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Optimizing Mixture Proportions for Constructability, Economy, and Durability

Presentation to NCC 2023
Tuesday, September 12; 2:15 – 2:45pm

David Trejo[1] and Erick Moreno Rangel[2]

1. Professor & Hal Pritchett Endowed Chair; 2. Ph.D. Student

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Outline

- Introduction
- Research Objectives
- Phase 1 Objectives, Program, and Results
- Phase 2 Objectives, Program, and Results
- Phase 3 Objectives, Program, and Results
- Summary of Overall Findings

Introduction

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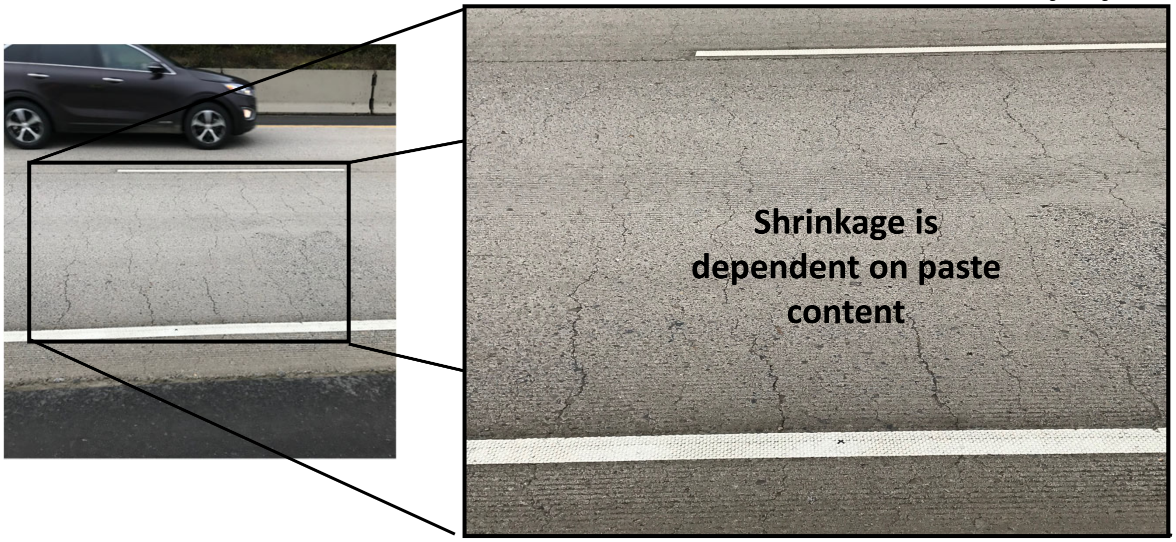

Introduction

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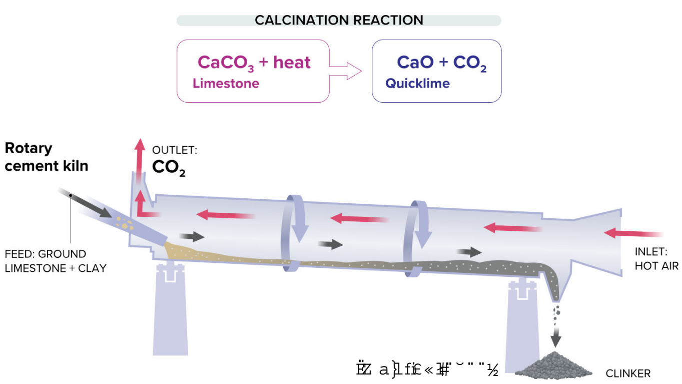
Cement production (and source of CO_2)



Lower cement quantities can reduce carbon footprint

Introduction

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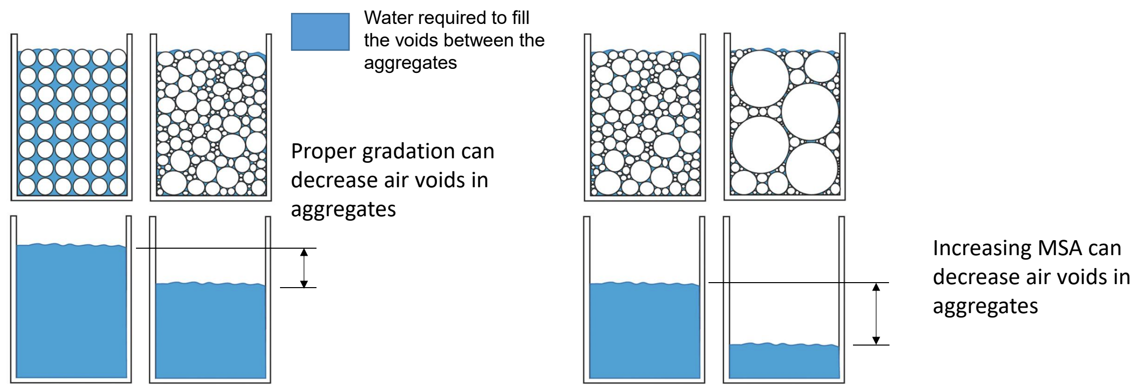
- The amount of paste content (cementitious materials and water) required for a concrete mixture is dependent on the volume of voids in the aggregate system.
- The volume of voids in aggregates can be influenced by:



Aggregate gradation **Maximum aggregate size**

Picture source: concreteconstruction.net

Introduction

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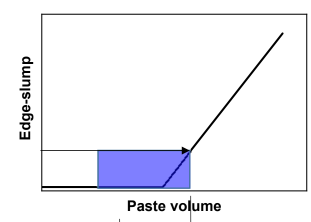
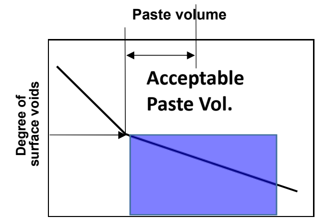
The amount of paste required for a concrete paving mixture (PV_{total}) is the amount of paste required: 1) to fill the aggregate voids (AV) volume; 2) to cover the surface of aggregates; and 3) to make the concrete workable for the specific project.

PV_{total} = 1.25*AV

PV_{total} = 1.5*AV

PV_{total} = 1.75*AV





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- A higher PV_{total} can increase the vulnerability of concrete to
  - Shrinkage cracking (Roziere et al. 2017)
  - Permeability (Kolias and Georgiou 2005)
  - Chloride ingress (Yurdakul et al. 2013)
  - Sulfate attack (Yang et al. 1996)
  - Others?…

- Concrete mixtures should be proportioned with a low PV_{total}. For this, an understanding of various factors on AV content is essential.

Research Objectives

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Phase 1

To determine the influence of aggregate characteristics (shape and gradation) on the aggregate-void content of the combined aggregate system

Phase 2

To identify a range of paste volumes (PV/AV values) for the different aggregates that result in low paste content and ***workability***. Only fresh characteristics were assessed in Phase 2.

Phase 3

To determine the effects of aggregate characteristics and mixture proportions on the ***workability*** and ***performance*** of concrete mixtures for pavements.

Phase 1 Objectives

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- To assess the influence of coarse aggregate type, coarse aggregate gradation, fine aggregate fineness, and fine to coarse aggregate ratio (F/C) on AV content.

- AASHTO T 19, Standard Method of Test for Bulk Density ("Unit Weight") and Voids in Aggregate, was used to assess aggregate voids.

Phase 1 Experimental Program

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Agg. ID	Aggregate type	Source
QR	Quarry rock	Pleasant Valley, OR
CG	Crushed gravel	Knife River, Corvallis, OR
G	Gravel	
CS	Concrete sand; FM > 3.0	Pleasant Valley, OR
FS	Concrete sand; FM < 3.0	Knife River, Corvallis, OR

Agg. ID	Size ranges procured
QR1	1.5 inch - 0.75 inch
QR2	0.75 inch - 0.187 inch
CG1	1.5 inch - 0.75 inch
CG2	0.75 inch - 0.187 inch
G1	1.5 inch - 0.75 inch
G2	0.75 inch - 0.187 inch

Phase 1 Experimental Program

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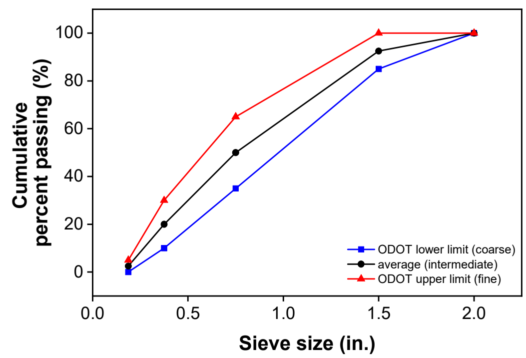
Coarse aggregates

- The lower and upper gradation limits specified by ODOT were targeted as coarse and fine gradations. The average of lower and upper limits was chosen as intermediate gradation.
- Three Coarse Aggregates Assessed
  - ✓Quarry Rock
  - ✓Crushed Gravel
  - ✓Gravel



Gradation limits for 1.5 to 0.187 inch size range

Phase 1 Experimental Program

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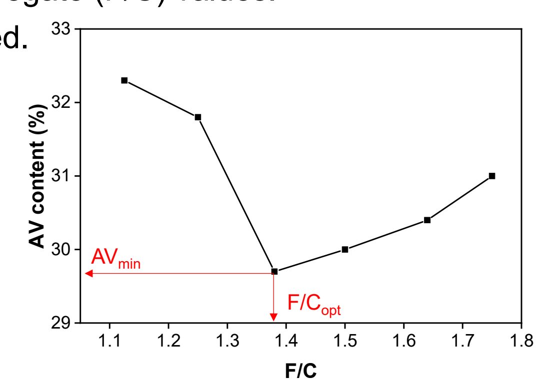
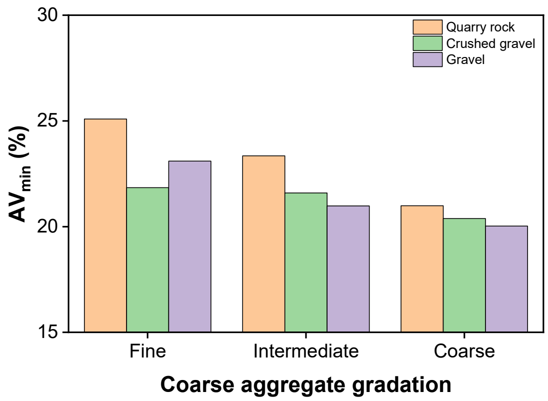
- Eighteen different combinations (3 coarse aggregate types x 3 coarse aggregate gradations x 2 fine aggregates) of aggregates were investigated.
- For each combination, the AV content values were measured at four to six different fine aggregate to coarse aggregate (F/C) values.
- The minimum AV content was identified.

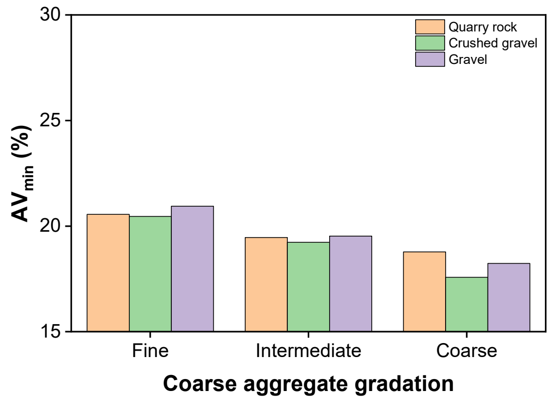


Phase 1 Results

Effect of coarse aggregate type



Coarse sand



Fine sand

Phase 1 Summary

Summary

- Choosing a coarse gradation for coarse aggregates can result a lower AV_{min} compared to choosing a finer gradation for coarse aggregates.
- Using a finer sand (lower FM) results in lower AV_{min} compared to using a coarse sand (higher FM).
- Among all possible combinations assessed, a coarser gradation for coarse aggregates and a finer sand (FM < 3.0) resulted in the lowest AV_{min}.

Phase 2 Objectives

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- To identify a range of acceptable PV/AV_{min} values for concrete mixtures containing different aggregate systems.

Note: “Acceptable” PV/AV_{min} values are defined as values that pass the Box test.

Phase 2 Results

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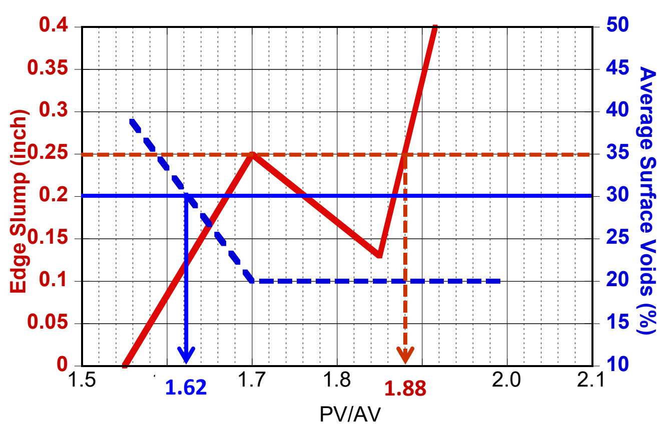
- Quarry Rock (with WR and AEA)



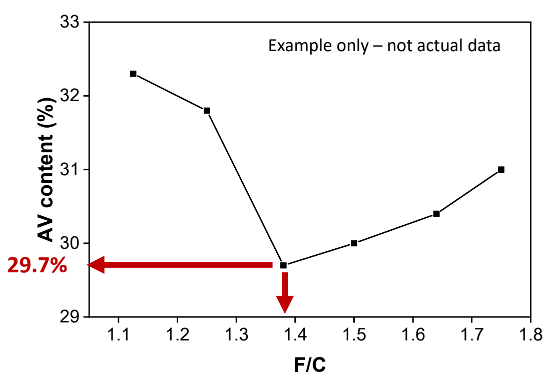
Range of appropriate PV/AV values is 1.62 to 1.88

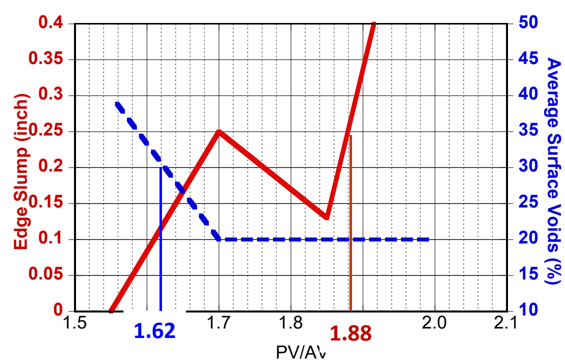
Phase 2 Results

- Quarry Rock: PV/AV = 1.62 to 1.88
- Crushed Gravel: PV/AV = >1.9 @AV$_{min}$ (F/C = 0.5)
  PV/AV ~1.7 to 2.0 @ AV (F/C=0.75)
- Gravel: PV/AV = 1.55 to 1.9

Phase 1 & 2 Summary

Mixture Proportioning Method to Minimize Paste Content





Step 1. Determine paste content (example only): 29.7%*1.65
Step 2. Use w/c to determine water and cementitious materials contents
Step 3. Determine aggregate contents: F/C = 1.38
Step 4. Correct for yield

Phase 3 Objectives

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To determine the effects of

1. aggregate characteristics,
2. constituent material type, and,
3. mixture proportions,

on the ***workability*** and ***performance*** of concrete mixtures for pavements.

All mixtures are designed following the 'minimum aggregate-void' approach to minimize the paste volume (PV).

Phase 3 Mixtures

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Mix number	Coarse aggregate type	Coarse aggregate gradation	Sand	Binder type	PV/AV_{min}	w/cm	OPC content (lb/yd^3)	Fly ash content (lb/yd^3)	Slag content (lb/yd^3)	Total binder (lb/yd^3)	Water content (lb/yd^3)
1	Quarry	Coarse	Fine	70% OPC + 30% ash	**1.7**	0.41	367	157	–	524	215
2	Quarry	Coarse	Fine	70% OPC + 30% ash	**1.8**	0.41	385	165	–	551	226
3	Quarry	Coarse	Fine	70% OPC + 30% ash	**1.9**	0.41	403	173	–	576	236
4	Quarry	Fine	Coarse	70% OPC + 30% ash	**1.35**	0.41	413	177	–	590	242
5	Quarry	Fine	Coarse	70% OPC + 30% ash	**1.45**	0.41	438	188	–	625	256
6	Quarry	Fine	Coarse	70% OPC + 30% ash	**1.55**	0.41	461	198	–	659	270
7	Quarry	Coarse	Fine	100% OPC	**1.7**	0.41	538	–	–	538	221
8	Quarry	Coarse	Fine	100% OPC	**1.8**	0.41	565	–	–	565	232
9	Quarry	Coarse	Fine	100% OPC	**1.9**	0.41	591	–	–	591	242
10	Crushed gravel	Coarse	Fine	70% OPC + 30% slag	**1.85**	0.41	385	–	165	550	225
11	Crushed gravel	Coarse	Fine	70% OPC + 30% slag	**2**	0.41	411	–	176	587	241
12	Crushed gravel	Coarse	Fine	70% OPC + 30% slag	**2.15**	0.41	436	–	187	623	255
13	Crushed gravel	Fine	Coarse	70% OPC + 30% slag	**1.5**	0.41	393	–	169	562	230

Text highlighted in yellow represents water content below 230 lb/yd^3

Phase 3 Mixtures

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Mix number	Coarse aggregate type	Coarse aggregate gradation	Sand	Binder type	PV/AV_{min}	w/cm	OPC content (lb/yd^3)	Fly ash content (lb/yd^3)	Slag content (lb/yd^3)	Total binder (lb/yd^3)	Water content (lb/yd^3)
14	Crushed gravel	Fine	Coarse	70% OPC + 30% slag	**1.65**	0.41	426	–	182	607	249
15	Crushed gravel	Fine	Coarse	70% OPC + 30% slag	**1.8**	0.41	456	–	196	652	267
16	Crushed gravel	Coarse	Fine	100% OPC	**1.85**	0.41	556	–	–	556	228
17	Crushed gravel	Coarse	Fine	100% OPC	**2**	0.41	594	–	–	594	243
18	Crushed gravel	Coarse	Fine	100% OPC	**2.15**	0.41	612	–	–	612	251
19	Gravel	Coarse	Fine	100% OPC	**1.6**	0.41	493	–	–	493	202
20	Gravel	Coarse	Fine	100% OPC	**1.7**	0.41	521	–	–	521	214
21	Gravel	Coarse	Fine	100% OPC	**1.8**	0.41	548	–	–	548	225
22	Crushed gravel	Coarse	Fine	70% OPC + 30% slag	**1.85**	0.38	428	–	184	612	233
23	Crushed gravel	Coarse	Fine	70% OPC + 30% slag	**1.85**	0.44	395	–	169	564	248
24	Quarry	Coarse	Fine	70% OPC + 15% ash + 15% slag	**1.8**	0.41	388	83	83	554	227
25	Crushed gravel	Coarse	Fine	70% OPC + 15% ash + 15% slag	**2**	0.41	408	87	87	583	239

Text highlighted in yellow represents water content below 230 lb/yd^3

Phase 3 Assessments

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Study parameter	Groups of different mixtures considered for assessing study parameter
Paste volume and total binder content	(1, 2, 3); (4, 5, 6); (7, 8, 9); (10,11,12); (13, 14, 15); (16, 17, 18); (19, 20, 21)
Binder type	(1, 7); (2, 8); (3, 9); (10, 16); (11, 17); (12, 18); (11, 17, 25)
w/cm	(11, 22, 23)
Aggregate type	(9, 17)
Aggregate gradation	(3, 4); (12, 13)

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Phase 3 Test Procedures

Fresh concrete characteristics

- AASHTO TP 118 – Air content
- Box test (Cook et al. 2014)

Hardened concrete characteristics

- AASHTO T 22 – Compressive strength (28 and 56 days)
- AASHTO T 97 – Flexural strength (28 and 56 days)
- AASHTO T 161 – Freeze-thaw resistance (56 days; select mixtures)
- AASHTO T 160 – Length Change (drying shrinkage; 28 days; select mixtures)
- AASTHO T334 – Restrained shrinkage (limited tests)

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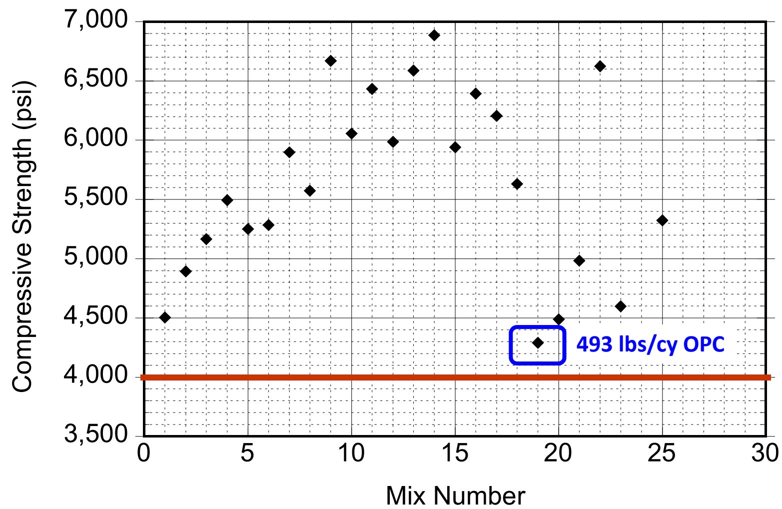
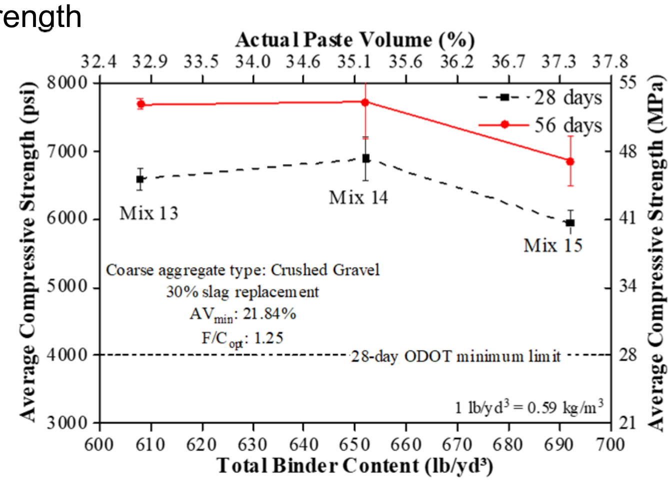
Phase 3 Results

Compressive Strength



Phase 3 Results

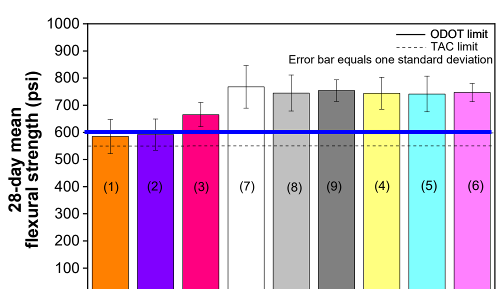
Compressive Strength



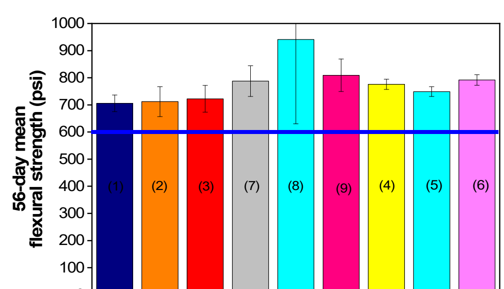
Most mixtures exhibited no improvement in strength when increasing binder content
Mixtures 1,2, and 3 (QR with fly ash) exhibited an increase and Mixtures 13, 14, and 15 (CG with slag) exhibited a decrease.

Phase 3 Results

Flexural Strength



Total binder (lb/yd³)	524	551	576	538	565	591	590	625	659
Fly ash (% mass)	30			0			30		
PV/AV_{min}	1.7	1.8	1.9	1.7	1.8	1.9	1.35	1.45	1.55
Paste volume (% total)	28.82	29.02	30.89	28.59	30.28	31.25	31.14	32.83	34.04
AV_{min} (%)	18.78						25.09		
Coarse Agg gradation	Coarse						Fine		
Fine Agg. fineness	Fine						Coarse		



Total binder (lb/yd³)	524	551	576	538	565	591	590	625	659
Fly ash (% mass)	30			0			30		
PV/AV_{min}	1.7	1.8	1.9	1.7	1.8	1.9	1.35	1.45	1.55
Paste volume (% total)	28.82	29.02	30.89	28.59	30.28	31.25	31.14	32.83	34.04
AV_{min} (%)	18.78						25.09		
Coarse Agg. gradation	Coarse						Fine		
Fine Agg. fineness	Fine						Coarse		

Phase 3 Results

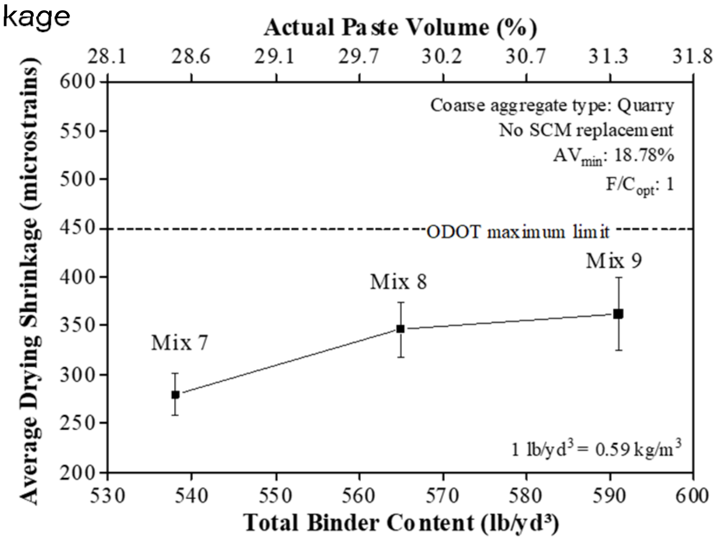
Chloride Permeability

RCP test classification	Total charge passed, coulombs	Formation factor	List of Phase 2C mixtures that meet the criteria
High	>4000	<520	--
Moderate	2000 – 4000	520-1040	1, 2, 4, 8, 21
Low	1000 – 2000	1040-2080	3, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 22, 23, 25
Very low	100 – 1000	2080 – 20800	--
Negligible	<100	>20800	--

Note that RCP was determined from 56-day FF (test method recommends 91 days)

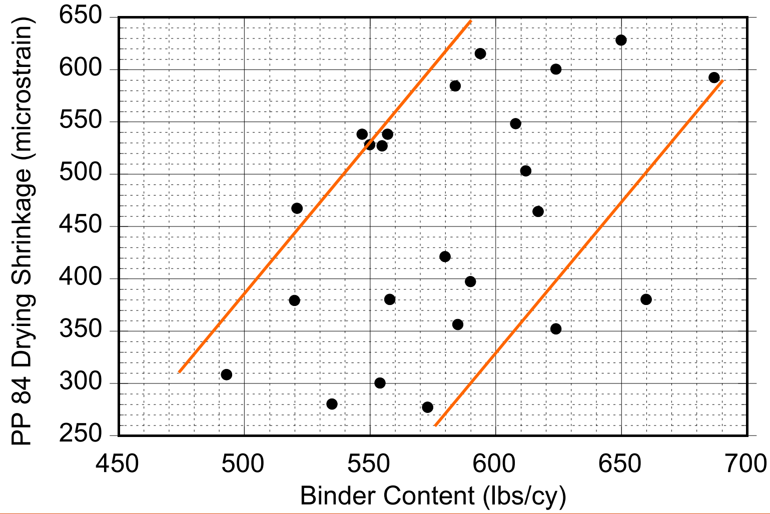
Phase 3 Results

Drying Shrinkage



Phase 3 Results

Drying Shrinkage



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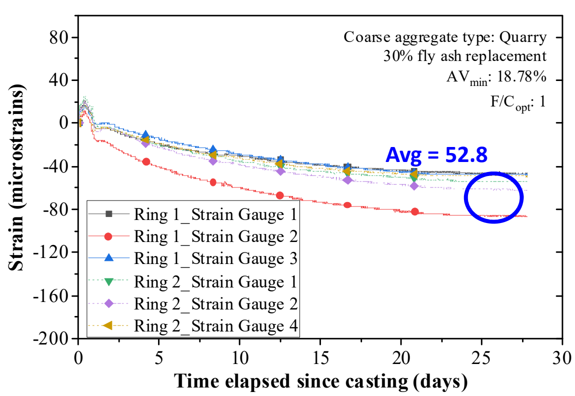
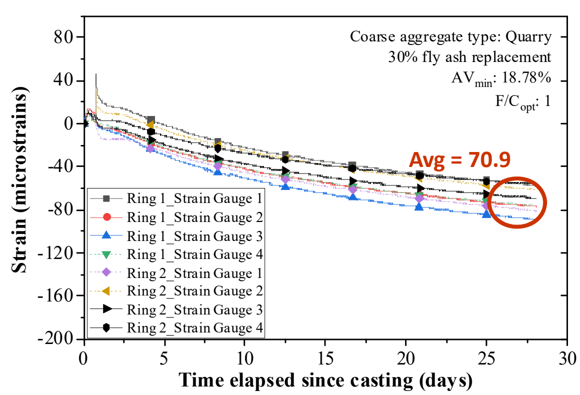
Phase 3 Results

Shrinkage Ring Results



Mixture 1 (520 lbs/cy of binder)



Mixture 3 (573 lbs/cy of binder)

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Phase 2C Results

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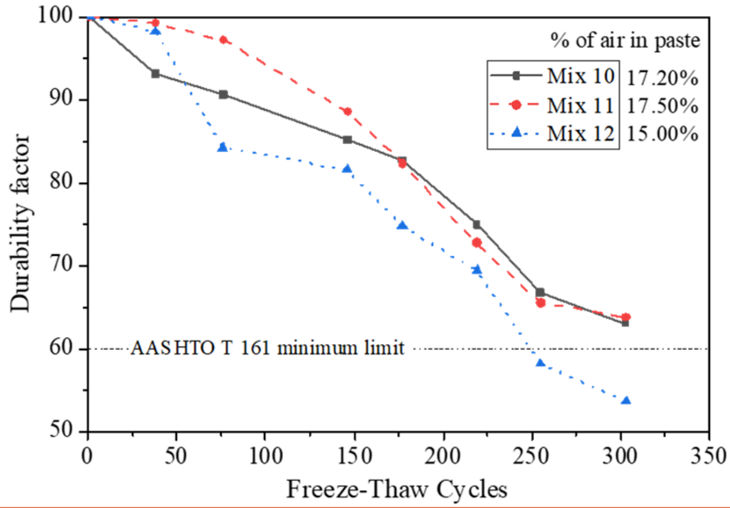
Freeze-thaw Performance



Summary of Findings

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- This research hypothesized that if aggregates to be used on a project can be characterized for void content, a minimum aggregate void content can be identified and the paste content required for a mixture can be minimized
- The required paste content can be determined using the Box Test (stability and workability)
- The required paste content to achieve workability and stability is dependent on coarse aggregate gradation, texture, and shape, fine aggregate fineness, and the weight ratio of fine to coarse aggregate (MSA is likely another factor but was not assessed in this work)
- In the majority of cases, compressive strength was found to be independent of paste volume; that is, there is no benefit from increasing paste content for compressive strength
- In all cases for 28-day flexural strength it was found that flexural strength is independent of paste volume; that is, there is no benefit from increasing paste content for flexural strength

Summary of Findings

- Most mixtures exhibited a low permeability rank even when tested early; no correlation was identified for permeability and paste content
- Drying shrinkage tended to increase with increasing paste content
- Shrinkage rings showed promise to quantify overall shrinkage and limited results indicate shrinkage is dependent on paste content
- The freeze-thaw performance (durability factor) seems to be mostly dependent on the air content of the paste, although higher paste content exhibited lower durability factor.

Acknowledgements

Research was funded by ODOT under SPR 823

OSU UG Students: Nicholas Ole Peterson, Thanh Dat Mai, Kevin M Davis, and Rafael Ramirez Vargas

OSU Grad Students: Dr. Keshav Bharadwaj Ravi and Dr. Siva Teja Chopperla

OSU Staff: Greyson Teremi, Jeff Gent, and James Batti

Oregon Department of Transportation personnel: Justin Moderie, Austin Johnson, Norris Shippen, Scott Nelson, Daniel Schiller, and Cristhian Galvez.

Industry Partners: Greg Wong (Knife River Corporation), Jon Berger (Concrete Placing Co., Inc.), and Jim Powell (American Concrete Pavement Association).

Special thanks to Jon Berger and Dave Burg (AshGrove Cement) for providing aggregates and cementitious materials for the project

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Questions?