RECYCLED CONCRETE AGGREGATE WHAT DO WE KNOW?

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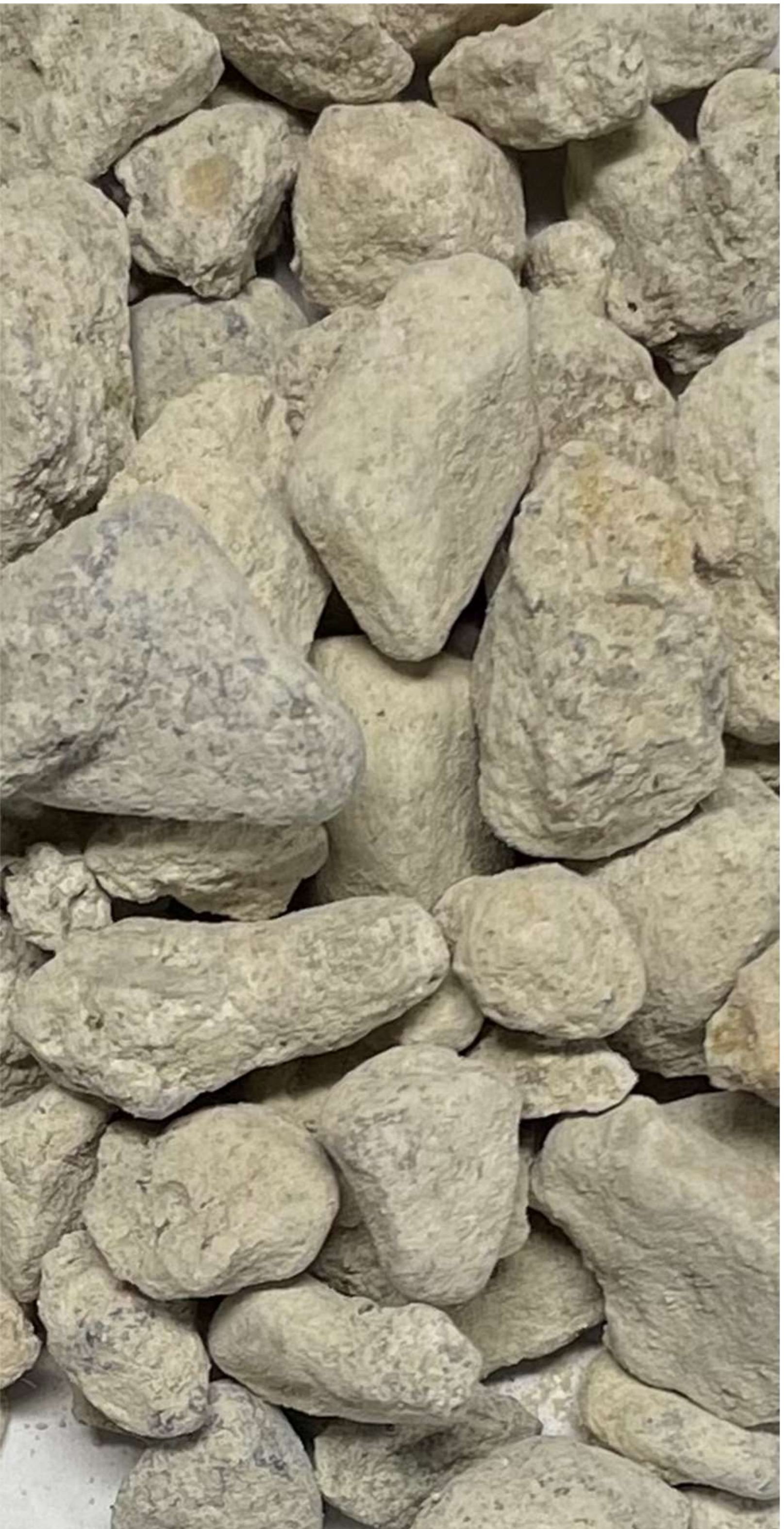


Recycled Concrete Aggregate (RCA)

- Crushed old concrete
  - Original aggregate
  - Adhered mortar
- Use to replace virgin aggregate
  - Granular base
  - In new concrete
- Only considering coarse aggregate
  - Fine aggregate known to be very problematic

RCA Characteristics

- Differences due to adhered mortar
- Mortar content depends on crushing technique
  - 25-70% reported values
  - 30-35% common
- Higher absorption capacity
  - Up to 12-20% reported
  - 4-7% common
  - <5% recommended

RCA Usage in New Concrete

- 1940's – some documented use
- 1970's-1990's – many attempts, mixed results
- 1994 – 11 states using
- 2004 – 11 states using
- 2018 – 6 of 15 survey respondents using
- Some ready-mix producers use on non-DOT projects

RCA Usage

Why use RCA

- Sustainability
- Aggregate shortages
- Cost

Why not to use RCA

- Changes concrete properties
- Poor past experiences
- Uncertainty
  - Performance
  - Durability
  - Consistency
  - Will material distresses reappear
- Availability
- Lack of technical guidance
- Specs ban it
- Contractor reluctance

What Do We Actually Know?

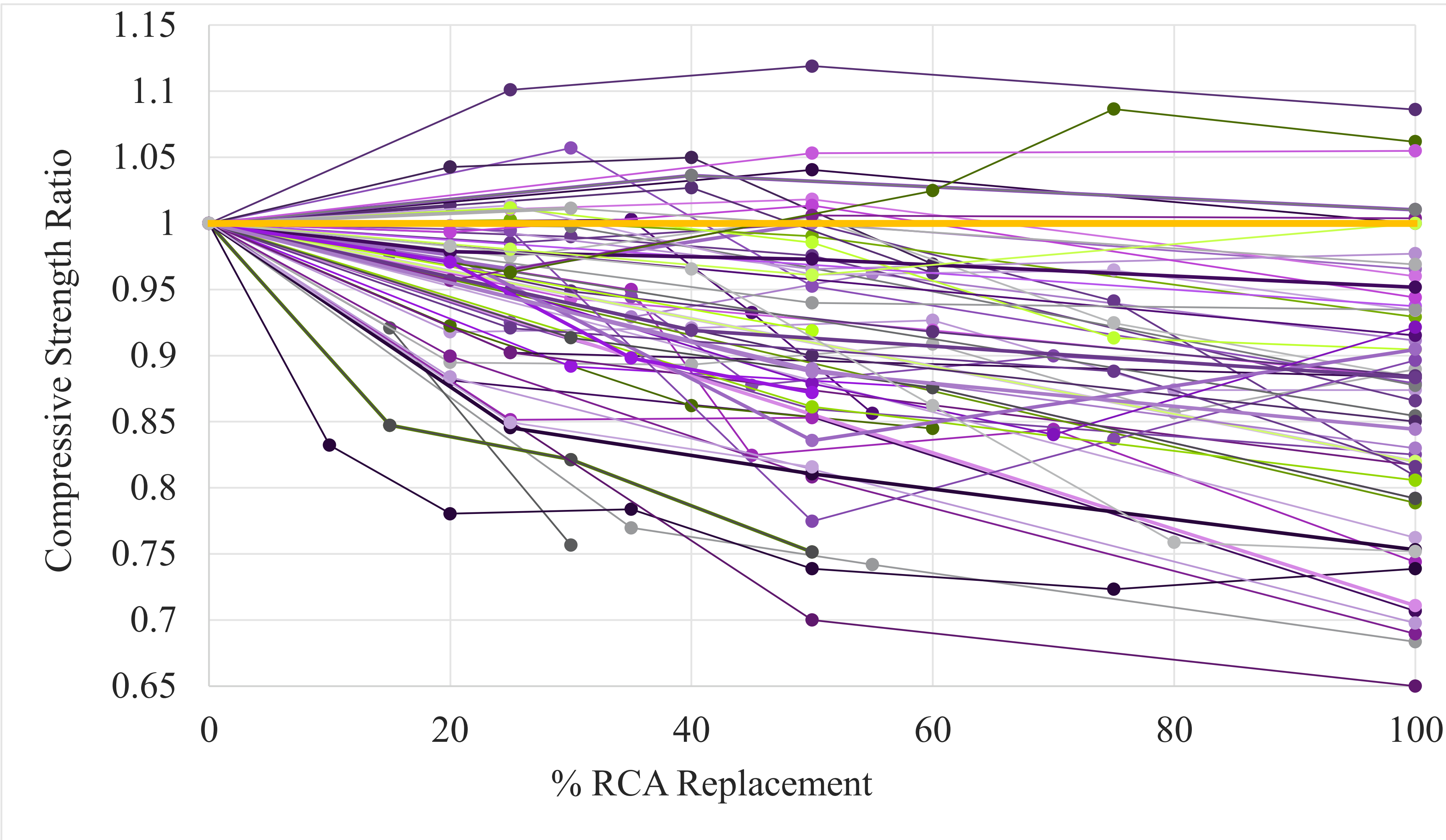
Methods

- Data from the literature
- Ratio of property of RCA concrete to control
  - Example:

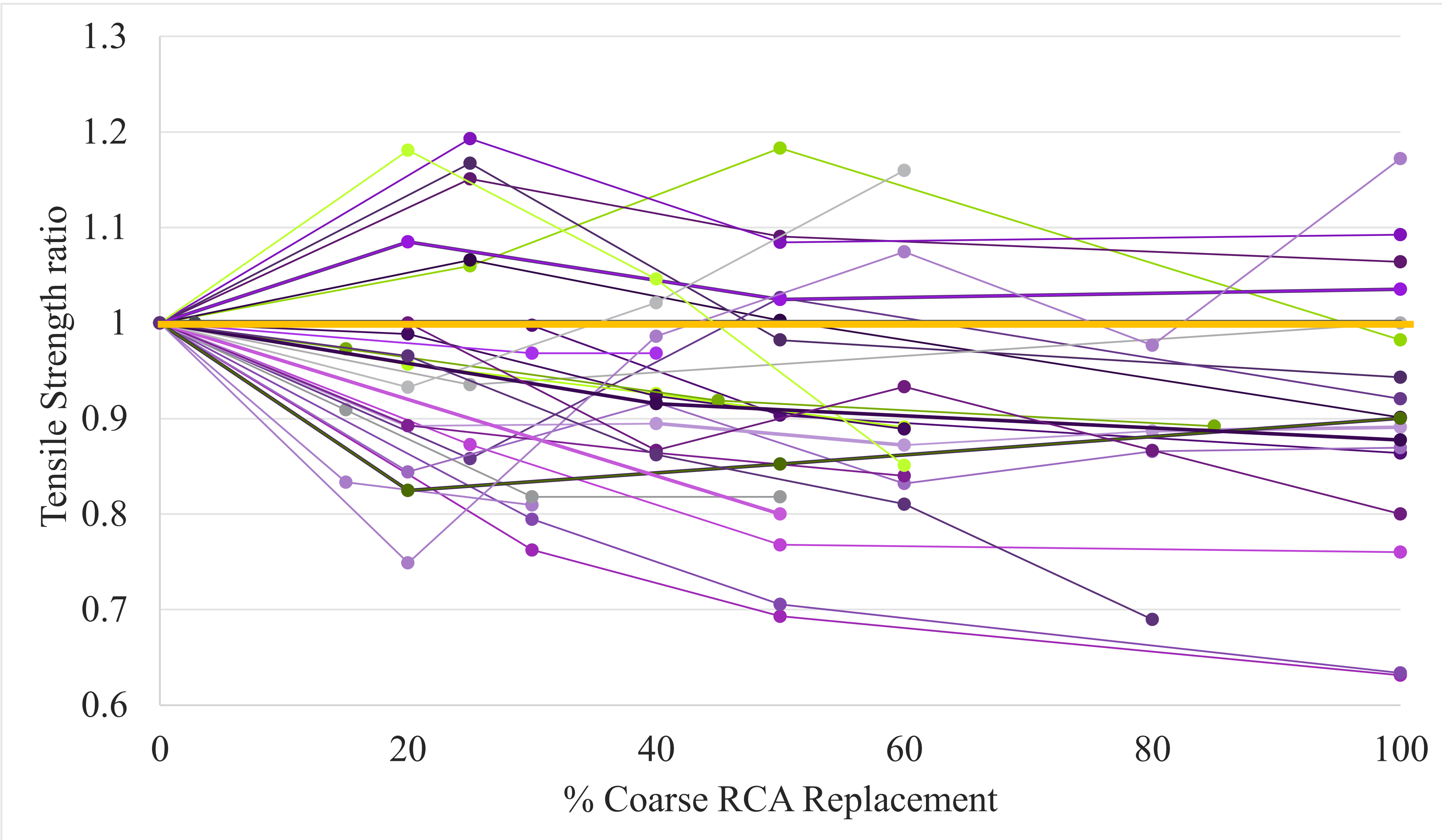
$$Compressive\ Strength\ Ratio = \frac{RCA\ compressive\ strength}{Control\ compressive\ strength}$$

- Many different mixes
  - RCA type (only coarse aggregate)
  - w/c
  - SCMs
  - Mix designs
  - Admixtures

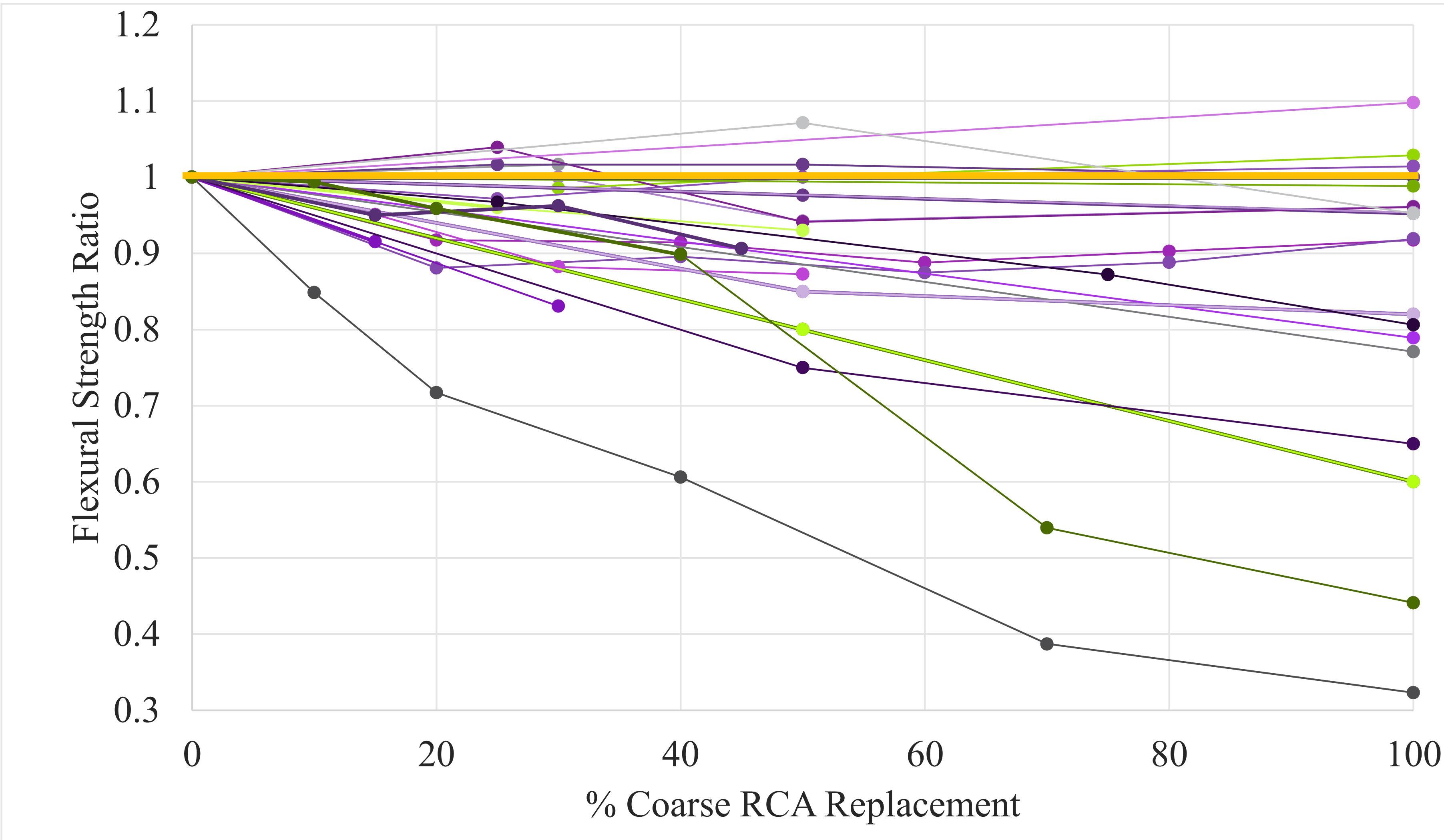
Compressive Strength



Tensile Strength



Flexural Strength



Why Strength Decreases

- RCA has lower strength/quality than virgin aggregate
- Crushing process may weaken aggregate
- Lower bond between new paste and RCA
- Less actual aggregate in the mix
- Higher air content
- Second ITZ
- Higher variability
- Harder to cast samples properly

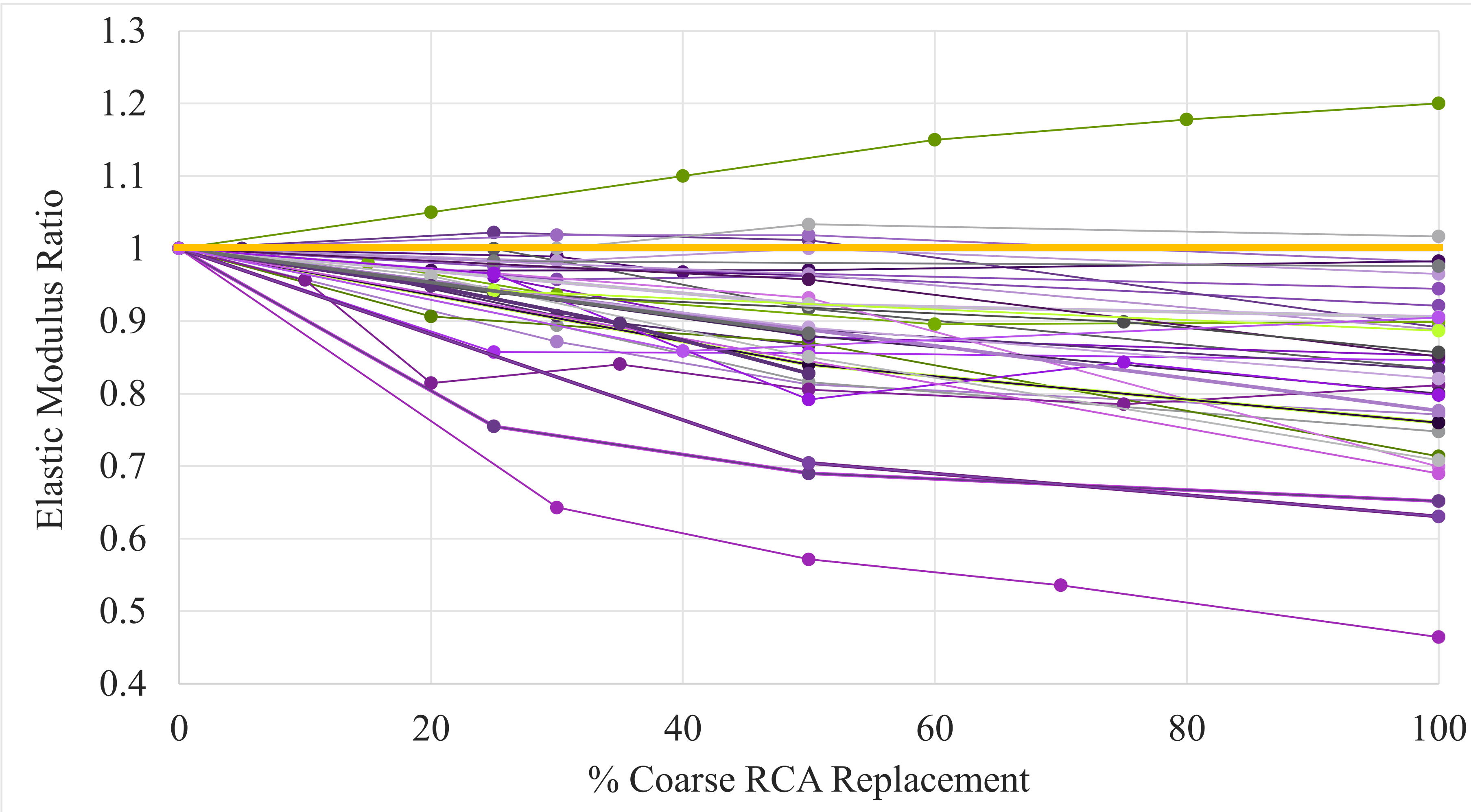
Why Strength Increases

- Improved ITZ characteristics
- Internal curing
- High performance parent concrete
- Unhydrated cement in RCA now hydrating
- Faster strength gain, only comparing at 28 days
- No moisture corrections → lower w/c than control

Strength Predictions from f'c

- Flexural strength
  - $f_r = 9.5\sqrt{f_c'}$
  - **As valid** for concrete containing RCA as for regular concrete
- Tensile strength
  - $f_r = 6.365\sqrt{f_c'}$
  - **Less valid** for concrete containing RCA as for regular concrete

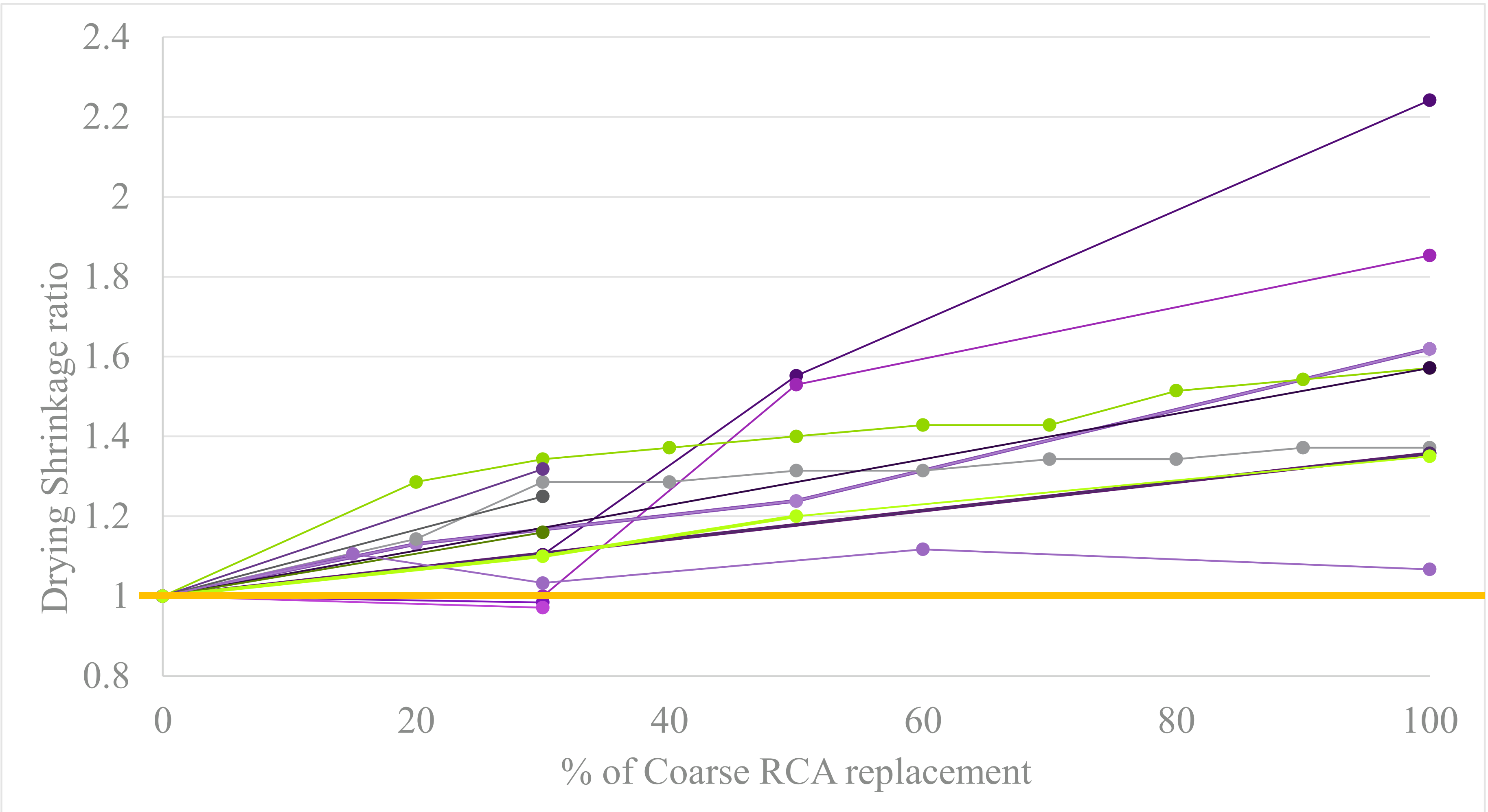
Elastic Modulus



Elastic Modulus

- RCA has lower E than virgin aggregate
  - Adhered mortar
  - Higher porosity
- Less stiff aggregate = less stiff concrete
- Standard $57\sqrt{f_c'}$ equation is **less valid** for predicting E when RCA is present
  - Change in unit weight not accounted for

Shrinkage



Drying Shrinkage ratio
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0
20
40
60
80
100
% of Coarse RCA replacement

Shrinkage

- Higher shrinkage due to:
  - Higher porosity
  - Higher paste fraction
  - RCA restrains paste less than virgin aggregate
  - If higher w/c used, further increases shrinkage
- Reversible shrinkage level still similar
- May not have as much cracking as expected for the shrinkage levels
  - Longer time to crack
  - RCA restrains paste less

Other Hardened Properties

- Poisson's ratio
  - No definitive trend
- Coefficient of Thermal Expansion
  - RCA typically lowers CTE
  - RCA can increase CTE
- Stress strain curve
  - Curve shifts slightly right
  - Higher strains, lower peak stresses
  - Differences in behavior likely due to microcracking in adhered mortar and lower RCA stiffness

Fresh Properties

- Air content
  - Can still use pressure meter
  - What air content is being measured? Old vs. new paste
- Workability
  - Lower slump due to higher absorption
  - Adding water to increase slump could be source of hardened property differences
  - Admixtures (or adjustments to admixtures) often needed

Concrete Durability

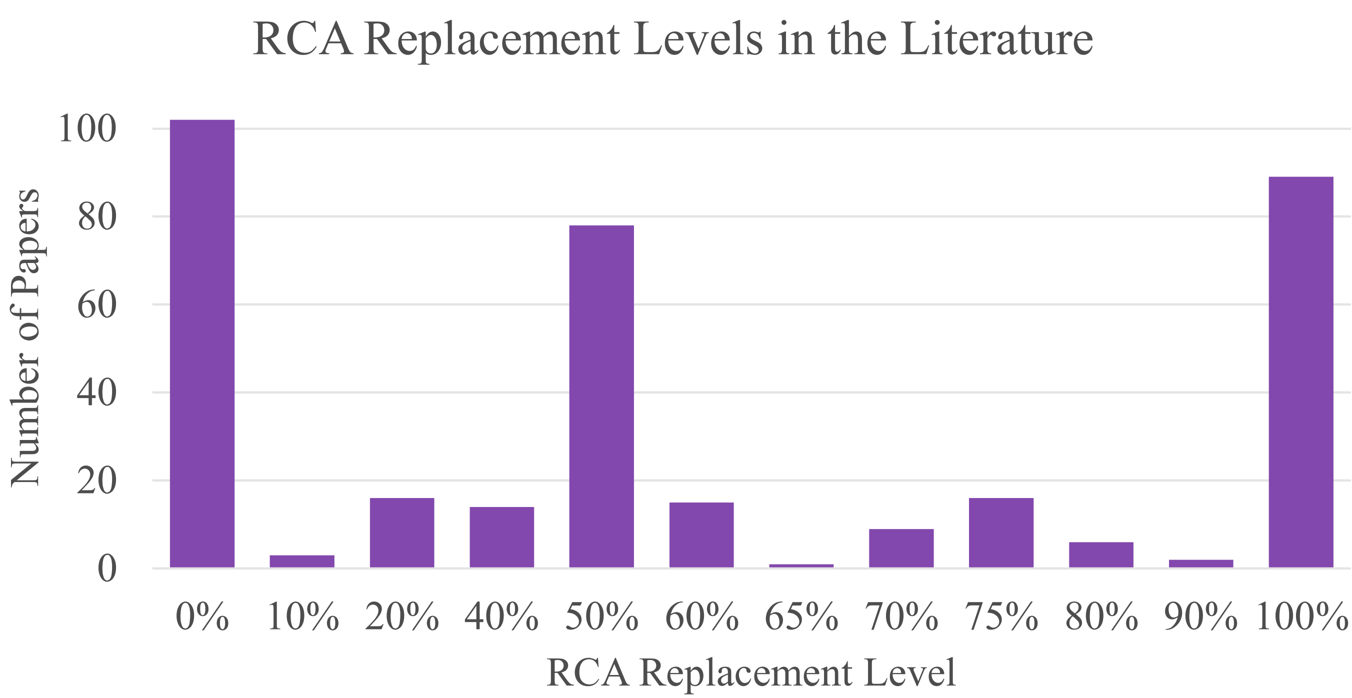
- Higher porosity and permeability
- Increases chloride diffusion coefficients
- Lower surface resistivity
- Lower concrete abrasion resistance
- ASR
  - Crushing RCA exposes new sites for reaction
  - Test and mitigate as normal

Freeze-Thaw Durability

- No consensus on effect of RCA
- Higher porosity → more water movement, storage
- Higher paste fraction
- Parent concrete should have air entrained paste

RCA Replacement Levels

- High replacement levels
  - Uncertainty and hesitance for use
  - Material availability – using up as base
- Low levels not well researched



What About Low Replacement Levels?

- NRRA funded study
- Is there some replacement level at which RCA has negligible effects?
- What parameters would need to be investigated to make a spec?
- Make sure research represents realistic use of RCA

The Question: Is there a low replacement level of RCA we can consistently use?

- Low replacement levels (5-15%)
- 4 sources
- Fresh properties
  - Slump
  - Air
  - SAM
  - Box Test
- Hardened properties
  - Compressive strength
  - Flexural strength
  - Elastic modulus
  - Poisson's ratio
  - Shrinkage
  - CTE
- Durability
  - Resistivity
  - Freeze-Thaw

Mix

Control mix

- Type IL cement
- Fly ash
- Mix design from local ready-mix supplier with admixtures adjusted
- Coarse aggregate blend (limestone)
  - #67
  - #4 sieved to 1¼ in max aggregate size
- Natural sand
  - 2 deliveries with slightly different gradations

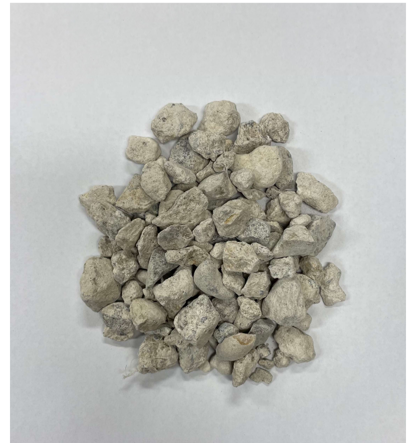
Ingredient	lb/cy
Water	224
Cement (Type IL)	448
Fly ash	112
#67 coarse aggregate	1323
#4 coarse aggregate	410
Sand	1376
Admixture	**oz/cwt**
MRWRA	0.37
AEA	2.6

Total cementitious content = 560 lb/cy

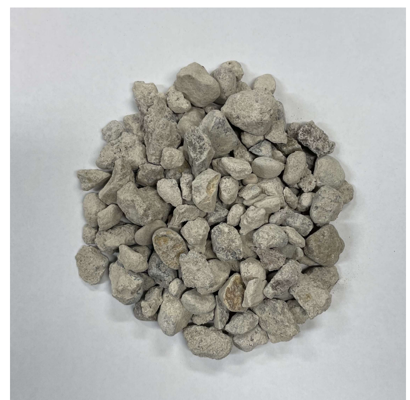
w/c = 0.4

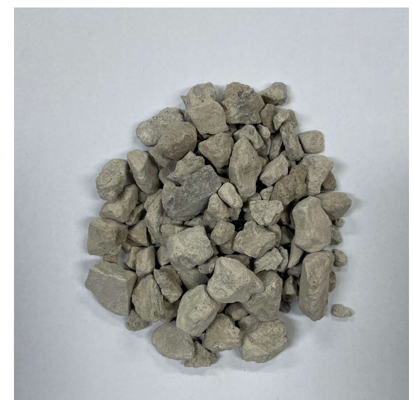
RCA Types

- 4 RCA sources
  - A – returned concrete with some unknown rubble
  - B – unwashed crushed returned concrete
  - C– multi-source demolition waste + returned concrete
  - D – crushed airfield pavement from St. Louis airport (limestone agg)
- 3 replacement levels
  - 5%, 10%, 15% of total CA
  - Replacing only #67 portion of CA


A


B


C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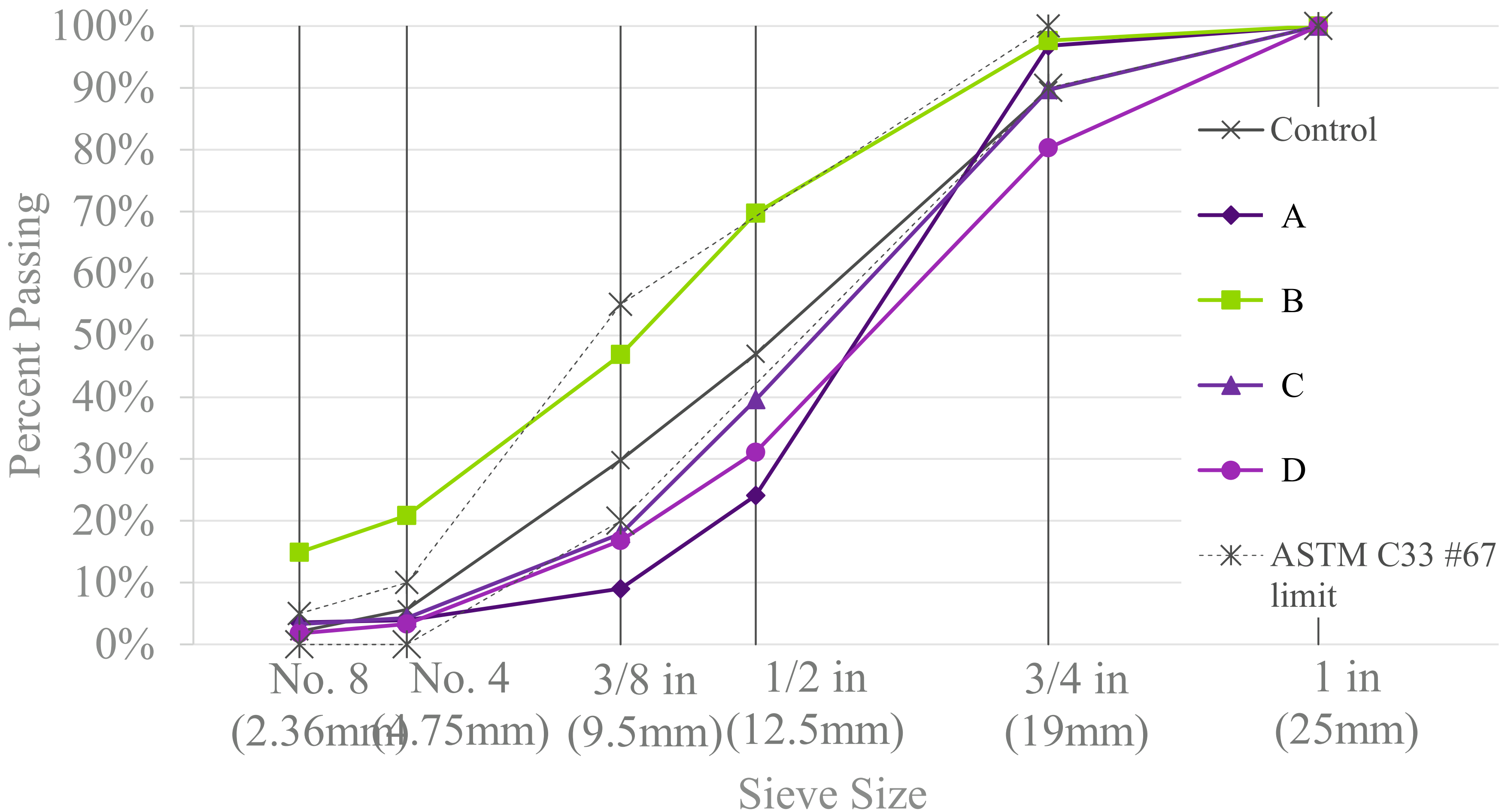
RCA Coarse Aggregate Gradations

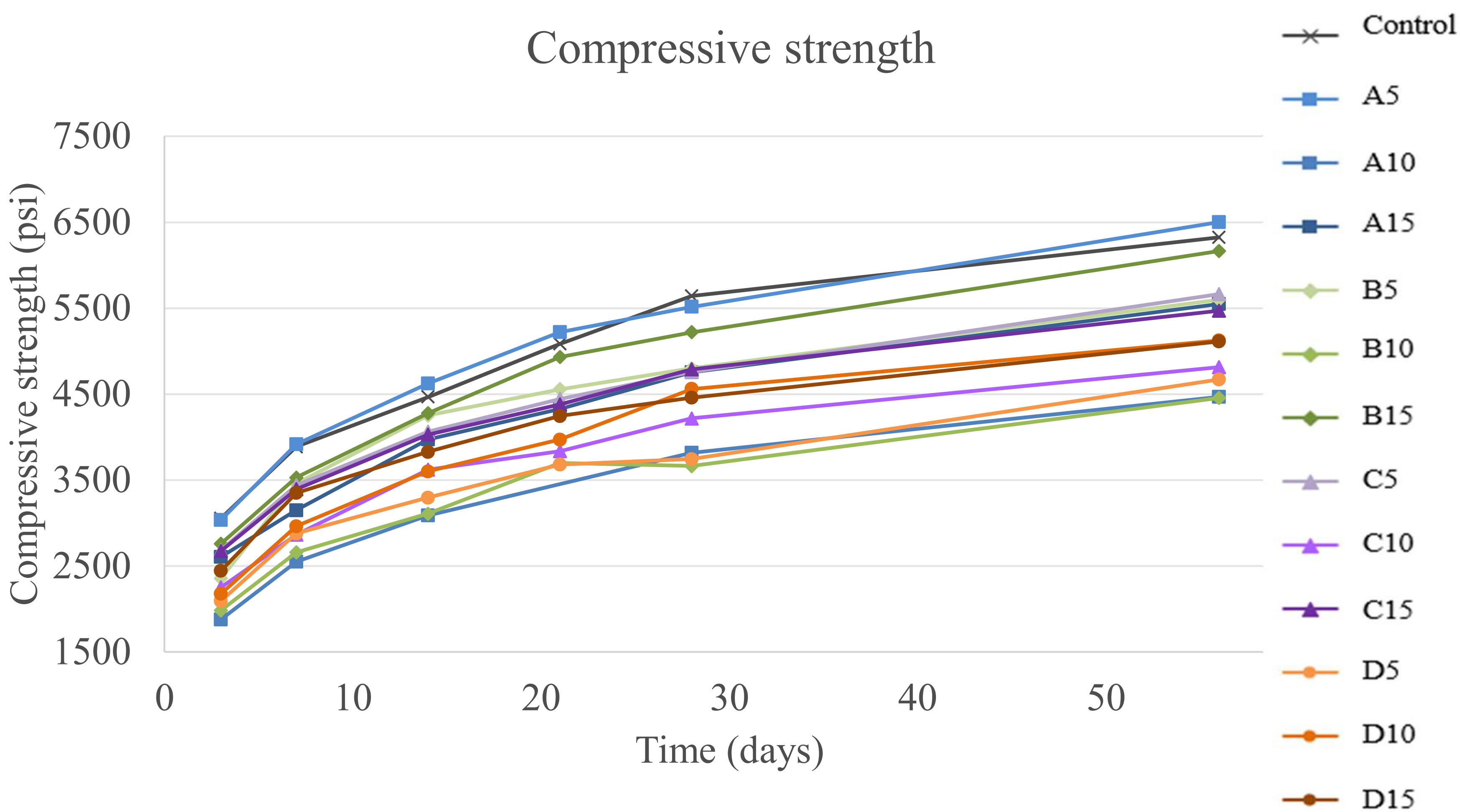


Coarse Aggregate Properties

Aggregate Source	Specific Gravity	Absorption Capacity	P-200	FM	Micro-Deval
Control	2.68	1.06%	0.10%	3.78	10.4%
A	2.32	5.32%	0.70%	3.77	21.4%
B	2.18	8.78%	2.89%	2.50	20.5%
C	2.29	6.05%	0.67%	3.45	19.7%
D	2.40	3.50%	0.70%	3.67	14.4%

Hardened Properties

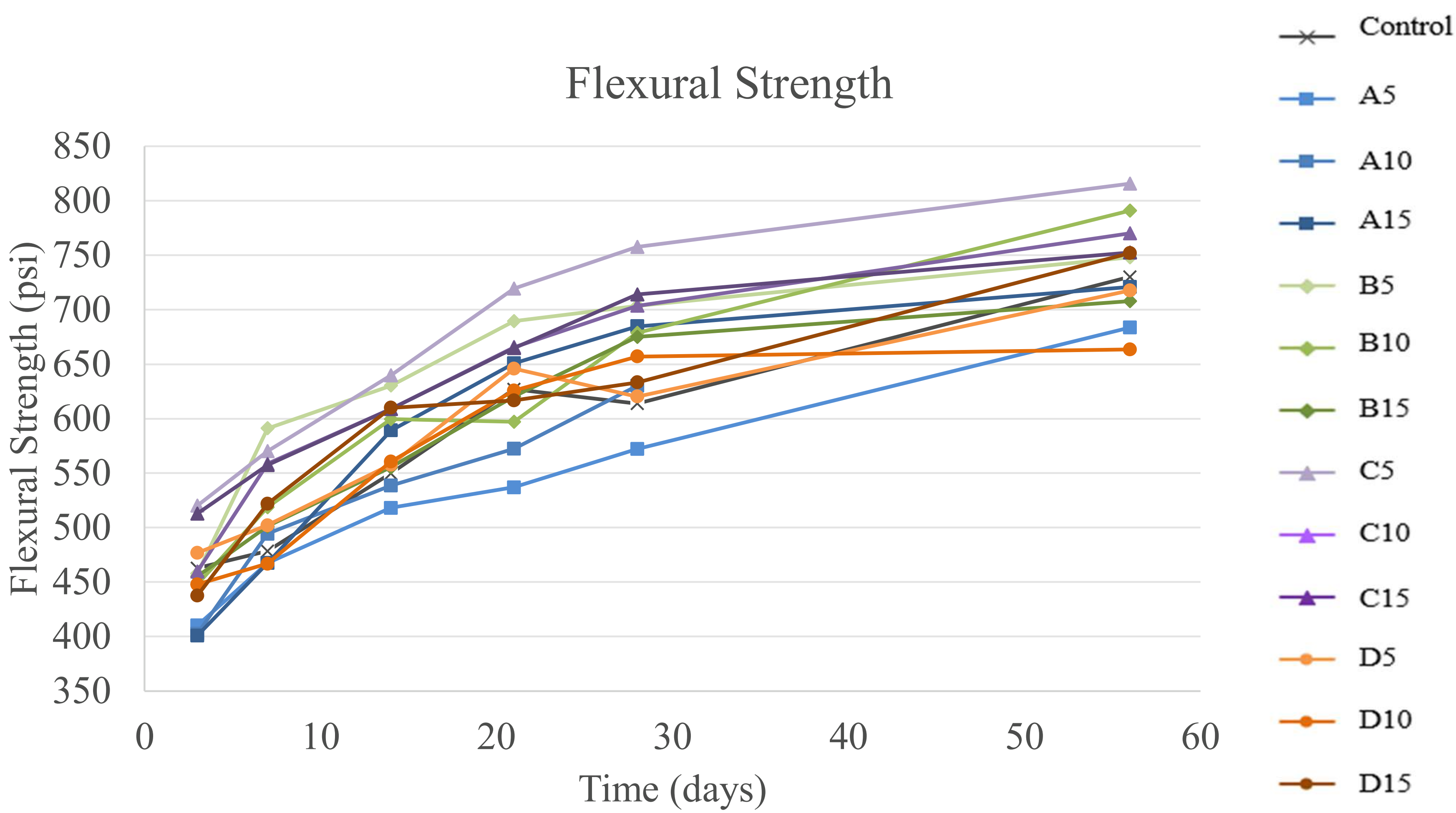
Compressive Strength



Compressive Strength

- Compressive strength reduction was statistically significant
- Matches expected trend from lit review
  - Low RCA levels saw 12-22% reduction (very few studies to compare with)
- Lower rate of strength gain suggests not getting benefits of internal curing or unhydrated cement

Flexural Strength



Flexural Strength

- Not statistically significantly different
- Standard $9.5\sqrt{f_c'}$ equation underpredicts MOR by 4%

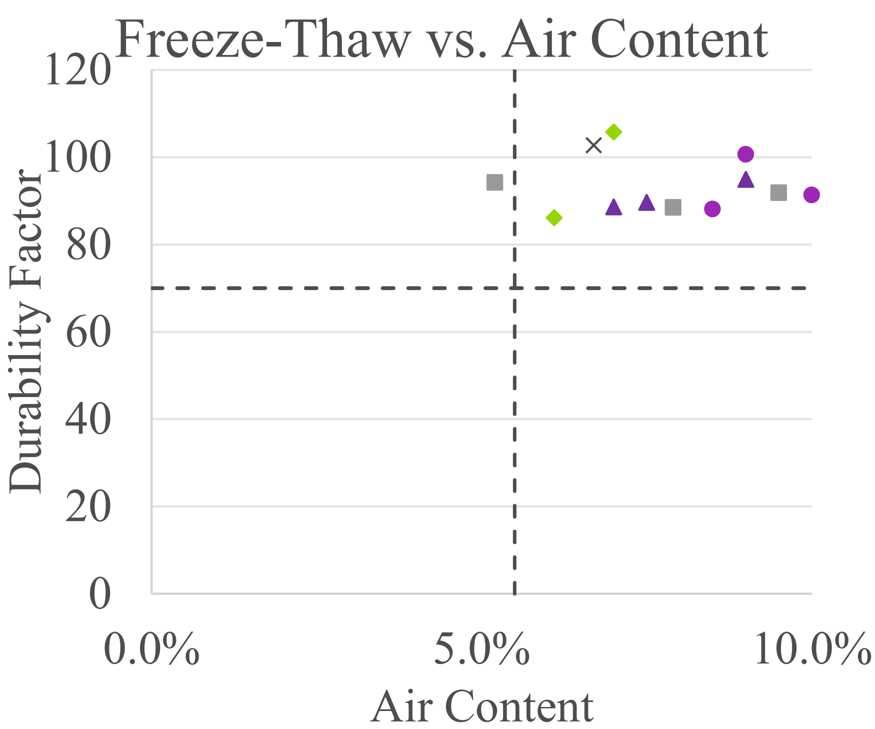
Elastic Modulus

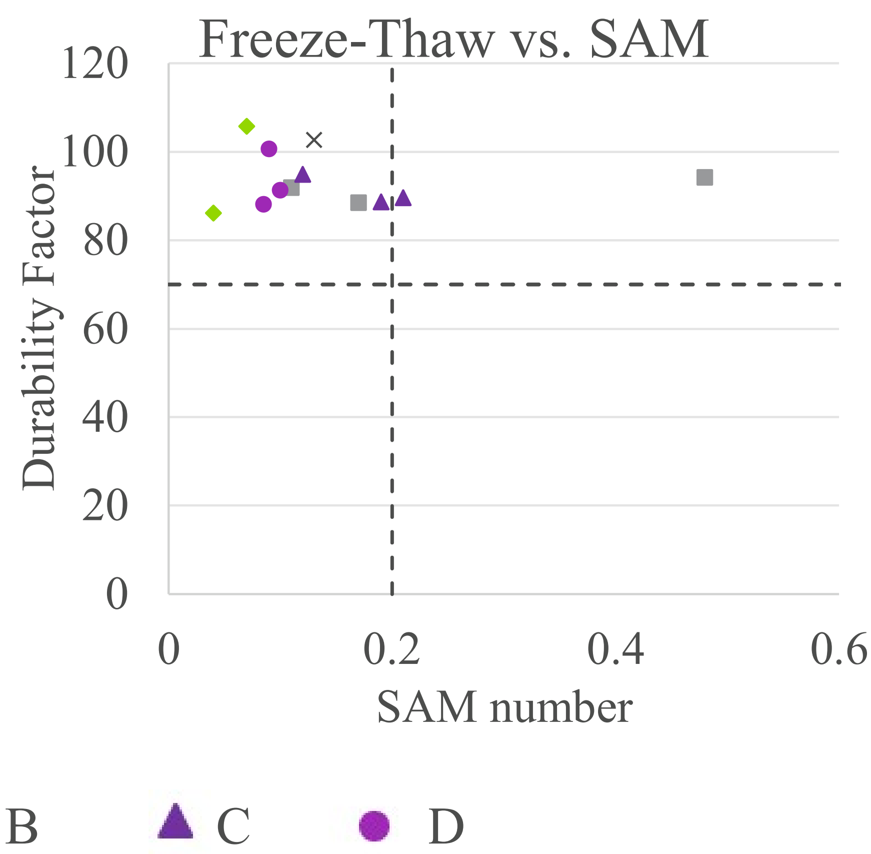
- Only statistically significantly different for B 10 and B 15
  - E decreased
- Standard $57\sqrt{f_c'}$ equation overpredicts E by 25%
  - Unit weight may yield better prediction?
  - Practicality of needing unit weight?

Other Hardened Properties

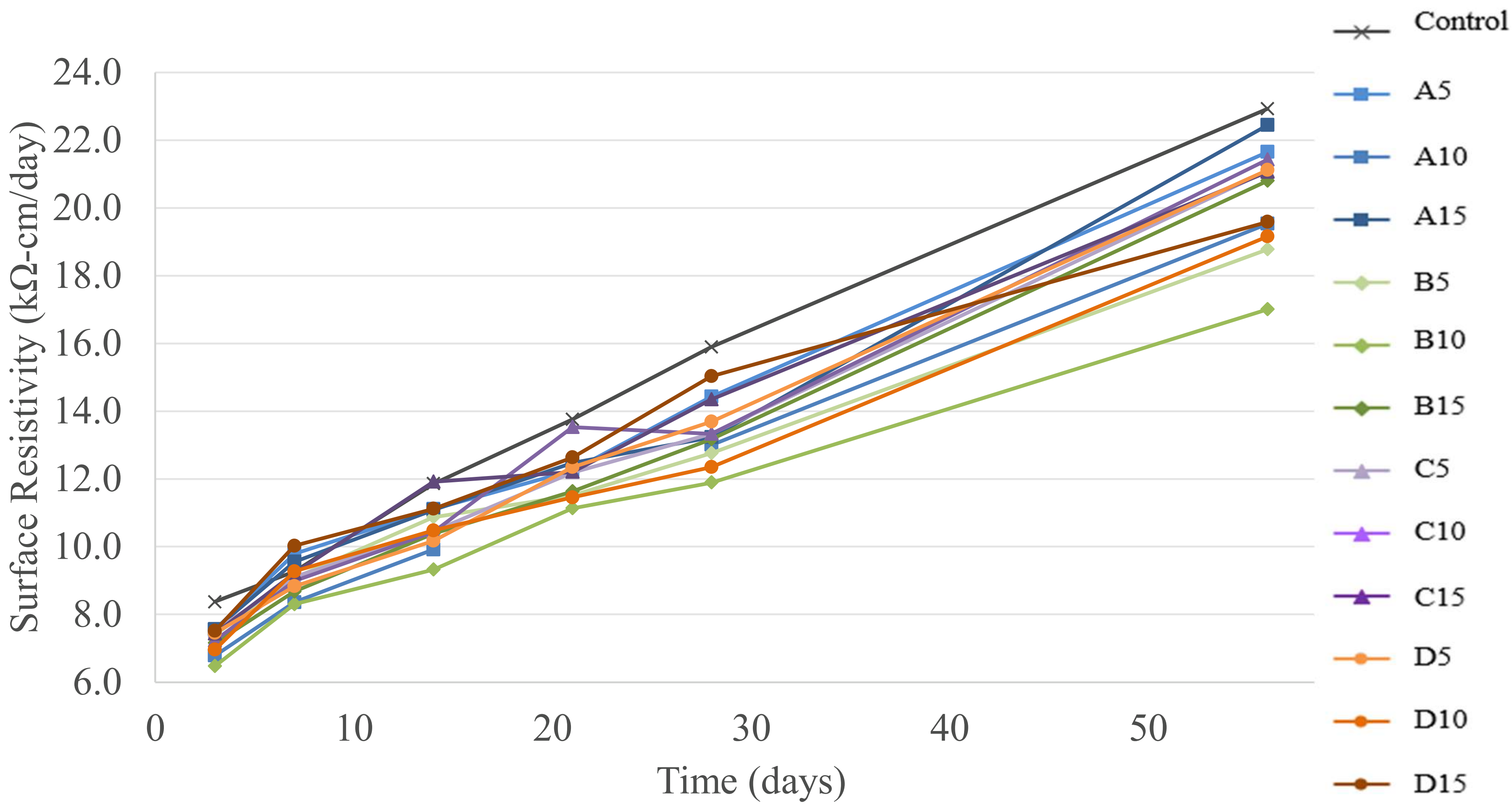
- Poisson's ratio
  - not statistically significant
- Shrinkage
  - not statistically significant
- Coefficient of thermal expansion
  - significant only for aggregate B
- Freeze-thaw
  - Not statistically significant
  - All tests had durability factor above 70

Freeze Thaw Vs. Air Content and Super Air Meter





Surface Resistivity



Surface Resistivity

- Values are statistically significant for most cases
- All samples are moderate risk at 28 days except B10 (high risk)
- Many samples move to low risk by 56 days

Specification Roadmap

Getting to a Specification

Need to define "reasonable RCA" – look to coefficient of determination

	Absorption capacity	Percent Fines	Fineness Modulus	Micro-deval	Specific Gravity
Compressive Strength	0.127	0.057	Not Significant	0.145	0.178
Flexural Strength	0.228	Not Significant	Not Significant	0.202	0.223
Elastic Modulus	0.356	0.426	0.318	0.244	0.360
Poisson's Ratio	Not Significant	0.167	0.144	Not Significant	Not Significant
CTE	0.585	0.295	0.212	0.656	0.638
Resistvity	0.278	0.217	0.162	0.249	0.285
Shrinkage	0.108	Not Significant	0.091	Not Significant	Not Significant
Freeze-Thaw Durability	0.201	0.086	Not Significant	0.246	0.228

Getting to a Specification

- Replacing virgin with RCA of same gradation band is ok
  - Only practical option
- Specific gravity and/or absorption capacity must be limited
  - Literature suggests 5% AC as a guideline
  - Up to 6% AC worked here
- SG and AC both proxy for adhered mortar content
  - SG has more variability because of density of aggregate
  - AC likely the better metric to use

Getting to a Specification

- Limit fines
  - 1% as a starting point?
  - Most producers don't want to wash RCA
- Micro-Deval
  - May be useful but would not have flagged Aggregate B here
- Other properties not tested here could also be investigated
- What counts as uniformity?
  - When is one RCA different from another in terms of effect on properties?
  - For volume based replacement, when is specific gravity different enough to affect replacement level if RCA is measured via weight?

Conclusions

Conclusions

- RCA can have a wide range of effects on concrete properties
- Using up to 15% of "reasonable" RCA likely only impacts compressive strength
- Fresh properties
  - Air content likely still valid
  - May have considerable variation due to RCA absorption
- Correlations with f'c may be less valid
  - E and tensile strength more affected
  - Flexural strength less affected

Conclusions

- Need a good specification for RCA
  - Don't reuse spec for other aggregates
  - Limit absorption capacity
  - Limit fines
  - Some type of aggregate quality test
- How to consider consistency between sources?
  - When is the pile different enough from earlier?

Acknowledgements

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Questions?

Have some RCA?

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