Optimization of shrinkage compensating fiber-reinforced mortar for repair

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Outline

- Investigation method
- Factorial design
- Experimental methods and results
- Optimization
- Large-scale beam repair
- Conclusions

Investigation method

- Design of experiment
- Slump
- Compressive strength
- Fiber pull-out
- Shrinkage
- IRH
- BSEM
- Hydration kinetics
- XRD
- MIP
- Large-scale beam repair

Repair criteria (Slump, Compressive strength, Fiber pull-out, Shrinkage)

Microstructure analysis for measuring effect of variables (SMM) on responses (IRH, BSEM, Hydration kinetics, XRD, MIP)

Factorial design

Factorial design

- Structured, statistics based, active regression approach to determine the effects of multiple variables on responses.
- Aims to optimize responses with respect to different factors by minimum number of trials.

Advantages

- Reduces the number of experiments by examining multiple variables simultaneously
- Reduces experiment time and cost, more efficient than one factor at a time approach
- Investigates both main effects and interaction effects
- Applicable to large number of trials (best for up to 3 variables)
- Works well when individual variables are significant and there is strong interactions among multiples variables
- Reduces potential bias on results by randomizing experimental runs

Full factorial: includes no less than one trial for every possible combination of variables and levels.

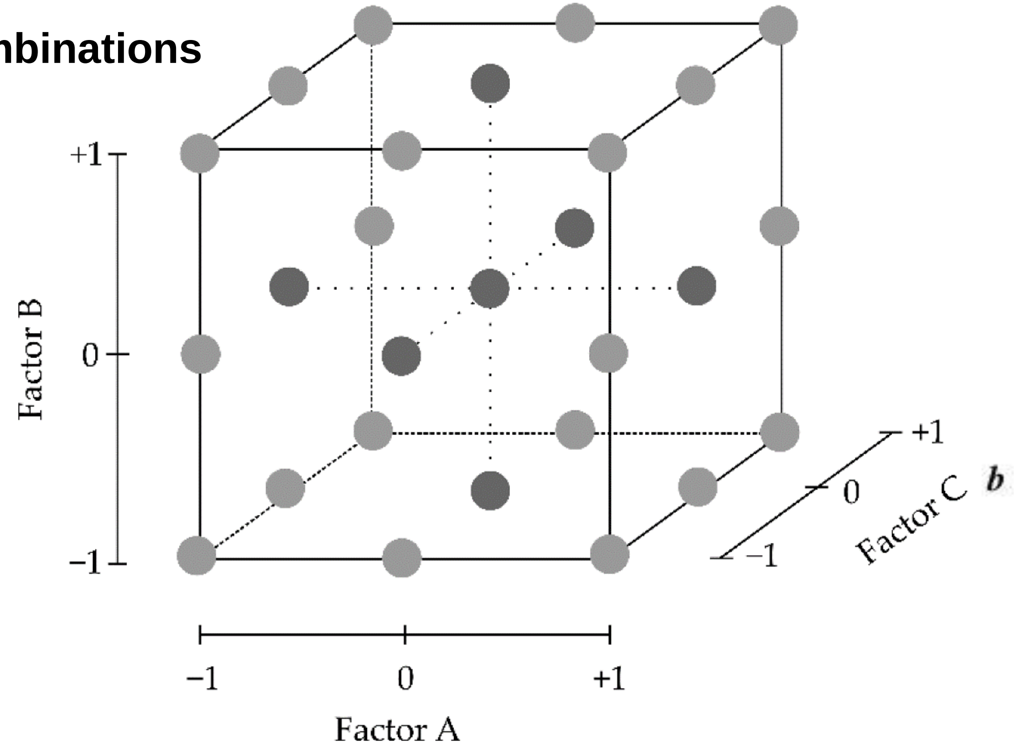
Partial or fractional factorial: includes no less than one trial for a few possible combination of variables and levels.

Variables = n

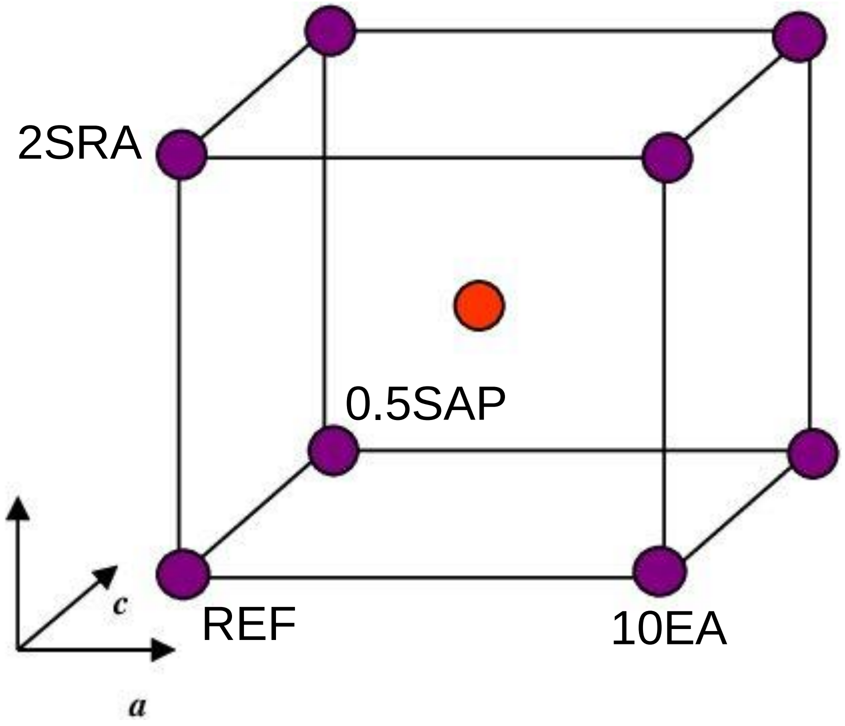
Levels = X

X^n Combinations

$3^3 = 27$



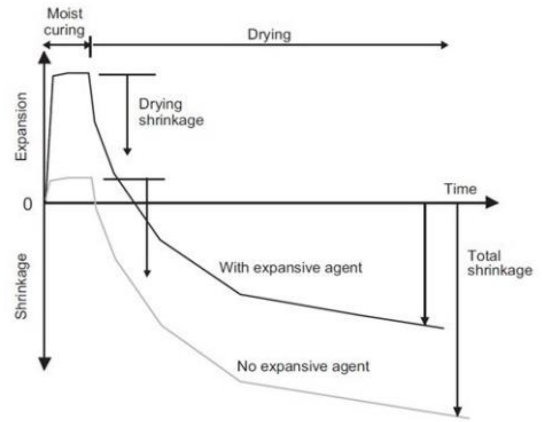
$2^3 = 8$



Experimental methods

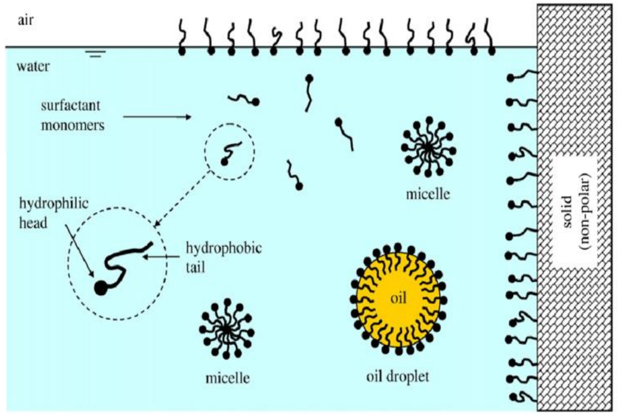
- Expansive agent (EA)

Initial expansion compensates for shrinkage
CaO-based (Portlandite) $CaO + H_2O \rightarrow Ca(OH)_2$



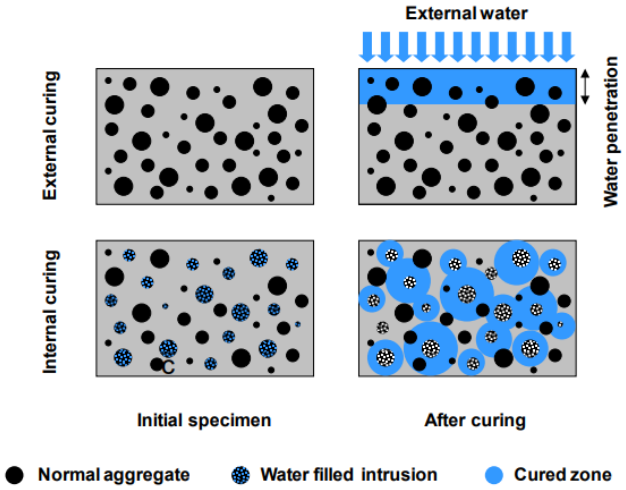
- Shrinkage reducing admixture (SRA)

Non-ionic surfactant reduces the surface tension of pore solution.



- Superabsorbent polymer (SAP)

Polymetric materials (ionic, non-ionic, and cationic)
Rapid absorption and gradual release



Mixture matrix

Variables = n

Levels = X

X^n Combinations

$3^3 = 27$

$2^3 = 8$

Central points:
Zero coded values to determine experimental error

Validation points:
Intermediate coded values to validate statistical models

	Mixture	Coded values			Absolute values		
		EA	SRA	SAP	EA	SRA	SAP
8 Fractional factorial points	REF	-1	-1	-1	0	0	0
	10EA	1	-1	-1	10	0	0
	2SRA	-1	1	-1	0	2	0
	0.5SAP	-1	-1	1	0	0	0.5
	10EA2SRA	1	1	-1	10	2	0
	10EA0.5SAP	1	-1	1	10	0	0.5
	2SRA0.5SAP	-1	1	1	0	2	0.5
	10EA2SRA0.5SAP	1	1	1	10	2	0.5
4 Central points	5EA1SRA0.25SAP	0	0	0	5	1	0.25
	5EA1SRA0.25SAP	0	0	0	5	1	0.25
	5EA1SRA0.25SAP	0	0	0	5	1	0.25
	5EA1SRA0.25SAP	0	0	0	5	1	0.25
6 Validation points	2.5EA1.5SRA0.17SAP	-0.5	0.5	-0.33	2.5	1.5	0.17
	2.5EA0.5SRA0.17SAP	-0.5	-0.5	-0.33	2.5	0.5	0.17
	2.5EA1.5SRA0.33SAP	-0.5	0.5	0.33	2.5	1.5	0.33
	7.5EA1.5SRA0.33SAP	0.5	0.5	0.33	7.5	1.5	0.33
	7.5EA1.5SRA0.17SAP	0.5	0.5	-0.33	7.5	1.5	0.17
	7.5EA0.5SRA0.33SAP	0.5	-0.5	0.33	7.5	0.5	0.33

w/cm = 0.4

Steel fiber = 0.5%

Aspect ratio = 65

Coded EA = (Absolute EA–5)/5

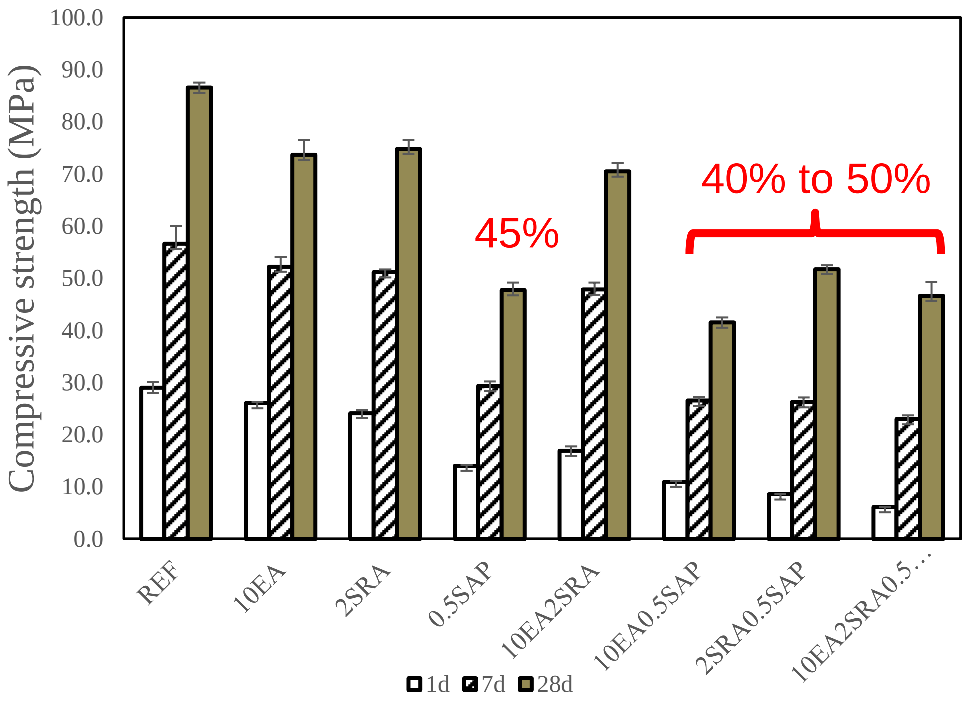
Coded SRA = (Absolute SRA–1)/1

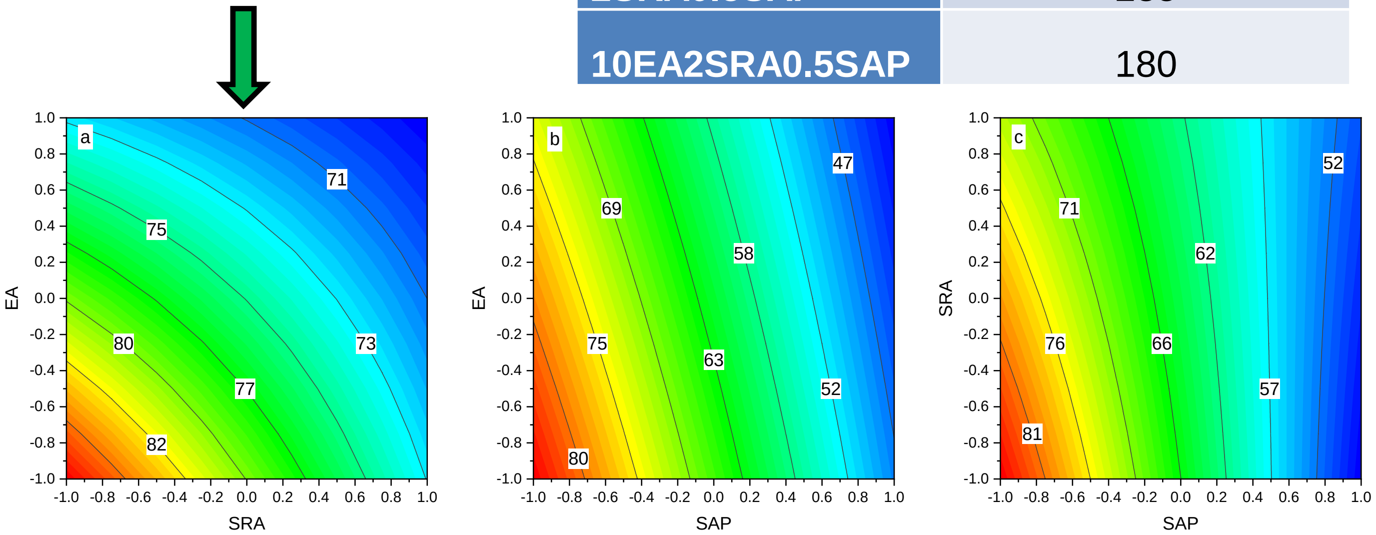
Coded SAP = (Absolute SAP–0.25)/0.25

Experimental results

Slump and compressive strength

Mixture	Slump spread (mm)
REF	215
10EA	205
2SRA	250
0.5SAP	185
10EA2SRA	165
10EA0.5SAP	170
2SRA0.5SAP	235
10EA2SRA0.5SAP	180

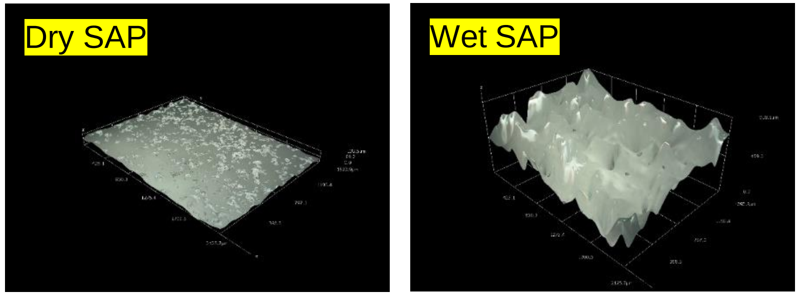




Coupled effect of SMM on 28-d compressive strength

Over 60 MPa (EA=5%, SRA=1%, SAP=0.25%)

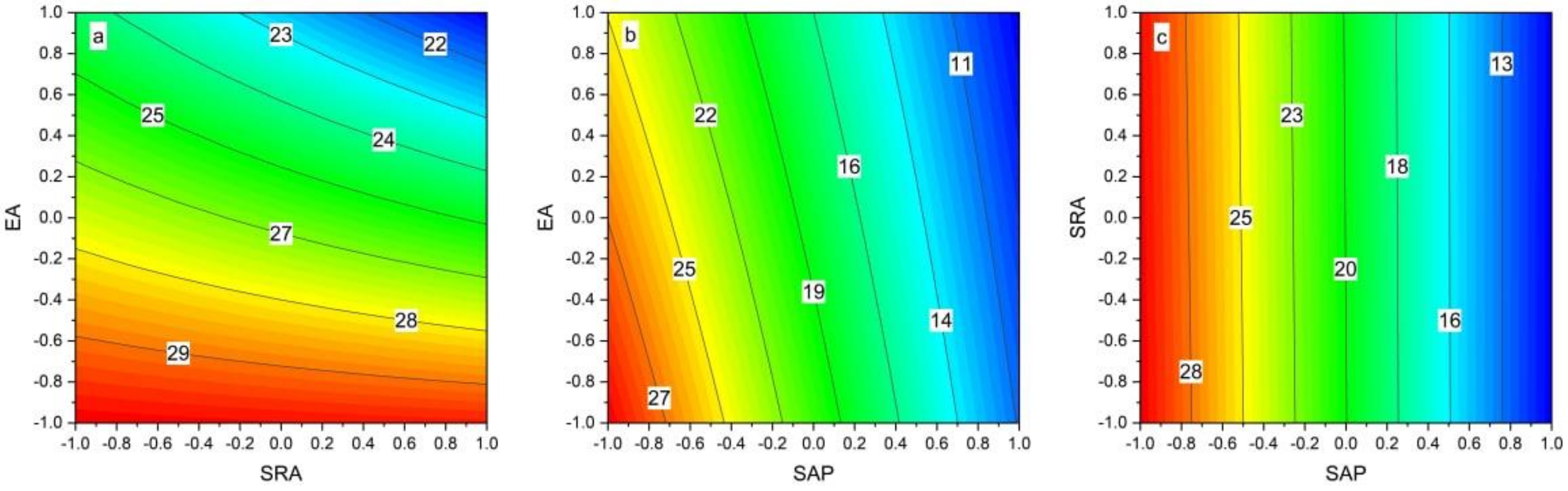
Fiber pull-out



Fiber pull-out strength and energy at 28 days

$$\tau_{max} = \frac{P_{max}}{n\pi dl}$$

Mixture	Bond strength (MPa)	Energy (N.mm)
REF	31	104
10EA	26	98
2SRA	28	92
0.5SAP	12	51
10EA2SRA	22	83
10EA0.5SAP	10	48
2SRA0.5SAP	11	56
10EA2SRA0.5SAP	11	62



Coupled effect of SMM on 28-d fiber pull-out strength

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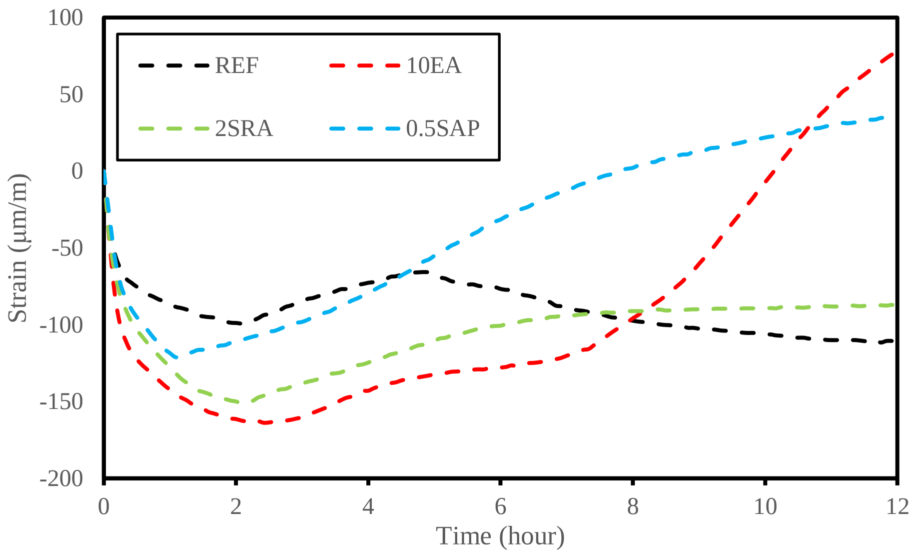
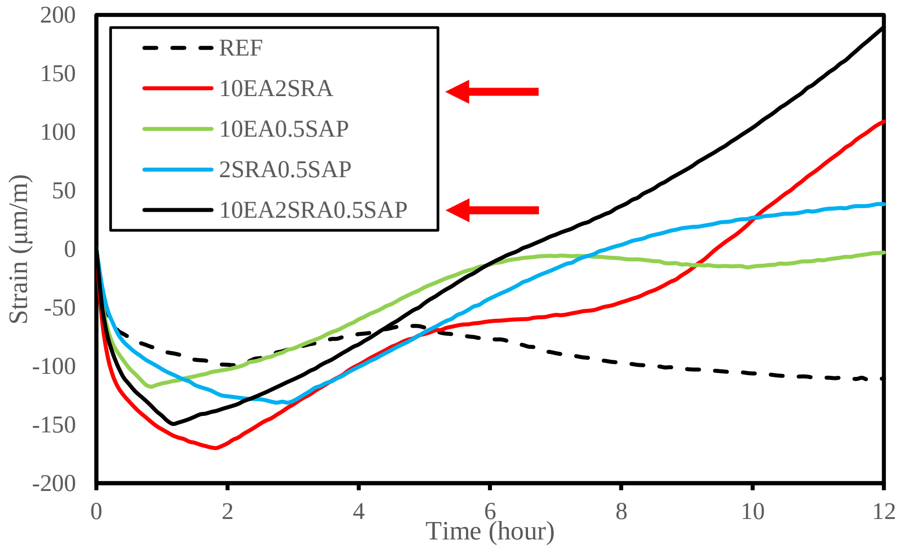
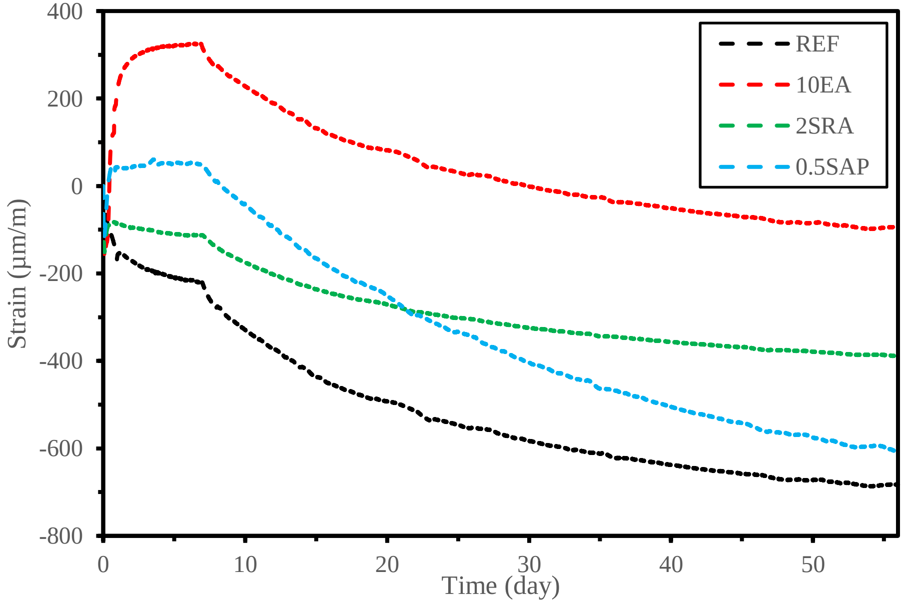
Shrinkage

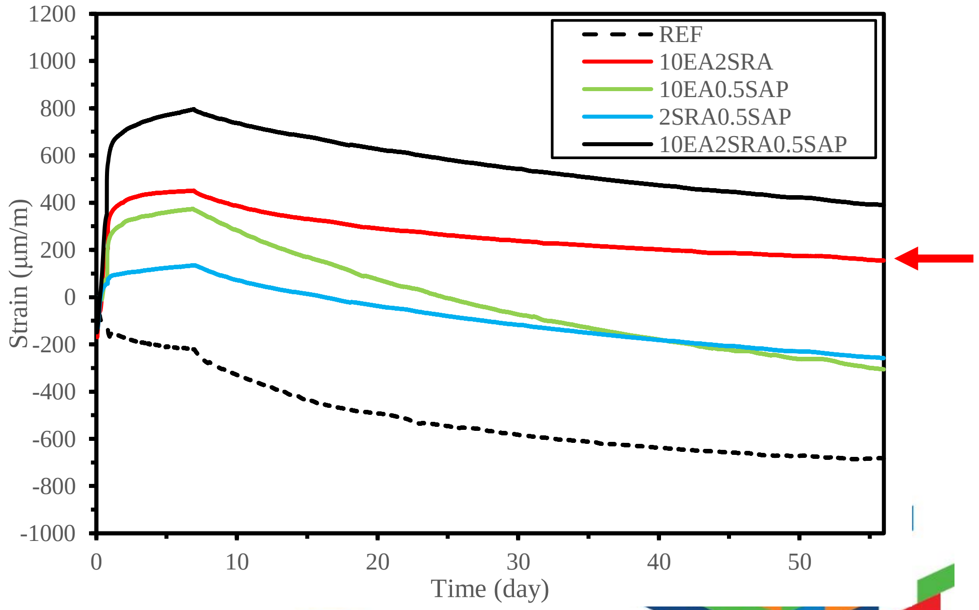
Initial shrinkage





Shrinkage

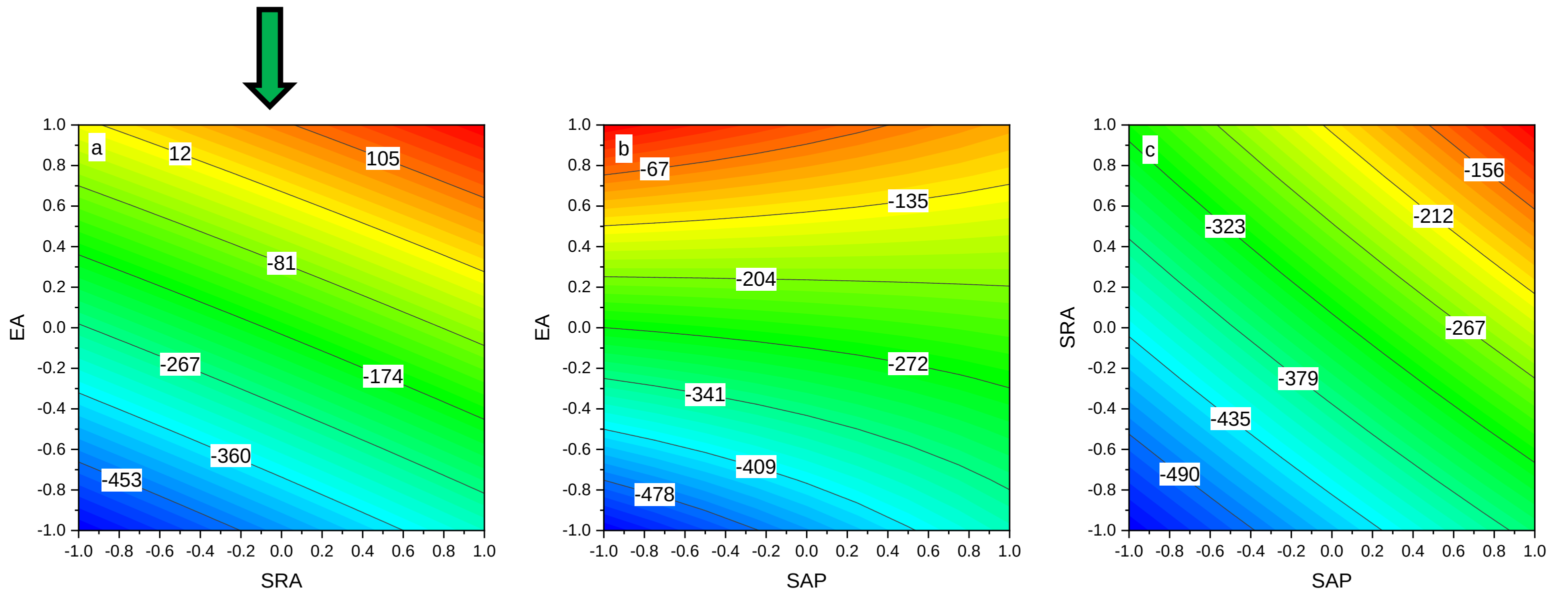




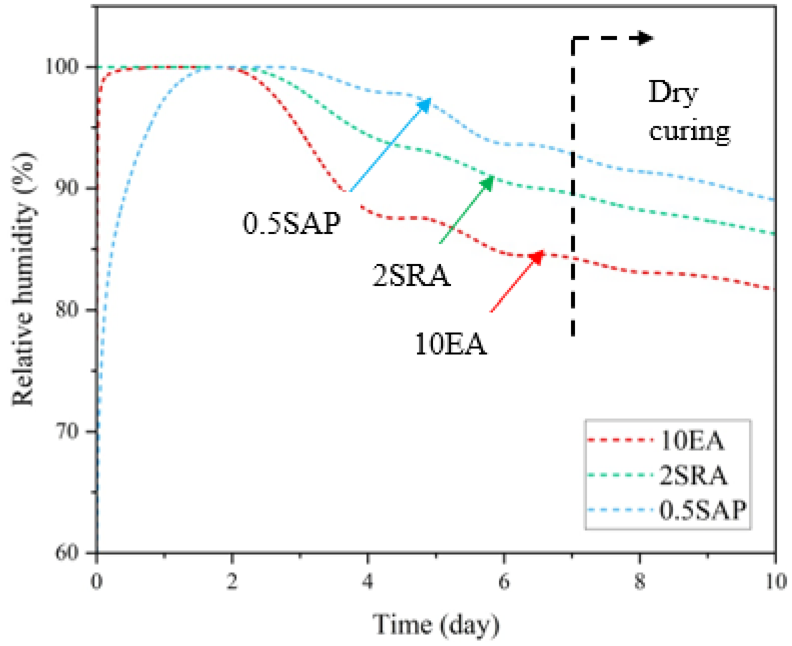
Effect of SMM on shrinkage and IRH

Ion concentration in SAP

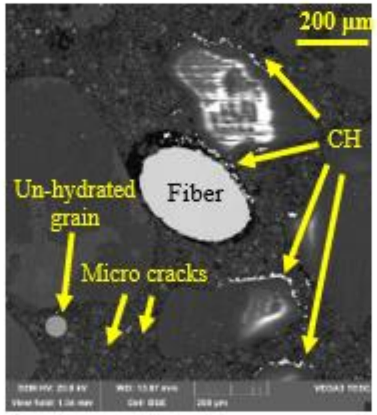
Water absorption by EA



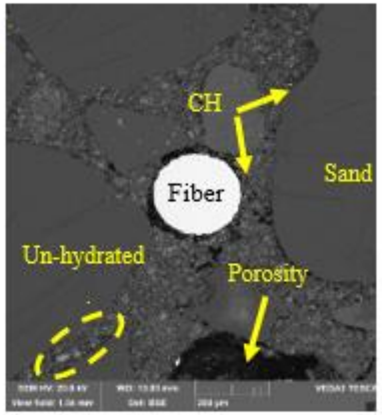
Coupled effect of SMM on 28-d shrinkage



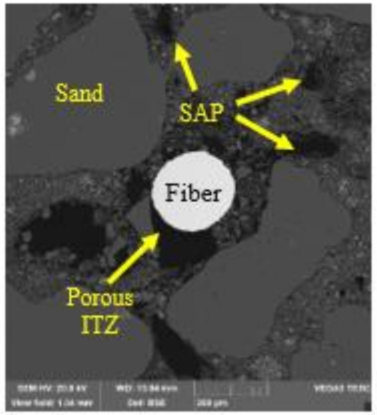
Microstructural characteristics



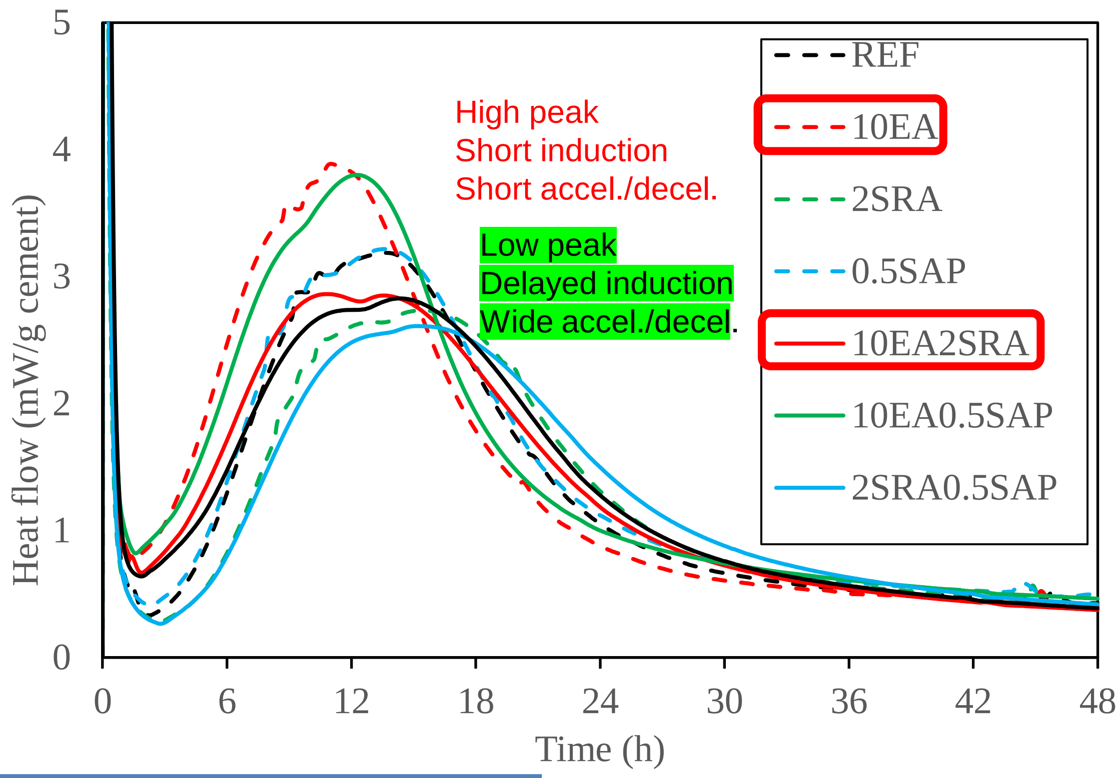
10EA



2SRA

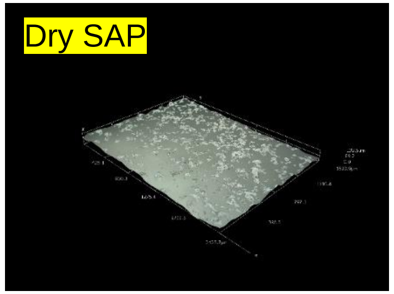


0.5SAP

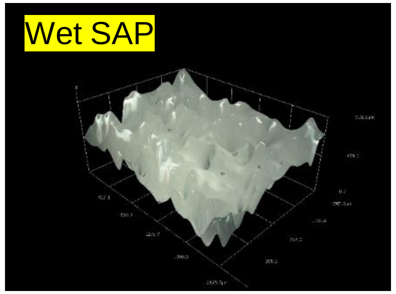


Difference vs. REF at 48 h

100%
110%
94%
102%
103%
113%
97%
104%



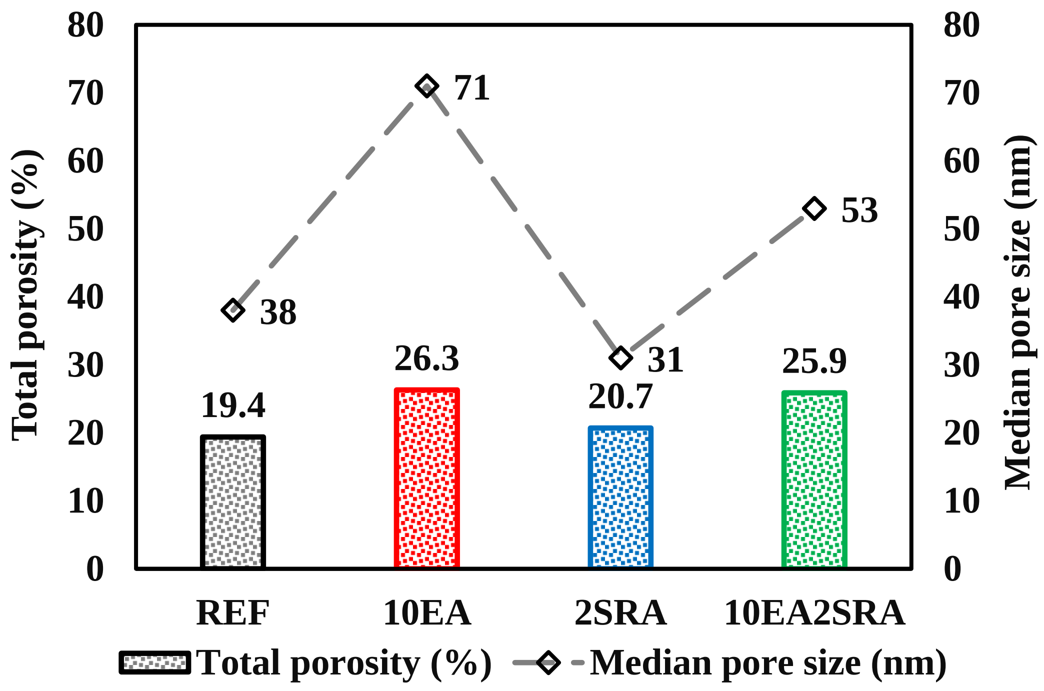
$$\sigma_{cap} = \frac{2\gamma_{1g} Cos\ \alpha}{r}$$



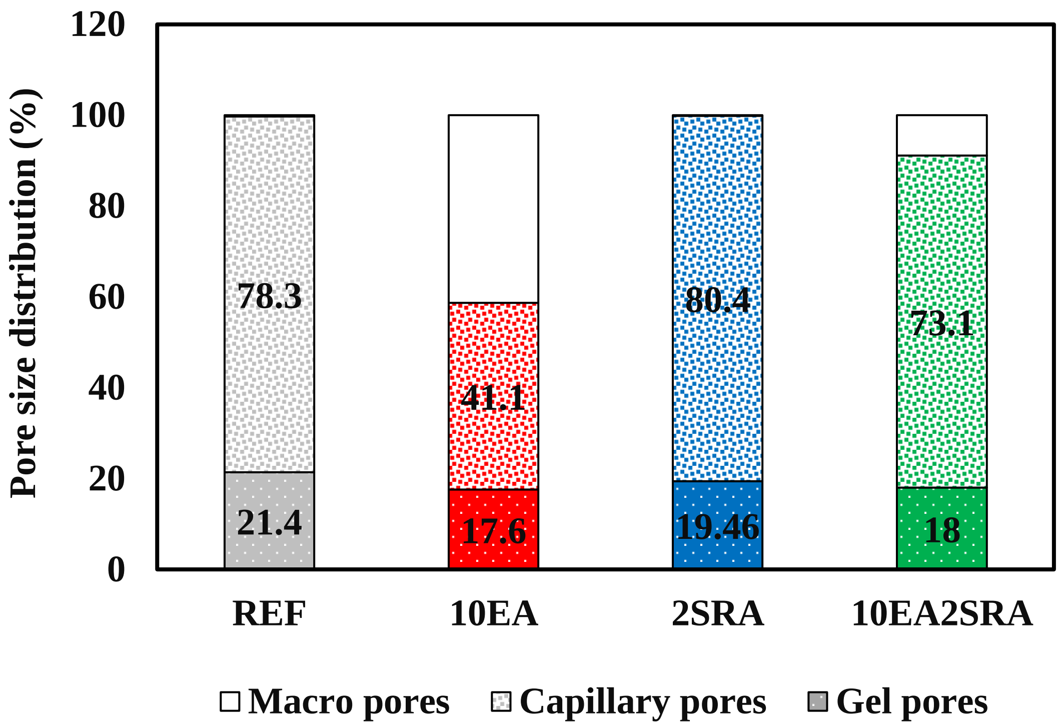
Mixture	Crystalline phase (%)			
	Ettringite	CH	C_3S/C_2S	SiO_2
REF	3.5	13.2	6.0	14.3
10EA	2.8	19.3	5.5	5.4
2SRA	3.4	13.1	6.3	8.1
0.5SAP	4.1	15.1	3.9	12.3
10EA2SRA	3.5	14.4	5.3	5.0
10EA0.5SAP	4.2	21.5	4.0	2.0
2SRA0.5SAP	4.3	17.0	3.7	11.1
10EA2SRA0.5SAP	4.0	17.6	3.4	6.1

Analysis of crystalline phases

MIP



80
70
60
50
40
30
20
10
0
Total porosity (%)
Median pore size (nm)
38
71
31
53
19.4
26.3
20.7
25.9
REF
10EA
2SRA
10EA2SRA
Total porosity (%)
Median pore size (nm)



120
100
80
60
40
20
0
Pore size distribution (%)
78.3
21.4
41.1
17.6
80.4
19.46
73.1
18
REF
10EA
2SRA
10EA2SRA
Macro pores
Capillary pores
Gel pores

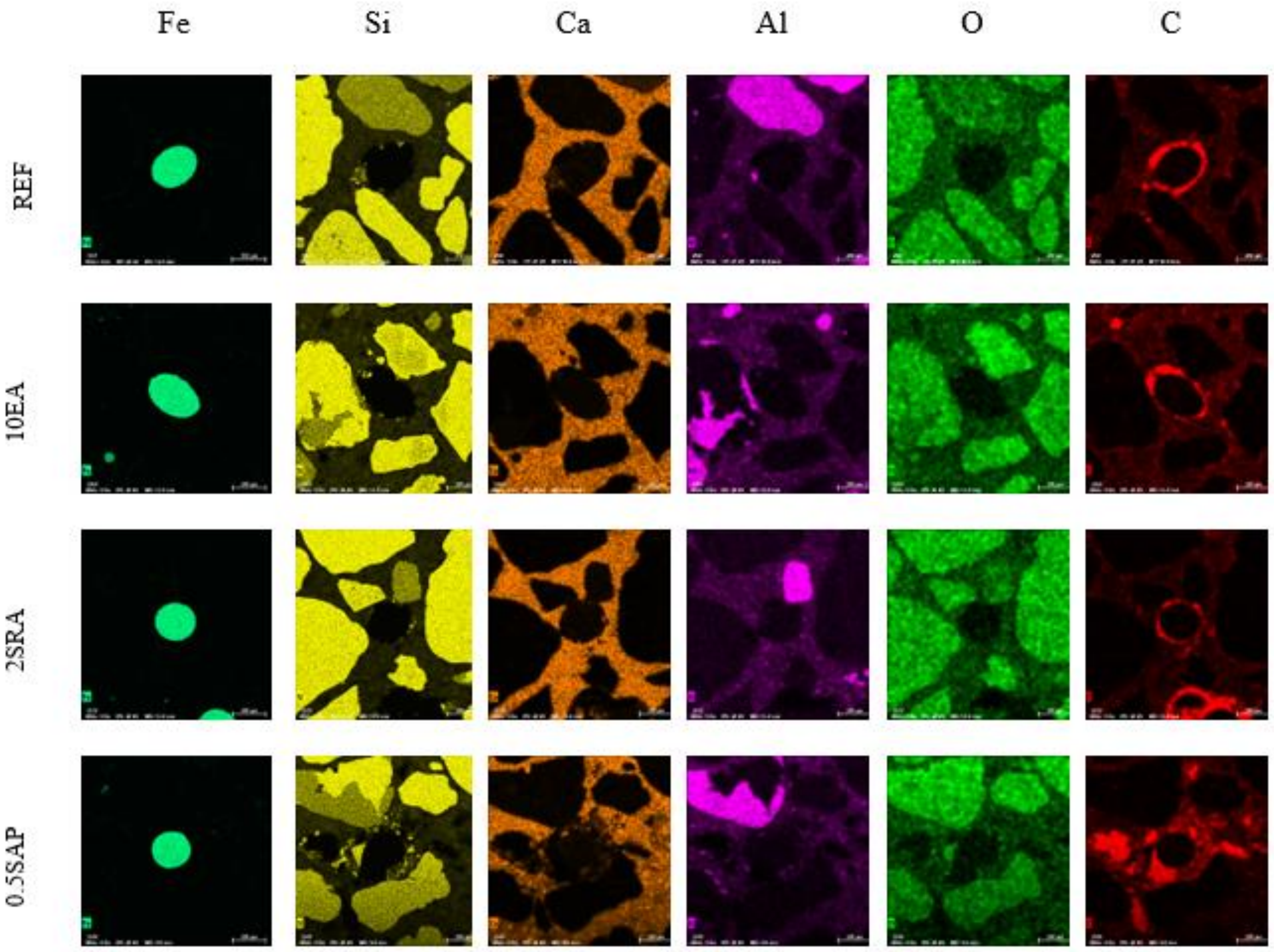
Element-mapping at interface of fiber and matrix

Fe → Fiber

Si → Sand

Ca → CH

C → Porosity



Optimization

Criteria for mixture optimization

No.	Material property	Goal	Low limit	High limit	Importance
1	Slump (mm)	Match Target	160	260	1
2	28-d compressive strength (MPa)	Maximize	40	90	3
3	28-d fiber pull-out strength (MPa)	Maximize	10	32.5	2
4	28-d shrinkage (µm/m)	Match Target	-600	600	3

Derived statistical models (based on coded values)

Property	Derived equation	R^2	p-value
Slump (mm)	-18.9 EA – 13.4 EA.SRA – 9.0 SAP + 7.4 SRA.SAP + 198.7	0.84	<0.001
28-d compressive strength (MPa)	-14.7 SAP – 3.5 EA + 2.9 SAP (SRA - 0.05) + 60.6	0.97	<0.001
28-d fiber pull-out strength (MPa)	-8.2 SAP – 2.3 EA + 18.0	0.88	0.0007
28-d shrinkage (µm/m)	246.5 EA + 158.7 SRA +79.5 SAP - 86.1	0.90	<0.001

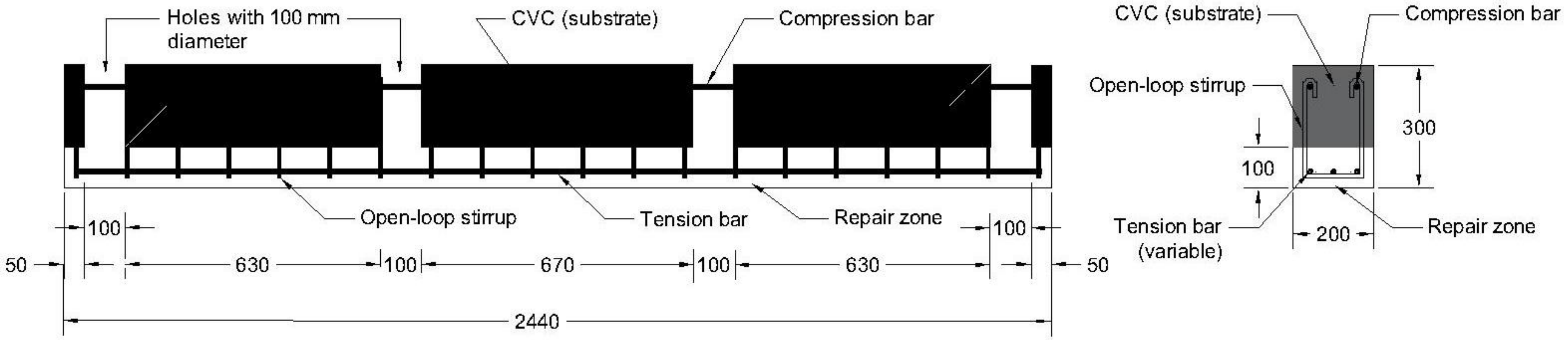
Optimized mixtures	Slump (mm)	28-d compressive strength (MPa)	28-d fiber pull-out strength (MPa)	28-d shrinkage (µm/m)	Desirability
7.5EA	206	76	26	-136	0.77
5EA0.5SRA	208	78	27	-218	0.71
5EA0.125SAP	201	71	23	-258	0.60

Characteristics of optimized mixtures

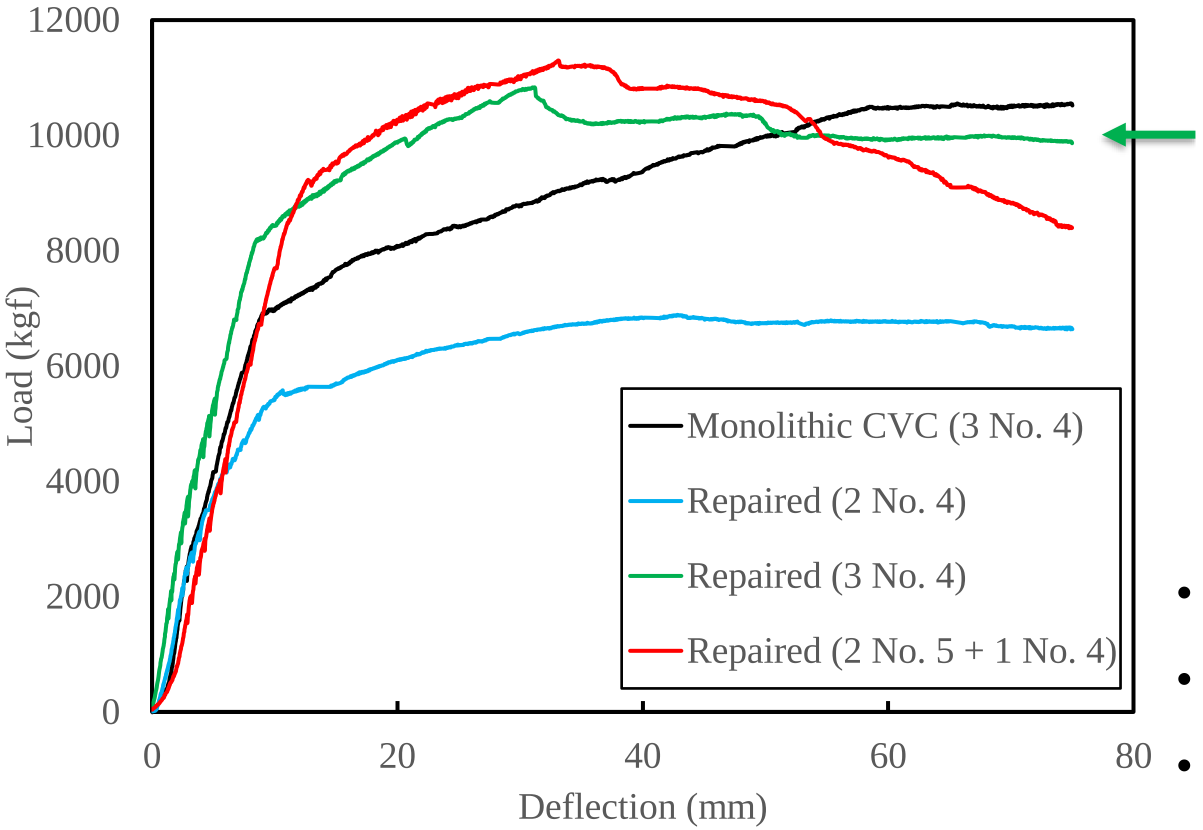
Large-scale beam repair

Evaluate the performance of proven FRSCC mixture in repairing applications to enhance the flexural properties and crack resistance of repair.

- Optimized mixture from Task I-C
- 2 types of fibers (fixed content)
- Flexural Properties of 200 × 300 × 2440 mm conventional vibrated concrete (CVC) beams with 100 mm thickness of repair concrete



Structural performance of FRSCC in repair



- Repaired beam FC > CVC (6 to 48%)
- Medium reinforcement (soft failure)
- Medium reinforcement repaired beam +5% YS ↑

Flexural properties of the monolithic CVC and CVC beams repaired with FRSCC [5EA0.5SRA0.5FR (PLP) mixture]

	First crack load, kgf	Load corresponding to steel yield, kgf	Peak load, kgf	Toughness (area from 0 to L/150), kgf-mm
Monolithic CVC (3 No. 4)	3398	8800	14023	335262
Repaired (2 No. 4)	3613	7400	8956	270429
Repaired (3 No. 4)	5031 48%	9200	14524 4%	444371 32%
Repaired (2 No. 5 + 1 No. 4)	3584	10400	15177	508552

Summary

1. SMM limited to 5% EA, 1% SRA, and 0.25% SAP
2. EA+SRA preferred SMM combination considering compressive strength, fiber pull-out strength, and shrinkage
3. 10% EA → high heat of hydration → excessive CH formation and high expansion → microcracks and macro pores → adverse effect on mechanical properties
4. 0.5% SAP with additional water → swelling of SAP → voids → lower compressive strength and fiber-matrix bonding
5. Multi-objective optimization → 7.5EA, 5EA0.5SRA and 5EA0.125SAP → flowable, high strength, and low shrinkage → Enhanced flexural properties in repair

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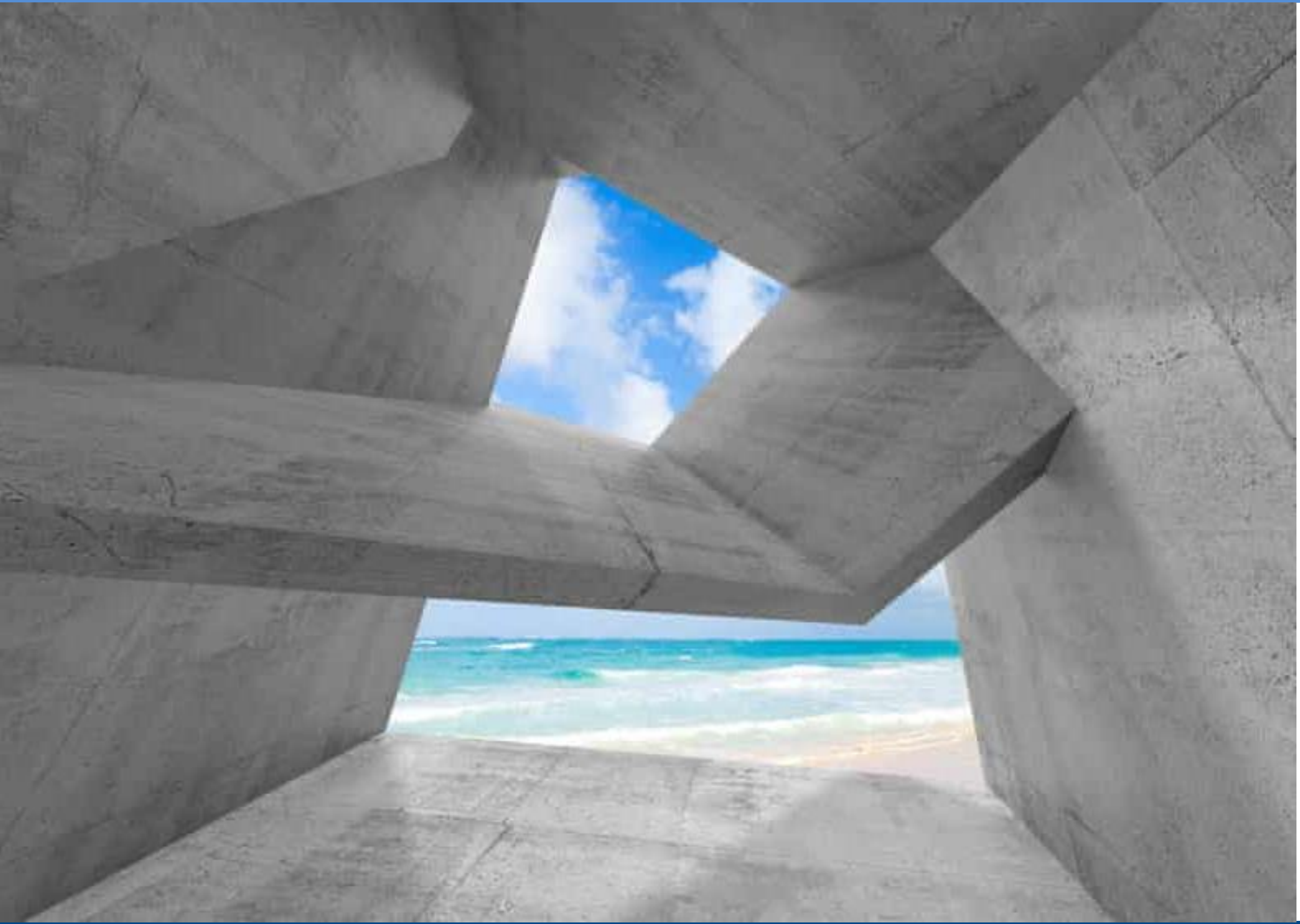

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Any Questions?

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