Development of a Screening Tool to Predict Optimum Fly Ash Dosage for ASR Mitigation In Concrete

Pravin Saraswatula

Ph.D. Candidate (TAMU) (& today's speaker)

Anol K Mukhopadhyay, Ph.D., P.G.

Senior Research Scientist (TTI) & Adjunct Professor (TAMU)

Kai Wei Liu, Ph.D.

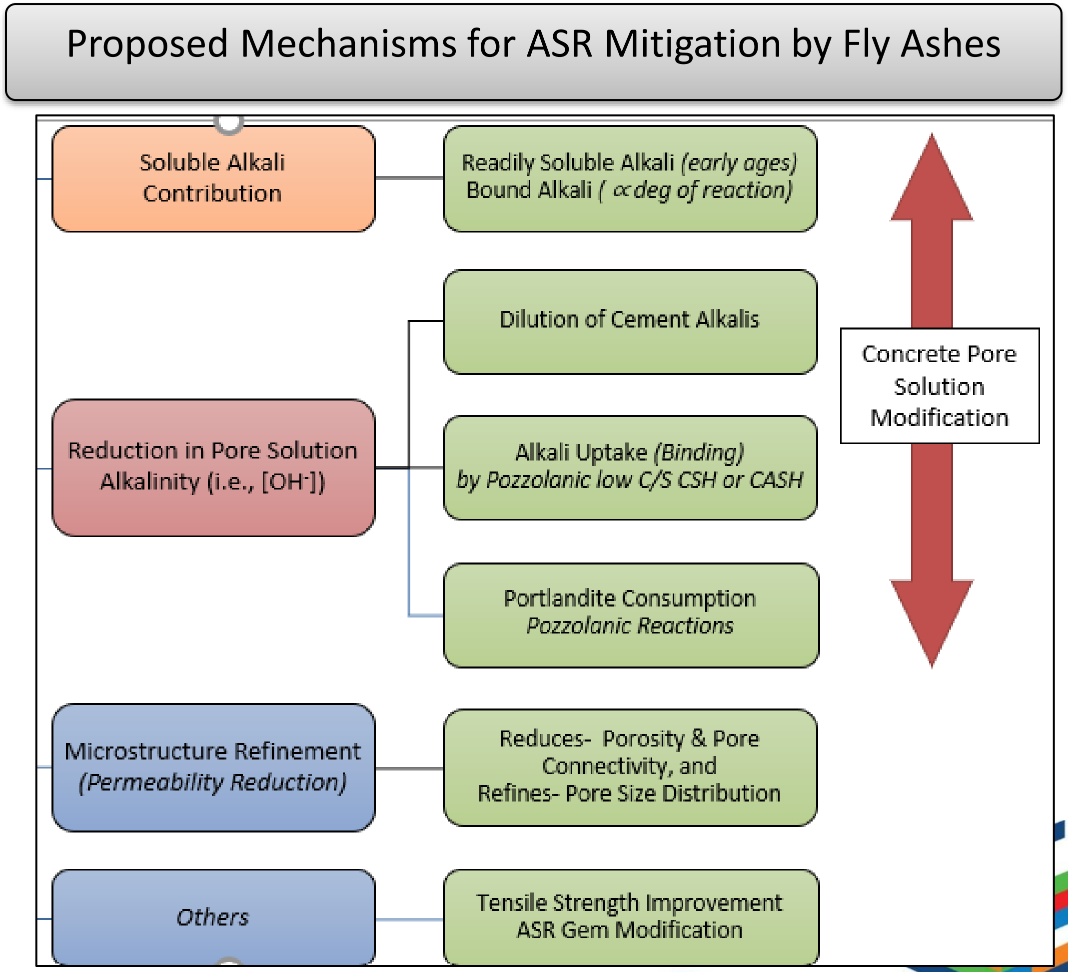
Assistant Research Scientist (TTI)

Alkali Silica Reaction (ASR)

- Alkali-silica reactivity (ASR) remains a major durability issue affecting concrete structures, including heavy civil infrastructure, such as dams, bridges, pavements, etc.,
  - [Alkali hydroxides]$_{\text{Conc pore solution}}$ + [Reactive Silica Minerals]$_{\text{Aggregates}}$ → ASR Gel *(Hygroscopic & Expansive)*
- Three requirements for damaging ASR
  - Sufficient Quantity of Reactive Silica *(within aggregates)*
  - Sufficient concentration of alkali *(primarily from portland cement)*
  - Sufficient moisture

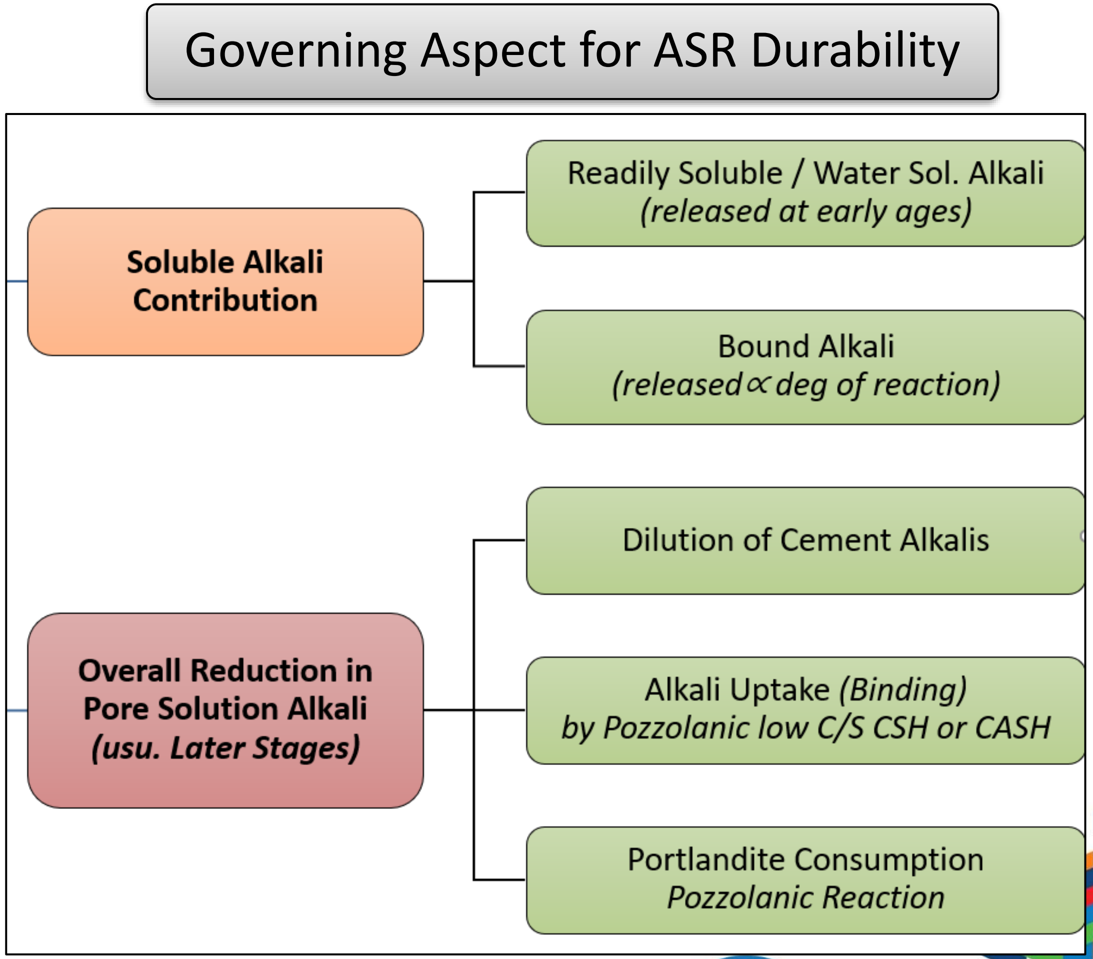
Alkali Silica Reaction - Mitigation

- ASR Mitigation : Primary Approach - Design By Avoidance (Elimination of requirements)
  1. Use Non-Reactive Aggregates → Not Always Feasible
  2. Use of Low Alkali Cement to Lower Pore Solution Alkalinity → Not Effective (by itself)
  3. Use of SCMs (especially Fly Ashes) is most common practice for ASR Mitigation



Alkali Silica Reaction - Mitigation

- Use of SCMs (especially Fly Ashes) is most common practice for ASR Mitigation
  - Concrete Pore Solution Modification by Fly Ashes: **Governing Aspect for ASR Durability**



Performance Based Evaluation Approach for ASR Mitigation

- Objective: Determination of Optimum Fly Ash (FA) Dosage for ASR Mitigation

- **Primary Approach: ASR Tests**
  - Testing at Multiple Replacement Levels → Optimum FA dosage (≤ threshold expansion)
  - Time Consuming, cost and labor intensive
  - Not Ideal for Rapid Fly Ash Evaluation

Test Method	*Test Attributes*			
	Alkali boosting	**Alkali Leaching**	**Effect of cement and Fly Ash soluble alkali ?**	**Time Duration**
ASTM C 1567 (Accelerated Mortar Bar Test)	✓	×	No	14-16 days
ASTM C 1293 (Concrete Prism Test)	✓	✓	No	2 years
AASHTO T 380 (Miniature Concrete Prism Test)	✓	×	No	75 - 90 days
AASHTO TP 142 (Accelerated Concrete Cylinder Test)	**×**	**×**	**Yes**	**75 – 90 days**

Performance Based Evaluation Approach for ASR Mitigation

- Objective: Determination of Optimum Fly Ash (FA) Dosage for ASR Mitigation

- **Rapid Approach: Prediction Models/Prescriptive Approaches**
  - Cement and FA Bulk Oxide Composition → Predict Optimum FA dosage
  - Regression Approaches based on Expansion Measurements
  - Do not address influence of Pore Solution on ASR evaluation

Approach	Methodology	Effect of Fly Ash Soluble Alkali	Effect of pore solution
ASTM C 1778 / AASHTO R 80	Prescriptive & only for Class F FA (<18% CaO)	No	No
Chemical Index Model	Regression & Based on ASTM C 1567	No	No
Extended Chemical Index Model	Regression & Based on ASTM C 1293	No	No

Current Challenge: Changing Fly Ash Composition

Decrease in Fly Ash Production

- Rapid Rise of Natural gas
- Emission Standards requirements for coal fired power plants
  - *No New plants constructed after 2013*
  - *Existing Plant Retirement*

Continuous Changes in Fly Ash Composition

- Changes to Plant Operations *(to meet emission standards)*
- Changes to Coal Burning Processes
- Changing Coal Type being burnt

Decreasing Usage Rate of Fly Ash

- Fly Ash not meeting "traditional" ASTM Specifications
  - *80% of unused fly as disposed as landfill (Lack of Storage Options)*

Increase in Supply "alternative" fly ash varieties

- Blended Coal Ash
- Blended Fly As
- Beneficiated Fly Ash
- Ponded Fly Ash
- Remediated Fly Ash

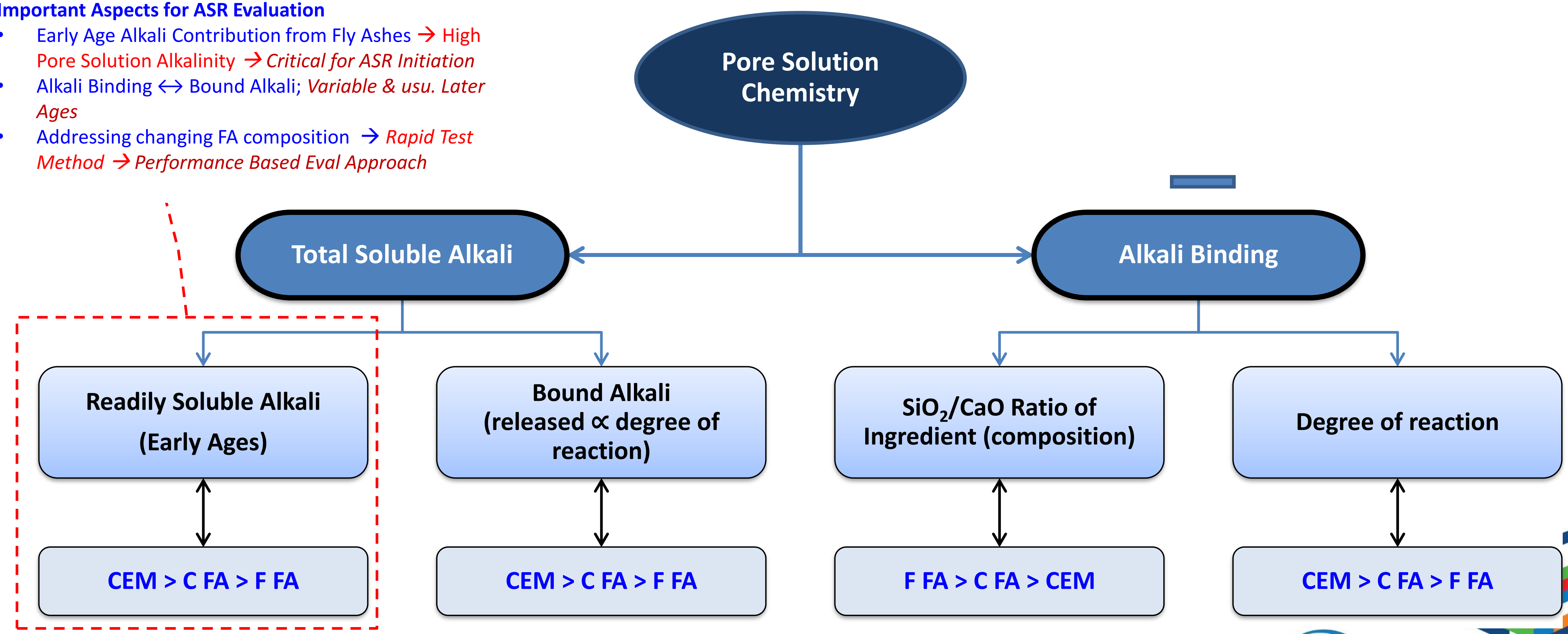
Decreasing Availability

- "quality", "traditional" or "production" fly ash varieties (Class C & F)
- Fly Ash meeting ASTM Specifications

Application of Pore Solution for Rapid ASR Evaluation

Important Aspects for ASR Evaluation

- Early Age Alkali Contribution from Fly Ashes → High Pore Solution Alkalinity → *Critical for ASR Initiation*
- Alkali Binding ↔ Bound Alkali; *Variable & usu. Later Ages*
- Addressing changing FA composition → *Rapid Test Method* → *Performance Based Eval Approach*



Objective: Development of a Screening Tool to Predict Optimum Fly Ash Dosage in Concrete for ASR Mitigation

Investigate WSA from FA → **Model to Predict WSA from FA** → **TTI Model-1 to Estimate Concrete PSA** → **Screening Tool Development** → **Validation Study of ST**

Investigate WSA from FA

- Water Soluble Alkali (WSA) from Fly Ashes (FA)
  - *mod. ASTM C 114*
  - *26 Fly Ashes → Class C, F, Blended, Reclaimed, Nat Pozzolans*

Model to Predict WSA from FA

- Non-Linear Regression Model Development to predict WSA from FA
  - *61 Data Points → 26: Current Study & 35: Literature*

TTI Model-1 to Estimate Concrete PSA

- Development of TTI Model-1 to Estimate Concrete PSA
  - *Combined Effect →*
    - *Total Sol. Alkali : CEM*
    - *Water Sol. Alkali: FA*
  - *Empirical Eqns*
    - *Snyder et al., 2003*

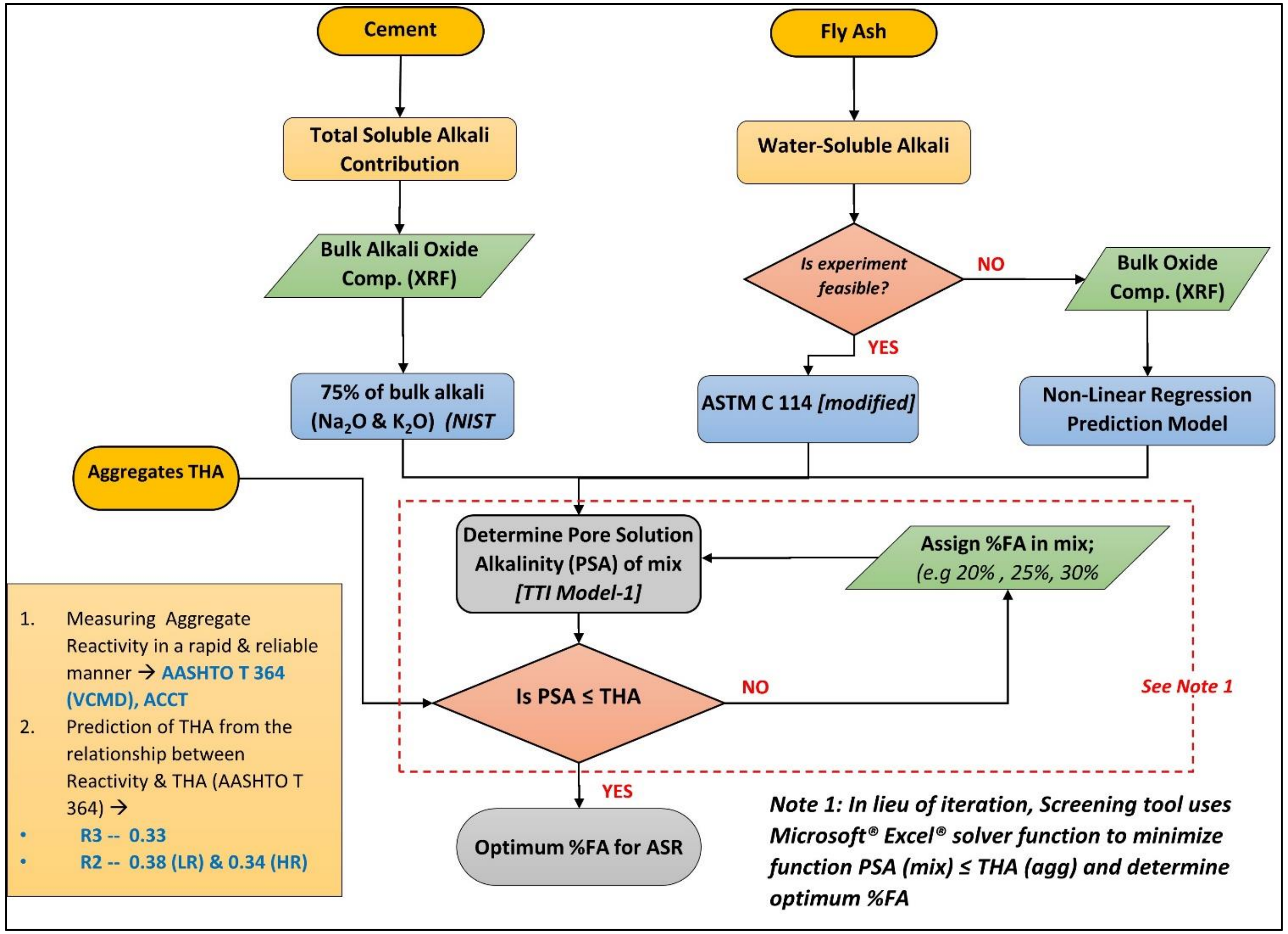
Screening Tool Development

- Predict Optimum FA Dosage for ASR Mitigation →
  - *Concrete PSA vs.*
  - *Aggregate Threshold Alkalinity (THA)*
    - *PSA ≤ THA (ASR mitigation) (Mukhopadhyay et al., 2014)*

Validation Study of ST

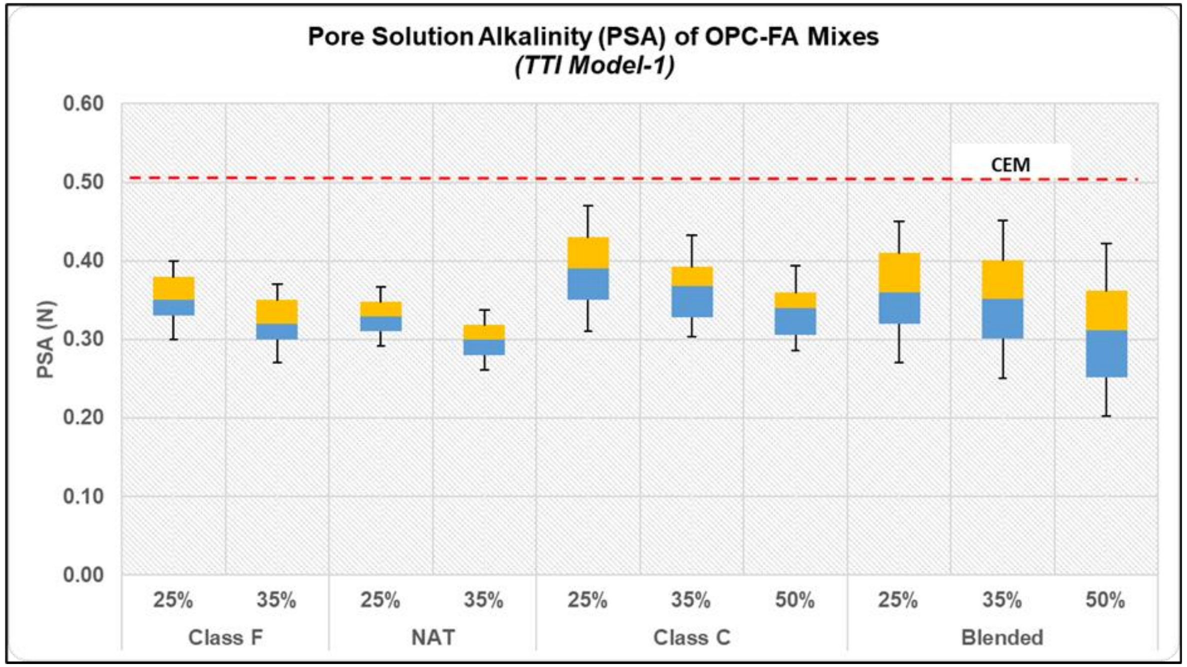
- Current Study: 27 Fly Ashes →
  - *AASHTO TP 142 (ACCT)*
  - *ASTM C 1567 (AMBT)*
- Literature: 22 Fly Ashes →
  - *ASTM C 1293 (CPT)*
- Prediction models

Methodology



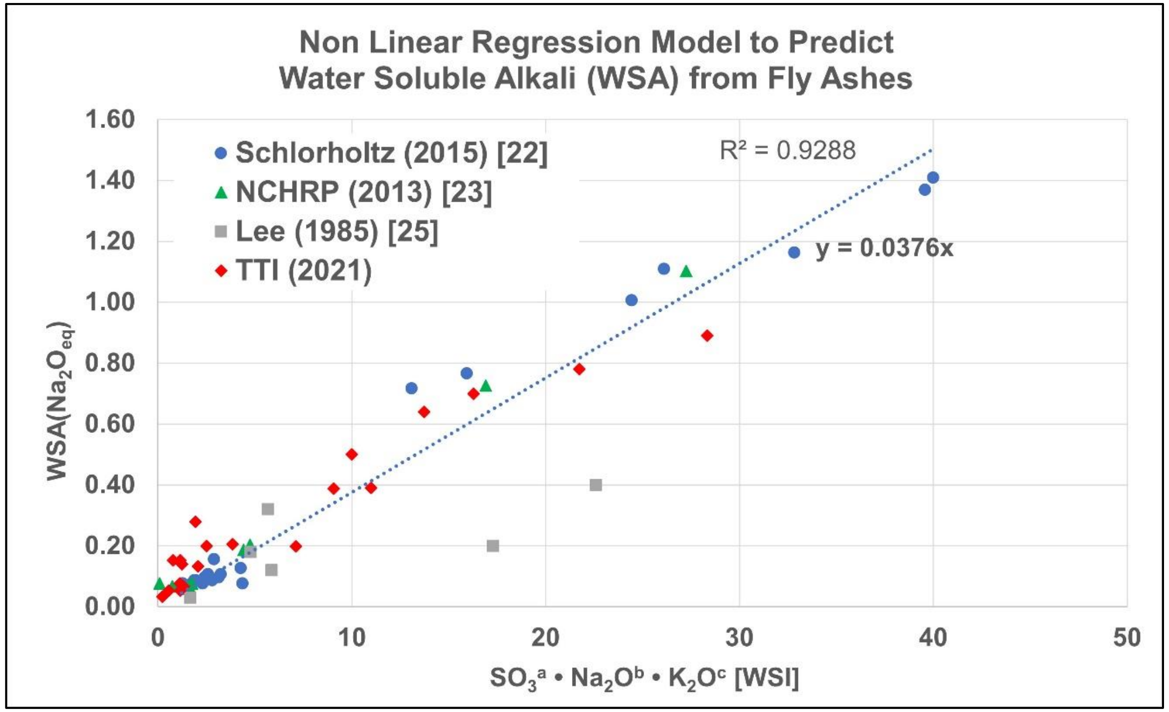
Major Findings & Results

- 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



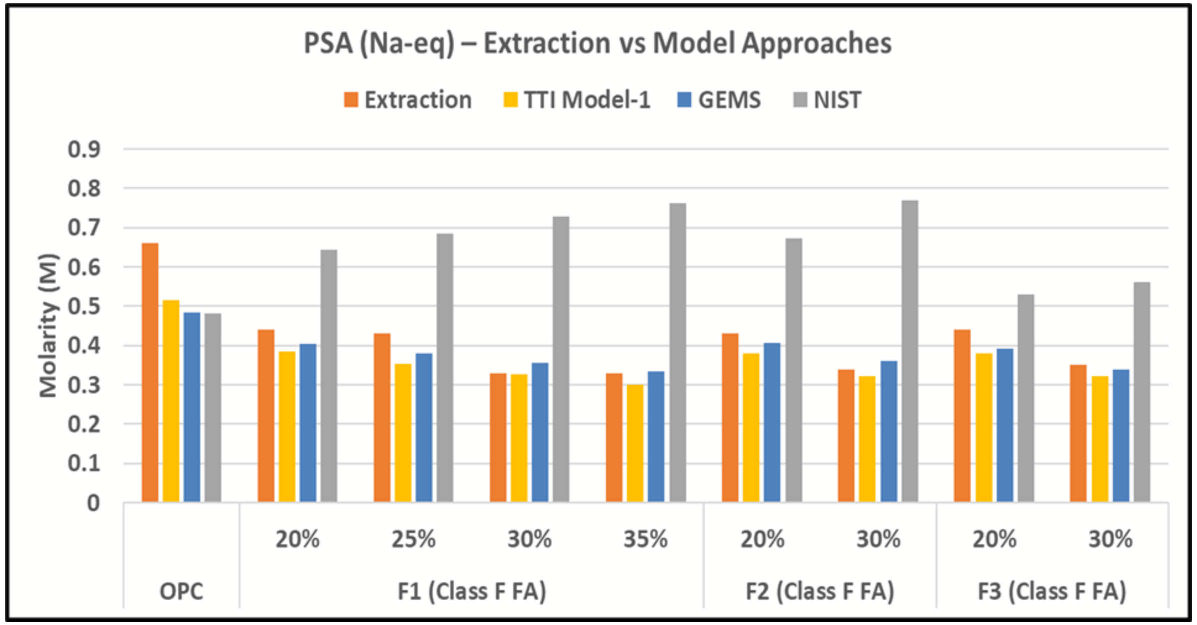
Major Findings & Results

- Nonlinear Regression Model to Predict Water Soluble Alkali from Fly Ashes
  - Primary Variables → Na_2O, K_2O & SO_3 *(p value <5%)*
  - R^2=0.92, MAE = 6.7%



Major Findings & Results

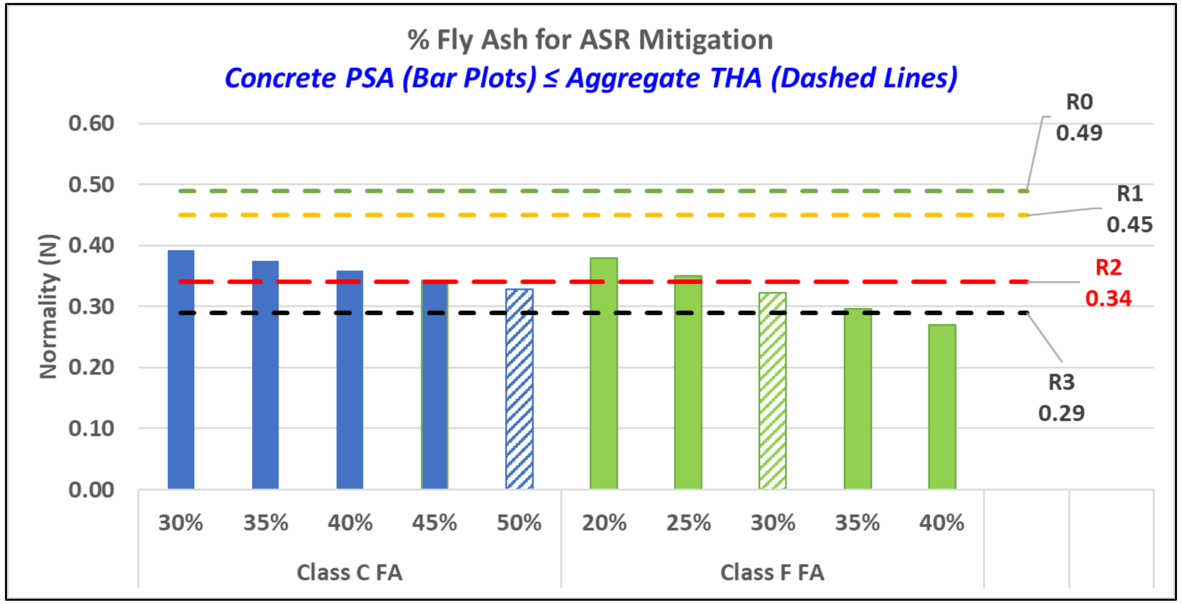
- TTI Model-1 PSA Determination
  - Good reliability in PSA Determination
  - 4.3% MAE, 6.2% RMSE with extraction measurements



Results – Screening Tool Predictions

- Fly Ash Replacement Level Depends on
  1. Concrete Pore Solution Alkalinity (PSA)
     - ***TTI Model-1***
  2. Aggregate Threshold Alkalinity (THA)
     - ***Aggregate Reactivity vs. THA***
       (Mukhopadhyay et al., 2014)

Aggregate	Reactivity	Class	THA, N	C1260	C1293
A	Very Highly Reactive	R3	0.29	1.3	n/a
B	Highly Reactivity	R2	0.34	0.381	0.391
C	Moderately Reactive	R1	0.45	0.317	0.058
D	Slow Reactivity	R0	0.49	0.1	0.054



- ***Screening Tool Predictions for R2 Aggregate***
  - Class C FA: 48%
  - Class F FA: 28%
- ***AASHTO TP 142 Test (ACCT) for R2 Aggregate***
  - Class C FA: 45-40%
  - Class F FA: 25%

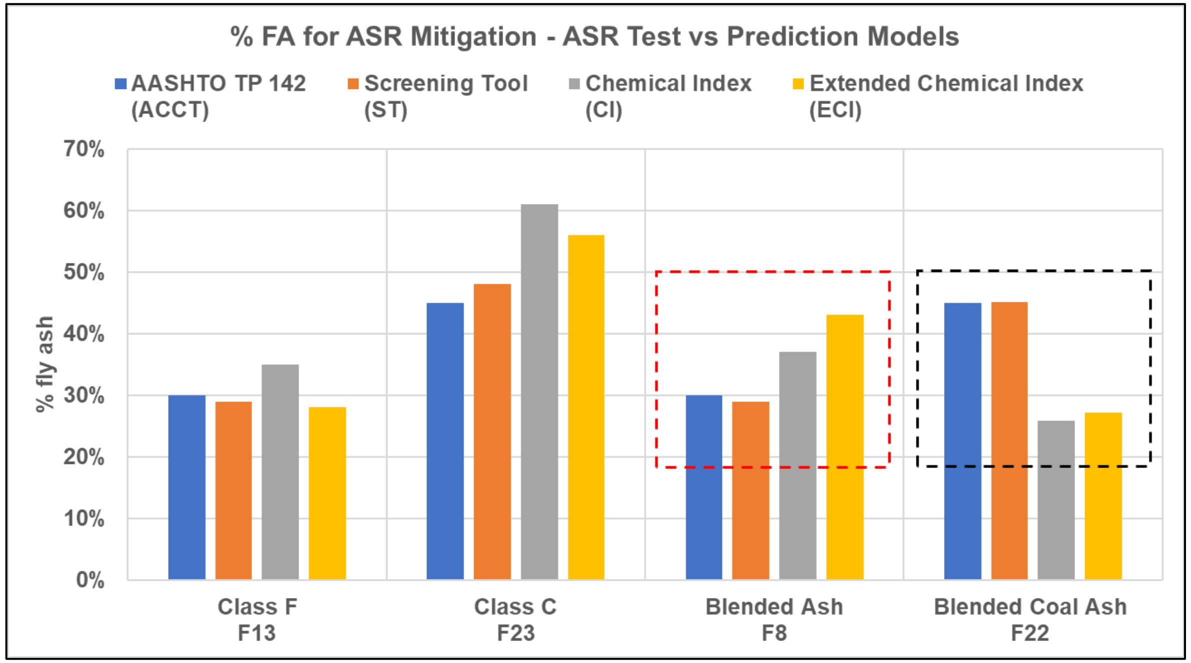
Results - Screening Tool vs. ASR Tests

- 27 Fly Ashes Evaluated in Current Study.
  - ASR Tests: AASHTO TP 142 (ACCT) & ASTM C 1567 (AMBT): → % Fly Ash ≤ Threshold Expansion
  - Screening Tool (ST)→ Predictions of Optimum Fly Ash Dosage

Classification Group	Group Description	No. of Fly Ashes
G1	ST = ACCT = ASTM C 1567	14 / 27 ≈ 52%
G2	ST = ACCT; ***but ASTM C 1567 underestimates***	9 / 27 ≈ 33%
G3	ST Predictions ± 5-8% deviation compared to both ACCT & ASTM C1567	4 / 27 ≈ 15%

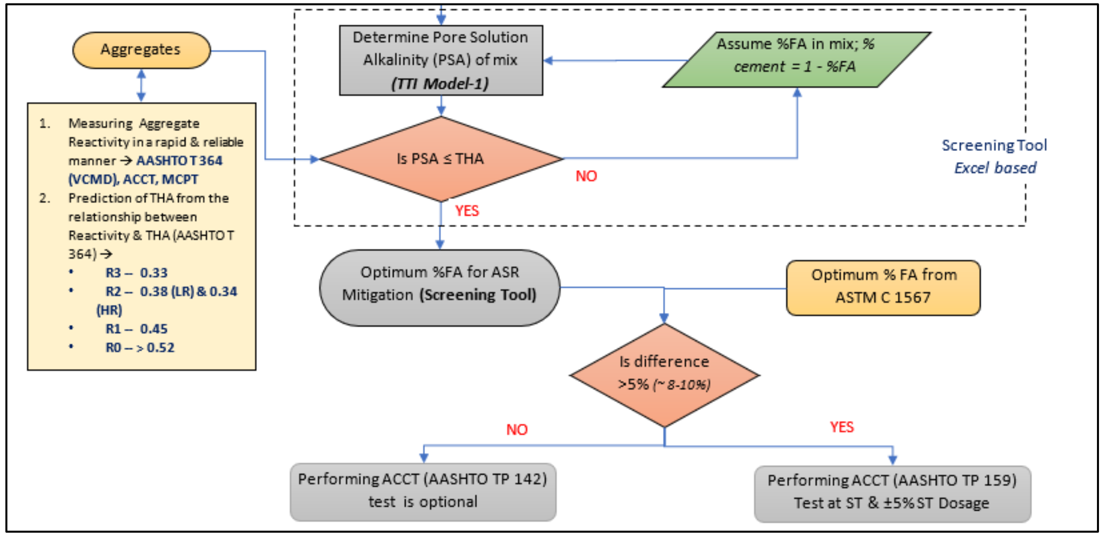
Major Findings – Sensitivity of Prediction Models

- Fly Ash ASR performance is contingent on minerology characteristics and not bulk oxide composition (e.g., F8 & F22)
  - F8
    - Blended ash: 50% Class C ash + 50% pumice
    - ASTM C 618: Class C but ***Behaves as Class F***
  - F22
    - Blended coal ash: 80% PRB + 20% lignite
    - ASTM C 618: Class F but ***Behaves as Class C***



Recommendations on Screening Tool Application

- Preventive Measures (Proposed Performance-based Approach)
  1. Screening tool to determine Fly Ash (FA) Content
     - 1 day → ASTM C 114 mod. test to ***measure*** WSA from FA *(~ 1-2 hrs./test)*
     - Instantly → Non-Linear Regression model to ***predict*** WSA from FA
  2. Compare fly ash content by screening tool vs ASTM C1567 (14 days)
  3. Selective ACCT validation for the mismatch cases: 75-90 days



Results - Mean Absolute Error (MAE) *(Predictions vs. Tests)*

- Prediction Models vs. ASR Tests
  - Screening Tool: ST
  - Chemical Index: CI
  - Extended Chemical Index: ECI

- Screening Tool Predictions:
  - Low MAE (≤ ± 6-8%) vs. ASR tests;
  - Lowest MAE vs. other prediction models,
  - Higher accuracy & reliability in predictions for unconventional ashes — blended, reclaimed & natural pozzolans

	27 Fly Ashes (Current Study)						22 Fly Ashes (Literature)		
	vs. AASHTO TP 142 (ACCT)			vs. ASTM C 1567 (AMBT)			vs. ASTM C 1293 (CPT)		
	ST	**CI**	**ECI**	**ST**	**CI**	**ECI**	**ST**	**CI**	**ECI**
Overall	3.5%	6.1%	6.7%	4.6%	5.5%	8.3%	9.2%	12.4%	10.4%
Class C	4.6%	16.0%	20.9%	6.6%	22.0%	26.9%	13.4%	18.6%	13.7%
Class F	3.3%	3.9%	4.1%	3.9%	3.6%	6.7%	5.6%	6.3%	7.5%
Blended & Reclaimed	4.1%	7.6%	7.6%	-	-	-	-	-	
Natural Pozzolans	1.9%	8.5%	6.9%	3.1%	3.5%	1.9%	-	-	

Vayghan et al., 2016)

Conclusions

1. Consideration of Pore Solution Alkalinity (PSA) is Important for ASR Evaluation
2. Certain fly ashes contribute significant water soluble alkali into pore solution
   – Significant modification of concrete pore solution (i.e., high pore solution alkalinity)
3. TTI Model -1: Combined Effect of Soluble Alkali: Cement & Fly Ashes
   – Good reliability in PSA determination
4. Screening Tool is not a regression model. Optimum FA dosage is dependent upon two fundamental chemical parameters:
   – Concrete PSA ≤ Aggregate THA relationship
5. Screening Tool Predictions:
   – Low MAE (≤ ± 6-8%) vs. ASR tests; Lowest MAE vs. other prediction models; Higher reliability for unconventional ashes — blended, reclaimed & natural pozzolans

Acknowledgements

Texas Department of Transportation (TxDOT)

American Coal Ash Association Educational Foundation (ACAAEF)

United States Bureau of Reclamation

Los Alamos National Laboratory

Thank you

Any Questions?

Anol K. Mukhopadhyay, Ph.D., P.G., (anol@tamu.edu)

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

Kai-Wei (Victor) Liu (k-liu@tti.tamu.edu)