CAL POLY

Factors Affecting Shrinkage of Concretes Containing Recycled Concrete Aggregates

Daniel C. Jansen, PhD, PE, FACI
Cal Poly State University, San Luis Obispo

Brett Schoppe, PE
Mark Thomas, Sacramento, CA

Research Objectives

It's well accepted that concrete with recycled concrete aggregates (RCA) have greater shrinkage:

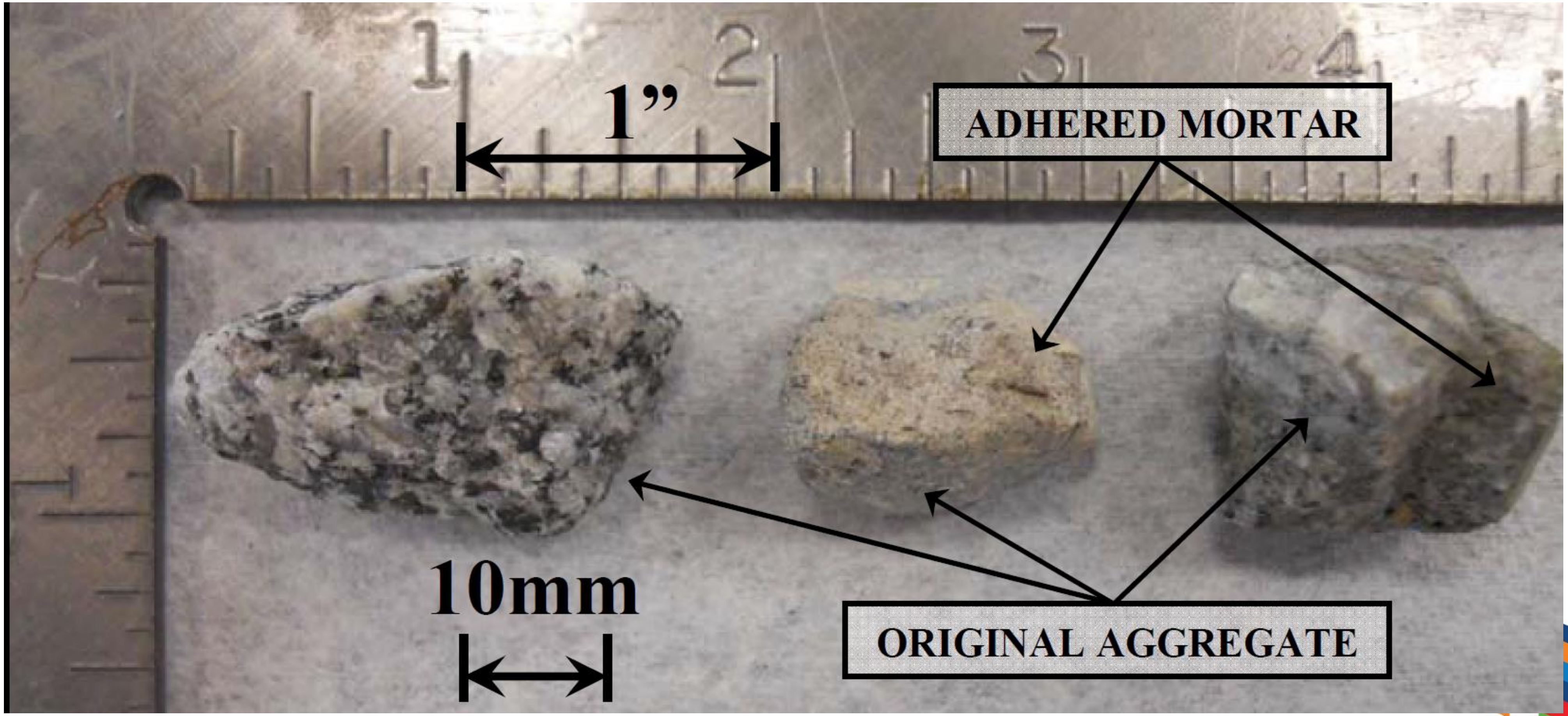
- The paste phase in RCA contribute additional shrinkage
- BUT shouldn't this paste largely have gone through its shrinkage over its lifespan?

Gain insight to how much the paste phase of RCA contributes to the overall shrinkage of concrete.

Outline

- Description of aggregates and concrete batches
- Determination of modulus of elasticity of aggregates
- Shrinkage testing results and analysis
- Modeling of shrinkage
- Conclusions

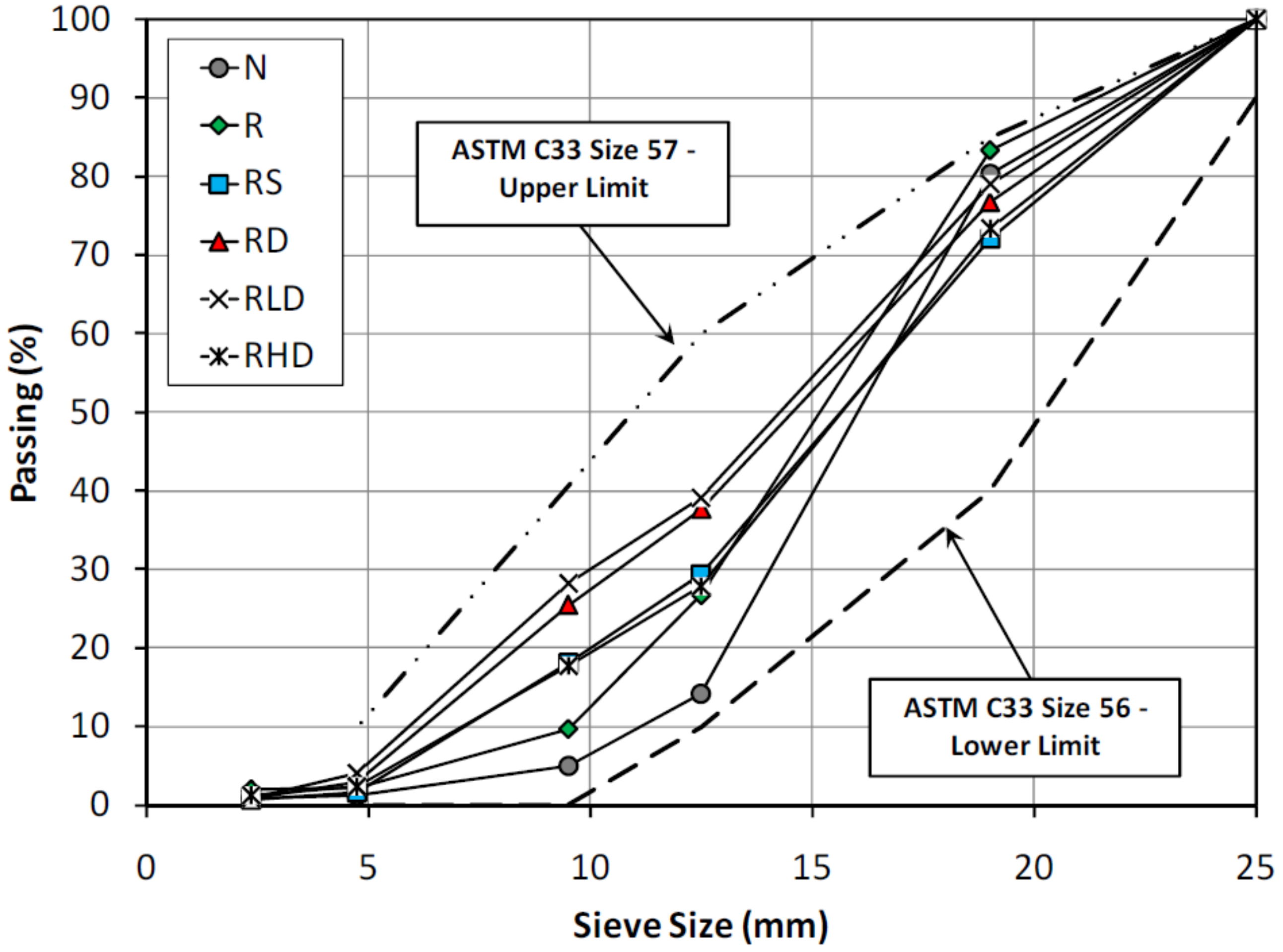
Coarse Aggregates



Aggregate Properties

Material ID	Description of Materials	Max. Size, mm (in)	*BSG	Absorption %
Fine Agg.	Sisquoc C33 Sand - Fine Aggregate	4.75 (1/8)	2.56	2.2
N	Natural Coarse Aggregates - Santa Margarita Crushed Granite	25 (1)	2.61	1.4
R	RCA - w/c unknown; from San Diego, CA		2.47	4.9
RS	Saturated RCA - 0.45 w/c Parent Concrete		2.44	5.4
RD	Dried RCA - 0.45 w/c Parent Concrete		2.43	5.3
RLD	Dried RCA - 0.30 w/c Parent Concrete		2.46	4.7
RHD	Dried RCA - 0.60 w/c Parent Concrete		2.44	5.1

Coarse Aggregate Gradations



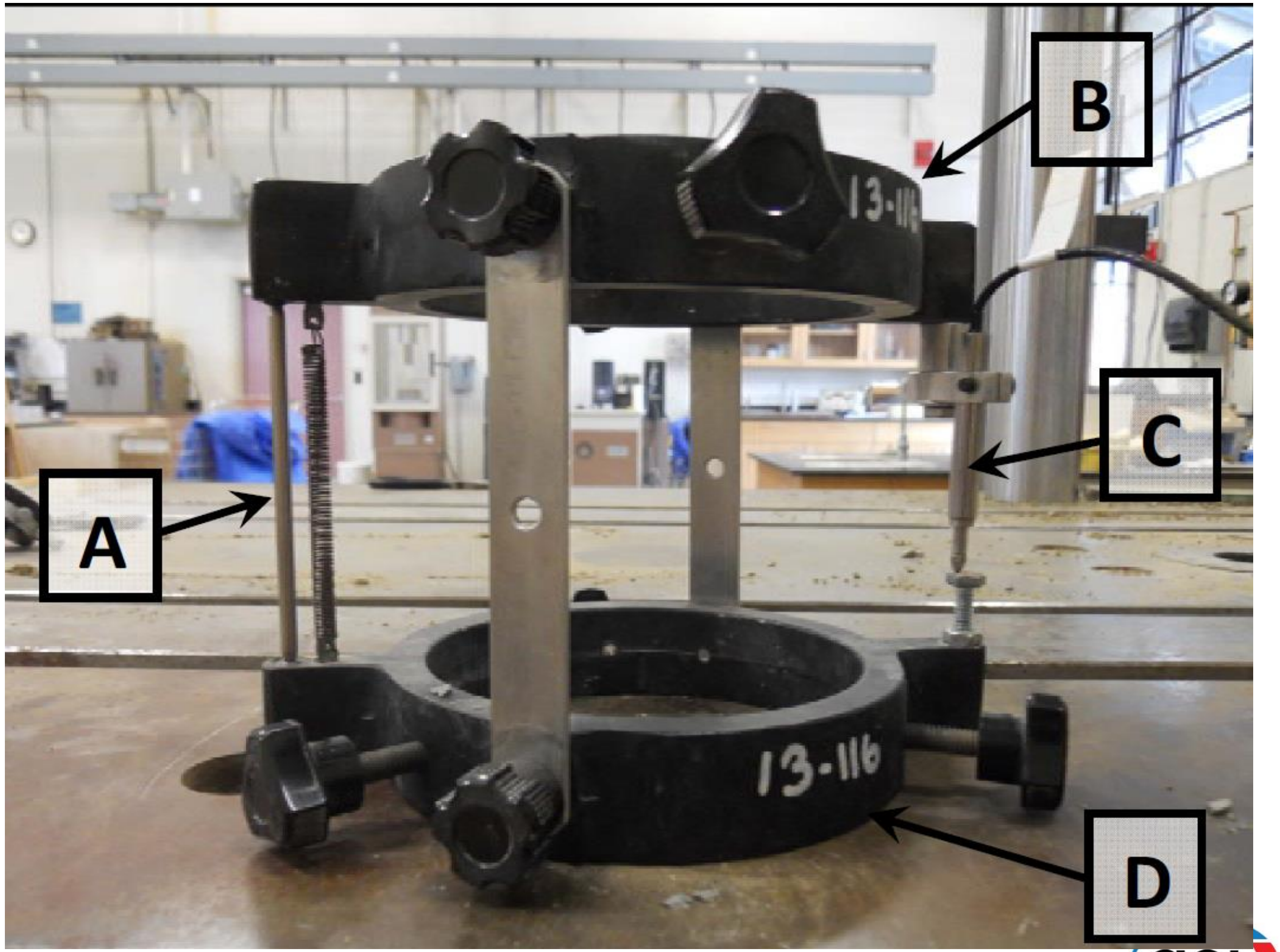
Variables in Concrete Produced

w/c	0.30	0.45				0.6
N Replacement	100%	25%	50%	75%	100%	100%
R	X	X	X	X	X	X
RS	X		X		X	X
RD	X		X		X	X
RLD					X	
RHD					X	

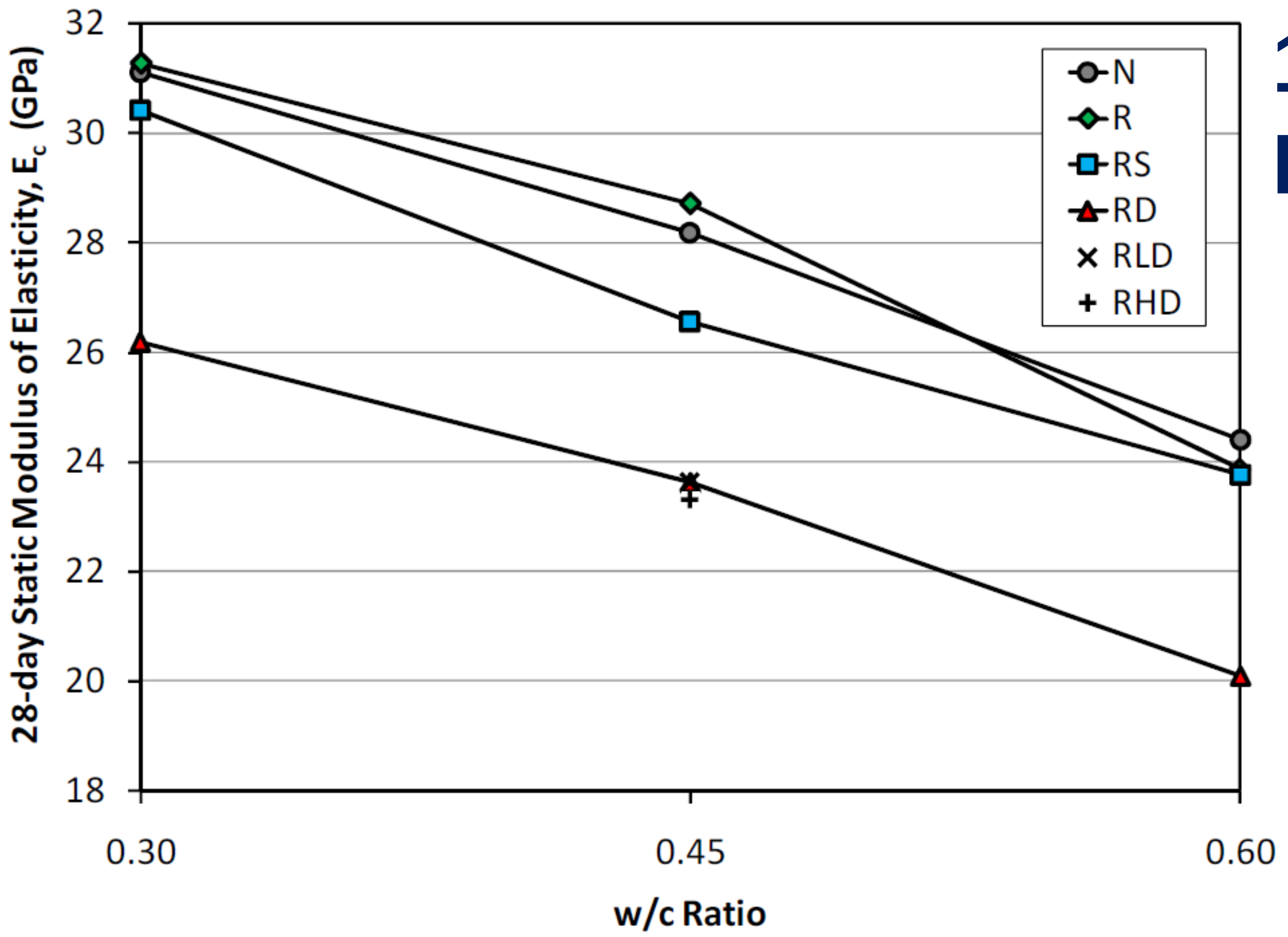
+ 4 with 0% Replacement @ w/c = 0.30, 0.45, 0.60

Coarse aggregates occupied 37% of total volume

Static MOE Test Apparatus



MOE for Different Recycled Aggregate Types



100% Replacement

28 Day Elastic Model - exponential mixture rule

$$E_{c,pred} = (E_N)^{V_N} (E_R)^{V_R} (E_{RS})^{V_{RS}} (E_{RD})^{V_{RD}} (E_{RLD})^{V_{RLD}} (E_{RHD})^{V_{RHD}} \left(E_{M,0.30}\right)^{V_{M,0.30}} \left(E_{M,0.45}\right)^{V_{M,0.45}} \left(E_{M,0.60}\right)^{V_{M,0.60}}$$

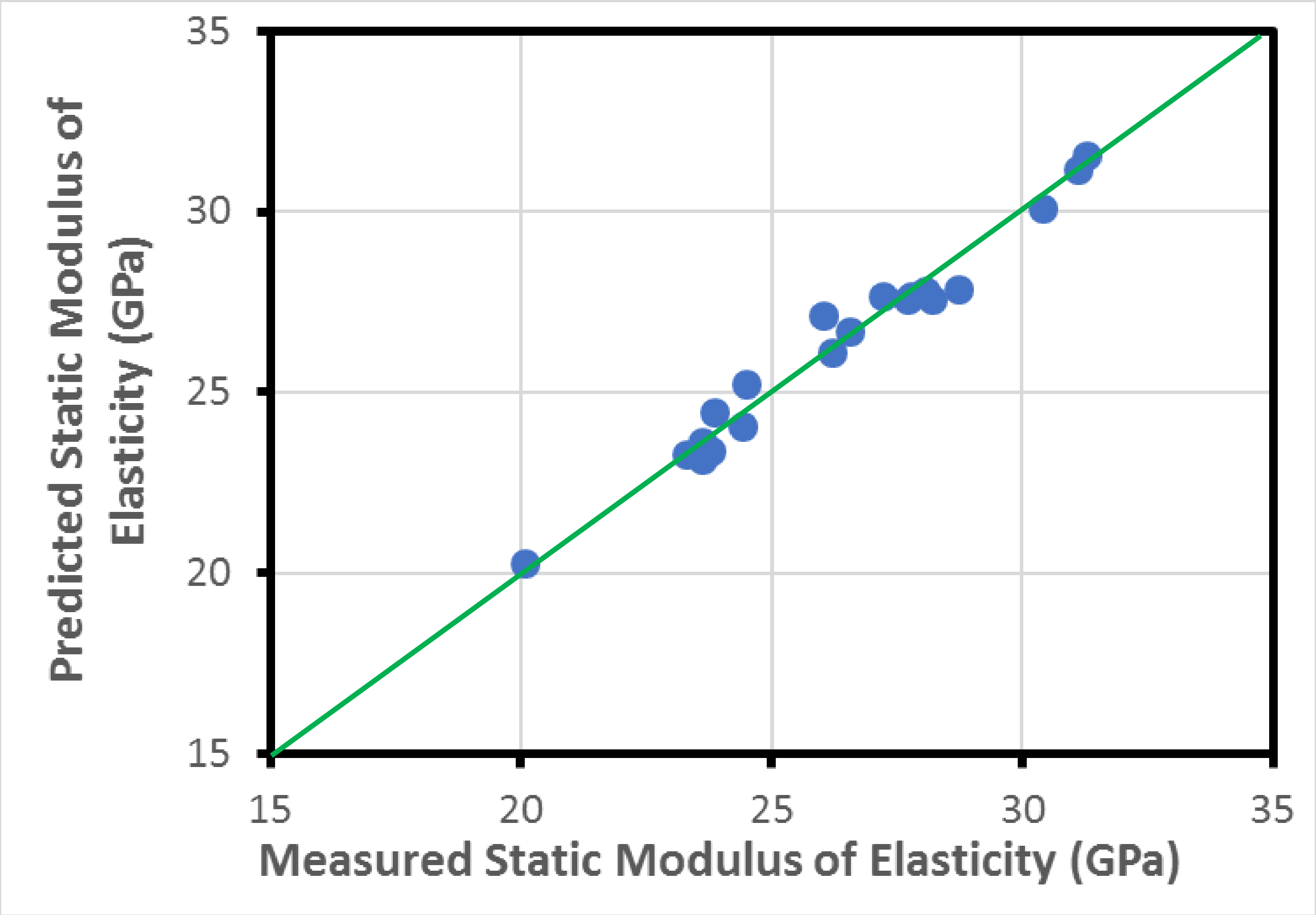
Total volume fraction of coarse aggregates = 37%

Example: R45-25

$$E_{c,pred} = (E_N)^{0.2775} (E_R)^{.0925} \left(E_{M,0.45}\right)^{0.63}$$

Solved using least squares regression

- 9 unknowns (E_N, E_R, E_{RS}, etc…)
- 20 batches of concrete


Predicted Static Modulus of Elasticity (GPa)
Measured Static Modulus of Elasticity (GPa)
15
20
25
30
35
15
20
25
30
35

28 Day Elastic Model

E_N (GPa)	37.9
E_R (GPa)	39.2
E_{RS} (GPa)	34.6
E_{RD} (GPa)	23.6
E_{RLD} (GPa)	25.0
E_{RHD} (GPa)	24.1

$E_{M,0.30}$ (GPa)	27.8
$E_{M,0.45}$ (GPa)	22.8
$E_{M,0.60}$ (GPa)	18.5

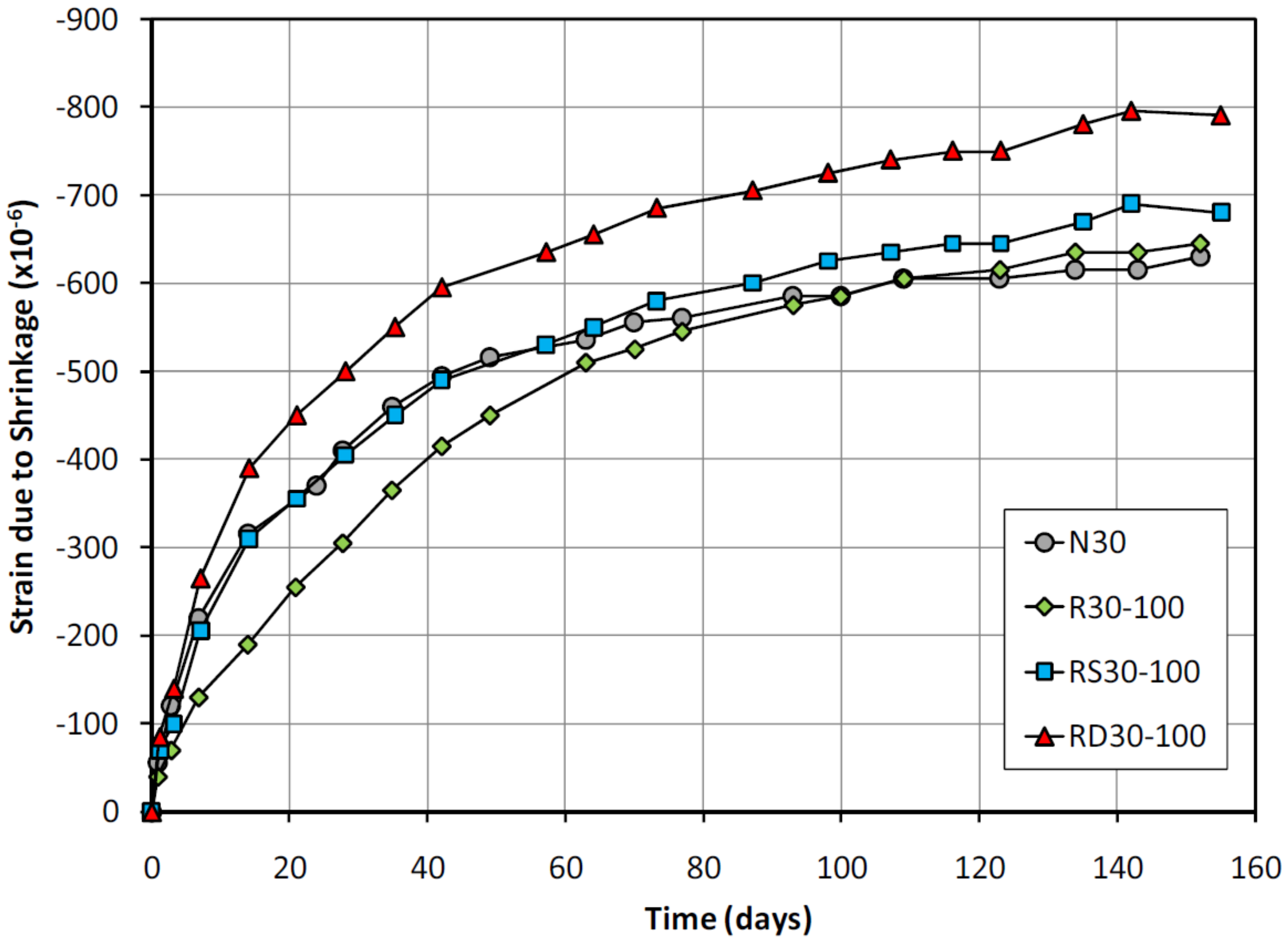
$$E_{c,pred} = (E_N)^{V_N}\,(E_R)^{V_R}\,(E_{RS})^{V_{RS}}\,(E_{RD})^{V_{RD}}\,(E_{RLD})^{V_{RLD}}\,(E_{RHD})^{V_{RHD}}\,(E_{M,0.30})^{V_{M,0.30}}\,(E_{M,0.45})^{V_{M,0.45}}\,(E_{M,0.60})^{V_{M,0.60}}$$

Shrinkage Test Results

50% RH

23° C

Shrinkage vs. Time



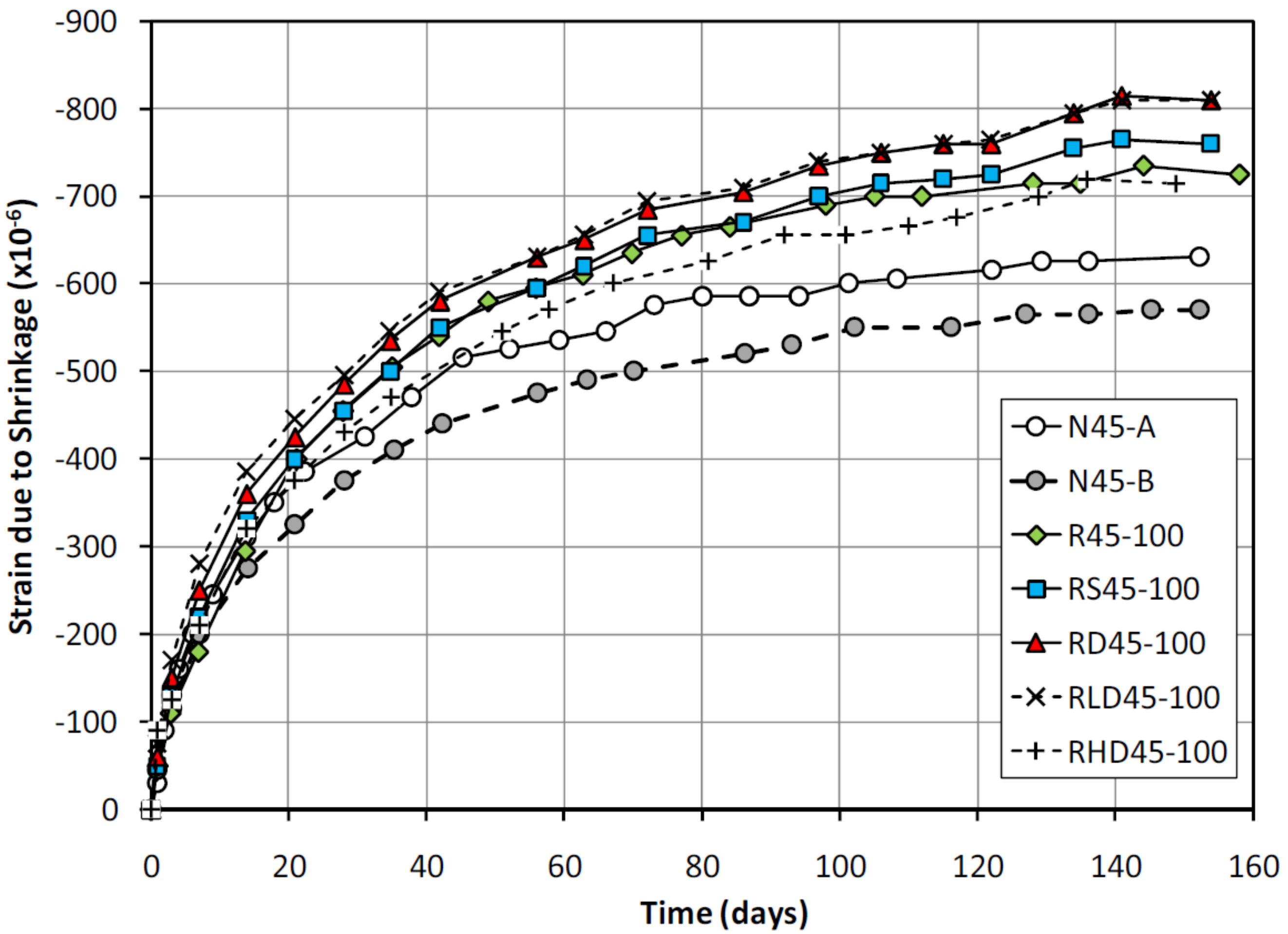
w/c = 0.30

100% Replacement all aggregate types

Contrary to expectations:

- **RD shrank more than RS**
- **R and N shrank about the same**

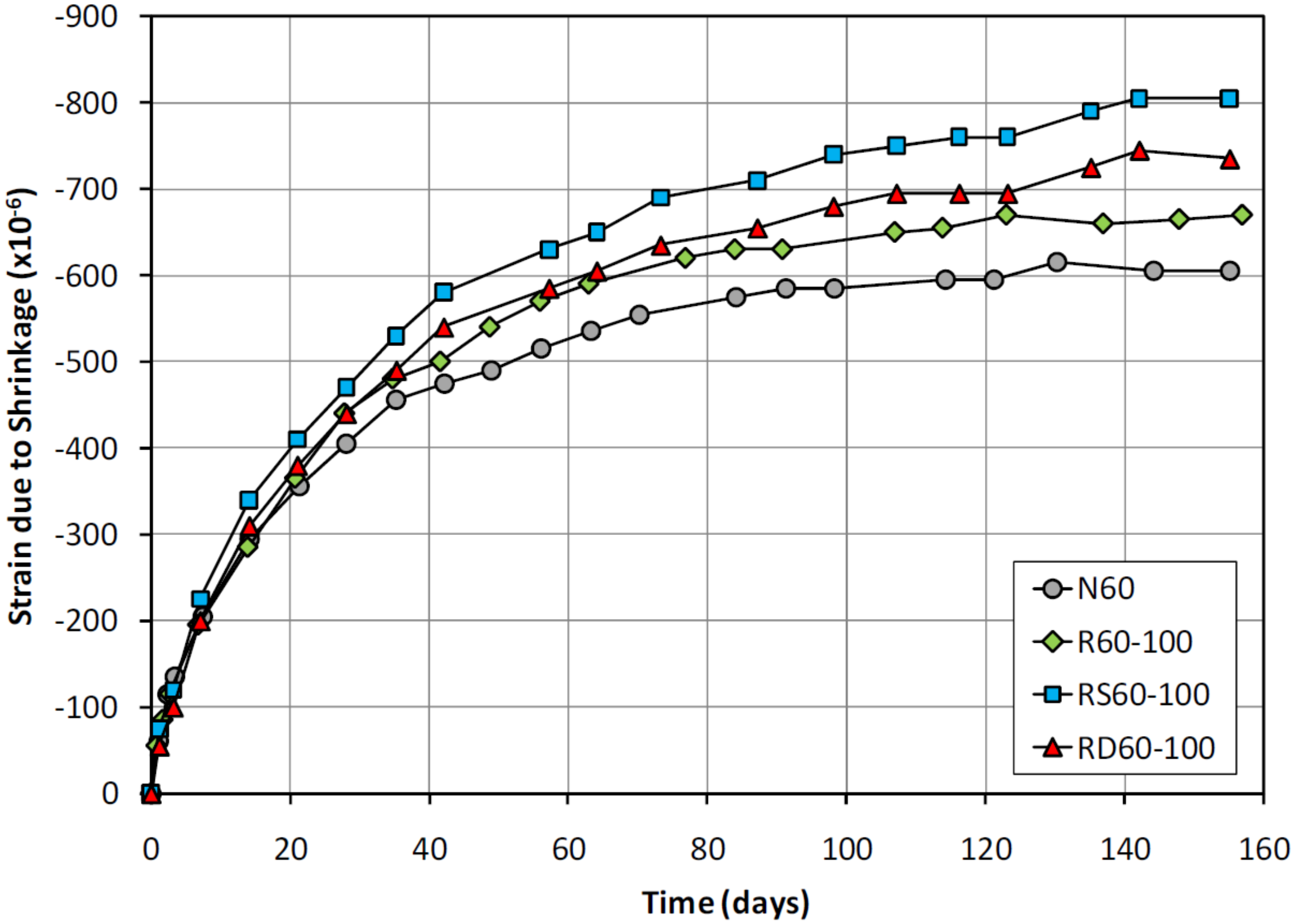
Shrinkage vs. Time



w/c = 0.45

100% Replacement all aggregate types

Shrinkage vs. Time



w/c = 0.60

100% Replacement all aggregate types

Ultimate Shrinkage Models

ACI 209R

$$S_t = \frac{t}{t_o + t} S_{ult}$$

Where: S_t = shrinkage after t days

t = time in days

t_o = shrinkage half time

S_{ult} = ultimate shrinkage

RILEM TC-107 Model B3

$$\varepsilon_{sh} = \varepsilon_{sh\infty}(1 - h^3)\, tanh\left(\frac{t}{\tau_{sh}}\right)^{1/2}$$

Where: ε_{sh} = shrinkage after t days

t = time in days

τ_{sh} = shrinkage half time

$\varepsilon_{sh\infty}$ = ultimate shrinkage

h = relative humidity

With 50% RH: $(1\text{-}h^3) = (1\text{-}0.5^3) = 0.875$

S_{ult} should ~ 0.875 $\varepsilon_{sh\infty}$

CAL POLY

Ultimate Shrinkage

Mix ID	S_{ult} (10^{-6})	$\varepsilon_{sh\infty}$ (10^{-6})	$S_{ult}/\varepsilon_{sh\infty}$
N45-A	697	804	0.867
N45-B	637	721	0.883
R45-25	704	805	0.875
R45-50	819	946	0.866
R45-75	709	812	0.873
R45-100	852	974	0.875
RS45-50	789	930	0.848
RS45-100	874	1025	0.853
RD45-50	789	916	0.861
RD45-100	911	1067	0.854
RLD45-100	889	1026	0.866
RHD45-100	810	959	0.845

Mix ID	S_{ult} (10^{-6})	$\varepsilon_{sh\infty}$ (10^{-6})	$S_{ult}/\varepsilon_{sh\infty}$
N60	685	777	0.882
R60-100	773	876	0.882
RS60-100	929	1098	0.846
RD60-100	855	1005	0.851
N30	689	775	0.889
R30-100	844	1181	0.715
RS30-100	777	914	0.850
RD30-100	871	996	0.874
Average			0.858
St. Deviation			0.036

$S_{ult} \sim 0.875\ \varepsilon_{sh\infty}$

2 Phase Composite Shrinkage Model

Paste and Aggregates:

$$\varepsilon_{shr} = \frac{E_p}{E_c}\left(1 - V_{agg}\right)\varepsilon_{shr,p}$$

Mortar and Coarse Aggregate:

$$S_{ult} = \frac{E_m}{E_c}\left(1 - V_{agg}\right)\varepsilon_{shr,m}$$

$$\varepsilon_{shr,m} = \frac{E_c}{E_m}\frac{1}{\left(1 - V_{agg}\right)}S_{ult}$$

Mix ID	E_c (GPa)	E_{agg} (GPa)	E_m (GPa)	Measured S_{ult} ($x10^{-6}$)	$\varepsilon_{shr,m}$ ($x\,10^{-6}$)
N45-A	27.7	37.9	22.8	697	1344
N45-B	28.2	37.9	22.8	637	1251

Average $\varepsilon_{shr,m0.45}$ = 1297 $\mu\varepsilon$

2 Phase Composite Shrinkage Model

Mix ID	E_c (GPa)	E_{agg} (GPa)	E_m (GPa)	Measured S_{ult} ($x10^{-6}$)	$\varepsilon_{shr,m}$ ($x\,10^{-6}$)	Predicted S_{ult} ($x10^{-6}$)	Meas S_{ult} / Pred. S_{ult}
N45-A	27.7	37.9	22.8	697	1297	673	1.04
N45-B	28.2			637		661	0.96
R45-100	28.7	39.2		852			

Mortar and Coarse Aggregate:

$$S_{ult} = \frac{E_m}{E_c}\left(1 - V_{agg}\right)\varepsilon_{shr,m}$$

Average $\varepsilon_{shr,m0.45}$ = 1297 $\mu\varepsilon$

2 Phase Composite Shrinkage Model

Mix ID	E_c (GPa)	E_{agg} (GPa)	E_m (GPa)	Measured S_{ult} ($x10^{-6}$)	$\varepsilon_{shr,m}$ ($x\ 10^{-6}$)	Predicted S_{ult} ($x10^{-6}$)	Meas S_{ult} / Pred. S_{ult}
N45-A	27.7	37.9	22.8	697	1297	673	1.04
N45-B	28.2			637		661	0.96
R45-100	28.7	39.2		852		649	1.31

Mortar and Coarse Aggregate:

$$S_{ult} = \frac{E_m}{E_c}\left(1 - V_{agg}\right)\varepsilon_{shr,m}$$

31% additional shrinkage

2 Phase Composite Shrinkage Model

Mix ID	E_c (GPa)	E_{agg} (GPa)	E_m (GPa)	Measured S_{ult} ($x10^{-6}$)	$\varepsilon_{shr,m}$ ($x\ 10^{-6}$)	Predicted S_{ult} ($x10^{-6}$)	Meas S_{ult} / Pred. S_{ult}
N45-A	27.7	37.9		697		673	1.04
N45-B	28.2			637		661	0.96
R45-100	28.7	39.2		852		649	1.31
RS45-100	26.6	34.6	22.8	874	1297	700	1.25
RD45-100	23.6	23.6		911		789	1.15
RLD45-100	23.6	25.0		889		789	1.13
RHD45-100	23.3	24.1		810		800	1.01

Mortar and Coarse Aggregate:

$$S_{ult} = \frac{E_m}{E_c}\left(1 - V_{agg}\right)\varepsilon_{shr,m}$$

2 Phase Composite Shrinkage Model

Mix ID	E_c (GPa)	E_{agg} (GPa)	E_m (GPa)	Measured S_{ult} ($x10^{-6}$)	$\varepsilon_{shr,m}$ ($x\,10^{-6}$)	Predicted S_{ult} ($x10^{-6}$)	Meas S_{ult} / Pred. S_{ult}
N60	24.4	37.9	18.5	685	1434	685	1.00
R60-100	23.9	39.2		773		699	1.11
RS60-100	23.8	34.6		929		702	1.32
RD60-100	20.1	23.6		855		832	1.03
N30	31.1	37.9	27.0	689	1260	689	1.00
R30-100	31.3	39.2		844		685	1.23
RS30-100	30.4	34.6		777		705	1.10
RD30-100	26.2	23.6		871		818	1.06

Mortar and Coarse Aggregate:

$$S_{ult} = \frac{E_m}{E_c}\left(1 - V_{agg}\right)\varepsilon_{shr,m}$$

Mortar Phase

From model, the mortar phase shrank more with higher w/c (higher water contents):

w/c	$\varepsilon_{shr,m}$ $(x\ 10^{-6})$
0.30	1260
0.45	1297
0.60	1434

Recycled Aggregates – “pre-shrunk”

The RCAs not allowed to dry (RS) before being do significantly promote overall concrete shrinkage

Mix ID	E_c (GPa)	E_{agg} (GPa)	E_m (GPa)	Measured S_{ult} ($x10^{-6}$)	$\varepsilon_{shr,m}$ ($x\,10^{-6}$)	Predicted S_{ult} ($x10^{-6}$)	Meas S_{ult} / Pred. S_{ult}
RS30-100	30.4	34.6	22.8	777	1434	705	1.10
RS45-100	26.6	34.6	18.5	874	1434	700	1.25
RS60-100	23.8	34.6	27.0	929	1434	702	1.32
RD30-100	26.2	23.6	22.8	871	1260	818	1.06
RD45-100	23.6	23.6	18.5	911	1260	789	1.15
RD60-100	20.1	23.6	27.0	855	1260	832	1.03

Recycled Aggregates – field vs. lab manufactured

The high quality RCAs from aggregate supplier (“R) contributed more to concrete shrinkage than younger ‘lab manufactured RCAs (RD)

Mix ID	E_c (GPa)	E_{agg} (GPa)	E_m (GPa)	Measured S_{ult} ($x10^{-6}$)	$\varepsilon_{shr,m}$ ($x\ 10^{-6}$)	Predicted S_{ult} ($x10^{-6}$)	Meas S_{ult} / Pred. S_{ult}
R30-100	31.3	39.2	22.8	844	1297	685	1.23
R45-100	28.7	39.2	18.5	852	1297	649	1.31
R60-100	23.9	39.2	27.0	773	1297	699	1.11
RD30-100	26.2	23.6	22.8	871	1260	818	1.06
RD45-100	23.6	23.6	18.5	911	1260	789	1.15
RD60-100	20.1	23.6	27.0	855	1260	832	1.03

Conclusions

- RCA modulus of elasticity plays significant role in countering concrete shrinkage: the greater the aggregate's MOE, the less the shrinkage.
- When RCAs are allowed to go through drying shrinkage (in most cases in practice) prior to use, their contribution to the overall concrete shrinkage is diminished.
- RCAs contributions to overall concrete shrinkage is complex, and should be evaluated prior to use if an issue.