Practical Implementation of Internally Cured Slag Cement Concrete Using Superabsorbent Polymers

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Outline

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- Summary

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MOTIVATION

The growing demand for sustainable construction is driving innovative solutions aimed at enhancing the **durability** and **service life** of concrete infrastructure by improving the microstructure quality through **internal curing**.

Superabsorbent polymers (SAPs) are one such innovations, which create reservoirs in concrete that provides additional water for **optimum hydration** within the cement matrix.

❖ **Internal curing.**

- relies on the controlled release of water within concrete to enhance

✓ **Cement hydration,**

✓ **Mitigate self desiccation** [1].

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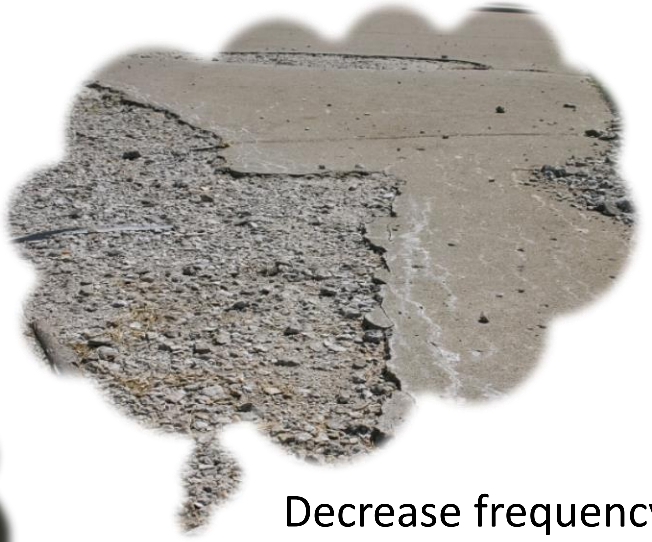
Durable concrete usage helps;

Decrease CO_2 emissions and energy consumption



Decrease frequency of replacement of existing structures

Increase return on investment

Reduce maintenance costs

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Dry SAP

Wet SAP

Superabsorbent polymers (SAPs) popularly known as **hydrogels**, are cross-linked polymers with capability of absorbing large volume of fluid in comparison to its own mass, forming insoluble gel [2].

They act as;

✓ **Internal water reservoirs**

✓ Alternative to pre-wetted lightweight aggregates (LWA) for **internal curing** purposes.

Benefits:

✓ **Improve hydration**

✓ **Reduce moisture gradient**

- Mitigate **durability** challenges in cementitious systems
  - Drying and autogenous shrinkage,
  - Scaling resistance (by improving strength and minimizing near-surface drying)
  - Improve quality of microstructure (reduce chloride permeability, etc.)

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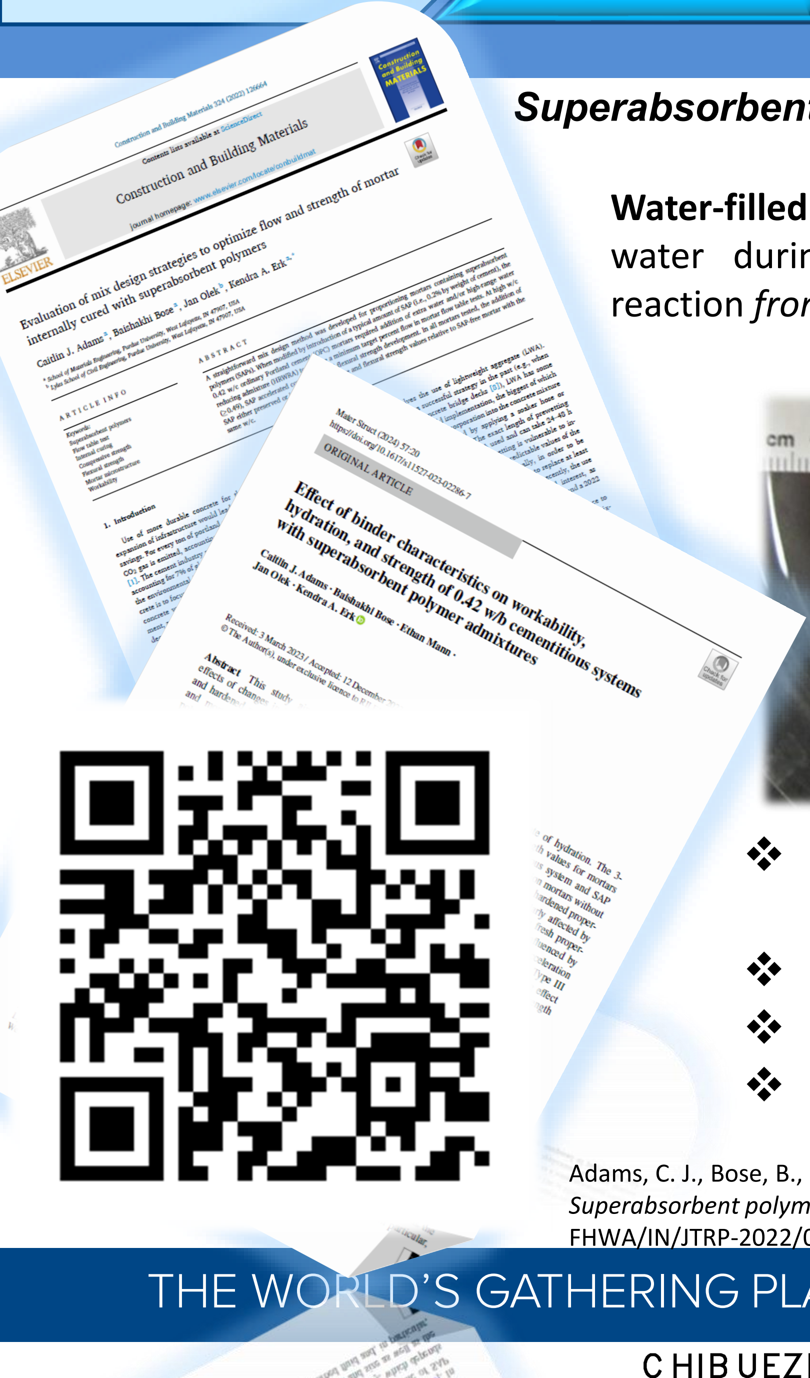
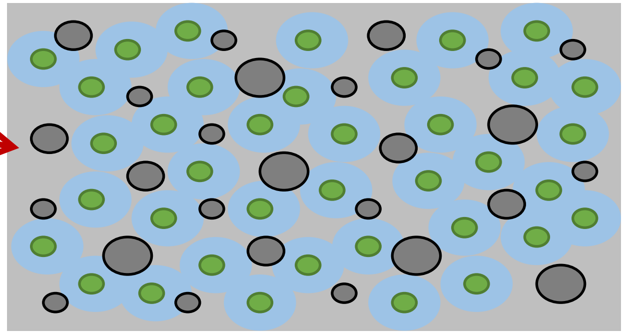
Superabsorbent polymers (SAPs) as internal curing agents



Water-filled SAP particles (“hydrogels”) release water during curing to fuel the hydration reaction *from the inside*.

Output

- ✓ Absorption capacity of SAP in cement mortar
- ✓ When in the mixing sequence should SAP be added
- ✓ Is extra water required to maintain workability of mortar using SAP.
- ✓ Effect of extra water on mechanical properties of SAP mortar [5].



- ❖ Comparable or improved mechanical properties
- ❖ Reduces autogenous shrinkage
- ❖ Improves hydrations [1]
- ❖ Increases durability [6],[7]

Adams, C. J., Bose, B., Mann, E., Erk, K. A., Behnood, A., Castillo, A., Rodriguez, F. B., Wang, Y., & Olek, J. (2022). *Superabsorbent polymers for internally cured concrete* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2022/04). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317366

Project Goal

To determine how **delivery method** and **mixture composition** influence the curing performance of concrete containing a commercial SAP formulation and **Type IL cement slag-cement**, and colloidal **nanosilica.**

Research Objectives

1. Evaluate the **internal curing performance** of commercial SAP in concrete mixtures containing Type IL cement as well as slag-cement, and colloidal nanosilica.

2. Develop and evaluate practical field **implementation strategies** to successfully deliver and disperse SAP in concrete mixtures.

3. Conduct field trials to compare the **strength** and **durability** of SAP-containing mixtures with mixtures cured with curing compound.

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Dissolvable bag enclosed in an outer, **water-proof plastic bag** *(outer bag removed before the dissolvable bag introduced to the mixer)*

Packaged SAP particles

Approx. 1 lb. of dry SAP is needed for 1 cu. yd. class C concrete (**0.2% SAP by weight of binder**)

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LABORATORY EXPERIMENTS

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Cement
Type IL

Coarse Aggregate
(25 mm – 2.36 mm)

Superabsorbent polymer
Polyacrylamide-based particles
Dry diameter < **300 µm**

CONCRETE

Slag Cement
Grade 100

Admixtures

Potable Water

Fine Aggregates
(4.75mm – 75µm)

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Evaluate the impact of SAP delivery method, on fresh properties, mechanical and durability properties of SAP-modified concrete.

Mix Design

No.	Mix Description	w/b ratio	Cement (kg/m3)	Coarse Agg. (kg/m3)	Fine Agg (kg/m3)	Water (kg/m3)	Slag (kg/m3)	SAP (kg/m3)	HRWRA (mL/100kg)	AEA (mL/100kg)
1	**Reference**	0.44	390.39	1007.36	706.57	171.77			-	50
2	**Ref+SAP_DB**	0.44	390.39	1007.36	706.57	171.77			-	50
3	**Ref+SAP_DP**	0.44	390.39	1000.36	706.57	171.77		0.78	400	50
4	**Ref+S+SAP_DB**	0.44	273.27	1000.36	706.57	171.77	117.12	0.78	400	50
5	**Ref+S+SAP_DP**	0.44	273.27	1000.36	706.57	171.77	117.12	0.78	400	50

Abbreviation	Meaning
DB	Dissolvable Bag
DP	Direct Pour

Target Slump and Air Content

Slump (inches)	Air Content (%)
3 - 5	5 - 8

Dissolvable Bags

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Slump and Air Content

Mix Description	Slump (inches)	Air Content (%)
REF	7.0	7.0
REF+SAP_DP	4.5	7.5
REF+SAP_DB	5.0	6.5
REF+S+SAP_DP	4.75	6.6
REF+S+SAP_DB	4.75	7.5

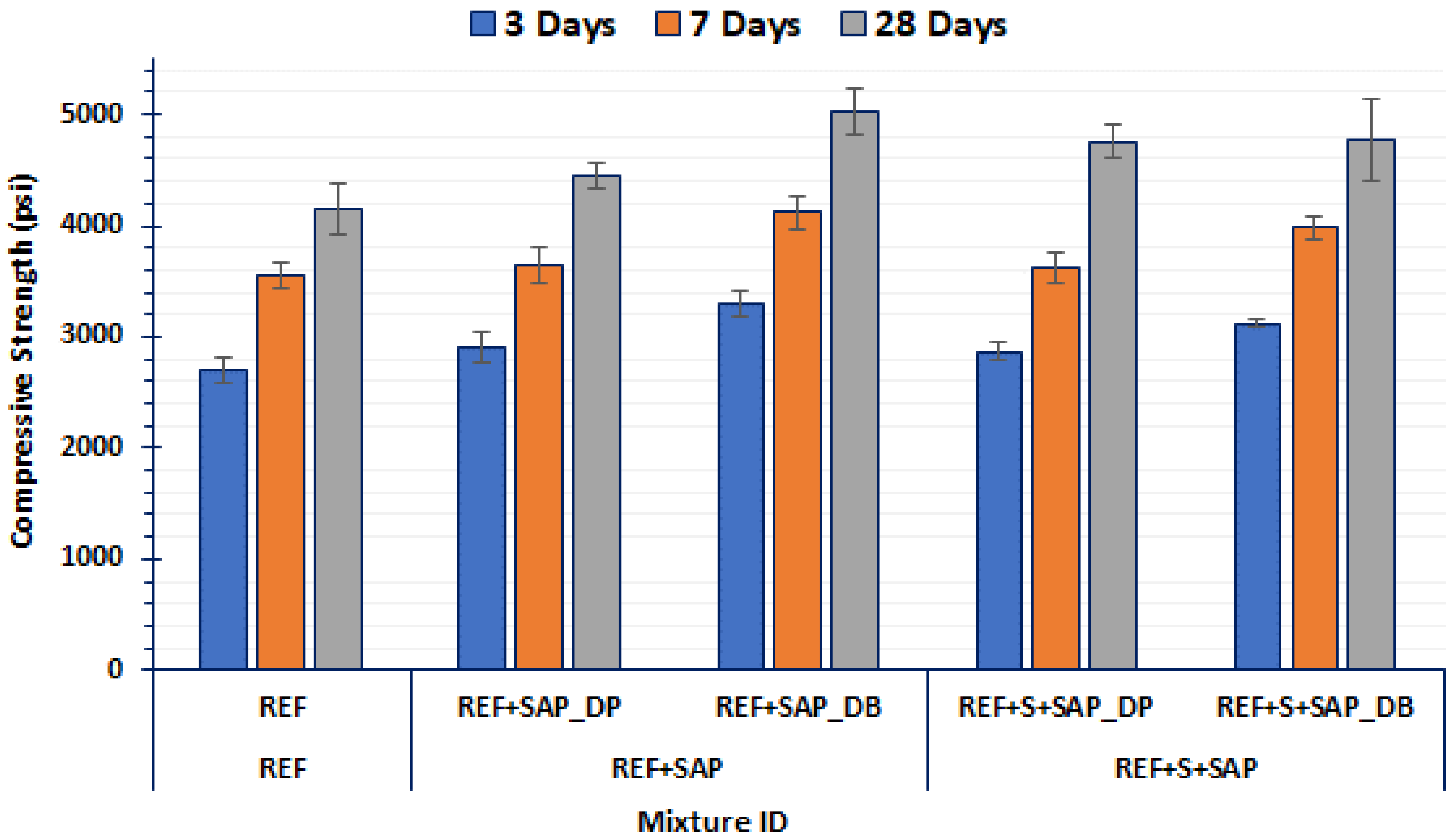
REF+SAP_DP

REF+SAP_DB

REF+S+SAP_DP

REF+S+SAP_DB

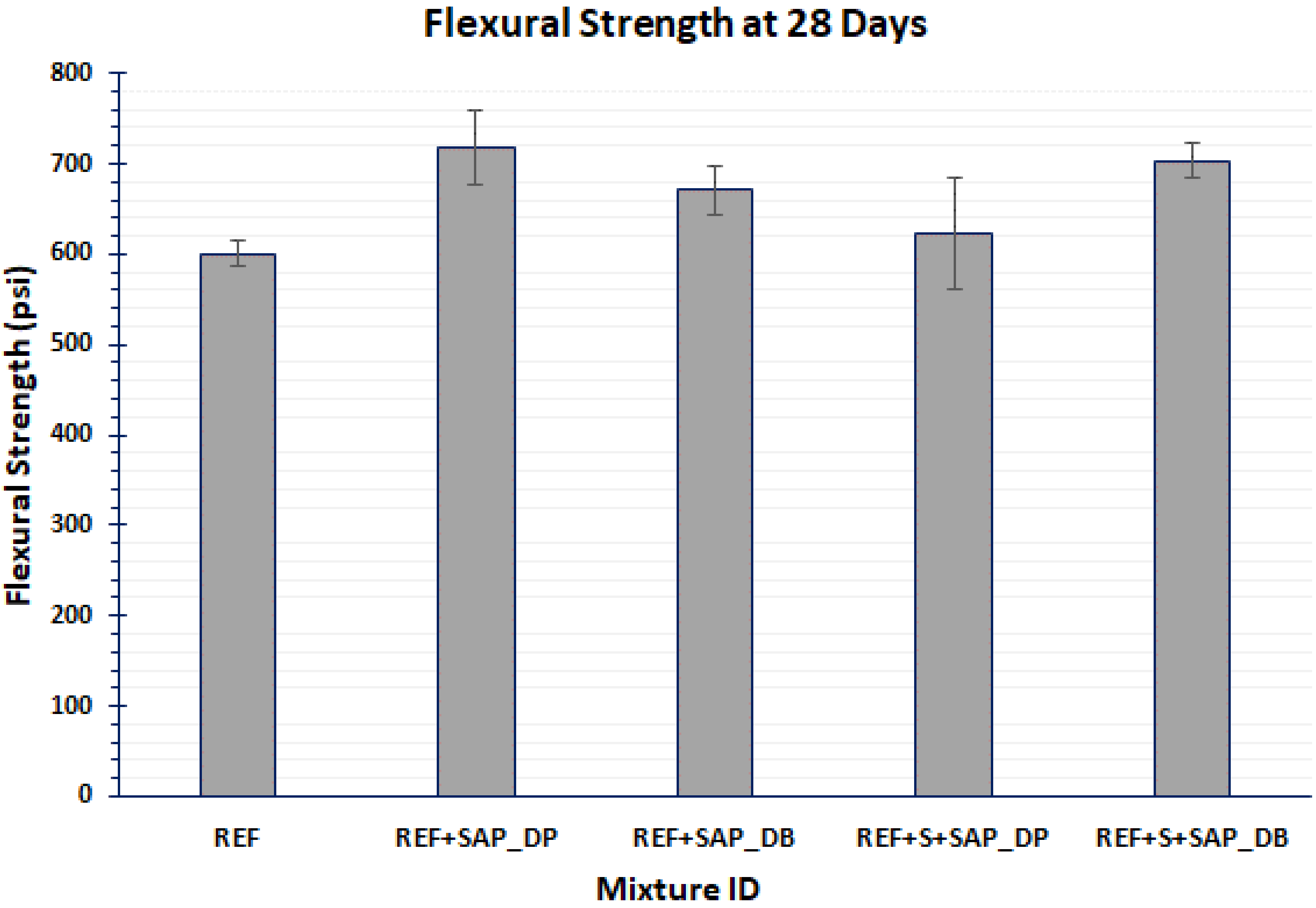
Compressive Strength



Compressive Strength Ranges:

- **3 Days:** 2700 – 3300 psi
- **7 Days:** 3550 – 4120 psi
- **28 Days:** 4160 – 5025 psi

Flexural Strength



Flexural Strength Range:

28 Days: 600 – 720 psi

- ***Direct addition of SAP (DP)*** into the concrete mixtures resulted to increased flexural strength of **20%** while SAP addition using dissolvable bags increased the strength value by 12% at 28 days

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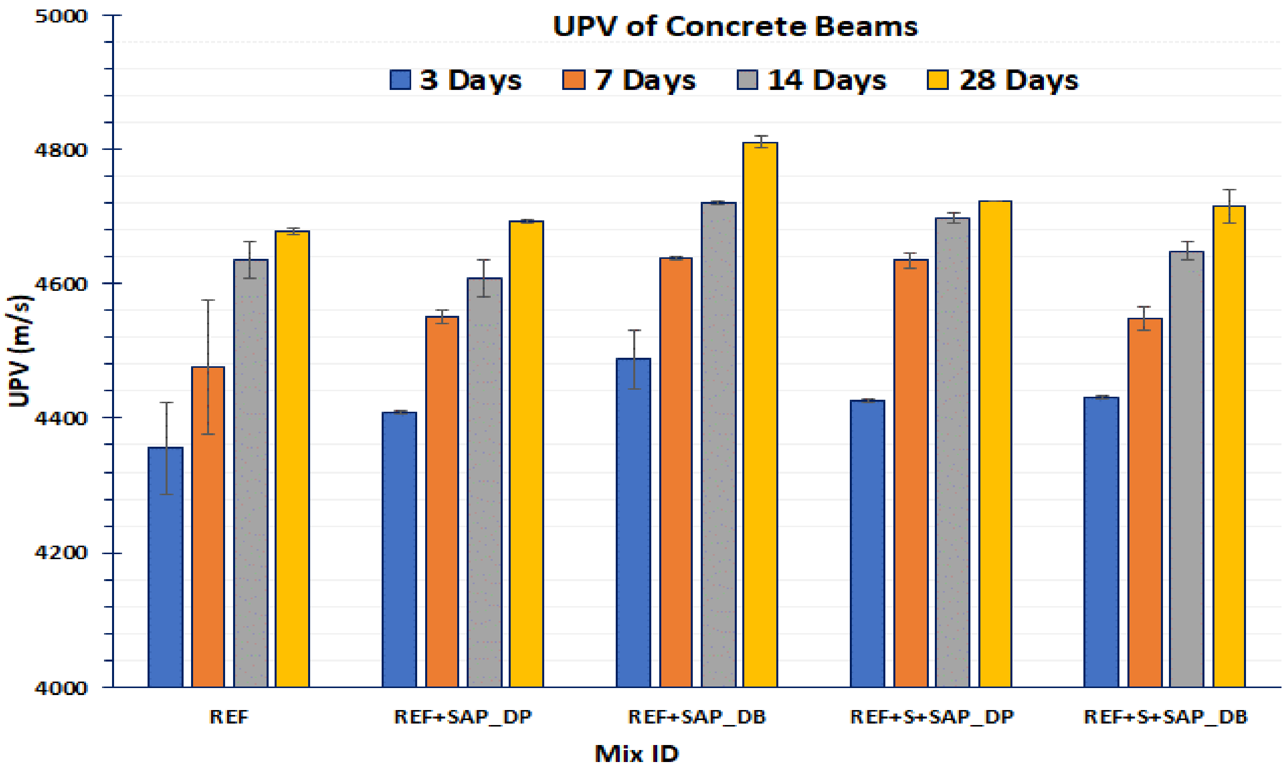
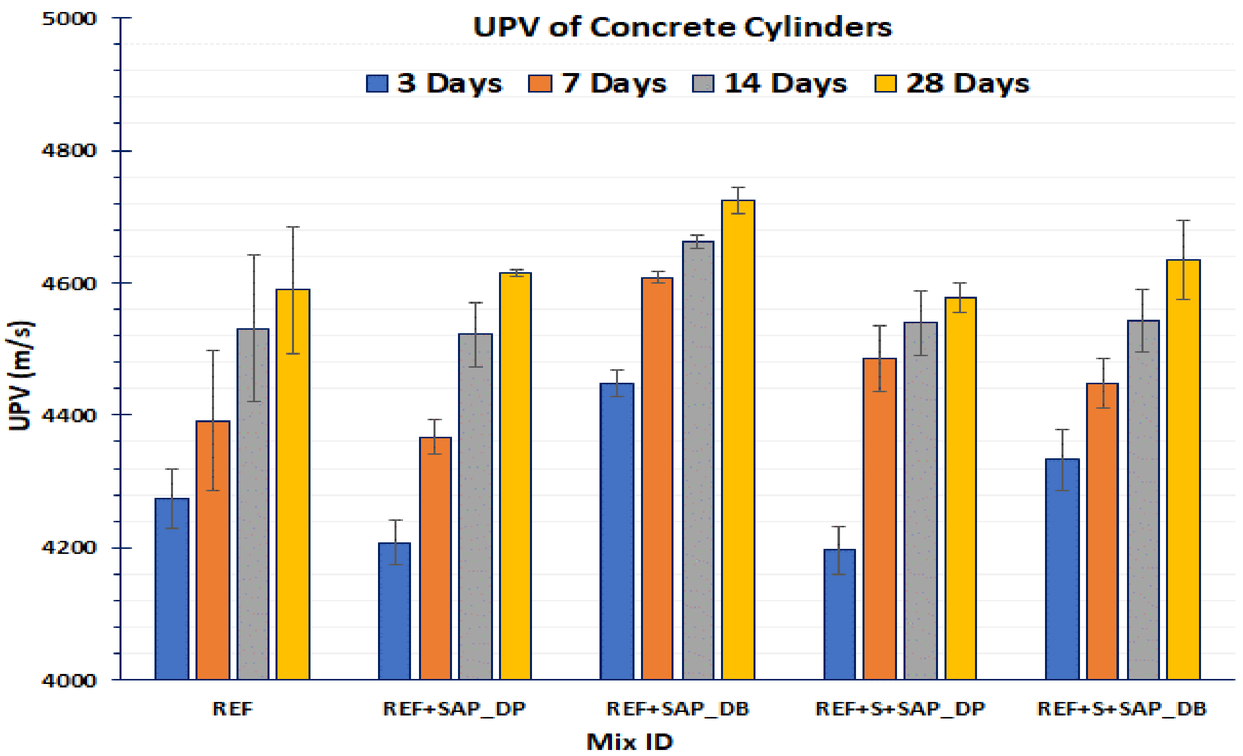
Ultrasonic Pulse Velocity (UPV)





Ultrasonic Pulse Velocity (UPV) (m/s)		
Age (Days)	4” x 4” x 16” Beams	4” x 8” Cylinders
3	4430 – 4490	4200 - 4450
7	4480 – 4635	4370 – 4610
14	4635 – 4720	4520 – 4660
28	4680 – 4800	4580 – 4725

Dynamic Elastic Modulus, E (ASTM C597-22
Standard Test Method for Ultrasonic Pulse Velocity through Concrete

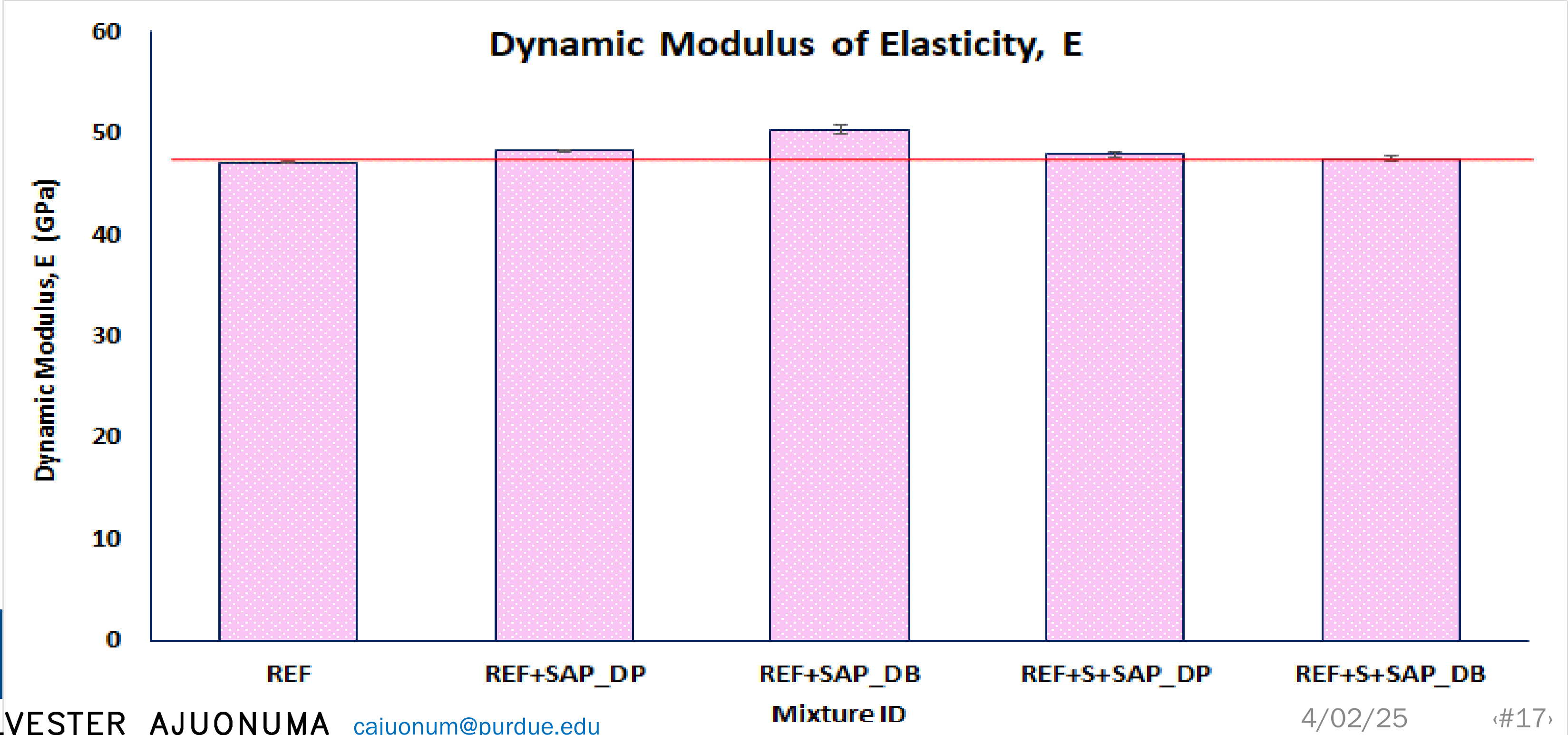
5.1 The ultrasonic pulse velocity, V, of longitudinal ultrasonic stress waves in a concrete mass is related to its elastic properties and density according to the following relationship:

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad (1)$$

where:

E = dynamic modulus of elasticity,
μ = dynamic Poisson's ratio, and
ρ = density.

	UPV	Resonant Frequency (Flexure)	
Mix Description	Dynamic Modulus of Elasticity, E	Dynamic Modulus of Elasticity, E	Shear Modulus of Elasticity, G
	GPa	GPa	GPa
REF	47.07	33.72	15.68
REF+SAP_DP	48.25	36.73	17.08
REF+SAP_DB	50.29	38.14	17.74
REF+S+SAP_DP	47.84	36.52	16.99
REF+S+SAP_DB	47.42	35.51	16.52



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Dynamic Elastic Modulus, E (ASTM E1876-22)

Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's ratio by Impulse Excitation of Vibration.

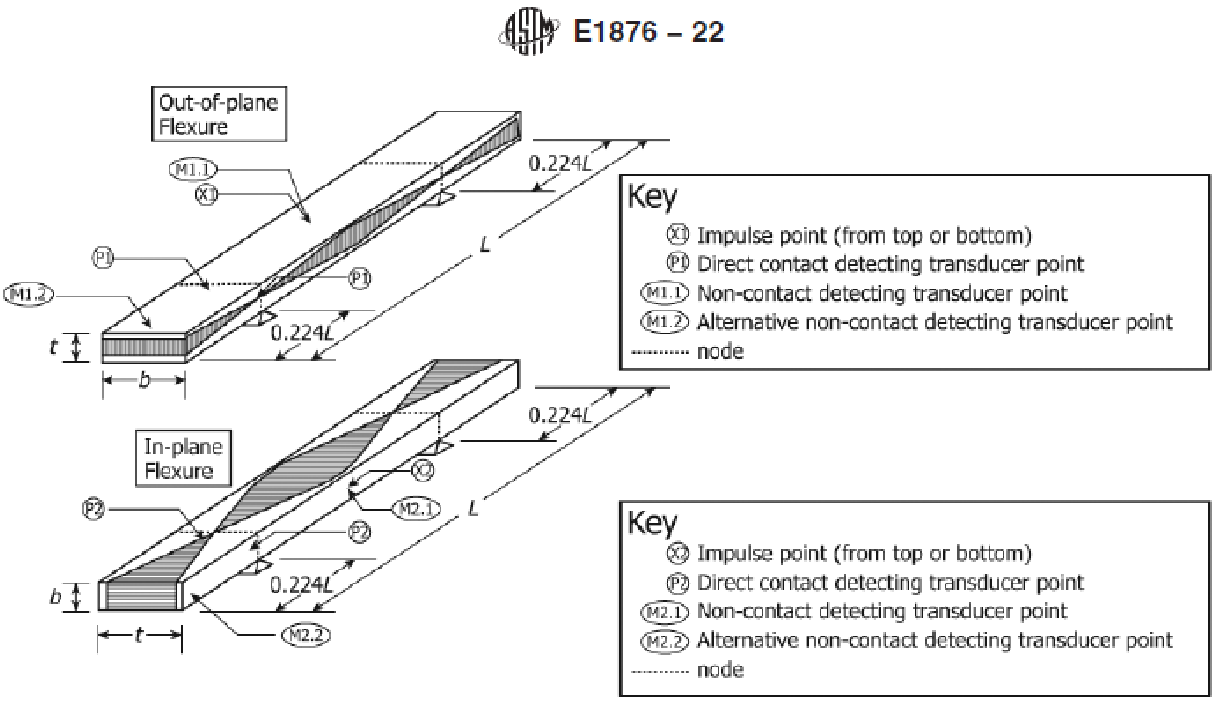
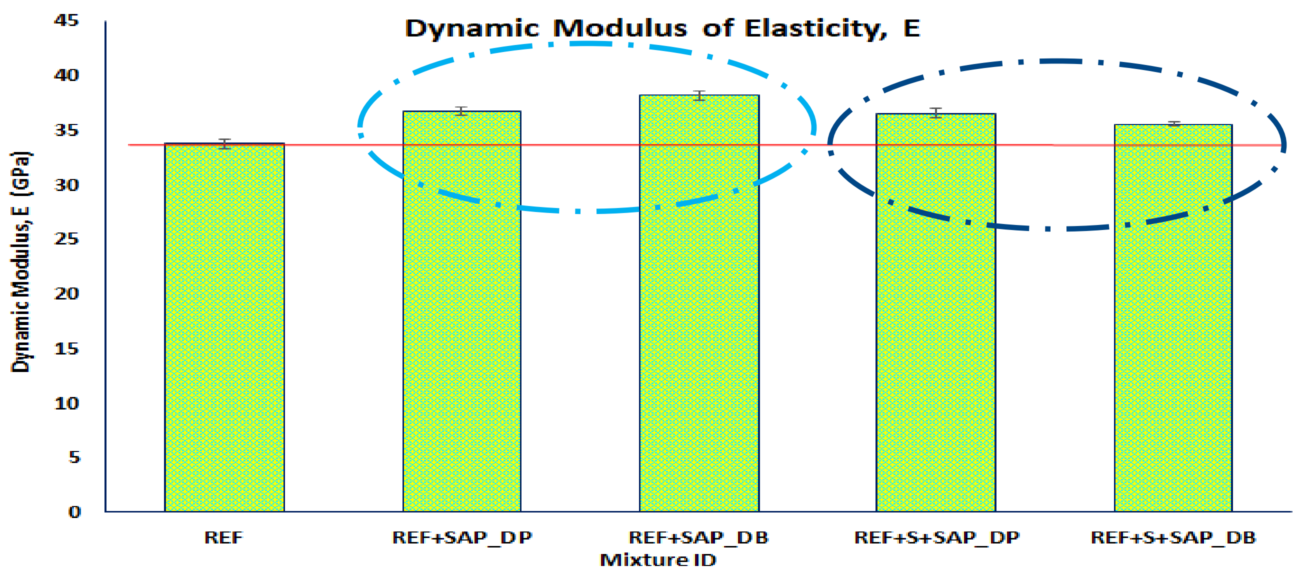
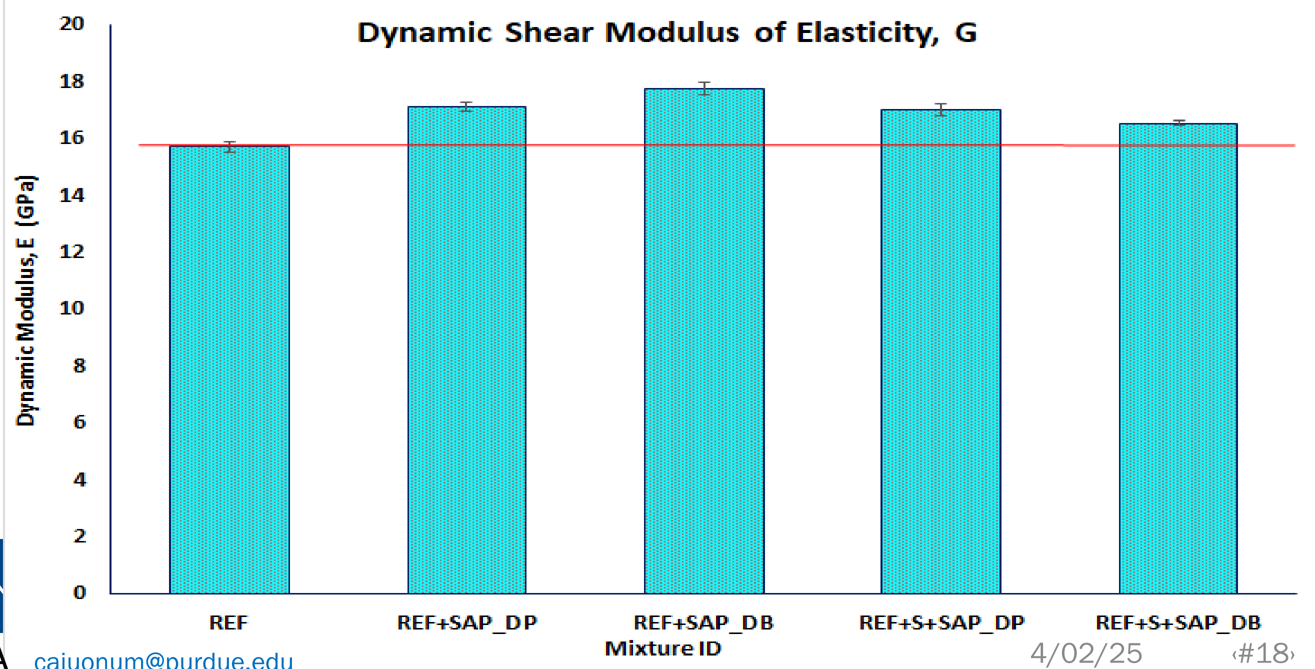


FIG. 3 Rectangular Specimens Tested for In-Plane and Out-of-Plane Flexure

Resonant Frequency (Transverse) Flexure Out-of-Plane





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FROM THE LABORATORY TO THE FIELD

(FIELD TRIALS)

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Summary of CMDs (Slabs 6 – 11)

Target Slump (inches)	3 – 7
Target Air Content (%)	5 – 8

Mix	Cement (lb./cuyd)	Slag (by weight of cement)	w/cm	Nano silica IC	SAP (bags/cy)	FA/tot. agg	WRA (fl. oz/ 100 lbs. of cementitious)	AEA (fl. oz/ 100 lbs. of cementitious)
Slab 6 (Reference)	658		0.44			0.41	–	~ 0.9
Slab 7 (Ref + Nano silica IC)	658		0.44	4 oz/cwt		0.41	–	~ 0.8
Slab 8 (Ref + Slag)	461	197	0.44			0.41	–	~ 0.8
Slab 9 (Ref + Slag + Nano silica IC)	461	197	0.44	4 oz/cwt		0.41	_	~ 0.8
Slab 10 (Ref + SAP)	658		0.44		1 bag	0.41	–	~ 0.8
Slab 11 (Ref + SAP+ Slag)	461	197	0.44		1 bag	0.41	–	~ 0.9

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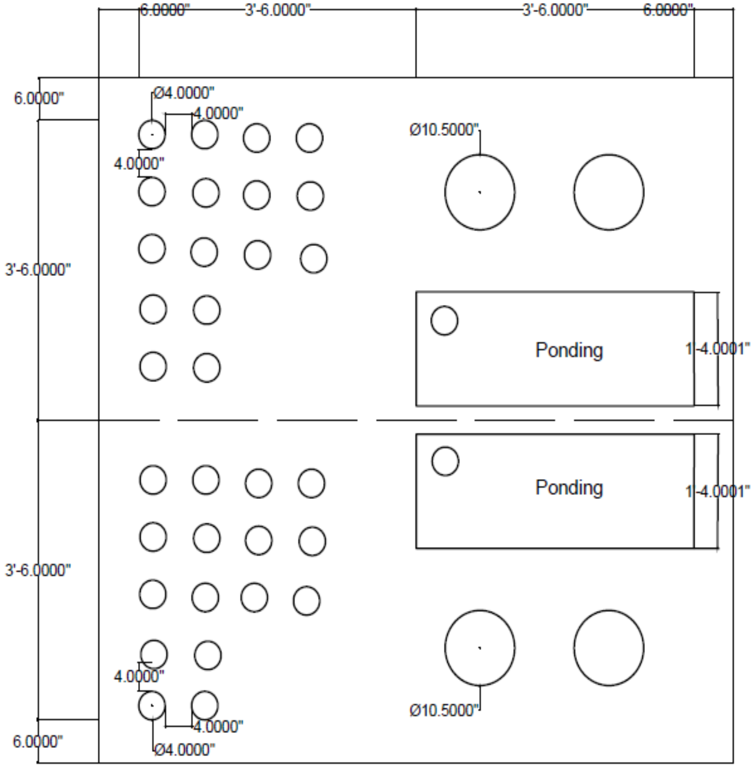

No curing compound

Curing compound

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Placing plastic sheet over concrete

Application of curing compound

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Slabs

Beams

Prisms

Cylinders

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Application of curing compound

cylinders connected to Data logger

Cores from the slabs retrieved at age of 7, 28, 56, 90 and 365 days

CURING REGIMES

Laboratory Curing

Specimens: Cast concrete cylinders and beams

Conditions:

Constant temperature 23°C, Relative humidity ~ 50%, wet curing

Variables:

Curing compound (CC), without curing compound (NC), addition of colloidal nanosilica (NS1), and incorporation of SAP

Field Curing

Specimens: Field cast slabs, Concrete cores

Conditions:

Variable temperature, moist environment, cyclic freezing and thawing

Variables:

Curing compound (CC), without curing compound (NC), addition of colloidal nanosilica (NS1), and incorporation of SAP

Test Name	Procedure	Specimen Specification
Air Content and Workability	ASTM C143-20; C231-24	Fresh concrete
Compressive strength	ASTM C39-24	4 in. x 8 in. concrete cylinder/ cores
Flexural strength	ASTM C78-22	6 in. x 6 in. x 18 in. concrete beams
Splitting tensile strength	ASTM C496-17	4 in. x 8 in. cores
Scaling resistance	ASTM C672-12	10 in. x 4 in. cylindrical specimens
Resistivity and Formation factor	AASHTO T402-23	4 in. x 8 in. cores and cast cylinde

Air Content

Workability (Slump)

Electrical Resistivity Testing

Compressive Strength Testing

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Specimens: 10 -in (260 mm) diameter x 4 -in (100 mm) height special cylinders.

No. of Cycles: 50 cycles of freezing at thawing; freezing at **-18 °C (0 °F)** for **16** hours and thawing at **4 °C (40 °F)** for **8** hours. The deicing solution was replaced at the end of every **5th cycle**.

2 -in (50 mm) high dikes were created and **0.5 -in (2 cm)** depth of **CaCl2** deicing solution added to the concrete surface

Extraction of test specimen from the field

Specimen for scaling resistance test

Power washing of test specimen

Diked specimen ponded with chloride solution

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The **chloride ion penetration test** is a critical assessment method used to evaluate the durability of concrete, especially in environments exposed to de-icing salts, seawater, or industrial chemicals.

Creation of dikes on field-cast slabs

Field-cast slab ponded with chloride solution

Covering dikes to avoid evaporation

Extraction of concrete cores from the field

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Cutting cores to dimension

Vacuum-saturation of cores

Cores drying in the environmental chamber

Evaluation of the rate of water absorption of test specimens

ASTM C1585-20:
Standard Test Method for Measurement of Rate of Water Absorption by Hydraulic Cement Concretes

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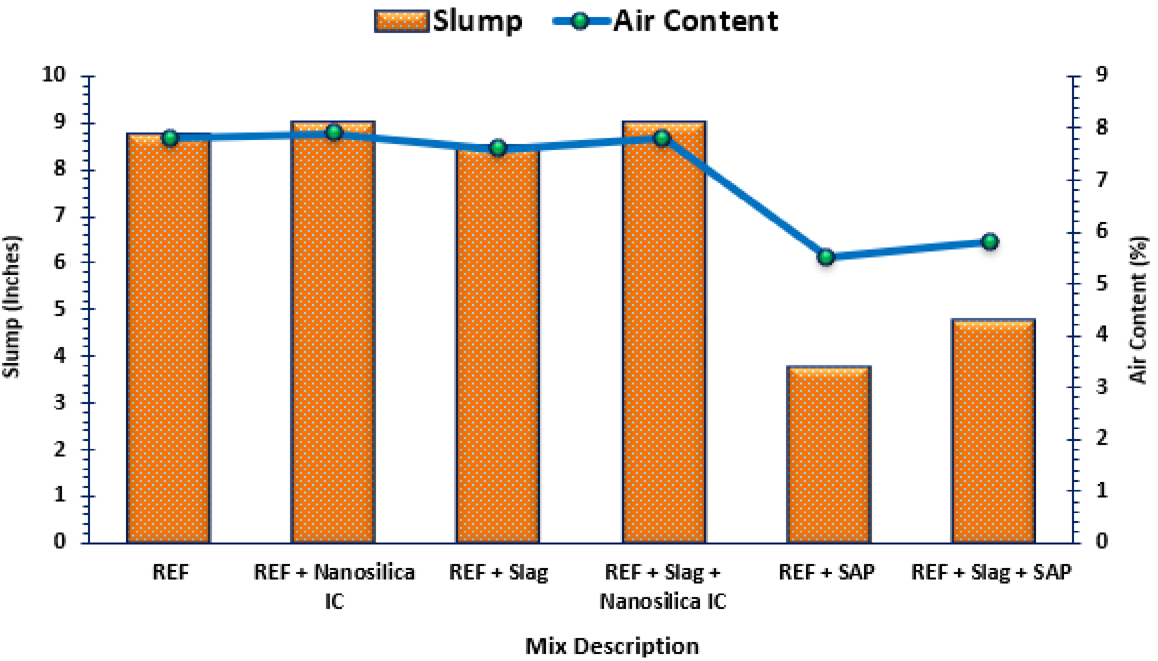
Slab Description	Slump (inches)	Air Void (%)	Unit Weight (lb)
Reference	8.75	7.80	34.30
REF + Nanosilica IC	9.00	7.90	34.39
REF + Slag	8.50	7.60	34.53
REF + Slag + Nanosilica IC	9.00	7.80	34.52
REF + SAP	3.75	5.50	35.61
REF + SAP + Slag	4.88	5.80	35.42



Target Air Content (%) = 5 – 8

Target Slump (inches) = 3 – 7

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REF

REF + SAP

REF + Slag +SAP

Air Content (%) = 7.80
Slump (inches) = 8.75

Air Content (%) = 5.50
Slump (inches) = 3.75

Air Content (%) = 5.80
Slump (inches) = 4.88

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Field Acceptance Properties:

Minimum water/cementitious ratio .... 0.320[B]
Maximum water/cementitious ratio .... 0.450[B]
Slump, formed .... 2 to 6 in.
Slump, slipformed .... 1.25 to 3 in.
Air Content .... 5.0% to 8.0%
Minimum modulus of rupture .... 570 psi at 7 days[C]
Relative Yield .... 0.98 to 1.02

[A] The target cement content during production shall not be adjusted from the value stated on the CMDP.

[B] The water cementitious ratio during production shall not deviate more than 0.020 from the target stated in the CMDP and shall not fall outside the limits above.

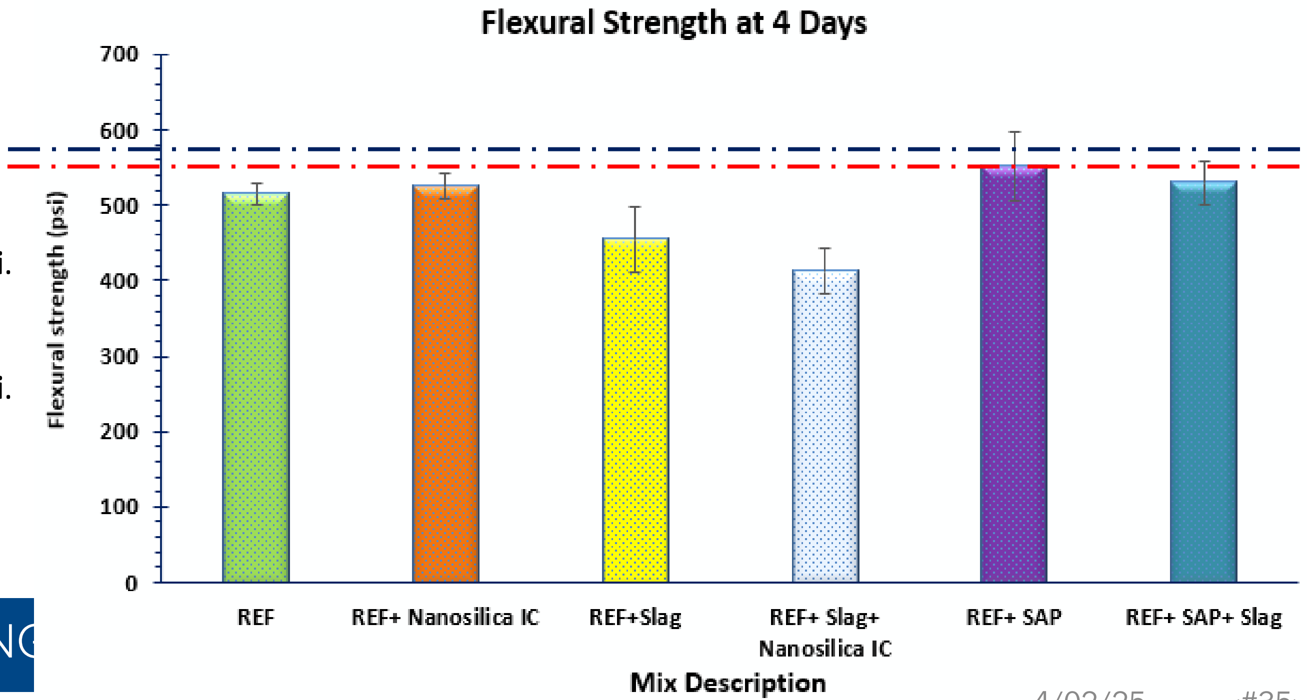
[C] Beams shall be standard cured in a water tank in accordance with AASHTO T 23 and 505.01(a). The water does not need to be saturated with calcium hydroxide. Minimum flexural strength for opening to traffic shall be in accordance with 506.12.

- Flexural strength at 4 days, ~ **412 – 551 psi.**
- Achieved the minimum specified standard at 7 days by 3 days earlier.

Slab No.	Description	w/b	Flexural Strength at 4 Days	
			psi	MPa
6	REF	0.44	515.13	3.55
7	REF+ Nanosilica IC	0.44	524.96	3.62
8	REF + Slag	0.44	454.21	3.13
9	REF+ Slag+ Nanosilica IC	0.44	411.79	2.84
10	REF+ SAP	0.44	550.63	3.79
11	REF+ SAP+ Slag	0.44	530.33	3.65

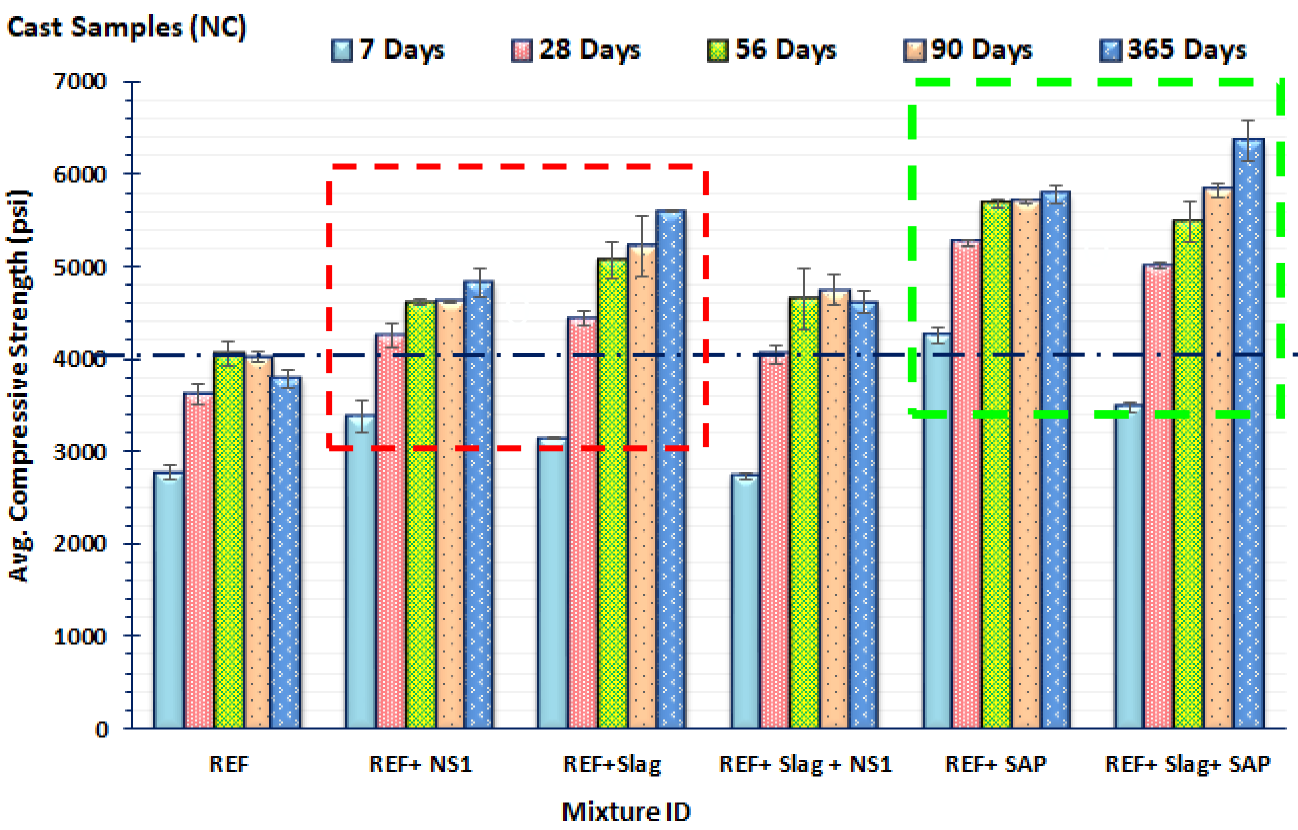
Structural Concrete
- Minimum modulus of rupture at **7 days = 570 psi**.

Concrete Patches
- Minimum modulus of rupture at **3 days = 550 psi**.

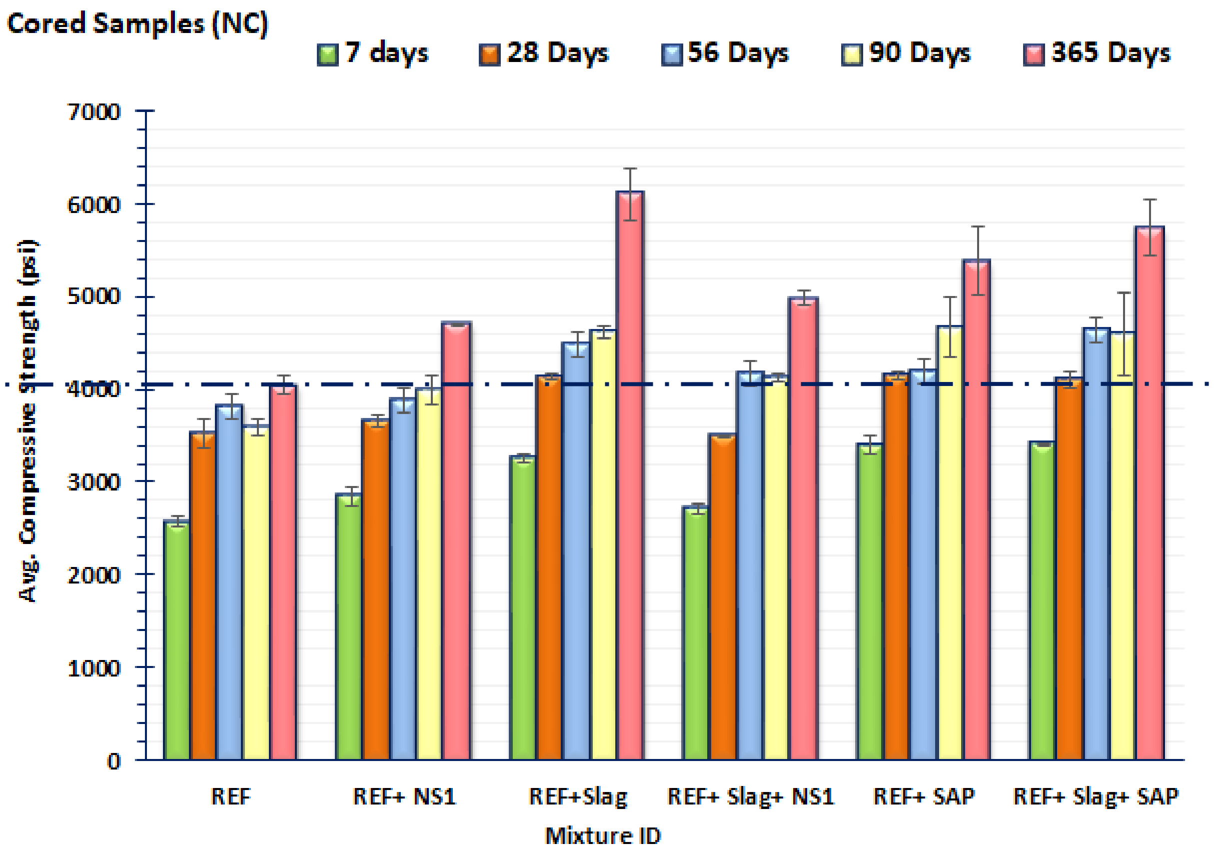


INDOT. (2024). 2024 Standard Specifications. Retrieved from INDOT website

Compressive strength for cast samples with age



Compressive strength for cored samples with age



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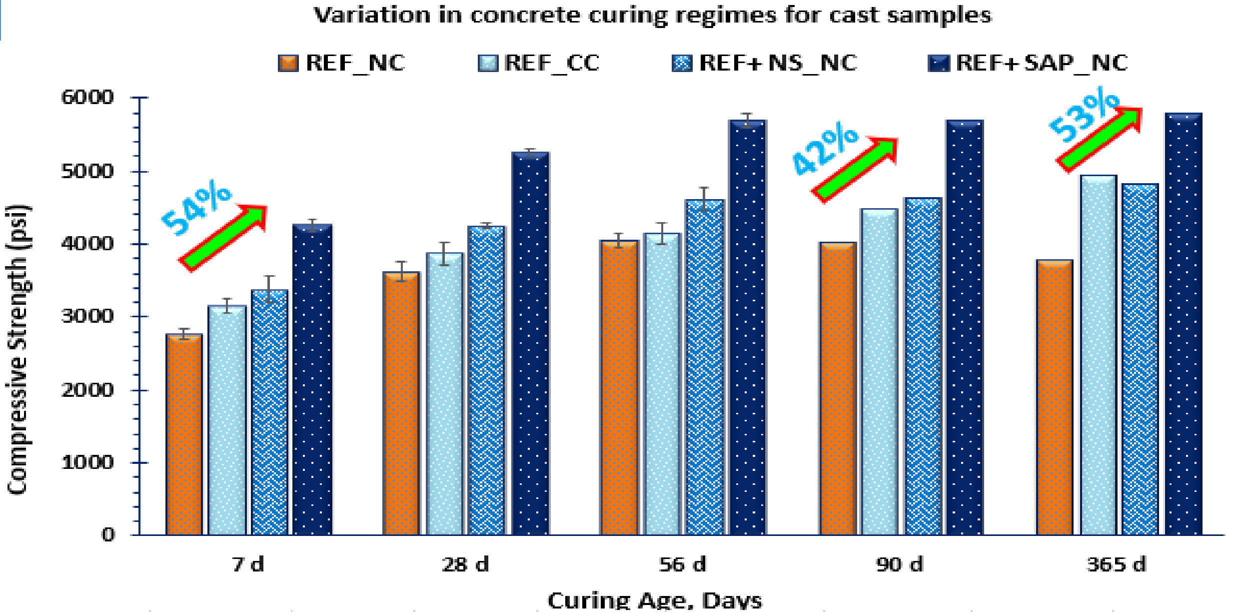
Curing Condition	Designation
No Curing Compound	NC
Curing Compound	CC



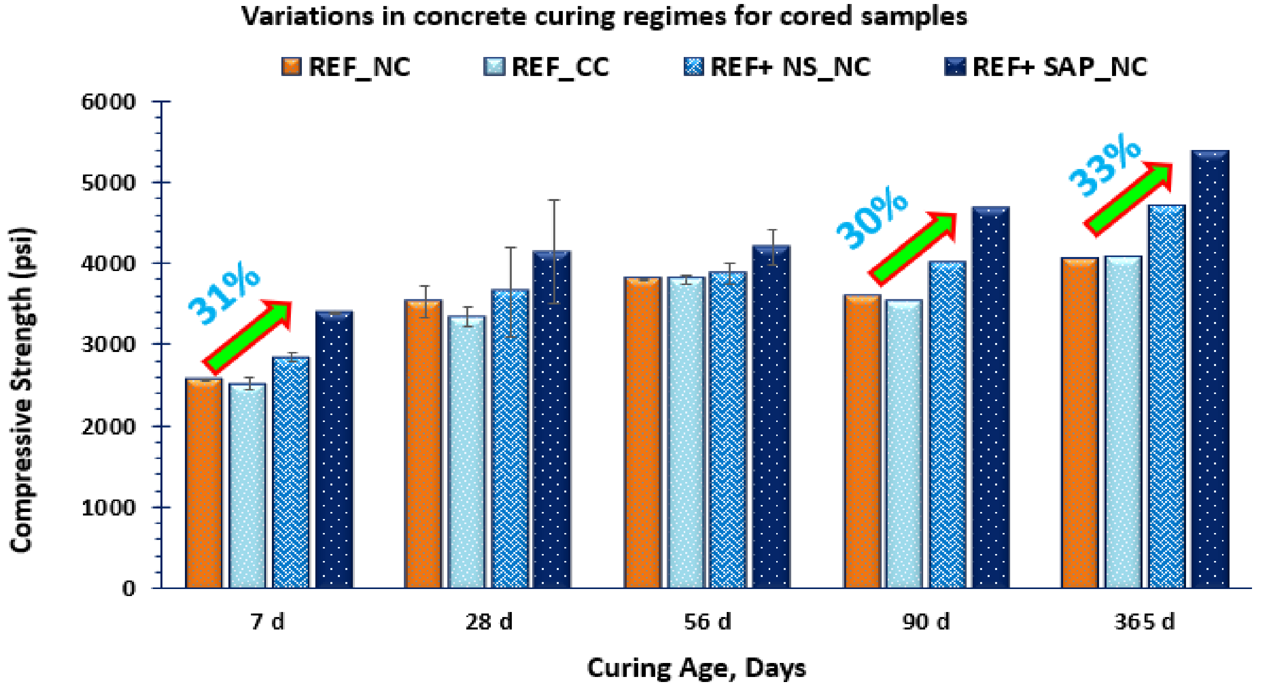
Highpoints

Cast:

- The application of the curing compound improved the strength by **14%, 7%, 2%, 12%** and **31%** for the 7, 28, 56, 90 and 365 days respectively.
- Addition of SAP improved the strength by **54%, 45%, 40%, 42%** and **53%** for the 7, 28, 56, 90 and 365 days respectively.

Cores:

- The impact of curing compound application on compressive strength was negligible at all curing ages
- Addition of SAP improved the strength by **31%, 18%, 10%, 30%** and **33%** for the 7, 28, 56, 90 and 365 days respectively.
- The effect of NS on compressive strength was obvious at later ages (11% and 16% increment at 90 and 365 days)



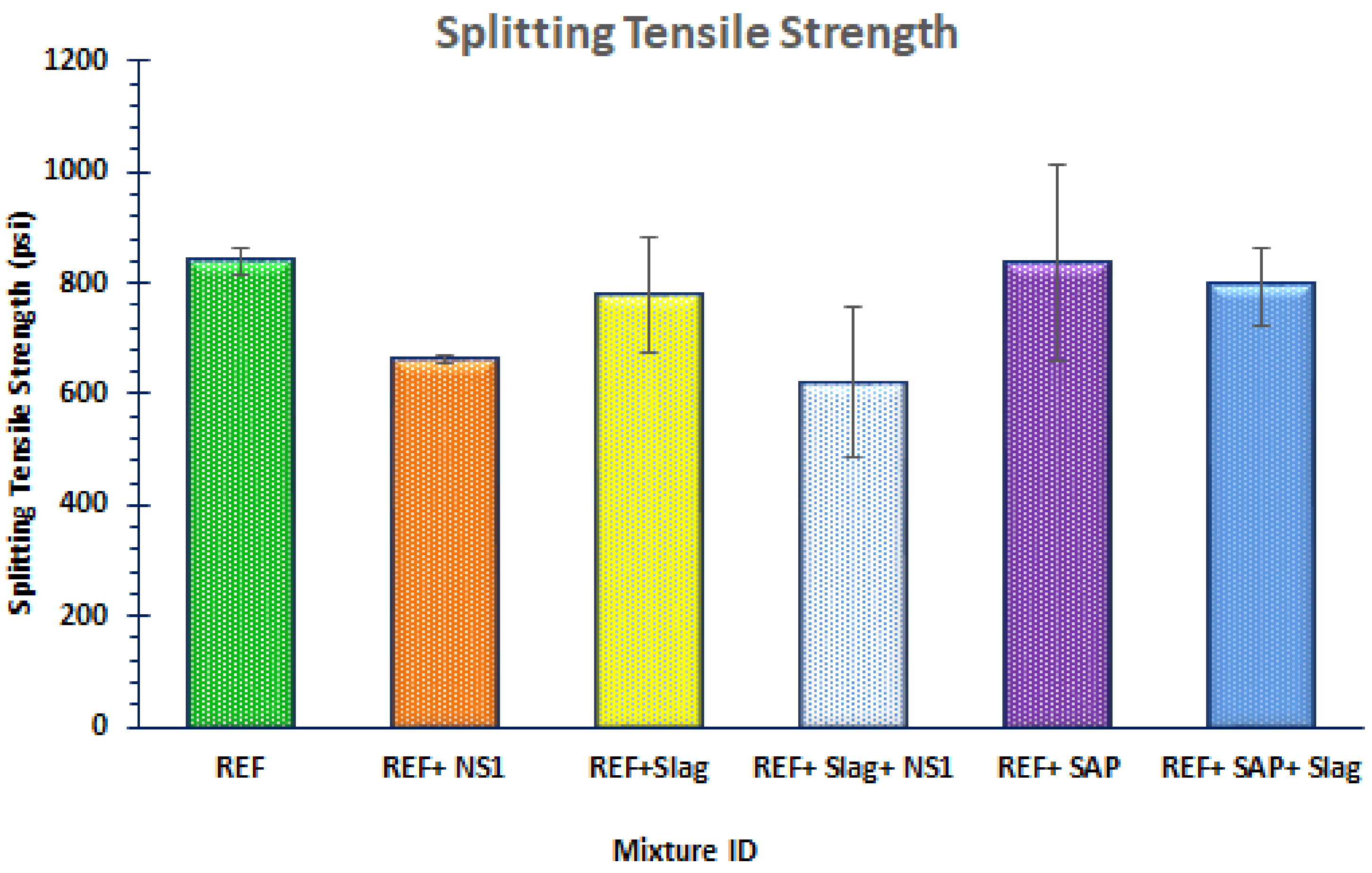
ASTM C496 – 17

Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

Concrete splitting tensile strength measures the material's ability to resist tension forces, which can be critical in many structural applications.

Test Specimens: Concrete cores

Age at testing: 180 days



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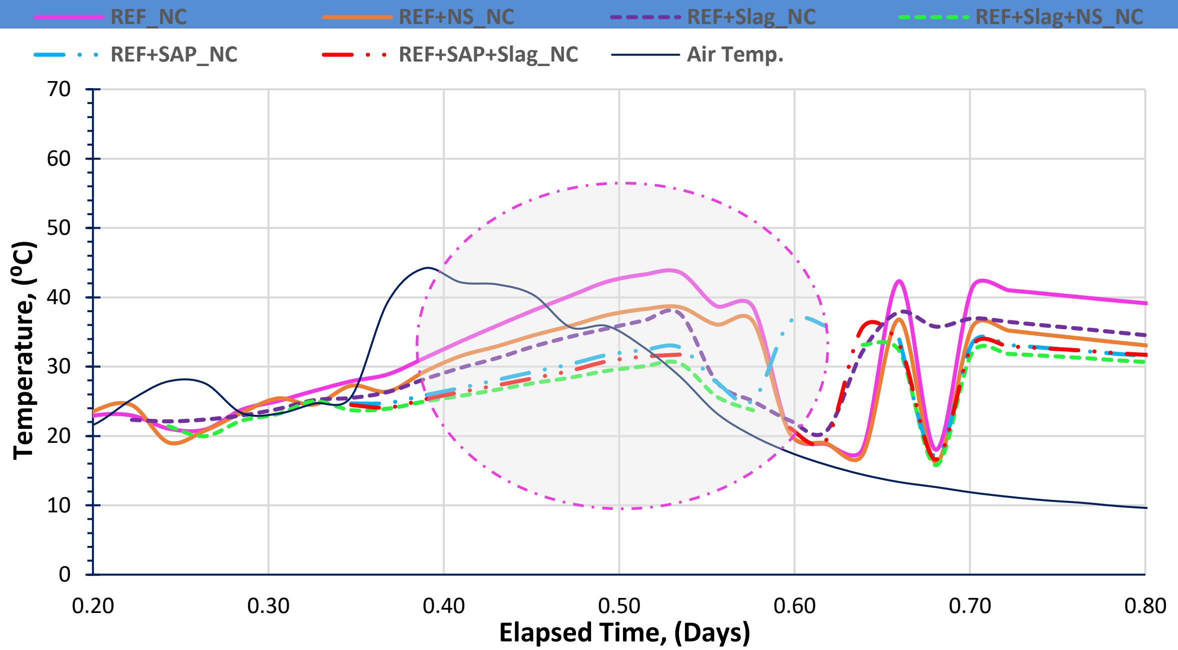
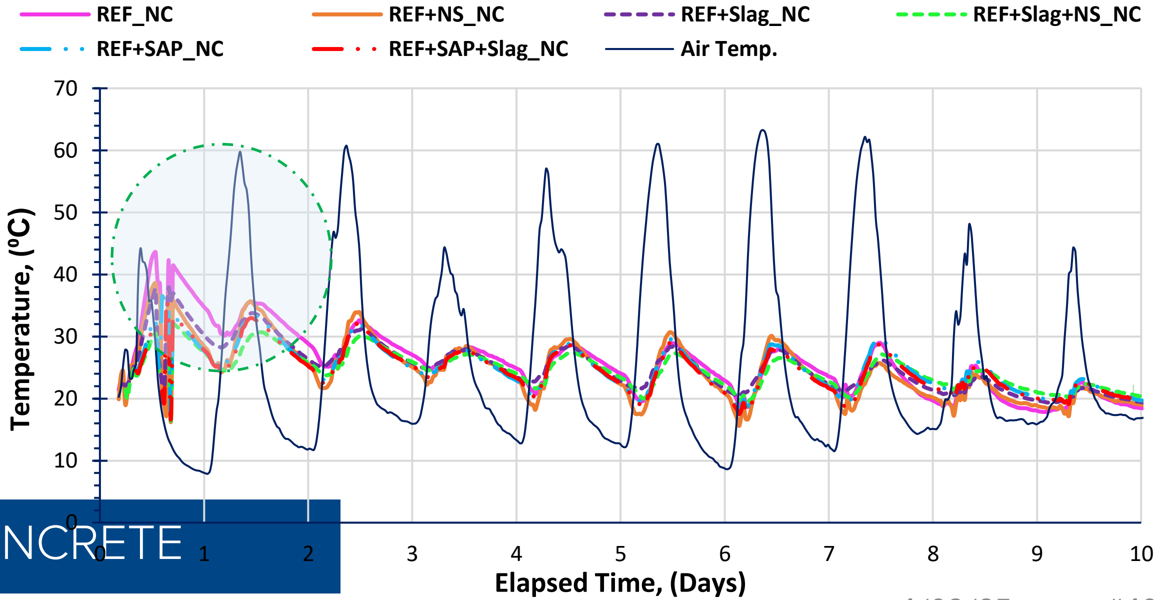
Description	Peak Temp. (^0C)	Time to Peak Temp. (Hrs.)	Air Temp. at Peak (^0C)
REF	43.59	8.30	28.56
REF + NS	38.58	8.30	28.56
REF + Slag	37.86	10.30	13.35
REF + Slag + NS	33.14	9.30	14.42
REF + SAP	36.45	6.00	17.64
REF + SAP + Slag	35.69	7.00	14.42



Highpoints

- Addition of nanosilica, **decreased** the slab core temperatures by **13%,** but the time to reach peak temperature remained **unchanged.**
- Replacement of cement with 30% slag **decreased** the slab core temperature by **13%**, but it **extended** the time to reach peak temperature by 2 hrs. (~10 hrs.)
- Addition of SAP **decreased** the slab core temperature by **16%**, and **decreased** the time required to attain peak temperature by 2 hrs. (~6 hrs.).



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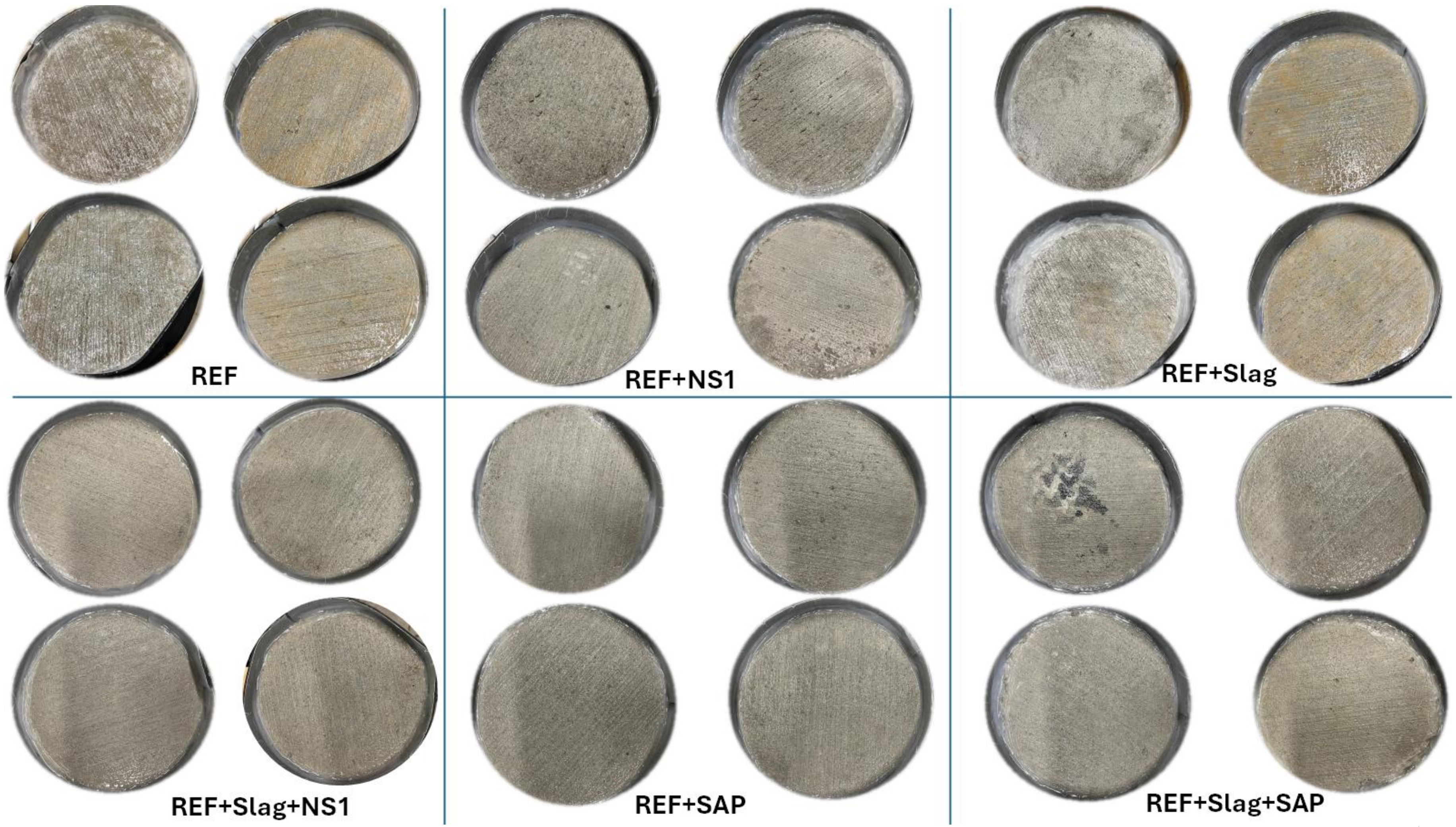
ASTM C672 – *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*

The surface scaling visual rating scale recommended in the standard was used to evaluate the extent of scaling.

- **None** of the specimens tested showed any signs of scaling.
- **No mass loss** was recorded.
- Visual rating of all surfaces was **zero**.



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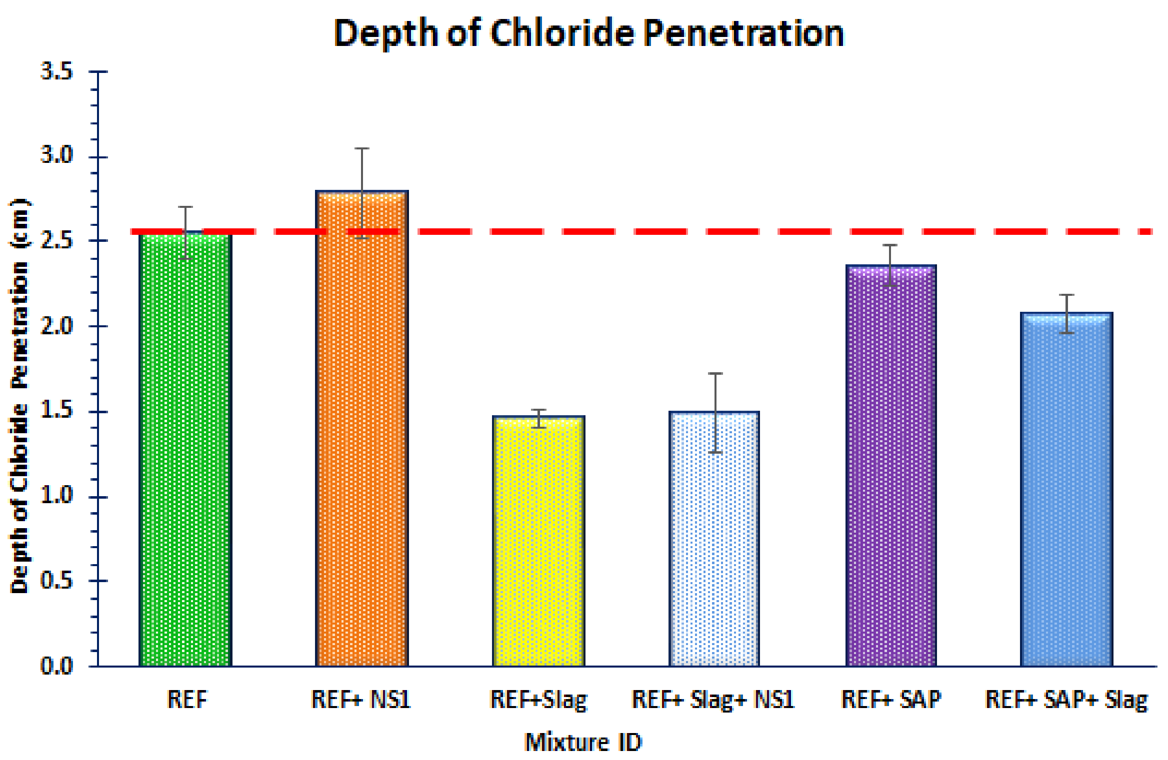

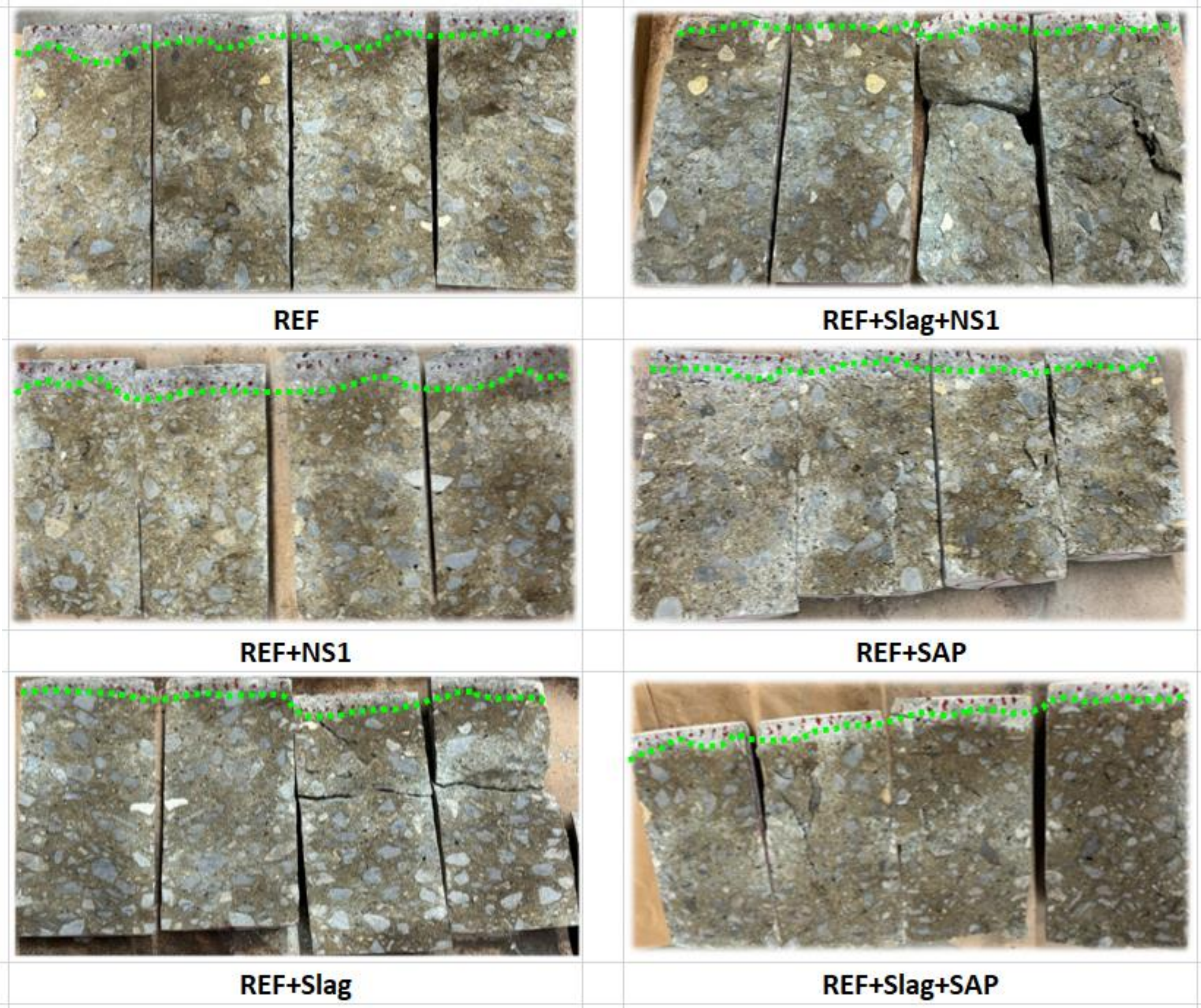

The chloride ion penetration test is a critical assessment method used to evaluate the durability of concrete, especially in environments exposed to de-icing salts, seawater, or industrial chemicals.

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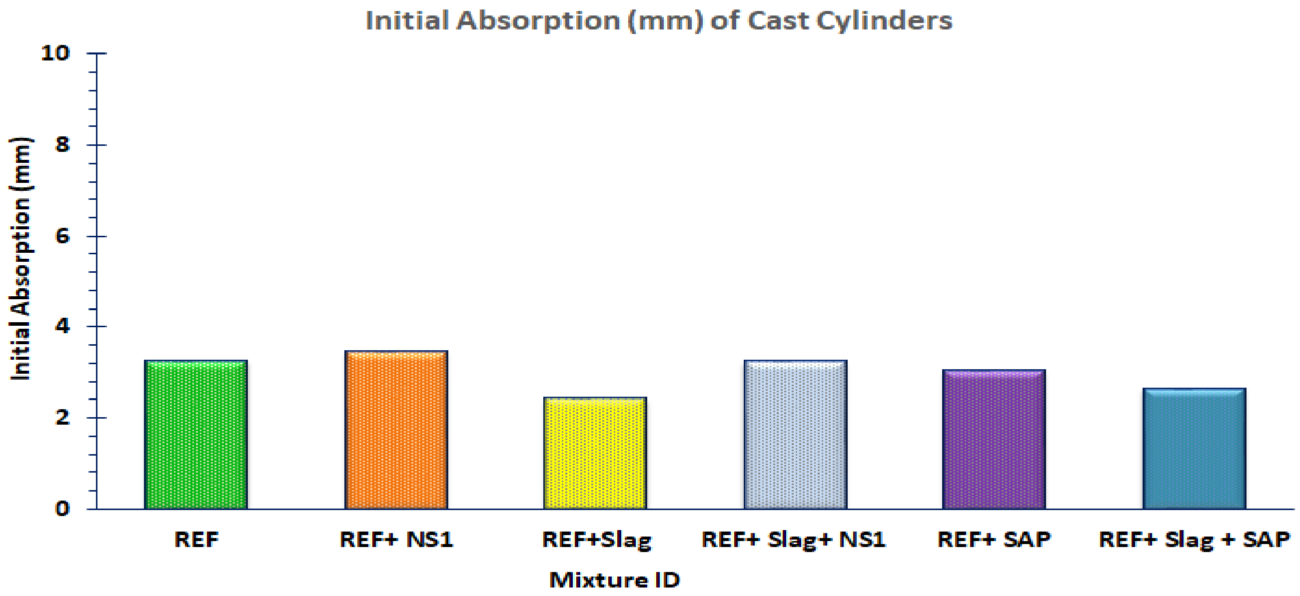
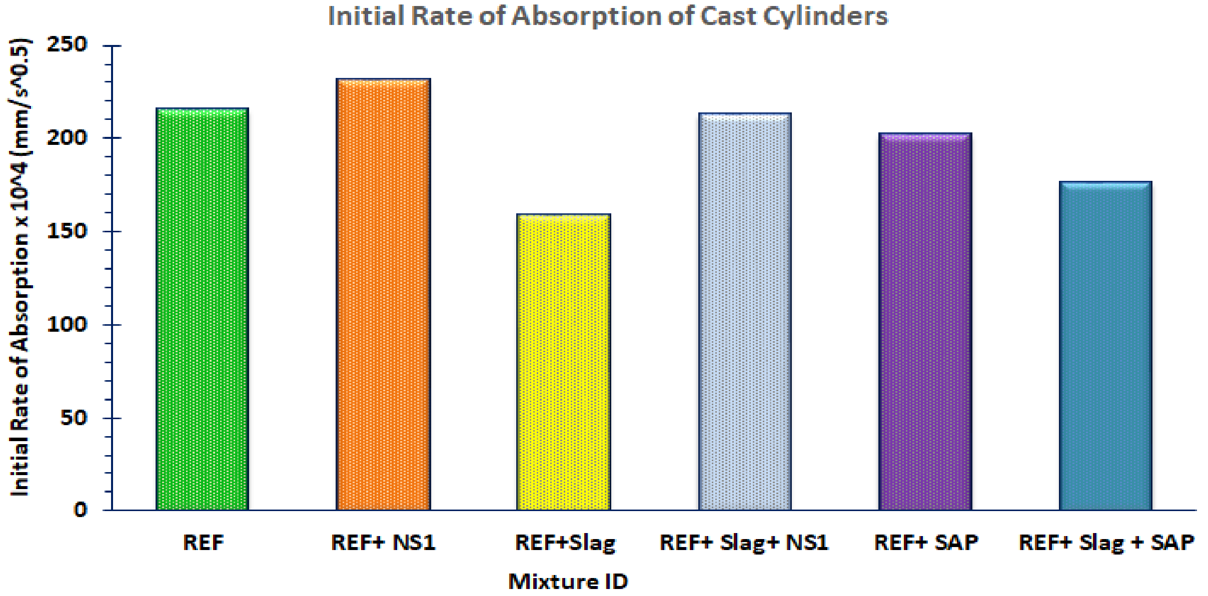
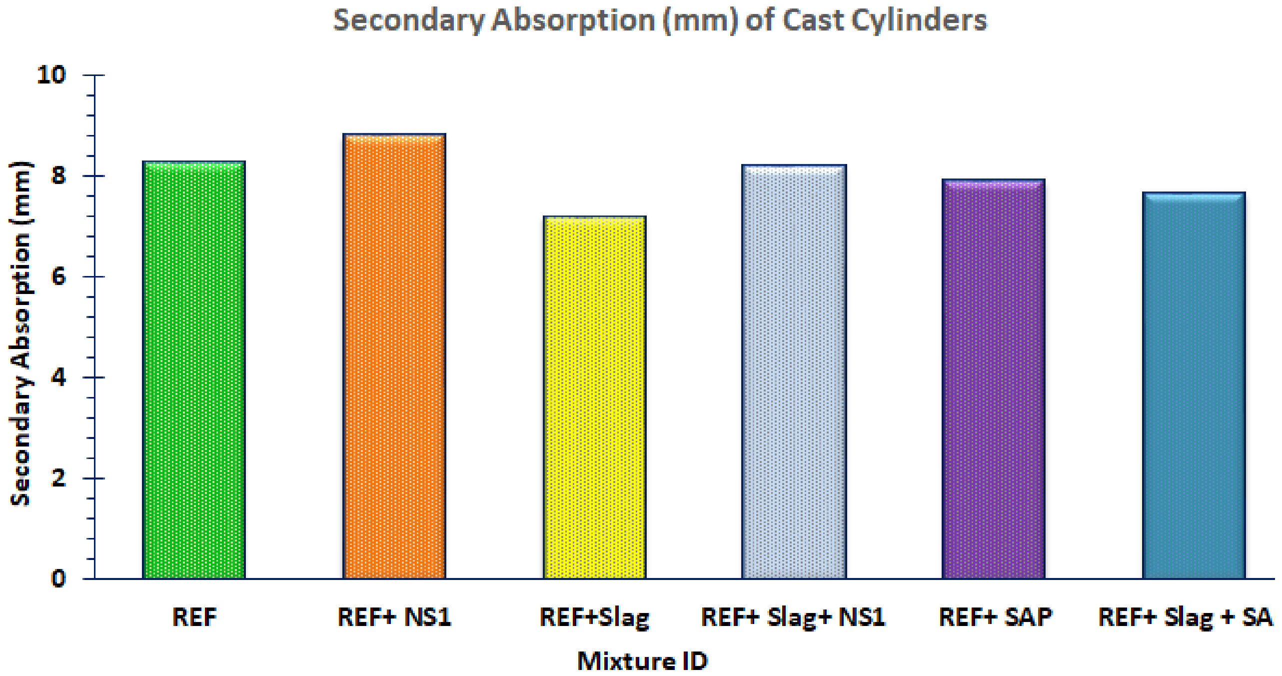
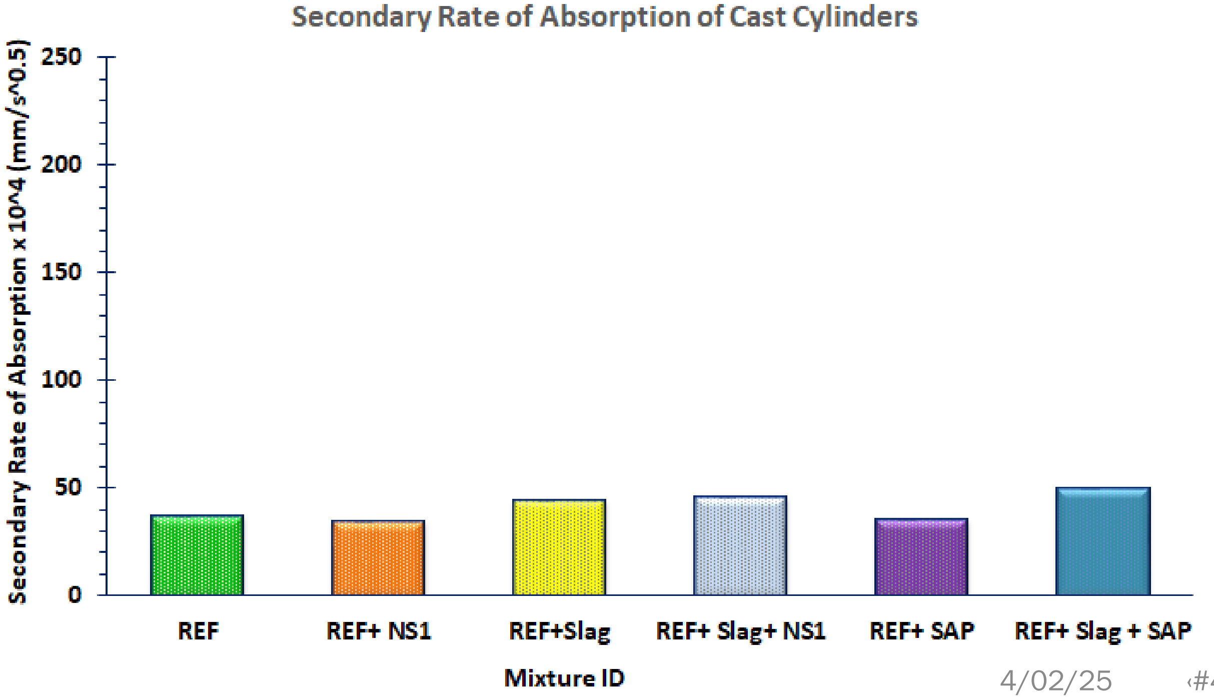

Initial Absorption (mm) of Cast Cylinders
Initial Absorption (mm)
0
2
4
6
8
10
REF
REF+ NS1
REF+Slag
REF+ Slag+ NS1
REF+ SAP
REF+ Slag + SAP
Mixture ID

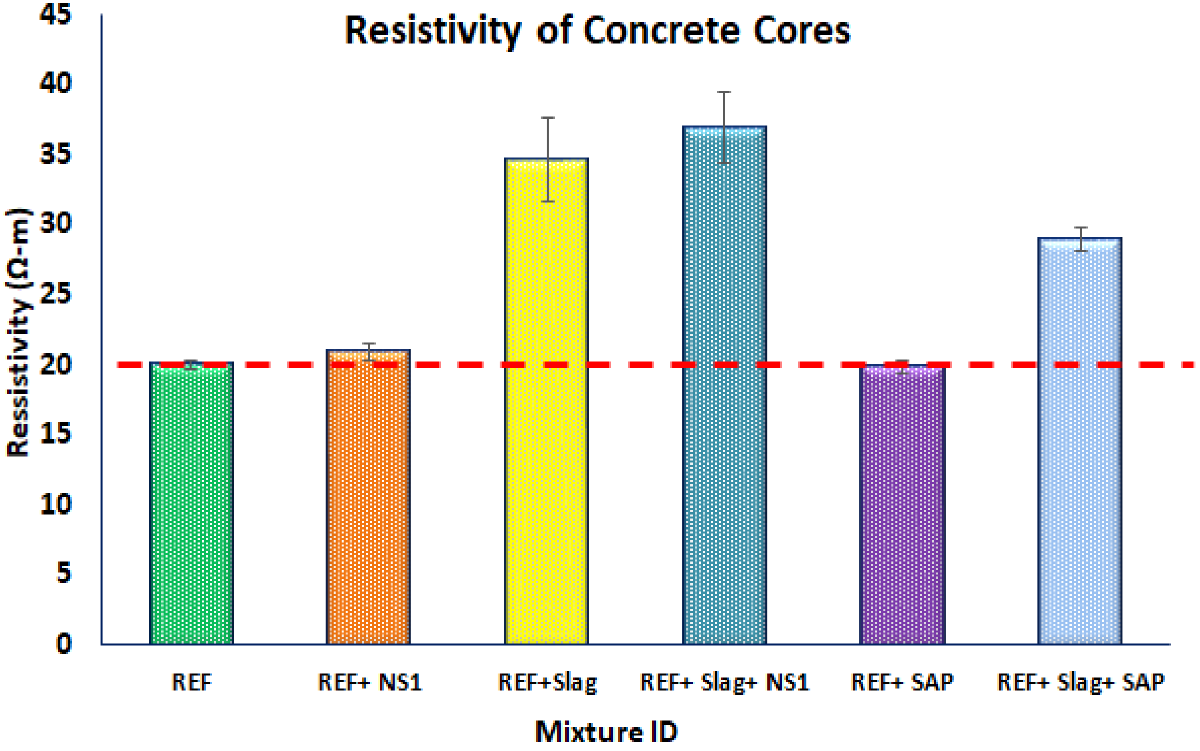

Initial Rate of Absorption of Cast Cylinders
Initial Rate of Absorption x 10^4 (mm/s^0.5)
0
50
100
150
200
250
REF
REF+ NS1
REF+Slag
REF+ Slag+ NS1
REF+ SAP
REF+ Slag + SAP
Mixture ID


Secondary Absorption (mm) of Cast Cylinders
Secondary Absorption (mm)
0
2
4
6
8
10
REF
REF+ NS1
REF+Slag
REF+ Slag+ NS1
REF+ SAP
REF+ Slag + SA
Mixture ID


Secondary Rate of Absorption of Cast Cylinders
Secondary Rate of Absorption x 10^4 (mm/s^0.5)
0
50
100
150
200
250
REF
REF+ NS1
REF+Slag
REF+ Slag+ NS1
REF+ SAP
REF+ Slag + SAP
Mixture ID

AASHTO T402-23 *Electrical Resistivity of a Concrete Cylinder Tested in Uniaxial Resistance Test*.

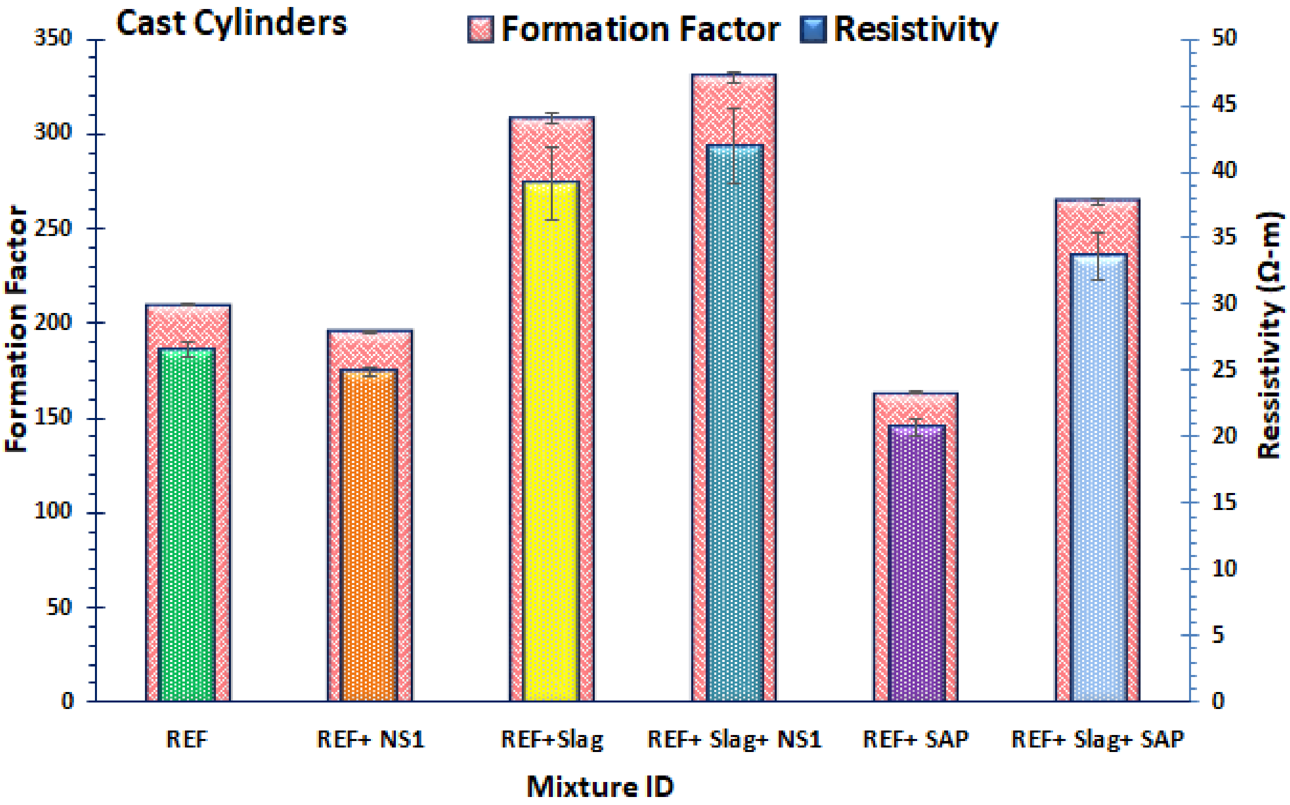
The values of the resistivity and formation factor were determined following the test procedure outlined above.



The formation factor (F), which represents the ratio of the **concrete resistivity** to the **resistivity of the pore solution** was calculate using equation below.

$$F = \frac{\rho}{\rho_0} = \frac{1}{\varphi . \beta}$$

Where: $F = Formation\ factor, \rho = Concrete\ resistivity, \rho_0 = Pore\ solution\ resistivity, \varphi = Concrete\ porosity,\ \ \beta = Concrete\ pore\ connectivity$



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In summary, having performed the field trials on the practical implementation of superabsorbent polymers for internally cured concrete, the following remarks have been drawn:

- The use of **dissolvable bags** was an effective approach for the SAP delivery in the field, achieving appropriate **dispersion** and **mixture consistency**.

- Mixtures containing SAP showed improved **early-age flexural** strength performance compared to SAP-free mixtures. The addition of SAP also counteracted the early-age strength reduction caused using slag.

- When compared with using a surface-applied curing compound, the addition of SAP **significantly improved the compressive** strength of field cast and cored samples (by more than 30-50%) across all ages compared to SAP-free plain cement reference mixtures with and without curing compound.

- Mixtures containing both slag and SAP displayed **reduced chloride penetration depths** compared to reference and SAP-only mixes. The combination of SAP and slag appeared to provide a synergistic effect, together reducing permeability and enhancing resistance to chloride penetration.

- Concrete mixtures containing slag showed **higher resistivity** and **lower volume** of interconnected pores, **decreased ionic mobility**, **lower chloride ion permeability** and improved durability.

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Thank You

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aci CONCRETE CONVENTION

Acknowledgment

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