RUTGERS
Infrastructure Monitoring & Evaluation (RIME) Group

ACI CONCRETE CONVENTION

Validation of Predicted Stress in Polypropylene Fiber-Reinforced Self-Consolidating Concrete (FR-SCC) under Restrained Shrinkage Conditions

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Outline

- Research Significance
- Experimental Program
- Results and Discussion
- Summary and Conclusions

Why FR-SCC? – Research Significance

- Fiber-reinforced self-consolidating concrete (FR-SCC) is designed to simultaneously address two inherent issues with concrete:
  - **shrinkage** and **consolidation**.
- **Shrinkage**: higher cementitious content of SCC results in higher shrinkage which is prone to cracking
- **Consolidation**: conventional concrete requires a consolidating method that is labor intensive work as well as increases the project cost
- SCC eliminates the consolidation and fiber reinforcement reduces the shrinkage.
- Need to understand the shrinkage behavior of FR-SCC under restrained conditions in bridge decks.

Experimental Program

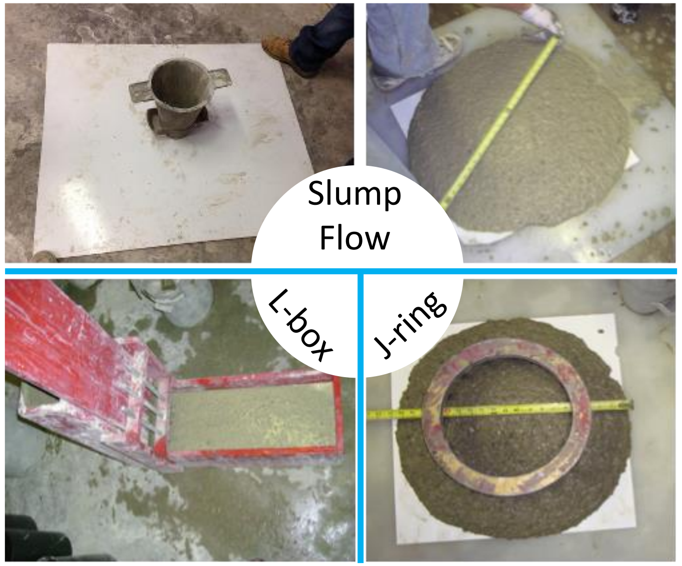
- Mix Design & Fiber
  - **Control Mix (PPE0)**
    - Total Cementitious = 675 lb/cy (400 kg/m3)
    - Type I Cement 65% & Grade 120 Slag 35%
    - w/c ratio = 0.425
    - 3/8” gravel : sand = 1-to-1
    - HRWR = as needed for 22-in (560 mm) slump flow
  - **FR-SCC Mixes**
    - **PPE1** = Control + fiber **0.10% vol**.
    - **PPE2** = Control + fiber **0.15% vol.**
    - **PPE3** = Control + fiber **0.20% vol.**

Micro Polypropylene Fiber

- Length = 1/4 in. (6.35 mm)
- Denier = 15
- Specific Gravity = 0.91
- Aspect ratio = 13
- Complying with ASTM C 1116 and D 7508 (Type III)

Experimental Program

- Mixing and Fresh Property



Mixing → Fresh Property → Casting

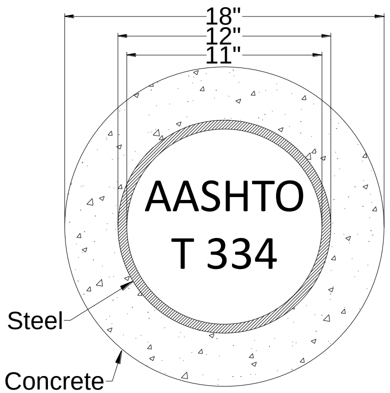
	PPE0	PPE1	PPE2	PPE3
Slump Flow, in (mm)	24 (610)	23 (585)	22 (560)	22.5 (570)
J-Ring [+/- Slump], in (mm)	22.5 [-1.5] (570 [40])	21 [-2.0] (535 [50])	19 [-3.0] (485 [75])	17 [-5.5] (430 [140])
L-Box (h1/h2)	1.2	1.5	2.0	2.5

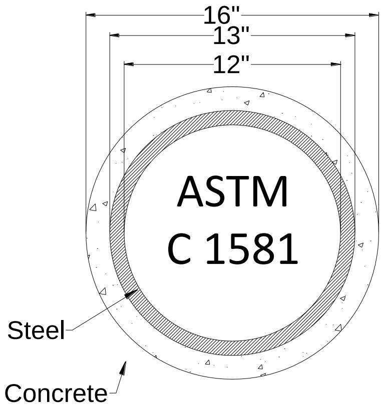
Specimens

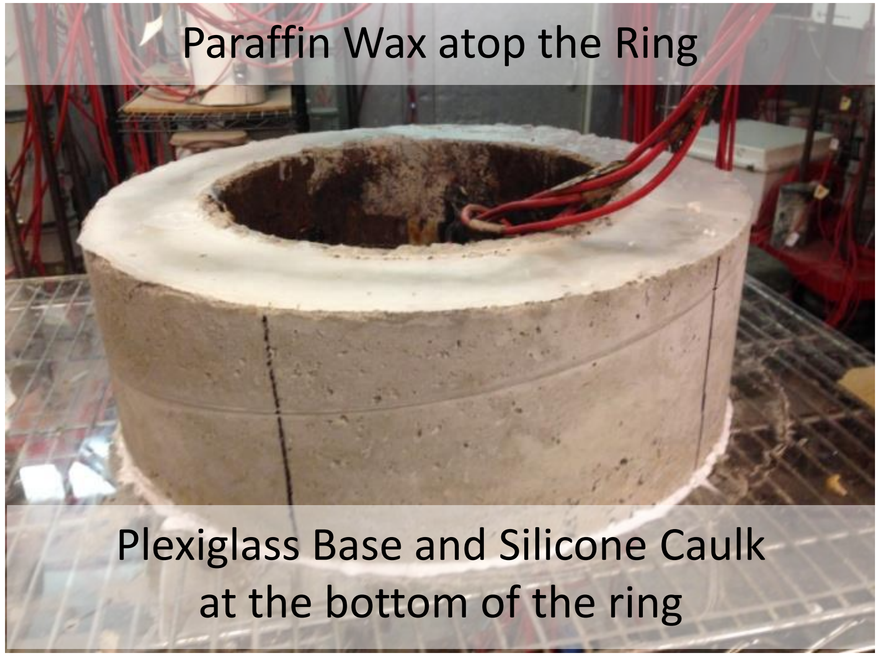
- **Cylinders =** compressive strength, tensile strength, modulus of elasticity
- **Prism =** free shrinkage
- **Ring =** restrained shrinkage

Restrained Shrinkage Test

- Comparative test for shrinkage induced cracking
- Two standards for restrained shrinkage ring test
  - **AASHTO T 334** vs. ASTM C 1581



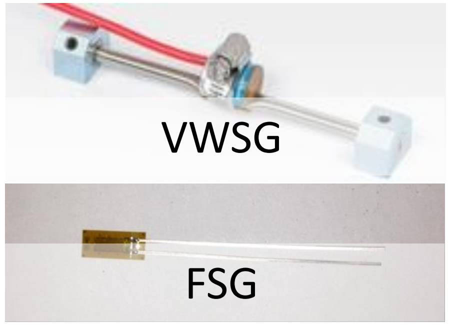


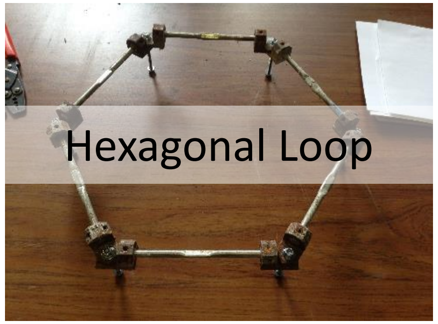


Curing → Preparing and Setup → Testing

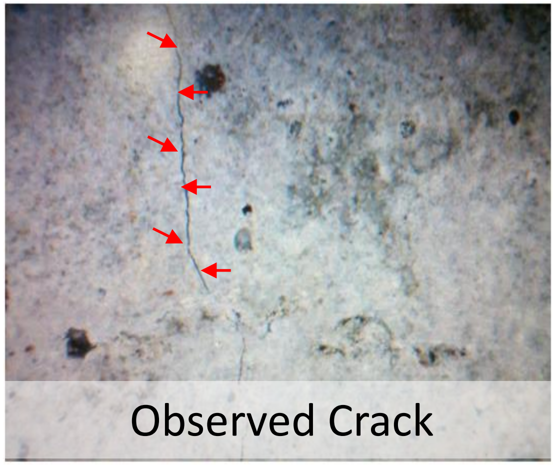
Crack Monitoring of the Rings

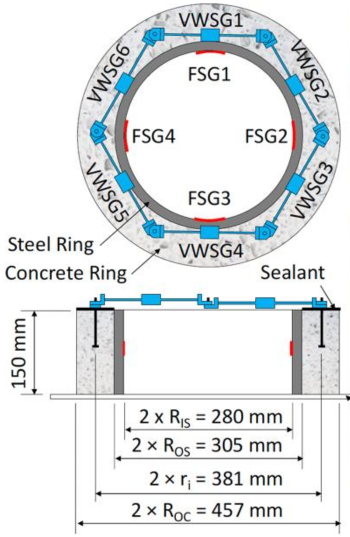
- **Data Acquisition (DAQ) System Monitoring**
  - Foil Strain Gage (FSG) & Vibrating Wire Strain Gage (VWSG)

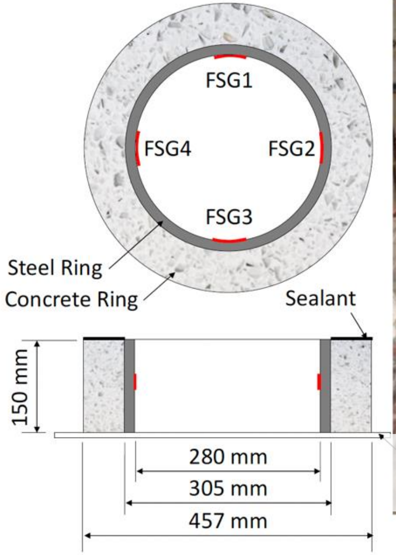




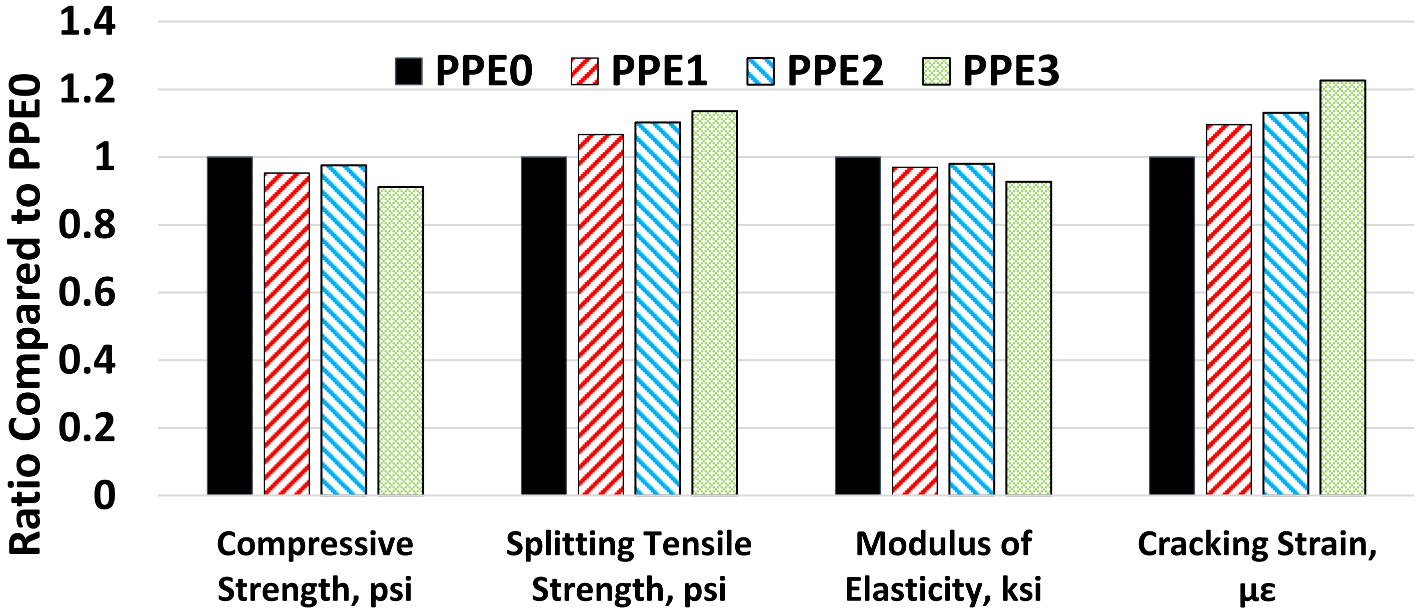
- **Visual Monitoring**
  - Digital Microscope

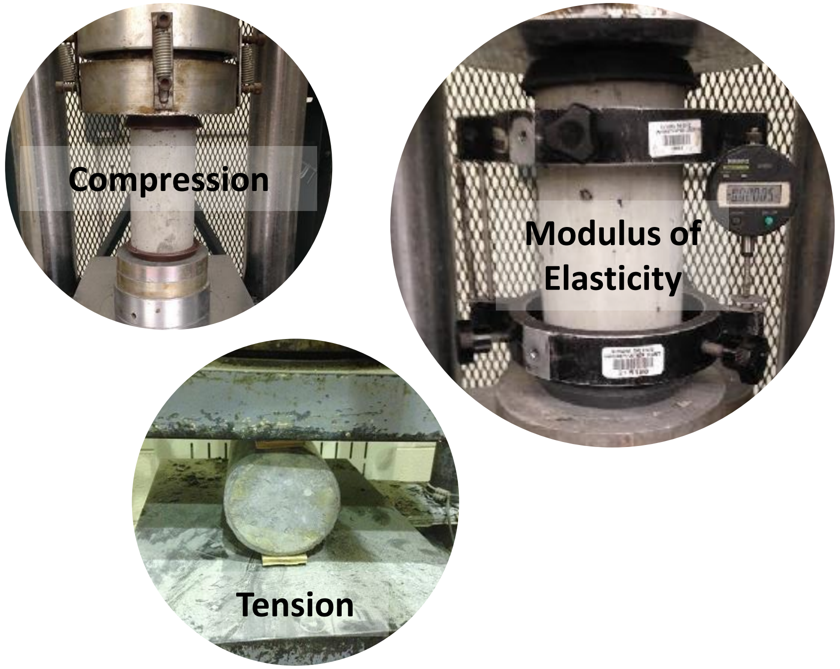






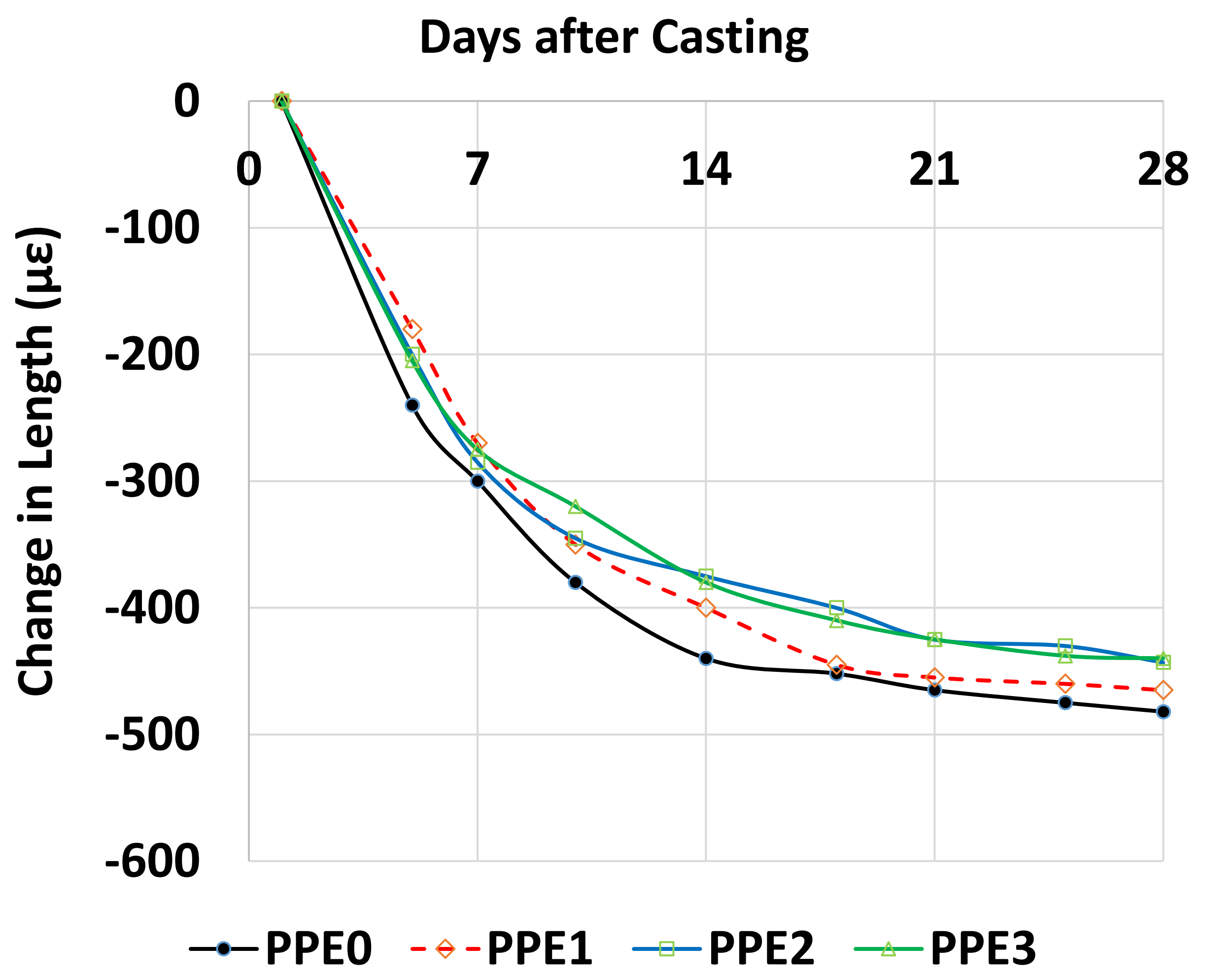
Results: Mechanical Properties at 28 days





	PPE0	PPE1	% Diff.	PPE2	% Diff.	PPE3	% Diff.
Compressive Strength	5,632 psi (38.8 MPa)	5,364 psi (37.0 MPa)	-4.8%	5,494 psi (37.9 MPa)	-3.5%	5,130 psi (35.4 MPa)	-8.9%
Tensile Strength	361 psi (2.49 MPa)	385 psi (2.65 MPa)	**6.6%**	398 psi (2.74 MPa)	**10.2%**	410 psi (2.83 MPa)	**13.6%**
Elastic Modulus	4,295 ksi (29.6 GPa)	4,165 ksi (28.7 GPa)	-3.0%	4,210 ksi (29.0 GPa)	-2.0%	3,981 ksi (27.4 GPa)	-7.3%
Cracking Strain	84 με	92 με	**9.5%**	95 με	**13.1%**	103 με	**22.5%**

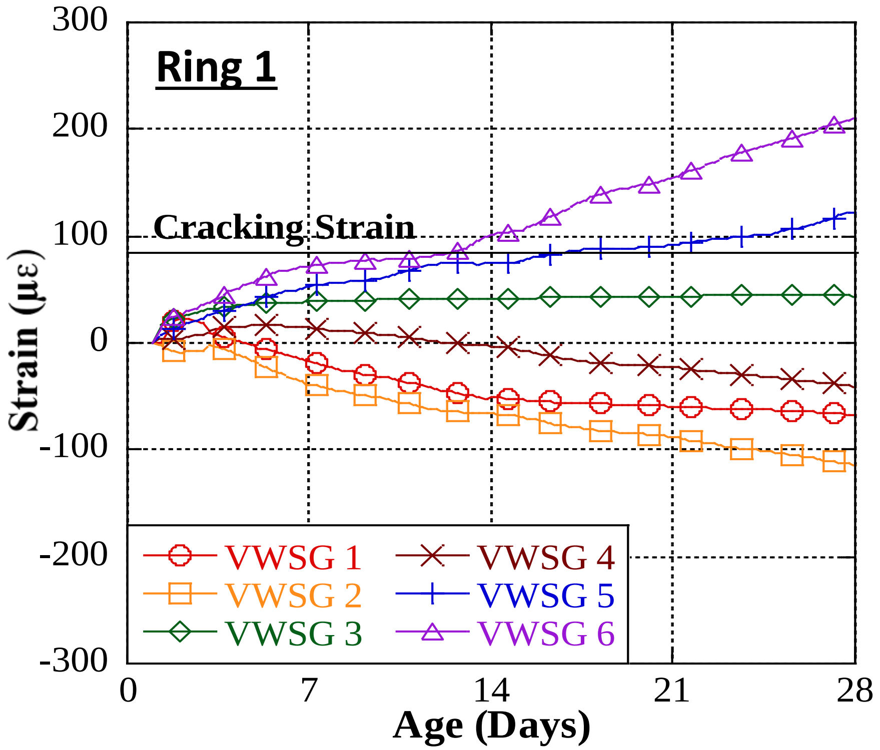
Results: Free Shrinkage Strain

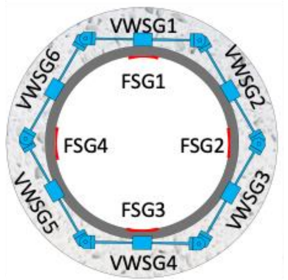


Free shrinkage improvement is not significant.

	Strain at 28 days	Improvement %
PPE0	482 με	-
PPE1	465 με	-3.5%
PPE2	443 με	-8.6%
PPE3	440 με	-8.7%

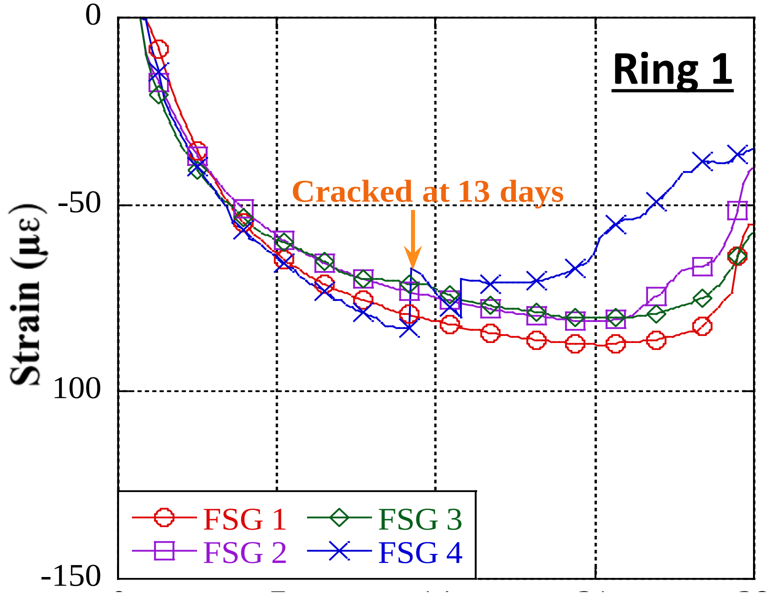
Results: Restrained Shrinkage (PPE0)

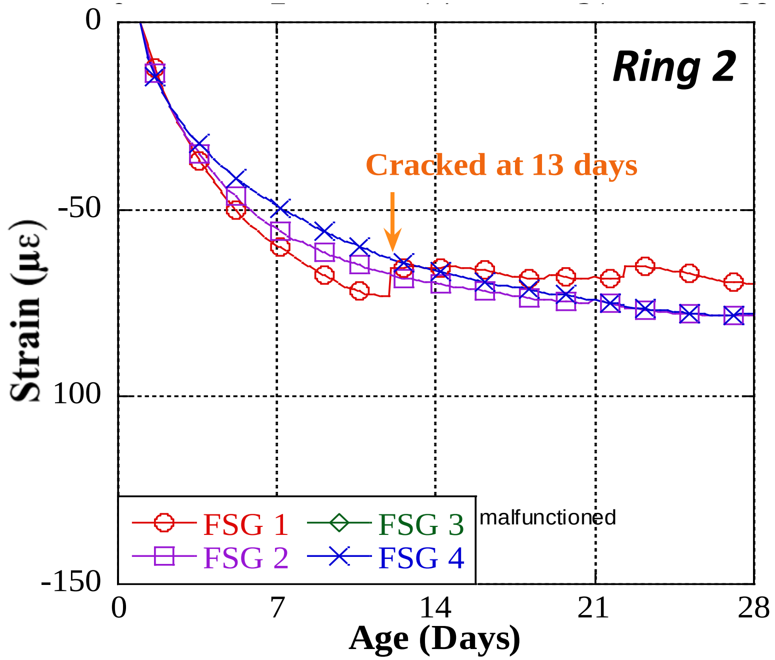




Ring 1

Ring 2



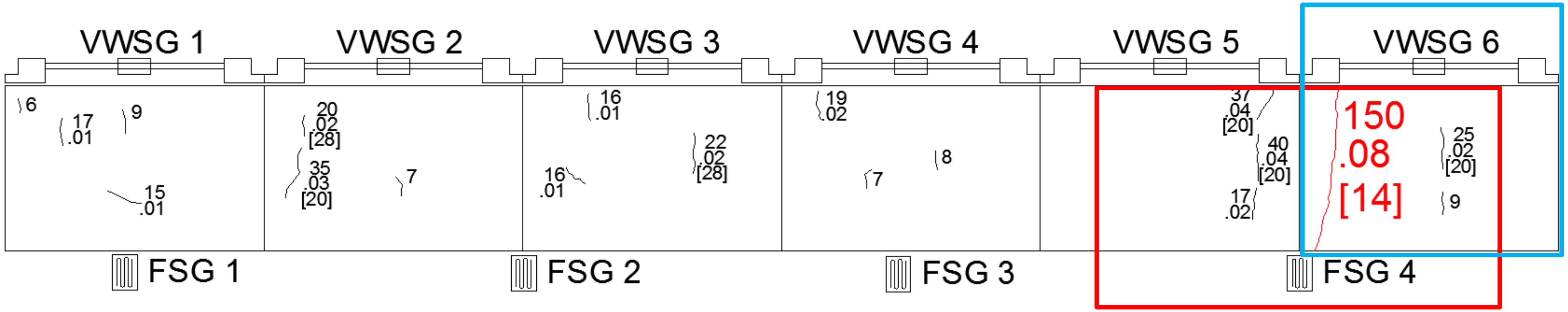


Days of First Crack	Ring 1	*Ring 2*
Foil Strain Gauge	13d	13d
VW Strain Gauge	13d	N/A
Microscope	14d	14d
Full Propagation	**20d**	**20d**

Results: Crack Map (PPE0)

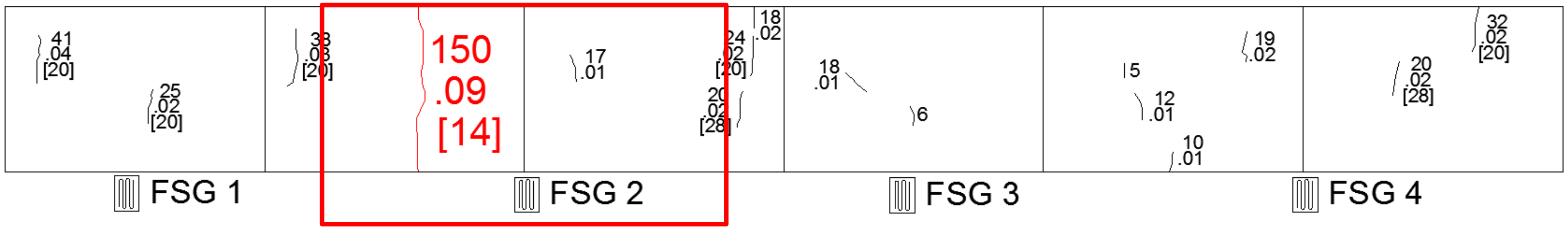
Crack Legend
- Length (mm)
- Width (mm)
- Initial Crack Age (days)

- **Ring 1 – Sensor Location for Cracking**
  - VWSG 6 & FSG 4

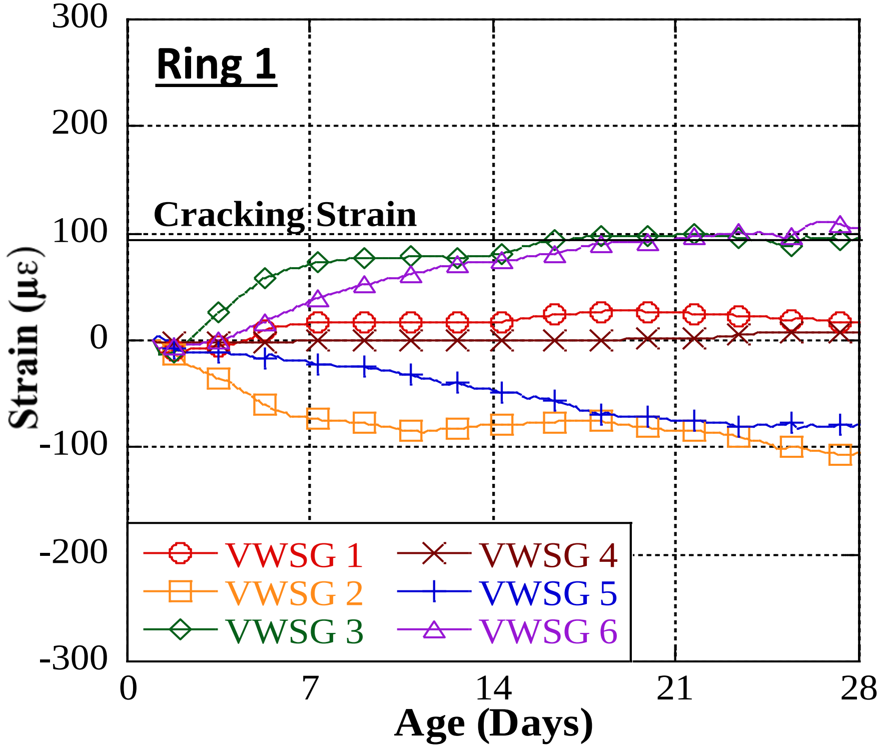


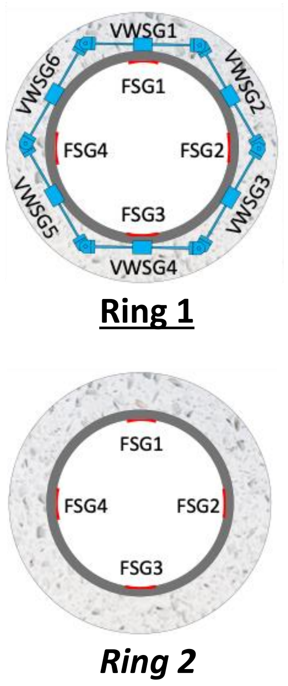
Major crack formed near VWSG anchor

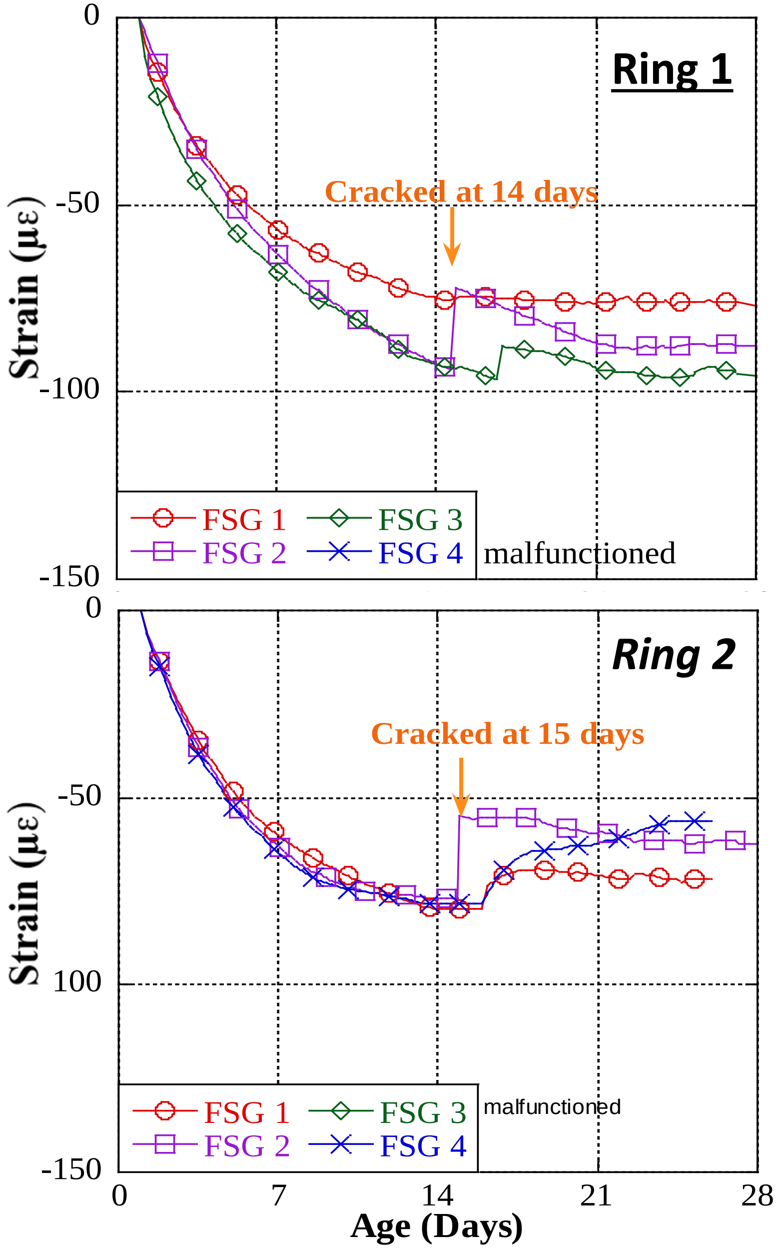
- **Ring 2 – Sensor Location for Cracking**
  - FSG 2



Results: Restrained Shrinkage (PPE1)





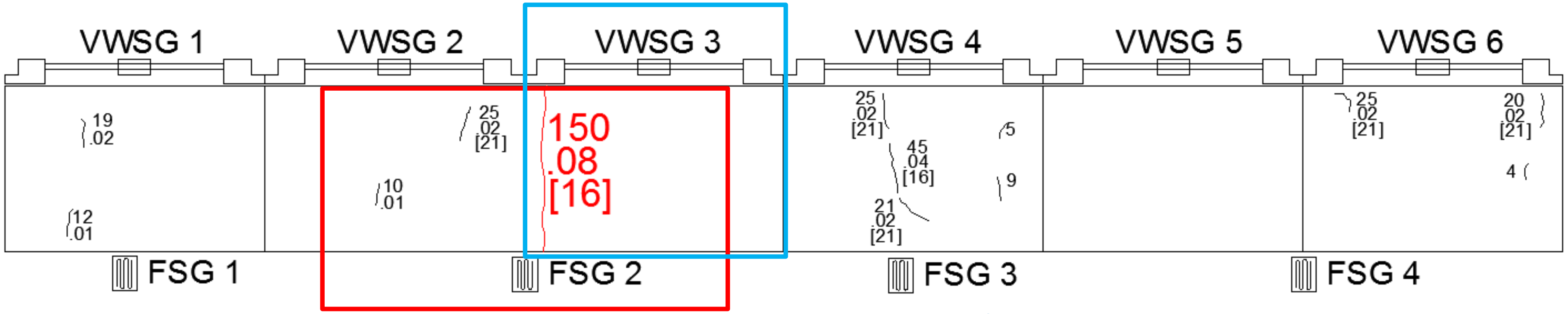


Days of First Crack	Ring 1	*Ring 2*
Foil Strain Gauge	14d	15d
VW Strain Gauge	15d	N/A
Microscope	16d	15d
Full Propagation	**22d**	**20d**

Results: Crack Map (PPE1)

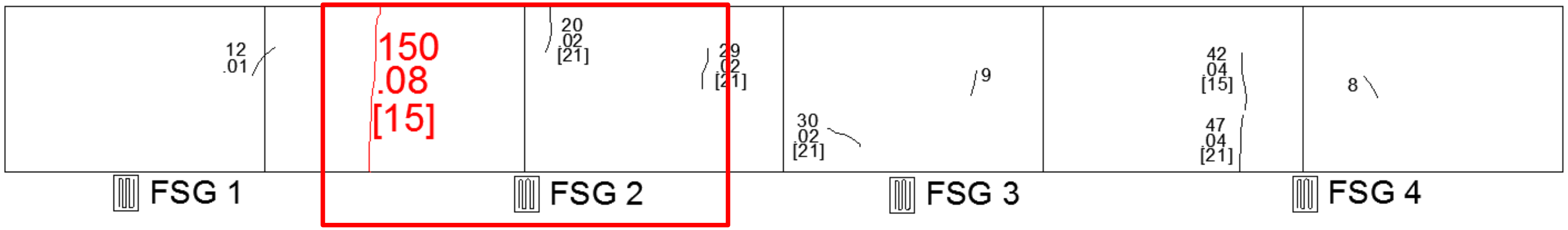
Crack Legend
- Length (mm)
- Width (mm)
- Initial Crack Age (days)

- **Ring 1 – Sensor Location for Cracking**
  - VWSG 3 & FSG 2

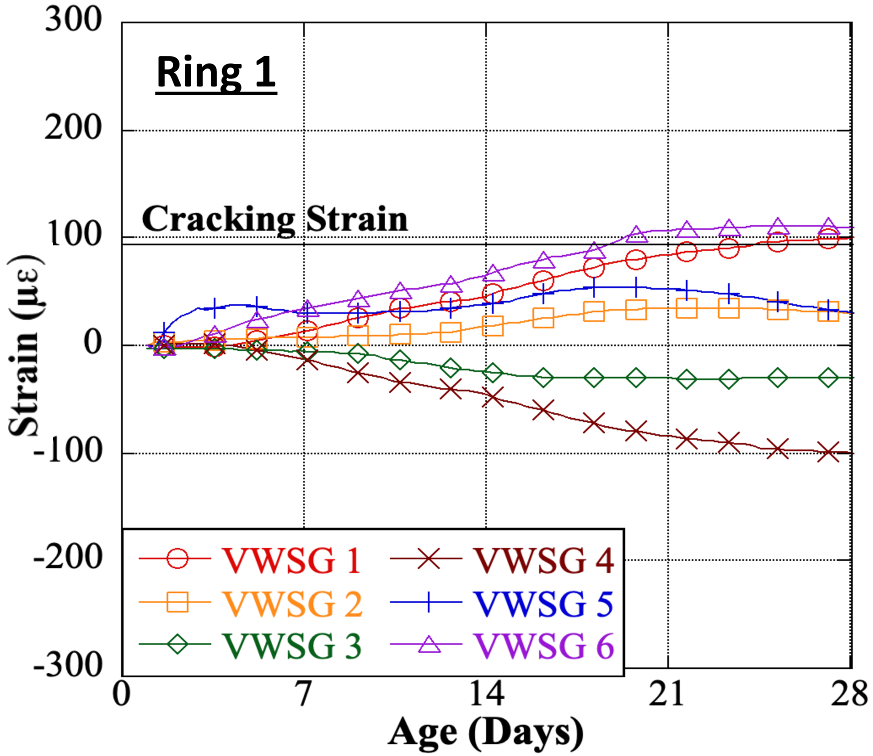


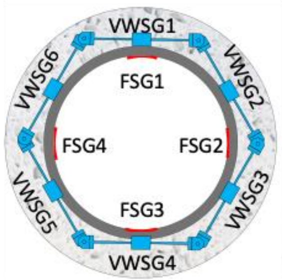
Major crack formed near VWSG anchor

- **Ring 2 – Sensor Location for Cracking**
  - FSG 2



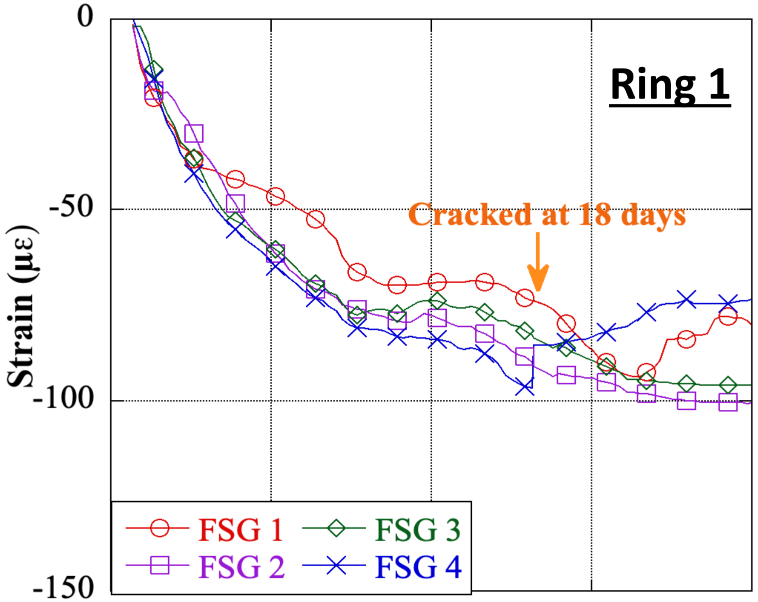
Results: Restrained Shrinkage (PPE2)

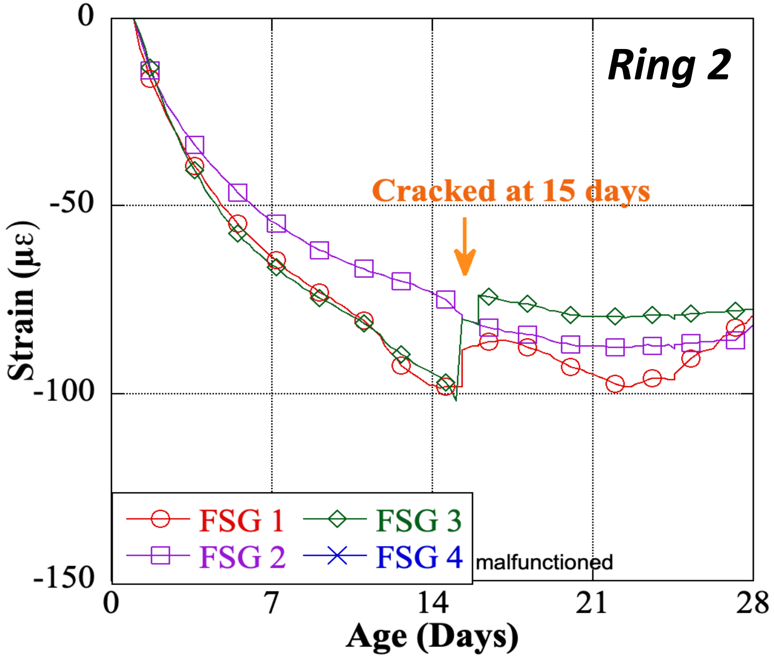




Ring 1

Ring 2



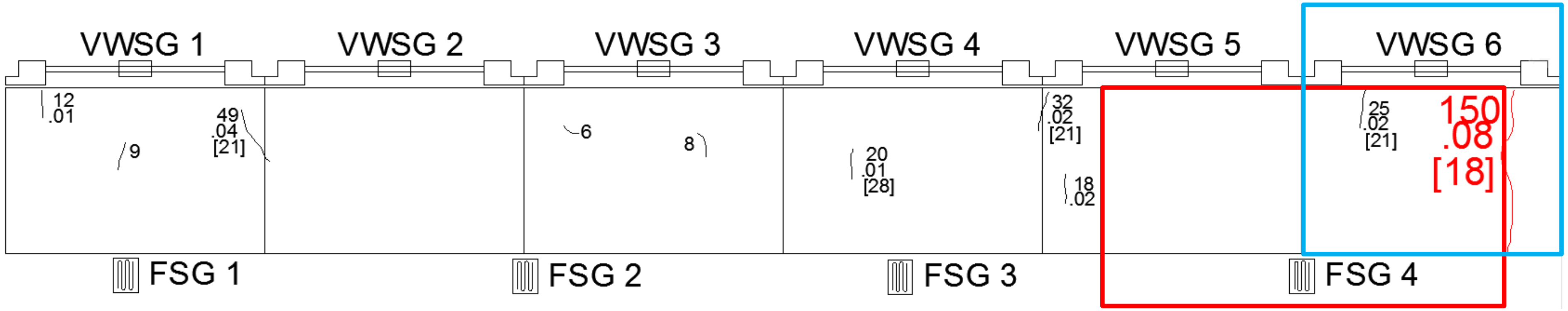


Days of First Crack	Ring 1	*Ring 2*
Foil Strain Gauge	18d	15d
VW Strain Gauge	19d	N/A
Microscope	18d	16d
Full Propagation	**23d**	**21d**

Results: Crack Map (PPE2)

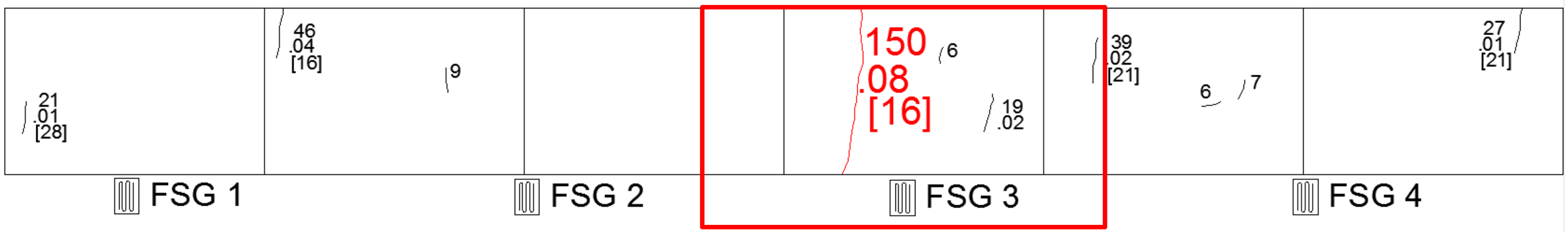
Crack Legend
- Length (mm)
- Width (mm)
- Initial Crack Age (days)

- **Ring 1 – Sensor Location for Cracking**
  - VWSG 6 & FSG 4 (or FSG 1)

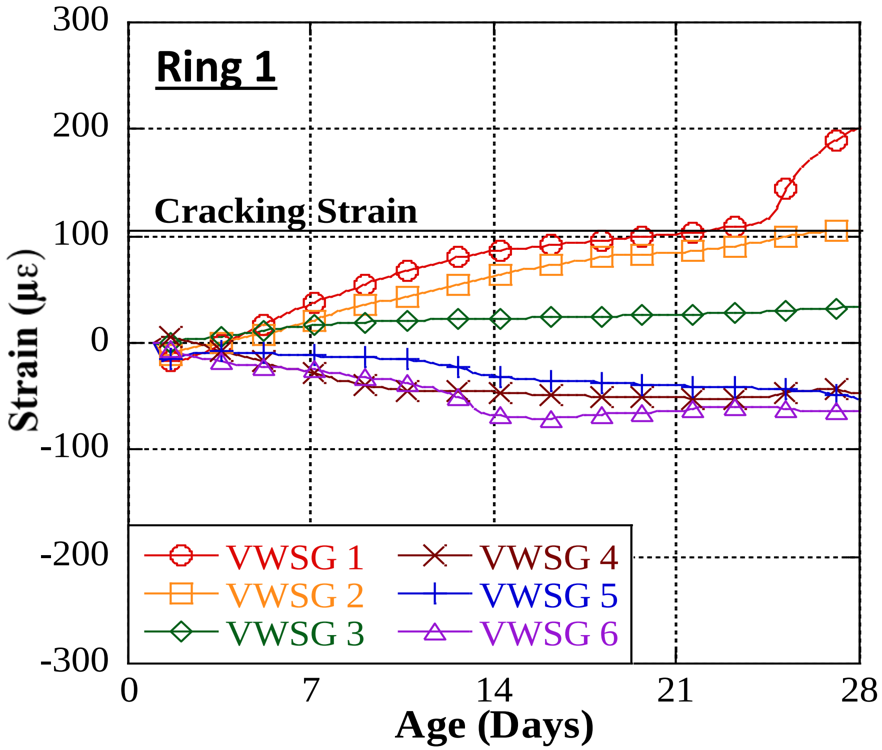


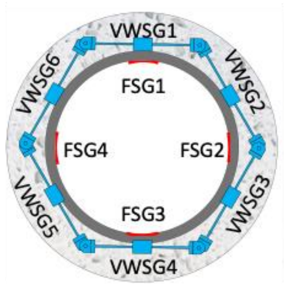
Major crack formed near VWSG anchor

- **Ring 2 – Sensor Location for Cracking**
  - FSG 2



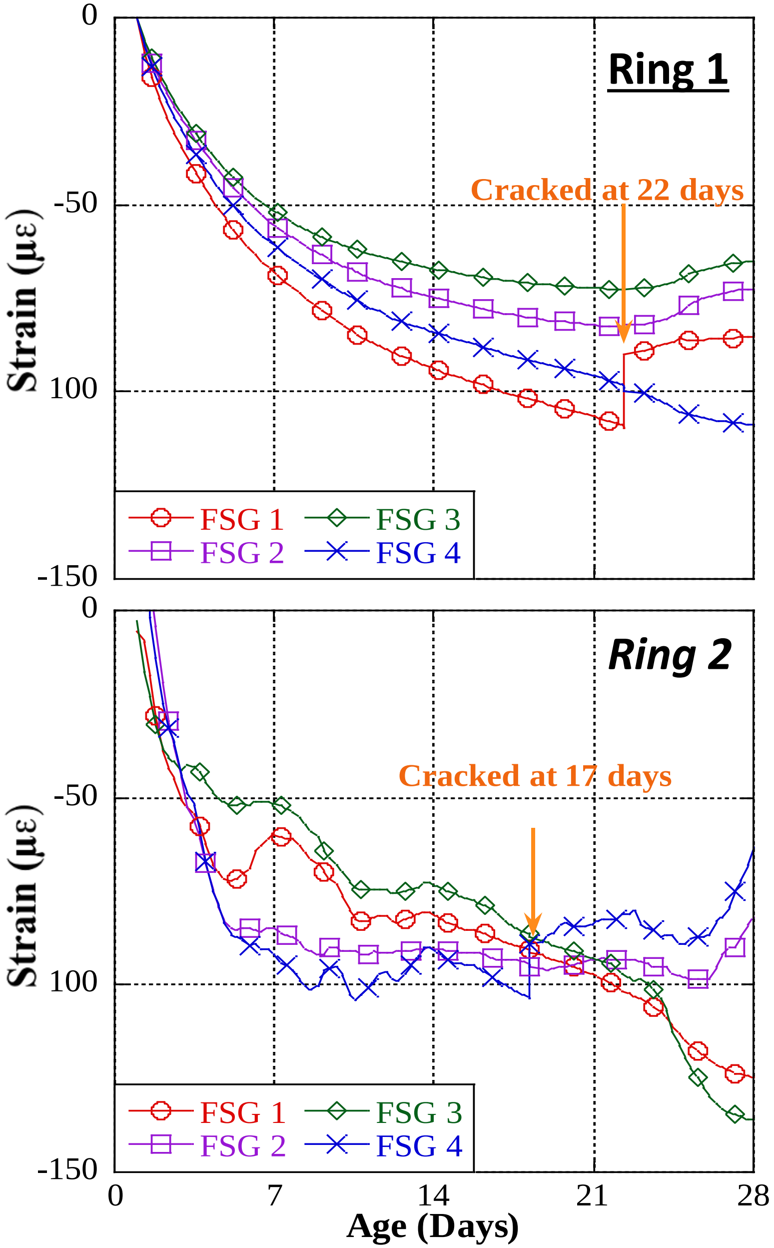
Results: Restrained Shrinkage (PPE3)





Ring 1

Ring 2

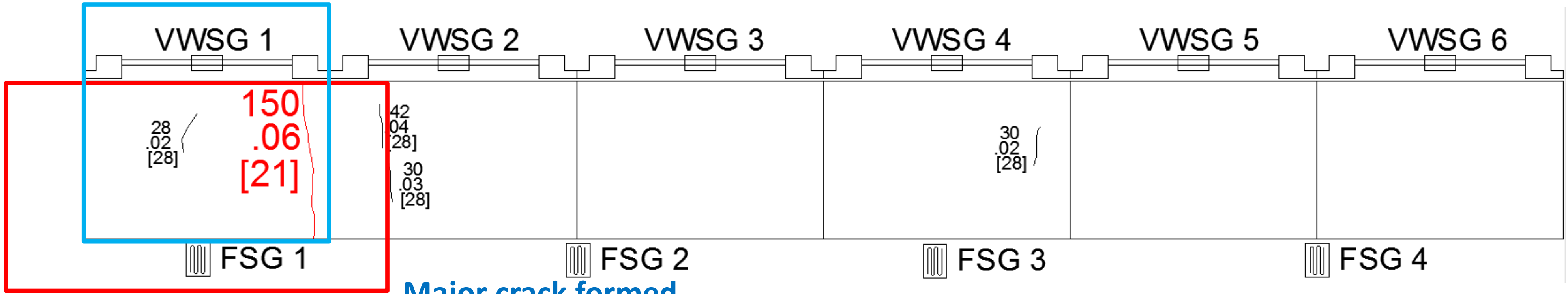


Days of First Crack	Ring 1	*Ring 2*
Foil Strain Gauge	22d	17d
VW Strain Gauge	22d	N/A
Microscope	22d	18d
Full Propagation	**25d**	**23d**

Results: Crack Map (PPE3)

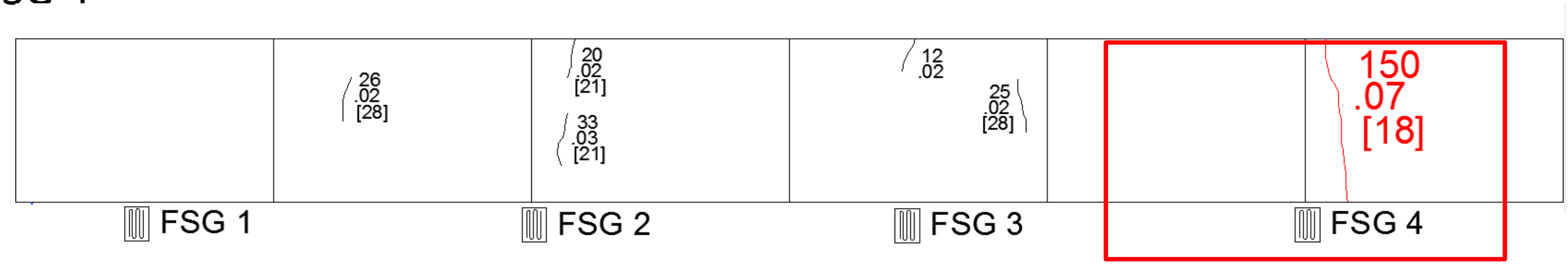
Crack Legend
- Length (mm)
- Width (mm)
- Initial Crack Age (days)

- **Ring 1 – Sensor Location for Cracking**
  - VWSG 1 & FSG 1

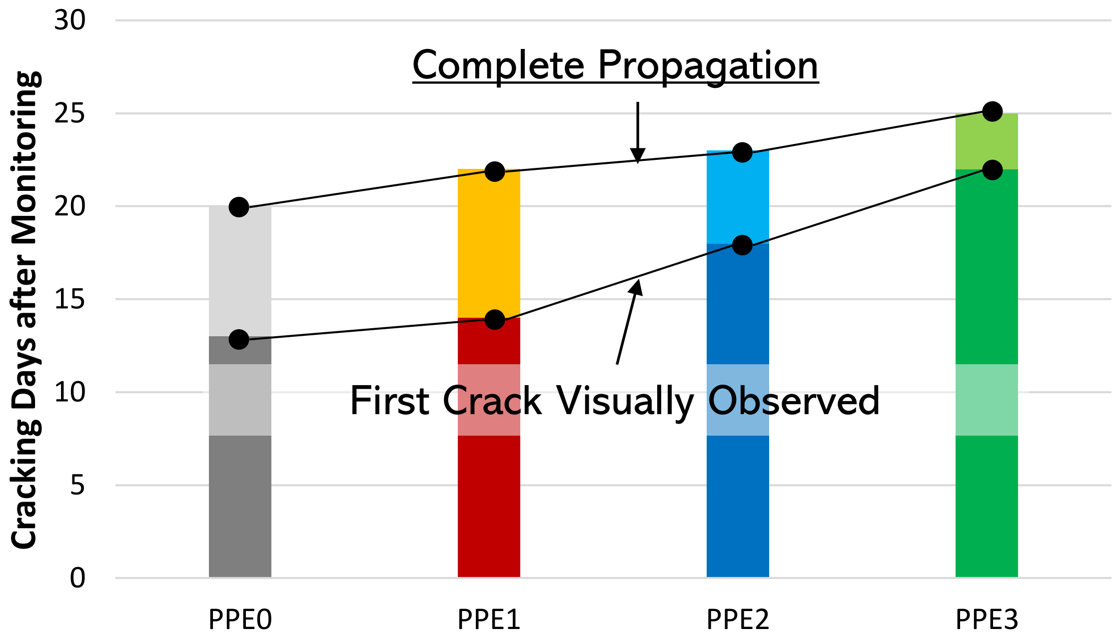


Major crack formed near VWSG anchor

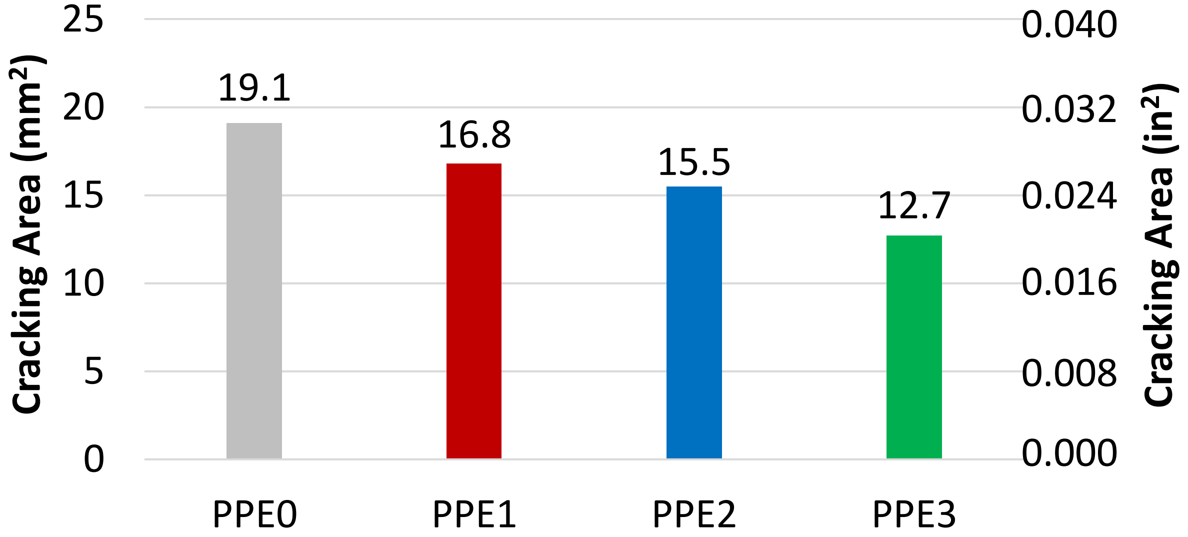
- **Ring 2 – Sensor Location for Cracking**
  - FSG 4

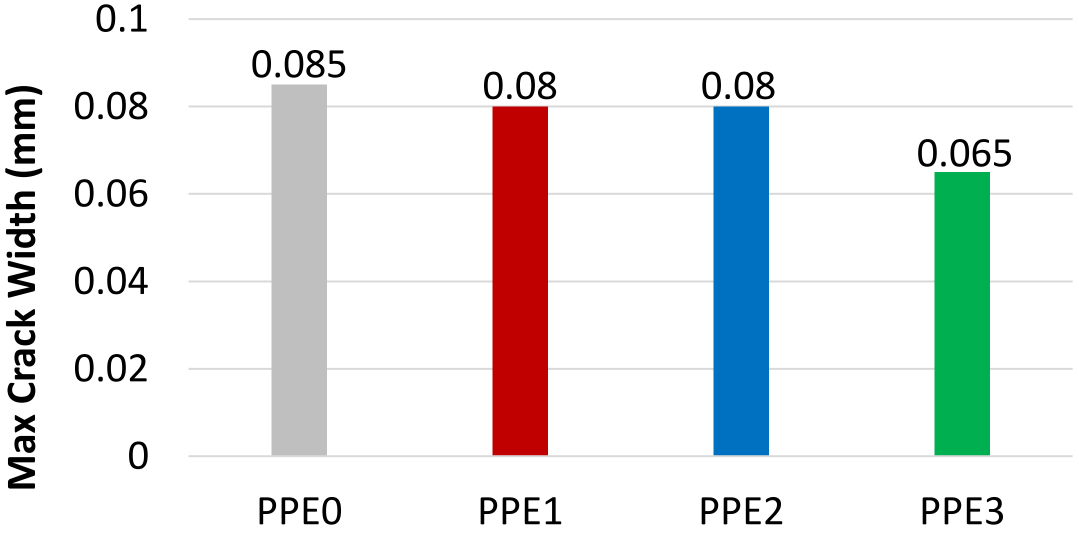


Analysis: Cracking Performance Comparison



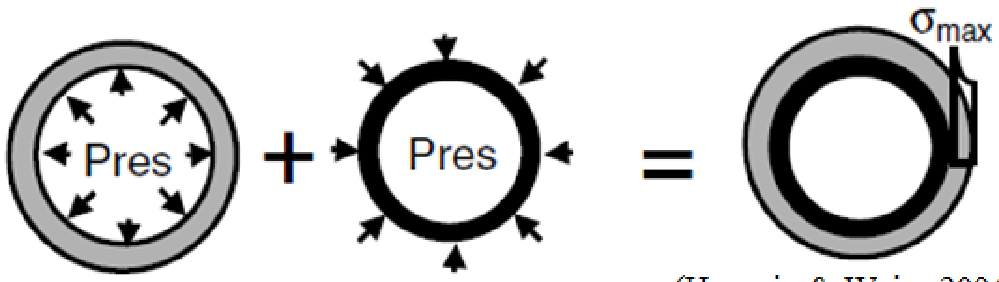
Days (Ring 1)	PPE0	PPE1	PPE2	PPE3
FSG	13	14	18	22
VWSG	13	15	19	22
First Crack Observed	14	16	18	22
Days Diff.	-	+2d	+4d	+8d
Complete Propagation	20	22	23	25
Days Diff.	-	+2d	+3d	+5d





Stress Calculations – Max Stress

- Determine stress at the concrete centerline using FSG and VWSG measurements
- Compare calculated stress vs tensile splitting strength



(Hossain & Weiss 2004)

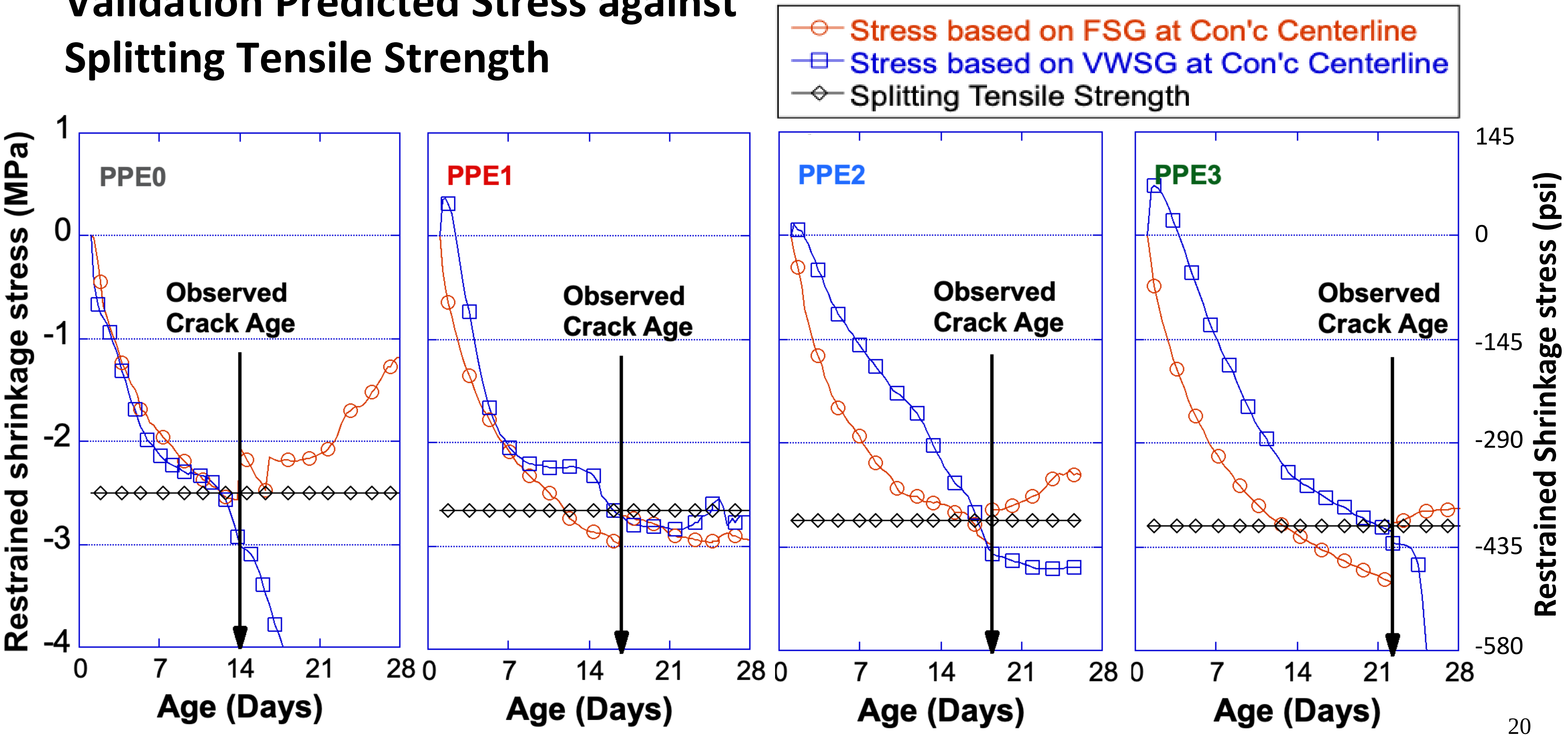
From FSG

$$\sigma_R = \boxed{-\varepsilon_{steel}(t)} * E_s * \frac{R_{OS}^2 - R_{IS}^2}{2R_{OS}^2} * \frac{R_{OS}^2}{R_{OC}^2 - R_{OS}^2} * \left(1 + \frac{R_{OC}^2}{r_i}\right)$$

From VWSG

$$\sigma_{c,r} = E_c * \boxed{\varepsilon_c} * \frac{1+\frac{R_{OC}^2}{r_i^2}}{\left(1+\frac{4R_{OC}^2}{(R_{OC}+R_{OS})^2}\right)}$$

Validation Predicted Stress against Splitting Tensile Strength



Conclusions

1) Inclusion of PPE in concrete decreases compressive strength and modulus of elasticity but increases tensile strength due to pull-out forces between cement and fibers.

2) The in-situ shrinkage performance of FR-SCC mixes can be assessed through restrained shrinkage ring tests. Higher fiber content yields a minor impact on free shrinkage; however, its implication on restrained shrinkage is significant, delaying initial cracking and reducing the cracking area by 34%.

3) VWSGs are more reliable than FSGs for predicting crack formation in FR-SCC, as they directly measure concrete strain, and crack location can be monitored using digital microscopes, although the presence of embedded bolts may affect accuracy.

4) The equation developed by Hossain and Weiss can accurately predict the actual concrete strain in the radial direction of the FR-SCC ring.

Acknowledgement

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