - Workability
  - Setting time
  - Strength
  - Prevent early cracking
  - Durability

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Introduction

- In Iowa today, many concrete pavements reach the end of their usable life upon failure of the materials
- Can result from several factors:
  - Poor selection of materials
  - Poor mix design
  - Inadequate drainage
  - Construction problems, quality

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Images: Todd Hanson, Iowa DOT

Introduction

- We want to select a concrete mix that can be placed successfully and can survive the environment to carry all of the traffic loads the pavement is designed for… and beyond!

Old US 20, Moville, IA
Constructed 1921

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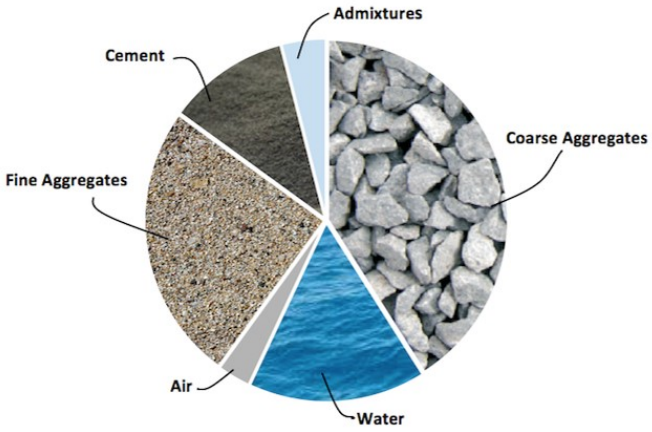
Concrete Materials



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Concrete Materials

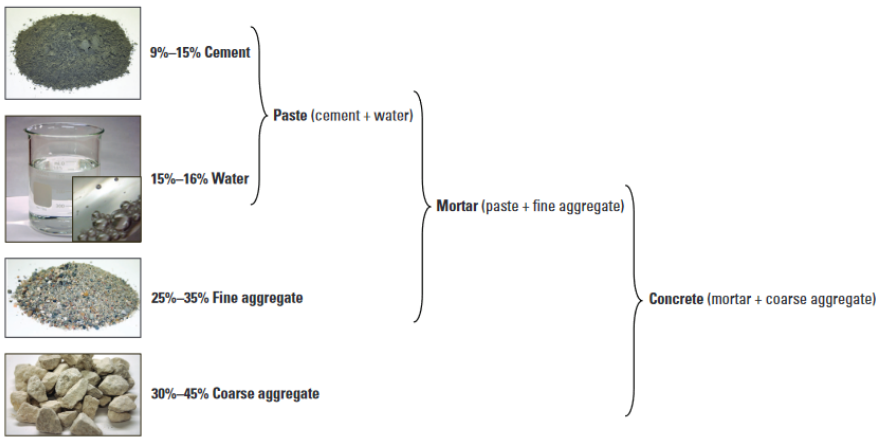

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Image: PCA

Concrete Mix Proportioning

- How do we proportion these materials to meet our design goals?

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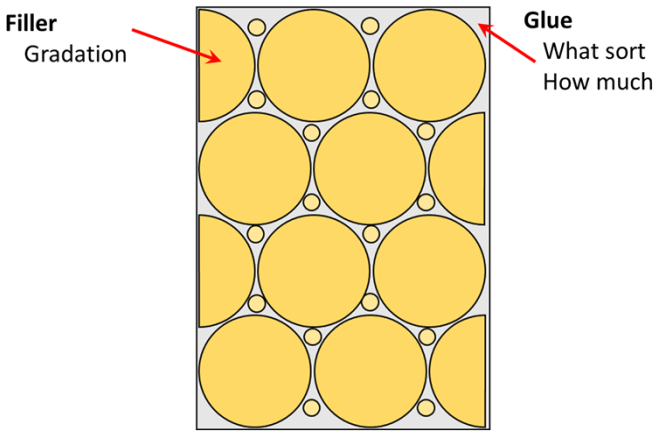
Concrete Mix Proportioning

- At a basic level:



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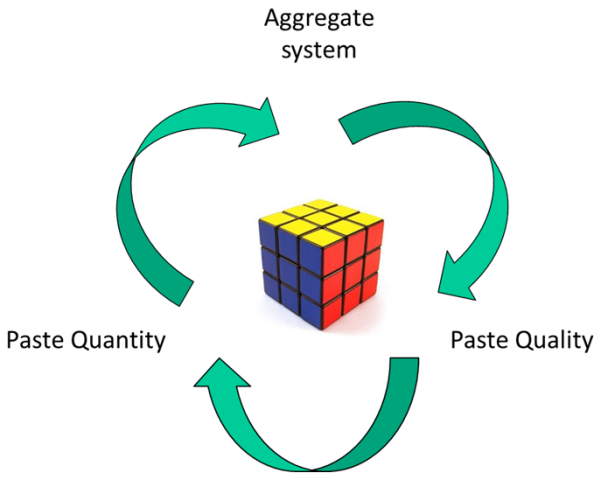
Concrete Mix Proportioning

- At a basic level:



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Concrete Mix Proportioning

- How these elements fit into our design goals:

		Workability	Transport	Strength	Cold weather	Shrinkage	Aggregate stability
Aggregate System	Type, gradation	✓✓	-	-	-	-	✓✓
Paste quality	Air, w/cm, SCM type and dose	✓	✓✓	✓✓	✓✓	✓	✓
Paste quantity	Vp/Vv	✓	-	-	-	✓✓	-

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Paste Quality

- Binder type
  - Cement type
  - SCM type and substitution rate

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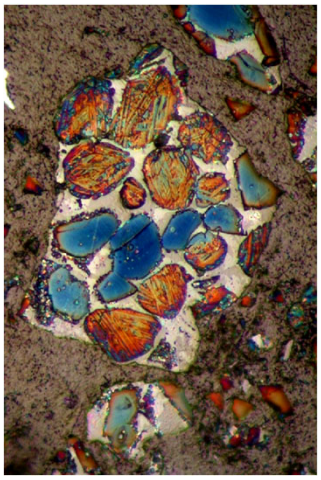
Portland Cement

- Manufactured by heating limestone and other minerals in a kiln and grinding to a fine powder
- Mainly consists of calcium-, silicon-, and aluminum-based compounds
- Type I/II cements were previously most common in Iowa paving mixes
  - Blended cements (e.g. Type IP, IS) containing fly ash, slag have also been used in Iowa
  - Currently, Type I/II cements are being replaced by Type IL cements



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Type IL Cement

- Introduced to most markets in Iowa (and around the U.S.) in 2022-23
- The final blend contains an increased amount of inert limestone
  - A typical Type I/II Portland cement had up to 5% limestone content
  - Up to 15% limestone is allowed in Type IL
    - Right now, most cements available in Iowa are at 8-10%
- Higher-limestone cements are not a new product, but are becoming the nationwide standard today to improve sustainability

US 30, Story County (2013)

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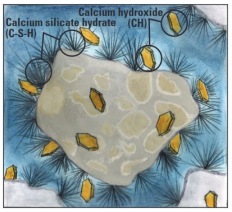
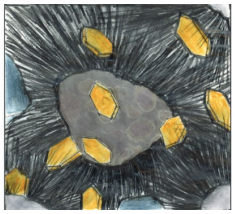
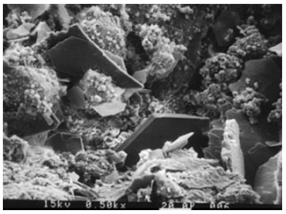
Cement Hydration

- The reaction between cement and water produces a number of hydration products, including C-S-H and CH
  - Calcium silicate hydrate (C-S-H) is an amorphous gel that grows out from cement grains and gradually binds the mixture together into a dense solid
  - C-S-H is the most abundant and most desirable hydration product
    - More C-S-H → stronger and less permeable concrete
  - Calcium hydroxide (CH) is a water-soluble crystal that can be a source of weakness in the microstructure and of durability-related issues







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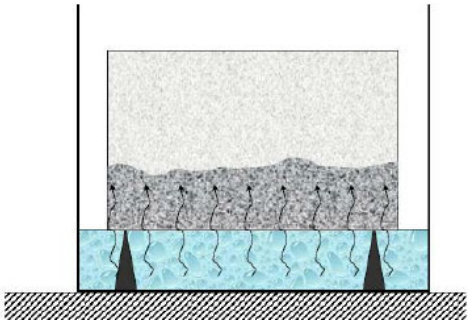
Paste Quality

- Concrete is porous at the microscopic level
  - Capillaries: space between hydrated cement grains
  - To make strong, durable concrete, we want to take steps to reduce permeability



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Images: Todd Hanson, Iowa DOT

Supplementary Cementitious Materials

- SCMs like fly ash and slag are useful because they react with CH to produce more C-S-H

Cement + Water = C-S-H + CH

SCM + Water + CH = more C-S-H

- These are secondary reactions, so substituting SCMs for cement slows the initial rate of strength gain
- However, from about 7-28 days and beyond, strength and permeability are greatly improved thanks to the production of more C-S-H

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Paste Quality

- Water-to-cementitious materials ratio (w/cm)
  - Lower w/cm → stronger and less permeable concrete

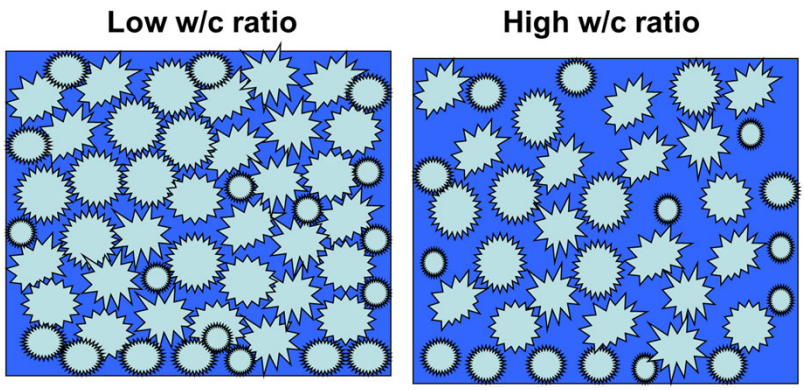

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Image: Todd Hanson, Iowa DOT

Paste Quality

- w/cm also has a significant impact on workability
  - Holding other factors equal, increasing w/cm will increase the workability of a given mix (higher slump)
    - Depending on the construction method, increasing w/cm makes the concrete easier to place and finish
    - In slipform paving, a too-high w/cm can cause edge slump
  - Water reducing admixtures can help achieve better workability while keeping w/cm low for strength and durability

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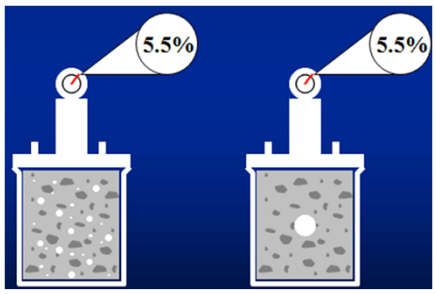
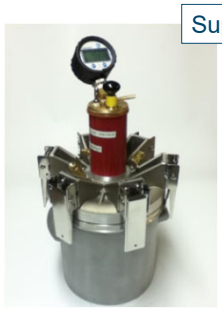
Paste Quality

- Air void system
  - Protects concrete against freeze-thaw damage
  - Minimum 6% air content behind the paver
  - Voids must be well-distributed throughout the concrete





Super Air Meter

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Images: FHWA, Oklahoma State University

Aggregate System

- Aggregates strongly influence workability and long-term durability
- Physical and durability requirements are outlined in ASTM C33
- Iowa DOT IM 409 classifies aggregate durability based on:
  - Clay content
  - Salt susceptibility
  - Pore system, i.e. freeze-thaw durability/resistance to D-cracking

DURABILITY CLASS	QUALITY	TEST LIMITS	TEST METHOD
Class 2	Salt susceptibility quality Secondary Pore Index	Max. 4.5 Max. 30	Iowa 223 Iowa 219
Class 3	Salt susceptibility quality Secondary Pore Index	Max. 1.5 Max. 25	Iowa 223 Iowa 219
Class 3i	Salt susceptibility quality Secondary Pore Index	Max. 1.0 Max. 20	Iowa 223 Iowa 219

More durable

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Aggregate System

- We generally want our aggregate system to be well-graded
  - Balanced variety of aggregate sizes to fill voids
  - Maximizes volume of aggregates in the mixture
  - Less cement paste needed to achieve desired workability

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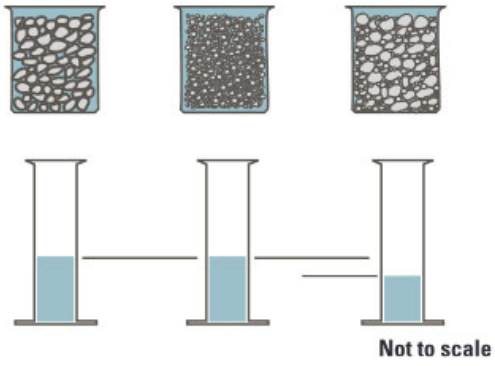
Image: Todd Hanson, Iowa DOT

Aggregate System

- Effect of grading on water demand/paste content:



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L Image: PCA, R Image: Todd Hanson, Iowa DOT

Aggregate System

- Combined aggregate gradation:

Component Blending for PCC Mixes

Sieve Size	% Passing Cement	% Passing Fly Ash	% Passing Mineral Admixture
#200	100.0	100.0	
#325	90.0	88.0	

	% Total Aggregate	A Number	Producer & Location
% Coarse	42.0	ASD002	L.G. Everist - Dell Rapids West
% Interm.	12.0	A84510	L.G. Everist - Hawarden
% Fine	46.0	A75502	L.G. Everist - Akron
Total	100.0		

(dependent on MIX DESIGN)

Sieve Size	% Passing Coarse	% Passing Intermediate	% Passing Fine	% Passing (Combined Agg)	% Retained (Combined Agg	% Passing Paste	% Passing (Combined Tot	% Retained (Combined Tot
1 1/2"	100.0	100.0	100.0	100.0	0.0	100.0	100.0	0.0
1"	100.0	100.0	100.0	100.0	0.0	100.0	100.0	0.0
3/4"	86.0	100.0	100.0	94.1	5.9	100.0	95.9	4.1
1/2"	46.0	100.0	100.0	77.3	16.8	100.0	84.2	11.7
3/8"	25.0	97.0	100.0	68.1	9.2	100.0	77.8	6.4
#4	3.0	24.0	95.0	47.8	20.3	100.0	63.6	14.1
#8	1.5	2.2	83.0	39.1	8.8	100.0	57.5	6.1
#16	1.3	1.8	65.0	30.7	8.4	100.0	51.7	5.9
#30	1.1	1.4	37.0	17.7	13.0	100.0	42.6	9.1
#50	1.0	0.9	9.9	5.1	12.6	100.0	33.8	8.8
#100	0.8	0.5	1.0	0.9	4.2	100.0	30.9	2.9
#200	0.6	0.1	0.2	0.4	0.5	100.0	30.5	0.3
#325	-	-	-	-	-	96.2	29.2	1.4
Liquid	-	-	-	-	-	63.7	19.3	9.9
					100.0			100.0

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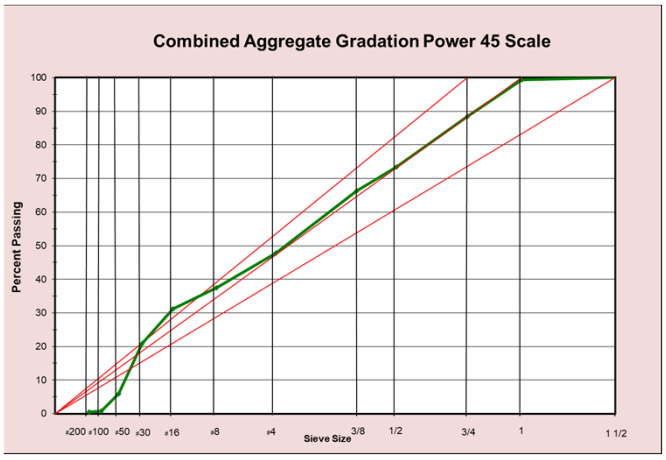
Aggregate System

- Combined aggregate gradation:



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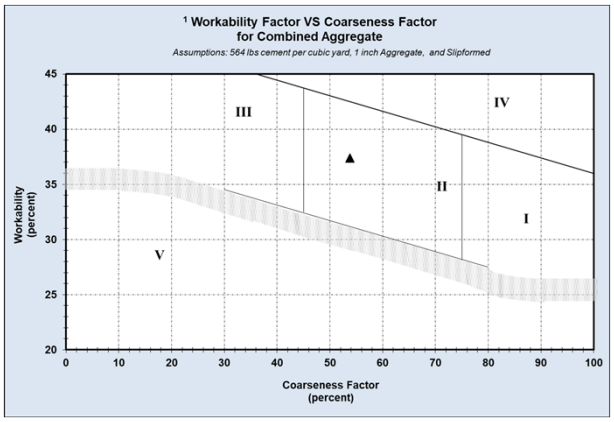
Aggregate System

- Tools for evaluating the combined aggregate gradation
  - Shilstone coarseness/workability chart:



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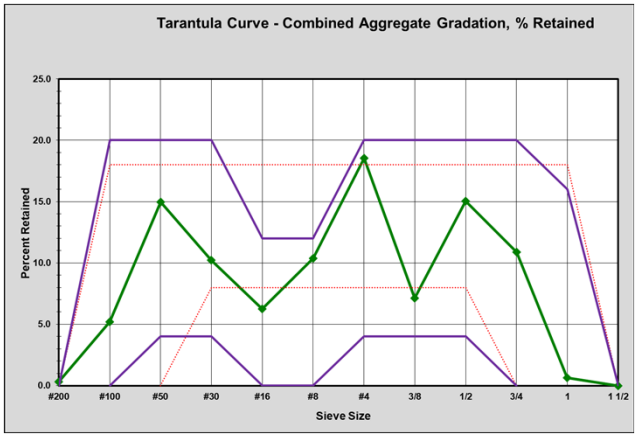
Aggregate System

- Tools for evaluating the combined aggregate gradation
  - Tarantula curve:



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Paste Content

- Target an optimum amount of paste (cement & water) in the mix
  - Enough to achieve workability for the placement method
  - But not too much – excessive paste content can lead to:
    - Increased permeability and decreased durability
    - Excessive shrinkage
    - Excessive cost
  - Avoid the misconception that we need more cement or more paste to achieve the strength that we need!
    - Designing pavement mixes for durability will give us the strength that we need

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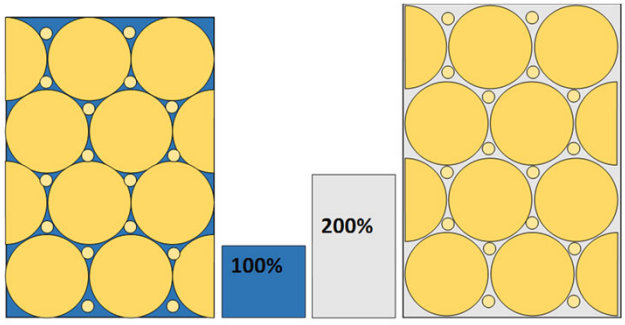
Paste Content

- How much is optimum?
  - Depends on the aggregate gradation
  - Typically a volume of paste 1.25-2x higher than volume of voids



Adding intermediate aggregates → less paste is required

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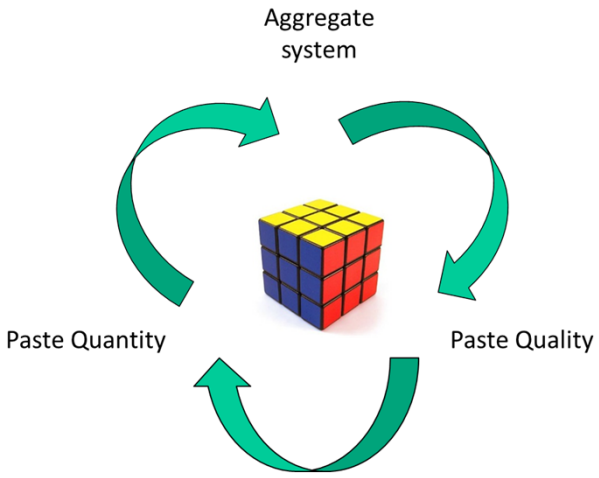
Concrete Mix Proportioning



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Iowa Concrete Paving Mixes

- In practice, every aspect of each paving mix isn't designed from scratch, but according to specifications and requirements
- How do I choose which mix to specify for a paving project?
  - Iowa DOT IM 529 & Iowa SUDAS 7010:

	C-4WR/C-4	C-3WR/C-3	QM-C	C-SUD
Coarse Aggregate Proportion	50%	55%	User-designed gradation	User-designed or 55% Coarse, 45% Fine
Fine Aggregate Proportion	50%	45%		
Intermediate Aggregate Proportion	n/a	n/a		
Cementitious Material Content (lb/cy)	581-624	560-603	550-560	550-560
Maximum SCM Content	Fly ash: 20%, Slag: 35%, Total: 40%	Fly ash: 20%, Slag: 35%, Total: 40%	Fly ash: 20%, Slag: 35%, Total: 40%	Class C fly ash: 35%, Class F fly ash: 25%, Slag: 35%, Total: 40%
Maximum w/cm	0.49	0.49	0.42	0.42

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Iowa Concrete Paving Mixes

- In practice, every aspect of each paving mix isn't designed from scratch, but according to specifications and requirements
- How do I choose which mix to specify for a paving project?
  - Iowa DOT IM 529 & Iowa SUDAS 7010:

	C-V47B	QM-C	CV-SUD
Coarse Limestone Proportion	30%	User-designed gradation	User-designed or 45% Coarse, 55% Class V
Class V Aggregate Proportion	70%		
Cementitious Material Content (lb/cy)	586-598	550-560	591-603
Maximum SCM Content	Fly ash: 20%, Slag: 35%, Total: 40%	Fly ash: 20%, Slag: 35%, Total: 40%	Class C fly ash: 35%, Class F fly ash: 25%, Slag: 35%, Total: 40%
Maximum w/cm	0.49	0.42	0.42

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Iowa Concrete Paving Mixes

- For many years, C-3, C-4 & C-V47B mixes have been used for Iowa streets, highways, and other kinds of pavement and flatwork applications
  - C-3: state and county highways
  - C-4: local streets and roads
  - C-V47B: standard paving mix with Class V aggregates

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Iowa Concrete Paving Mixes

- C-3/C-4/C47B mixes don't require analysis of the aggregate system
  - Aggregate proportions are determined from a chart regardless of the individual gradations of the coarse and fine aggregates
  - Paste content is higher than it needs to be for most mixes, but in some cases it might not actually be high enough
  - The maximum w/cm (0.49) is higher than it should be for pavements subject to Iowa's climate and de-icing practices
    - Most slipform paving is done around 0.40-0.42
    - More likely to push the limit on smaller fixed-form placements or hand placements: patches, turn lanes, intersections

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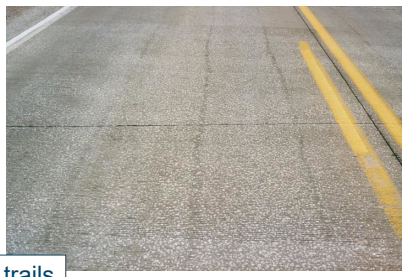
Iowa Concrete Paving Mixes

- While many concrete pavements made from C-3, C-4 & C-V47B mixes have shown great long-term performance, they aren't optimized for durability, & issues have been identified over the years
- Iowa DOT developed the QM-C mix design specification in the late 1990s to address workability problems that were leading to early durability failures



Vibrator trails

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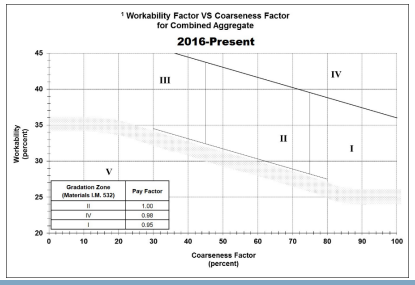
Image: Bob Steffes

QM-C Mixes

- The contractor became responsible for mix proportioning & enhanced QC procedures
- Aggregate proportions for every QM-C mix are designed and optimized according to the Shilstone chart
- Intermediate aggregates are used in most QM-C mixes, usually around 5-15% by volume
  - Pea gravel
  - Limestone chip
- Minimum cementitious content was reduced to 560 lb/cy



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QM-C Mixes

- When using Class V aggregates, contractors have usually opted for a coarser aggregate blend for QM-C mixes
  - Ballpark QM-C proportions:
    - 45% coarse limestone
    - 55% Class V aggregate
  - Compare to C-V47B proportions:
    - 30% coarse limestone
    - 70% Class V aggregate

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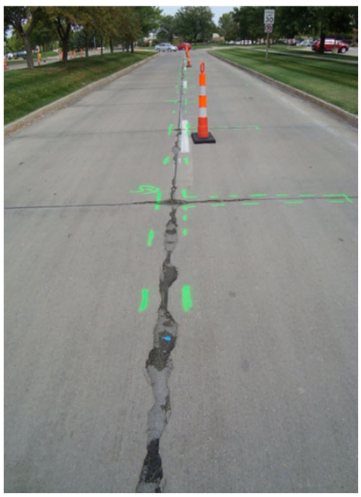
Iowa Concrete Paving Mixes

- In the 2000s, durability was recognized as an increasing issue on some city streets and roads, especially at joints
- Potential reasons for greater susceptibility on city streets:
  - More pavements placed by non-slipform methods (higher w/cm)
  - Greater emphasis on de-icing and changes to typical practices
  - Less favorable drainage environment
    - Subbase layers are also important!



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C-SUD Mixes

- C-SUD mixes were developed to provide an option for enhanced durability on city streets
- QM-C is the starting point for C-SUD, but there are a few other changes and options available to cities to further improve durability

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C-SUD Mixes

- Aggregate gradation design follows same procedure as QM-C
  - Design is generally left up to the ready mix producer
  - A 55% coarse, 45% fine aggregate mix option is available for cities or producers that lack access to intermediate aggregates
    - Even if intermediate aggregates are not available, check the gradations on the Shilstone chart and tarantula curve!
- Minimum cementitious material content matches QM-C (550-560 lb/cy)
- Maximum w/cm reduced to 0.42
  - QM-C has followed this change in recent years
- A higher amount of SCM substitution is allowed

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CV-SUD Mixes

- CV-SUD mixes are also available for use with Class V aggregates
- Same general principles as C-SUD mixes
- Differences:
  - Design is generally left up to the ready mix producer
  - A 45% coarse limestone, 55% Class V aggregate blend may be used (similar to typical QM-C gradations)
  - Minimum cementitious materials content is approximately the same as C-47B mixes and not as low as QM-C mixes

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C-SUD Mixes

- In addition to the benefits we've already discussed, SCMs also protect against attack from de-icing chemicals
- C-SUD mixes may use up to 35% Class C fly ash or 25% Class F fly ash substitution rates, which are greater than the 20% rates that are normally allowed

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \rightarrow CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$$

Calcium Oxychloride

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C-SUD Mixes

- Remember that the C-SUD specification allows, but does not require a higher SCM substitution rate
  - Some cities leave it up to the contractor or concrete producer, while others specify what type to use and how much
- What SCMs should I use, and how much?
  - Keep in mind that producers in your city may only have access to a limited variety of SCMs
  - Supply has become significantly more variable in recent years…
  - Slag is not readily available in all areas of Iowa
- Consider specifying SCM content beyond the typical 20% substitution rate for pavements that receive the heaviest de-icing treatment

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Benefits of QM-C & C-SUD Mixes

- Optimized mixtures will help improve long-term durability
- Producing consistent, predictable concrete benefits all aspects of the construction process
  - On mainline paving projects, QM-C has contributed to improvements in productivity and smoothness
  - C-SUD mixes are still relatively new, but the outlook is promising

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C-SUD Experience to Date

- Iowa cities and counties that have used C-SUD, QM-C, or a similar mix specification for enhanced durability:

Approximately 500,000 SY placed 2015-19

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C-SUD Experience to Date

- Many projects have been paved successfully and performance to-date (since 2015) has been excellent
- There are some challenges in paving with C-SUD mixes that can produce a learning curve
  - More stakeholders
  - Workability on fixed-form placements or hand placements
  - Cold weather paving
  - Saw cutting

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Workability

- The maximum w/cm for C-SUD mixes (0.42) is much tighter than C-3/C-4 (0.49)
- This is a lower ceiling than many contractors are used to for fixed-form placements or hand-placements
- In these cases, the mix can be less workable and more challenging to finish
  - Can worsen on hot, sunny days
  - High amounts of fly ash can also make finishing difficult, even for slipform paving

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Cold Weather Paving & Saw Cutting

- SCMs like fly ash and slag slow down initial strength gain
- Using the higher replacement rates allowed by C-SUD can delay time to saw cutting and time to reach opening strength
  - These effects are exacerbated at cold temperatures

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Troubleshooting

- Workability suggestions:
  - Use water reducing admixtures!
  - Consider using retarders/hydration stabilizers, especially in high temperatures
  - If more paste is absolutely needed for workability, consider allowing increased cementitious content before allowing a higher w/cm ratio

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Troubleshooting

- Cold weather suggestions:
  - Don't remove SCMs from the mix in cold weather
  - Use other cold-weather concreting practices heated water, accelerating admixtures, and blankets for curing
  - If opening strength is still too slow or joint raveling occurs, reduce SCM content back to typical limits
  - Consider allowing an increased cementitious content to help get the mix "kicked off" a bit faster

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C-SUD-CW (Cold Weather) Mix

- Potential option for overcoming cold weather challenges:
  - Maintain 0.42 maximum w/cm
  - Maintain specified SCM replacement rate
  - Increase total cementitious materials content to match C-4
- This type of approach is used by MnDOT in late-season paving
- This approach was used in the very first city street C-SUD projects in West Des Moines in November & December 2015
- This type of mix may also be useful to help provide some additional workability for hand placements any time of year

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Iowa Concrete Paving Mixes

- One last look at differences between mix types:

	C-4WR/C-4	C-3WR/C-3	QM-C	C-SUD
Coarse Aggregate Proportion	50%	55%	User-designed gradation	User-designed or 55% Coarse, 45% Fine
Fine Aggregate Proportion	50%	45%		
Intermediate Aggregate Proportion	n/a	n/a		
Cementitious Material Content (lb/cy)	581-624	560-603	550-560	550-560
Maximum SCM Content	Fly ash: 20%, Slag: 35%, Total: 40%	Fly ash: 20%, Slag: 35%, Total: 40%	Fly ash: 20%, Slag: 35%, Total: 40%	Class C fly ash: 35%, Class F fly ash: 25%, Slag: 35%, Total: 40%
Maximum w/cm	0.49	0.49	0.42	0.42

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Iowa Concrete Paving Mixes

- One last look at differences between mix types:

	C-V47B	QM-C	CV-SUD
Coarse Limestone Proportion	30%	User-designed gradation	User-designed or 45% Coarse, 55% Class V
Class V Aggregate Proportion	70%		
Cementitious Material Content (lb/cy)	586-598	550-560	591-603
Maximum SCM Content	Fly ash: 20%, Slag: 35%, Total: 40%	Fly ash: 20%, Slag: 35%, Total: 40%	Class C fly ash: 35%, Class F fly ash: 25%, Slag: 35%, Total: 40%
Maximum w/cm	0.49	0.42	0.42

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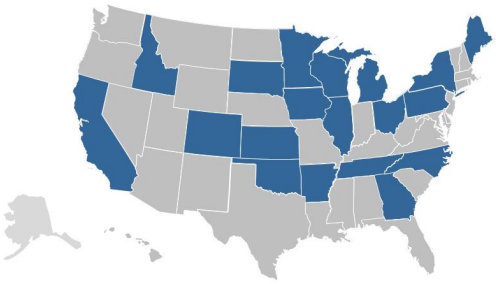
Performance Engineered Mixtures (AASHTO R 101)

- National program to re-think concrete pavement mix design specifications and quality control practices
- Prioritization of long-term durability
- Encompasses aspects of concrete mix design and materials relevant to all areas of the country, all climate types, etc.



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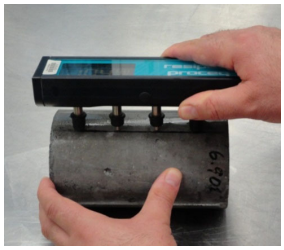
Performance Engineered Mixtures (AASHTO R 101)

- The PEM program has also introduced new test methods to better analyze the concrete characteristics that matter
  - Moving beyond the slump cone!



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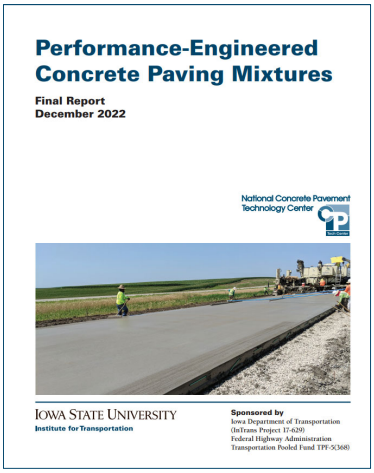
Performance Engineered Mixtures (AASHTO R 101)

- The PEM pooled fund study is finished (available soon)
- Some states like Iowa have already adopted many PEM principles and test methods (QM-C, C-SUD) while others are just starting out
- Even in states like Iowa, there may still be room to further improve efficiency, performance, and to produce more sustainable mixes
- Future: even more opportunity to improve and better tailor mix specifications to local agencies



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Performance Engineered Mixtures (AASHTO R 101)

- I-29, Harrison County, IA (2020)
  - 11% reduction in total cementitious content vs. standard QM-C
  - 40% total SCM replacement rate (C and F ash)

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Thank You!