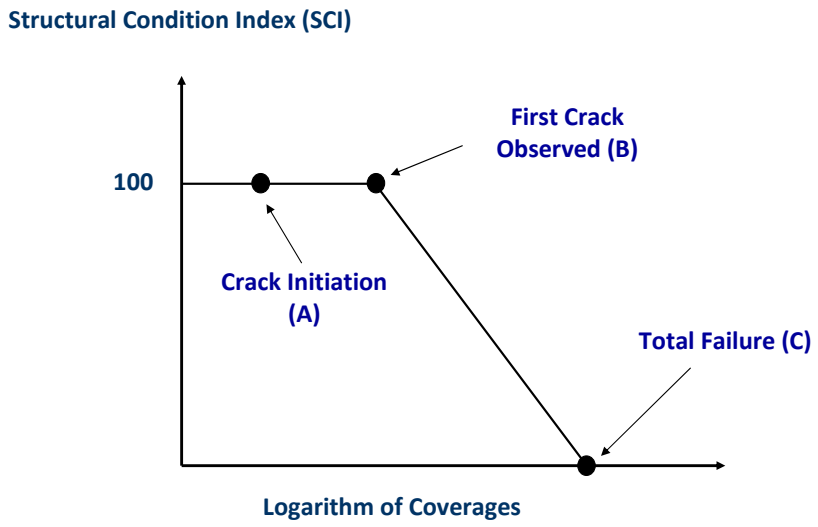
Fatigue and Fracture Characterization of CC6 Mixes

PENNSTATE

CC6 Objectives

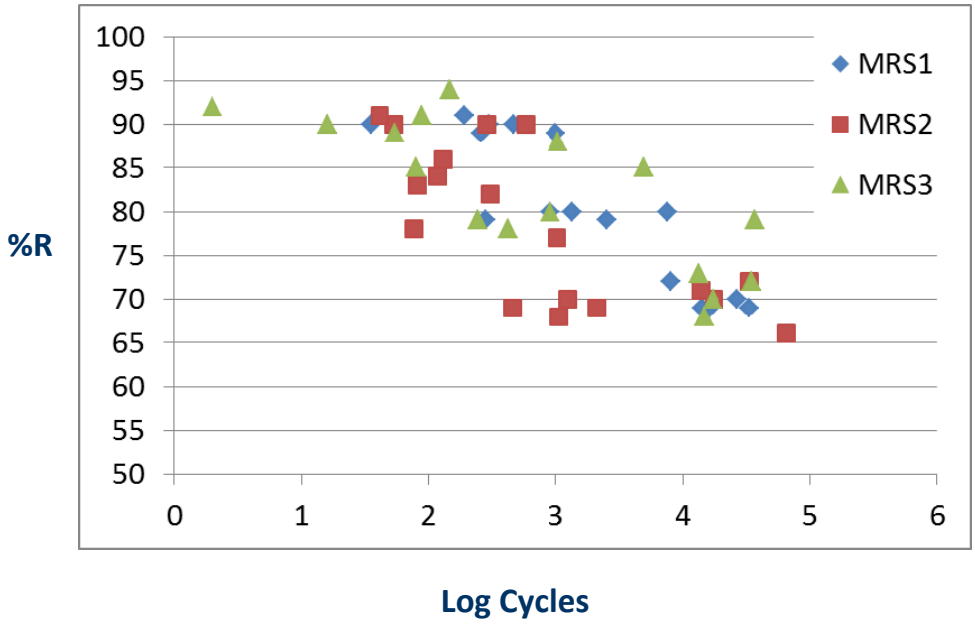
- **Investigate the relative effect of concrete strength on test item performance.**
  - Will concrete that is "too strong" perform poorly?
  - Is the current flexural strength limitation in AC 150/5320-6E justified by objective full-scale test data?
- **Investigate the effect of subbase material (cement stabilized vs. asphalt stabilized) on performance.**

Fatigue Characterization



Flexural Beam Fatigue Testing

- Initial testing of a limited number of cast beams at Penn State
- Remainder of fatigue testing conducted at NAPTF lab
- Beams sawn after full-scale loading completed


100
95
90
85
80
75
70
65
60
55
50
%R
0
1
2
3
4
5
6
Log Cycles
MRS1
MRS2
MRS3

Could material properties in addition to flexural strength improve the correlation to fatigue performance?

1N	2N	3N	4N*	5N	6N
20N	21N	22N	23N	24N	25N
1S	2S	3S	4S	5S	6S
20S	21S	22S*	23S	24S	25S

MRS1: Low-Strength Mix

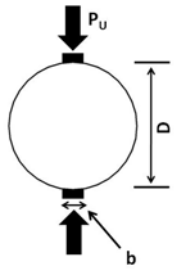
7N	8N	9N	10N	11N	12N	13N
26N	27N	28N	29N	30N	31N	32N
7S	8S	9S	10S	11S	12S	13S
26S	27S	28S	29S*	30S	31S*	32S

MRS2: Med-Strength Mix

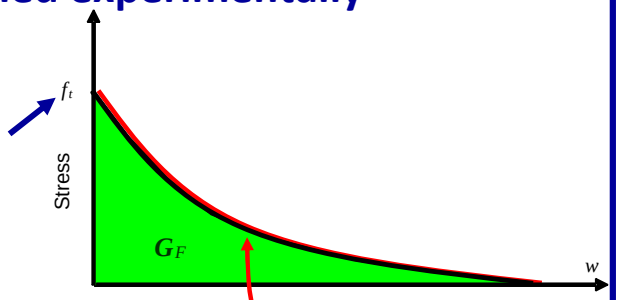
14N	15N*	16N	17N*	18N	19N
33N	34N	35N	36N	37N	38N
14S	15S	16S	17S	18S	19S
33S	34S	35S*	36S	37S	38S

MRS3: High-Strength Mix

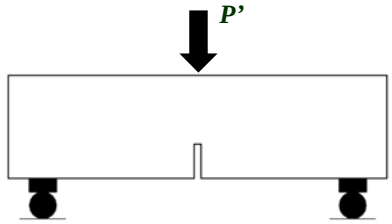
The fracture properties of concrete can be determined experimentally



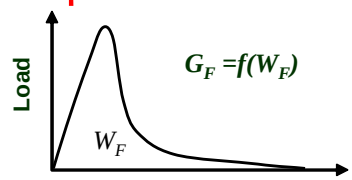
Splitting Tensile Test



Crack opening



Three Point Bending Test



Displacement

Split Tensile Test
- at the Beginning

Split Tensile Test
- at Conclusion

Splitting Tensile Test Results MRS1

Specimen ID	Test date	Length (mm)	Diameter (mm)	Bearing-strip width (mm)	b/D* (%)	Load (kN)	Tensile strength (MPa)
4N-1	04/04/13	304	146	12.9	8.84	170.98	2.45
4N-2	04/04/13	304	146	12.7	8.70	197.18	2.83
22S-1	04/04/13	301	146	12.9	8.84	162.75	2.36
22S-2	04/04/13	304	146	12.7	8.70	203.50	2.92

Average 2.64MPa (383 psi)

Splitting Tensile Test Results MRS2

Specimen ID	Test date	Length (mm)	Diameter (mm)	Bearing-strip width (mm)	b/D* (%)	Load (kN)	Tensile strength (MPa)
29S-1	3/18/2013	305	143	12.13	8.49	204.43	2.99
29S-2	3/18/2013	311	146	11.7	8.01	246.82	3.46
31S-1	3/18/2013	311	143	11.3	7.91	160.88	2.30
31S-2	3/18/2013	311	143	11.78	8.24	142.11	2.04

Average 2.70MPa (391 psi)

Splitting Tensile Test Results
MRS3

Specimen ID	Test date	Length (mm)	Diameter (mm)	Bearing-strip width (mm)	b/D* (%)	Load (kN)	Tensile strength (MPa)
15N-1	3/18/2013	311	143	12.13	8.49	179.65	2.57
15N-2	3/18/2013	311	143	11.75	8.22	223.69	3.20
17N-1	3/18/2013	298	143	11.7	8.19	275.06	4.11
17N-2	3/18/2013	298	143	11.75	8.22	176.85	2.64
35S-1	3/18/2013	305	143	11.78	8.24	221.2	3.23
35S-2	3/18/2013	305	143	11.2	7.84	284.85	4.16

Average 3.32MPa (481 psi)

Estimated Flexural Strength From Three Point Bending Test

$$MR^* = \frac{3PL}{2b(d-w)^2}$$

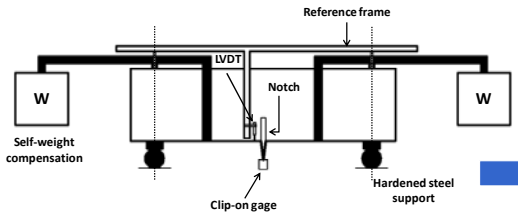
MR* = estimated modulus of rupture, MPa (psi)
P = maximum applied load, N (lbf)
L = span length, mm (in.)
b = average width of specimen, mm (in.)
d = average depth of specimen, mm (in.)
w = notch, mm (in.)

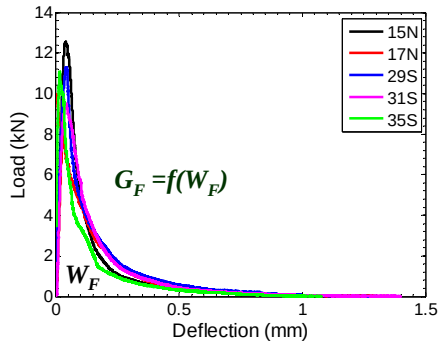
Estimated Flexural Strength From Three Point Bending Test

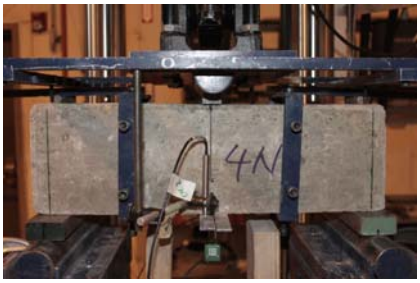
specimen ID	location	test date	specimen length (mm)	specimen width (mm)	specimen	notch (mm)	peak load (kN)	MR* (MPa)
15N-1	MRS3	1/11/2013	537	149	150	46	12.56	**6.28**
15N-2	MRS3	1/11/2013	530	156	148	47	12.24	**6.11**
17N-1	MRS3	1/18/2013	543	152	147	44	10.77	**5.44**
17N-2	MRS3	1/16/2013	527	146	149	45	12.78	**6.40**
35S-1	MRS3	1/10/2013	521	149	150	51	11.13	**5.96**
35S-2	MRS3	1/10/2013	518	146	150	46	12.34	**6.07**
29S-1	MRS2	1/12/2013	521	152	149	44	11.31	**5.27**
29S-2	MRS2	1/12/2013	527	156	144	44	10.96	**5.55**
31S-1	MRS2	1/14/2013	530	149	148	43	9.5	**4.60**
31S-2	MRS2	1/14/2013	533	151	152	48	8.62	**4.22**
4N-1	MRS1	4/2/2013	555	152	149	48	7.6	**4.08**
4N-2	MRS1	4/2/2013	552	152	149	48	9.39	**5.01**

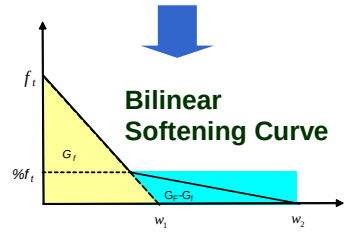
Estimated MR based on ASTM C293 with notch adjusted.

Closed-loop tests were used to determine the fracture energy









Bilinear Softening Curve

Three Point Bending Notched Specimens

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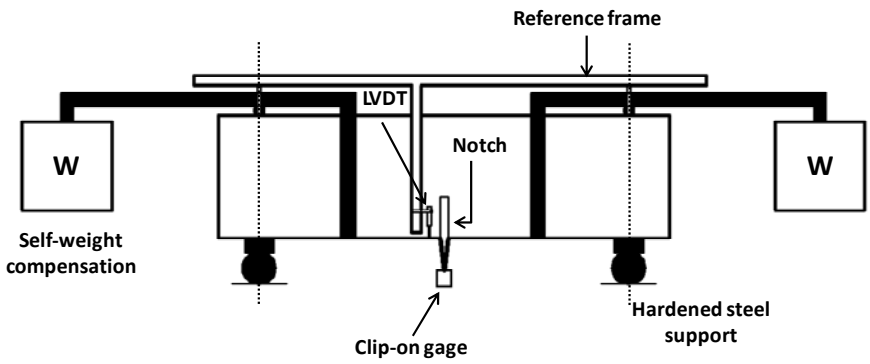
Fracture Testing

3-point bending tests of notched beams

- Protocol from American Concrete Institute, 2007
- Very similar to that used in Europe and published by RILEM
- All data recorded at 4 Hz
- Typical test durations were 210 minutes
- Peak load reached in less than 5 minutes

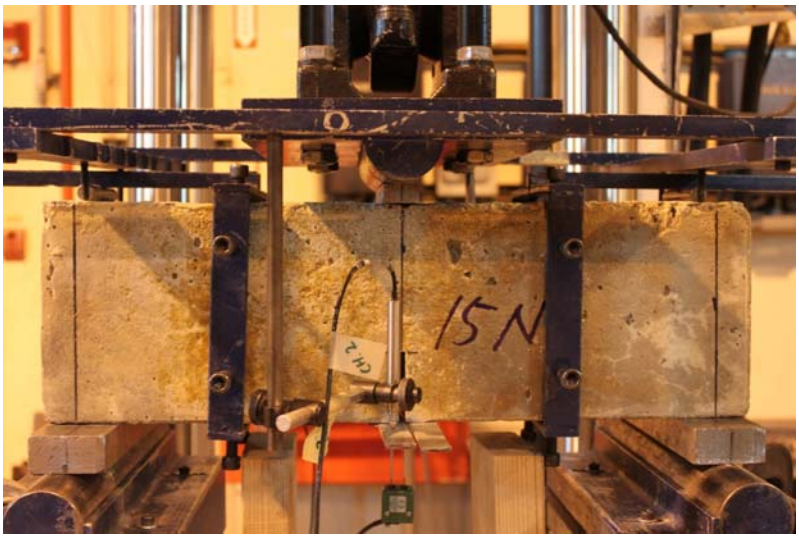
Three Point Bending Schematic



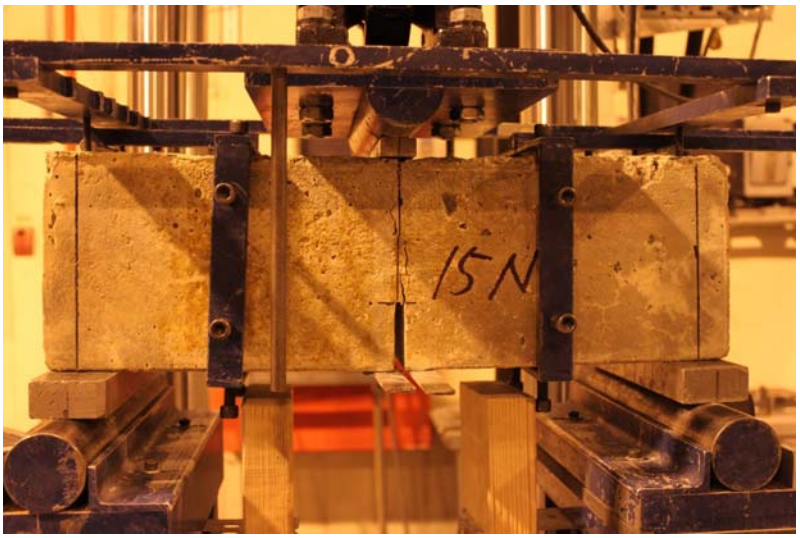
Three Point Bending Test
Controlled Variables

Closed-loop control used in three point bending test			
	Control variable	Rate	Ending point
Step 1	Load	0.5 kN/min	1 kN
Step 2	CMOD	0.01 mm/min	2 mm
Step 3	Displacement	0.1 mm/min	4 mm

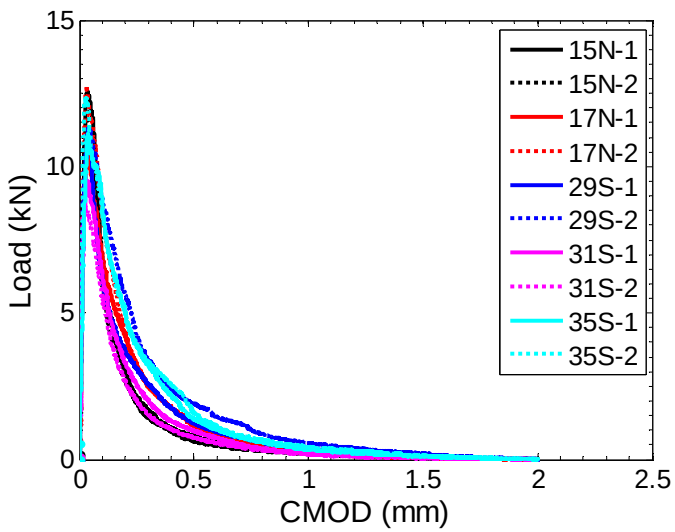
Three Point Bending Test
- at the Beginning



Three Point Bending Test
- at Conclusion



Three Point Bending Test
Load vs. CMOD



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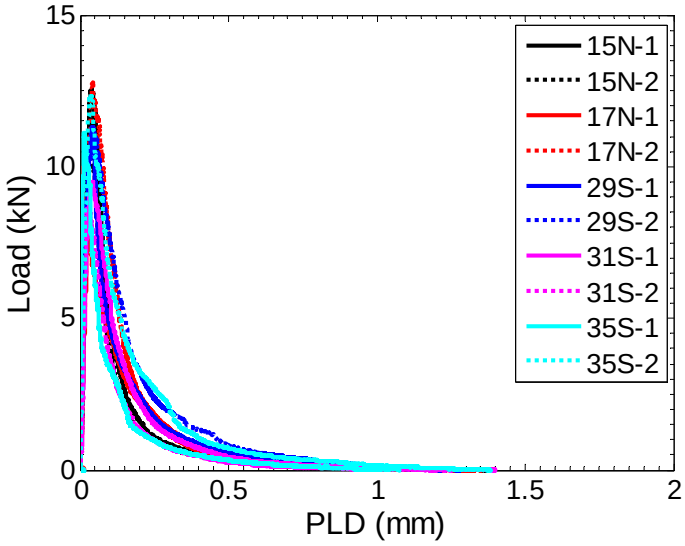
The experiment concludes when CMOD reaches 2mm. The linear part of curve can be used for elastic modulus determination.

Three Point Bending Test
Load vs. Plate Load Deflection



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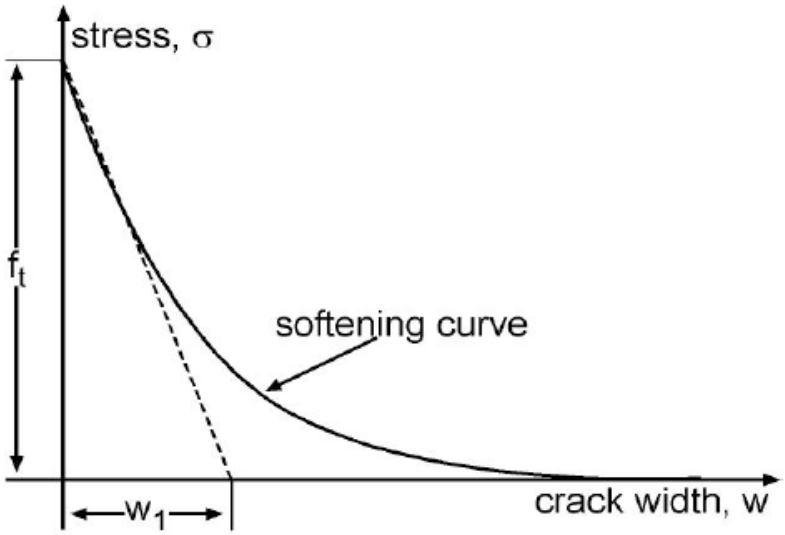
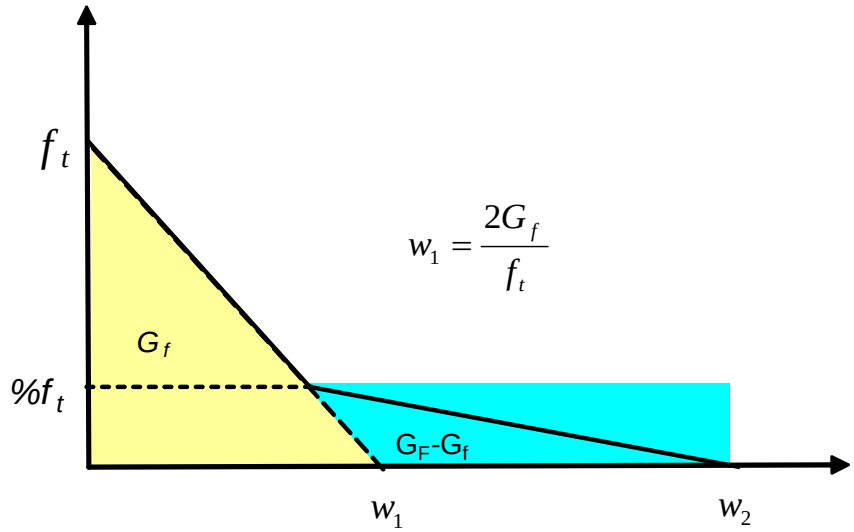
The area below the curve is fracture energy

Stress vs. Crack Opening Curve

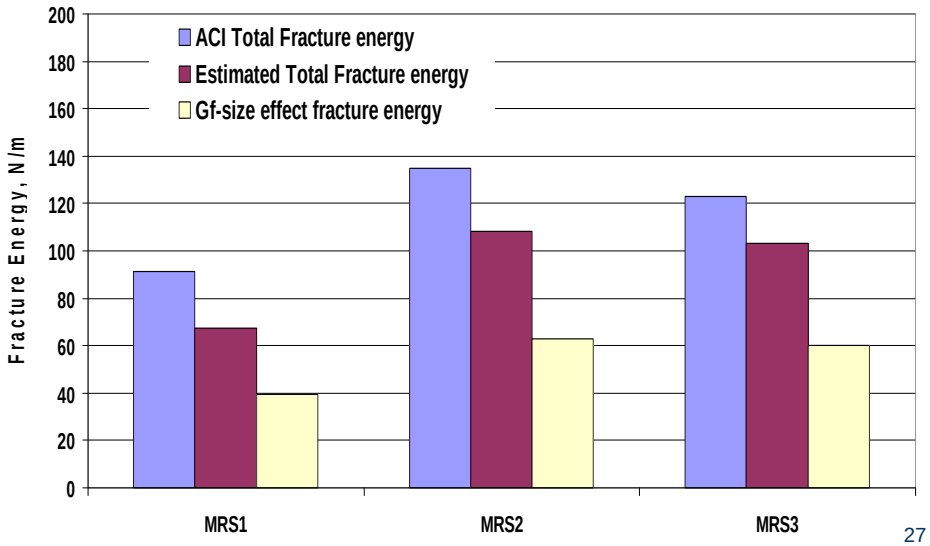



f_t
$w_1 = \frac{2G_f}{f_t}$
G_f
$\%f_t$
G_F-G_f
w_1
w_2

Fracture Energy by ACI Standard

Specimen ID	Location	Specimen length (mm)	Specimen width (mm)	Specimen	Notch (mm)	Peak load (kN)	Elastic modulus (GPa)	Fracture energy (N/m)
15N-1	MRS3	537	149	150	46	12.56	49.87	**128**
15N-2	MRS3	530	156	148	47	12.24	58.17	**95**
17N-1	MRS3	543	152	147	44	10.77	62.9	**101**
17N-2	MRS3	527	146	149	45	12.78	79.63	**131**
35S-1	MRS3	521	149	150	51	11.13	45.83	**104**
35S-2	MRS3	518	146	150	46	12.34	58.74	**178**
29S-1	MRS2	521	152	149	44	11.31	44.68	**138**
29S-2	MRS2	527	156	144	44	10.96	42.92	**205**
31S-1	MRS2	530	149	148	43	9.5	18.46	**112**
31S-2	MRS2	533	151	152	48	8.62	55.99	**85**
4N-1	MRS1	555	152	111	48	7.6	25.95	**92**
4N-2	MRS1	552	152	111	48	9.39	32.33	**119**
22S-1	Premature Failure probably due to low fracture energy							
22S-2	Premature Failure probably due to low fracture energy							

Fracture Energy Comparison



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Not statistically different; again, very very small n.

SUMMARY

- Additional fracture testing to be performed; about half the sawn beams remain
- Performance relationship completely confounded with flexural strength, since one mix at each strength level tested