Innovative Performance-based Approach Using Emerging Test Methods to Evaluate ASR Mitigation Effectiveness of Conventional and Alternative SCMs

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TEXAS A&M UNIVERSITY

Texas A&M Transportation Institute

Chemical Screening Tool (CST) to Estimate Fly Ash (FA) Dosage: Methodology

Aggregates THA

Measuring Aggregate Reactivity in a rapid & reliable manner

Option 1: **AASHTO T 364 (VCMD), ACCT (AASHTO TP 142)**

Option 2: Prediction of THA from the relationship between Reactivity & THA (AASHTO T 364) →

- **R3 — 0.29**
- **R2 — 0.38 (LR) & 0.34 (HR)**
- **R1 — 0.45**
- **R0 — > 0.52**

Determine Pore Solution Alkalinity (PSA) of mix *[TTI Model-1]*

Assign %FA in mix; *(e.g., 20% , 25%..)*

Is PSA ≤ THA

NO

YES

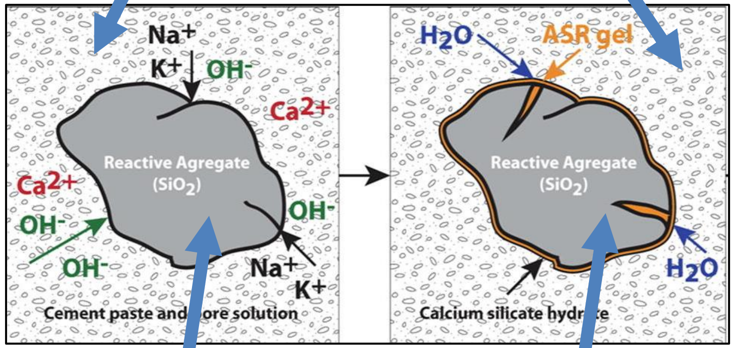
See Note 1

Optimum %FA for ASR Mitigation

***Note 1**: In lieu of iteration, Chemical Screening Tool (CST) uses Microsoft® Excel® solver function to minimize function PSA (mix) ≤ THA (agg) and determine optimum %FA*

Pore Solution Alkalinity (PSA)

ASR Mechanisms (Figueira et al., 2019)

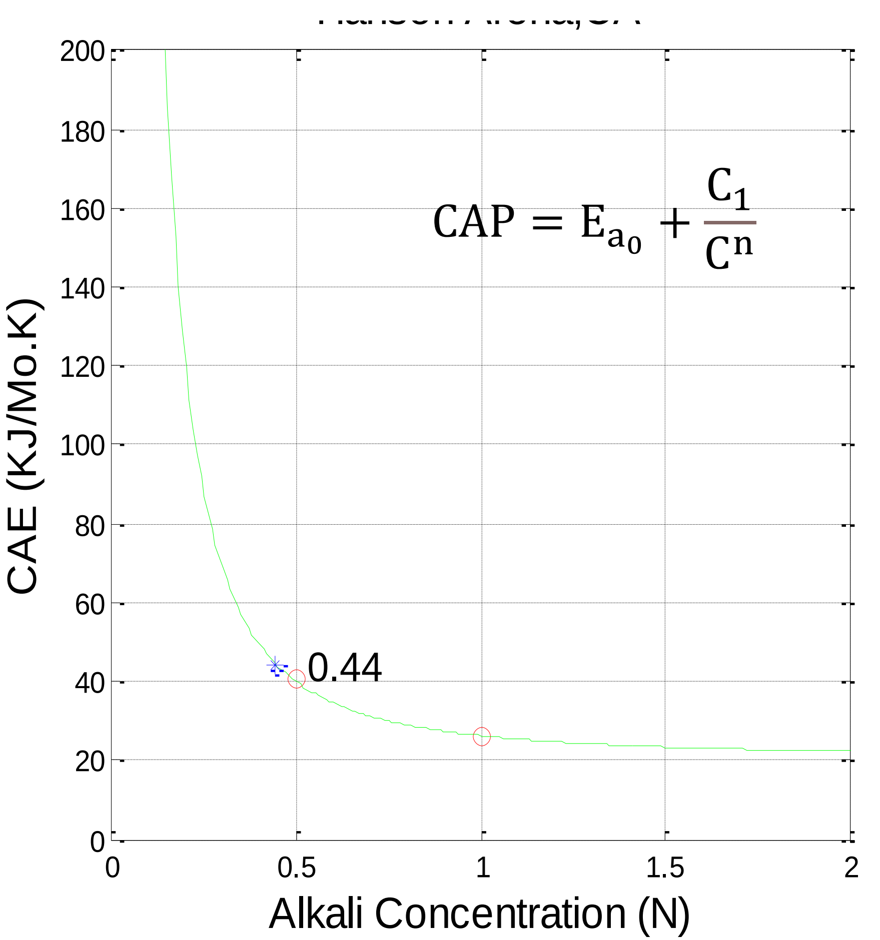


PSA > THA

Aggregate THA (Threshold Alkalinity)

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

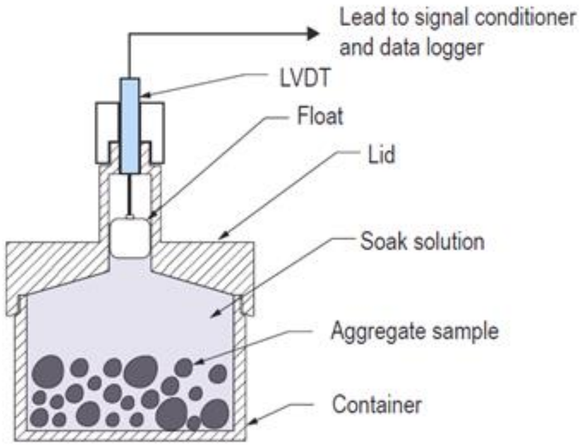
Measuring Aggregate Threshold Alkalinity (THA) Using AASHTO T364 (VCMD) Method



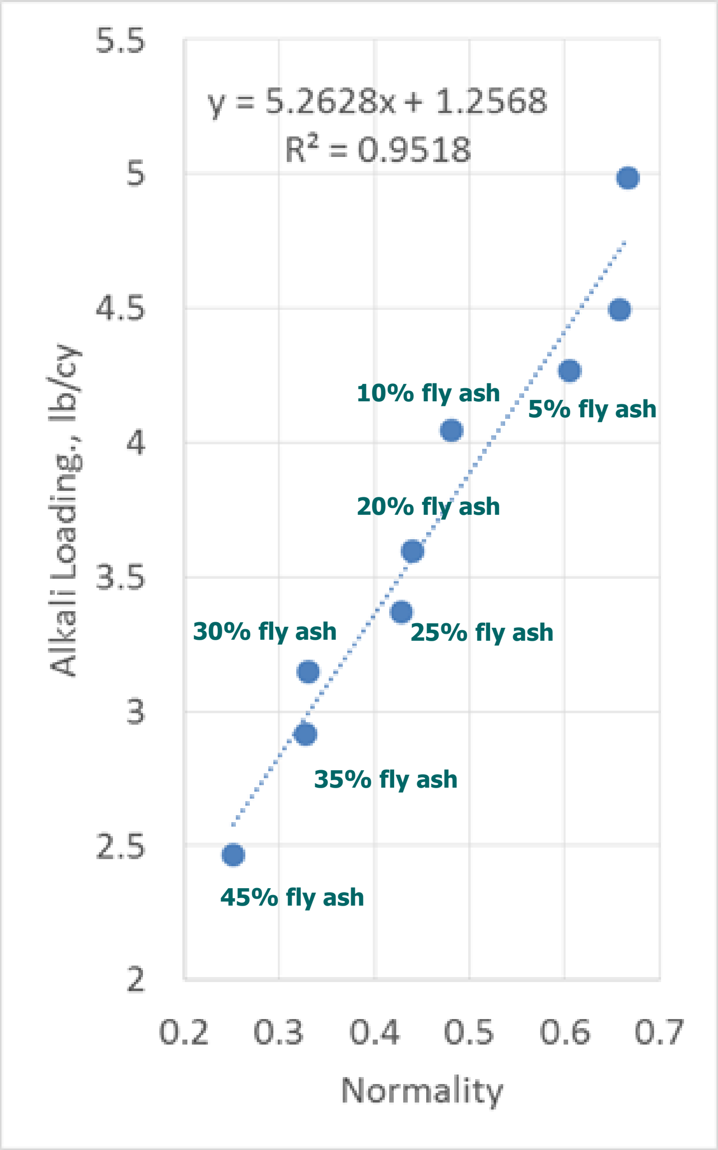
THA is calculated mathematically from the CAP vs alkalinity plot when the slope of Eq. (1) equals -100

AASHTO T 364-17: Determination of Composite Activation Energy of Aggregates due to Alkali-Silica Reaction (Chemical Method)

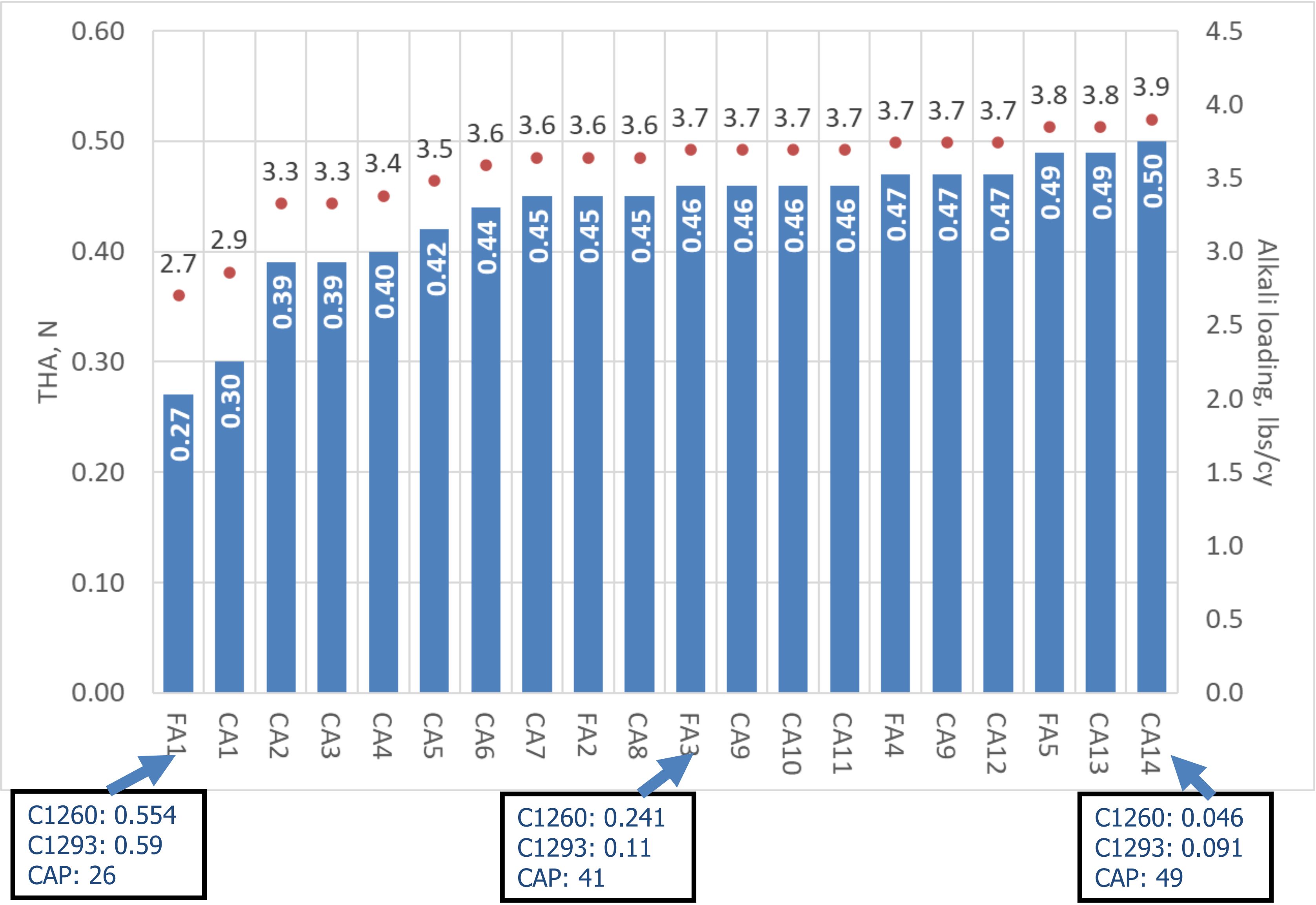
- ❖ Solution volume changes due to ASR over time – a float-LVDT-data acquisition system – 3 temperatures (e.g., 60, 70, and 80°C in an oven) and 3 levels of alkalinity [1N, 0.5N, and 0.25N NaOH + Ca(OH)2]
- ❖ Estimation of rate constants and determination of CAP using the Arrhenius rate theory



Conversion of THA into Alkali loading



Alkali Loading vs. THA

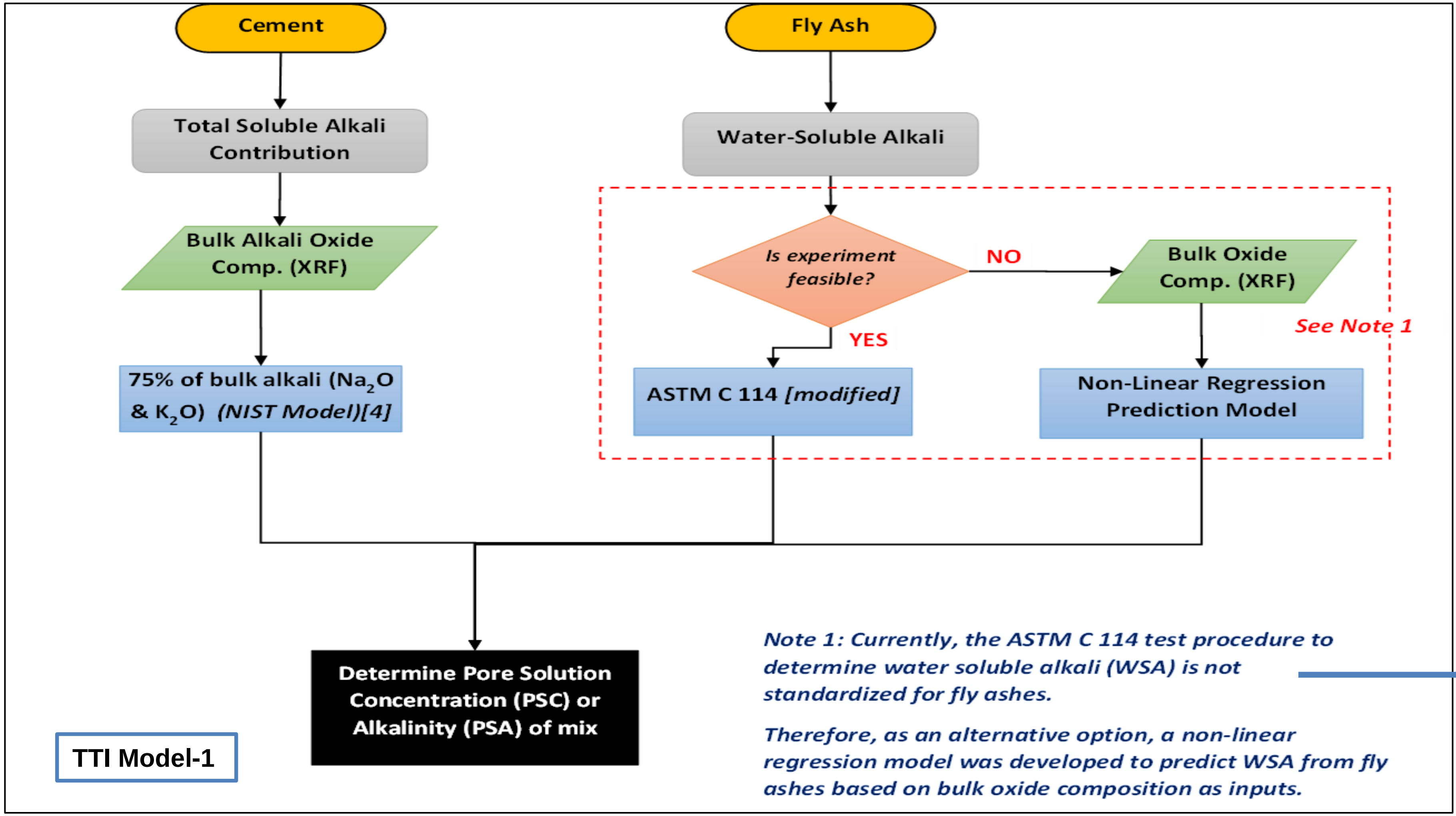


THa	Alkali loading, lbs/cy	
<0.3	≤3	R3
0.3 to 0.4	3 to 3.5	R2
0.4 to 0.5	3.5 to 4.0	R1
>0.5	4.0 to 4.5	NR

Available Approaches to Determine Concrete Pore Solution Alkalinity (PSA)

Parameter		NIST Model (Bentz et al., 2007)	GEMS Modelling (Lothenbach., 2008)	Extraction Technique
Overall Approach		Empirical	Thermodynamic model	❖Restricted to early ages (7-14 days) ❖No standardized procedure
Soluble Alkali from	Cement & Silica Fume	75% of Bulk Alkali	Accurate estimation of soluble alkali from both cement and fly ashes	
	Fly Ash (FA)			
Pros and Cons		• Rapid approach • Overestimation of PSA for FA mixes	• Accurate & Reliable • Complex and not suitable for practical applications	

Our Alternative Approach to Determine Pore Solution Alkalinity (PSA)

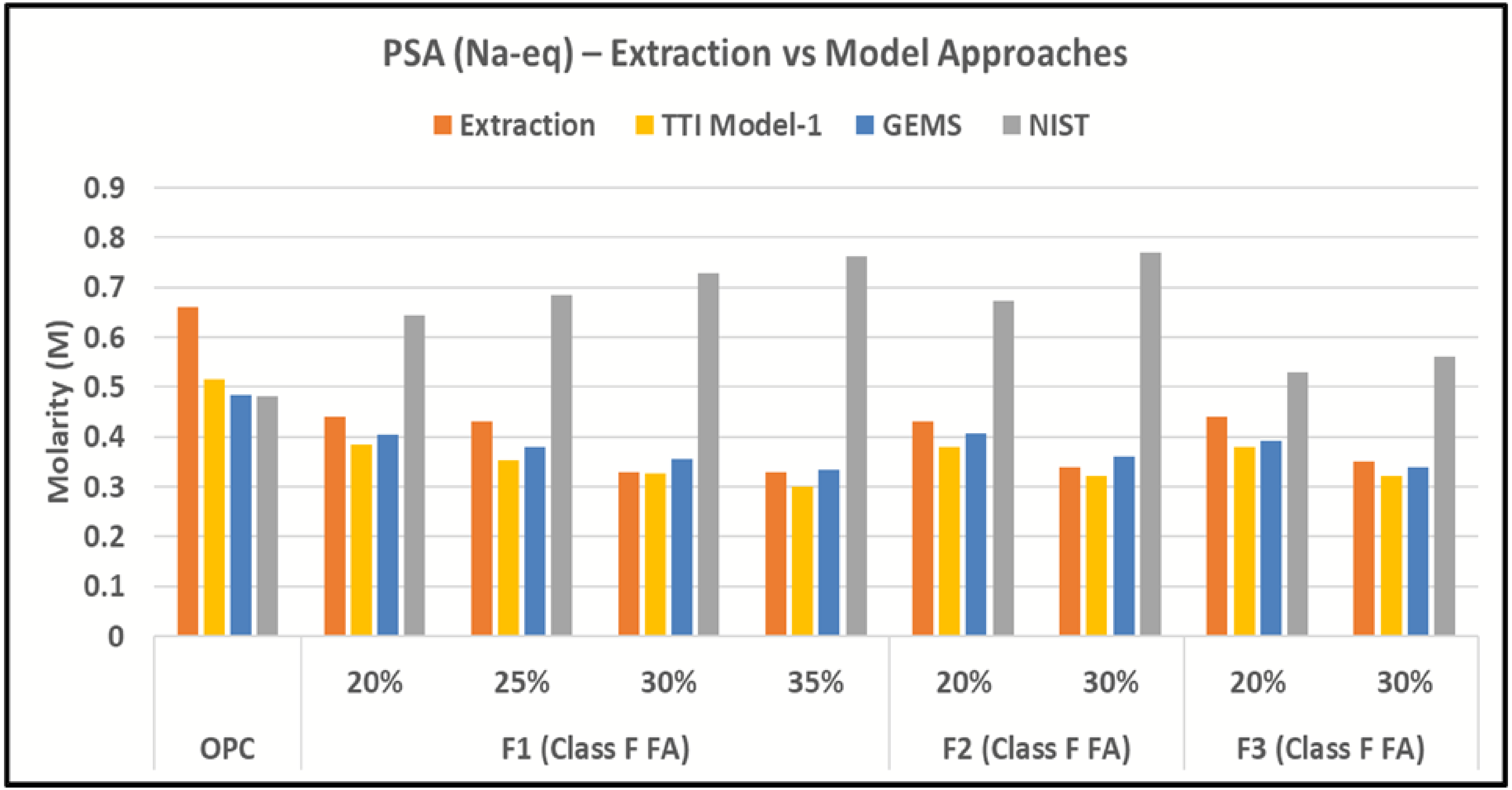


TTI-Model-1 estimates:
Early age PSA = Water soluble alkali (WSA) from cement + WSA from fly ash (immediate release mainly from crystalline soluble alkali sulfate phases)

NCHRP Report 749: Methods for Evaluating Fly Ash for Use in Highway Concrete (Sutter, Hooton, and Schlorholtz, 2013)

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

Validation of our PSA Estimation Approach



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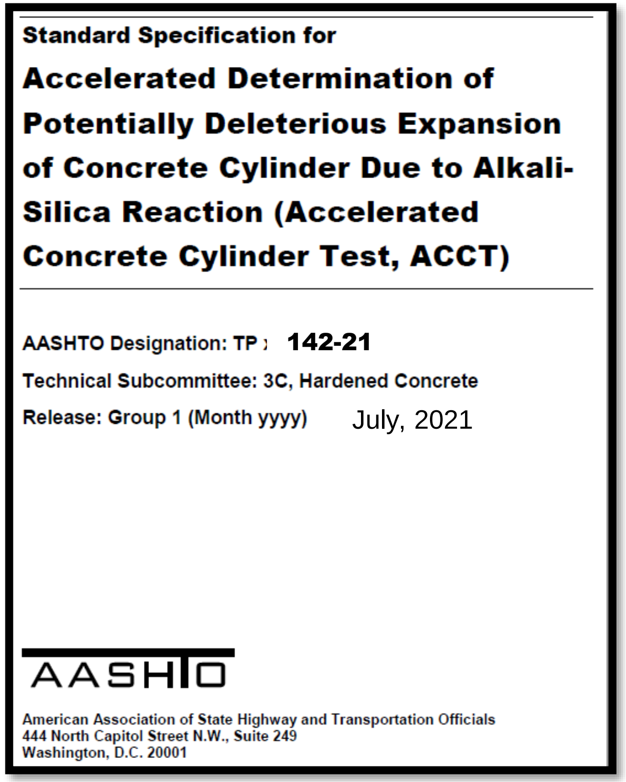
Performance Based Approach for Rapid Determination of Optimum Fly Ash Dosages

- **Step 1:** Chemical Screening tool (CST) based estimations of fly ash (FA) content
  - **1 day** → ASTM C 114 mod. test to measure water soluble alkali (WSA) from FA (~ 1-2 hrs./test)
  - **Instantly** → Non-Linear Regression model to predict WSA from FA

- **Step 2:** Determine fly ash dosage by ASTM C 1567 → 14 Days

- **Step 3:** Comparative assessment between CST vs ASTM C1567
  - If the difference in dosage is > 5% (e.g., 6-10%) → **Accelerated Concrete cylinder test (ACCT, AASHTO TP 142) validation is mandatory**
  - If the difference is < 5% → use CST-based replacement level → **ACCT validation can be considered optional**

Accelerated Concrete Cylinder Test (ACCT): 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)

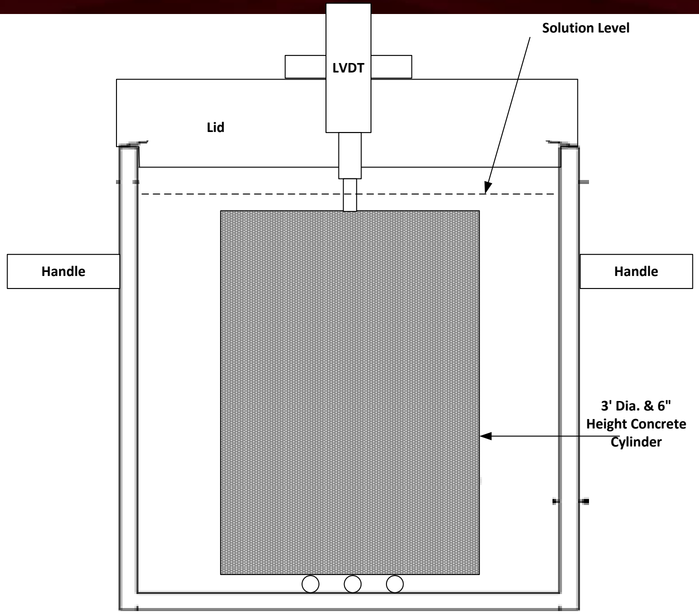
AASHTO Designation: TP 142-21

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 = 60ºC (140ºF)
- Aggregate gradation = as-received (no crushing)

- 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.

Effectiveness for Determination of Fly Ash Dosage to Mitigate ASR: Test Methods in ASTM C1778 vs ACCT

	ASTM C1567	**ASTM C1293**	**AASHTO TP142 (ACCT)**
Testing period	14-28 days	2 years	45 days (aggregate reactivity) and 75-90 days (fly ash dosage)
Alkali Leaching	NO	Yes	No
Alkali penetration	Yes (high)	NA	None or negligible
Accelerating effects due to alkali boosting	High, immersing in 1N NaOH	High, 8.9 lbs./cy in the mix	Mild, 4.5 lbs/cy in the mix and soak solution = pore solution
Effect of soluble alkalis from SCMs	No	No	**Yes**
Ability to test job field mixes	No	No	**Yes**

Application of the Performance-Based Approach: Dosage Estimation for the Conventional Ashes

Category	Category Description	No. Ashes Belong to a Category	Fly Ash Types
Category 1	CST = ACCT = ASTM C 1567	16 / 25 ≈ 64%	13 – Class F 1 – Class C 1- Blended (50% Class C + 50% Pumice) 1 – Reclaimed
Category 2	CST = ACCT ***but ASTM C 1567 underestimates***	9 / 25 ≈ 36% *5-7% lower for 6 ashes* *8-10% for 3 ashes*	6 – Class F 2 – Class C 1 – Blended Ash (80% PRB = 20% Lignite)
❖ *Several fly ashes (Class C and F) with C1293 data (literatures) – good correlation between CST and C1293*			

Blended Ash Evaluation

Blended Ash 1 (a 50:50 blend of Class C and pumice)

- Satisfies the Class F requirements (C618 criteria)
- CST estimated ~ 40% (behaves like a Class C ash) because of higher WSA which is supported by the ACCT

Blended ash 2 [a blend of PRB (80%) and lignite (20%) coal]

- Class C ash based on the CaO (18.3%) content
- CST estimated ~ 30% (behaves like a Class F ash) because of lower WSA, supported by the ACCT.

Evaluation of Natural Pozzolans Using the CST-ACCT Based Approach

#	Type	Class (C618)	SiO2	CaO	Al2O3	Fe2O3	MgO	SO3	Na2O	K2O	Na2Oeq
N1	Pumice	N	58.9	11.5	17.2	6.1	2.3	0.6	2.1	1.3	2.98
N2	Pumicite	N	75.0	1.1	12.9	2.4	0.4	0.1	3.9	4.3	6.76
N3	Rhylolitice	N	72.7	5.1	13.0	1.2	0.2	0.3	3.6	4.3	6.41
N4	Metakoalin	N	53.2	0.0	45.4	0.8	0.0	0.1	0.3	0.3	0.51
N5	Pumice	N	76.8	0.8	13.0	1.4	0.1	0.1	2.8	5.0	6.11
N6	Unknown	N	73.8	1.8	14.2	2.0	1.0	0.1	2.9	4.2	5.71
N7	Unknown	N	75.4	0.2	22.2	1.7	0.0	0.2	0.1	0.2	0.24
N8	Tephra	N	76.2	0.2	12.9	1.8	0.0	0.1	4.4	4.5	7.35
N9	Perlite	N	75.8	0.8	13.8	1.1	0.1	0.1	3.7	4.7	6.78
N10	Unknown	N	85.1	2.5	12.7	1.3	0.1	0.1	3.0	4.2	5.77
N11	Unknown	N	78.3	2.4	17.0	1.2	0.1	0.1	2.8	3.9	5.41
N12	Pumice	N	75.3	1.1	12.5	1.3	0.5	0.1	2.7	5.3	6.17

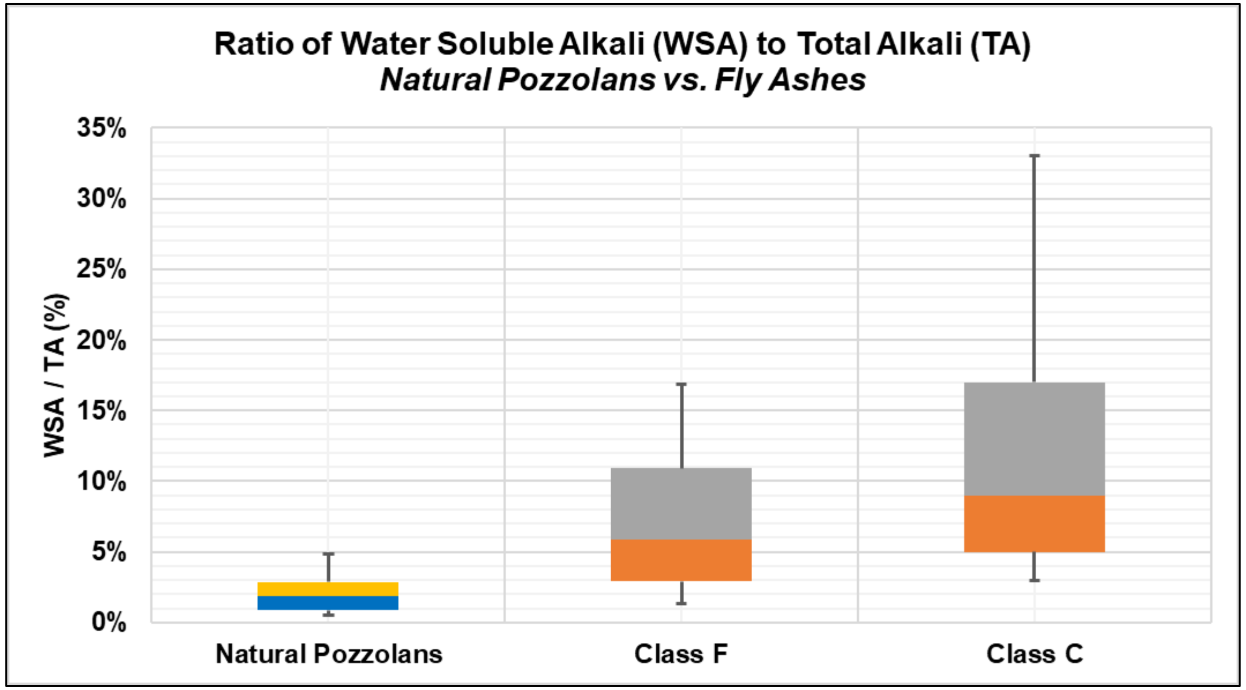
Natural Pozzolans Evaluation: Quantitative X-Ray Diffraction

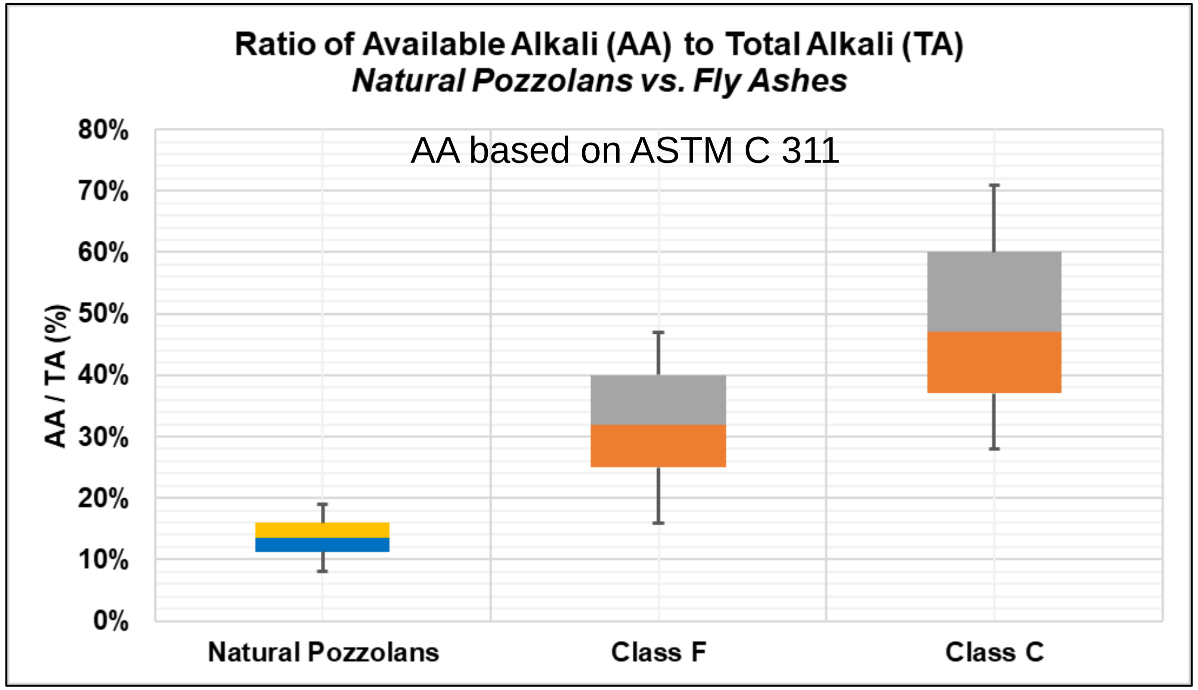
#	***Bulk Alkali (Na2Oeq)***	**Amorphous**	**Na-Feldspar (NaAlSi3O8) and K-Feldspar (KAlSi3O8)**	**Mica (K**$Al_2(AlSi_3O_{10})(F,OH)_{2})$	**Alkali Sulfates [Thenardite- Na2SO4 & Arcanite- K2SO4]**
N1	*2.98*	39.1	**4.0 - 25.0**	**1.0-11.0**	***0.2 - 1.7***
N2, N3, N5, N6, N8, N9, N10, N11, N12	***5.41 – 7.35***	67.0 – 93.0			
N4	*0.51*	91.1		1.0	1.2
N7	*0.24*	48.5			

Soluble Alkali Contribution: NPs vs Class F vs Class C

<table>
<tr><th></th><th>Total bulk alkalis</th><th colspan="2">Bound alkalis</th><th colspan="2">Alkali release into pore solution from</th><th>Alkali binding by pozzolanic C-A-S-H with low Ca/Si</th><th>Alkali release minus alkali binding = net soluble alkali into pore solution</th></tr>
<tr><th></th><th></th><th>Crystalline Phases</th><th>Amorphous Phase</th><th>Crystalline phases</th><th>Amorphous Phase</th><th></th><th></th></tr>
<tr><td>NPs</td><td>5-7%</td><td>➢ Up to 65% - alkali feldspar and mica (insoluble)
➢ Soluble alkali sulfates – Negligible</td><td>35-78%</td><td>Negligible</td><td rowspan="3">Released as a function of pozzolanic reaction</td><td>Very effective</td><td>Negligible</td></tr>
<tr><td>Class F</td><td>1.1-2.0</td><td>3-11% (mainly soluble alkali sulfates)</td><td>89-97%</td><td>3-11%</td><td>Effective</td><td>Low</td></tr>
<tr><td>Class C</td><td>2.2-5.8</td><td>14-17% (mainly soluble alkali sulfates)</td><td>83- 95%</td><td>14-17%</td><td>Less effective</td><td>High</td></tr>
</table>

Evaluation of Soluble Alkali: Natural Pozzolans vs. Fly Ashes





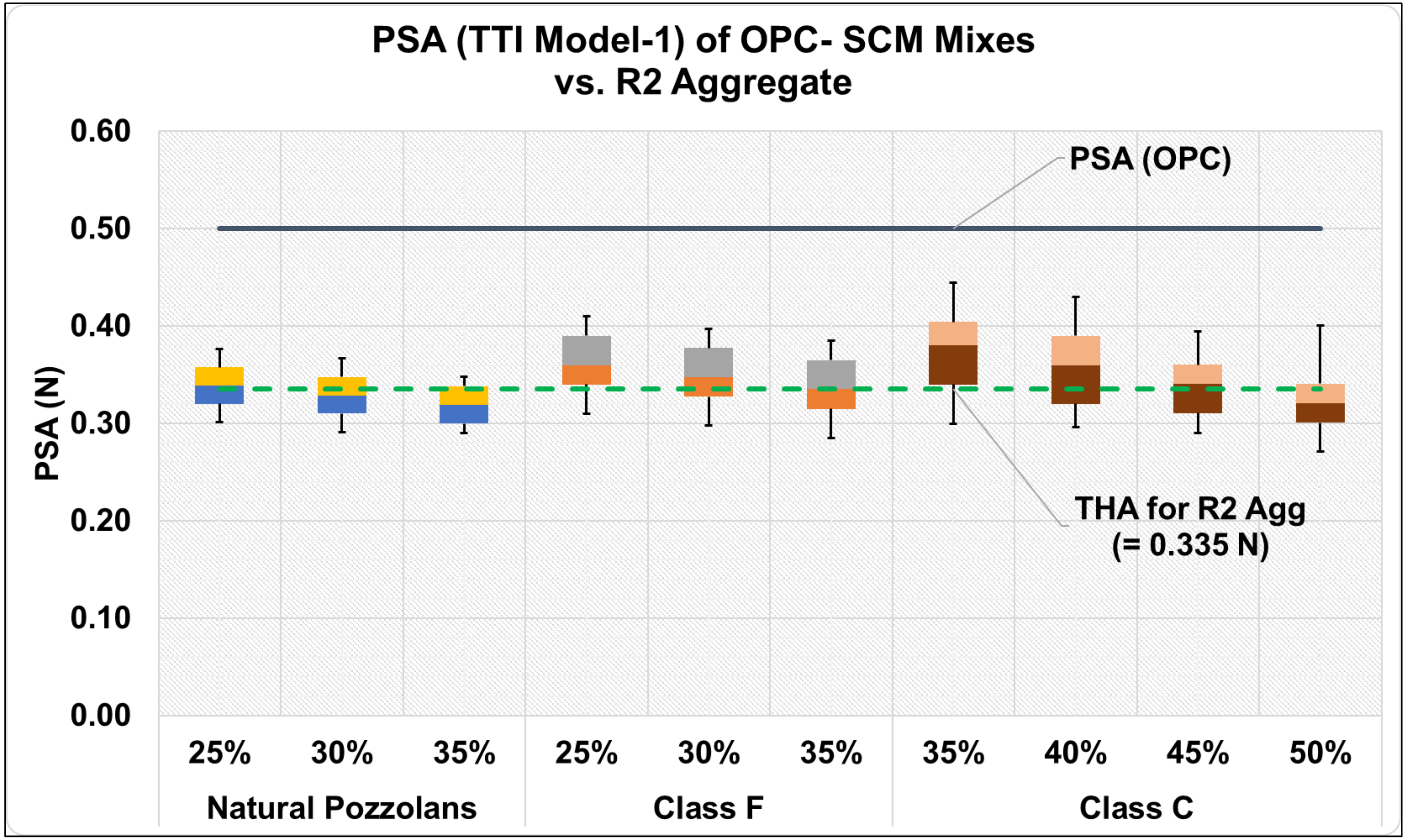
WSA/TA *(cluster)*
Natural pozzolans: 1-3%
Class F : 3-11%
Class C : 5-17%

AA/TA *(cluster)*
Natural pozzolans: 11-16%
Class F: 25-40%
Class C: 35-60%

(Mukhopadhyay et al., 2019)

Results: Pore Solution Alkalinity (PSA) Estimation and Dosage Predictions by the CST

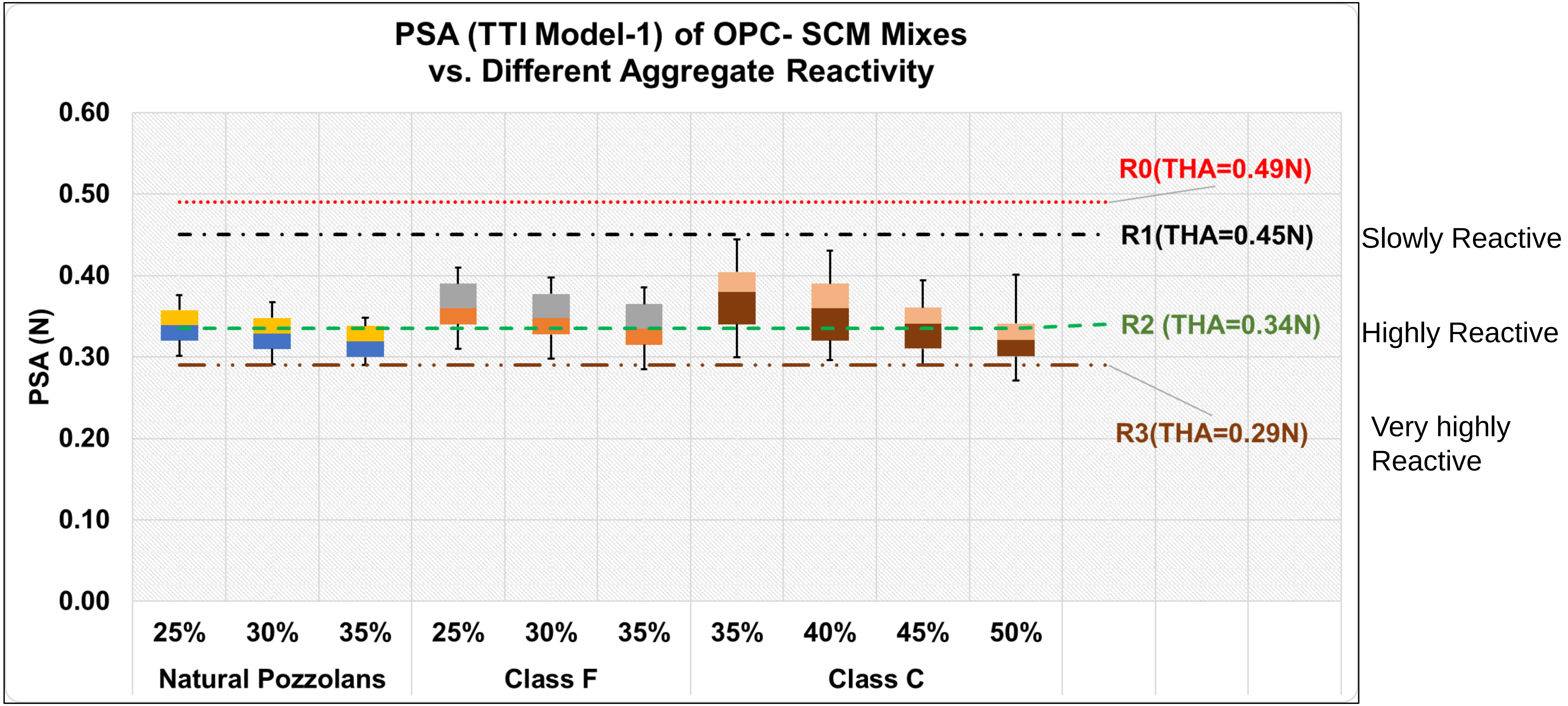
Fly Ash Dosage: to mitigate a highly reactive fine aggregate (R2) with THA = 0.335N (Green Dash line)



The dosage that makes PSA < THA is the optimum dosage

- 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
- Mukhopadhyay, A. K., Saraswatula, P., & Liu, K. W. (2023). Rapid estimation of natural pozzolan dosages for mitigating ASR using the innovative chemical screening tool (CST). Construction and Building Materials, 408, 133609.

Estimation of SCM Dosages based on SCM Characteristics (Role of SCM to modify PSA) and Aggregate Reactivity



Determination of Fly Ash Dosage: CST vs AMBT vs. ACCT

#	% Fly Ash based on the CST (PSA ≤ THA)	AMBT (ASTM C 1567) 14d-Expansion @ CST %RL	ACCT (AASHTO TP 142) 78d Expansion @ CST %RL
N1	27%	0.07%	0.03%
N2	29%	0.04%	0.01%
N3	28%	0.02%	0.039%
N4	27%	0.04%	0.02%
N5	27%	0.03%	0.01%
N6	27%	0.02%	0.02%
N7	27%	0.02%	0.01%
N8	28%	0.03%	0.01%
N9	28%	0.04%	0.01%
N10	30%	0.04%	0.02%
N11	30%	0.05%	0.03%
N12	30%	0.03%	0.02%

Determination of Other Alternative SCM Dosage: AMBT vs. ACCT

Mix type	AMBT (ASTM C1567)		ACCT (AASHT TP 142)
	%Expansion @14 d	%Expansion @28 d	%Expansion @90d
30% Ground Glass (GG)	0.14%	0.20%	0.41%
45% GG	0.08%	0.12%	0.21%
22% GG + 8% SF	0.07%	0.09%	0.07%
20% GG + 5% CS	0.08%	0.11%	0.27%
20% GG + 10% MK	0.07%	0.12%	0.06%
25% GG + 15% MK	0.05%	0.08%	0.03%
17% MK + 8% SF	0.08	0.09	0.02
15% MK + 5% CS	0.10	0.15	0.03

- Available alkali (AA) based on C311 is very high for GG: CST was not useful
- Concrete made of an R3 coarse aggregate and R1-R2 fine aggregate
- Net Concrete Pore Solution Alkalinity = (Alkali release from cement + Alkali release from GG) – alkali binding by pozzolanic C-S-H with low Ca/Si

Conclusions

The Application of CST (PSA ≤ THA criterion) was validated to determine the dosage of natural pozzolans for ASR mitigation for a highly reactive fine aggregate

- Although the bulk alkali contents of the studied NPs high (Na_2O_{eq} ~ 3 – 8%), their soluble alkali contribution to pore solution was found to be low
- The WSA trend matches the estimated dosages
  - WSA: natural pozzolans < Class F ashes < Class C fly ashes
  - Dosage: 25-30% for NPs < ~ 35% for Class F < 45-50% for Class F
- CST predictions for optimum dosage for ASR mitigation for all the studied NPs were favorably validated by both ACCT (AASHTO TP 142) and AMBT (ASTM C 1567) ASR tests.
  - ASTM C1567 is not recommended when the Na_2O_{eq} of any SCMs ≥4.5% - Because of low WSA & AA for the NPs, AMBT provided acceptable results

Conclusions

A combined approach of CST and ACCT with judicious use of AMBT can reliably be used to determine optimum NPs dosage quickly and thus, save time and money and increase reliability while promoting making ASR resistant concrete using locally available natural pozzolans.

- ❖ Testing wide varieties of NPs to validate the robustness of the CST method is needed – Under progress

Acknowledgements

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Los Alamos National Laboratory

Natural Pozzolan Associations

FAA / IPRF