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Durability of Concrete Members Incorporated with Conventional and Advanced Materials, Part 2 of 3

Microscopic cracking of ASR-affected fiber-reinforced concrete

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Introduction

- ASR: causes expansion, cracking and degradation of mechanical properties of concrete
- Fiber reinforcement: bridges cracks, and improves tensile strength
- **Fiber reinforcement appears promising for reducing ASR damage of concrete**

- Effectiveness of fibers is mostly evaluated in terms of reductions in expansion and loss of mechanical properties.
- **This study is focused on microscopic cracking of ASR affected fiber reinforced concrete.**

Mix Design of Concrete [kg/ m^3 (lb/yd^3)]

- Based on ASTM C1293 (CPT)
- Sand tested for reactivity as per ASTM C1260 (AMBT)

Material ↓ Mix →	M0.0	M0.65	M1.3
Cement	420 (707.9)	420 (707.9)	420 (707.9)
Coarse aggregate (Spratt) (12.5 – 9.5 mm) [1/2 – 3/8 in.] 50% (9.5 – 4.75 mm) [3/8 – 3/16 in.] 50%	1112 (1874.2)	1112 (1874.2)	1112 (1874.2)
Water	185 (311.8)	185 (311.8)	185 (311.8)
Alkali pellet	1.4 (2.4)	1.4 (2.4)	1.4 (2.4)
Sand	688 (1159.6)	688 (1159.6)	688 (1159.6)
Steel fiber	-	51 (86)	102 (171.9)

Test Variables

Mix	Test series	Cylinders		Prisms	
		#	Tests	#	Tests
M0.0	M0.0-p	9	• E_c, 28d (23 °C), 28d (50 °C), 91d (50 °C) • f_c' 28d (23 °C), 28d (50 °C), 91d (50 °C)	7	• Expansion (7, 28, 56 and 91d) • MOR (28 and 91d) • DRI (28 and 91d)
	M0.0-r			5	
M0.65	M0.65-p	9		5	
	M0.65-r			5	
M1.3	M1.3-p	9		5	

Note: "p" stands for plain and "r" stands for reinforced with a 6.4 mm dia. central threaded steel reinforcement of **0.365%** reinforcement ratio.

Accelerated conditioning of specimens at 50 °C (122 °F) and >95% relative humidity

Properties of Reinforcing Steel

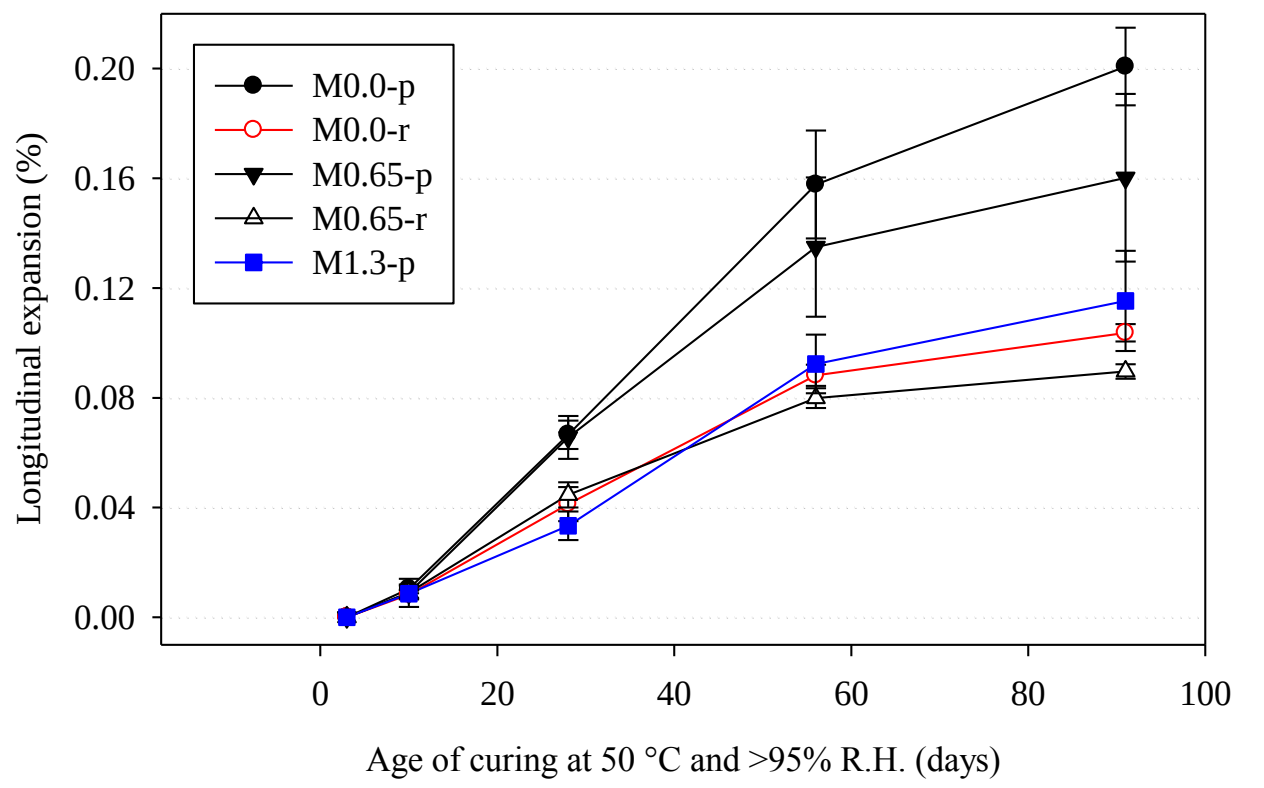
A. Steel fiber

Properties	Steel Fiber
Length (mm)	30
Diameter (mm)	0.38
Aspect ratio	79
Tensile Strength (N/mm^2)	3070
Young's Modulus (N/mm^2)	200,000
Density (kg/m^3)	7850

B. Reinforcing bar

- 6.4 mm diameter all-thread stainless steel rod
- Tensile strength 655 MPa
- Cross-sectional area: 20.5 mm^2

Longitudinal Expansion



⬆ Fiber content ⇨ ⬇ longitudinal expansion

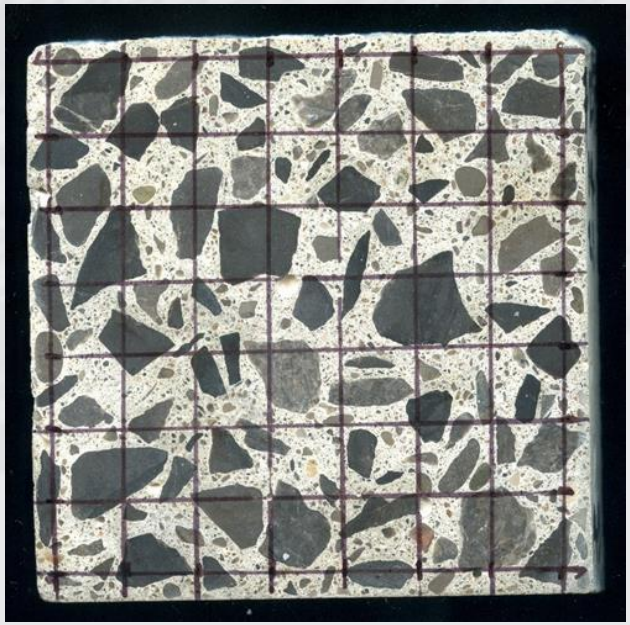
M0.0-p > M0.65-p > M1.3-p;
M0.0-r > M-0.65-r

Longitudinal expansion of both reinforced prisms was significantly smaller compared to the prisms without a reinforcing rod. At 91 days, expansion of M0.0-r ≈ 52% of M0.0-p; expansion of M0.65-r ≈ 55% of M0.65-p

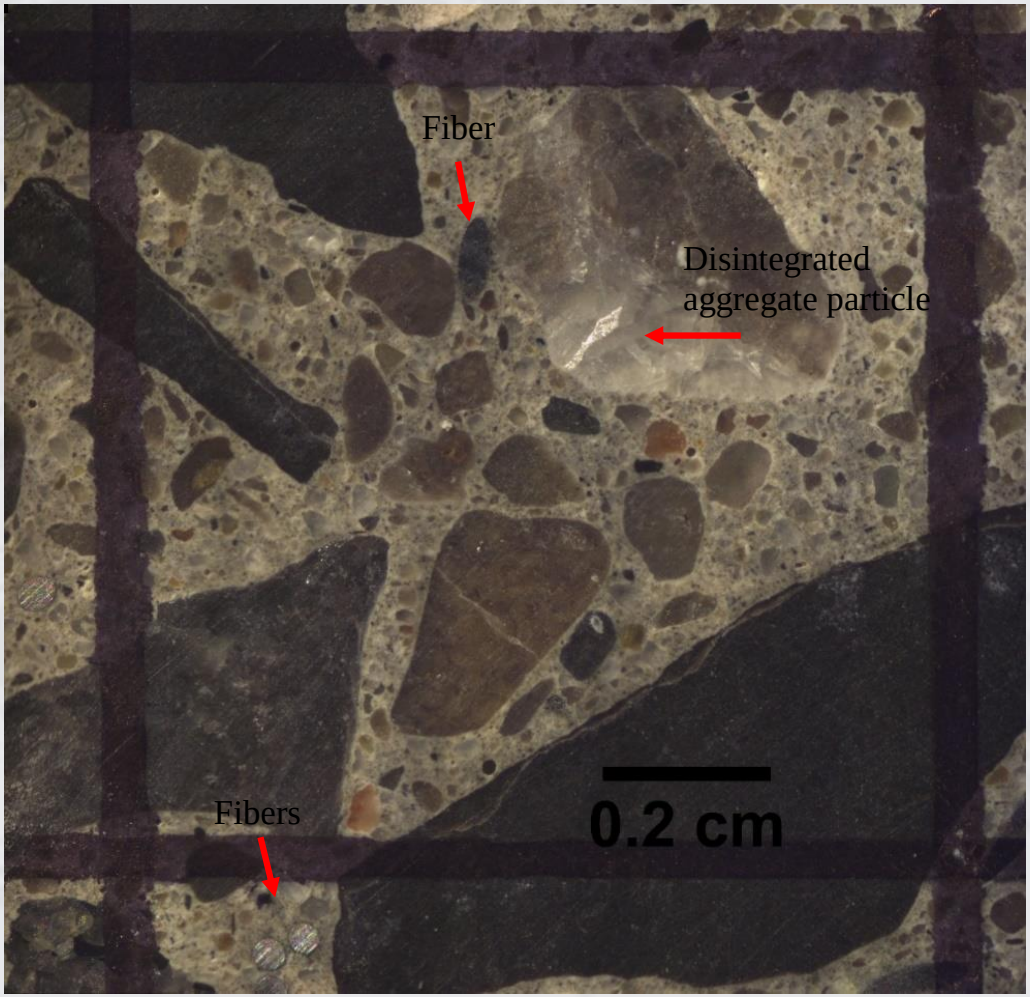
Damage Rating Index

- Cross-section of prisms polished to 1500 grit (~5 µm)
- Examined under stereo-binocular microscope at ~16x magnification
- Counted seven petrographic features in each grid of 1 cm by 1 cm
- Calculated DRI value based on the counts and the weighting factors

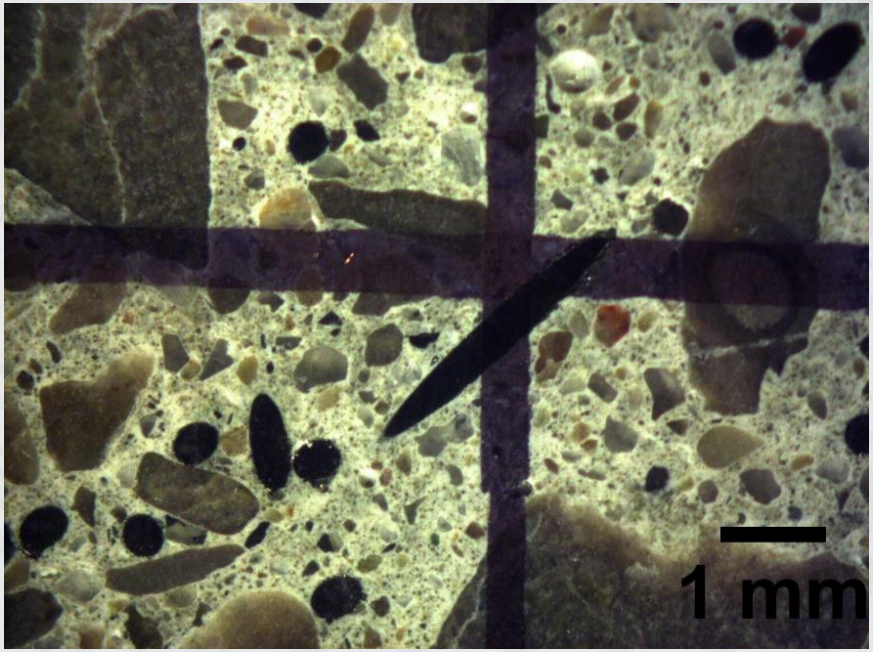
Petrographic features	Weighting factors
Closed/tight cracks in coarse aggregate particle	0.25
Opened cracks or network cracks in coarse aggregate particle	2
Cracks or network cracks with reaction product in coarse aggregate particle	2
Debonded coarse aggregate	3
Disaggregated / corroded aggregate particle	2
Cracks in cement paste	3
Cracks with reaction product in cement paste	3



Field of View Under A Stereo-binocular Microscope

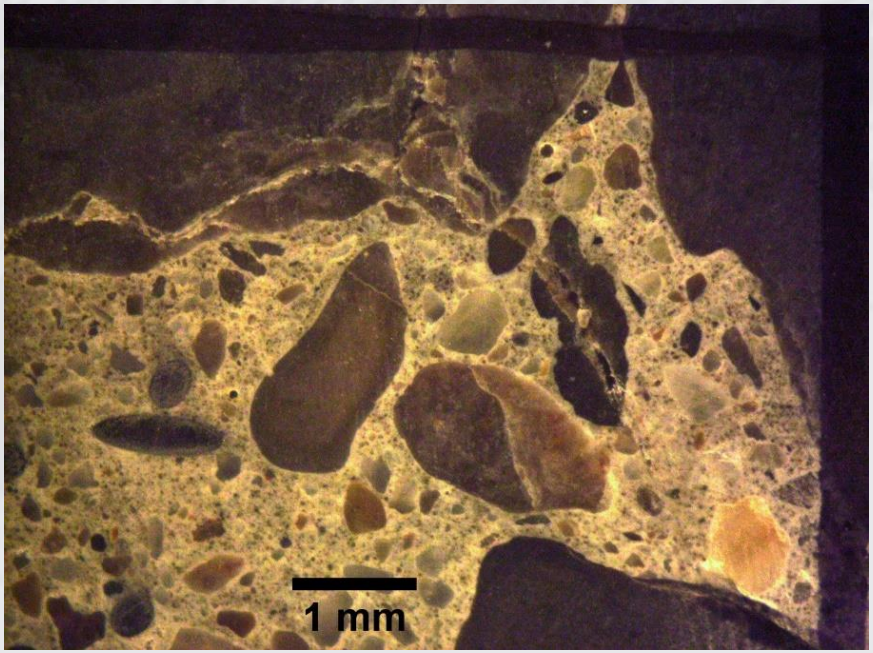


Fibers and Cracks

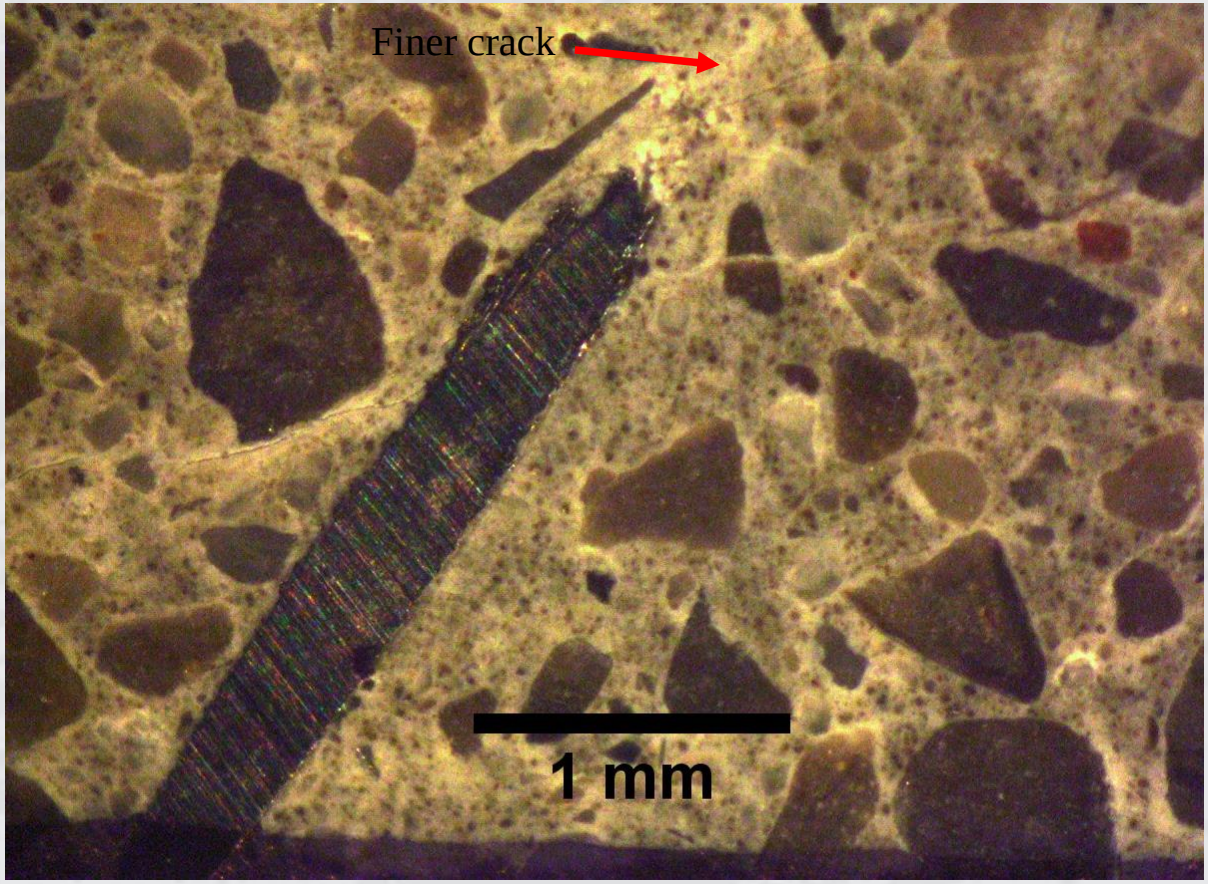


M1.3-p specimen (age 91 days)

M0.65-r specimen (age 91 days)

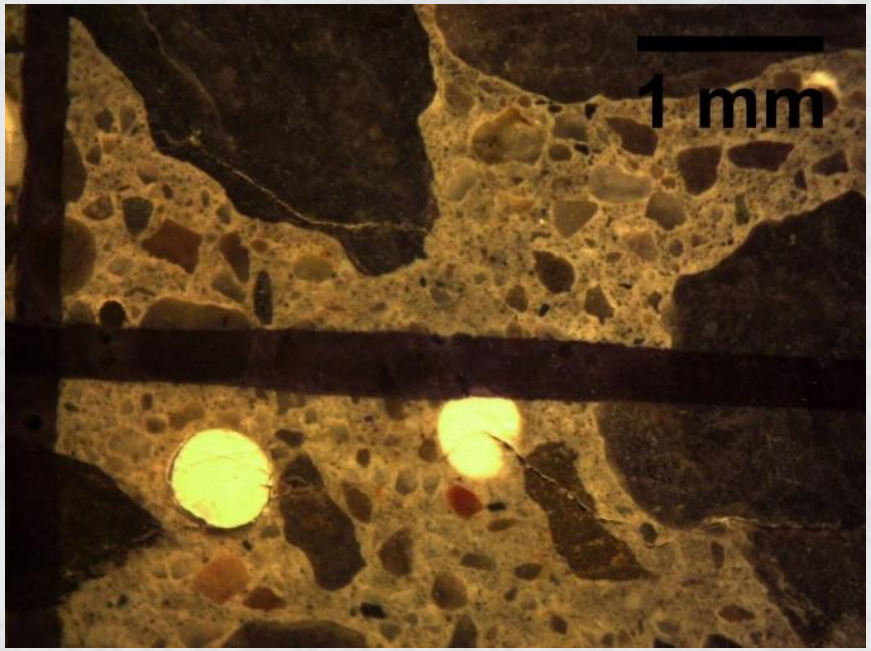


ASR Crack Branched by A Fiber



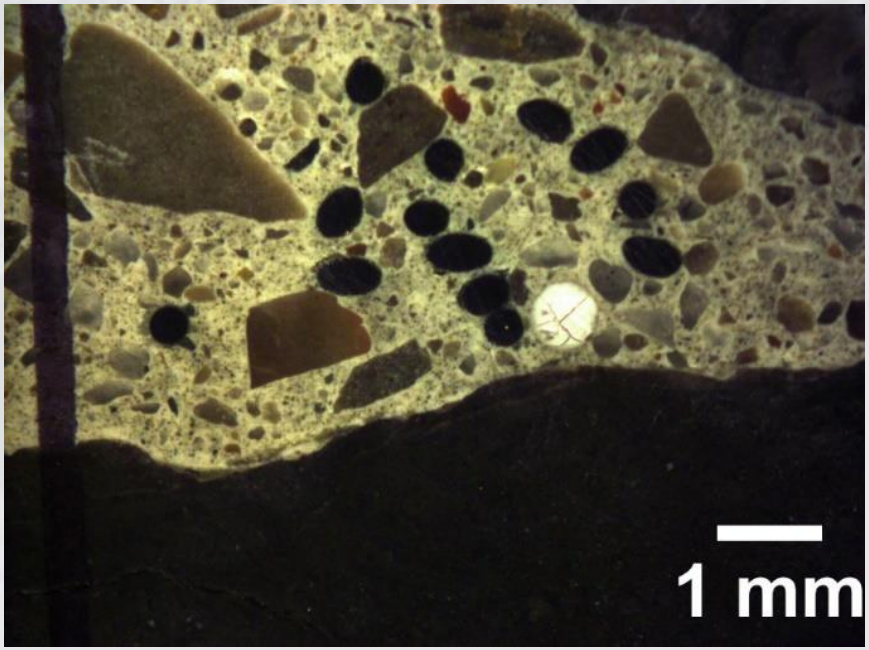
Number of counts of cracks may likely increase and hence the DRI value may increase!

Air Voids Filled with ASR Products

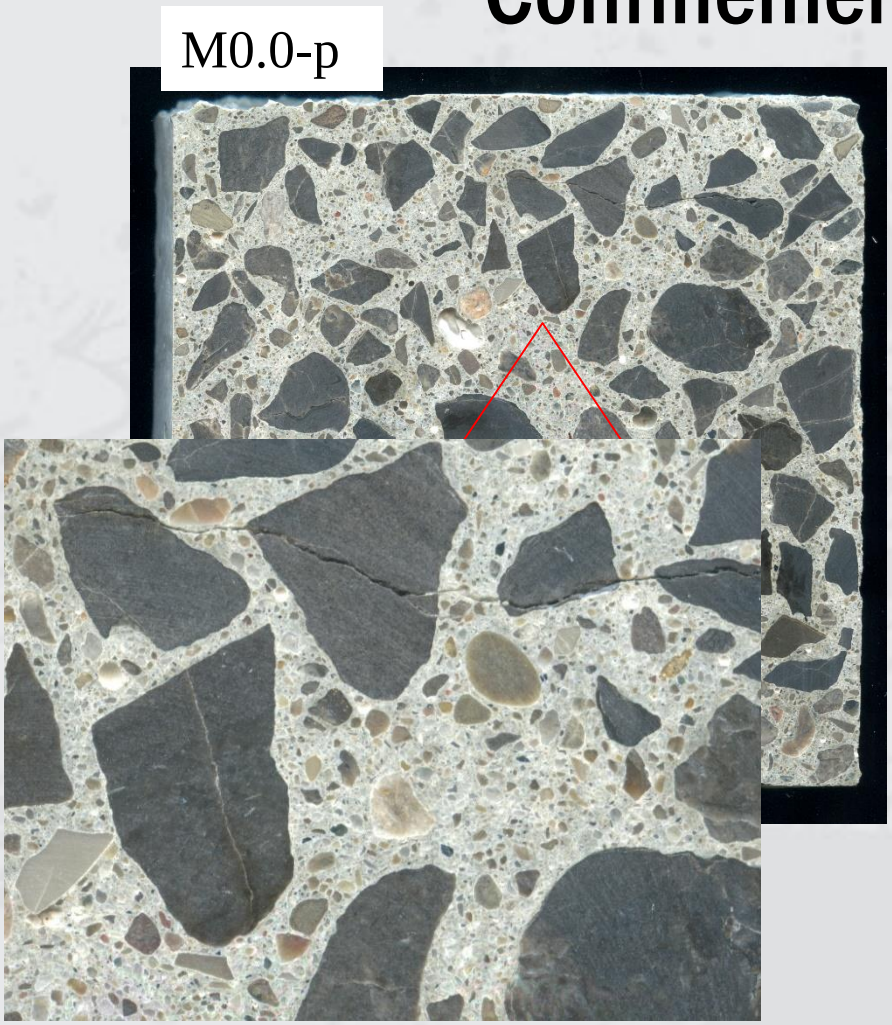


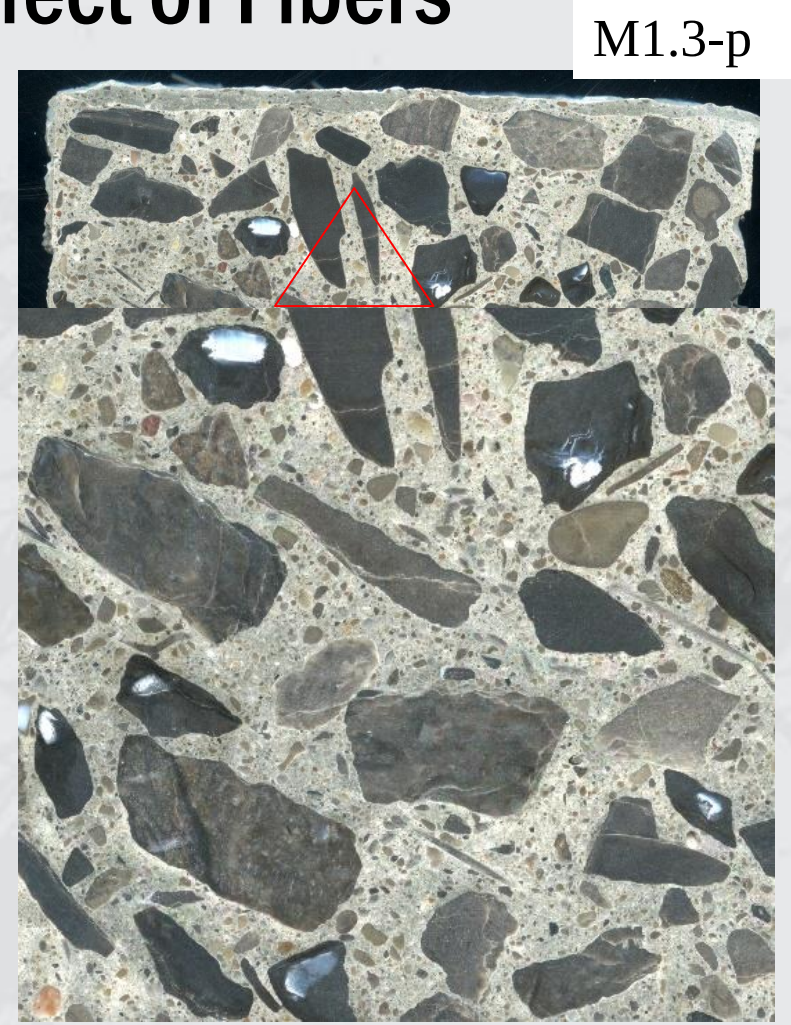
M0.0-r specimen (age 91 days)

M1.3-p specimen (91 days)



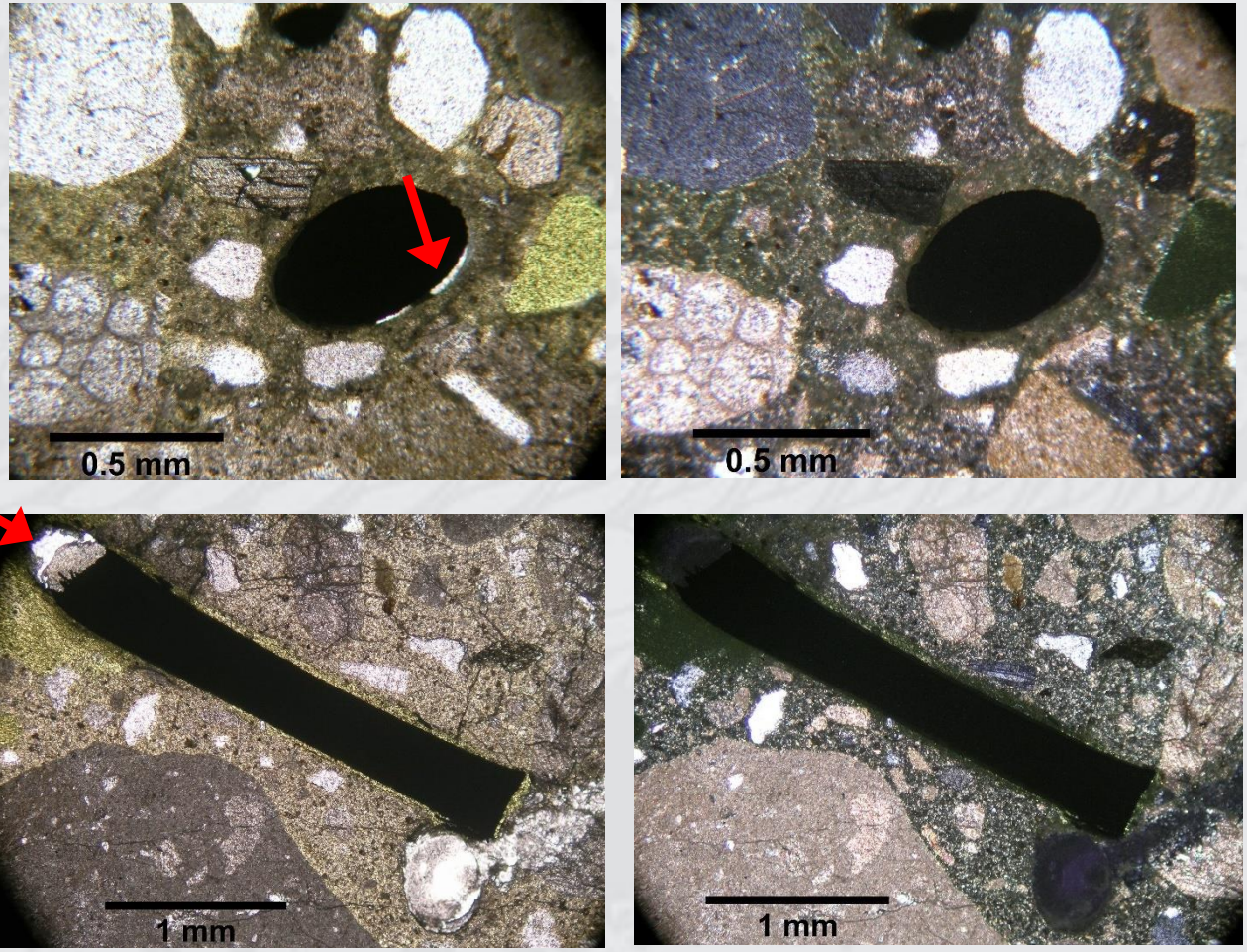
Confinement Effect of Fibers





- M0.0p: No restraint; cracks opened, extended to paste matrix and gel flowed to paste
- M1.3-p: Less cracking; gel confined at the source; less dispersion of gel into the paste matrix. 1.3% fiber volume fraction significantly reduced paste cracking.

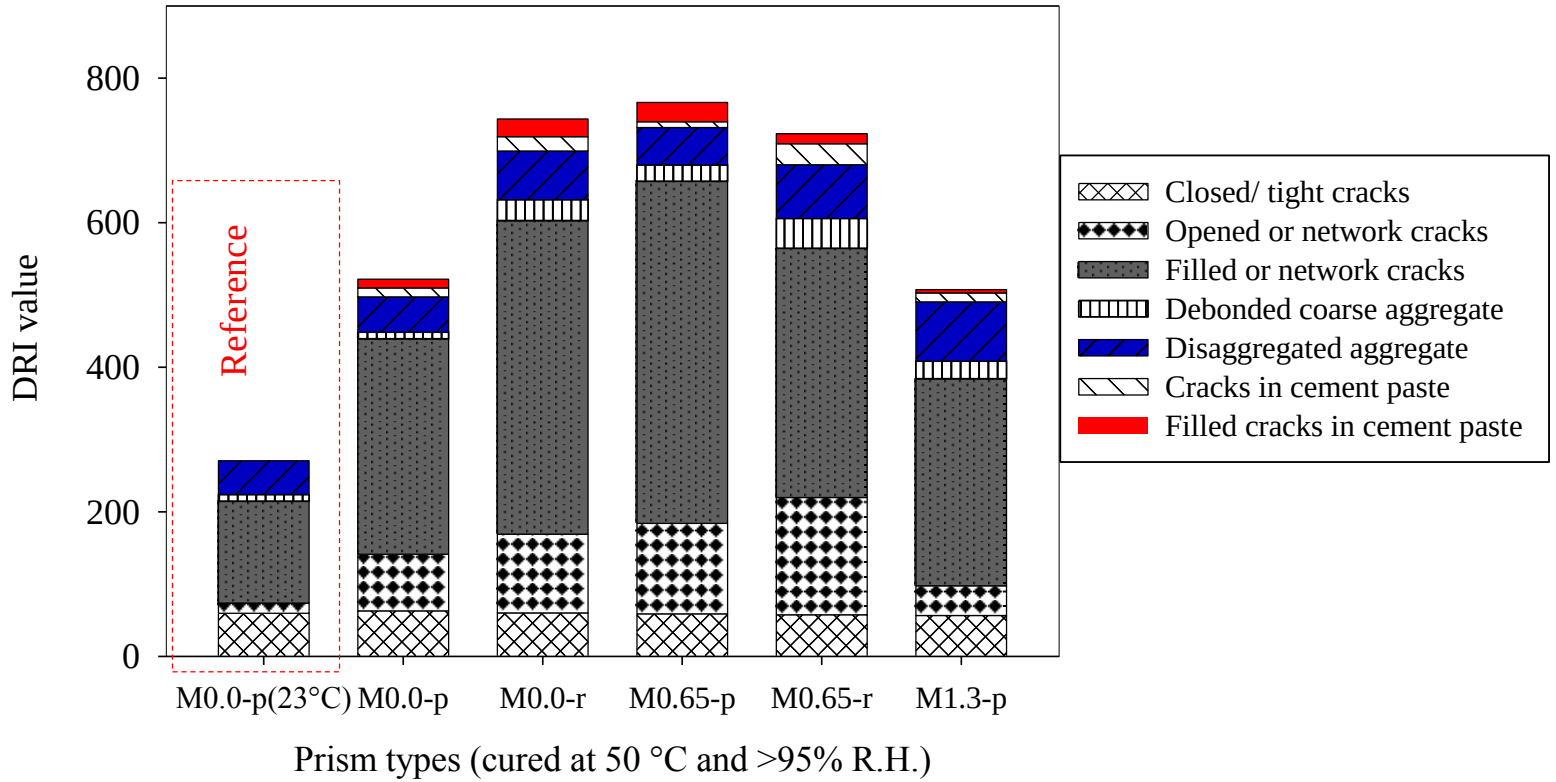
ASR Product Around Fibers



Plane polarized

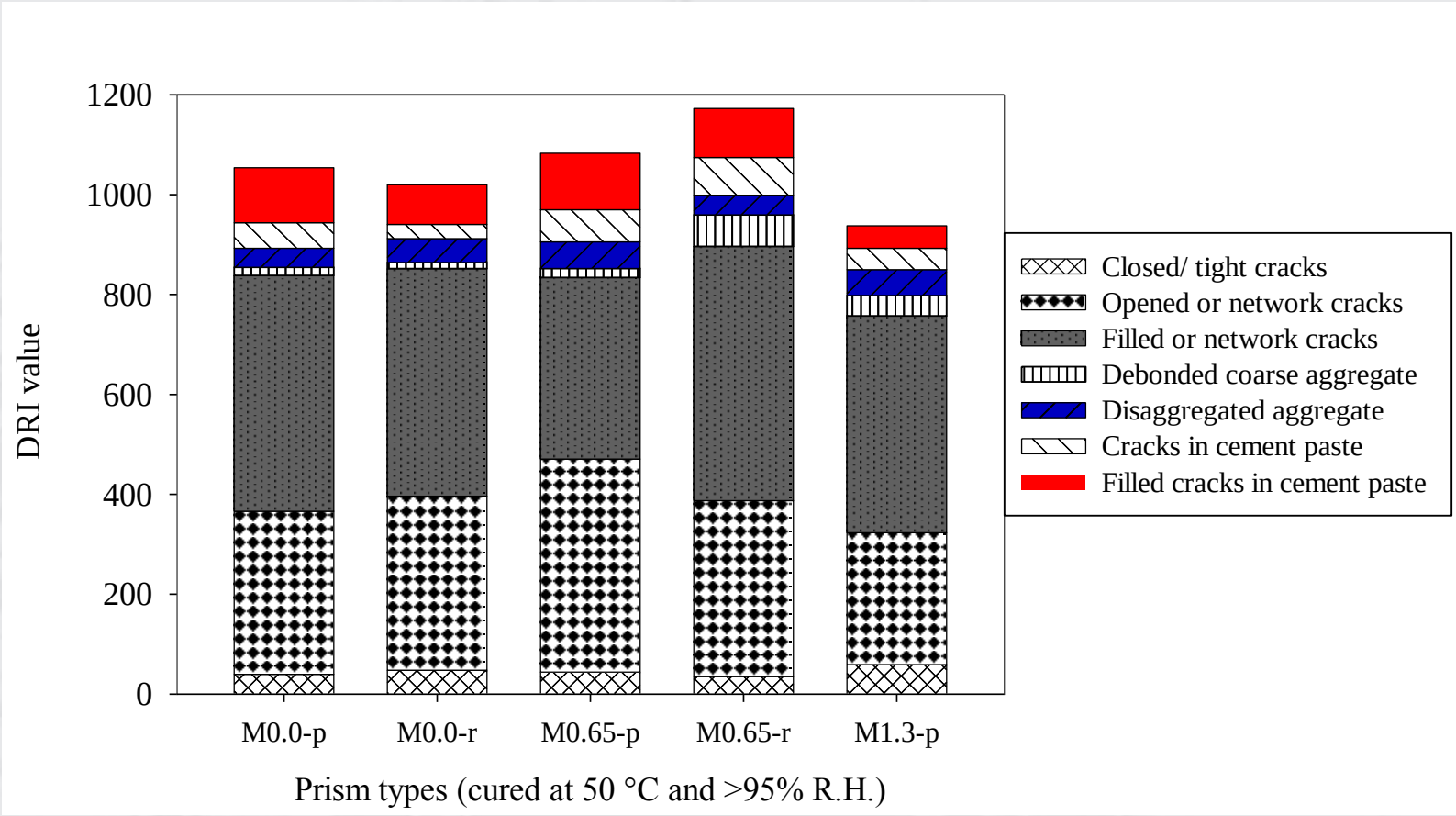
cross-polarized

DRI Analysis after 28 Days



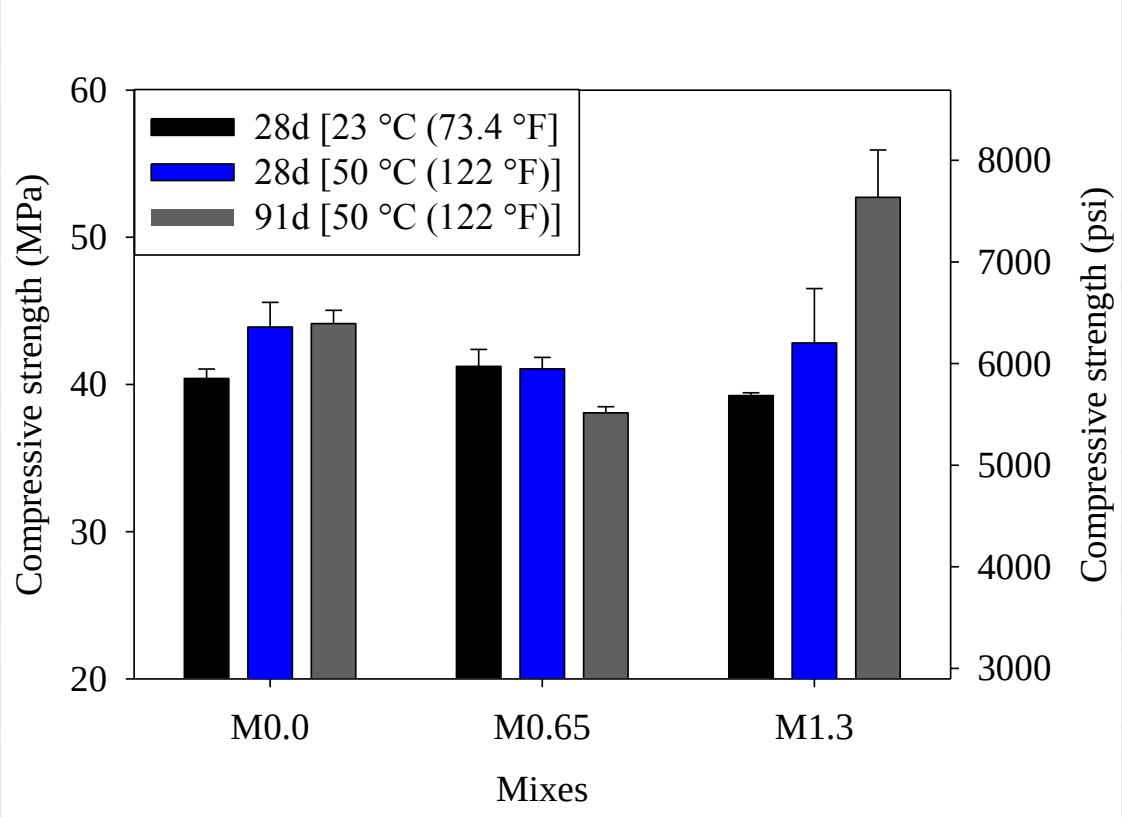
- DRI values for the specimens cured at 50 °C (122 °F) were significantly greater compared to the reference specimen.
- DRI value for the M1.3-p was the lowest of the five series.
- DRI of M-0.0-r, M0.65-p and M0.65-r (all with steel) was greater than of M0.0-p.
- Steel increased the anisotropy which must have caused greater number of cracks in M0.0-r, M0.65-p and M0.65-r.

DRI Analysis after 91 Days



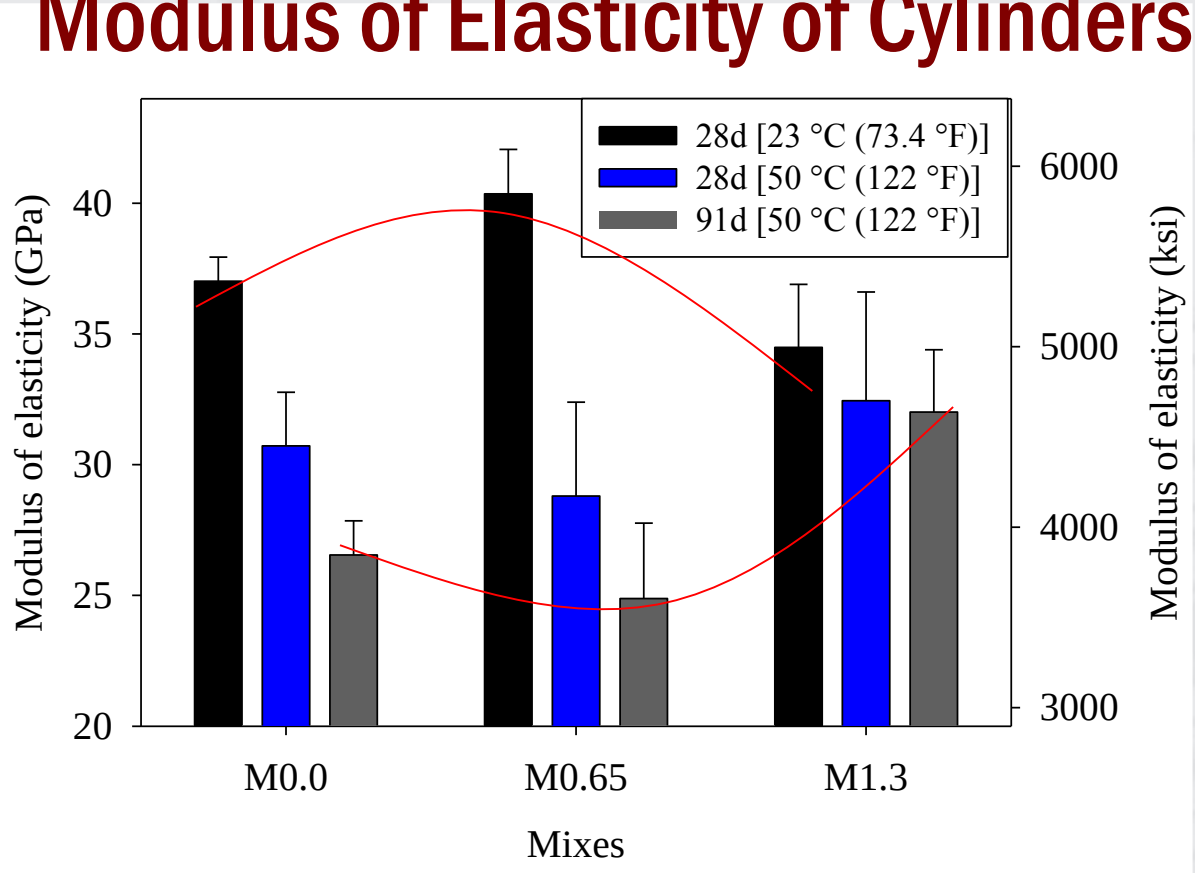
- M1.3-p showed less cracking compared to other four series; paste cracking is significantly reduced.
- M0.0-p (without steel) had relatively less cracking at 28 days but cracking increased at 91 days.
- No restraint = slower rate of cracking

Compressive Strength of Cylinders



- fc‘ increased with accelerated conditioning. fc’ increased significantly for M1.3 mix (by 34% of the 28d strength).
- This must have been due to the confinement of ASR product by densely distributed fibers:
  1) Fluid pressure sharing part of the compressive force
  2) Prestressing of concrete due to tension in the fibers due to ASR expansion

Modulus of Elasticity of Cylinders



- Ec decreased with accelerated curing. Max. degradation was 29% for M0.0 and 38% for M0.65.
- Only 9% degradation occurred in M1.3; this could be due to the stiffness of the fibers and the confinement of ASR products by the dense network of fibers.
- The "optimum" fiber content appears to be influenced by ASR: ~M0.65 for non-ASR; M1.3 for ASR concrete.

Modulus of Rupture

Mix	28d at 23 °C (73.4 °F)		28d at 50 °C (122 °F)		91 days at 50 °C (122 °F)	
	Mean [MPa (psi)]	St. deviation [MPa (psi)]	Mean [MPa (psi)]	St. deviation [MPa (psi)]	Mean [MPa (psi)]	St. deviation [MPa (psi)]
M0.0	6.52 (945)	0.57 (83)	4.66 (676)	0.17 (25)	4.07 (591)	0.33 (49)
M0.65	-	-	7.90 (1145)	1.59 (232)	5.49 (796)	0.26 (39)
M1.3	-	-	10.97 (1590)	0.00 (1)	8.23 (1193)	0.79 (116)

- ASR degradation in modulus of rupture from 28 to 91 days was 13%, 31% and 25%, respectively, for M0.0, M0.65 and M1.3 mixes.
- Modulus of rupture of M0.65 and M1.3 mixes was, respectively, 1.35 and 2.02 times that of M0.0 mix at 91 days.
- 1.3% fiber volume fraction completely offset the ASR degradation of modulus of rupture. Undoubtedly, fibers were useful to increase the flexural strength of ASR-affected concrete.

Conclusion

- DRI method can be used to investigate the cracking of fiber-reinforced ASR-affected concrete. DRI method was able to demonstrate the lowered paste cracking due to 1.3% fiber volume fraction.
- Fiber volume fraction of 1.3% was effective in reducing longitudinal expansion, paste cracking and degradation of modulus of elasticity, and in completely offsetting the ASR degradation of modulus of rupture.
- Fibers exhibited a tendency of optimum content in which 0.65% fiber volume fraction was not adequate to reduce ASR damage but 1.3% fiber volume fraction was effective in reducing ASR damage.
- Fibers provided confinement to the ASR product which resulted in less migration of the reaction product from the aggregate particles to the paste matrix.
- Many instances were observed in which the interface between fibers and paste matrix was filled with ASR products.

Acknowledgement

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Thank you