A Durability-based Performance Evaluation Approach for the Effective Use of Uncommon Coal Ashes in Concrete

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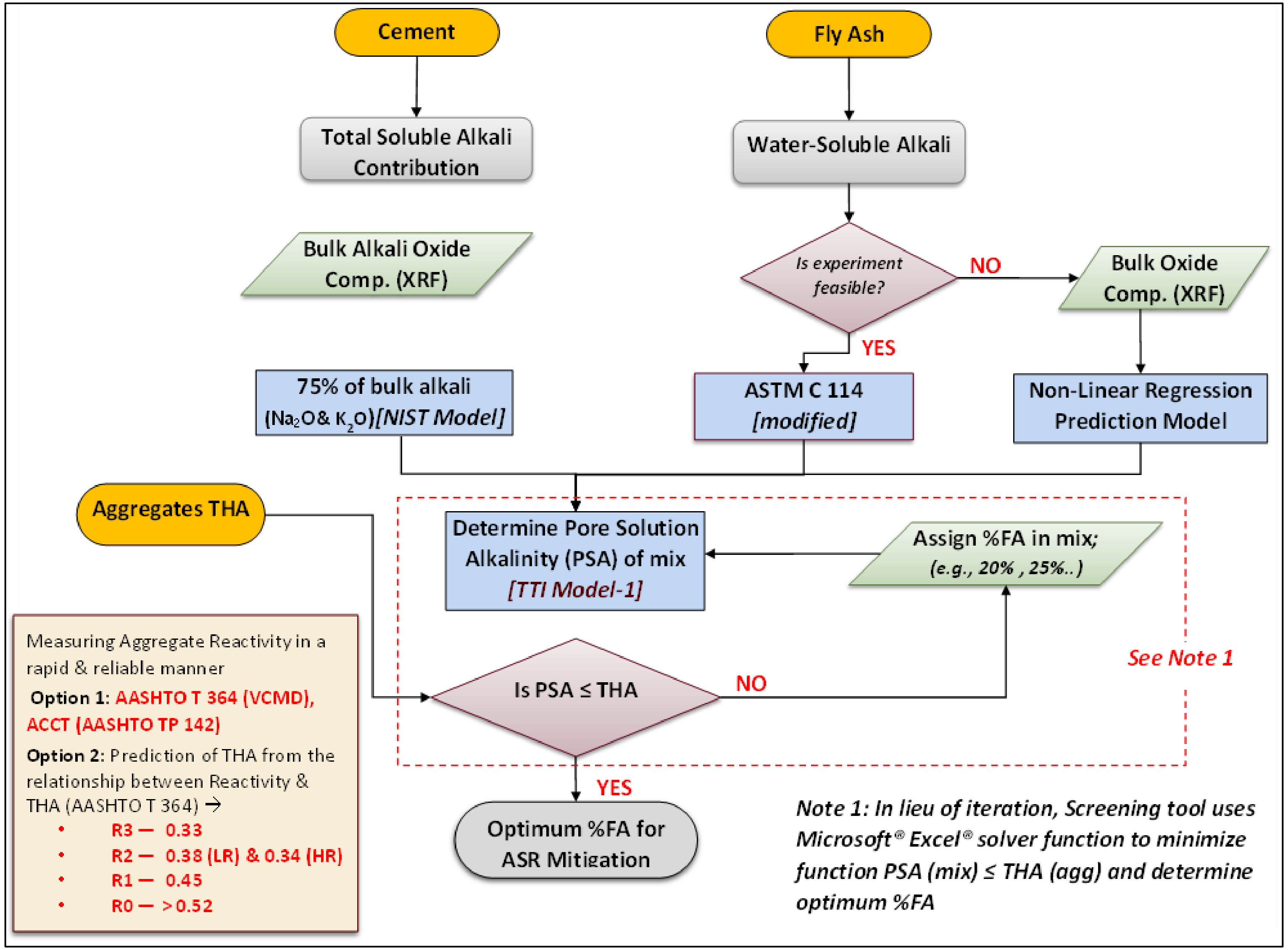
Our Approach to Durability-Based Performance Evaluation of SCMs in HPC Bridge Deck Mixes

- **Rapid & comprehensive durability-based performance evaluation** of cast-in-place **High-Performance Concrete (HPC)** bridge deck mixes during the mix design and trial batch stages.
- Covers four major durability aspects:

1. **Alkali Silica Reaction (ASR) Mitigation:** Chemical Screening Tool (CST) to predict SCM dosage for ASR mitigation
2. **Shrinkage:** Estimation of Autogenous & Drying Shrinkage strains & predicts cracking potential based on RILEM B4 Model (RILEM TC 242)
3. **Chloride Durability:** resistance to chloride ion ingress:
    1. Estimation of Anticipated Time to Rebar Corrosion.
    2. Determination of Probability of Failure Based on Target Reliability Levels using the SHRP2-probabilistic model
4. **Freeze-Thaw (F/T) Durability**: F/T performance prediction in terms of estimating "Time to Critical Saturation"

A simplified, user-friendly Excel-based spreadsheet was developed for DOT practitioners and contractors

Durability Evaluation (Part 1)- ASR Mitigation: Chemical Screening Tool (CST)



Publication

Saraswatula, P., A. Mukhopadhyay, and K.-W. Liu. Development of a Screening Tool for Rapid Fly Ash Evaluation for Mitigating Alkali Silica Reaction in Concrete. *Transportation Research Record: Journal of the Transportation Research Board*, 2022

Durability Evaluation (Part 1) - ASR Mitigation: Application of CST

- **Step 1**: Use Chemical Screening Tool (CST) to predict for optimum Fly Ash (FA) dosage for ASR mitigation
  - ASTM C 114 mod. test to measure water soluble alkali (WSA) from FA (~ 1-2 hrs./test) → ***1 day***
  - Using Non-Linear Regression model to predict WSA from FA → ***Instantly***
- **Step 2**: Determine FA dosage by ASTM C 1567 (% Fly Ash ≤ 0.10% Threshold Expansion)→ ***14 Days***
- **Step 3**: Comparative assessment between CST vs ASTM C1567 FA Dosage
  - If difference is more than 5% (e.g., 6-10%) → **ACCT (AASHTO TP 142) validation is mandatory**
  - If difference is less than 5% (e.g., between 2-5%) → use CST-based replacement level → **ACCT(AASHTO TP 142) validation can be considered optional**

Accelerated Concrete Cylinder Test (ACCT) [AASHTO TP142] ASR Test Method Developed at TTI

Standard Specification for

Accelerated Determination of Potentially Deleterious Expansion of Concrete Cylinder Due to Alkali-Silica Reaction (Accelerated Concrete Cylinder Test, ACCT)

AASHTO Designation: TP **142-21**

Technical Subcommittee: 3C, Hardened Concrete

Release: Group 1 (Month yyyy) **July 2021**

AASHTO

American Association of State Highway and Transportation Officials
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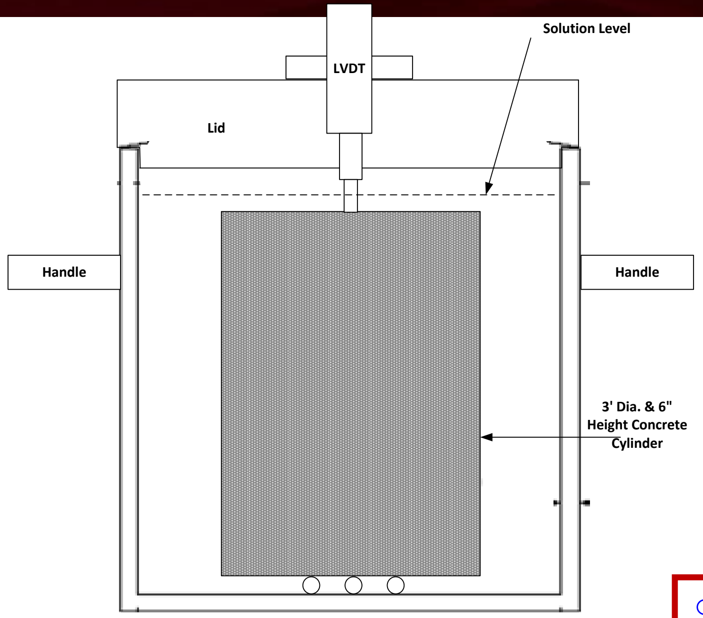


- Concrete cylinder = 3 inch x 6 inch
- Coarse aggregate factor = 0.76
- Cement content = 6 ± 0.4 sacks/cy (563 ± 38 lb/cy)
- Cement alkali content = 0.8 ± 0.05% Na_2O_e
- Concrete alkali loading = 4.5 lb/cy
- w/c = 0.45
- Soak solution = pore solution
- Temperature = 60°C (140°F)
- Aggregate gradation = as-received (no crushing)

	ASTM C1567	ASTM C1293	ACCT
Effect of soluble alkalis from SCMs	No	No	Yes
Ability to test job field mixes	No	No	Yes

- Mukhopadhyay AK, Liu Kai-Wei and Jalal M.," An innovative approach of fly ash characterization and evaluation to prevent ASR, ACI Materials Journal, 2019, Vol. 116, Issue 4, 173-181.
- Liu, Kai-Wei and Mukhopadhyay, A. K., "Accelerated Concrete-Cylinder Test for Alkali–Silica Reaction," Journal of Testing and Evaluation (IF: 0.644) ASTM International, Vol. 44, No. 3, 2015, pp. 1–10.

ASR Mitigation: Application of the Performance-Based Approach for the Conventional Ashes

- ❖ Estimation of fly ash (23 Fly Ashes - **19 Class F & 4 Class C) dosages using**
  - Chemical Screening Tool **(CST)**
  - AASHTO TP 142 **(ACCT) and** ASTM C 1567 **(AMBT)**

Classification Group	Group Description	No. of Fly Ashes	Fly Ash Types
G1	CST = ACCT = ASTM C 1567	15/ 23 ≈ 65%	13 – Class F 1 – Class C
G2	CST = ACCT; ***but ASTM C 1567 underestimates***	8 / 23 ≈ 35% *(4/8 ~ 5% lower; 4/8 ~ 7-10% lower)*	6 – Class F 2 – Class C
❖ *21 fly ashes (Class C and F) with C1293 data (literatures) – good correlation between CST and C1293*			

Publication

Saraswatula, P., A. Mukhopadhyay, and K.-W. Liu. Development of a Screening Tool for Rapid Fly Ash Evaluation for Mitigating Alkali-Silica Reaction in Concrete. *Transportation Research Record: Journal of the Transportation Research Board*, 2022

Durability Evaluation (Part 2) - Shrinkage

- Mixture Properties (w/cm ratio, cem content, air content, & 28 day compressive st.)
- Aggregate Properties
- Binder Proportions

→

Shrinkage Inputs (C 157):

- Specimen Dimensions
- Initial curing conditions→ Temp (23°C) & Duration (7d)
- Rel. humidity for curing (50%)
- Age for Evaluation (28d)

→

RILEM B4- TC 242 Model
(Model parameters revised based on experimental data)

→

- 0-28 days Autogenous Shrinkage (AS) Strain
- 28-day Drying Shrinkage (DS) Strain
- 28-day Cracking Potential (CP)

↕

Validation Testing

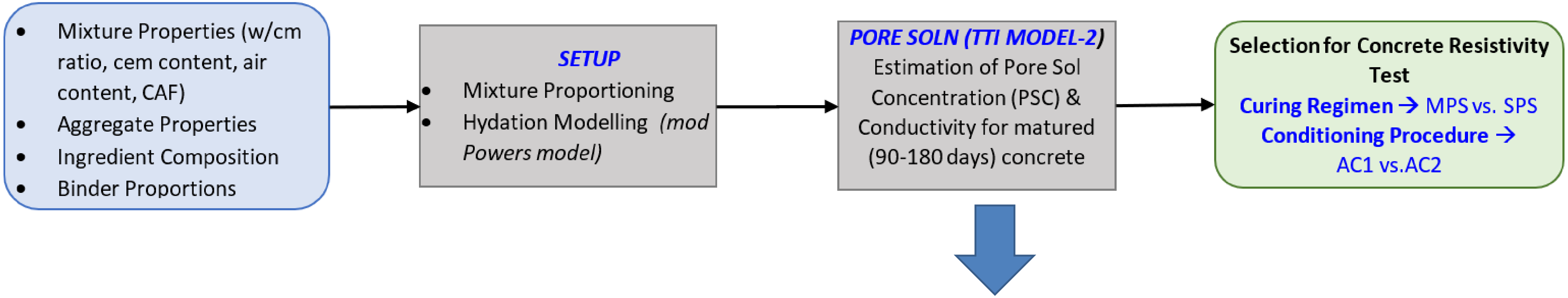
1. Autogenous Shrinkage (AS) Evaluation → sealed concrete prisms, mod. ASTM C 1698 *(only for selective "High AS" warning mixes)*
2. Drying Shrinkage Evaluation (7-28 days) →ASTM C 157
3. Cracking Potential Estimation
   - Based on measured tensile strength, MOE and 28-days AS and DS, and estimated creep (in-built model).

Tool Outputs:

1. **If 28-day AS/DS> 30%: "High AS" warning**
2. **If 28-day DS ≥ 400 µS: "High DS" warning**
3. **If CP > 1.5: "High CP" warning**

CP works: Fu et al., 2013 – Iowa State, Oregon DOT, 2015

Aspect 1: Guidance on Curing Protocol and conditioning procedure for Resistivity Testing



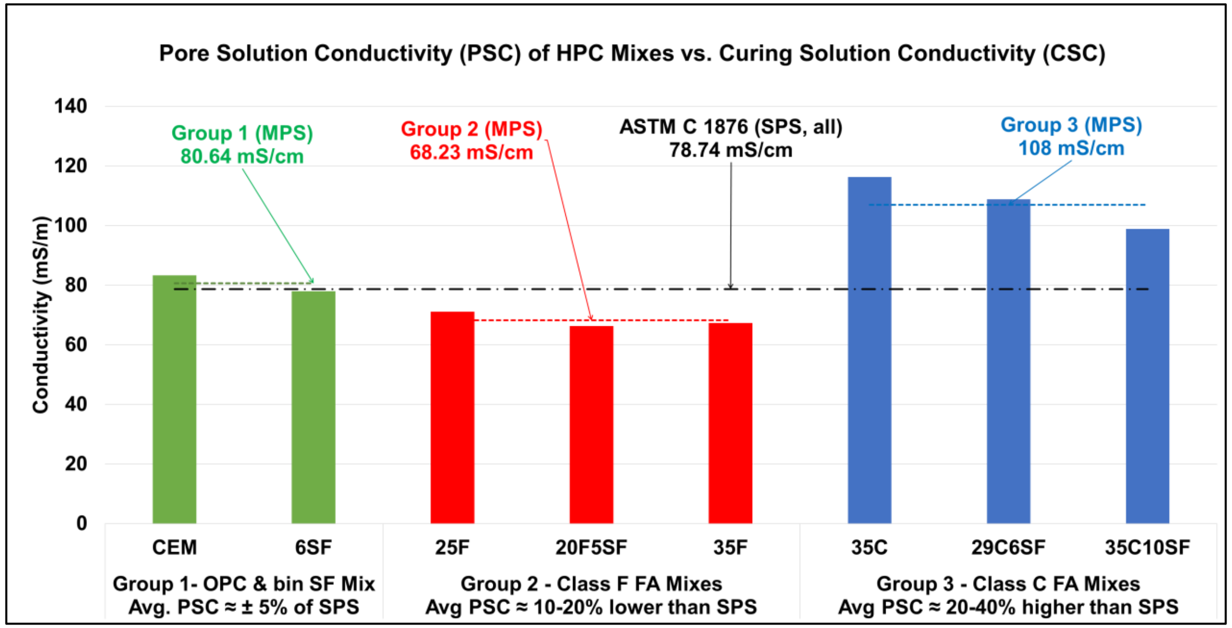
- **TTI Model-2 (a combined effect of soluble alkali contribution from both cement & SCMS and alkali binding):**

  1. **Soluble Alkali contribution:**
     - **Cement & Silica Fume →** 75% of Bulk Alkali (NIST Model)
     - **Fly Ashes →** Measured Available Alkali (AA) [ASTM C 311]
       - Estimation of AA: Regression equations based on Machine Learning Model using bulk chemical composition (oxide wt%) as inputs (inbuilt into the Tool).
  2. **Alkali Binding:**
     - **Assignment of binding factors depending on Ca/Si of predicted C-S-H** from cement, FA & SF based on *established literature studies (Hong and Glasser, 1999; Kulik 2011; Lothenbach et.al., 2019)*
     - Model parameters refined/validated based on GEMS thermodynamic modeling & 150 literature extraction measurements.

Concrete Resistivity Testing (contd.)

Increasing the Reliability of Formation Factor Based Transport Property Prediction for High Performance Concrete (HPC) Mixtures Through Innovative Matching Pore Solution (MPS) Curing

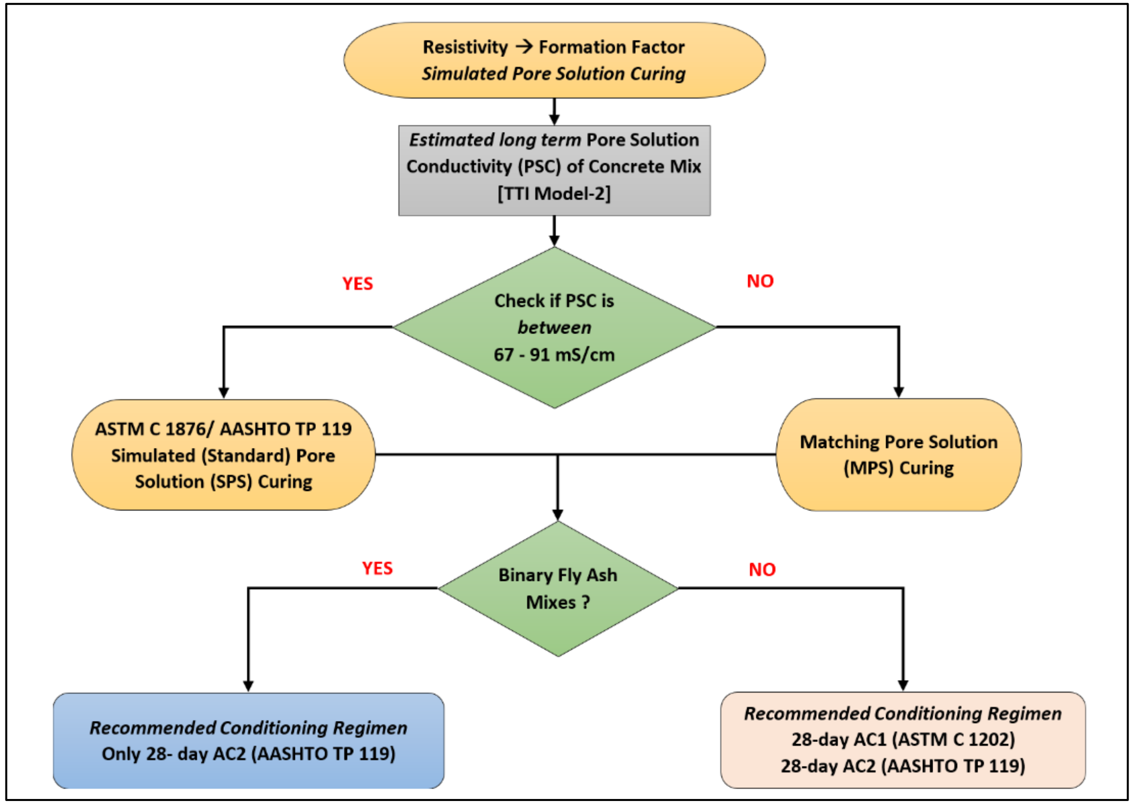
(Accepted for Publication, TRR 2023)



$$FF = \frac{\rho^{conc}}{\rho^{pore\ soln}} = \frac{\rho^{conc \rightarrow SPS\ or\ MPS}}{\rho^{SPS\ or\ MPS}}$$

Curing Guidelines based on TTI Model-2

(developed under 0-6958 TxDOT Project)



Note:

AC1 → Acc. Conditioning-Type 1 [ASTM C 1202] → 7 days @ 23°C and 21 days @ 40°C

AC2 → Acc. Conditioning-Type 2 [AASHTO TP 119]→ 3 days @ 23°C and 25 days @ 50°C

Durability Evaluation (Part 3 & 4) - Chloride & F/T Durability

- **Chloride Durability**
  - **Primary Input:**
    1. **28-day Resistivity Value (MPS/SPS & AC2)**
       - Resistivity → AFF → Diffusion Coefficients
       - inbuilt chloride binding prediction model based on mix design information (i.e., alumina content of binder, Azeez et al, 2020)
  - **Exposure & Construction Inputs:**
    1. **Chloride Loading**: Surface chloride concentration (Cs) *(based on ConcreteWorks)*
    2. **Construction Inputs**: Concrete Cover, Rebar Type & CNI Dosage *(Used to estimate Chloride Threshold (Ct), ConcreteWorks)*
    3. **Location & Month of Construction**: Monthly ambient (mean) temperatures in-built for **18 regions in Texas** and **for Jan – Dec** (NOAA database)
    4. **Design Service Life & Target Reliability Index:** Based on SHRP2 guidelines

- **F/T Durability**
  - **Primary Input**: **28-day Resistivity Value (MPS/SPS & AC2)**
    - Resistivity → AFF → Secondary Sorptivity (Todak et al., 2017)
  - **Saturation Input: Critical Degree of Saturation (DOS_{cr})**

Sample Report (29%C+6%SF mix) – TxDOT Tool

	INPUTS		OUTPUTS	
Resistivity & Forntion Factor	Curing Type	MPS	*Permeability Classification (Value & Class)*	
	Conditioning Regimen	AC2	Resistivity (Mea), k.Ohm-cm	45 *Very Low*
	Age of Resistivity Test (days)	28	Resistivity (Sat), kOhm-cm	28 *Very Low*
	Measured (avg.) Resistivity (Kohm.cm)	45	Apparent Formation Factor	4476 *Very Low*
			Saturated Formation Factor	2740 *Very Low*
Chloride Exposure & Rebar Corrosion	Max Surface Cl Conc (Cs)	0.60%	Apparent Diff Coff (Da,m^2/s)*(Pred based on FF)*	4.5E-12
	Rebar depth (Cover, in)	2.50	Chloride Binding Factor *(Pred)*	1.67
	Rebar Type	Epoxy Coated	Effective Diff Coff (De,m^2/s)*(Pred based on FF)*	1.7E-12
	Corrosion Inhibitor (gal/CY)	2.00	Estimated Time to Corr Repair, yrs	>75 years
	Location (In Texas)	Amarillo	Probability of Failure (SHRP2 Model)	5%
	Month of Construction	July	Reliability Index Calculated	1.685
	Target Realibility Index	1.3	*Pass or Fail? (Reliability -Calc vs Target)*	*Passes*
F/T Service Life	Critical Degree of Saturation (DOScr %):	86%	Est. Time to Critical Saturation (TTRCS) yrs	42

Durability Evaluation (Part 3 & 4)- Chloride & F/T Durability

- **Evaluating Chloride Durability**
  - **Approach 1: Est. Time to Rebar Corrosion**
    - Deterministic Approach based on Fick's 2nd law
  - **Approach 2: Probability of Failure Based on Target Reliability Levels**
    - Fully Probabilistic Approach (SHRP 2 Service Life Design for Bridges :R19-A)

SHRP2 Model Modified Based On TxDOT Tool Approach

- Chloride Ingress – Fick's 2[ND] Law of Diffusion for Corrosion Initiation

$$C_{crit} \geq C(x=a,t) = C_o + (C_{s,\Delta x} - C_o) \cdot \left[1 - \operatorname{erf}\left(\frac{a - \Delta x}{2\sqrt{k_e \cdot D_{eff} \cdot A(t) \cdot t}}\right)\right]$$

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{T_{real}}\right)\right)$$

$$A(t) = \left(\frac{t_o}{t}\right)^{\alpha}$$

$$D_{eff} = \frac{(D_o/AFF)}{\left(1 + \frac{1}{\phi} \cdot (cb_f)\right)}$$

(Accepted for Publication, TRR 2023)

- **Red → Chloride & Environmental Loading**
  - C_o & C_s → Background & surface Chloride Concentration
  - T_{real} → Ambient Mean Temperatures from Project Site
- **Green → Material Resistance**
  - a → concrete cover
  - D_{eff} → Effective Diffusion Coff (based on AFF & w/ inclusion of chloride Binding)
  - α → aging exponent (function of ΔFF vs time)

- **Evaluating Freeze-Thaw (F/T) Durability**
  - **Determination of Time to Critical Saturation (TTRCS or t_{SL}) based on rate of fluid absorption (sorptivity)**

    (Fagerlund 2004, Todak et al., 2017, etc.)

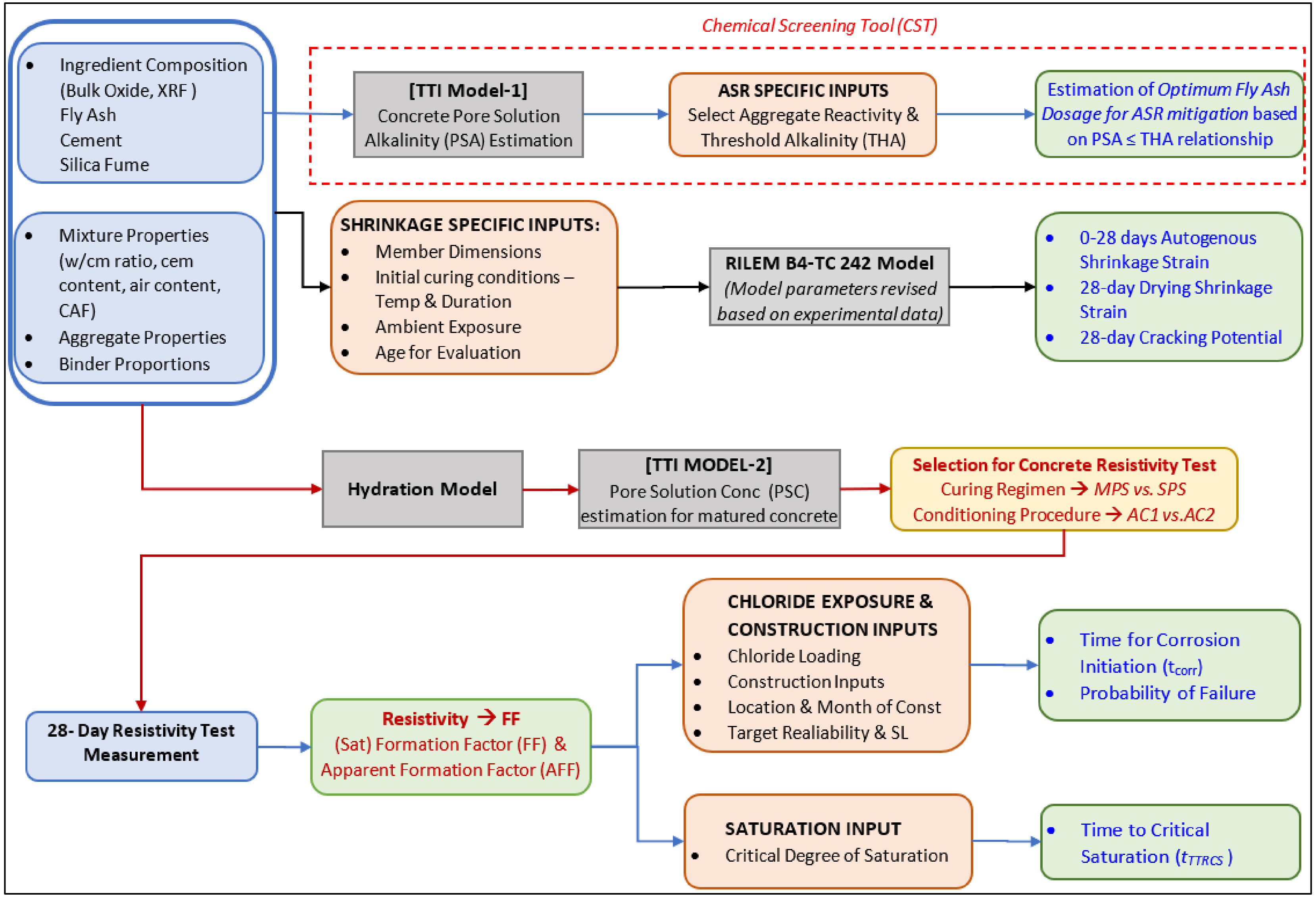
$$t_{SL} = \left(\frac{DOS_{Critical} - DOS_{matrix}}{\phi * S_2'}\right)^2$$

Critical Saturation Limit to Start F/T Failure (typ. 85-88%)
Input Tool (default) – 86% *(Obla et al., 2016)*

Matrix Degree of Saturation & Porosity (Φ)
Predicted based on in-built Hydration Model
(validated by experimental data)

Secondary Sorptivity $S_2' \propto 1/\sqrt{F_{APP}}$
Input Resistivity → Apparent Formation Factor (F_{APP}) → Sorptivity Coff (S_2') *(Validated from ASTM C 1585 Sorptivity Experiments)*

TxDOT Tool: Overall



Case Study 1: Bridge Deck concrete with 25% F Ash - Galveston, TX

TxDOT Tool Predictions vs. Laboratory Measurements

#Mix	#Type	SHRINKAGE		RESISTIVITY & FORMATION FACTOR				CHLORIDE DURABILITY					F/T DURABILITY
		Autogenous/ Drying Shr **(AS/DS)**	Cracking Potential **(CP)**	Measured Resistivity **(ρ_{mea})**	Saturated Resistivity **(ρ_{sat})**	Apparent Formation Factor **(AFF)**	Saturated Formation Factor **(FF)**	Chloride Binding Factor **(Cb)**	Effective Diffusion Coff **(De)**	Est. Time to Rebar Corrosion **(t_{corr})**	Prob of Failure & Reliability **(P_f)**	*Pass or Fail*	Time to critical saturation **(t_{sl})**
25% F Ash HPC Mix	*Tool Predicted*	17%	**Low (0.99)**	28.2 (L)	17 (L)	2039 (L)	1213 (L)	1.69	3.7E-12	**>75 years**	**17% (0.94)**	**Fail**	**19**
	Lab Measured	20%	**Low (0.87)**	28.2 (L)	19 (L)	1974 (L)	1329 (L)	1.71	2.9E-12				**27**
20% F ash + 5% SF HPC Mix	*Tool Predicted*	31%	**Moderate(1.11)**	42.7 (L)	26 (VL)	2852 (L)	2048 (VL)	1.6	2.8E-12	**> 75 years**	**2% (2.14)**	***Pass***	**26**
	Lab Measured	32%	**Moderate(1.20)**	42.7 (L)	30.8 (VL)	2989 (L)	2157 (VL)	1.63	1.6E-12				**30**

**Note: Chloride Durability Eval → surface chloride conc (Cs) - 0.6% (<1 mi from the ocean); Reported use of Black Steel & 2 Gal/yd3 CNI; July (high ambient temp)*

25% F ash Mix (Observations)

- ❖ **ASR Evaluation: CST predicted** 25% F ash is adequate to mitigate ASR; the difference between CST & C1567 is <5%, no need for ACCT validation

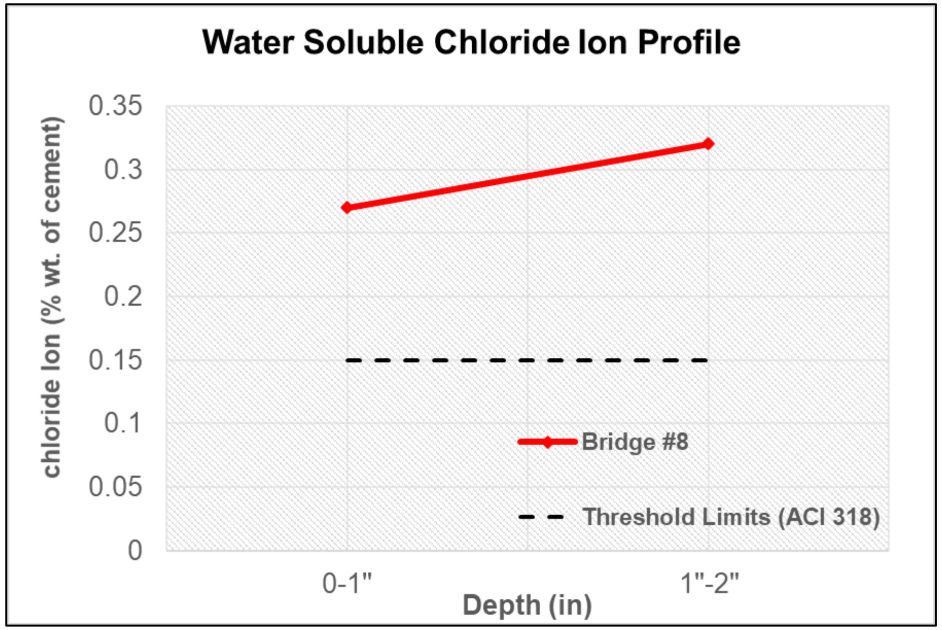
20% F ash + 5% SF Mix (Observations)

- ❖ **ASR Evaluation:** Ternary blend is very effective to mitigate ASR, no need for ACCT validation
- ❖ **Shrinkage → As CP increases due to the addition of 5% SF,** *selecting the right placement time and good curing practice is highly recommended*

Case Study 1 : Bridge Deck concrete with 25% F Ash - Galveston, TX

TxDOT Tool Predictions vs. Field Observations

LAB STUDY USING HPC BRIDGE DECK MIXES		
Shrinkage	**Transport Properties @ early ages (within 28 days)**	**Durability Performance**
Autogenous Shrinkage - low Drying Shrinkage– low (320-350) Cracking potential - low	Poor - slower microstructure development – no or negligible reduction in permeability	Poor at early ages but improvement at later ages



Galveston aggressive exposure conditions:

- Surface chloride conc (Cs) - 0.6% (<1 mi from the ocean)
- Use of Black Steel and 2 Gal/yd3 CNI

Case Study 2: Bridge Deck Concrete with 29% C Ash+ 6% SF - Amarillo, TX

TxDOT Tool Predictions vs. Laboratory Measurements

#MIX	#TYPE	SHRINKAGE		RESISTIVITY & FORMATION FACTOR				CHLORIDE DURABILITY*					F/T DURABILITY
		Autogenous/ Drying Shr **(AS/DS)**	Cracking Potential **(CP)**	Measured Resistivity **(ρ_{mea})**	Saturated Resistivity **(ρ_{sat})**	Apparent Formation Factor **(AFF)**	Saturated Formation Factor **(FF)**	Chloride Binding Factor **(Cb)**	Effective Diffusion Coff **(De)**	Est. Time to Rebar Corrosion **(t_{corr})**	Prob of Failure & Reliability **(P_f)**	*Pass or Fail*	Time to critical saturation **(t_{sl})**
29% C ash + 6% SF HPC Mix	*Tool Predicted*	35%	**Moderate-High (1.32)**	30 (L)	20 (L)	3068 (L)	2058 (VL)	1.72	2.50E-12	>75 years	**8% (1.42)**	***Pass***	47
	Lab Measured	34%	**Moderate-High (1.40)**	30 (L)	19.9 (L)	3186 (L)	2146 (VL)	1.64	2.00E-12				48

**Note: Chloride Durability Evaluation → Bridge Deck in Amarillo, TX; surface chloride conc (Cs)- 0.6%; Reported use of Epoxy coated steel w/ 2 Gal/yd3 CNI ; July (high ambient temp)*

Observations for 29% C ash + 6% SF Mix :

1. **ASR Evaluation: A**dequate to mitigate ASR, the difference between CST & C1567 is <5%, no need for ACCT validation
2. **Mix Satisfies ASR, Chloride & F/T durability**;
3. **Shrinkage → predicted CP is moderate-high due to the addition of 6% SF & low w/cm ratio (0.40) -** *selecting the right placement time (i.e., evening or nighttime) and good curing practice is very important to eliminate early-age cracking potential*

Case Study 2: Bridge Deck Concrete with 29% C Ash+ 6% SF - Amarillo, TX

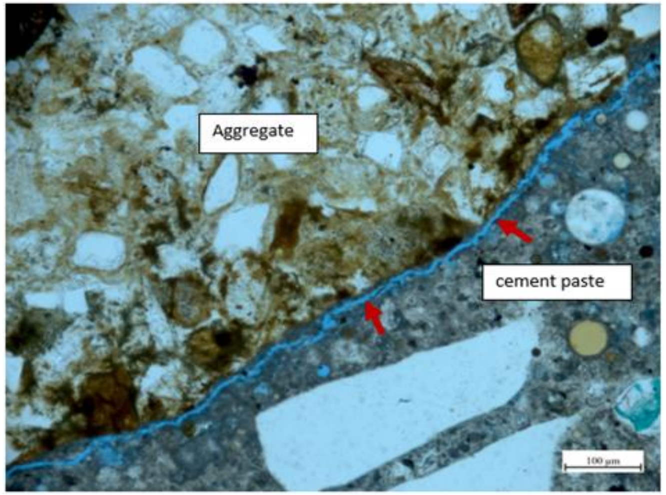
TxDOT Tool Predictions vs. Field Observations

LAB STUDY USING HPC BRIDGE DECK MIXES

Shrinkage	Transport Properties @ early ages (within 28 days)	Durability Performance
Drying shrinkage: *(≤ 400 µs, 28d)* High Autogenous shr ***– increased cracking potential***	Dense microstructure development & permeability reduction *at early ages*	***Good*** - early and later ages

Field Evaluation of Bridge Deck → Amarillo, TX:

- Low w/cm ratio (truck tickets ~0.38-0.4)→ **High autogenous shrinkage strain** *(TxDOT Tool)*
- Early morning concrete placement (truck tickets, 4-7 am) → **“mod-very high” cracking probability** *(ConcreteWorks)*
- ***Overall: Increased potential for early age crack formation → Verified from field observations***



Comprehensive Evaluation of Unconventional Coal Ashes (Our Approach)

ASTM C 618 /C311 (Completed)	**Advanced Characterizations (completed)**	**Reactivity (completed)**	**Effect on Air Entrainment (completed)**	**Soluble Alkali Evaluation (completed)**	**Selective Fresh and Hardened Properties *(in progress)***	**Durability-Based Performance Evaluation *(in progress)***

• Bulk Oxide Composition (XRF)
• Moisture Content
• Fineness, Soundness & Density
• Loss of Ignition *(LOI)*
	• Laser Particle Size Distribution
	• Phase identification and quantification *(QXRD)*
		• R3 Test *(ASTM C 1897)*	• Unburnt Carbon on Air (*Foam Index Test)*	• Water Soluble Alkali (modified *ASTM C 114 test)*
				• Available Alkali Test (*ASTM C 311)*
				•
					• Workability & Water Demand
					• Strength properties (compressive, flexural, etc.)
						• Alkali Silica Reaction (ASR)
						• Shrinkage
						  • *Autogenous,*
						  • *Drying &*
						  • *Cracking Potential*
						• Formation Factor-based Transport Properties
						• Chloride Durability
						  • *time to rebar corrosion*
						  • *probability of failure)*
						• Freeze Thaw (F/T) Durability

Evaluation of Unconventional Coal Fly Ashes *(Blended & Reclaimed Ashes)*

Bulk Oxide Composition – XRF (%)

#	BL1	BL2	R1
Type	Blended Ash-1 *blend of 50% Class C ash and 50% pumice*	Blended Ash-2 *80% Powder River Basin (PRB) coal and 20% lignite coal*	Reclaimed
Class (C618)	F	C	F
SiO2	75.1	48.2	49.1
CaO	9.1	18.3	2.8
Al2O3	18	20.7	25.4
Fe2o3	3.2	5	12.5
MgO	2.1	4	1
SO3	3.4	0.8	0.1
Na2O	3	1.1	0.2
K2O	3.2	1	2.4
Na2Oeq	*5.11*	*1.76*	*1.78*

Quantitative X-Ray Diffraction – QXRD (%)

	BL1	BL2	R1
Amorphous	74.8	48.6	71.9
Calcite		1.3	
Ca-SO4	4.3	3.2	
Fe-Phases			3.6
Merwinite	3.1	10.9	
Periclase		2.5	
Mullite	1.8	5.3	17.4
Quartz	6.8	18.8	7
Arcanite (K_2SO_4)	0.8	2.7	
Na-Feldspar	7		
K-Feldspar	3.3		

Na– Feldspar Phases: (Primary)
- albite → $NaAlSi_3O_8$
- andesine → $NaAlSi_3O$– $CaAl_2Si_2$

K– Feldspar Phases: (Primary)
- orthoclase (monoclinic) → $KAlSi_3O_8$
- microcline (triclinic) → $KAlSi_3O_8$

Evaluation of Unconventional Coal Fly Ashes *(Bottom Ashes)*

Bulk Oxide Composition – XRF (%)

#	**B1**	**B2**
Type	Bottom Ash	Bottom Ash
Class (C618)	F	F
SiO2	41	56.8
CaO	0.6	9.6
Al2O3	20.2	16.8
Fe2o3	11	13.1
MgO	1.5	1
SO3	0.2	0.4
Na2O	1.4	0.9
K2O	0.1	1.4
Na2Oeq	*1.4*	*1.8*

Quantitative X-Ray Diffraction – QXRD (%)

	B1	**B2**
Amorphous	69.4	60.3
Fe-Phases	2.7	12.3
Mullite	16	2.3
Quartz	10	6.2
Arcanite (K_2SO_4)	-	1.4
Ca-Feldspar		16.1

Ca– Feldspar Phases: (Primary)

•anorthite → $CaAl_2Si_2O_8$

Results from Characterization Tests (C 618, contd.)

#	*SiO_2+Al_2O_3+ Fe_2O_3* *(C 618 limit ≥ 70%)*	*SO_3(%)* *(C 618 limit ≤ 4%)*	**Fineness** *% Retained on #325 (45 micron) Sieve* *(C 618 limit ≤ 34%)*	**Laser Particle Size Distribution (d50, micron)**	**Moisture Content (MC, %)** *(C 618 limit ≤ 3%)*	**Loss on Ignition (LOI, %)** *(C 618 limit ≤ 6%)*	**Foam Index Test (AEA ml/100 kg cem)** *(5% vol AEA @ 33% cem replacement)* *[control Class F paste → Foam Index = 5]*
BL1 *(as received)*	96.3	3.4	13%	11.2	1.1%	2.1%	6
BL2 *(as received)*	73.9	0.8	27%	12.5	1.2%	3.2%	7
R1 *(as received)*	87	0.1	14%	19.6	1.7%	3.3%	10
B1 *(after grinding)*	72.2	0.2	**74% (as received)** 21% (after grinding)	**92.9 (as received)** 19.71 (after grinding)	0.8%	**12.6%**	**17**
B2 *(after grinding)*	86.7	0.4	14%	**Chunks (as received)** 4.83 (after grinding)	0.18%	**10.3%**	**15**

- **R1 (Reclaimed Fly Ash)**
  - Low LOI but requires higher AEA dosage to stabilize foam (vs. control). *Limitation → LOI test does not distinguish between unburnt & activated carbon*
  - May require appropriate remediation techniques to remove activated carbon.
- **Bottom Ashes**
  - Grinding is needed to meet C 618 fineness criteria
  - LOI higher than the prescribed 6% limit - Foam index test results agree with high LOI results.

R3 Reactivity Tests for Unconventional Ashes

ASTM C 1897 R3 Reactivity Test & Classification based on Isothermal Calorimetry (0-7 days) & CH Consumption (7th day, TGA Test)

#	7d-Heat Release (J/g SCM)	7d-CH consumed (g/100g SCM)
BL1	197	74
BL2	254	37
R1	214	72
B1	152	54
B2	135	57

Classification based on Reactivity		7d-Heat Release (J/g SCM)	7D-CH consumed (g/100g SCM)	SCMs Evaluated in Current Work	#TTI's Database of other SCMs
Inert	Non-Reactive	<120	<50		Quartz
Hydraulic	Less Reactive	120-370		BL2	*Class C Fly Ash*
	More Reactive	>370			
Pozzolanic	Less Reactive	120-370	50-100	BL1, R1 B1, B2	Class F Fly Ashes Natural Pozzolans *(volcanic origin e.g., pumice, etc)*
	More Reactive	>370	>100		Silica Fume, Metakaolin Calcined Clays

Preliminary Limits – Based on Limited Testing (TTI) & Literature – [Kalina et al.,(2019), Suraneni et al., (2019)]
Further Evaluation in progress

Soluble Alkali, Chemical Screening Tool (CST) & ASR Test

	Total Bulk Alkali *(TA, XRF)*	Water Soluble Alkali (WSA, ASTM C 114 mod.)	Available Alkali (AA, ASTM C 311)	Chemical Screening Tool (CST) Prediction *(for R2 Aggregate)*	AASHTO TP 142 (ACCT) ASR Tests *(for R2 Aggregate)*
#	*TA, Na_2O_{eq}*	*WSA, Na_2O_{eq} (%TA)*	*AA, Na_2O_{eq} (%TA)*	**Optimum SCM dosage % (PSA ≤ THA=0.34N)**	**Expansion @ % SCM *(at 78 days)*** *(threshold limit 0.04%)*
BL1	5.11	0.29 (5.7%)	0.98 (22%)	45%	0.060% @35%
BL2	1.76	0.06 (3.6%)	1.1 (63%)	30%	0.027% @ 35%
R1	1.78	0.07 (4%)	0.49 (28%)	29%	0.014% @ 35%
B1	1.4	0.07 (5%)	0.84 (58%)	29%	
B2	1.8	0.13 (7.3%)	0.73 (40%)	35%	

Comparative Assessment Of Durability Evaluation For The Unconventional Ashes

	ASR EVALUATION *(DOSAGE FOR ASR MITIGATION)*		**SHRINKAGE EVALUATION**	**RESISTIVITY TESTS *(under progress)***	**CHLORIDE & F/T DURABILITY EVALUATION (PREDICTED) *(Lab Validation after obtaining resistivity data)***
	Prediction (CST)	***ASR Test (ACCT)***	***Cracking Potential (CP)***	***Curing & Conditioning Procedure*** *(based on PSC using TTI-Model 2)*	***Anticipated Predictions*** *(Tool inputs to be revised based on resistivity data, followed by lab validation of predictions)*
BL1	~ 45%	40%	Low CP	MPS, AC2@28 days	Ternary blend with SF will work better
BL2	30%	<35%	Low CP	SPS, AC2@28 days	Adequate chloride durability performance may not be satisfied - poor microstructure development (may be connected to poor reactivity based on R3 test)
R1	29%	<35%	Low CP	SPS, AC2@28 days	Behave like Classical Class F Fly ash
B1	29%	NA	Low CP	SPS, AC2@28 days	
B2	35%	NA	Low CP	SPS, AC2@28 days	

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THANK YOU

ANY QUESTIONS ?

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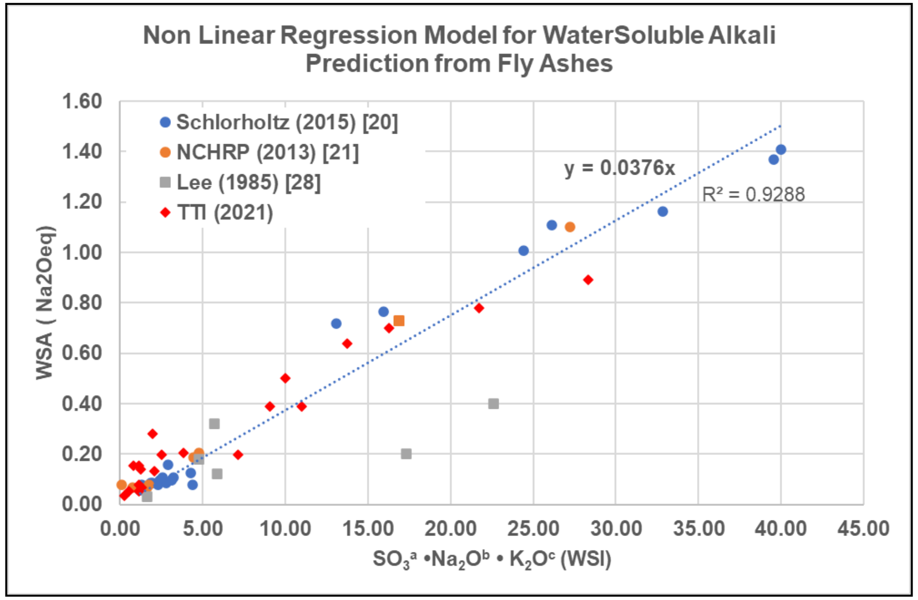
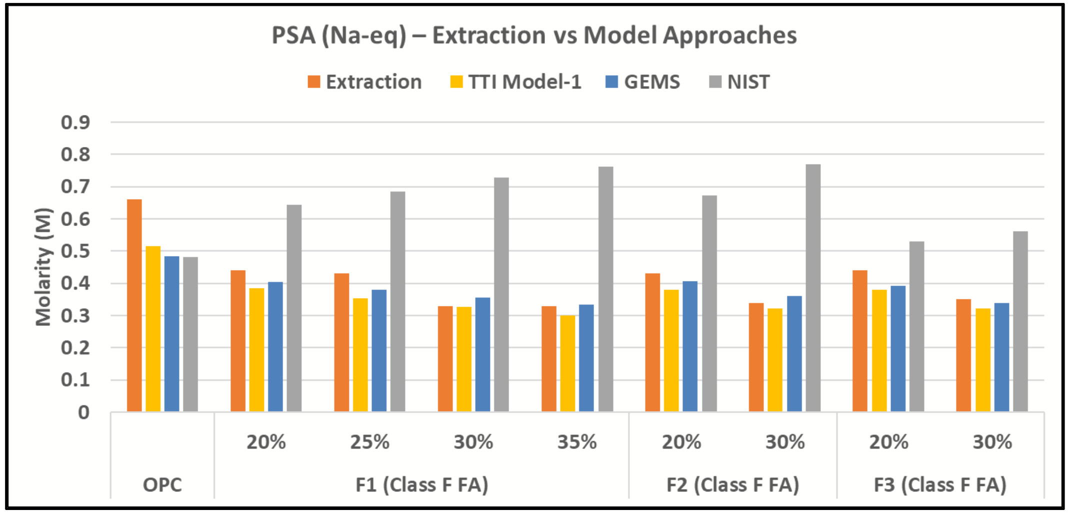
TTI Model-1: Pore Solution Alkalinity (PSA)

Major Findings & Results

1. Certain Class C FA and blended fly ashes contribute very high levels of soluble alkali at early ages
   - Significant modification of concrete PSA by FA
2. Nonlinear Regression Model to predict WSA
   - Primary Variables → Na_2O, K_2O & SO_3
   - R2=0.92, MAE = 6.7%
3. TTI Model-1 Performance
   - Good reliability in PSA Determination
   - 4.3% MAE, 6.2% RMSE with extraction measurements





ASTM C 1581 Single Ring Shrinkage Tests: Results & Cracking Potential Discussion

Mix #ID	Single Ring Test (ASTM C 1581/AASHTO T 334)			28 days Drying Shrinkage (µs)	Cracking Potential *Based On Drying Shrinkage (DS)*		
	Crack ?	Peak Strain in Ring (µs) *28-days*	Cracking Potential		Cracking Potential (Only DS, no creep)	Creep (CP) *(B3 Model)*	Cracking Potential (DS + Creep)
CEM				400	**Mod-High**	1.22	**Mod**
6SF	**No**	162	**Mod-Low**	436	**Mod-High**	1.46	**Mod**
25F	**No**	135	**Mod-Low**	250	**Low**	0.86	**Low**
20F5SF	**No**	133	**Low**	280	**Low**	0.83	**Low**
35F			**-**	230	**Low**	0.66	**Low**
35C	**No**	109	**Low**	300	**Low**	0.84	**Low**
29C6SF	**No**	115	**Low**	350	**Mod-Low**	1.1	**Mod**
35C10SF			**-**	382	**Mod-High**	1.31	**Mod**

- **Single Ring Tests**
  - **No rings cracked at 28 days**
  - **Cracking Potential: Low to Moderate-Low**
  - **Peak Strain at 28 days: 162 microstrain (6SF)**
- **Cracking Potential Based On Drying Shrinkage**
  - **C157 DS+ Creep → Good Predictor of Ring Test Performance**
  - **Considering creep is Important**
    - ***Almost Similar Classification to Ring Test Results***

Evaluating Cracking Potential for HPC Mixes

Cracking Potential Based on Ring test – ASTM C 1581 Classification

Net Time to Cracking (days)	Average Stress Rate (psi/day)	Cracking Potential (σring/f't)	Potential for Cracking Classification
$0 < t_r \leq 7$	S ≥ 50	>2.75	High
$7 < t_r \leq 14$	$25 \leq S < 50$	2.15 – 2.75	Moderate-High
$14 < t_r \leq 28$	$15 \leq S < 25$		Moderate-Low
$t_r > 28$	$S < 15$	<2.15	Low

Cracking Potential Based on Free Drying Shrinkage (ASTM C 157)

CPI – Only Free Drying Shrinkage And No Creep

CP – Free Drying Shrinkage + Creep

Fu et al., 2013 – Iowa State, Oregon DOT, 2015

Cracking Potential Indicator (CPI)	Cracking Potential (CP)	Potential for Cracking
CPI ≥ 4.0	CP > 1.5	High
3.0 ≤ CPI < 4.0	1 < CP ≤ 1.5	Moderate-High
2.5 ≤ CPI < 3.0		Moderate-Low
CPI < 2.5	CP ≤ 1	Low

Drying Shrinkage (DS) & Autogenous Shrinkage (AS) Evaluation for HPC Mixes

SUMMARY OF DRYING SHRINKAGE PERFORMANCE								
	CEM	**6SF**	**25F**	**2055SF**	**35F**	**35C**	**29C6SF**	**35C10SF**
Cem Content (lb/yd3)	580	520	584	584	584	520	541	541
Paste Volume %	26.3%	25.8%	26.1%	26.2%	26.3%	25.3%	25.6%	25.8%
28-day DS (µs)	400	436	250	280	230	300	350	382
Ring Test *Crack?*		No	No	No		No	No	
Cracking Potential	Mod	Mod	Low	Low	Low	Low	Mod	Mod
7-28 Days Strain Rate	***17.39***	***18.11***	*10.60*	***12.23***	*10.06*	*11.73*	***14.44***	***15.57***

	CEM	**6SF**	**25F**	**20F5SF**	**35F**	**35C**	**29C6SF**	**35C10SF**
AS – 7days , (µs)	89	102	55	70	50	65	69	80
AS – 28 days, (µs)	150	165	50	90	45	80	122	154
DS – 28 days, (µs)	400	436	250	280	230	300	350	382
% AS/DS - 28 days	38%	38%	20%	32%	20%	27%	35%	40%
AS Strain Rate *(0-28 days)*	5.11	6.88	2.21	3.79	1.54	3.07	4.98	5.74
DS Strain rate *(7-28 days)*	17.39	18.11	10.6 0	12.23	10.06	11.73	14.44	15.57

- Current HPC Mix Practice in Texas appear to be optimized for drying shrinkage performance
  - Low Cementitious Contents (520-584 lbs./CY), Low W/cm ratio – 0.40-0.42
  - Paste Volume – 25-26%, ~ 75% Aggregate Volume

- Low w/cm ratio W/ HRWR + Silica Fume → High AS
  - AS in C ash + SF mixes comparable with AS in control mix (CEM)
- Higher early age AS strain rate in the Ternary, 6SF and CEM mixes
- The higher the AS strain rate, the higher the DS strain rate

Models for Shrinkage Prediction

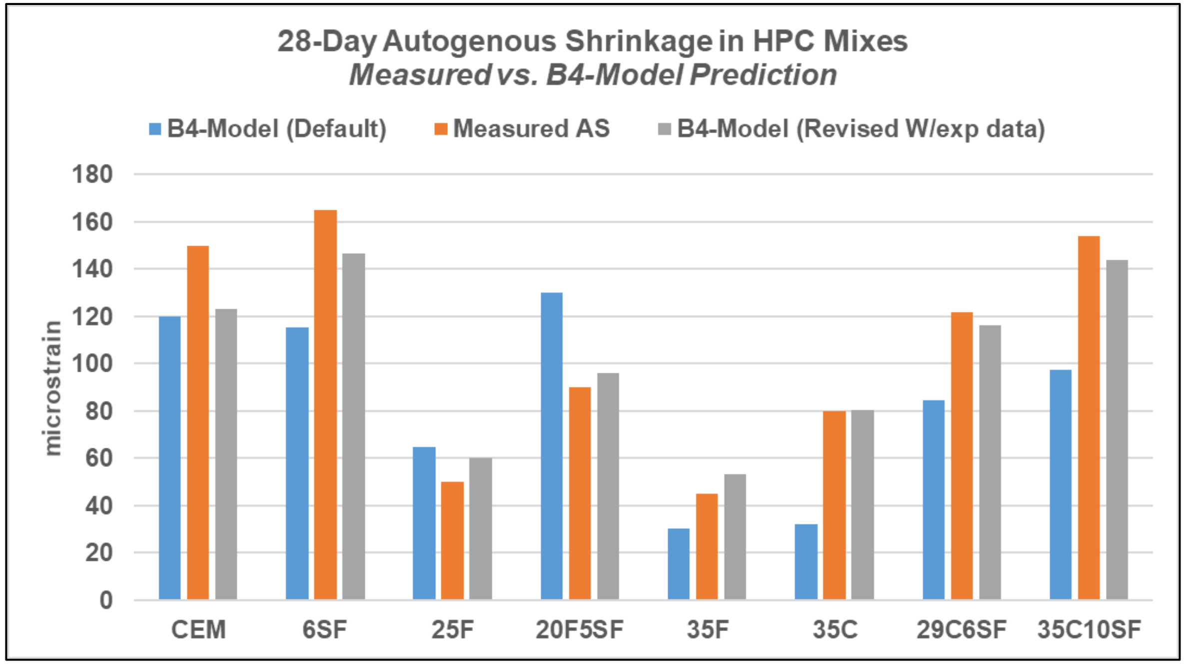
- Objective: A model to predict drying shrinkage & autogenous shrinkage based on w/cm ratio, binder composition & concrete mix proportions *(incorporating the effect of paste volume)*. Primary considerations
  - **Predicts Autogenous Shrinkage**
  - **Sensitive to Effect of Silica Fume Addition on Autogenous Shrinkage Strain Predictions**
  - **Incorporates SCM effect (type & replacement level) in Drying Shrinkage Strain Predictions**

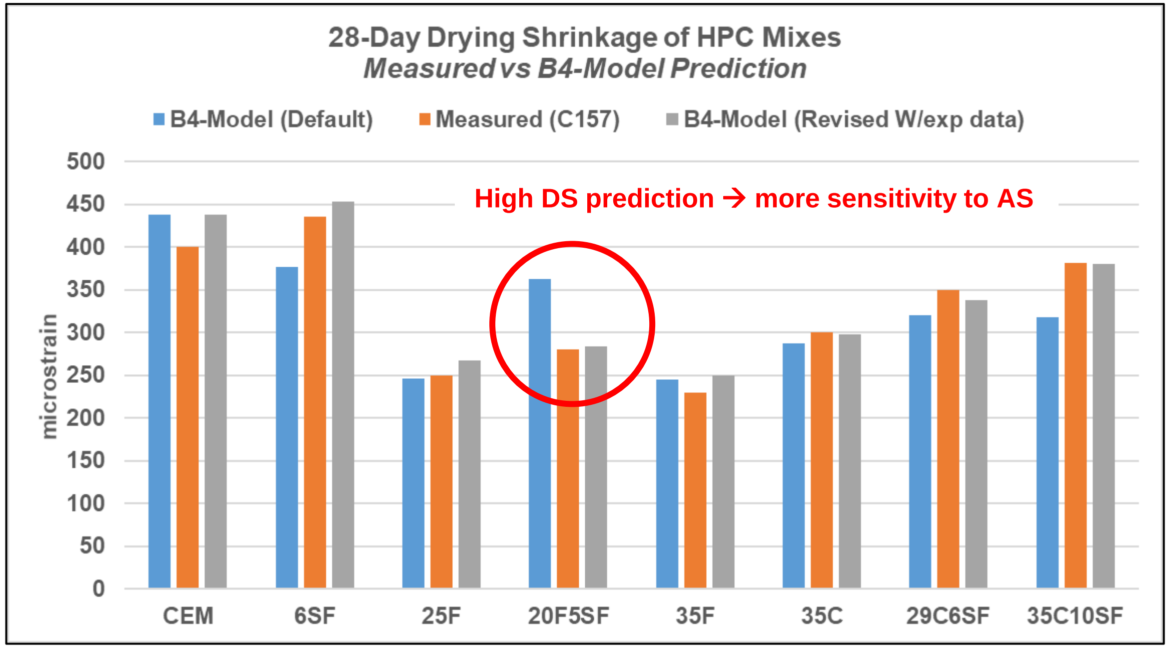
We explored available models from ACI-209 & RILEM TC 242

	Drying Shrinkage (DS)	**Autogenous Shrinkage (AS)**
ACI 209-R	Only CEM *SCM effect incorporated as cement replacement*	×
Bazant-Baweja B3		×
RILEM B4 Model, 2015	✓ *(flexible model parameters flexible to include SCM effect & modify)*	✓

RILEM B4 Model TC 242
DS & AS evaluated based on 1. Binder composition 2. Concrete Mix Proportions 3. W/cm ratio 4. SCM type & replacement levels
Minimal Additional inputs 1. Specimen Dimensions 2. Initial curing conditions – Temp & Duration 3. Ambient Exposure 4. Age for Evaluation

B4 Model & B4 Model (revised parameters) vs. Lab Data





1. Default B4- model parameters (blue bars)
    - not sensitive to Class C vs. Class F Fly ash differences.
    - Highly sensitive to SF & total cement replacement for ternary mixes

2. Model parameters (grey bars) were revised based on experimental data

Approaches to Determine Concrete Pore Solution

ACCURACY - RELIABILITY - COMPLEXITY

Parameter		**NIST Model (Bentz et al., 2007)**	**NIST + ASTM C 311 (Mukhopadhyay et al., 2019)**	**TTI Model-2**	**GEMS Thermodynamic Modelling (Lothenbach., 2008)**
Overall Approach		Empirical	Empirical	Mix of Empirical & Kinetic Modelling	Thermodynamic model
Soluble Alkali from Ingredients	Cement & Silica Fume	75% of Bulk Alkali	75% of Bulk Alkali	75% of Bulk Alkali	Alkali dissolution based on Ingredient's degree of reaction *(measured → QXRD/ TGA/ SEM)*
	Fly Ash (FA)		Available Alkali (AA,ASTM C 311)	Machine Learning Model for direct AA prediction *(Input XRF)*	
Alkali Binding		✓ Silica Fume ✗ Fly ashes & Cement	✓ Silica Fume ✗ Fly ashes & Cement	✓ Silica Fume, Fly Ash & Cem *CSH predictions & distribution ratios*	✓Silica Fume, Fly Ash & Cem *In Built CSHQ model*
Ease of Use & Reliability		• Rapid approach • *High error & Low reliability for FA mixes*	• Rapid approach & Improved accounting for FA soluble alkali • *Does not Consider of alkali binding from FA* • *ASTM C 311 test discontinued*	• Rapid Estimating Tool & Easy to Implement • Higher Reliability compared to other rapid approach Models	• Accurate & High Reliability • *However, reliability → accuracy in quantifying minerology & degree of reaction inputs* • *Complex and not suited for rapid implementation*

TTI Model-2: Pore Solution Chemistry Prediction (Methodology)

Concrete PSC prediction by accounting for

1. Total soluble alkali contribution from all concrete ingredients
2. Effect of alkali binding by hydration product (CSH) from Cement, FA & SF pozzolanic reactions.

$$Na^{+}\left(\frac{mol}{L}\right) = \frac{\sum_{i}^{n} \frac{\left(2m_{f,i}^{(Na_2O)} \cdot \frac{M_i}{M_{cm}} \cdot f_i\right)}{mm_{Na_2O}}}{\left[\left(\frac{w}{cm} - \sum_{i}^{n} k_i \alpha_i\right) + \left(\sum R_d \cdot m_{CSH}\right)\right]}$$

- **Total Soluble alkali dissolution from cement & SCMs**
  - *fi → AA/TA ratio*
  - *fi for Cement & SF → 75% (NIST)*
  - *fi for Fly Ashes → Available alkali (using Machine Learning model)*

- **Alkali Binding by hydration products (CSH)**
  - ***m_{csh}*** *→ mass and Ca/Si stochiometric composition for CSH (literature & refined by GEMS modelling)*
  - ***Rd*** *→ distribution ratio of alkali in hydration product based on Hong & Glassier (1999)*

$$R_d = \frac{\text{alkali in solid } C-S-H \left(\frac{mM}{g}\right)}{\text{alkali concentration in solution } (mM/mL)}$$

Ca/Si	Rd	
1.8	0.4-0.5	Hong and Glassier (1999,2001)
1.5	0.8 – 1.0	
1.2	1.5 – 2	
0.85	4-5	

Cement Hydration	$C_3S + 2H = 0.5C_{1.7}S_1H_{1.5} + 0.5\,CH$
	$C_2S + 3H = 0.5\,C_{1.7}S_1H_{1.5} + 1.5\,CH$
Fly Ash Hydration	$1.5\,CH + S = C_{1.5}SH_{1.5}$
Silica Fume Hydration	$S + 1.1\,CH + 2.8\,H = C_{1.1}SH_{3.9}$

(De Weerdt et al., 2011; Fan et al., 2015; Haha et al., 2010; Liao et al., 2019; Lothenbach et al., 2011; Ramanathan et al., 2019; Zeng et al., 2012)

TTI Model-2: Research Approach

Experimental Study

- Available Alkali (AA) from Fly Ashes (*ASTM C 311)*
- QXRD Measurements
- GEMS Modelling

Machine Learning Model Development

- Bayesian ML Model to predict AA from FA
- 230 Data Points (1980-2019)
- 75%/25% train/test

Development of TTI Model-2

- Combined Effect of

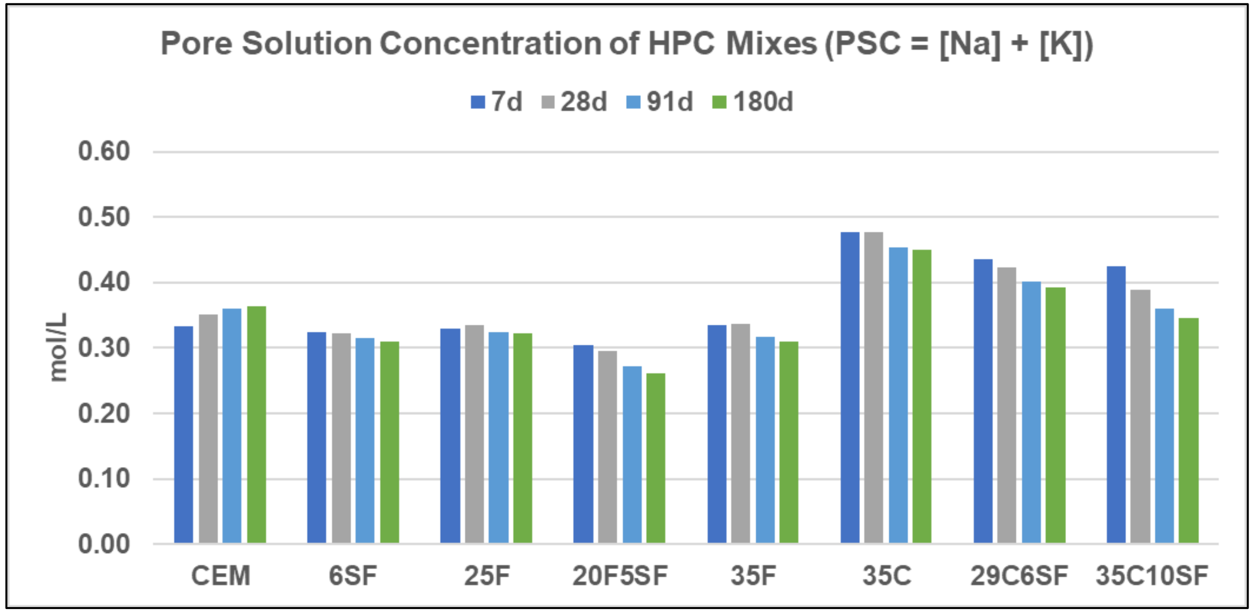
1.Soluble Alkali from CEM & SF
2.Available Alkali from FA
3.Alkali Binding by pozz. CSH

Validation Study

- Extraction Measurements
- GEMS Thermodynamic Modelling

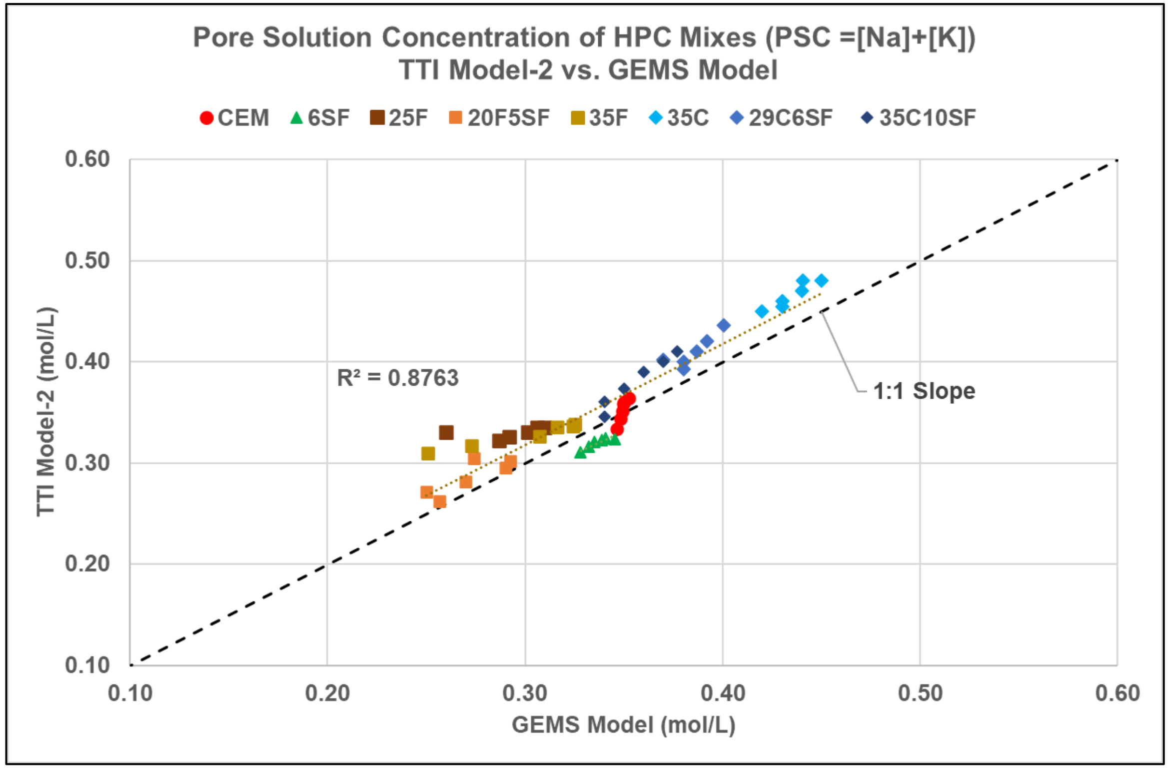
TTI Model-2: Results & Validation

TTI Model-2 PSC predictions for binary & ternary mixes from 7-180 days of hydration



TTI Model-2 PSC vs. GEMS Thermodynamic Model

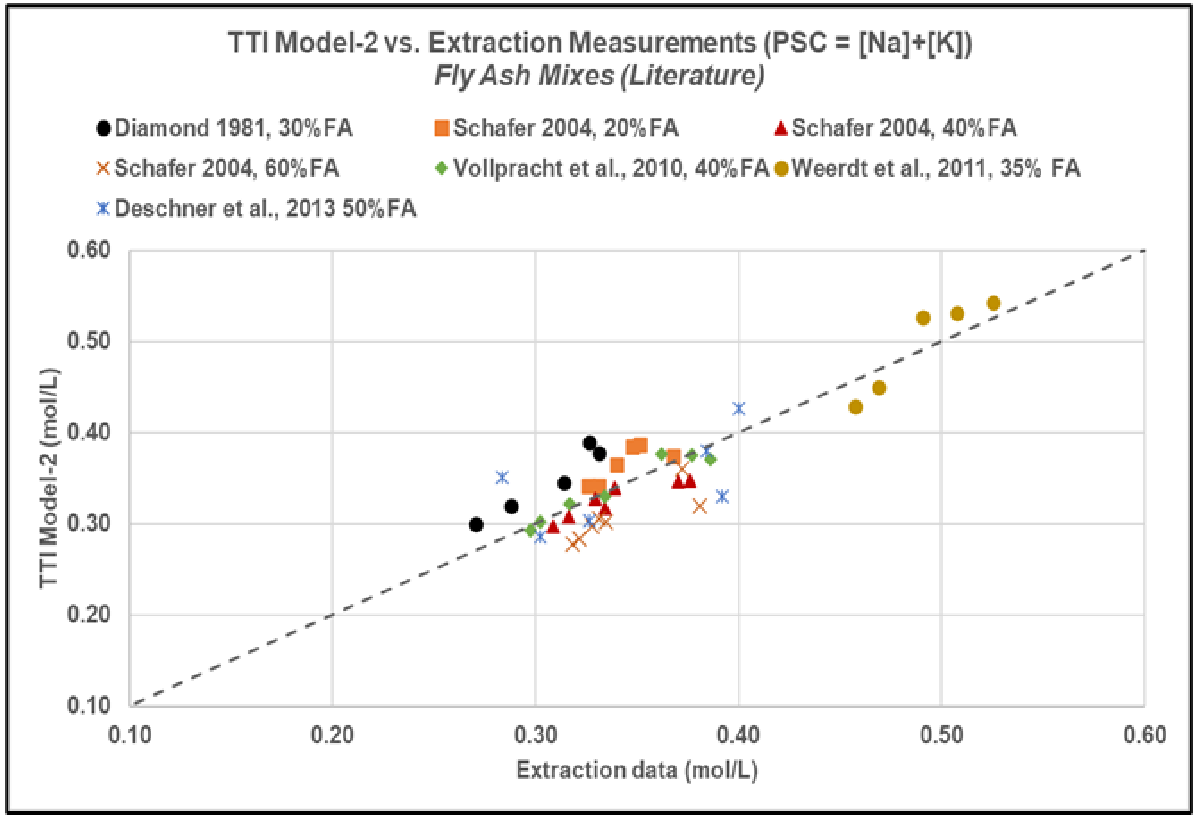
Marginally higher for FA mixes (secondary hydration products); model R2~ 87%

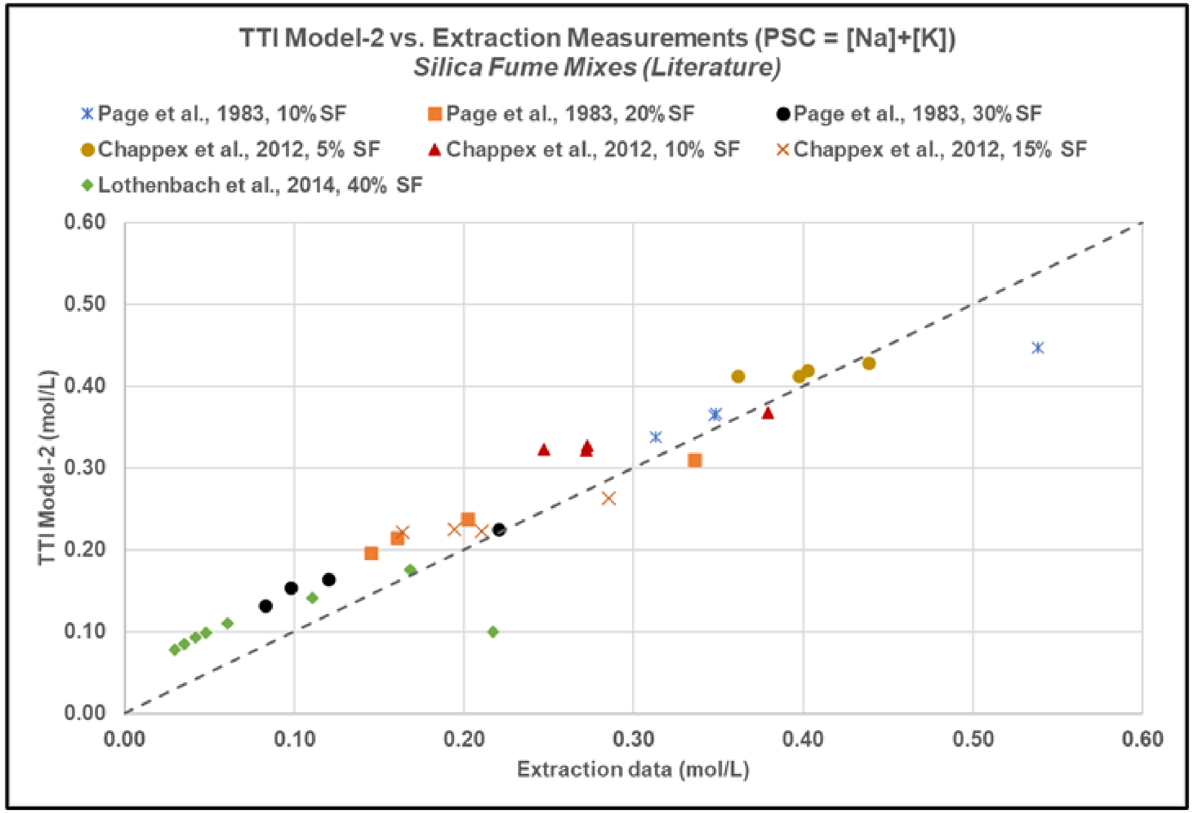


TTI Model-2: Results & Validation

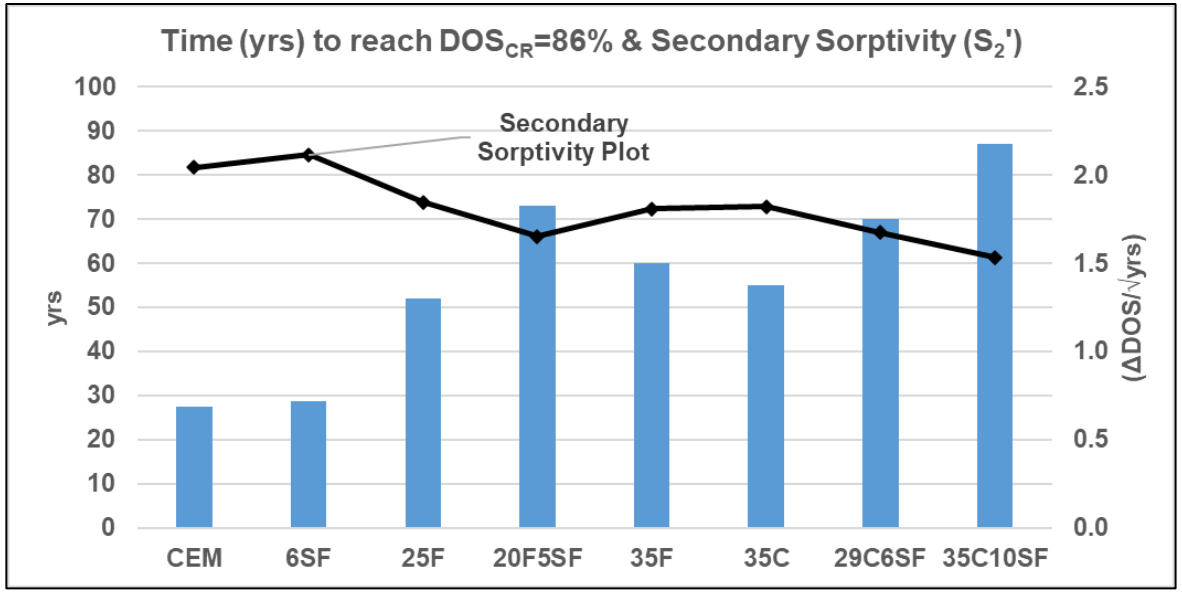
TTI Model-2 PSC vs. Literature Extraction Measurements

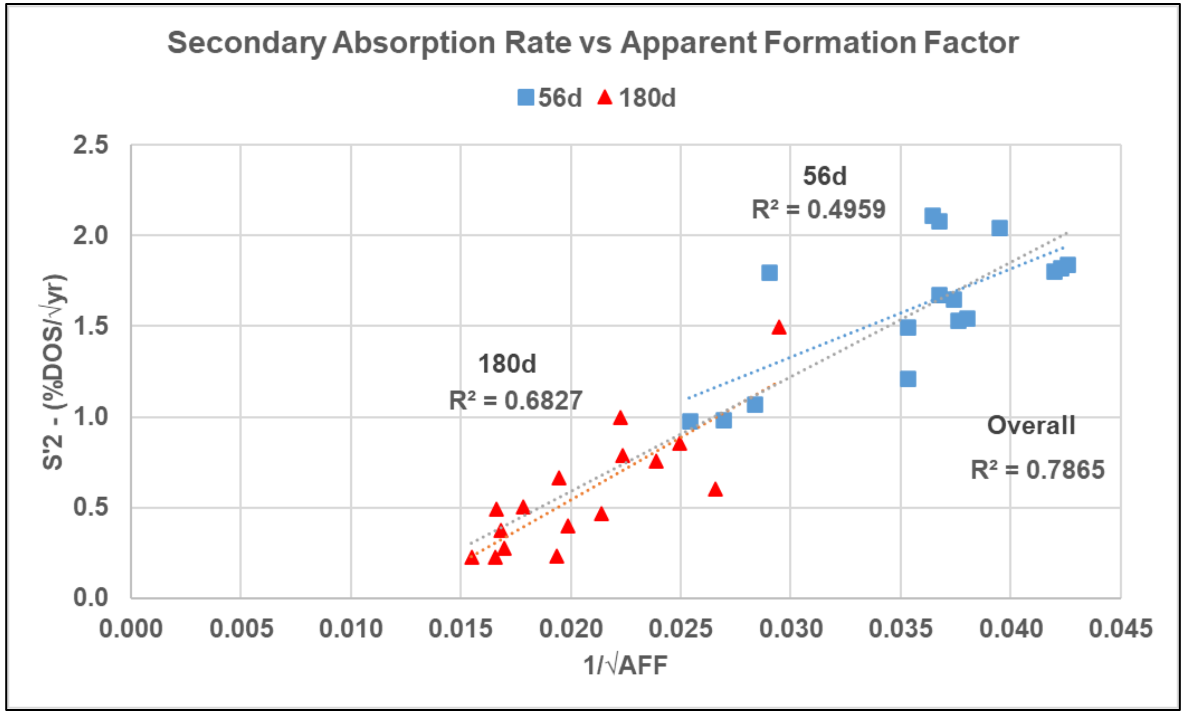
- Fly Ash Mixes → MAE ~ 7.8%
- SF Mixes → MAE ~ 10.3%





Estimation of F/T performance Using Resistivity / Apparent Formation Factor





- Time to Critical Saturation using Experimental Secondary Sorptivity (ASTM C 1585)
- Pore Solution Curing Resistivity → Apparent Formation Factor → Secondary Sorptivity (Above) → Time to Critical Saturation