ASR-induced Anisotropy in The Mechanical Properties of Concrete

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Frank Vecchio

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"6th Street Viaduct Seismic Improvement Project," *California Department of Transportation and City of Los Angeles*, 2011.

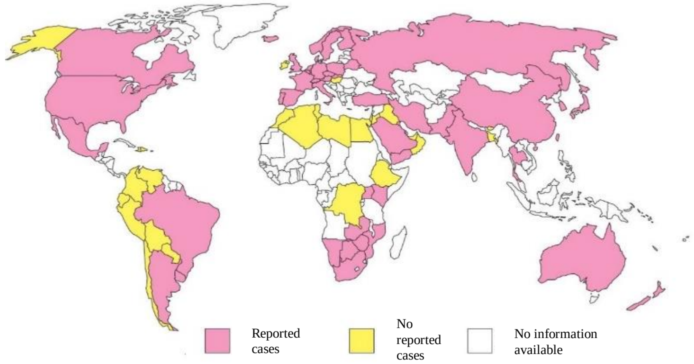
ACI CONCRETE CONVENTION

OUTLINE

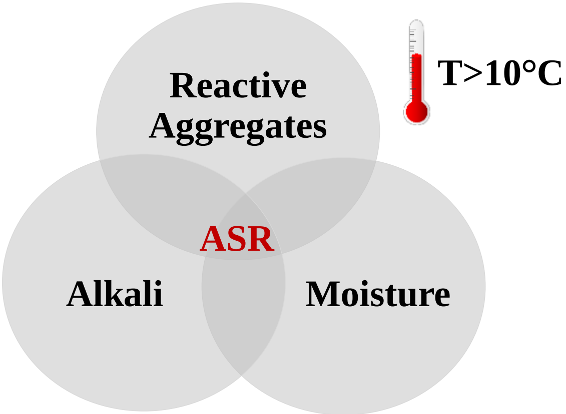
1. INTRODUCTION
2. MECHANICAL PROPERTIES OF ASR-AFFECTED CONCRETE
   - EXPERIMENTAL PROGRAM
   - ANALYTICAL PROGRAM
3. VALIDATION STUDIES
4. CONCLUSIONS

1. Introduction

Alkali-Silica Reaction



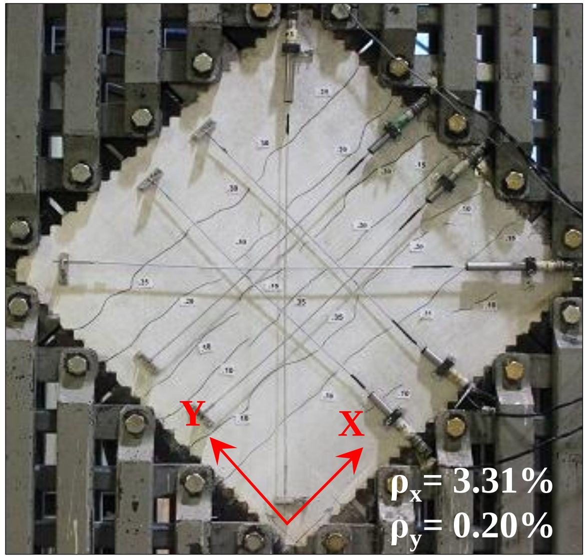
(adapted from Sims and Poole, 2017)



Influencing Factors
• Temperature, • Water availability, • Alkali content, • Type of reactive aggregates, • Aggregate size, • Air entrainment and porosity, • Long-term stress level.

Source: "Condition assessment of an ASR-affected overpass after nearly 50 years in service," Sanchez et al., *Construction and Building Materials*, 2018.

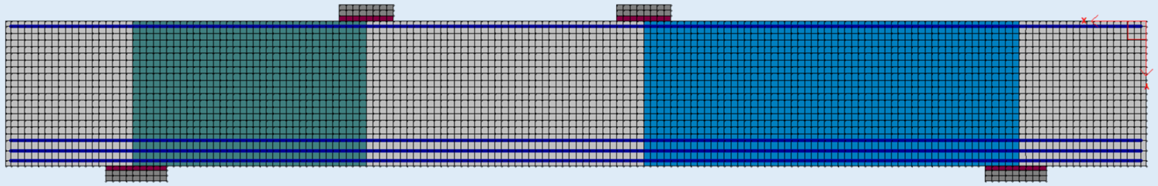
ASR-Affected Dam, Norway
(Thomas et al., 2013)

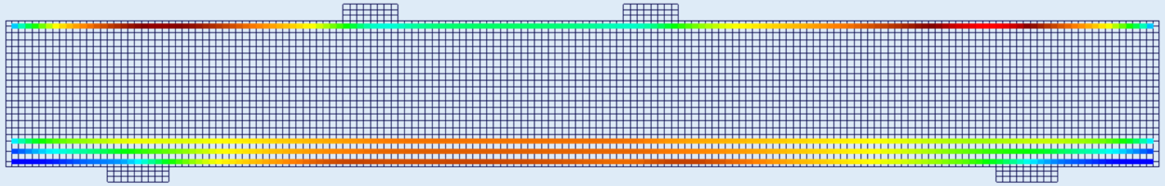


1. Introduction

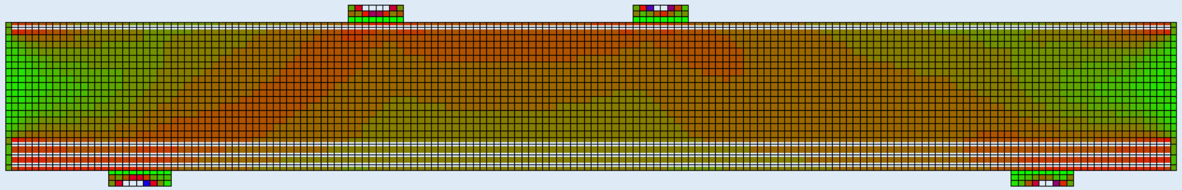
ASR-Related Structural Implications

Expansion-Induced Prestress





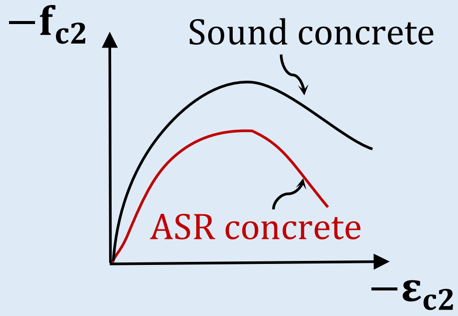
Longitudinal reinforcement stress



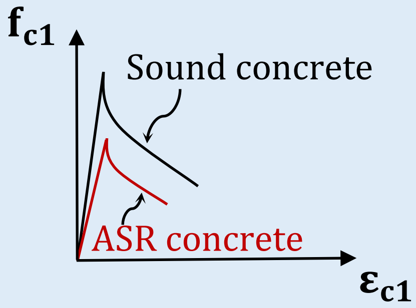
Concrete stress profile along the second principal direction

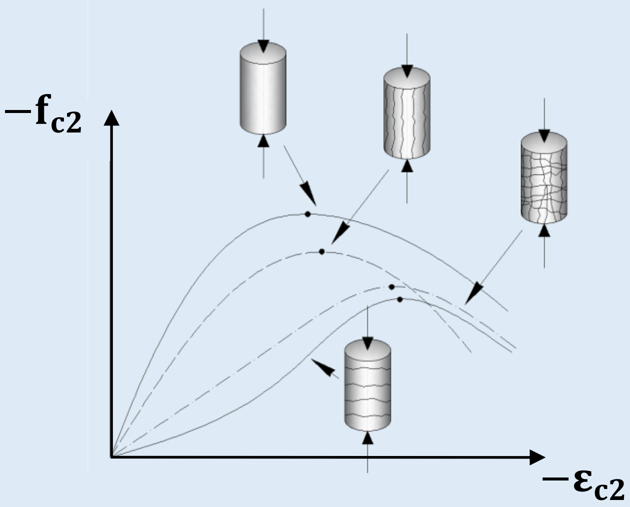
Concrete Mechanical Properties Degradation

Compression



Tension





⚠ The mechanical properties of ASR-affected concrete vary significantly with the principal stress directions.

1. Introduction

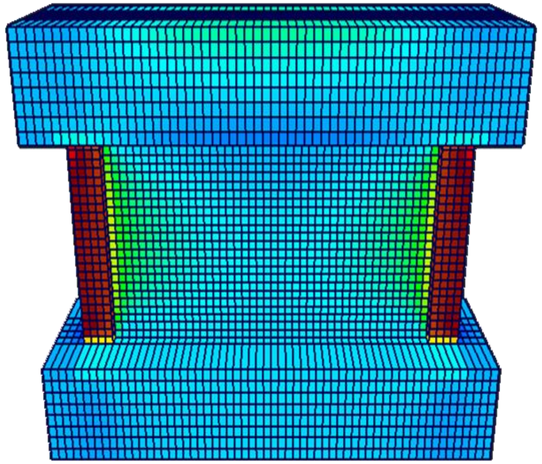
Numerical Procedure for Modeling ASR-Damaged Structures

Modeling ASR Effects with the VecTor Programs → VecTor2 & VecTor3

Stage 1: **ASR Analysis**	*Stage 2*: **Nonlinear Analysis**

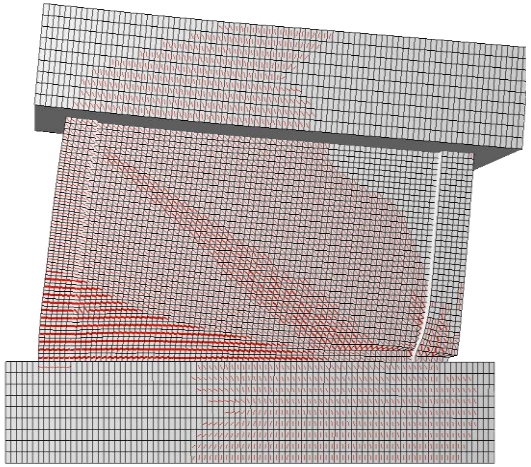
Evaluation of **ASR-induced strains** and **deterioration of mechanical properties** based on **long-term stress conditions.**

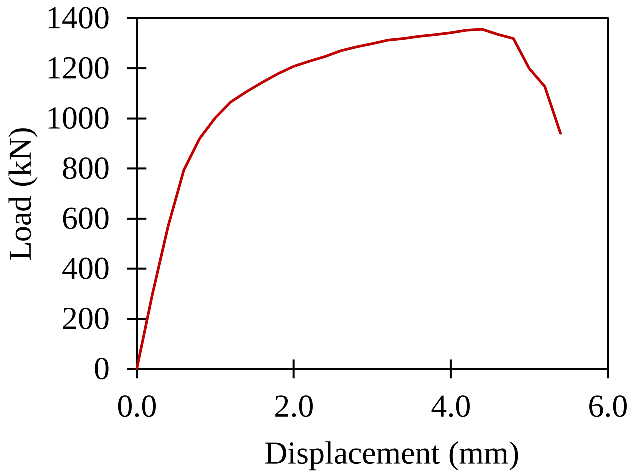
Required input for the ASR analysis:
- Unrestrained ASR expansion.
- Or characterization of the expansion & age of the structure.



Outcomes:
- Stress and strain state in concrete and reinforcement caused by ASR expansion;
- Cracking characteristics.

Nonlinear analysis considering the results obtained in Stage 1 to evaluate the **behavior** of the structure.





Outcomes:
- Load, deformation, and cracking response;
- Failure mode.

1. INTRODUCTION

NUMERICAL PROCEDURE FOR MODELING ASR-DAMAGED STRUCTURES

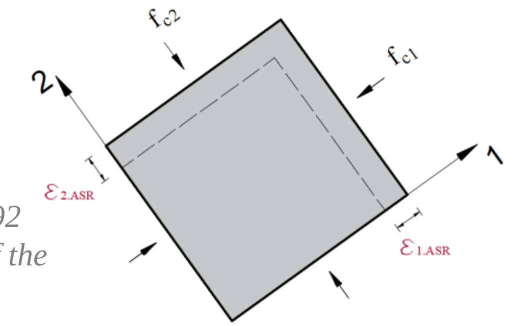
Stage 1: **ASR Analysis** → Evaluation of ASR-induced strains and deterioration of mechanical properties

ASR-Induced Strains Calculation

1. Uniform in each principal direction
2. Charlwood et al., 1992 model

   Strains are independently evaluated in each direction, limited by confinement stress.
3. Curtis, 2014 model

   A refined version of the Charlwood et al., 1992 model. Formulated based on field observations of the Mactaquac powerhouse.



4. Saouma and Perotti, 2006 model

   Expansion is treated as a volumetric strain.
5. Sellier et al., 2009 model

   Strains are evaluated as a consequence of the gel pressure.

Kinetics model

6. Gautam et al., 2017 model

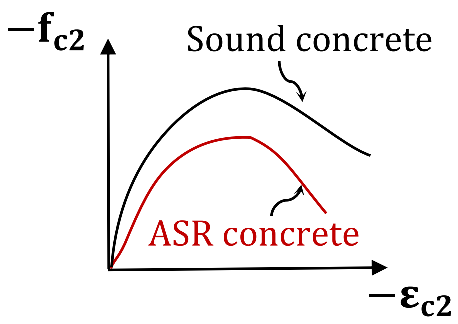
   Developed based on empirical data collected from ASR-affected multiaxially-loaded cube specimens.

Deterioration of Mechanical Properties

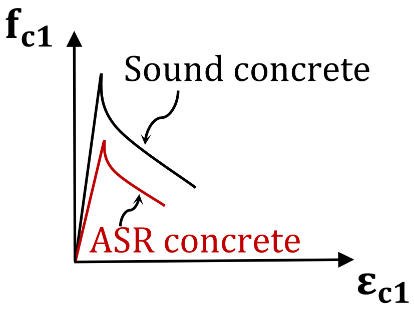
1. ISE recommendations
2. User-defined properties
3. Anisotropic model
4. Isotropic model

→ Reduction functions for:
- Compressive strength
- Tensile strength
- Modulus of elasticity

Compression

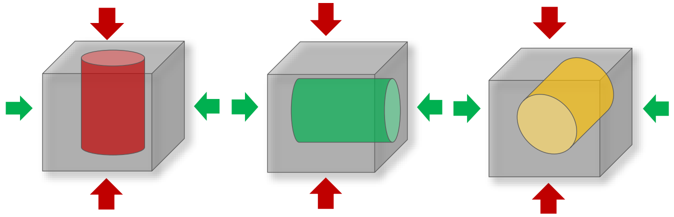


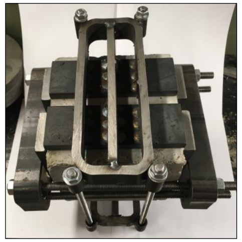
Tension



2. Mechanical Properties of ASR-Affected Concrete

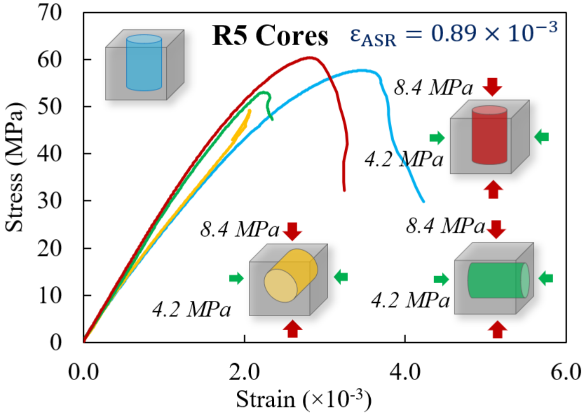
Experimental Program	Analytical Program
Material-Level Study designed to capture the anisotropy of the mechanical properties of ASR-affected concrete.	*Model for the Mechanical Properties of ASR-Affected Concrete* developed to describe the directionality of the mechanical properties of ASR-affected concrete.

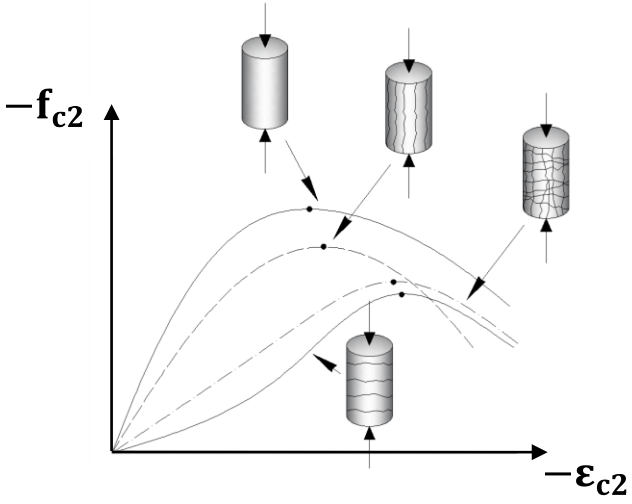




Tensile splitting

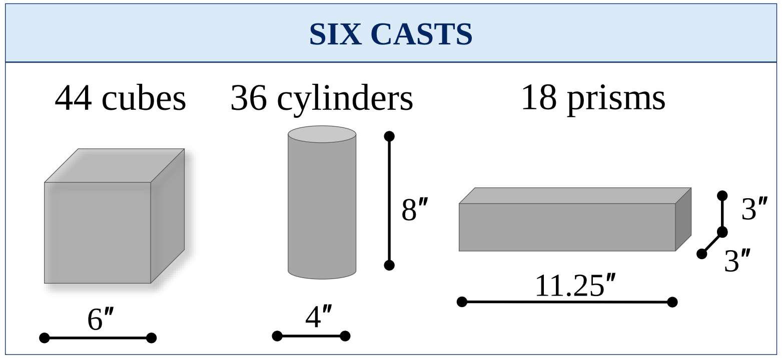
Uniaxial compression

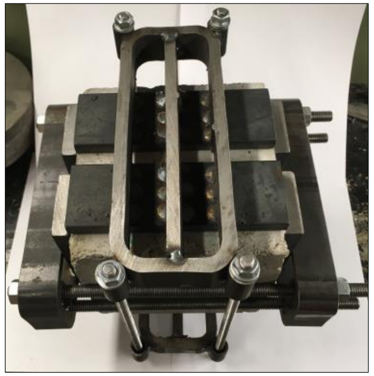


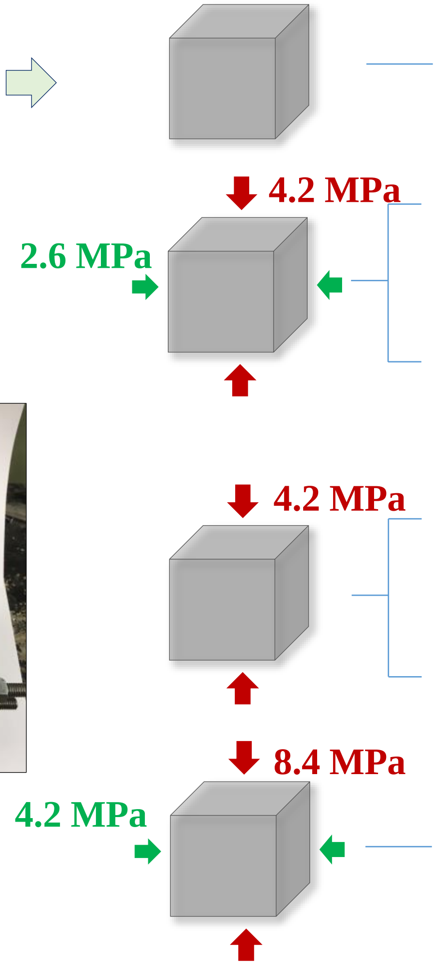


2. Mechanical Properties of ASR-Affected Concrete

Experimental Program



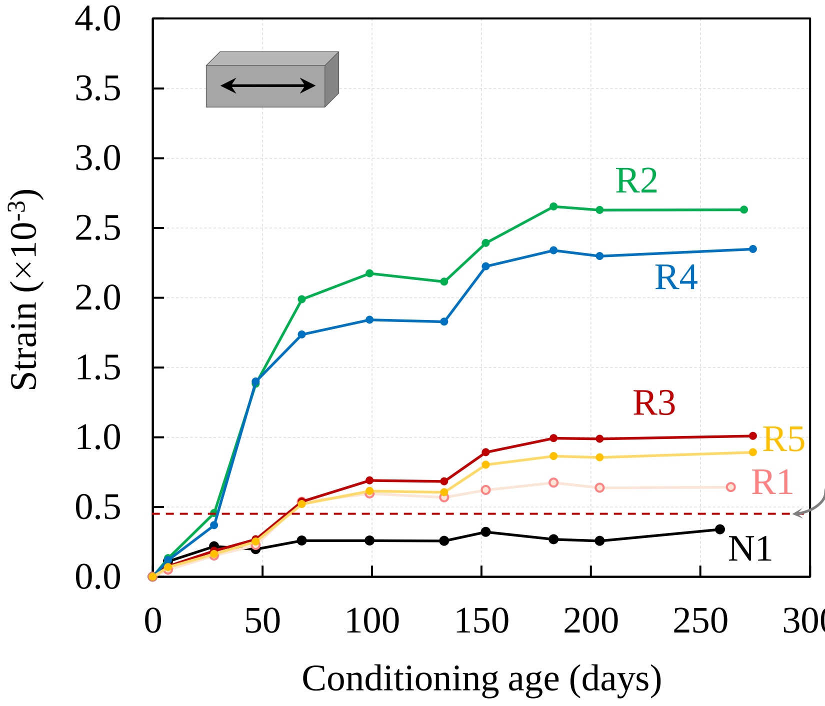


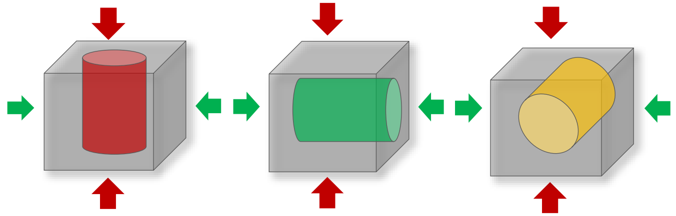


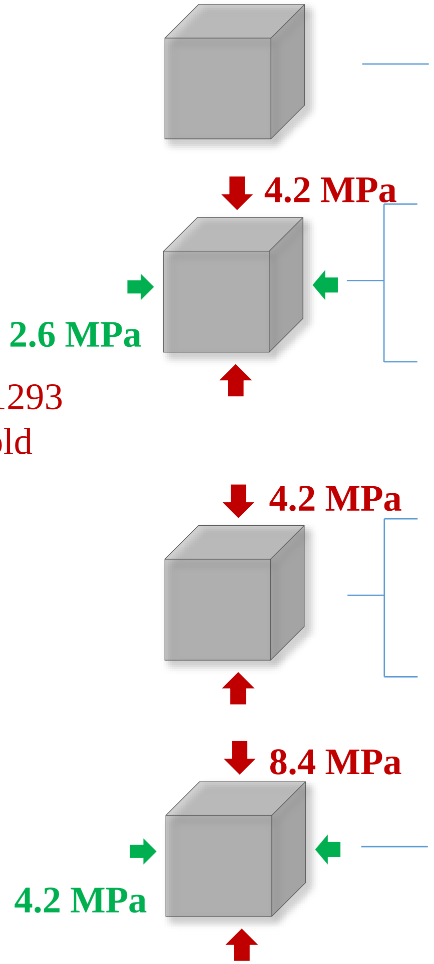
Cubes set	# of cubes	σ_x (MPa)	σ_y (MPa)	σ_z (MPa)	Test method	Reactive aggregate
N1	4	0.00	0.00	0.00	Compression	None
	4	0.00	0.00	0.00	Tensile splitting	
R1	3	4.22	2.57	0.00	Compression	Spratt
	1	0.00	0.00	0.00		
	3	4.22	2.57	0.00	Tensile splitting	
	1	0.00	0.00	0.00		
R2	3	4.22	2.57	0.00	Compression	Jobe-Newman
	1	0.00	0.00	0.00		
	3	4.22	2.57	0.00	Tensile splitting	
	1	0.00	0.00	0.00		
R3	2	4.22	0.00	0.00	Compression	Spratt
	1	0.00	0.00	0.00		
	2	4.22	0.00	0.00	Tensile splitting	
	1	0.00	0.00	0.00		
R4	2	4.22	0.00	0.00	Compression	Jobe-Newman
	1	0.00	0.00	0.00		
	2	4.22	0.00	0.00	Tensile splitting	
	1	0.00	0.00	0.00		
R5	3	8.44	4.22	0.00	Compression	Spratt
	1	0.00	0.00	0.00		
	3	8.44	4.22	0.00	Tensile splitting	
	1	0.00	0.00	0.00		

2. Mechanical Properties of ASR-Affected Concrete

Experimental Program



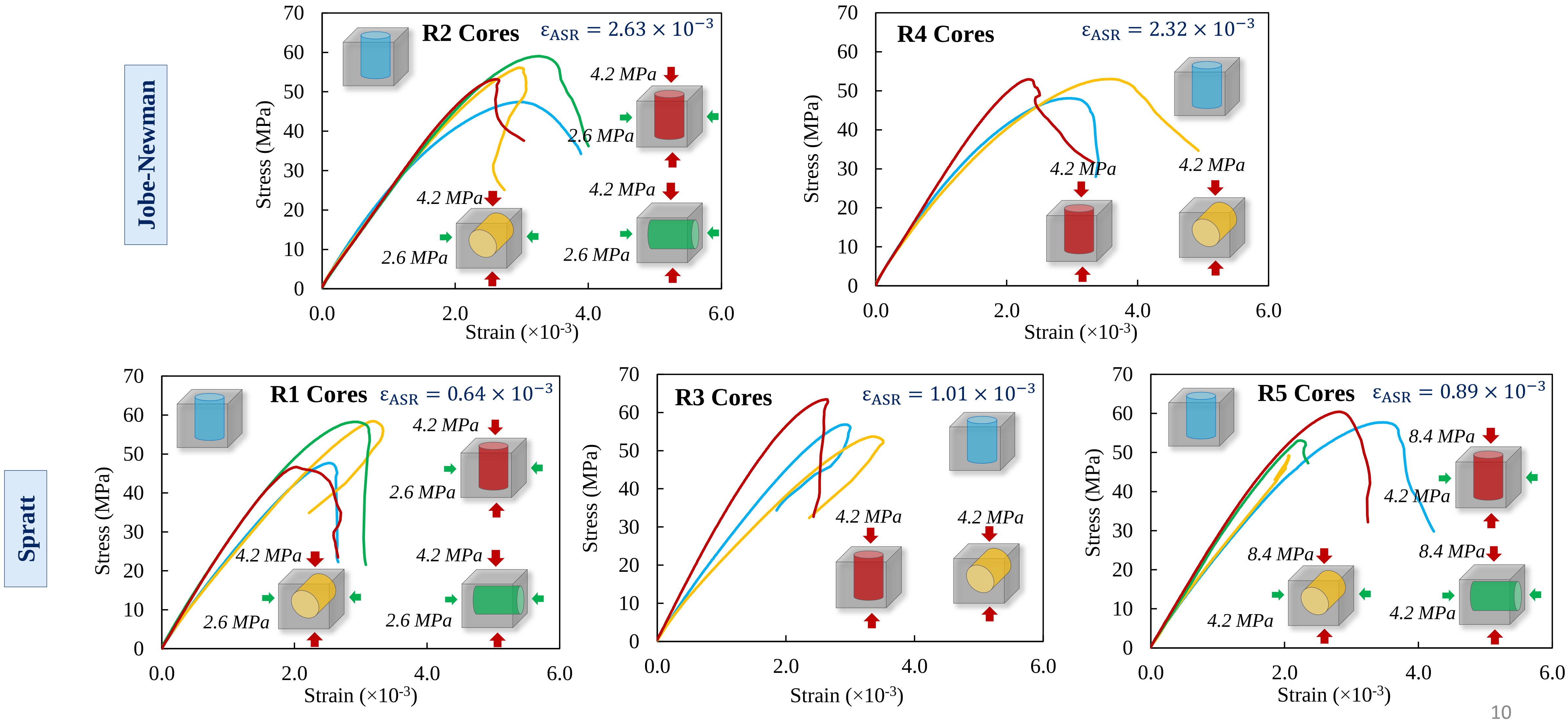




Cubes set	# of cubes	σ_x (MPa)	σ_y (MPa)	σ_z (MPa)	Test method	Reactive aggregate
N1	4	0.00	0.00	0.00	Compression	None
	4	0.00	0.00	0.00	Tensile splitting	
R1	3	4.22	2.57	0.00	Compression	Spratt
	1	0.00	0.00	0.00		
	3	4.22	2.57	0.00	Tensile splitting	
	1	0.00	0.00	0.00		
R2	3	4.22	2.57	0.00	Compression	Jobe-Newman
	1	0.00	0.00	0.00		
	3	4.22	2.57	0.00	Tensile splitting	
	1	0.00	0.00	0.00		
R3	2	4.22	0.00	0.00	Compression	Spratt
	1	0.00	0.00	0.00		
	2	4.22	0.00	0.00	Tensile splitting	
	1	0.00	0.00	0.00		
R4	2	4.22	0.00	0.00	Compression	Jobe-Newman
	1	0.00	0.00	0.00		
	2	4.22	0.00	0.00	Tensile splitting	
	1	0.00	0.00	0.00		
R5	3	8.44	4.22	0.00	Compression	Spratt
	1	0.00	0.00	0.00		
	3	8.44	4.22	0.00	Tensile splitting	
	1	0.00	0.00	0.00		

2. Mechanical Properties of ASR-Affected Concrete

Experimental Program



2. Mechanical Properties of ASR-Affected Concrete

Experimental Program

1. ASR-induced deterioration affects differently the compressive strength, modulus of elasticity, and the tensile strength of concrete cured in stress free conditions.
2. Long-term compressive stresses of 2.6 MPa and higher can essentially counteract the ASR-induced deterioration with respect to the concrete compressive strength along the restrained direction.
3. The modulus of elasticity measured along the restrained directions is considerably more affected by ASR than the compressive strength.

Post-Conditioning Mechanical Properties

Core	f_p (MPa)	ε_p ($\times 10^{-3}$)	E_c (MPa)	f_{sp} (MPa)	μ
N1, non-reactive					
1	64.3	2.70	33800	5.19	0.16
2	63.1	2.56	33000	5.43	0.17
3	64.2	2.47	34200	5.20	0.16
Avg.	63.9	2.58	33700	5.27	0.17
R1, Spratt coarse aggregate: $\varepsilon_{ASR}=0.64\times 10^{-3}$					
0.0 MPa	58.4	3.19	22100	4.21	0.16
2.6 MPa	58.3	2.91	27400	4.34	0.14
4.2 MPa	46.6	2.02	28400	4.12	0.18
free	47.7	2.52	23500	3.59	0.15
R2, Jobe-Newman fine aggregate: $\varepsilon_{ASR}=2.63\times 10^{-3}$					
0.0 MPa	56.1	2.97	23600	3.82	0.19
2.6 MPa	59.0	3.25	23800	5.07	0.19
4.2 MPa	53.2	2.60	24000	3.97	0.20
free	47.4	2.97	25600	3.73	0.14
R3, Spratt coarse aggregate: $\varepsilon_{ASR}=1.01\times 10^{-3}$					
0.0 MPa	53.7	3.35	20600	4.03	0.11
4.2 MPa	63.4	2.64	32500	3.76	0.13
free	56.8	2.91	24400	3.47	0.11
R4, Jobe-Newman fine aggregate: $\varepsilon_{ASR}=2.35\times 10^{-3}$					
0.0 MPa	53.0	3.58	23200	4.16	0.17
4.2 MPa	52.9	2.33	26900	3.62	0.15
free	48.1	2.94	25500	4.01	0.13
R5, Spratt coarse aggregate: $\varepsilon_{ASR}=0.89\times 10^{-3}$					
0.0 MPa	49.2	2.07	24600	4.74	0.15
4.2 MPa	53.0	2.24	27000	3.81	0.17
8.4 MPa	60.4	2.81	28700	5.12	0.15
free	57.7	3.47	23300	3.86	0.14

28-Day Mechanical Properties

Cast	f'_c (MPa)	ε_o ($\times 10^{-3}$)	E_c (MPa)
N1	45.9	2.69	30200
R1	40.1	2.30	30100
R2	42.7	2.54	31600
R3	38.6	2.45	29500
R4	46.6	2.73	31200
R5	38.0	2.42	28500

f_p: compressive strength

ε_p: strain at peak stress

E_c: modulus of elasticity

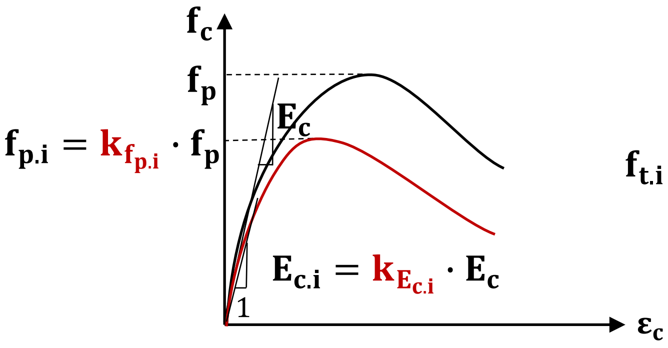
f_{sp}: splitting tensile strength

μ: Poisson's ratio

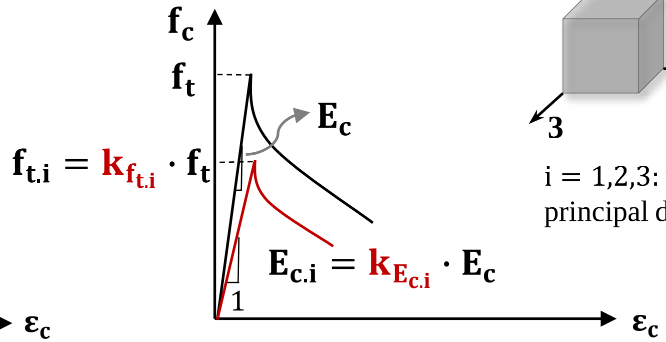
2. Mechanical Properties of ASR-Affected Concrete

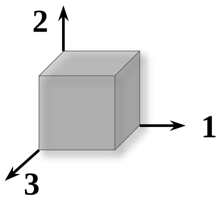
Model for the Mechanical Properties of ASR-Affected Concrete

Compression Response



Tension Response





i = 1,2,3: the principal directions.

Experimental modification factors

Compressive Strength

$$k_{f_{p.i}} = \frac{f_{p.Ri}/f_{p.N}}{f'_{c.Ri}/f'_{c.N}}$$

Post-conditioning

At 28 days

Modulus of Elasticity

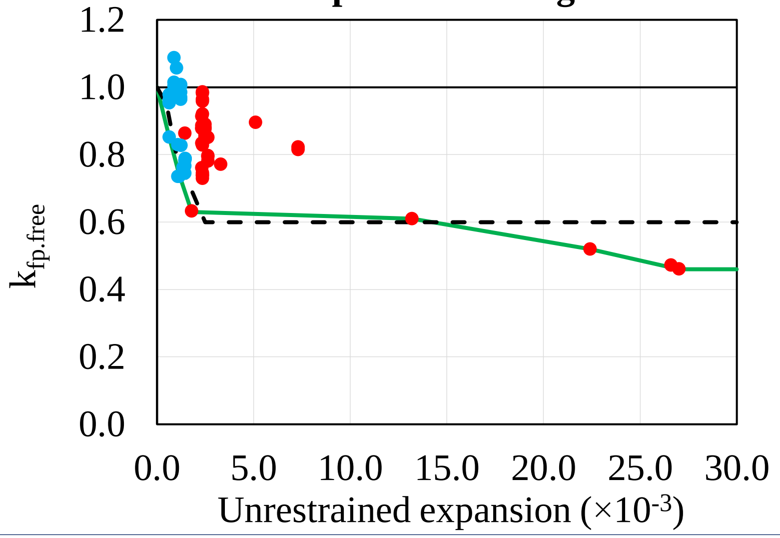
$$k_{E_{c.i}} = \frac{E_{c.Ri}/E_{c.N}}{E_{c.Ri.28}/E_{c.N.28}}$$

Tensile Strength

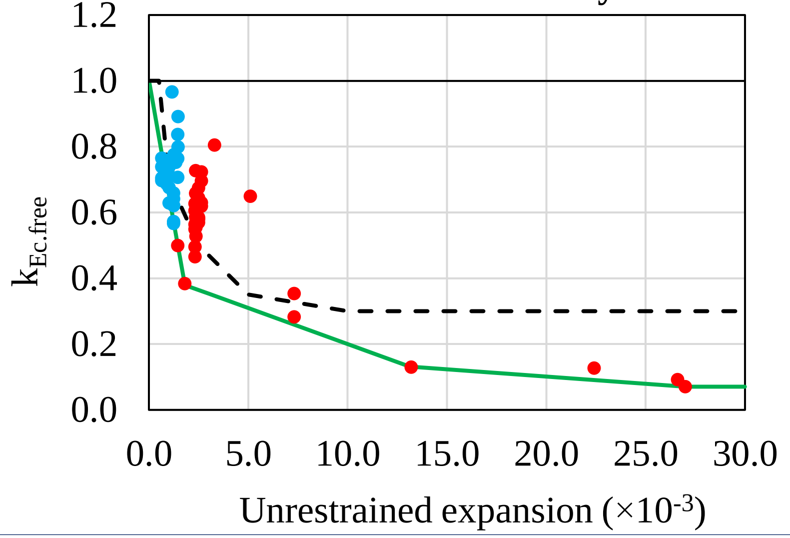
$$k_{f_{t.i}} = \frac{f_{t.Ri}/f_{t.N}}{f_{t.Ri.28}/f_{sp.N.28}} \quad \text{or} \quad k_{f_{t.i}} = \frac{f_{t.Ri}/f_{t.N}}{\sqrt{f'_{c.Ri}/f'_{c.N}}}$$

Modification factors for long-term ***stress-free condition***

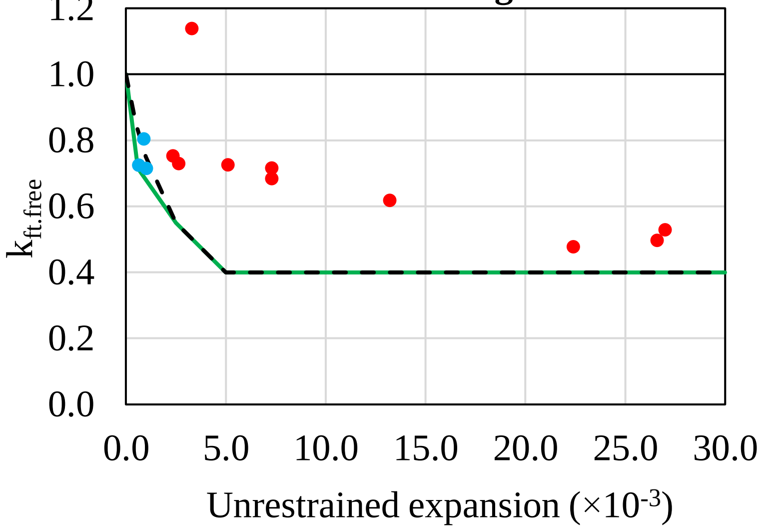
Compressive Strength



Modulus of Elasticity



Tensile Strength

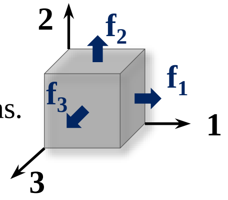


2. Mechanical Properties of ASR-Affected Concrete

Model for the Mechanical Properties of ASR-Affected Concrete

*Modification factors for long-term **restrained condition***

$i = 1,2,3$: the principal directions.



Stress in the principal direction

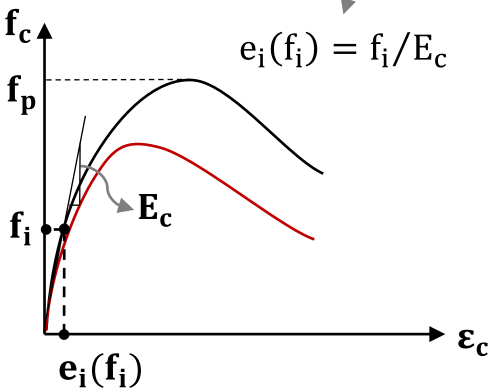
Modification factor for the stress-free condition

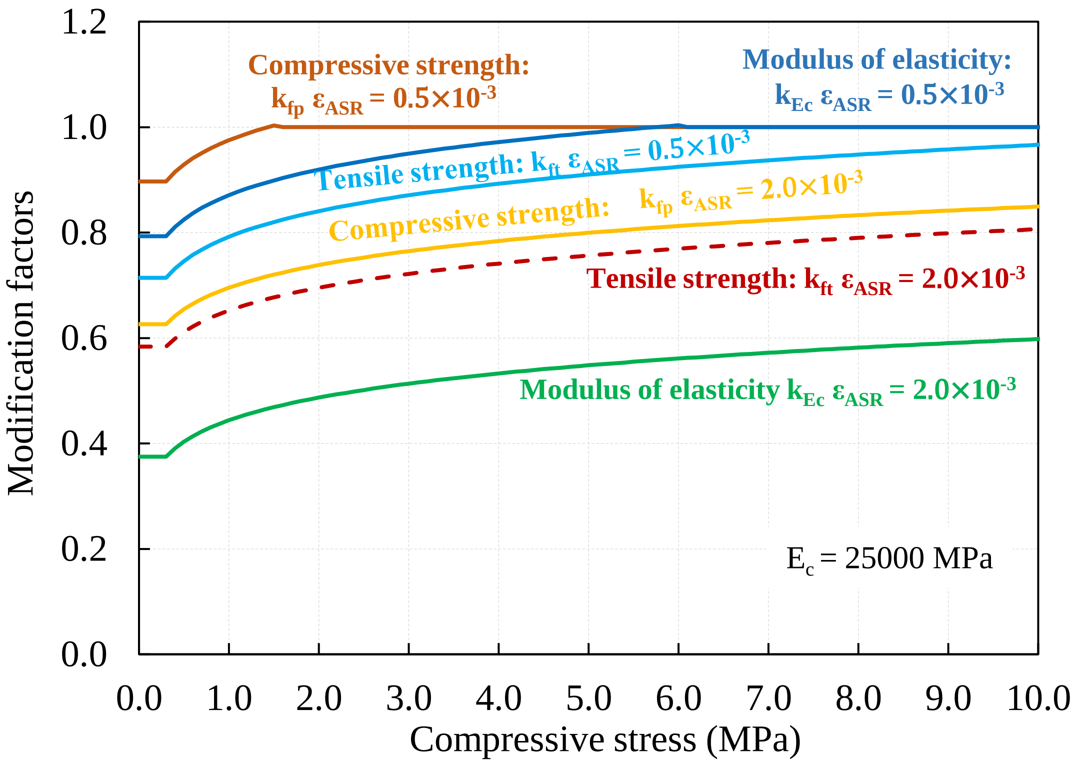
$$\mathbf{k_{j,i}(f_i) = k_{j,i,free} + \frac{1}{1.05 \cdot \left(-\frac{\varepsilon_{ASR}}{e_i(f_i)}\right)^{0.09}} - \frac{1}{1.05 \cdot \left(-\frac{\varepsilon_{ASR}}{e_i(0)}\right)^{0.09}}}$$

$j = f_p, E_c, f_t$

$e_i(f_i) = f_i/E_c$

$e_i(0) = e_i(0.3\ \text{MPa})$





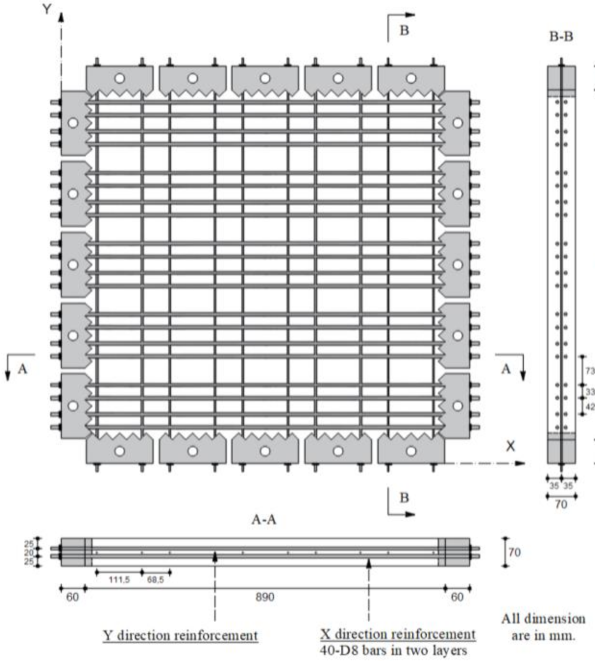
Isotropic Model

$$\mathbf{f_{p.isotropic}} = \frac{(\mathbf{k_{f_{p.1}} + k_{f_{p.2}} + k_{f_{p.3}}})}{\mathbf{3}} \cdot \mathbf{f_p} \qquad \mathbf{E_{c.isotropic}} = \frac{(\mathbf{k_{E_{c.1}} + k_{E_{c.2}} + k_{E_{c.3}}})}{\mathbf{3}} \cdot \mathbf{E_c} \qquad \mathbf{f_{t.isotropic}} = \frac{(\mathbf{k_{f_{t.1}} + k_{f_{t.2}} + k_{f_{t.3}}})}{\mathbf{3}} \cdot \mathbf{f_t}$$

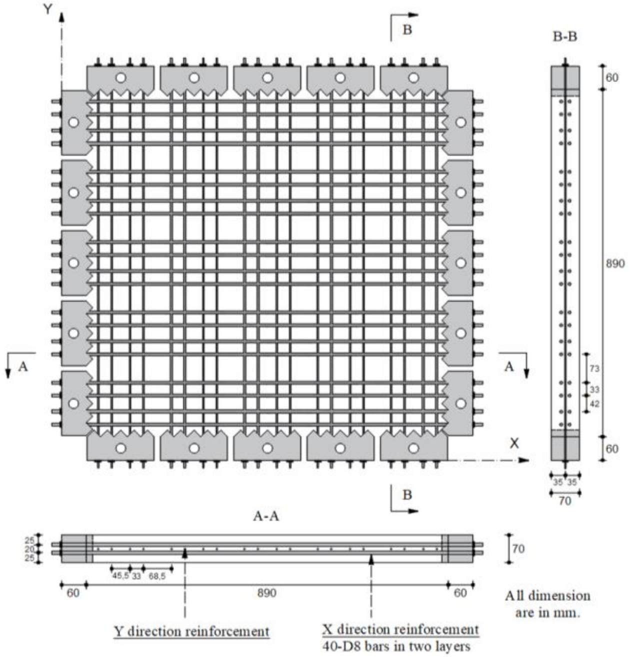
3. Validation Studies

ASR-Affected Shear-Critical Elements

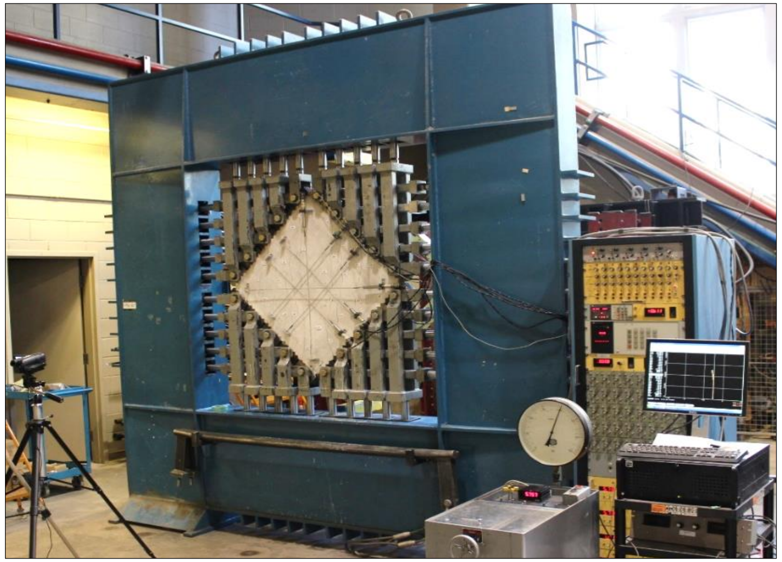
Cast no.	Specimen	ρ_x (%)	ρ_y (%)	ρ_z (%)	Reactive agg.	Loading
1	AF1	3.31	0.42	-	None	Monotonic
	AF2	3.31	0.84	-		
2	AF3	3.31	0.42	-	Jobe-Newman	Monotonic
	AF4	3.31	0.84	-		
3	AF5	3.31	0.42	-	Spratt	Monotonic
	AF6	3.31	0.84	-		
4	AF7	3.31	0.42	1.69	Jobe-Newman	Monotonic
	AF8	3.31	0.84	1.69		
5	AF9	3.31	0.20	-	Jobe-Newman	Monotonic
	AF10	3.31	1.66	-		Cyclic



Reinforcement configuration for Panels AF1, AF3, AF5, AF7, and AF9



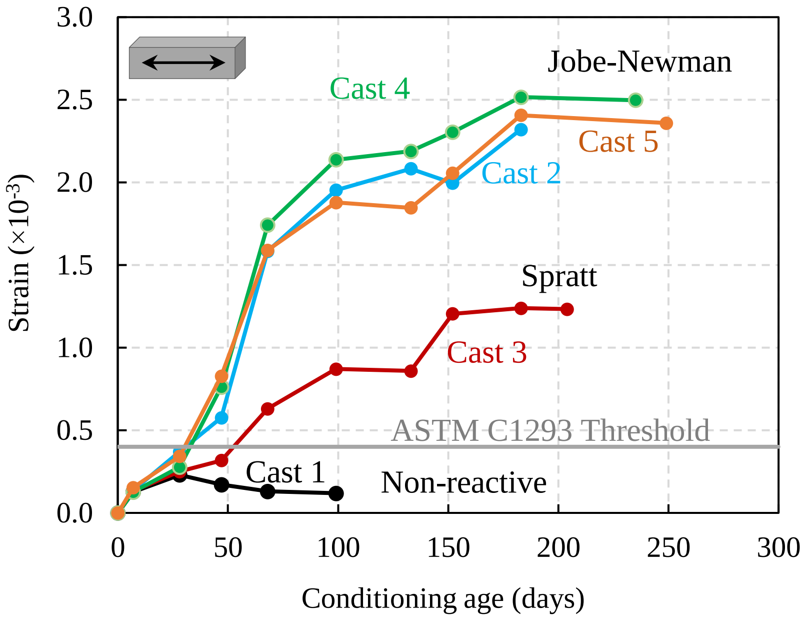
Reinforcement configuration for Panels AF2, AF4, AF6, AF8, and AF10

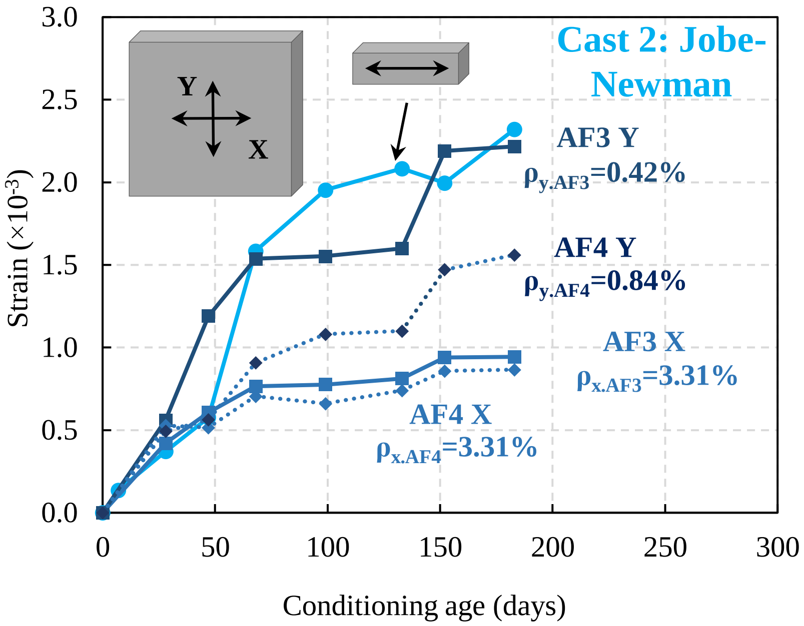


3. Validation Studies

ASR-Affected Shear-Critical Elements

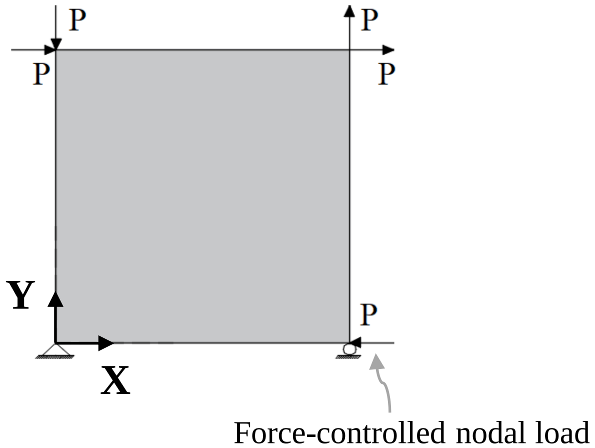
Expansion Monitoring

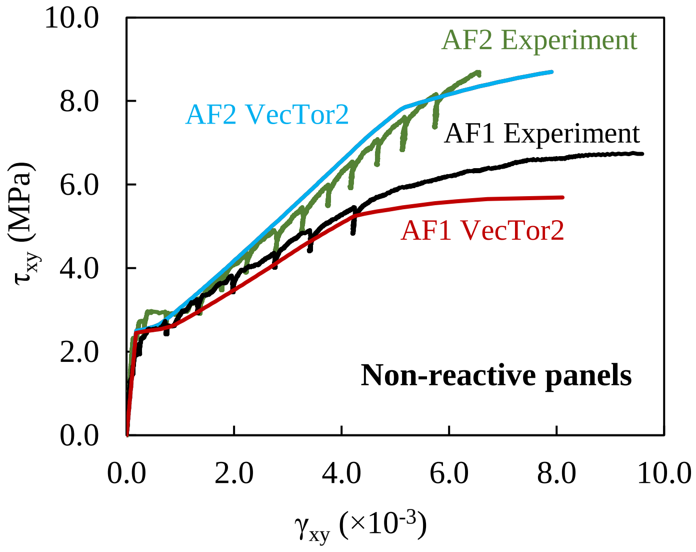




3. Validation Studies

ASR-Affected Shear-Critical Elements





FEA Concrete Properties Inputs			
ε_{ASR} (×10^{-3})	required input	C_c (/°C)	$10 \times 10^{-6\dagger}$
f_p(MPa)	required input	Max. agg. size (mm)	10
f'_t (MPa)	$0.33\sqrt{f'_c}^{\dagger}$	Density (kg/m^3)	2400†
E_c (MPa)	$3320\sqrt{f'_c} + 6900^{\dagger}$	K_c (mm^2/s)	1.2†
ε_o (×10^{-3})	$1.8 + 0.0075 \times f'_c{}^{\dagger}$	Sx (mm)	1000†
μ	0.15†	Sy (mm)	1000†

† Default properties assumed by VecTor2.

ASR Analyses

⇩

Concrete mechanical properties:

1. f_p at test day from reactive cylinders → Cylinder at test day
2. f_p at test day from non-reactive cylinders + anisotropic model → Anisotropic
3. f_p at test day from non-reactive cylinders + isotropic model → Isotropic

⇩

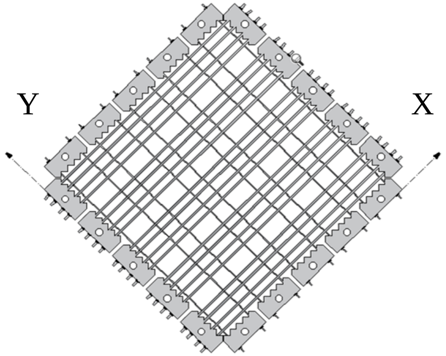
Charlwood model for expansion

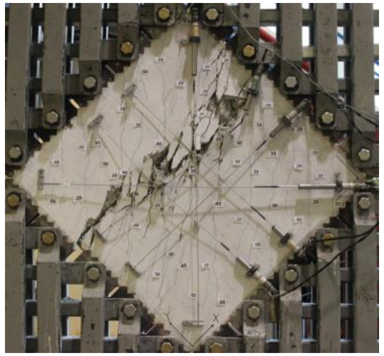
3. VALIDATION STUDIES

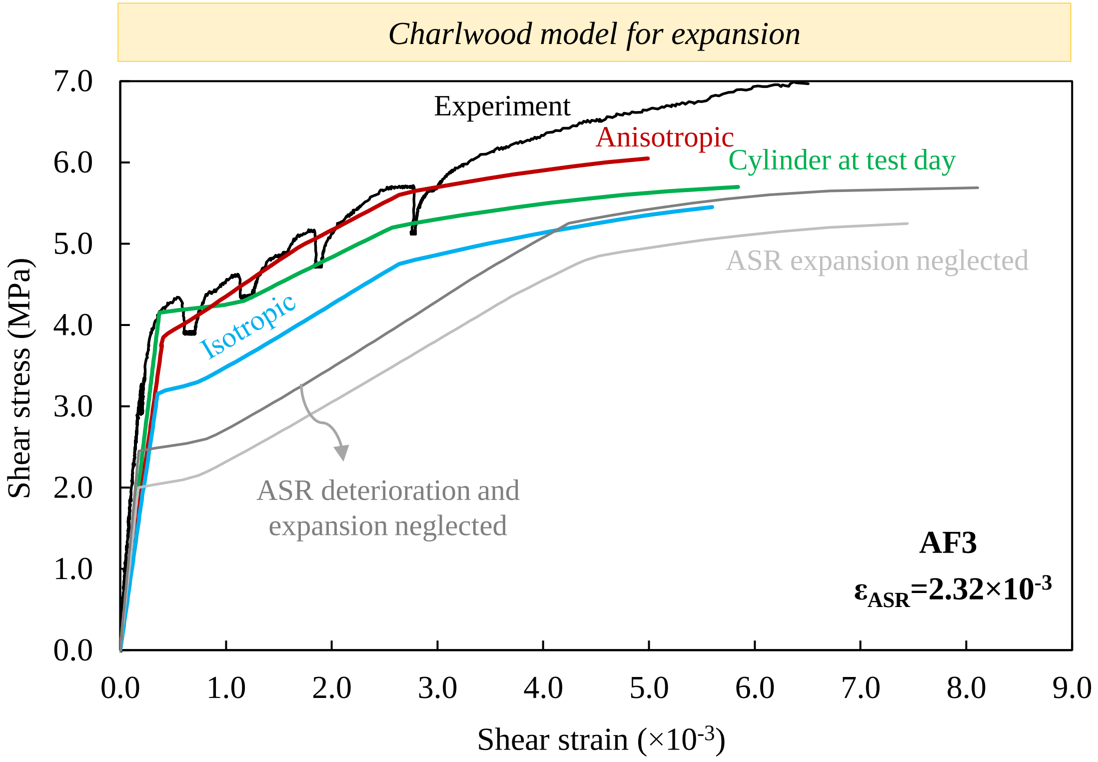
ASR-AFFECTED SHEAR-CRITICAL ELEMENTS

Panel Specimen AF3

ρ_x= 3.31%
ρ_y= 0.42%

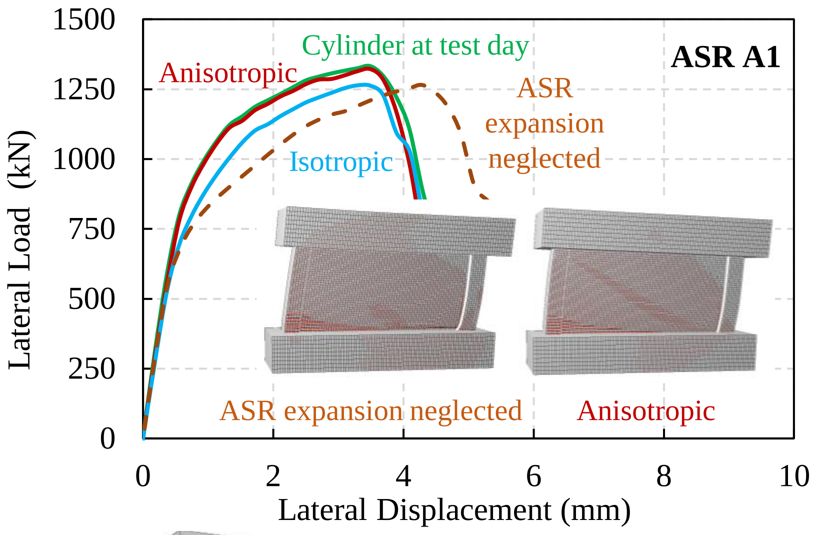


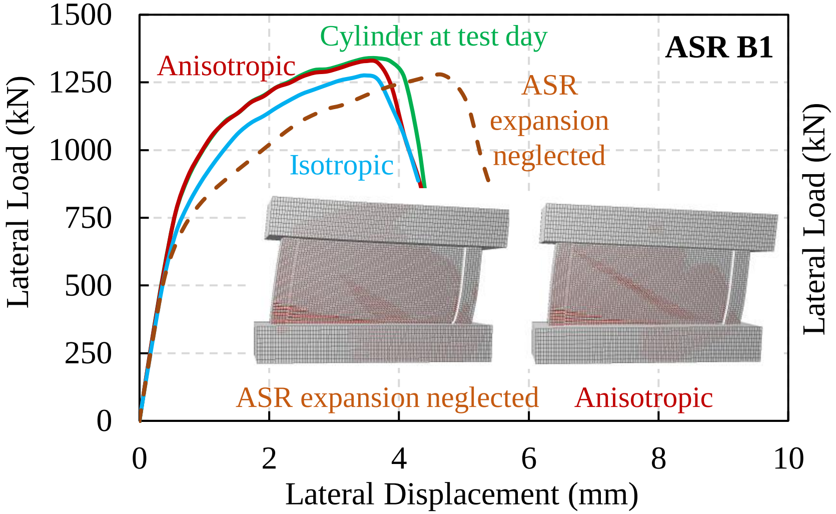


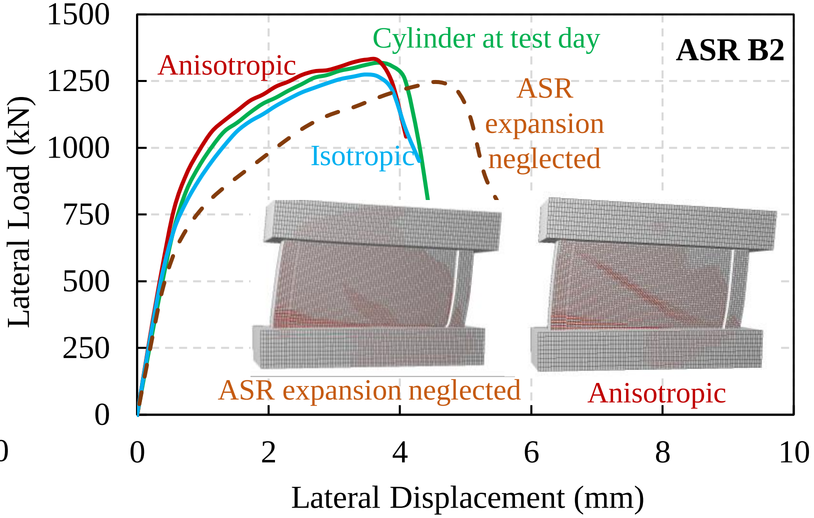


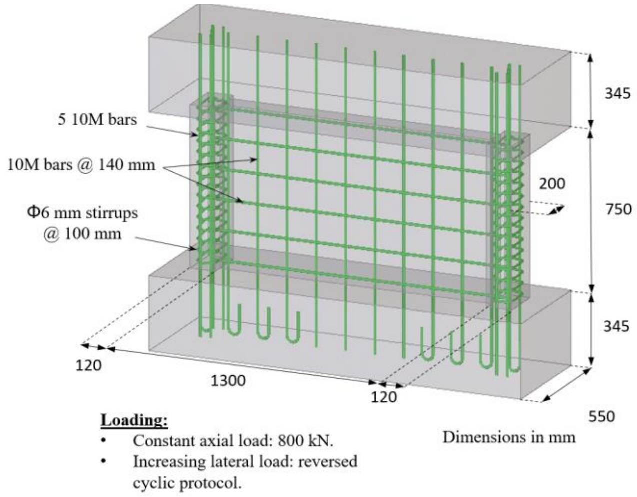
3. Validation Studies

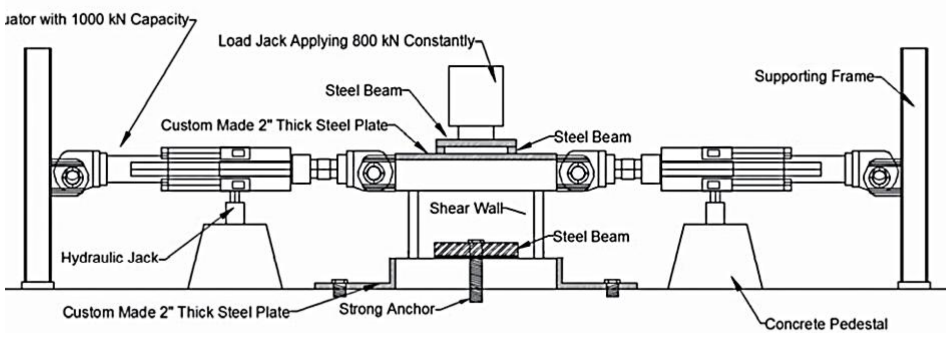
ASR-Affected Shear Walls









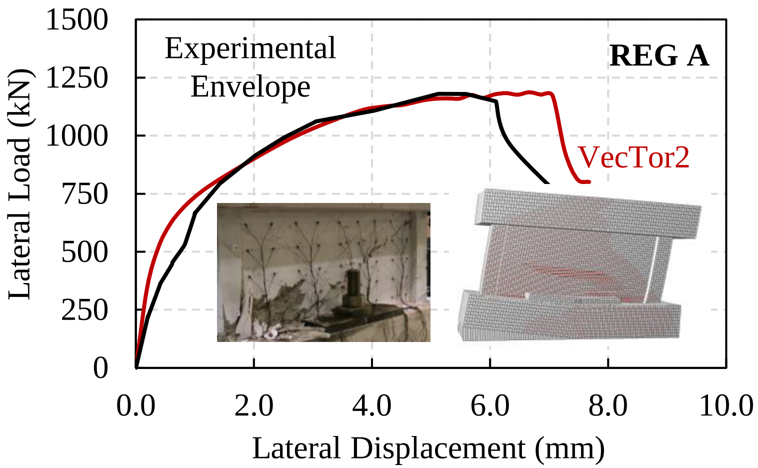


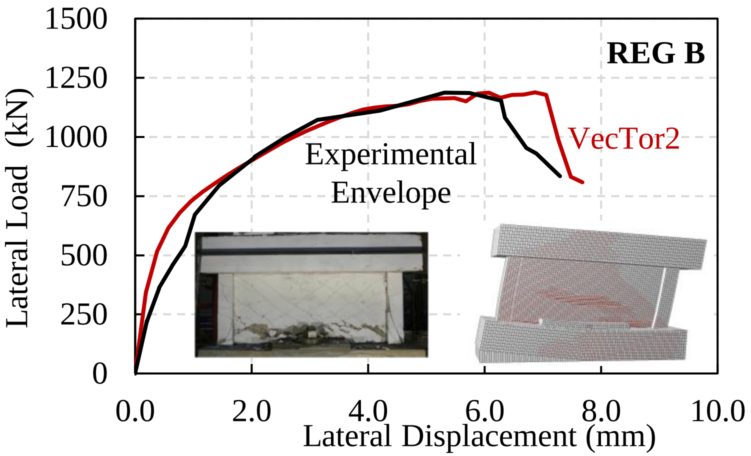
Specimen	f'_c (MPa)	E_c (MPa)	ε_{ASR} ($\times 10^{-3}$)	Age (days)
REG A	79.0	47150	---	240
ASR A1	63.7	35750	1.90	260
ASR B1	67.1	32600	2.15	610
ASR B2	63.0	28100	2.23	995
REG B	80.1	46652	---	975

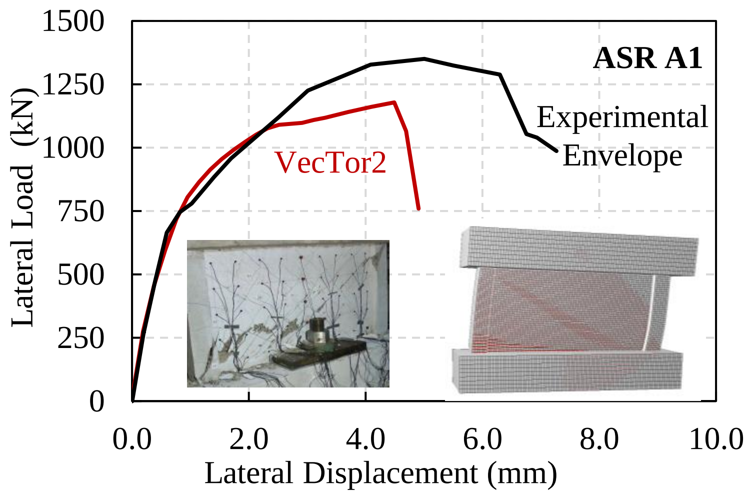
†**Tested by** Habibi, F., Sheikh, S. A., Vecchio F. J., and Panesar, D. “Effects of Alkali-Silica Reaction on Concrete Squat Shear Walls,” *ACI Structural Journal*, V. 115, No. 5, 2018, pp. 1329-1339.

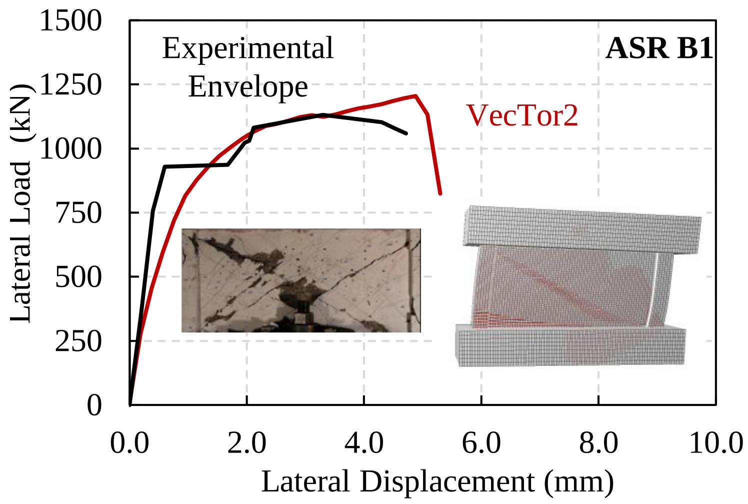
3. Validation Studies

ASR-Affected Shear Walls







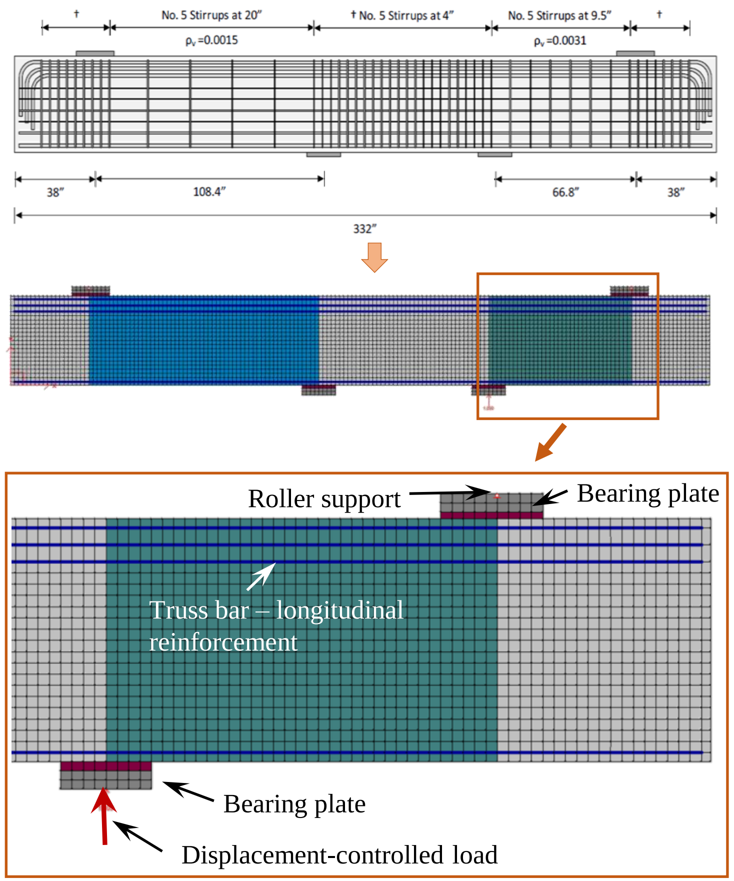


Specimen	$P_{u.Calc}$ (kN)	$P_{u.Exp}$ (kN)	$\delta_{u.Calc}$ (mm)	$\delta_{u.Exp}$ (mm)	$P_{u.Calc}/P_{u.Exp}$	$\delta_{u.Calc}/\delta_{u.Exp}$
REG A	1172	1180	7.00	6.10	0.99	1.15
REG B	1178	1187	7.06	6.30	0.99	1.12
ASR A1	1180	1355	4.50	6.20	0.87	0.73
ASR B1	1205	1240	4.88	4.90	0.97	1.00
ASR B2	1187	1243	4.60	2.60	0.95	1.77
Mean					**0.96**	**1.15**
COV (%)					4.72	29.8

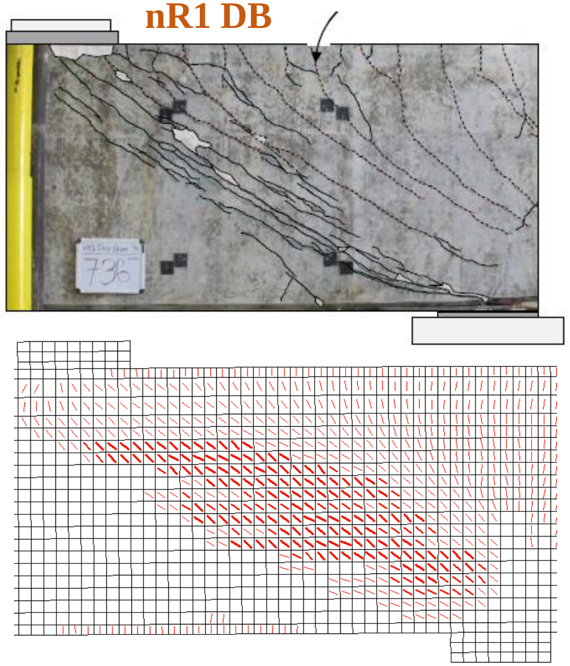
†**Tested by** Habibi, F., Sheikh, S. A., Vecchio F. J., and Panesar, D. "Effects of Alkali-Silica Reaction on Concrete Squat Shear Walls," *ACI Structural Journal*, V. 115, No. 5, 2018, pp. 1329-1339.

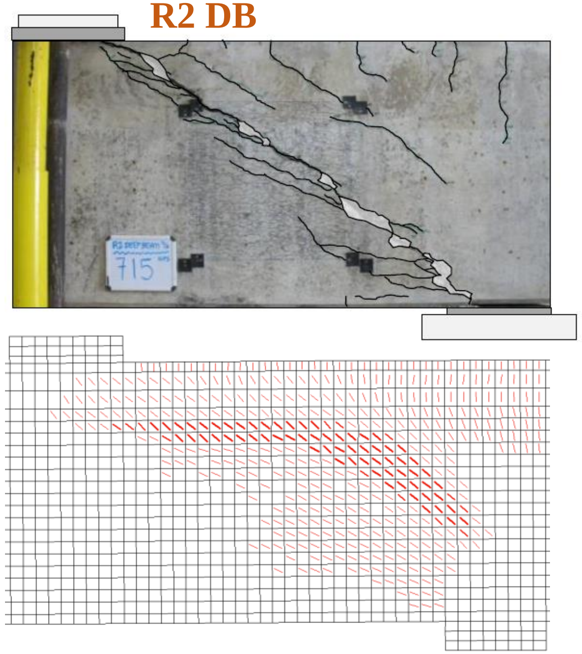
3. Validation Studies

Shear-Critical Beam Specimens



Specimen	f'_c (MPa)	ε_{ASR} ($\times 10^{-3}$)	$V_{u.test}$ (kN)	$V_{u.calc}$ (kN)		$V_{u.calc}$ / $V_{u.test}$	
				Cylinder	Anisotropic	Cylinder	Anisotropic
nR1 DB	50.3	---	2500	2105		0.84	
R1 DB	31.7	0.90	2309	2202	2155	0.95	0.93
R2 DB	27.0	4.40	2440	2692	2590	1.10	1.06
nR1 SS	49.6	---	1230	1440		1.17	
R1 SS	31.0	1.70	1496	1627	1530	1.09	1.02
R2 SS	29.0	6.30	1570	1409	1644	0.90	1.05



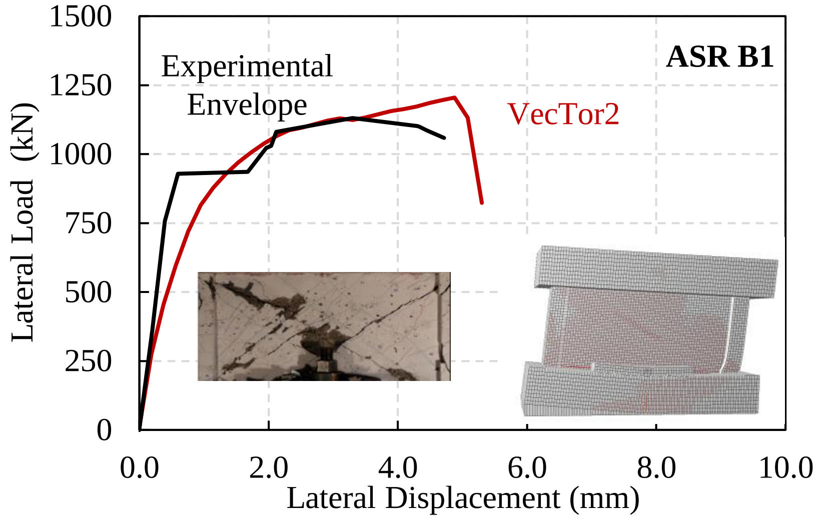


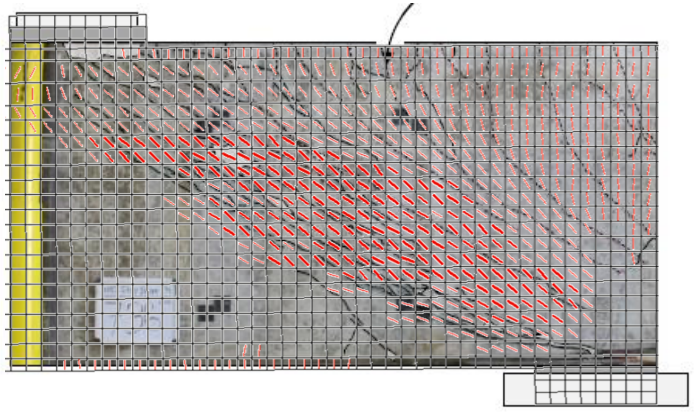
†**Tested by** Deschenes, D. J., Bayrak O., and Folliard, K.J. "ASR/DEF – Damaged bent caps: shear tests and field implications," Technical Report for the Texas Department of Transportation, 2009, 271 pp.

4. Conclusions

The proposed anisotropic model for the mechanical properties of concrete results in the most accurate predictions of the overall response of the panels.

The similarity of the analytical responses obtained using either concrete properties determined from reactive cylinders or the anisotropic model for concrete properties indicates that, for an ASR-affected structure in the field, material information from either damaged or undamaged concrete can be used as valuable information for numerical analysis.





Ferche, A. C. and Vecchio, F. J. (2022) "Modeling of ASR-Affected Shear-Critical Reinforced Concrete Structures." ACI Structural Journal 119 (2), 75-88.
Ferche, A. C. and Vecchio, F. J. (2022) "Mechanical Properties of ASR-Affected Concrete." ACI Materials Journal 119 (1), 251-262.
Ferche, A. C. and Vecchio, F. J. (2021) "Behavior of ASR-Affected Reinforced Concrete Elements Subjected to Shear," ACI Structural Journal, No. 118, No. 4, pp. 163-174.
Ferche, A. C., Panesar, D. K., Sheikh, S. A., and Vecchio, F. J. (2017) "Toward Macro-Modeling of Alkali-Silica Reaction-Affected Structures," ACI Structural Journal, V. 114, No. 5, pp. 1121-1129

Thank You