Performance Based Tests and Criteria for Concrete Durability

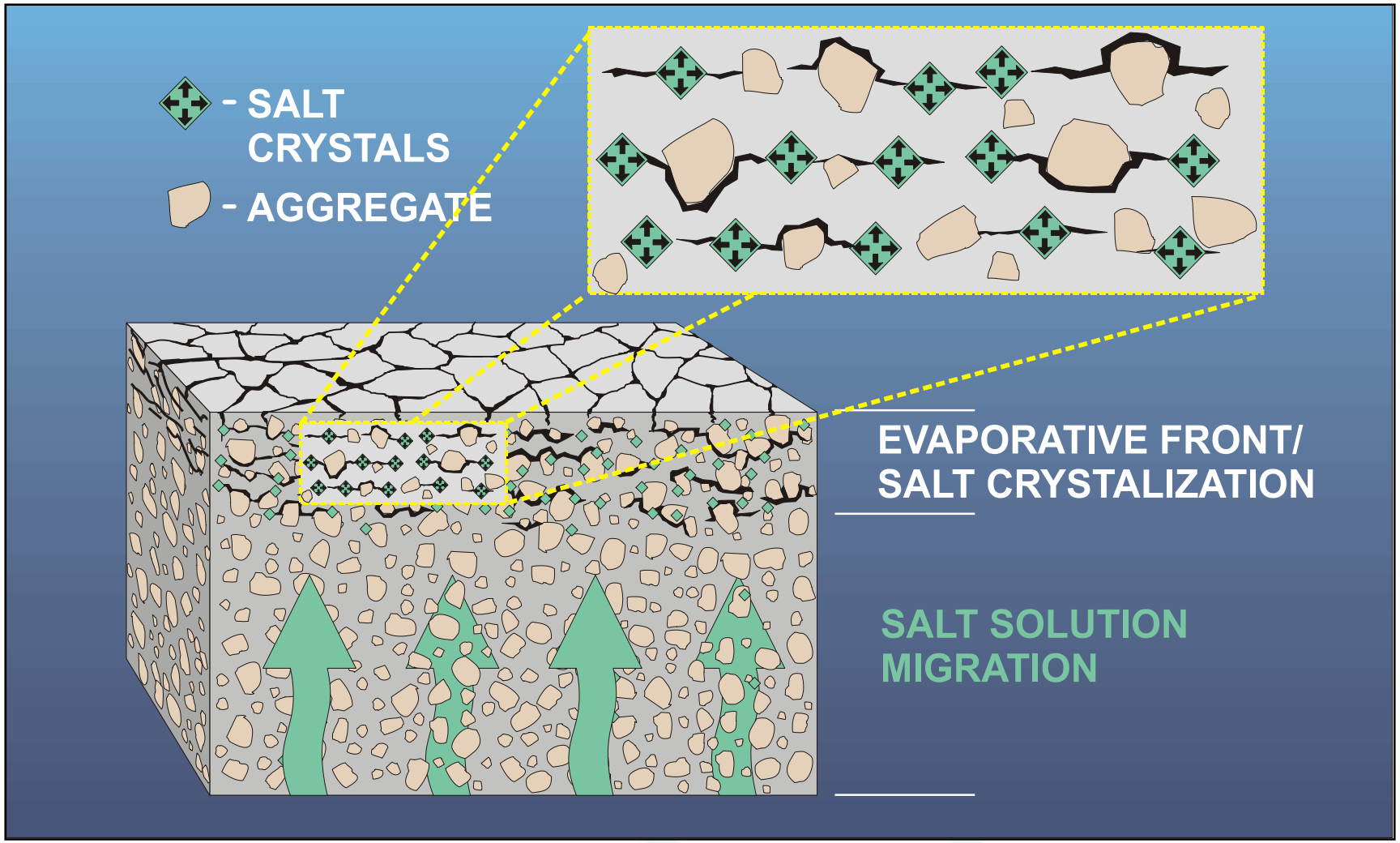
ACI Fall Convention
October 2016

NRMCA

For successful performance specification

- Need test procedure/criteria to select mixtures with desired resistance to
  - Chlorides
  - Freeze thaw
  - Sulfates
    - Physical salt attack (PSA)

Physical Salt Attack



Requirements for PSA

- No ASTM tests
- ACI 201
  - Recommends w/cm < 0.50 for PSA

Material Characteristics

Item	Type I	Type II	Type V1	Type V2	Slag Cement	Fly Ash
Cement Type	**I**	**II**	**V-1**	**V-2**	**SL**	**FA**
Silicon oxide (SiO_2), %	19.3	20.6	22.2	20.7	-	60.5
Aluminum oxide (Al_2O_3), %	5.9	5.0	3.7	4.4	11.8	29.1
Iron oxide (Fe_2O_3), %	1.9	3.2	4.1	4.0	-	2.9
Calcium oxide (CaO), %	62.3	62.8	64.7	64.8	-	0.7
Sulfur trioxide (SO_3), %	3.9	2.9	2.1	2.5	2.40	0
Total Alkali (as Na_2O eq), %	0.94	0.53	0.41	0.30	0.49	0.54
Tricalcium Silicate (C_3S), %	53	53	58	64	-	-
Dicalcium silicate (C_2S), %	16	-	20	11	-	-
Tricalcium Aluminate (C_3A), %	12	8	3	5	-	-
Tetracalcium Aluminoferrite (C_4AF), %	6	-	12	12	-	-

Mixture Proportions

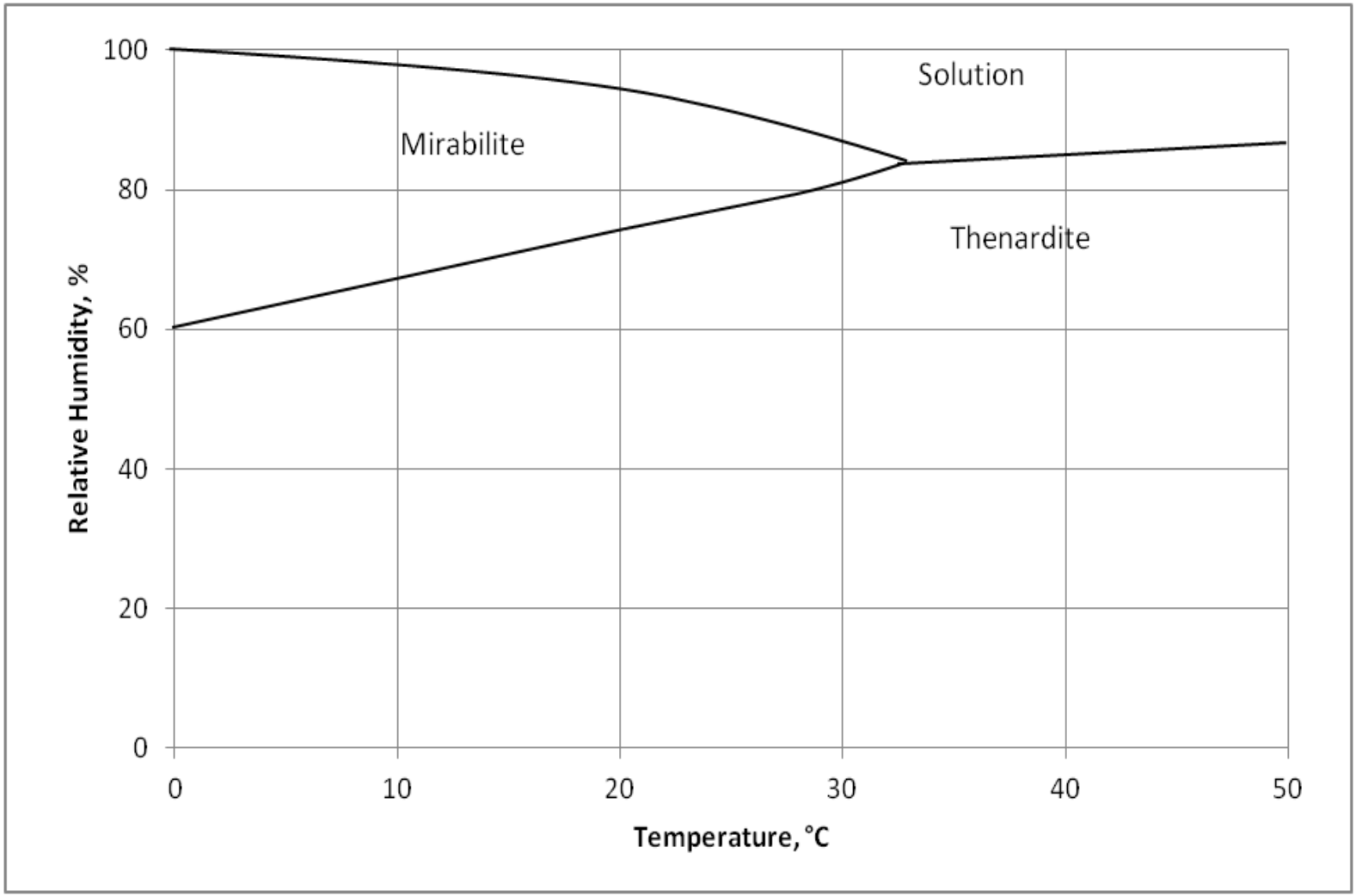
- ASTM C33 No. 57 crushed coarse aggregate
- ASTM C33 natural sand

- w/cm=0.40 to 0.60
- Type I, II, V-1, V-2
- Class F (15-30%), slag cement (25-50%)
- Non-air-entrained
- ASTM C494 Type A with 3 oz/cwt. (200 ml/100 kg)
- Type F varied for target slump of 4-7 in. (125-175 mm)

Tests Conducted

- Fresh properties, strength, RCPT, sorptivity, absorption
- PSA test
  - 3 x 3 x 11 ¼ in. prisms
  - Specimen moist cured for 28 d + 28 d air drying
  - Partial immersion (5 in.) in 10% sodium sulfate
  - Lab environment (73°F and 60% RH)
  - After 12 months started weekly cycling with hot room (100°F and 30% RH)
  - Temp and RH measured at 1 in. above surface

Sodium sulfate conversion

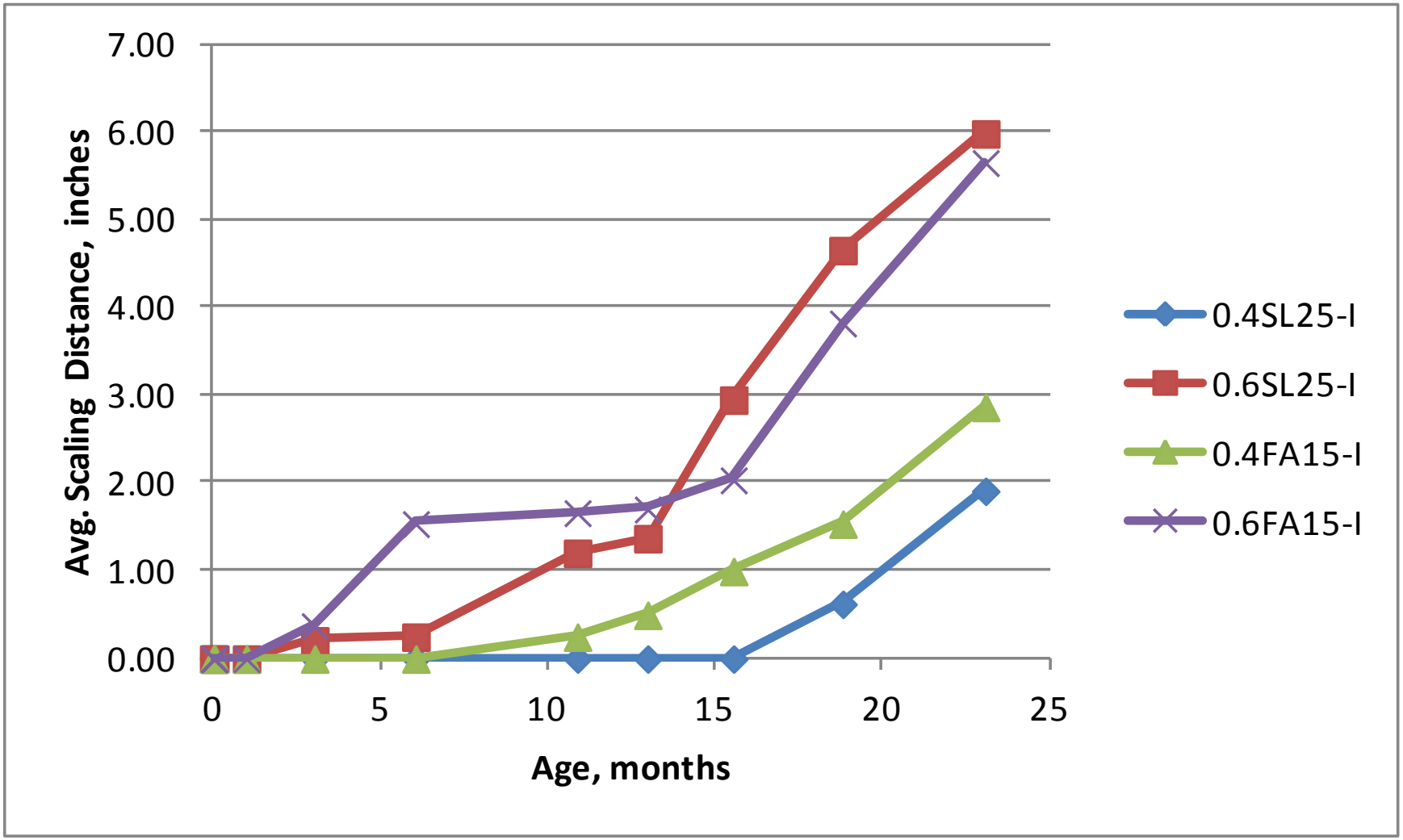


Test set up

Measurements

- Scaling distance
  - From solution surface upwards
- Scaling visual rating
- Mass loss

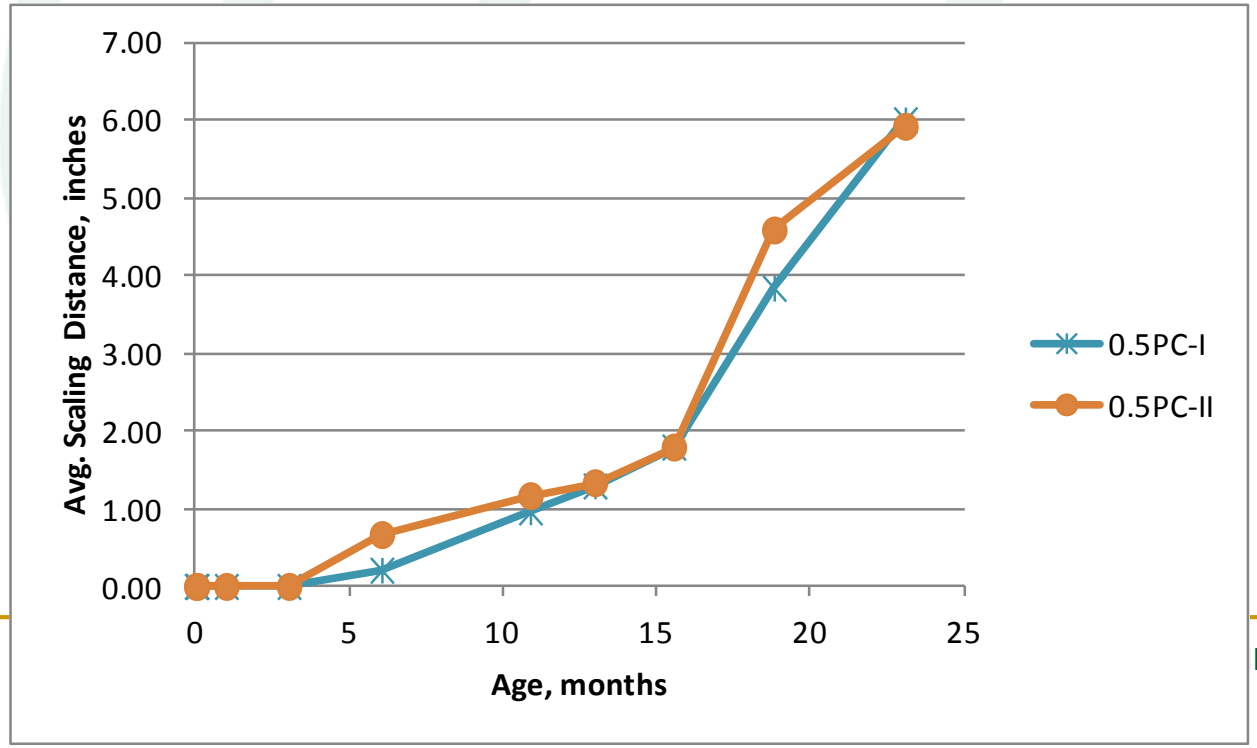
Results


7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Avg. Scaling Distance, inches
0
5
10
15
20
25
Age, months
0.4SL25-I
0.6SL25-I
0.4FA15-I
0.6FA15-I

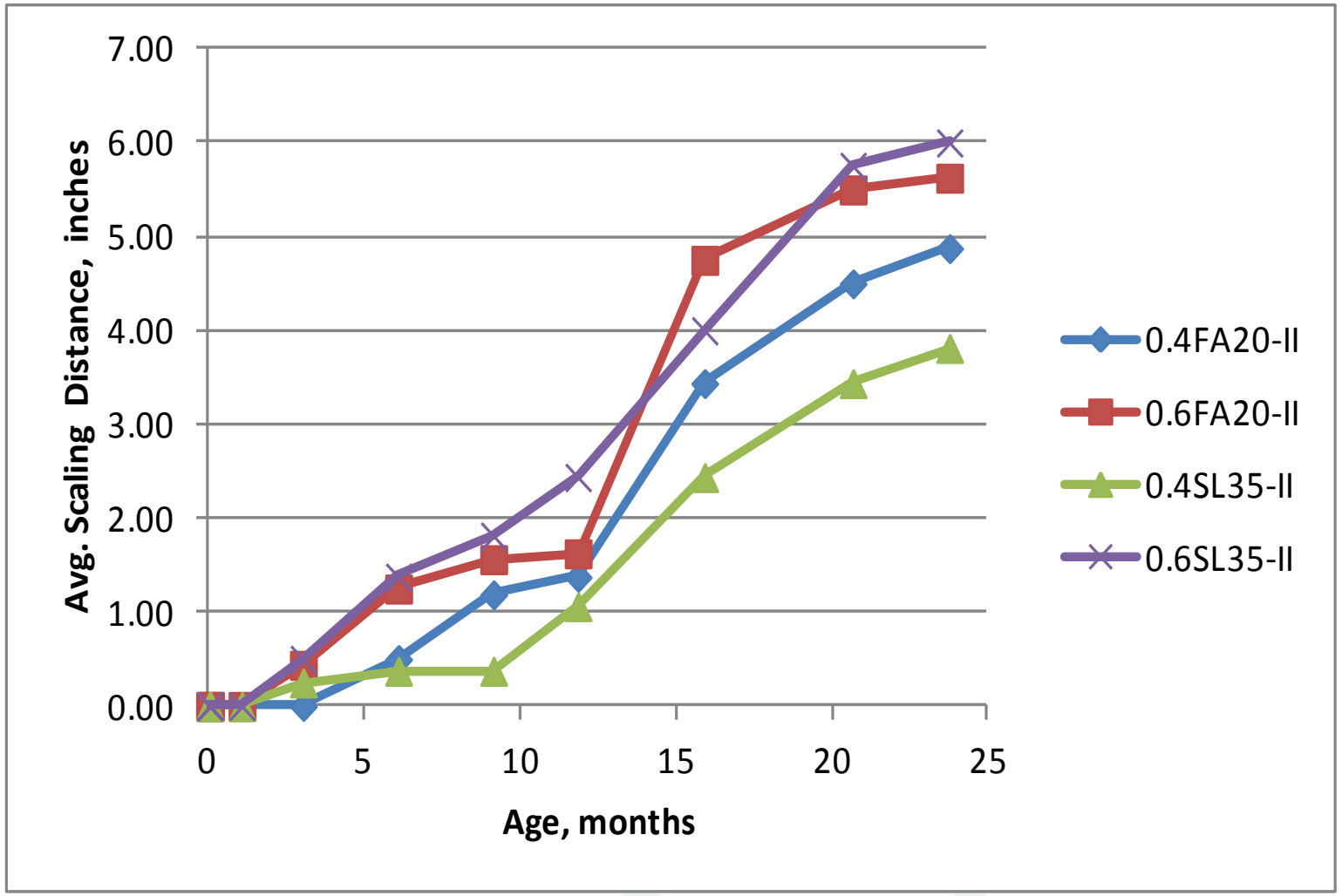

0.4SL25
0.6SL25
Terminated @ 23 months
3-4
3-5
3-6
0.4FA15
5-4
0.6FA15
7-4


0.5PC-I
Terminated @ 23 months
4-4
4-5
4-6

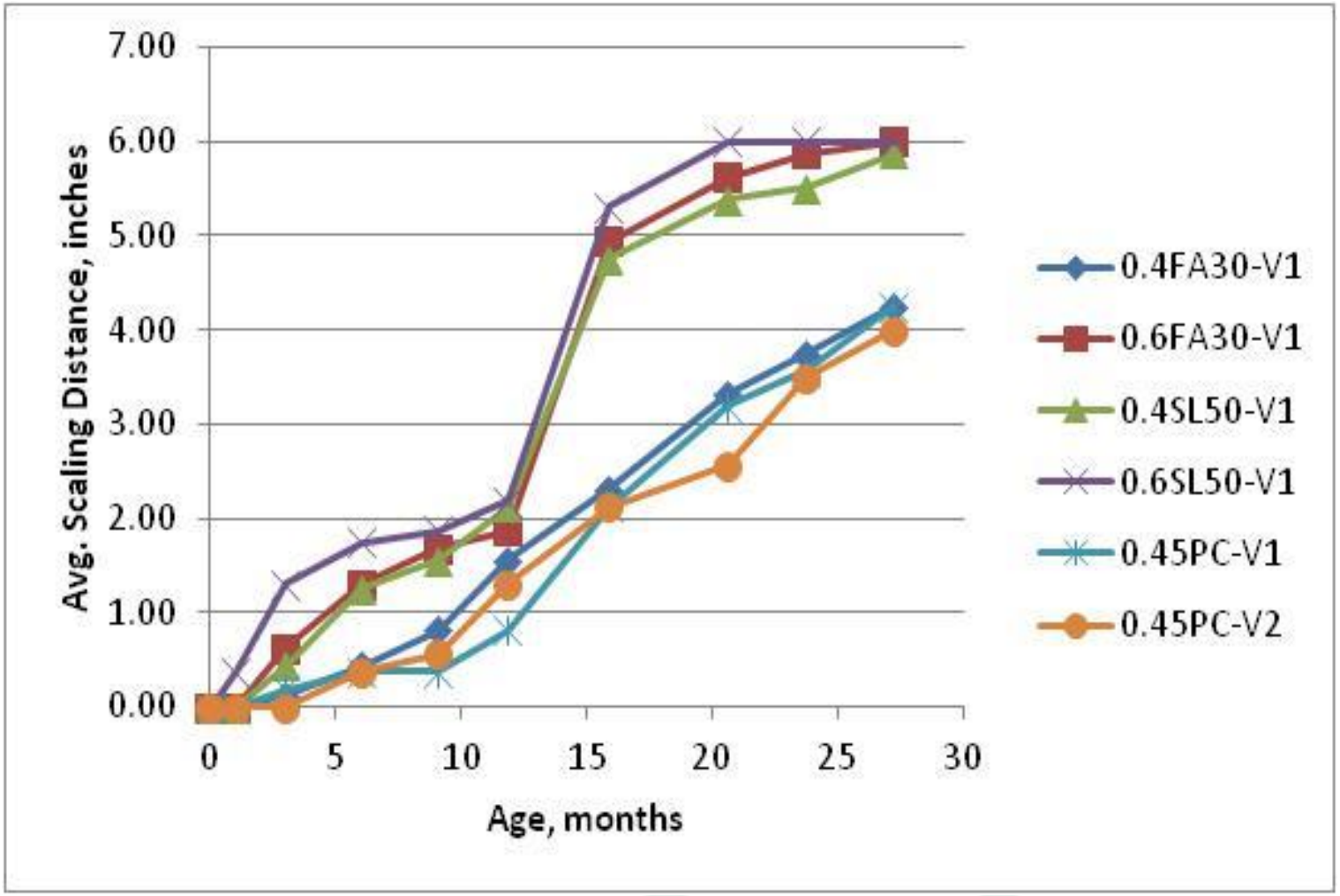

0.5PC-II
8-4

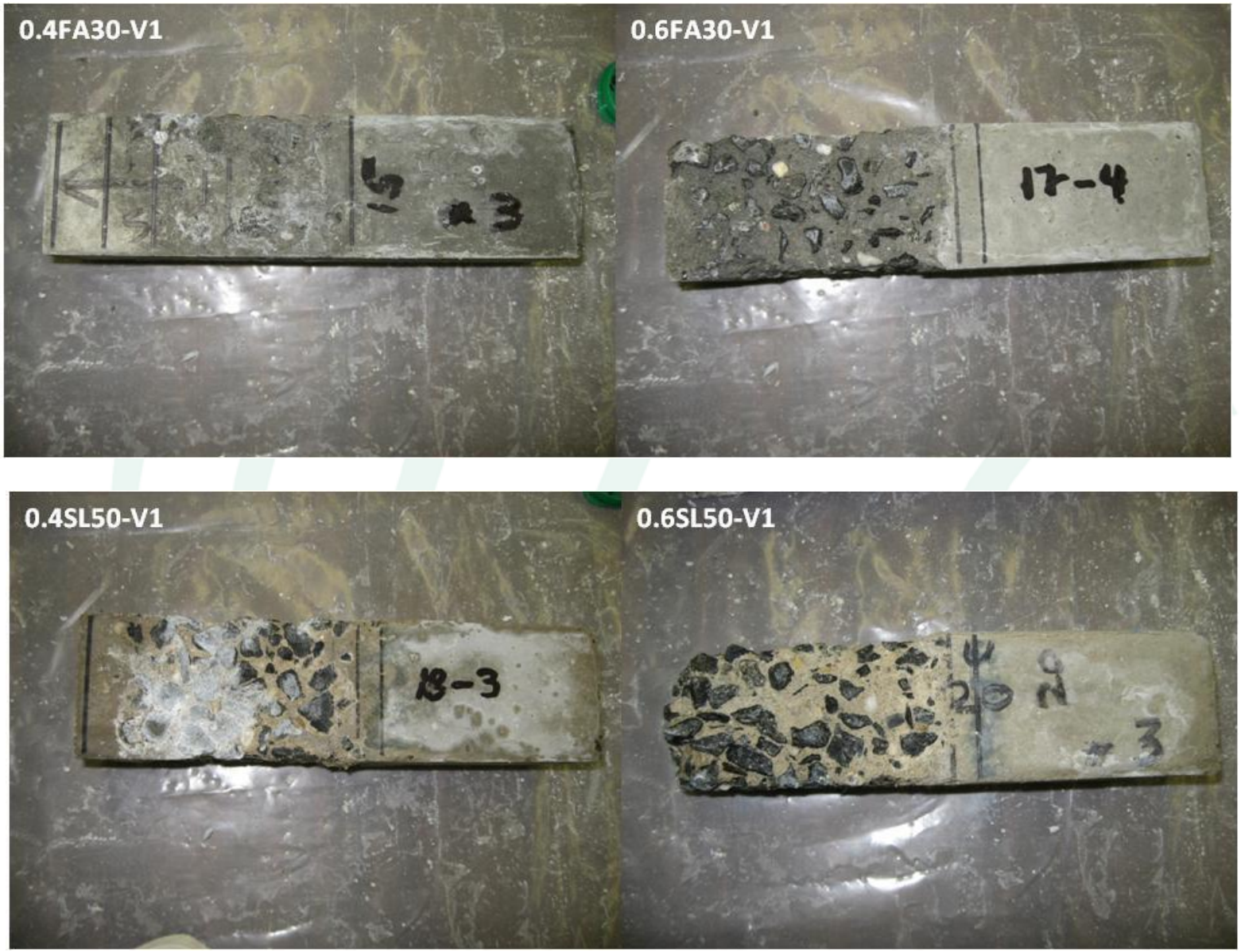

7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Avg. Scaling Distance, inches
0
5
10
15
20
25
Age, months
0.5PC-I
0.5PC-II

Results


7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Avg. Scaling Distance, inches
0
5
10
15
20
25
Age, months
0.4FA20-II
0.6FA20-II
0.4SL35-II
0.6SL35-II

Results

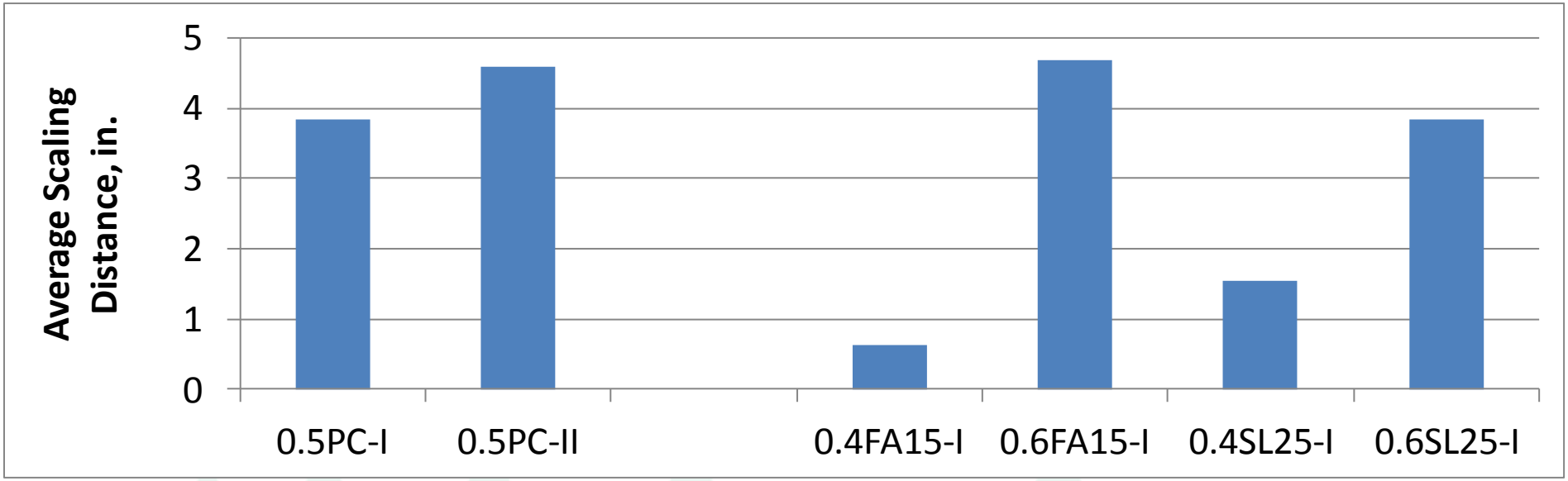

7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Avg. Scaling Distance, inches
0
5
10
15
20
25
30
Age, months
0.4FA30-V1
0.6FA30-V1
0.4SL50-V1
0.6SL50-V1
0.45PC-V1
0.45PC-V2

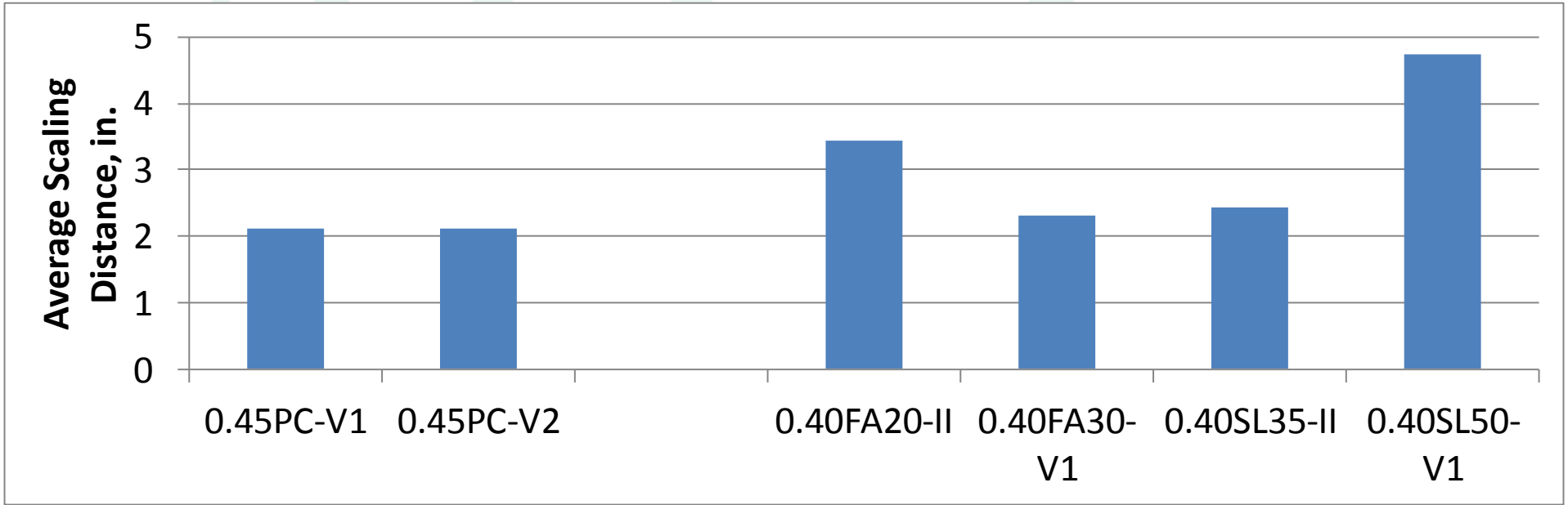

0.4FA30-V1
0.6FA30-V1
17-4
0.4SL50-V1
18-3
0.6SL50-V1


0.45PC-V1
21-3

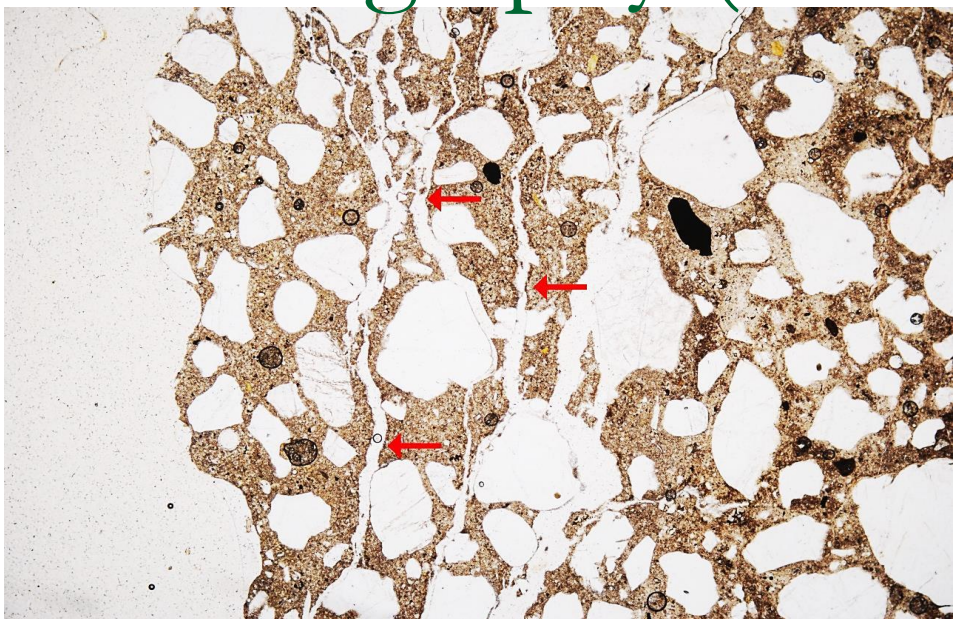

0.45PC-V2
22 3

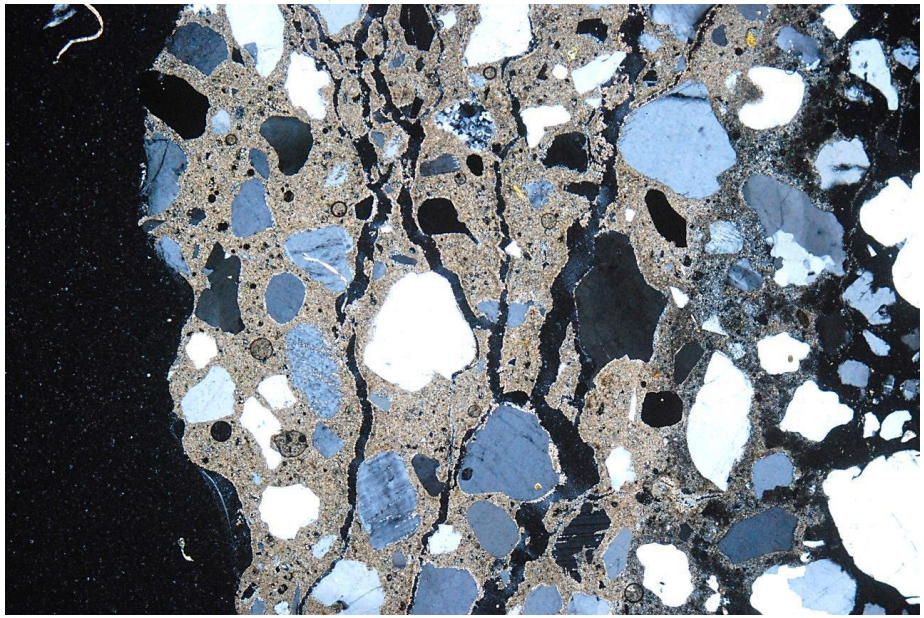
Effect of SCMs on PSA

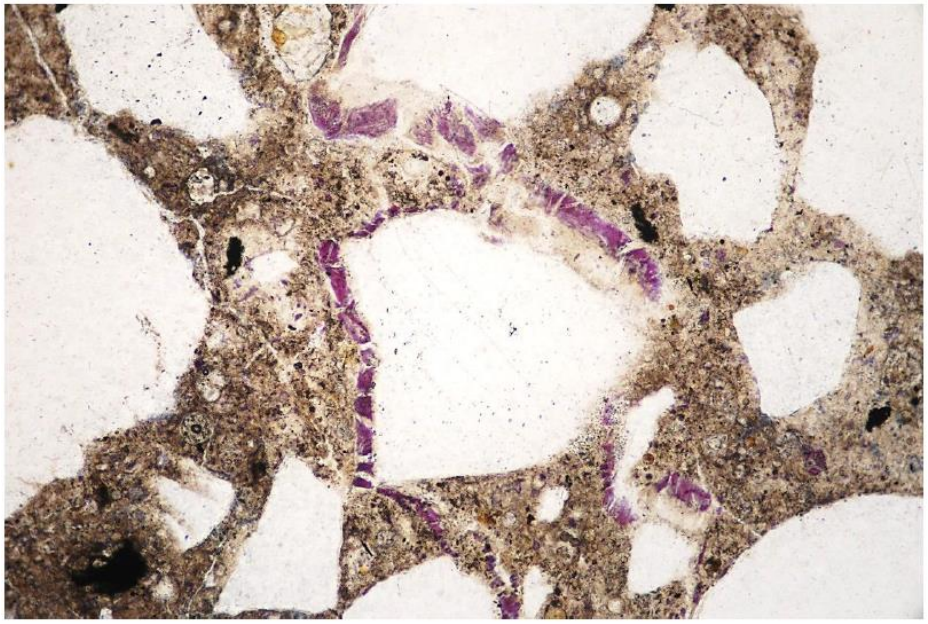


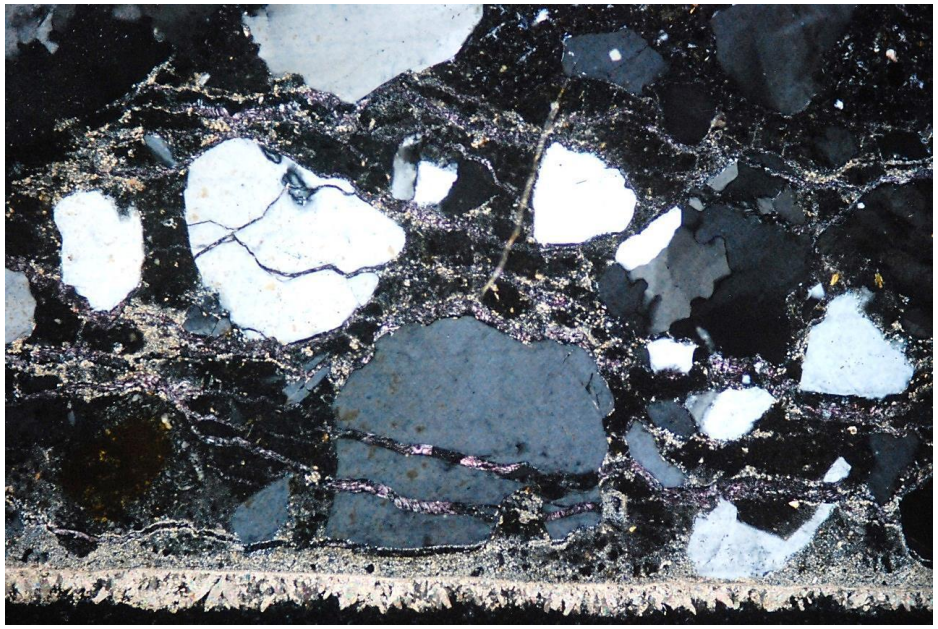


Petrography (Micro-chem)









Petrography (Micro-chem)

Stereomicroscope, thin section analysis

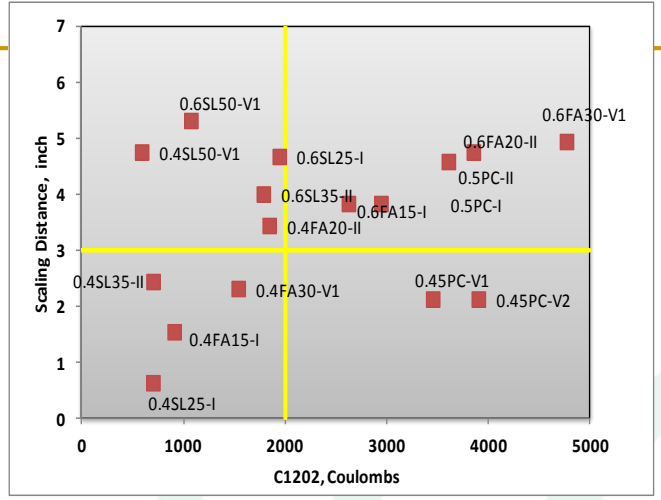
- Lesser secondary gypsum in exposed area
  - Scaling initiated by PSA
- Aggregate particles in exposed area cracked and degraded
  - Symptom of PSA

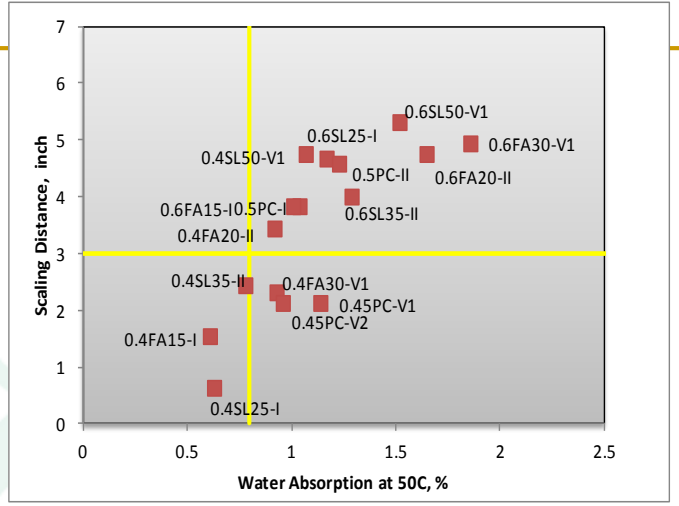
Resistance to PSA Categorization based on Scaling Distance

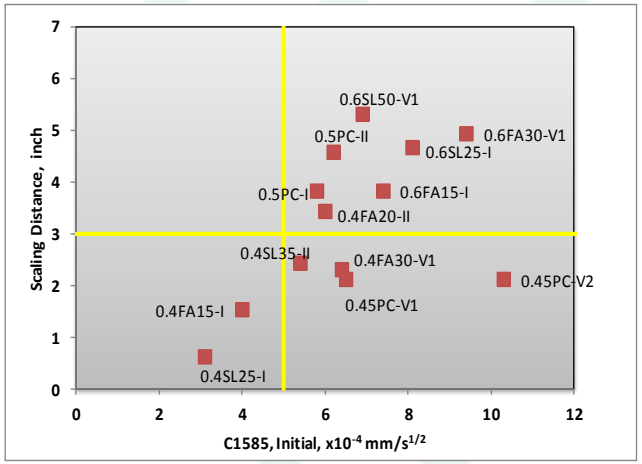
Resistance to Physical Salt Attack	Mixtures
Low	0.5PC-I, 0.5PC-II, 0.6FA15-I, 0.4FA20-II, 0.6FA20-II, 0.6FA30-V1, 0.4SL50-V1, 0.6SL25-I, 0.6SL35-II, 0.6SL50-V1
High	0.45PC-V1, 0.45PC-V2, 0.4FA15-I, 0.4FA30-V1, 0.4SL25-I, 0.4SL35-II

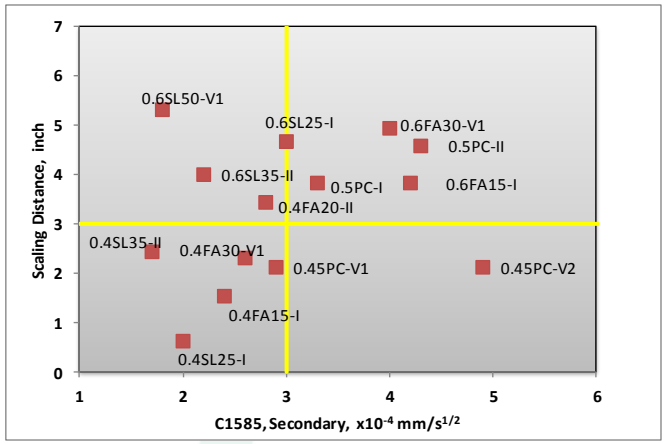
Low – 16 m scaling distance >3.0 in.

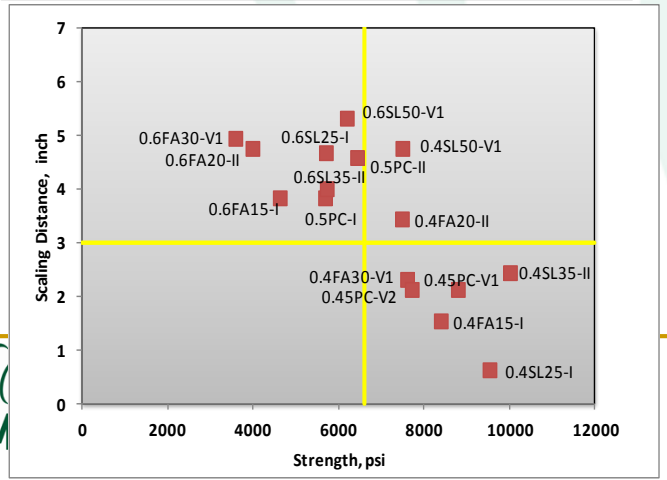
High – 16 m scaling distance ≤3.0 in.

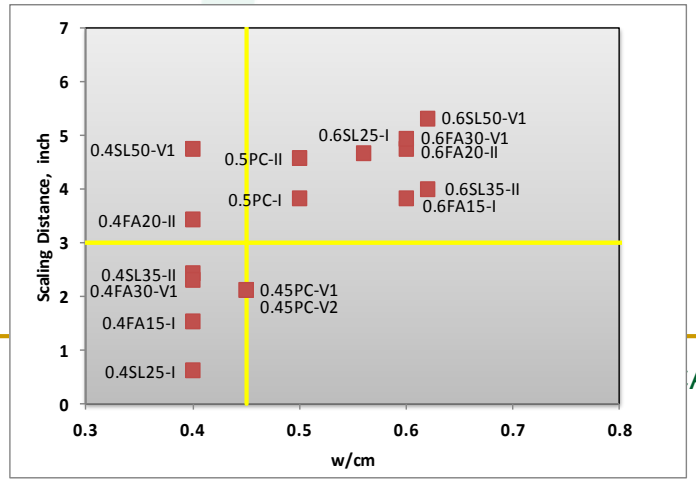

Scaling Distance, inch
C1202, Coulombs
0.6SL50-V1
0.4SL50-V1
0.6SL25-I
0.6FA30-V1
0.6FA20-II
0.5PC-II
0.6SL35-II
0.6FA15-I
0.5PC-I
0.4FA20-II
0.4SL35-II
0.4FA30-V1
0.45PC-V1
0.45PC-V2
0.4FA15-I
0.4SL25-I

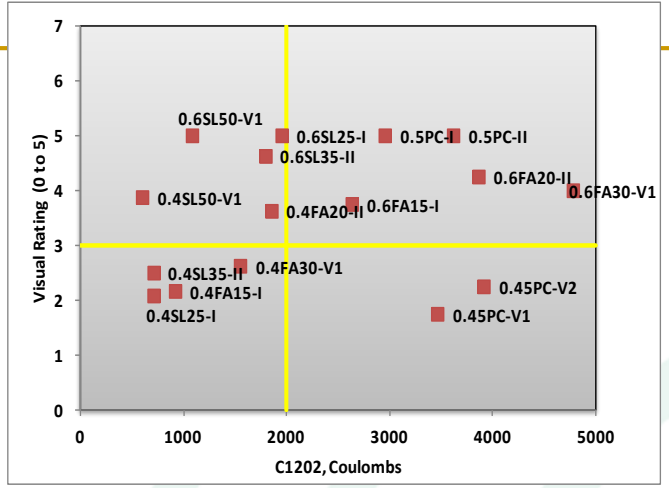

Scaling Distance, inch
Water Absorption at 50C, %
0.6SL50-V1
0.6SL25-I
0.4SL50-V1
0.6FA30-V1
0.5PC-II
0.6FA20-II
0.6FA15-I
0.5PC-I
0.6SL35-II
0.4FA20-II
0.4SL35-II
0.4FA30-V1
0.45PC-V1
0.45PC-V2
0.4FA15-I
0.4SL25-I

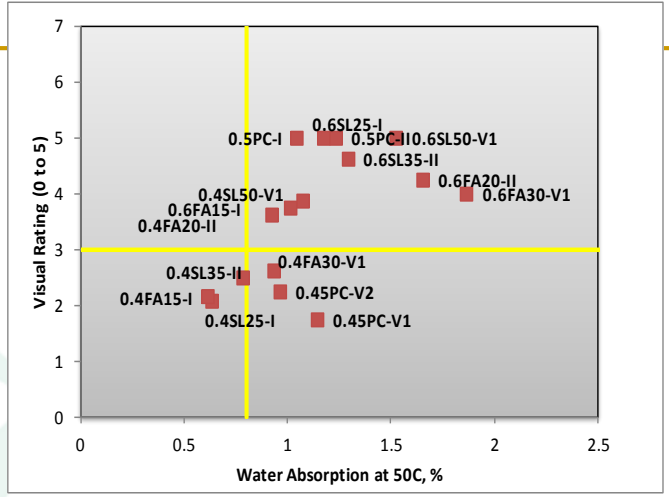

Scaling Distance, inch
C1585, Initial, x10-4 mm/s1/2
0.6SL50-V1
0.5PC-II
0.6FA30-V1
0.6SL25-I
0.5PC-I
0.6FA15-I
0.4FA20-II
0.4SL35-II
0.4FA30-V1
0.45PC-V2
0.45PC-V1
0.4FA15-I
0.4SL25-I

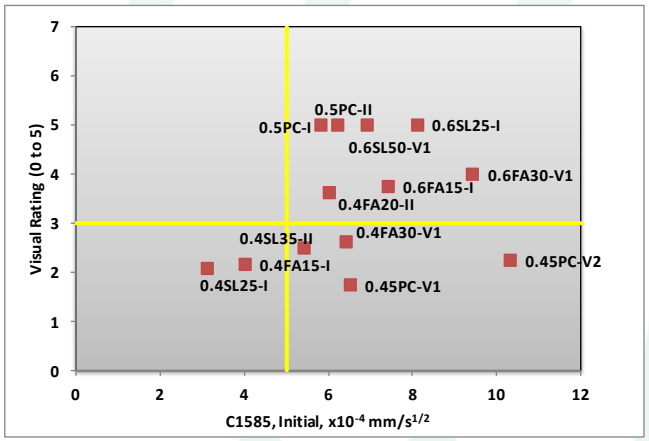

Scaling Distance, inch
C1585, Secondary, x10-4 mm/s1/2
0.6SL50-V1
0.6SL25-I
0.6FA30-V1
0.5PC-II
0.6SL35-II
0.5PC-I
0.6FA15-I
0.4FA20-II
0.4SL35-II
0.4FA30-V1
0.45PC-V1
0.45PC-V2
0.4FA15-I
0.4SL25-I

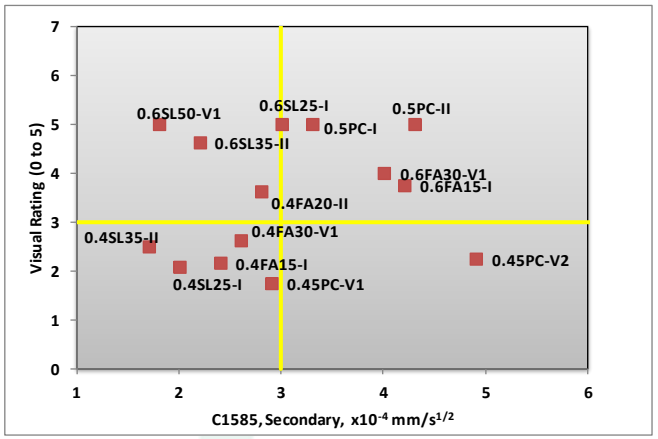

Scaling Distance, inch
Strength, psi
0.6SL50-V1
0.6FA30-V1
0.6SL25-I
0.4SL50-V1
0.6FA20-II
0.5PC-II
0.6SL35-II
0.6FA15-I
0.5PC-I
0.4FA20-II
0.4FA30-V1
0.45PC-V1
0.4SL35-II
0.45PC-V2
0.4FA15-I
0.4SL25-I

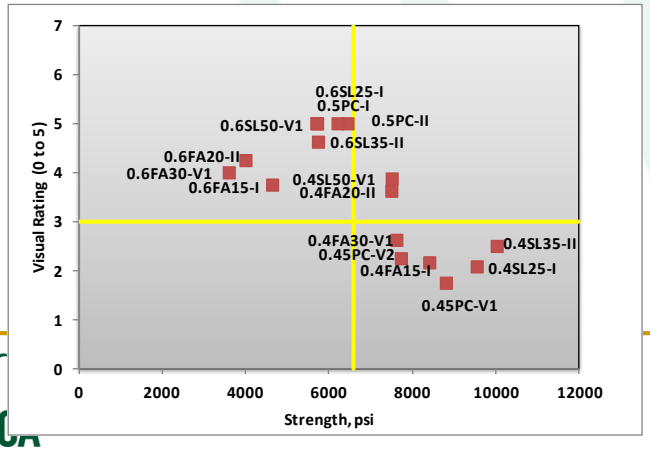

Scaling Distance, inch
w/cm
0.6SL50-V1
0.4SL50-V1
0.6SL25-I
0.6FA30-V1
0.5PC-II
0.6FA20-II
0.6SL35-II
0.5PC-I
0.6FA15-I
0.4FA20-II
0.4SL35-II
0.4FA30-V1
0.45PC-V1
0.45PC-V2
0.4FA15-I
0.4SL25-I

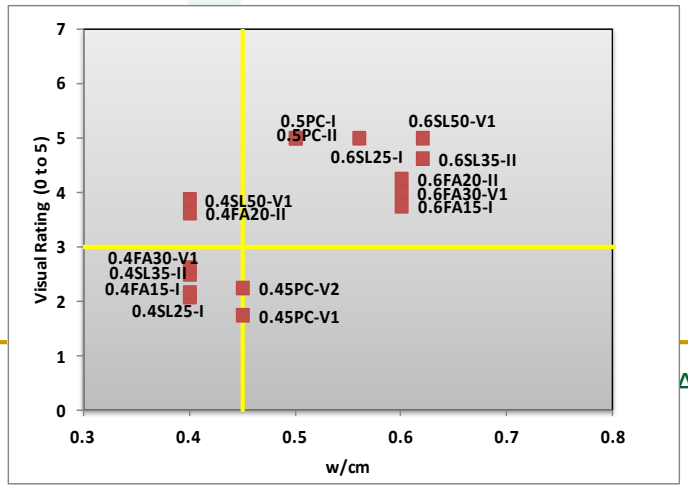

Visual Rating (0 to 5)
C1202, Coulombs
0.6SL50-V1
0.6SL25-I
0.5PC-I
0.5PC-II
0.6SL35-II
0.6FA20-II
0.6FA30-V1
0.4SL50-V1
0.4FA20-II
0.6FA15-I
0.4SL35-II
0.4FA30-V1
0.4FA15-I
0.4SL25-I
0.45PC-V2
0.45PC-V1


Visual Rating (0 to 5)
Water Absorption at 50C, %
0.6SL25-I
0.5PC-I
0.5PC-II
0.6SL50-V1
0.6SL35-II
0.6FA20-II
0.6FA30-V1
0.4SL50-V1
0.6FA15-I
0.4FA20-II
0.4FA30-V1
0.4SL35-II
0.4FA15-I
0.45PC-V2
0.4SL25-I
0.45PC-V1


Visual Rating (0 to 5)
C1585, Initial, x10-4 mm/s1/2
0.5PC-II
0.5PC-I
0.6SL25-I
0.6SL50-V1
0.6FA30-V1
0.6FA15-I
0.4FA20-II
0.4SL35-II
0.4FA30-V1
0.45PC-V2
0.4FA15-I
0.4SL25-I
0.45PC-V1


Visual Rating (0 to 5)
C1585, Secondary, x10-4 mm/s1/2
0.6SL50-V1
0.6SL25-I
0.5PC-II
0.5PC-I
0.6SL35-II
0.6FA30-V1
0.6FA15-I
0.4FA20-II
0.4SL35-II
0.4FA30-V1
0.45PC-V2
0.4FA15-I
0.4SL25-I
0.45PC-V1


Visual Rating (0 to 5)
Strength, psi
0.6SL25-I
0.5PC-I
0.6SL50-V1
0.5PC-II
0.6SL35-II
0.6FA20-II
0.6FA30-V1
0.6FA15-I
0.4SL50-V1
0.4FA20-II
0.4FA30-V1
0.4SL35-II
0.45PC-V2
0.4FA15-I
0.4SL25-I
0.45PC-V1


Visual Rating (0 to 5)
w/cm
0.5PC-I
0.5PC-II
0.6SL50-V1
0.6SL25-I
0.6SL35-II
0.6FA20-II
0.6FA30-V1
0.6FA15-I
0.4SL50-V1
0.4FA20-II
0.4FA30-V1
0.4SL35-II
0.4FA15-I
0.45PC-V2
0.4SL25-I
0.45PC-V1

Suggested criteria for PSA

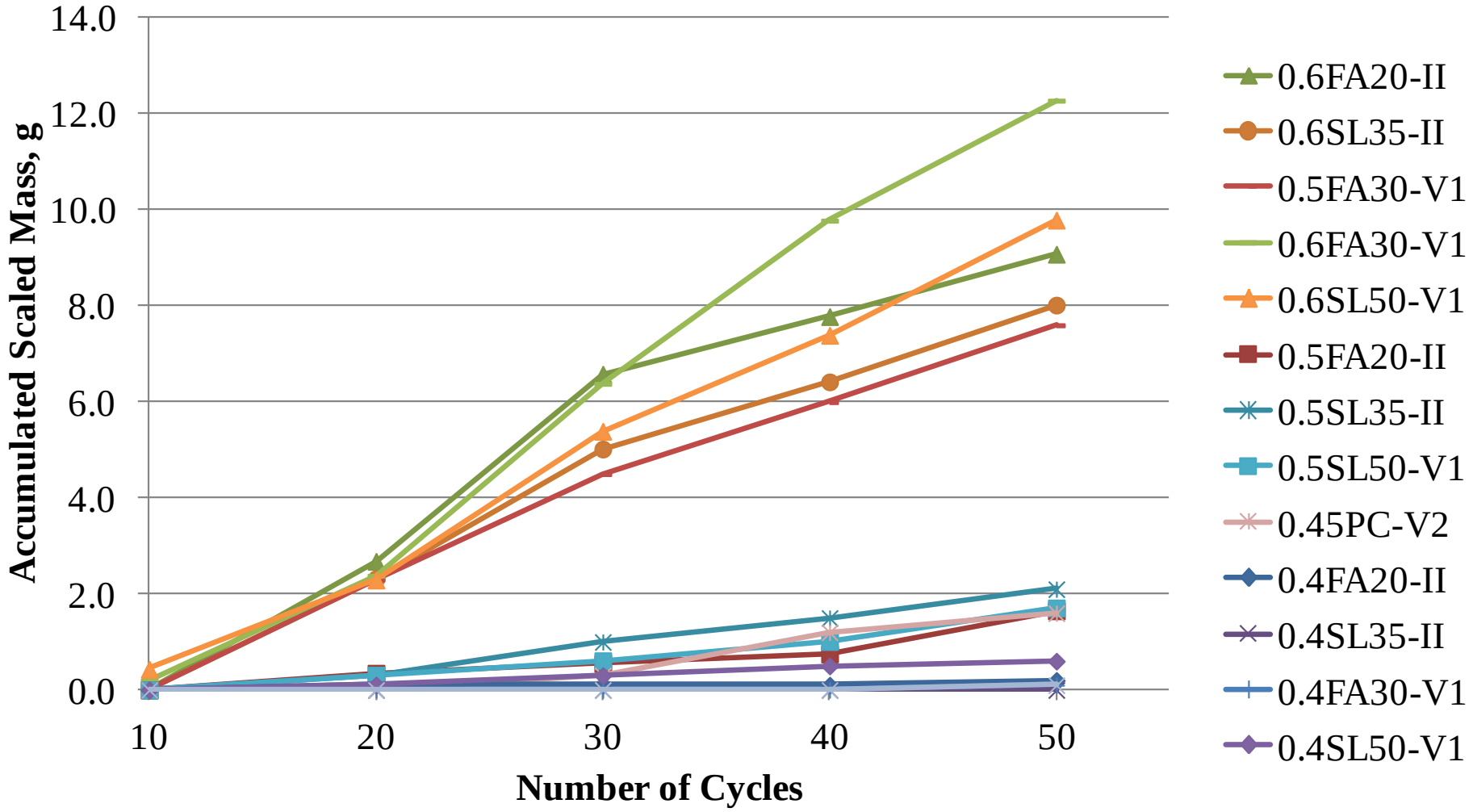
Resistance to Physical Salt Attack	Prescriptive option	Performance Option, psi
High	w/cm ≤ 0.45	Compressive Strength ≥ 4500*

*for air entrained concrete. For non-air-entrained concrete increase by 20%

An accelerated PSA test

- Daily cycling (16h in 73°F/80% RH and 8h in 100°F/30% RH)
  - Tested 4x8 in. cylinders
  - Partial immersion in 3 in. of 10% Na_2SO_4 solution
  - Accumulated scaled mass, scaling distance, visual rating every 10 cycles – 50 cycles

Results


14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Accumulated Scaled Mass, g
10
20
30
40
50
Number of Cycles
0.6FA20-II
0.6SL35-II
0.5FA30-V1
0.6FA30-V1
0.6SL50-V1
0.5FA20-II
0.5SL35-II
0.5SL50-V1
0.45PC-V2
0.4FA20-II
0.4SL35-II
0.4FA30-V1
0.4SL50-V1

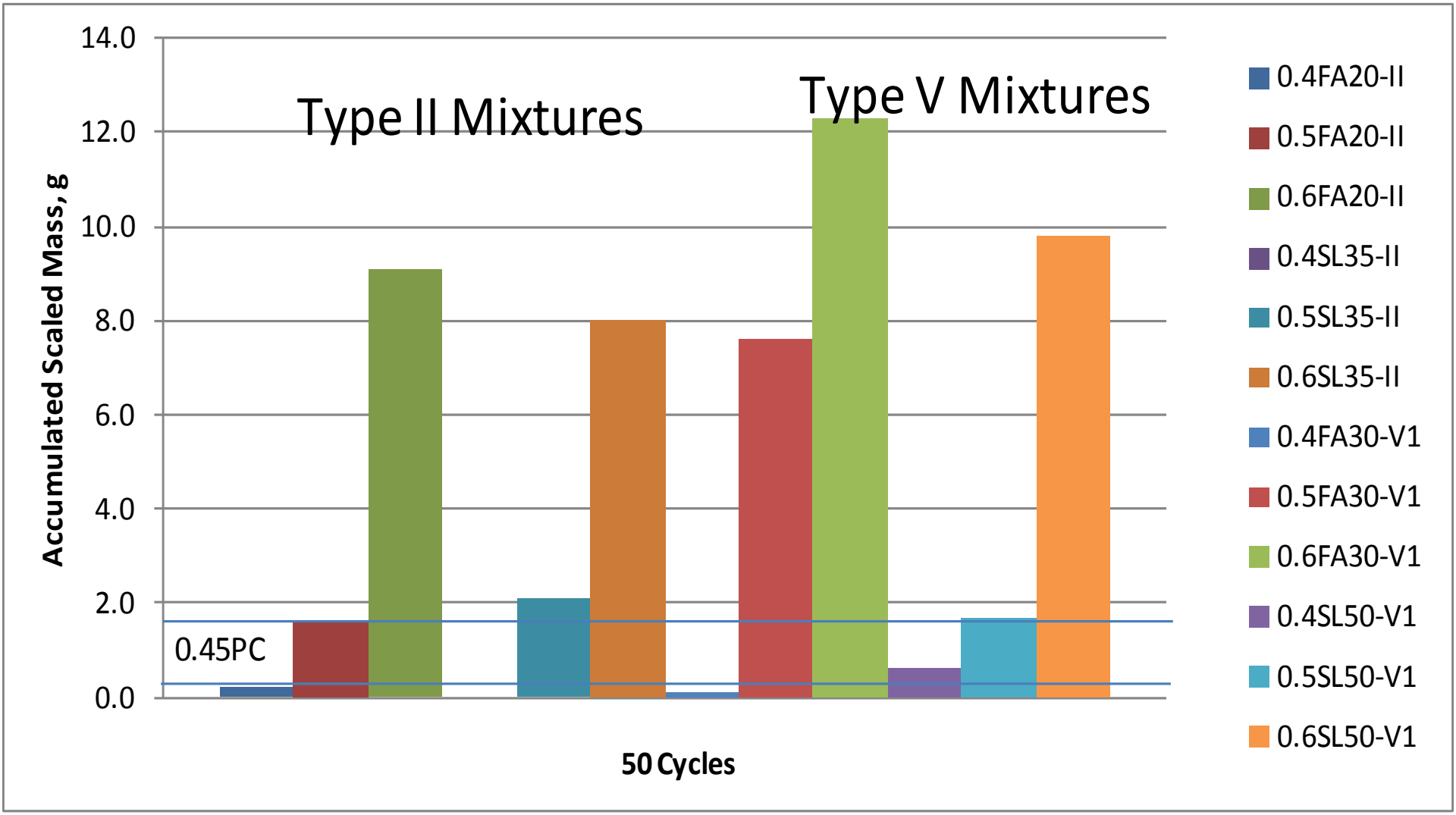

0.6FA20-II
Mix 11
@50 cycles

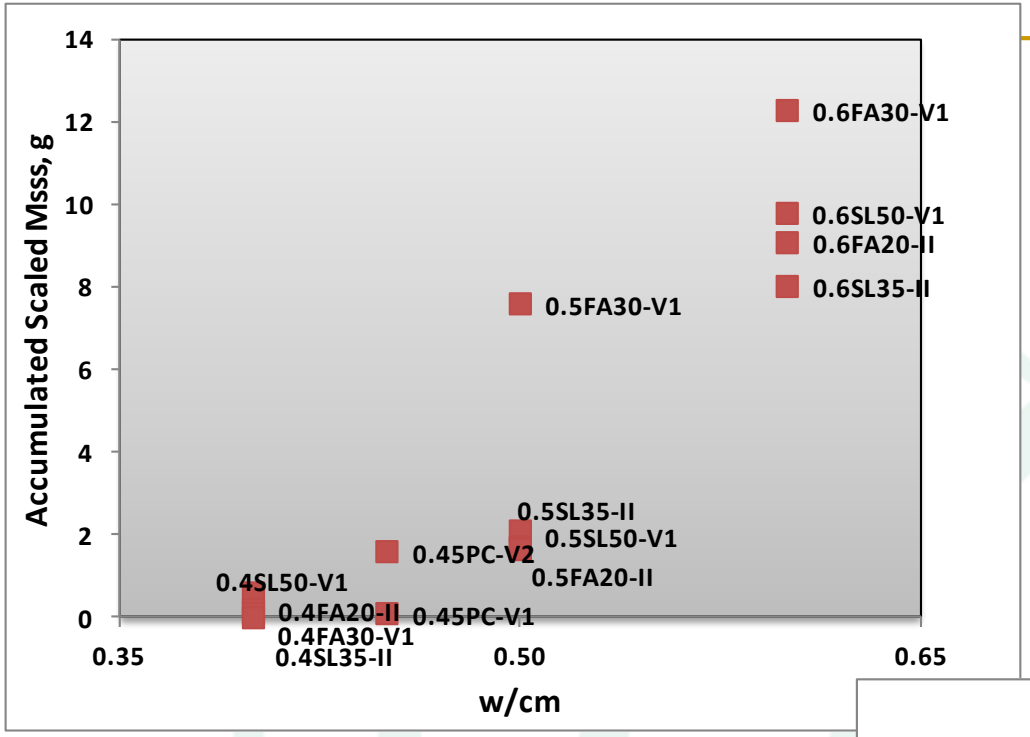

0.6SL35-II
14
Mix 14
@50 cycles

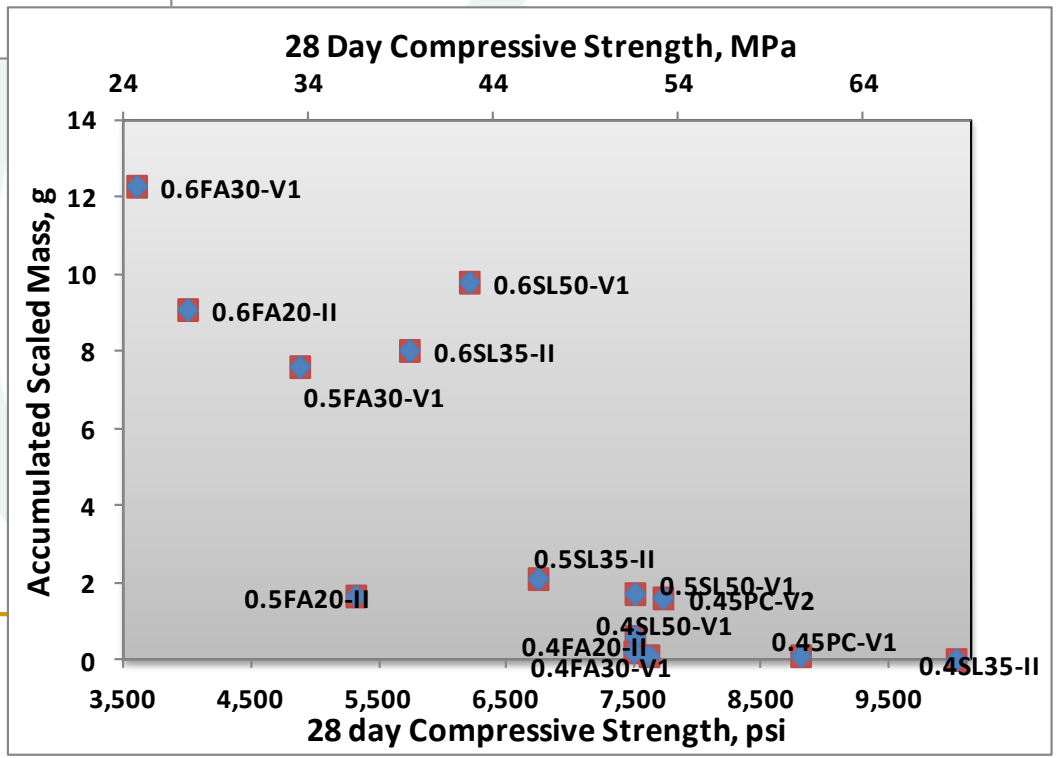

0.4FA20-II
9
Mix 9
@50 cycles


0.4SL35-II
Mix 12
@50 cycles

Results


Type II Mixtures
Type V Mixtures
Accumulated Scaled Mass, g
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.45PC
50 Cycles
0.4FA20-II
0.5FA20-II
0.6FA20-II
0.4SL35-II
0.5SL35-II
0.6SL35-II
0.4FA30-V1
0.5FA30-V1
0.6FA30-V1
0.4SL50-V1
0.5SL50-V1
0.6SL50-V1


Accumulated Scaled Msss, g
14
12
10
8
6
4
2
0
0.35
0.50
0.65
w/cm
0.6FA30-V1
0.6SL50-V1
0.6FA20-II
0.6SL35-II
0.5FA30-V1
0.5SL35-II
0.5SL50-V1
0.45PC-V2
0.5FA20-II
0.4SL50-V1
0.4FA20-II
0.45PC-V1
0.4FA30-V1
0.4SL35-II


28 Day Compressive Strength, MPa
24
34
44
54
64
Accumulated Scaled Mass, g
14
12
10
8
6
4
2
0
3,500
4,500
5,500
6,500
7,500
8,500
9,500
28 day Compressive Strength, psi
0.6FA30-V1
0.6SL50-V1
0.6FA20-II
0.6SL35-II
0.5FA30-V1
0.5SL35-II
0.5SL50-V1
0.45PC-V2
0.5FA20-II
0.4SL50-V1
0.4FA20-II
0.45PC-V1
0.4FA30-V1
0.4SL35-II

NRMCA

Conclusions

- Mixtures with high resistance to PSA
  - W/CM < 0.45 or f'_c > 4500 psi
- Cement types, SCMs did not greatly impact resistance to PSA
- Accelerated PSA test procedure (50 days) shows promise
  - Results consistent with 2 year test

Thank you