Development of the TxDOT Tool for Rapid Durability-Based Performance Evaluation of HPC Mixes (Project 0-6958)

Anol Mukhopadhyay – Principal Investigator (PI)
Pravin Saraswatula – Assistant Research Scientist

TxDOT Construction, Materials, and Alternative Delivery 2024 Conference
March 26, 2024, 3:30 – 4:30 PM CST, The Royal Sonesta Galleria, Houston, Texas

TEXAS A&M UNIVERSITY

Texas A&M Transportation Institute

Agenda

Presenting the TxDOT Tool

- ❖Our rapid durability-based performance evaluation approach led to the development of TxDOT Tool
- ❖Explaining input sheets, calculation sheets, and outputs
- ❖Field Case Studies to explain the usefulness of the Tool
- ❖A comprehensive durability-based performance evaluation using the Tool addresses the development of innovative performance-based specifications for HPC

Future work

Project 0-6958: Introduction

TxDOT employs Class S High-Performance Concrete (HPC) predominantly for bridge deck construction in Texas

› TxDOT's current HPC mix design options

Options 1-5 (primarily designed for ASR prevention): Predominantly Prescriptive with Min Performance Control

- ❖ SCMs: Class F & Class C Fly Ash (FA) & Silica Fume (SF)
- ❖ Max. w/cm ratio; Air content, Max. cementitious content, Min. 28-day compressive strength, and RCPT (ASTM C 1202)
- ❖ Indirect Approach: Use of SCMs + 28-day strength, air content, low w/cm, etc. for → shrinkage control & permeability reduction
- ❖ NO threshold limits for performance indicators related to drying shrinkage, transport properties, chloride, freeze-thaw durability

4.2.6. **Mix Design Options**.

4.2.6.1. **Option 1**. Replace 20% to 35% of the cement with Class F fly ash.

4.2.6.2. **Option 2**. Replace 35% to 50% of the cement with slag cement or MFFA.

4.2.6.3. **Option 3**. Replace 35% to 50% of the cement with a combination of Class F fly ash, slag cement, MFFA, UFFA, metakaolin, or silica fume; however, no more than 35% may be fly ash, and no more than 10% may be silica fume.

4.2.6.4. **Option 4**. Use Type IP, Type IS, or Type IT cement as allowed in Table 5 for each class of concrete. Up to 10% of a Type IP, Type IS, or Type IT cement may be replaced with Class F fly ash, slag cement, or silica fume. Use no more than 10% silica fume in the final cementitious material mixture if the Type IT cement contains silica fume, and silica fume is used to replace the cement.

4.2.6.5. **Option 5**. Replace 35% to 50% of the cement with a combination of Class C fly ash and at least 6% of silica fume, UFFA, or metakaolin. However, no more than 35% may be Class C fly ash, and no more than 10% may be silica fume.

4.2.6.6. **Option 6**. Use a lithium nitrate admixture at a minimum dosage determined by testing conducted in accordance with Tex-471-A. Before use of the mix, provide an annual certified test report signed and sealed by a licensed professional engineer, from a laboratory on the Department's MPL, certified by the Construction Division as being capable of testing according to Tex-471-A.

4.2.6.7. **Option 7**. Ensure the total alkali contribution from the cement in the concrete does not exceed 3.5 lb. per cubic yard of concrete when using hydraulic cement not containing SCMs calculated as follows:

$$\text{lb. alkali per cu. yd.} = \frac{(\text{lb. cement per cu. yd.}) \times (\%\ Na_2O \text{ equivalent in cement})}{100}$$

In the above calculation, use the maximum cement alkali content reported on the cement mill certificate.

(Item 421 Hydraulic Cement Concrete, TxDOT 2014)

Identify Critical Durability Indicators Through Different Tasks in the Project

To Identify Critical Durability Indicators that influence the field performance of HPC mixes, a combined approach was used involving:

1. Field investigation of selective HPC bridge decks & laboratory study of field cores (Tasks 3-4) covering current mix design practices (green highlighted mixes)
   - *5 Bridge Decks in Amarillo, 2 Bridge Decks in Lubbock, and 2 Bridge Decks in Galveston*
   - *To understand whether the selected HPC deck mixes meet the HPC requirements*

2. Detailed Lab evaluation program (Tasks 4-6): *Formulate 8 (7 + 1 control) representative mixes covering Item 421*
   - *commonly used SCM replacement levels in the State of Texas, and covering the min-max (low & high ends) replacement percentage for the current mix design options*
   - *Identify the performance indicators to do durability-based performance evaluations*

HPC Mix designs for Field Study *(green highlighted)* and Laboratory Evaluation *(all)*

Option	Mix	#1	#2
1	Replace 20% to 35% of the cement with Class F fly ash.	25% Class F Fly Ash *(Galveston, TX)*	35% Class F Fly Ash
3	Replace 35% to 50% of the cement with a combination of Class F fly ash or silica fume; however, no more than 35% may be fly ash, and no more than 10% may be silica fume.	20% Class F Fly Ash + 5% Silica Fume	
5	Replace 35% to 50% of the cement with a combination of Class C fly ash and at least 6% of silica fume. However, no more than 35% may be Class C fly ash, and no more than 10% may be silica fume.	29% Class C Fly Ash + 6 % Silica Fume *(Amarillo, TX)*	35% Class C Fly Ash + 10% Silica Fume
X	Binary Mixes *(Project Specific Mix Design Options)*	6% Silica Fume *(Amarillo, TX)*	35% Class C Fly Ash *(Lubbock, TX)*

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

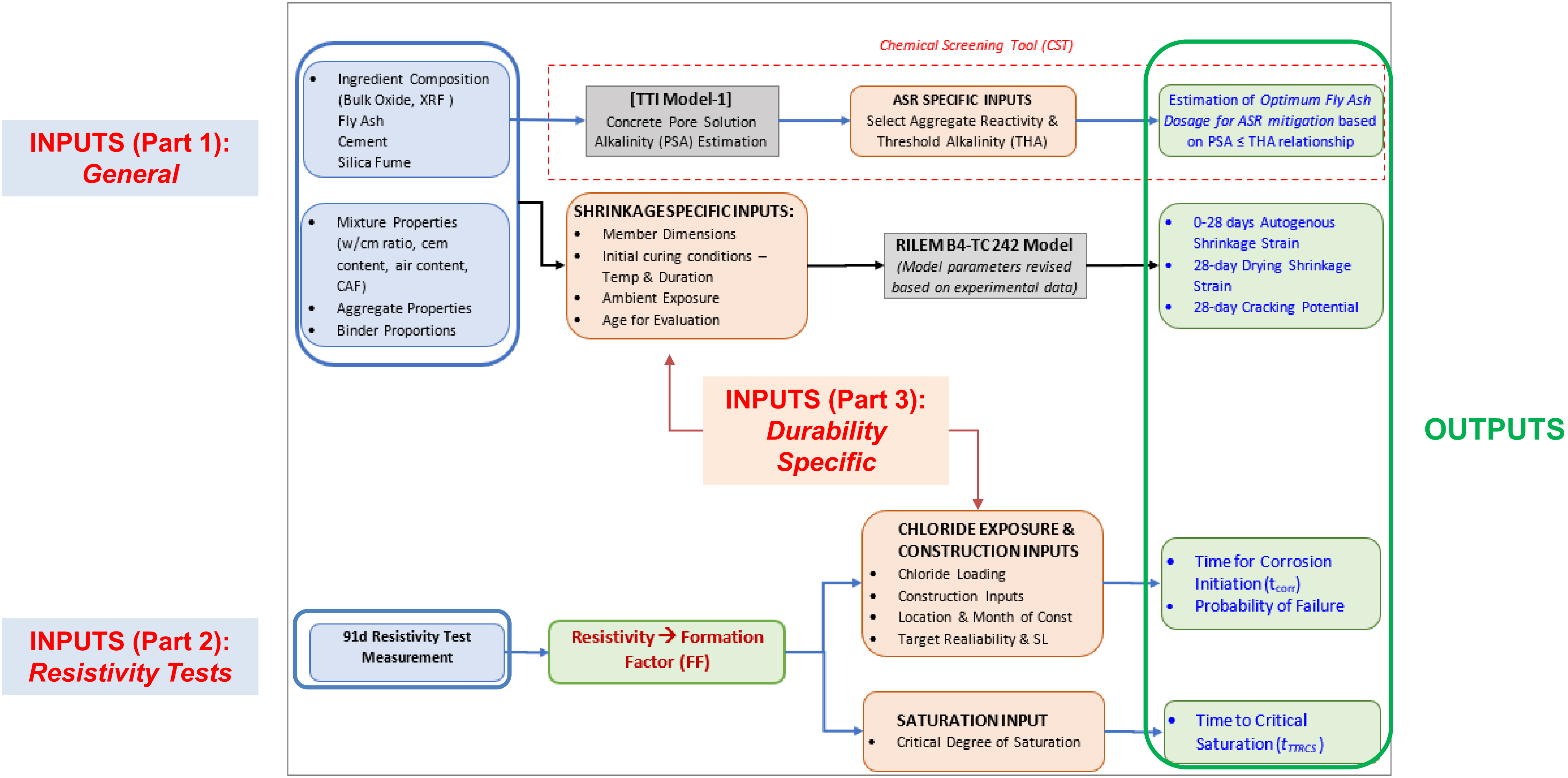
Rapid & comprehensive durability-based performance evaluation of cast-in-place **High-Performance Concrete (HPC)** bridge deck mixes during the **mix design stage, trial batch stage and/or field mix**.

› 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 and Cracking Potential based on RILEM B4 Model (RILEM TC 242)
3. **Chloride Durability:** resistance to chloride ion ingress:
    1. Estimated Time to Rebar Corrosion.
    2. Determination of Probability of Failure Based on Target Reliability Levels (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

TxDOT Tool: Input-Output Connections in the form of a Flow Chart



TxDOT Tool

Three Sections

5 INPUT SHEETS

↓

5 CALCULATION SHEETS →

↓

OUTPUTS

› **Calculation Sheets:** Background calculations, Prediction Models & Experimental data (Task 3 – Task 8)

1. Mixture Proportioning & Hydration Modelling (mod. Powers model)
2. Pore solution models (TTI Model-1 & TTI Model-2)
3. Shrinkage Evaluation
4. Resistivity-FF (also contains F/T durability model)
5. Chloride diffusion Modelling

↓

Use of experimental data (Tasks 3-8)

- ❖ Power model – hydration prediction
- ❖ TTI Model-2: alkali binding factors refined by GEMS and literature extraction
- ❖ Shrinkage – model corrections to fit the studied HPC mixes
- ❖ Resistivity-Formation Factor(FF): determination of saturation correction factors
- ❖ Cl diffusion: Binding model refinement

TxDOT Tool: Inputs (Part 1)

Key Input – **Project Information Sheet**

Direct Inputs from the 2014 TxDOT Mix Design Sheet

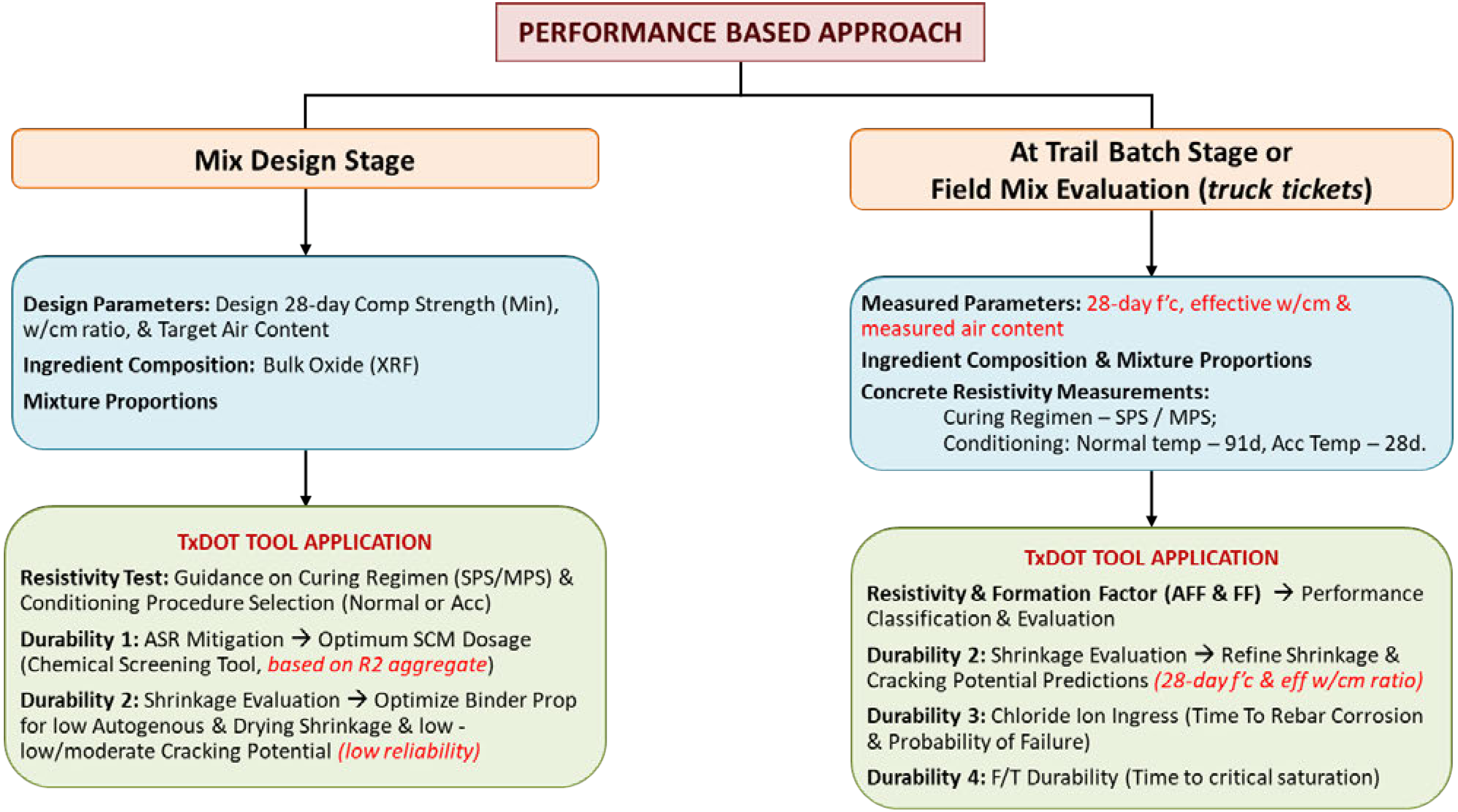
1. **HPC mix information***
2. Material & Mix Proportions
   - *Aggregate Properties*
   - *Cementitious Materials*
   - *Proportions*
3. Ingredient Composition

PROJECT INFORMATION (HYDRAULIC CEMENT CONCRETE MIX DESIGN & CONTROL)			
Remarks: *Input sheet for project summary information (Reference: TxDOT 2014-Hydraulic Cement Concrete Mix Design & Control)*	***Color Guide & Notation***	(blue)	**User Input**
		(orange)	**Select From List Option**
		(yellow)	**Warning Text or Note**
		(green)	**Intermediate Output**

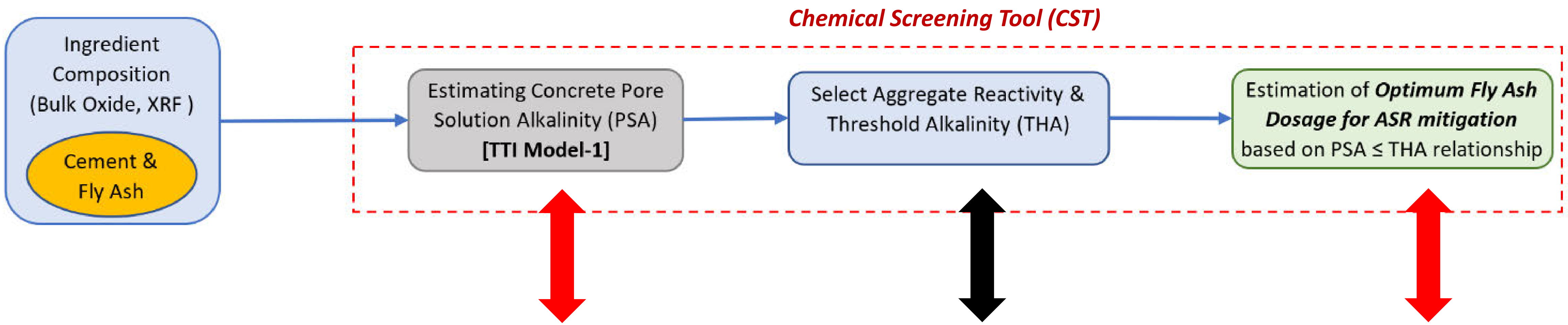
Project Information

		Comments	*Ref (2014 TxDOT Mix Design Sheet)*
Concrete Class on Plans:	Class S HPC		*Project Summary*
Compressive Strength, 28-Day f'c (psi):	4000	Design or Measured	*Project Summary or Trial Batch Results*
Mix design w/c or w/cm:	0.42	Design or Field	*Water&Cement or Truck Tickets*
Total Cementitious Content (lbs/CY):	504	Mix Design max.	*Water&Cement*
Air Content (%):	5.5%	Target or Measured	*Air-Entrainment or Trail Batch Results*
Specified Coarse Aggregate Factor (CAF):	0.71		*Dry Batch Weights*

Application of TxDOT Tool at Different Stages, Inputs & Outputs



TxDOT Tool Approach: Chemical Screening Tool (CST) to Predict Optimum SCM Dosage for ASR Prevention



A combined effect of water-soluble alkali (WSA) from both cement and fly ash

Cement WSA: 75% of bulk Na2Oeq (NIST)

Fly ash WSA:

- Measured: Mod. ASTM C114: 1 day
- Predicted: Non-linear regression model

AASHTO T364	
R3	0.29
R2	0.34 (HR) 0.38 (LR)
R1	0.45

Uses Excel Solver function

1. *Saraswatula, P., Mukhopadhyay, A., & Liu, K. W. (2022). Development of a Screening Tool for Rapid Fly Ash Evaluation for Mitigating Alkali Silica Reaction in Concrete. Transportation Research Record*
2. *Liu, K. W., & Mukhopadhyay, A. K. (2016). Accelerated concrete-cylinder test for Alkali-Silica Reaction. Journal of Testing and Evaluation*
3. *Mukhopadhyay, A. K., Liu, K. W., & Jalal, M. (2019). An innovative approach to fly ash characterization and evaluation to prevent alkali-silica reaction. ACI Materials Journal, 116*

Our Performance-Based ASR Evaluation Approach

Step 1: Use the 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 the 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 the dosage difference is > 5% (e.g., 6-10%) → **ACCT (AASHTO TP 142) validation is mandatory**
- If the dosage difference is < 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)

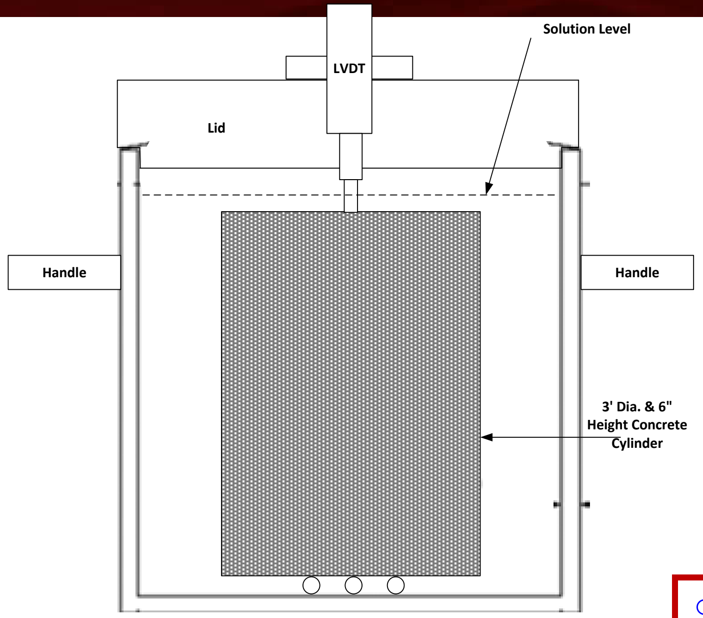
AASHTO Designation: TP 142-21

Technical Subcommittee: 3C, Hardened Concrete

Release: Group 1 (Month yyyy) July 2021

AASHTO

American Association of State Highway and Transportation Officials
444 North Capitol Street N.W., Suite 249
Washington, D.C. 20001



- 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.

TxDOT Tool Approach for Shrinkage Evaluation

- Inbuilt RILEM B4 model for **Autogenous & Drying Shrinkage** prediction and **Cracking Potential** estimation of HPC Mixes
  - *Replaces laborious and time-consuming laboratory tests*

Mix Design Inputs

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

→

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)*

→

Tool Predictions

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

→

Tool Output

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**

Validation Testing

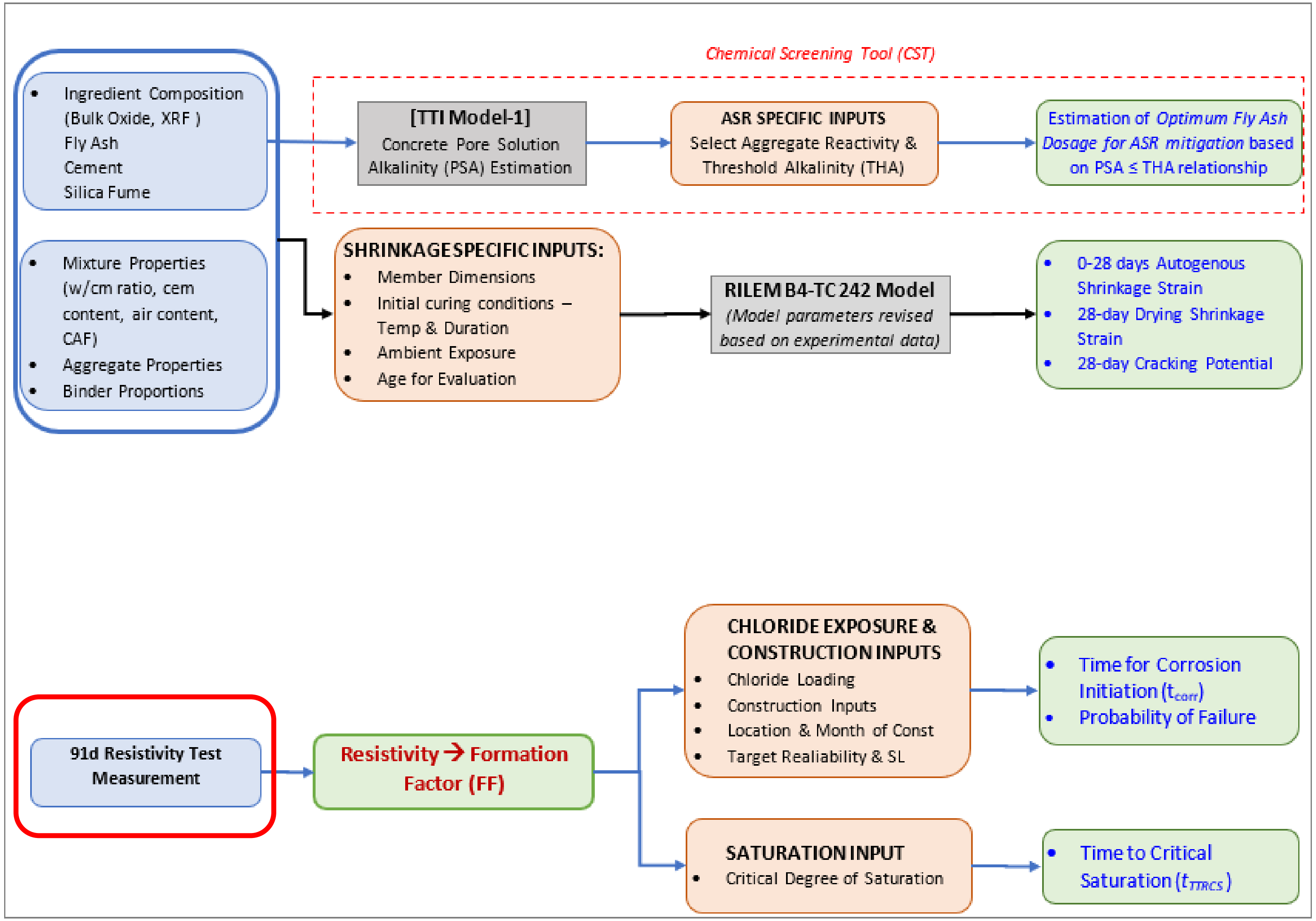
1. Autogenous Shrinkage (AS) Evaluation → sealed concrete prisms, mod. ASTM C 1698 *(only for se*
2. Drying Shrinkage Evaluation (7-28 days) →ASTM C 157
3. Cracking Potential Estimation
   - Based on measured tensile strength, MOE and 28-days AS and DS, and estimated creep (in-built model).

EVAL	Parameter	Recommended Performance (& Limit)
Autogenous Shrinkage (AS)	AS/DS	≤ 30%
Drying Shrinkage (DS)	28-Day DS	≤ 400 microstrains
Cracking Potential (CP)	CP based on 28-Day DS	Low or Moderate-Low (see below)

Cracking Potential (CP)	*Potential for Cracking*
CP > 1.5	High
1.25 < CP ≤ 1.5	Moderate-High
1 < CP ≤ 1.25	Moderate-Low
CP ≤ 1	Low

TxDOT Tool Inputs (Part 2): Resistivity Tests

✓ **INPUTS (Part 1)**



INPUTS (Part 2)

But which approach to follow?
Which curing regimen?
Specimen conditioning?

TxDOT Tool Inputs (Part 2): Resistivity Tests

Aspect 1: Guidance on Curing Protocol for Resistivity Testing (Based on Mix Design Parameters)

Aspect 2: Directions on Soak (or curing) solution Preparation

Aspect 3: Inputs: Measured Resistivity Value

- *Type → Bulk / Surface Resistivity Tests*
- *Curing → SE, LW, SPS or MPS*
- *Conditioning → NC (91d OR 180 d) , AC*

Guidance on Selecting Specimen Curing & Conditioning Procedures for Resistivity Testing

Est. Pore Solution Conductivity (S/m) [TTI Model2]:	75.33
Curing Regimen Selection:	*ASTM C 1876/TP 119 Simulated Pore Solution (SPS) Curing is OK*

Soak (or Curing) Solution Preparation

Dosage of NaOH, KOH & $Ca(OH)_2$ to be added in *grams per Liter* of Deionized (DI) Water *(ref ASTM C 1876/AASHTO TP 119)*	#	*(Dosage g/L DI water)*
	NaOH	7.6
	KOH	10.6
	$Ca(OH)_2$	2.0

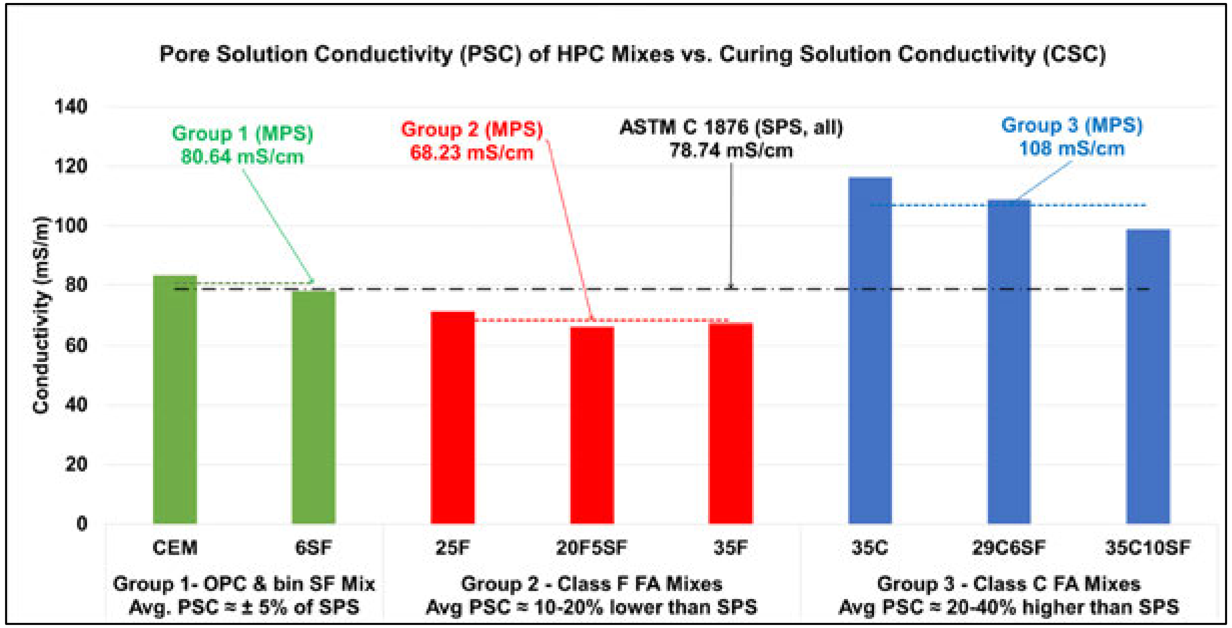
Concrete Resistivity Tests

Select Curing Regimen:	MPS	*Select from List*
Select Conditioning Procedure:	NC	*Select from List*
Age of Resistivity Test (days):	91	
Enter Resistivity Value (K.Ohm-cm):	30	

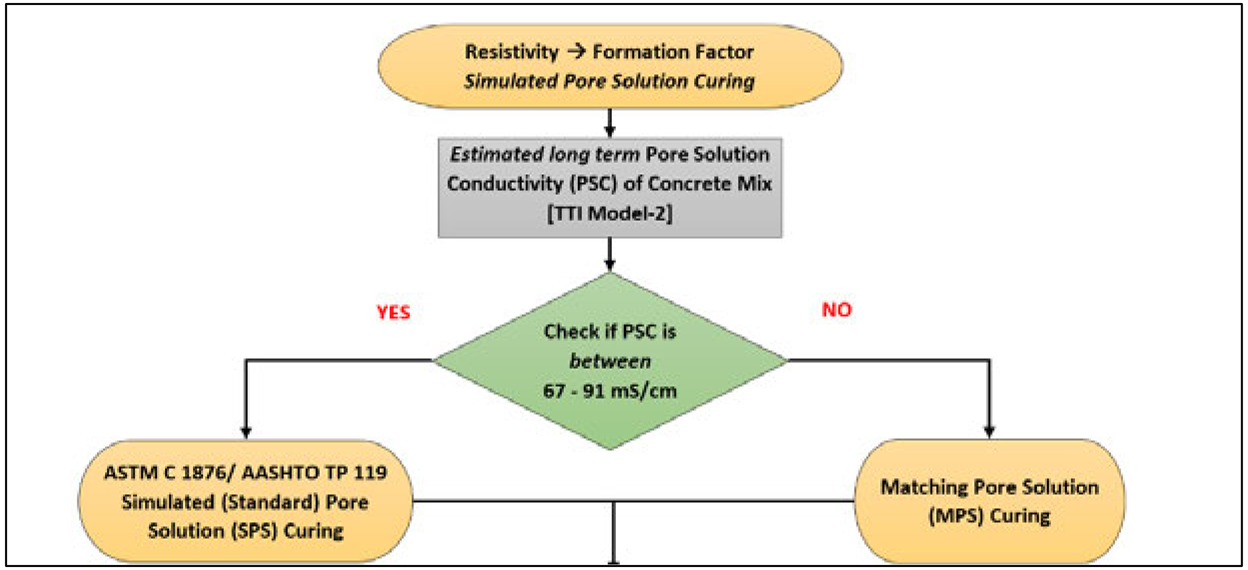
Aspect 1: Guidance on Curing Protocol for Resistivity Testing

Why Is Appropriate Curing Regimen Selection Important?

PSC of HPC Mixtures vs. Curing Solution Conductivity



Guidelines developed during Task 7 HPC Project (0-6958)



TRR 2023 – "Increasing the Reliability of Formation Factor Based Transport Property Prediction for High-Performance Concrete (HPC) Mixtures Through Innovative Matching Pore Solution (MPS) Curing" (Saraswatula et al., 2023)

TxDOT Tool: SPS vs MPS Curing Regimen Recommendations

SPS - 25% Class F Fly Ash Mix

CONCRETE RESISTIVITY TESTING		
Guidance on Curing Protocol for Resistivity Testing (Based on Mix Parameters)		
Est. Pore Solution Conductivity (S/m) [TTI Model2]:	70.03	
Curing Regimen Recommended:	*ASTM C 1897/AASHTO TP 119 Curing is OK*	
Soak (or Curing) Solution Preparation Dosage of NaOH, KOH & $Ca(OH)_2$ to be added in *grams per Liter* of Deionized Water:		*(Dosage g/L DI water)*
	NaOH	7.6
	KOH	10.6
	$Ca(OH)_2$	2.0

MPS - 29% Class C Fly Ash + 6% Silica Fume Mix

CONCRETE RESISTIVITY TESTING		
Guidance on Curing Protocol for Resistivity Testing (Based on Mix Parameters)		
Est. Pore Solution Conductivity (S/m) [TTI Model2]:	103.73	
Curing Regimen Recommended:	*MPS Curing Regimen*	
Soak (or Curing) Solution Preparation Dosage of NaOH, KOH & $Ca(OH)_2$ to be added in *grams per Liter* of Deionized Water:		*(Dosage g/L DI water)*
	NaOH	12.2
	KOH	12.1
	$Ca(OH)_2$	2.0

Aspect 3: Guidance on Conditioning Procedures for Resistivity Testing

What Is Guidance On Conditioning Procedure Selection?

Conditioning Procedure Recommendations

Normal Temperature Conditioning (NC)

Specimen Curing at 23°C for 91-180 days

Recommended for both:

*** Performance Classification**

*** Durability Based Performance Evaluation**

(i.e., Resistivity → FF → Transport Property Predictions)

Accelerated Temperature Conditioning (AC2 → AASHTO TP 119)

Specimen curing for 3 days at 23°C followed by 25 days at 50°C for total duration of 28 days.

Recommended only for

***Performance Classification**

28d AC2 vs. 91d NC → Similar Performance Classification but greater variation in Transport Prop Determination & Durability Evaluations

Resistivity Measurements (Normal & Accelerated) vs Performance Classification

Resistivity Measurements – SPS Curing

Mix #ID	Normal Curing (NC)		Acc Curing (AC2)
	91 days	180 days	28 days
CEM	15.8	18.0	16.0
6SF	26.7	27.8	35.3
25F	26.0	33.9	40.5
20F5SF	39.3	46.2	62.2
35F	32.0	44.1	66.4
35C	28.0	32.1	41.6
29C6SF	43.0	45.0	66.4
35C10SF	50.0	53.0	94.7

Performance Classification (*Measured Resistivity*)– SPS Curing

Mix #ID	Normal Curing (NC)		Acc Curing (AC2)
	91 days	180 days	28 days
CEM	Moderate	Moderate	Moderate
6SF	Low	Low	Low
25F	Low	Low	Low
20F5SF	*Low-Very Low**	Very Low	Very Low
35F	Low	Very Low	Very Low
35C	Low	Low	Low
29C6SF	*Low-Very Low**	Very Low	Very Low
35C10SF	Very Low	Very Low	Very Low

Permeability Classification	***Saturated* Bulk Resistivity** 4x8 Cylinder (kOhm.cm) *AASHTO PEM*	***Measured* Bulk Resistivity** 4x8 Cylinder (kOhm.cm) *@DOS=72% & n=2.2*
High	<5.2	**<11**
Moderate	5.2 – 10.4	**11 – 21**
Low	10.4 – 20.8	**21 – 43**
Very Low	20.8 – 208	**43 - 426**
Negligible	>208	**>426**

Resistivity – Curing Regimen (SPS & MPS) vs. FF Performance Classification Limits

SPS - 25% Class F Fly Ash Mix

Permeability Classification	*Saturated* Bulk Resistivity 4x8 Cylinder (kOhm.cm) *AASHTO PEM*	*Measured* Bulk Resistivity 4x8 Cylinder (kOhm.cm) *@DOS=72% & n=2.2*	*Saturated* Formation Factor (FF) 4x8 Cylinder AASHTO PEM	*Apparent* Formation Factor (AFF) 4x8 Cylinder *@DOS=72% & n=2.2*
High	<5.2	<11	<407	< 839
Moderate	5.2 – 10.4	11 – 21	407-815	839 - 1679
Low	10.4 – 20.8	21 – 43	815-1630	1679 - 3358
Very Low	20.8 – 208	43 - 426	1630-16299	3358 - 33576
Negligible	>208	>426	>16299	>33576

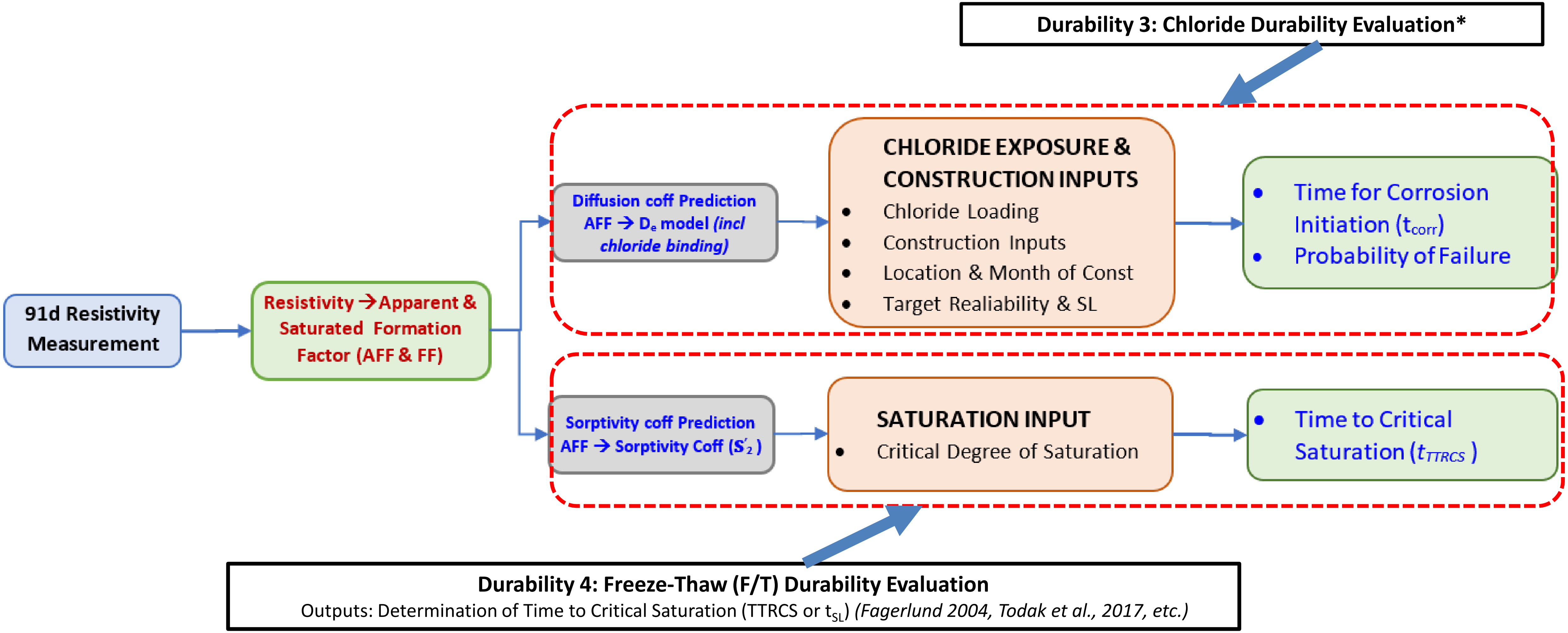
MPS - 29% Class C Fly Ash + 6% Silica Fume Mix

Permeability Classification	*Saturated* Bulk Resistivity 4x8 Cylinder (kOhm.cm) *AASHTO PEM*	*Measured* Bulk Resistivity 4x8 Cylinder (kOhm.cm) *@DOS=72% & n=2.2*	*Saturated* Formation Factor (FF) 4x8 Cylinder	*Apparent* Formation Factor (AFF) 4x8 Cylinder *@DOS=72% & n=2.2*
High	<5.2	<11	**<534**	**<1099**
Moderate	5.2 – 10.4	11 – 21	**534 -1067**	**1099 - 2198**
Low	10.4 – 20.8	21 – 43	**1067 - 2134**	**2198 - 4396**
Very Low	20.8 – 208	43 - 426	**2134 - 21340**	**4396 - 43961**
Negligible	>208	>426	**>21340**	**> 43961**

- ***TTI Model-2*** → $\rho^{SPS} = 0.127\ Ohm.m$
- $Formation\ factor = \dfrac{\rho_{mea}}{\rho^{SPS}(=0.127\ \text{Ohm.m})}$

- ***TTI Model-2*** → $\rho^{MPS} = 0.097\ Ohm.m$
- $Formation\ factor = \dfrac{\rho_{mea}}{\rho^{MPS}(=0.098\ \text{Ohm.m})}$

TxDOT Tool Approach for Chloride & Freeze-Thaw (F/T) Durability Evaluation



**TRR Publication " Increasing the Reliability of Formation Factor Based Transport Property Prediction for High Performance Concrete (HPC) Mixtures Through Innovative Matching Pore Solution (MPS) Curing" (Saraswatula et al., 2023)*

TxDOT Tool Inputs (Part 3) – Durability Specific: Chloride Induced Rebar Corrosion

- **Chloride Durability Specific Inputs**

1. **Location & Month of Construction** : Monthly ambient (mean) temperatures in-built from historical NOAA database for 18 regions in Texas and for Jan – Dec
   - **Panhandle Plains** → Amarillo & Lubbock
   - **Big Bend Country** →El Paso, Del Rio, Guadalupe & Big Bend
   - **South Texas Plains** → San Antonio & McAllen
   - **Hill Country** → Austin
   - **Prairies** → College Station & Dallas
   - **Piney Woods** → Texarkana, Lufkin & Tyler
   - **Gulf Coast** → Beaumont, Corpus Christi, Galveston & Houston

DURABILITY TO RESIST CHLORIDE INGRESS		
Location (In Texas):	Amarillo	*Select from List*
Month of Construction:	July	*Select from List*
Max Surface Chloride Concentration (Cs, %):	0.6%	*Select from List*
Rebar depth (Conc Cover, inches):	2.5	
Rebar Type:	Epoxy Coated	*Select from List*
Corrosion Inhibitor Dosage (gal/CY):	2	*Select from List*
Design Service Life (yrs):	75	
Target Reliability Index (beta,β):	1.3	

2. **Environmental Chloride Loading**: Surface chloride concentration (Cs)
   - *Guidance Provided based on ConcreteWorks*

Exposure condition	Maximum surface concentration (%)	Build-up rate constant
Splash zone	0.8	Instantaneous
Spray zone	1	0.15
Within 0.5 miles of ocean	0.6	0.06
Within 1 mile of ocean	0.6	0.03

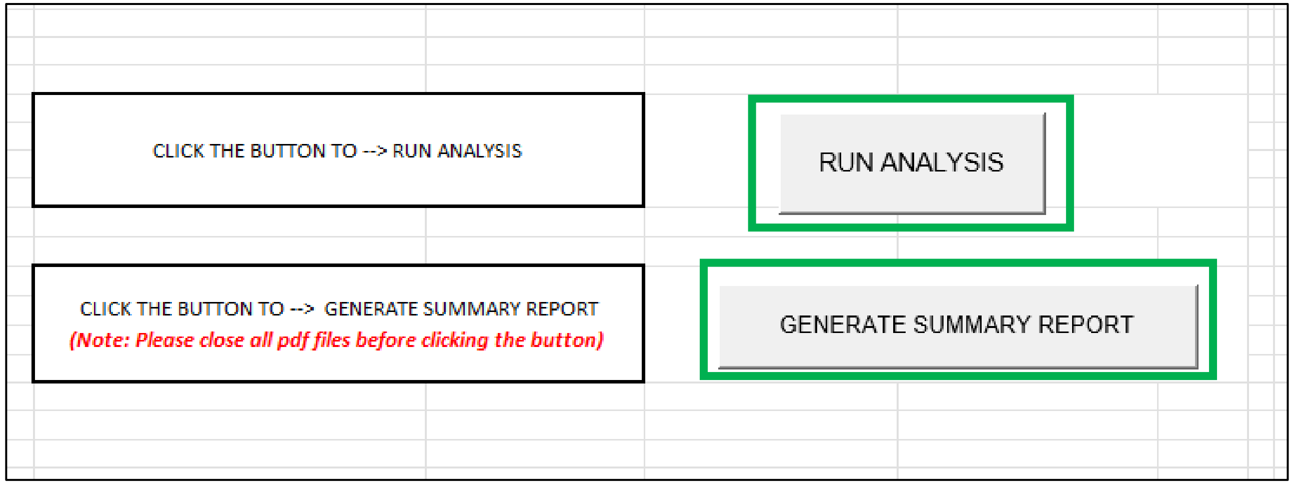
3. **Construction Inputs**: Concrete Cover, Rebar Type & CNI Dosage
   - *Ct (Chloride Threshold values inbuilt based on ConcreteWorks)*

4. **Design service Life & Target Reliability Index**

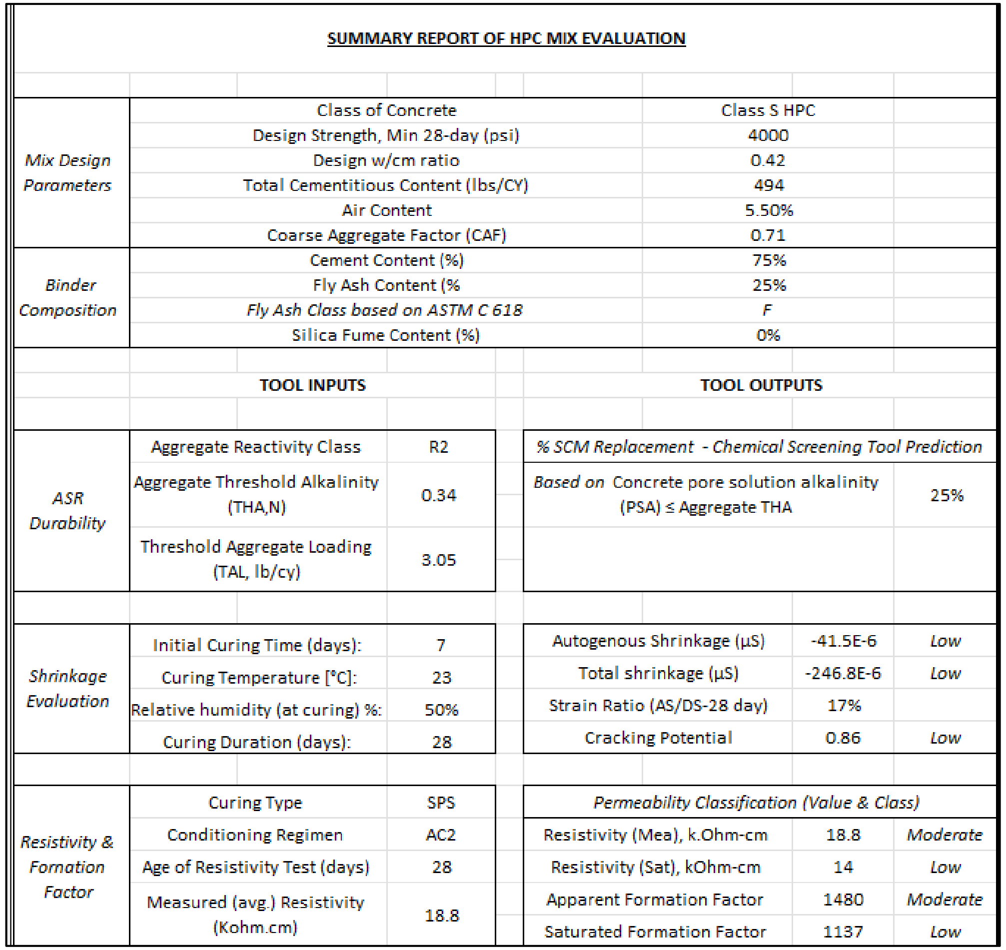
TxDOT Tool: Generating OUTPUTS

Output: 1 Page Summary Report of HPC Mix Evaluation

1. After entering all inputs → "**Run Analysis**"
2. Need pdf file of Report ? → "**Generate Summary Report**"



OUTPUT SHEET



SUMMARY REPORT OF HPC MIX EVALUATION

Mix Design Parameters	Class of Concrete	Class S HPC
	Design Strength, Min 28-day (psi)	4000
	Design w/cm ratio	0.42
	Total Cementitious Content (lbs/CY)	494
	Air Content	5.50%
	Coarse Aggregate Factor (CAF)	0.71
Binder Composition	Cement Content (%)	75%
	Fly Ash Content (%	25%
	Fly Ash Class based on ASTM C 618	*F*
	Silica Fume Content (%)	0%

	TOOL INPUTS		TOOL OUTPUTS		
ASR Durability	Aggregate Reactivity Class	R2	*% SCM Replacement - Chemical Screening Tool Prediction*		
	Aggregate Threshold Alkalinity (THA,N)	0.34	*Based on* Concrete pore solution alkalinity (PSA) ≤ Aggregate THA	25%	
	Threshold Aggregate Loading (TAL, lb/cy)	3.05			
Shrinkage Evaluation	Initial Curing Time (days):	7	Autogenous Shrinkage (μS)	-41.5E-6	*Low*
	Curing Temperature [°C]:	23	Total shrinkage (μS)	-246.8E-6	*Low*
	Relative humidity (at curing) %:	50%	Strain Ratio (AS/DS-28 day)	17%	
	Curing Duration (days):	28	Cracking Potential	0.86	*Low*
Resistivity & Formation Factor	Curing Type	SPS	*Permeability Classification (Value & Class)*		
	Conditioning Regimen	AC2	Resistivity (Mea), k.Ohm-cm	18.8	*Moderate*
	Age of Resistivity Test (days)	28	Resistivity (Sat), kOhm-cm	14	*Low*
	Measured (avg.) Resistivity (Kohm.cm)	18.8	Apparent Formation Factor	1480	*Moderate*
			Saturated Formation Factor	1137	*Low*

Case Study 1 & 2:

TxDOT Tool Predictions vs. Laboratory Measurements for Class F & Class C Fly Ash Mixtures

Case Study 1: 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 night-time) and good curing practice is very important to eliminate early-age cracking potential*

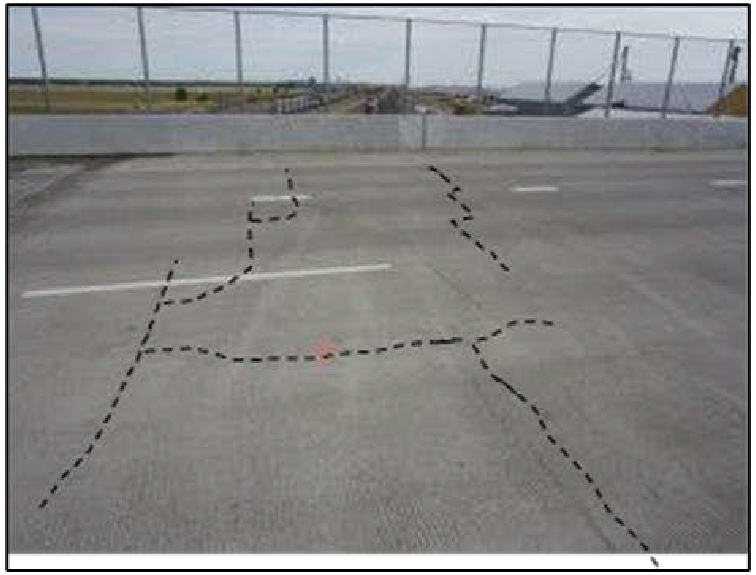
Case Study 1: Bridge Deck Concrete with 29% C Ash+ 6% SF - Amarillo, TX
TxDOT Tool Predictions vs. Field Observations

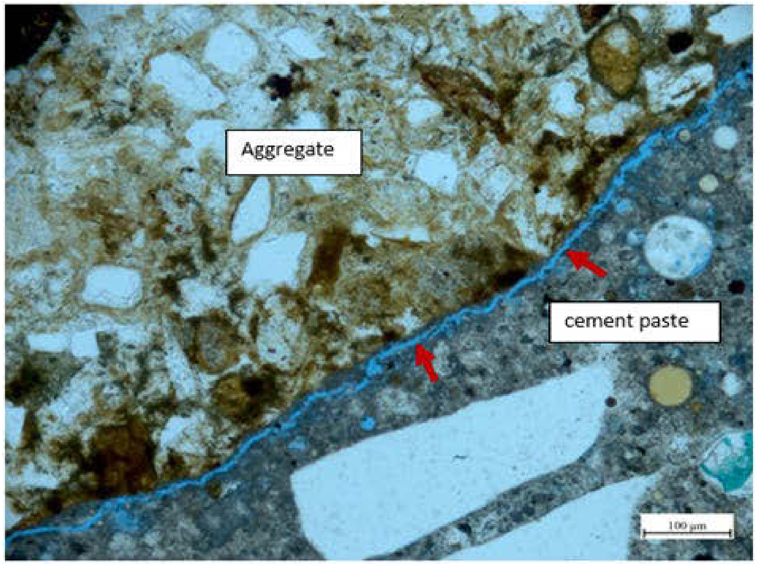
LAB STUDY USING HPC BRIDGE DECK MIXES		
Shrinkage	**Transport Properties @ early ages (within 28 days)**	**Durability Performance**
Drying shrinkage: *(≤ 400 µs, 28d)* High Autogenous shr ***– increased cracking potential***	Dense microstructure development & permeability reduction *at early ages*	***Good***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





Case Study 2: 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

**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)*

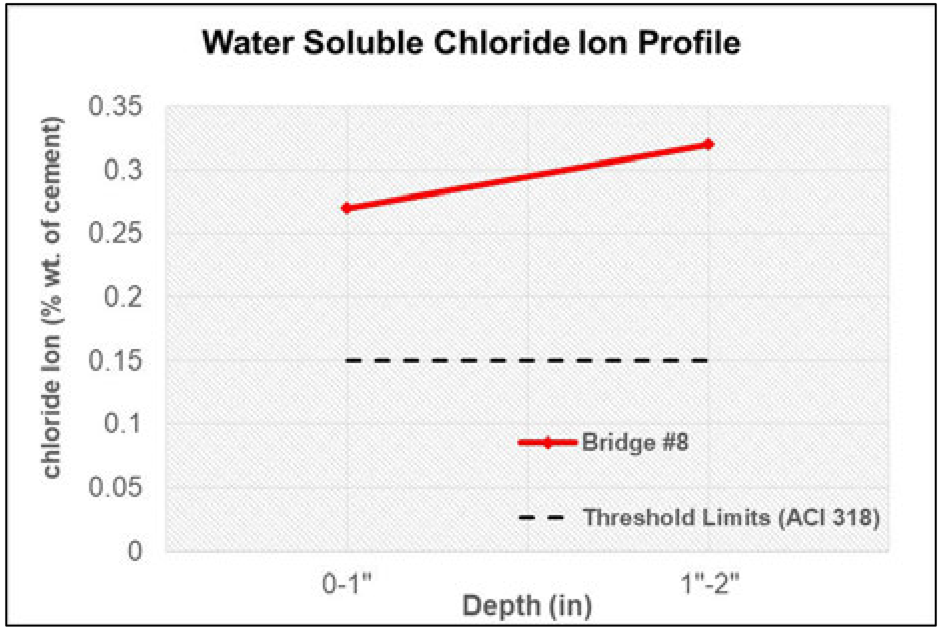
25% F ash Mix (Observations)

- **ASR Evaluation: CST predicted** 25% F ash is adequate to mitigate ASR; the difference between CST & C1567 is <5%, no need for ACCT validation
- Cracking potential: Low
- Chloride durability: Fail
- F-T durability: not adequate but not required

ok

Case Study 2: 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

Evaluation Using TxDOT Tool: Current Galveston Mix (Case Study 2, not Qualified as HPC), Better Steel Selection is Required (Option 1)

Shrinkage Evaluation	Initial Curing Time (days):	7	Autogenous Shrinkage (µS)	-48.7E-6	Low
	Curing Temperature [°C]:	23	Total shrinkage (µS)	-291.8E-6	Low
	Relative humidity (at curing) %:	50%	Strain Ratio (AS/DS-28 day)	17%	
	Curing Duration (days):	28	Cracking Potential	0.99	Low
Resistivity & Fornation Factor	Curing Type	MPS	*Permeability Classification (Value & Class)*		
	Conditioning Regimen	NC	Resistivity (Mea), k.Ohm-cm	28.2	Low
	Age of Resistivity Test (days)	**91**	Resistivity (Sat), kOhm-cm	17	Low
	Measured (avg.) Resistivity (Kohm.cm)	28.2	Apparent Formation Factor	2222	Low
			Saturated Formation Factor	1322	Low
Chloride Exposure & Rebar Corrosion	**Max Surface Cl Conc (Cs)**	**0.60%**			
	Rebar depth (Cover, in)	2.50	Chloride Binding Factor		1.69
	Rebar Type	Black Steel	Eff Diffusion Coff (m2/s)		3.4E-12
	Corrosion Inhibitor (gal/CY)	**2.00**	Est. Time to Corr Repair, yrs		>75 years
	Location (In Texas)	**Galveston**	Probability of Failure (SHRP Model)		15%
	Month of Construction	**July**	Reliability Index Calculated		1.02
	Target Realibility Index	1.3	*Pass or Fail? (Reliability -Calc vs Target)*		*Fails*
F/T Service Life	Critical Degree of Saturation (DOScr %):	86%	Time to Critical Saturation (TTRCS) yrs		19

INPUTS			OUTPUTS		
Shrinkage Evaluation	Initial Curing Time (days):	7	Autogenous Shrinkage (µS)	-48.7E-6	Low
	Curing Temperature [°C]:	23	Total shrinkage (µS)	-291.8E-6	Low
	Relative humidity (at curing) %:	50%	Strain Ratio (AS/DS-28 day)	17%	
	Curing Duration (days):	28	Cracking Potential	0.99	Low
Resistivity & Fornation Factor	Curing Type	MPS	*Permeability Classification (Value & Class)*		
	Conditioning Regimen	NC	Resistivity (Mea), k.Ohm-cm	28.2	Low
	Age of Resistivity Test (days)	**91**	Resistivity (Sat), kOhm-cm	17	Low
	Measured (avg.) Resistivity (Kohm.cm)	28.2	Apparent Formation Factor	2222	Low
			Saturated Formation Factor	1322	Low
Chloride Exposure & Rebar Corrosion	**Max Surface Cl Conc (Cs)**	**0.60%**			
	Rebar depth (Cover, in)	2.50	Chloride Binding Factor		1.69
	Rebar Type	Epoxy Coated	Eff Diffusion Coff (m2/s)		3.4E-12
	Corrosion Inhibitor (gal/CY)	**3.00**	Est. Time to Corr Repair, yrs		>75 years
	Location (In Texas)	**Galveston**	Probability of Failure (SHRP Model)		7%
	Month of Construction	**July**	Reliability Index Calculated		1.465
	Target Realibility Index	1.3	*Pass or Fail? (Reliability -Calc vs Target)*		*Passes*
F/T Service Life	Critical Degree of Saturation (DOScr %):	86%	Time to Critical Saturation (TTRCS) yrs		19

- **Case A: 25% Class F Fly Ash Mix with Black steel with 3 gal/cu yd. CNI**
  - **Chloride Durability evaluated for Ferry Landing Bridge Deck, Galveston, TX; Month – July (high ambient temperatures)**
  - **Chloride durability Fails**

- **Case B: 25% Class F Fly Ash Mix with Epoxy coated steel with 3 gal/cu yd. CNI**
- Chloride durability passes but reliability is marginally above 1.3 target.

Evaluation Using TxDOT Tool: The current Galveston Mix is not Qualified as HPC, Use of a Ternary Mix (20% Class F + 5% SF) Can Make it HPC (Option 2)

	INPUTS		OUTPUTS		
Shrinkage Evaluation	Initial Curing Time (days):	7	Autogenous Shrinkage (µS)	-48.7E-6	*Low*
	Curing Temperature [°C]:	23	Total shrinkage (µS)	-291.8E-6	*Low*
	Relative humidity (at curing) %:	50%	Strain Ratio (AS/DS-28 day)	17%	
	Curing Duration (days):	28	Cracking Potential	0.99	*Low*
Resistivity & Fornation Factor	Curing Type	MPS	*Permeability Classification (Value & Class)*		
	Conditioning Regimen	NC	Resistivity (Mea), k.Ohm-cm	28.2	*Low*
	Age of Resistivity Test (days)	**91**	Resistivity (Sat), kOhm-cm	17	*Low*
	Measured (avg.) Resistivity (Kohm.cm)	28.2	Apparent Formation Factor	2222	*Low*
			Saturated Formation Factor	1322	*Low*
Chloride Exposure & Rebar Corrosion	**Max Surface Cl Conc (Cs)**	**0.60%**			
	Rebar depth (Cover, in)	2.50	Chloride Binding Factor		1.69
	Rebar Type	Epoxy Coated	Eff Diffusion Coff (m2/s)		3.4E-12
	Corrosion Inhibitor (gal/CY)	**3.00**	Est. Time to Corr Repair, yrs		>75 years
	Location (In Texas)	**Galveston**	Probability of Failure (SHRP Model)		7%
	Month of Construction	**July**	Reliability Index Calculated		1.465
	Target Realibility Index	1.3	*Pass or Fail? (Reliability -Calc vs Target)*		*Passes*
F/T Service Life	Critical Degree of Saturation (DOScr %):	86%	Time to Critical Saturation (TTRCS) yrs		19

Case A: 25% Class F Fly Ash Mix with Epoxy coated steel with 3 gal/cu yd. CNI

- ❖ Chloride durability passes but reliability is marginally above 1.3 target.

	INPUTS		OUTPUTS		
Shrinkage Evaluation	Initial Curing Time (days):	7	Autogenous Shrinkage (µS)	-85.4E-6	*High*
	Curing Temperature [°C]:	23	Total shrinkage (µS)	-271.9E-6	*Low*
	Relative humidity (at curing) %:	50%	Strain Ratio (AS/DS-28 day)	31%	
	Curing Duration (days):	28	Cracking Potential	1.11	*Moderate*
Resistivity & Fornation Factor	Curing Type	MPS	*Permeability Classification (Value & Class)*		
	Conditioning Regimen	NC	Resistivity (Mea), k.Ohm-cm	37	*Low*
	Age of Resistivity Test (days)	**91**	Resistivity (Sat), kOhm-cm	23	*Very Low*
	Measured (avg.) Resistivity (Kohm.cm)	37	Apparent Formation Factor	2252	*Low*
			Saturated Formation Factor	1379	*Low*
Chloride Exposure & Rebar Corrosion	**Max Surface Cl Conc (Cs)**	**0.60%**			
	Rebar depth (Cover, in)	2.50	Chloride Binding Factor		1.60
	Rebar Type	Black Steel	Eff Diffusion Coff (m2/s)		3.5E-12
	Corrosion Inhibitor (gal/CY)	**2.00**	Est. Time to Corr Repair, yrs		>75 years
	Location (In Texas)	**Galveston**	Probability of Failure (SHRP Model)		3%
	Month of Construction	**July**	Reliability Index Calculated		1.95
	Target Realibility Index	1.3	*Pass or Fail? (Reliability -Calc vs Target)*		*Passes*
F/T Service Life	Critical Degree of Saturation (DOScr %):	86%	Time to Critical Saturation (TTRCS) yrs		19

- **Case C: Use of Mix option 3 → 20% Class F Fly Ash + 5% SF with Black Steel**
- Chloride durability passes with Black steel + 2 Gal/yd3 CNI
- **But the use of SF → moderate cracking potential due to high autogenous shrinkage (selecting the right placement time and good curing practice is highly recommended**

TxDOT Tool Reach TRL 8

- ❖Successfully validated through two field project evaluation
- ❖Based on evaluating one mix, the resistivity test methods have satisfied the within-the-lab and between-the-lab repeatability requirements.
  - ➢ *However, various representative mix designs need to be evaluated to establish acceptable within-the-lab and between-the-lab repeatability requirements.*

Future Work: Implementation

Our plan to achieve TRL 9

1. Apply the TxDOT tool to evaluate current mix design practices for several field projects and examine if the current mix designs qualify as HPC matching with the durability requirements.
2. Initial studies indicate that 28-day resistivity measurements with accelerated conditioning (AC) are acceptable for assigning performance classification categories (e.g., low, very low, etc.).
   - *Extensive validation with numerous field projects (Item 1) is essential to confirm*
3. **Based on several project evaluations**
   1. Establishing a connection between classification category and performance prediction/evaluation
   2. Develop guidelines on classification categories (very low, low, medium, etc.) vs geographic locations – one can select a particular class for bridges under a particular geographic location.
   3. In the future, TxDOT can use resistivity (28 days with AC) or formation factor-based performance classification category to verify if the selected mix is qualified as HPC for a project and avoid conducting long-term performance testing.

ANY QUESTIONS ?

Anol K. Mukhopadhyay, Ph.D., P.G., (a-mukhopadhyay@tti.tamu.edu)

Pravin Saraswatula, Ph.D., E.I.T. (spravin112@tamu.edu)