Asphalt Mixture Cold Temperature Performance Using the Bending Beam Rheometer (BBR)

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Joe Schroer, PE
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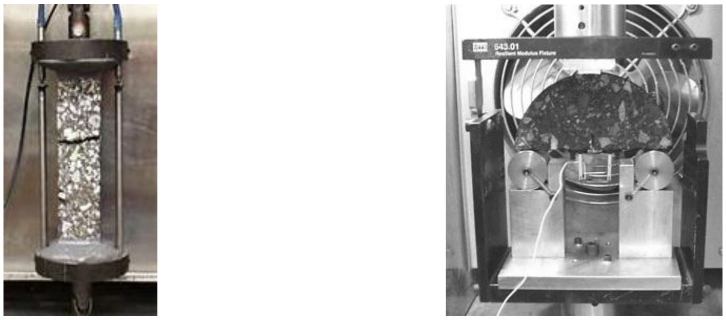
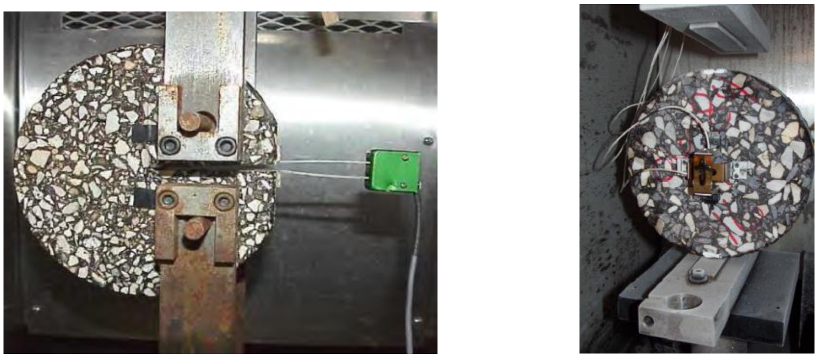
The use of recycled materials providing substitution of virgin binder in asphalt mixtures continues to increase. The current level of funding for highway construction is significantly less than 3 years ago and the level of competition between bidders is fierce. With the increased substitution of virgin binders, concern for cold weather performance of the mixtures has also increased. The binder in reclaimed asphalt pavement (RAP) is usually somewhat stiffer and the binder in reclaimed asphalt shingles (RAS) is remarkably stiffer than the virgin roadway binders. Extraction and recovery of the binders to determine the binder characteristics results in 100% blending of the binders, however, the actual amount of blending between the recycled and virgin binders in the mixtures is unknown. While estimates of the blended binder can be conjectured, it is believed that performance testing of the mixture is the best way to predict how the mixture will perform on the roadway. Cold temperature performance of the mixtures is not typically an evaluation made by MoDOT due to the complexity and cost for test equipment, preparation of test specimens and evaluation of the test results. However, one test was found that could be completed using the bending beam rheometer (BBR) currently in MoDOT's Central Laboratory.

As shown in Figure 1, several tests are available that require a low temperature environmental chamber capable of maintaining -28C. Tensile Strength Restrained Specimen Test (TSRST) restrains the ends of a square or cylindrical beam as it cools and records the temperature and tensile strength at which it breaks. Semicircular Bend Test (SCB) uses a 6 inch disk cut one-inch thick then cut in half with a notch at the radius point. The specimen is placed in a 3-point loading configuration with the mouth of the notch in tension. The crack mouth opening displacement (CMOD) is monitored at a constant rate. At failure, the peak load and fracture energy are computed. Disk-shaped Compact Tension Test (DC(T)) uses a 6 inch disk cut with a thickness approximately 4 times the nominal maximum aggregate size or the same as the lift thickness of the mixture placed on the roadway. Approximately ¼ inch is cut from one side with a notch cut at the center of the face and one inch diameter holes drilled on either side of the notch. The notch is pulled apart at a controlled CMOD rate where the peak load and fracture energy are computed as in the SCB. The other method is the more standard Indirect Tensile Strength (IDT) that uses a 1 ½ to 2 inch thick specimen that is axially loaded. Creep compliance curves for the mixtures are constructed which are inputs for the Mechanistic-Empirical Pavement Design Guide (MEPDG) for cold temperature cracking. Aside from the need of an environmental chamber for these tests, each one has had reports of trouble with uniform specimen fabrication and handling, strain rates, instrumentation and controls. There appears to be no consensus from experts in the field on a definitive cold temperature test for routine testing of mixtures.



TSRST SCB



DC(T) IDT

Figure 1

The University of Minnesota developed a method to test mixture beams in the BBR through NCHRP IDEA Project 133. Figure 2 shows the BBR loading frame outside the fluid bath and Figure 3 shows a typical mixture beam. Originally the beams were tested at 4413 millinewtons (mN) or 450 g, the maximum loading for the BBR. Later versions of the test method the load was changed to 4000 mN (407 g) as a round number slightly less than the maximum load. The properties obtained from this test are creep stiffness and m-value. M-value is the rate of change in creep stiffness over time. The MEPDG input for cold temperature cracking is creep compliance. Creep compliance may be determined by the inverse of stiffness obtained by the BBR. Higher compliance values indicate more compliance or resistance to cold temperature cracking. The UMn study compared BBR compliance with that from the IDT and found they compare reasonably well.

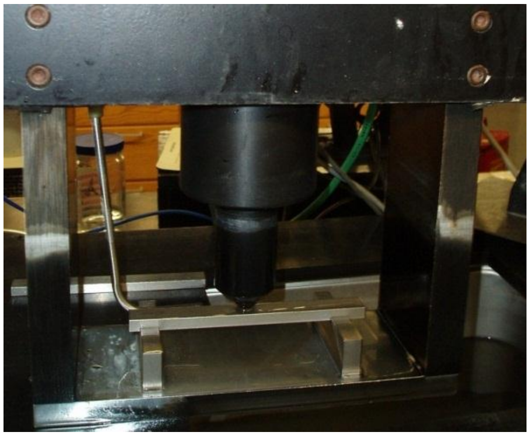


Figure 2

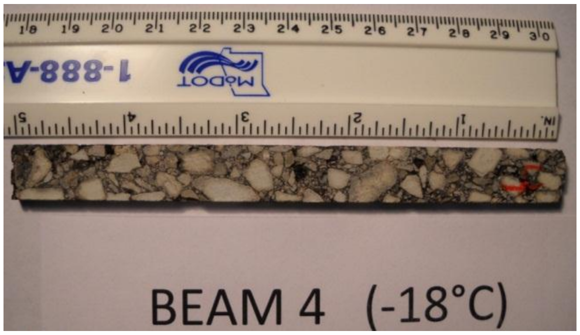


Figure 3

Testing beams in the BBR is familiar to MoDOT's Chemical Laboratory chemists and requires only changing the BBR test load. Using beams with the same dimensions and temperatures (10C above the low grade temperature) as when testing binders, beams were tested with a load of 4413 mN or roughly four times the binder beam loading. Through additional study by the Utah Department of Transportation, preliminary target values were set for m-value and creep stiffness. As demonstrated through their efforts, the test can be used to discriminate between anticipated performances of mixtures.

In order to validate the test method for Missouri mixtures, specimens compacted but not used for AASHTO T 283 (TSR) testing were gathered in the laboratory. Three specimens were also taken from mixture verification testing and six mixtures were collected specifically for performance testing in the Asphalt Mixture Performance Tester (AMPT.) It is interesting to note that only one mixture, which was chosen because it contained ground tire rubber (GTR,) did not contain either RAP or RAS. The mixtures could be tested at the low grading temperature, -12C or -22 plus 10C, but to examine the mixtures over a range of temperature, they were tested -6C, -12C and -18C.

Specimen fabrication was the biggest hurdle encountered. Dimension uniformity and meeting the tolerances of the test method were difficult. The Utah study recommended a tolerance of 0.25 mm which was found attainable. A masonry wet saw was needed to make the initial cuts on the 6 inch specimens because of they were too large for the tile saw but the final cut was made with a tile saw to reduce raveling of the edges and produce a more even cut. Additional efforts need to be made for a jig to securely hold the specimens while cutting in different orientations. Five beams were tested at each temperature.

Suggested target values for m-value and stiffness by Utah are a minimum of 0.12 and maximum of 15,000 MPa, respectively. As shown in Table 1, 7 of the 17 mixtures tested were over the minimum m-value and all were under the maximum stiffness, therefore 7 would pass for -22C grading. The m-value could not be anticipated entirely by mixture type or virgin binder grade. Various mixture properties such as PG grade, total binder content, effective binder content and virgin binder to total binder ratio were examined.

There were no clear trends observed to segregate the mixtures in this study other than looking at the mixtures individually. Mixture SP125 10-117 contained PG 58-28 which had the second highest m-value. While Mixture BP11-66 contained PG 58-22 (the true grading was -27.5C), the virgin binder ratio was 52% which was the lowest ratio of any mixtures tested. This mixture is also an example of why the virgin binder ratio was changed to be calculated with effective virgin binder and we no longer allow an availability factor for RAS to be used. Some variability was identified in the Utah study by fluctuations in plant production temperatures. This may explain why Mixtures SP125 09-120 and SP125 10-45 (produced as warm mix) had similar results with different binder constituents. Mixture SP125 11-13 contained 10% GTR and no RAP. Since that mixture was placed, more emphasis has been placed on the GTR modified mixtures in regard to the m-value of the binder prior to modification. The GTR absorbs some of the lighter compounds in the asphalt lowering the m-value slightly after blending. A binder with an m-value in excess of 0.320 is frequently needed for this modification. Additional mixture characteristics are shown in the Appendix.

Table 1

Cold Temperature Performance Experimental BBR Method			
		@ -12C, 60 sec.	
Mixture	Binder Performance Grade	m-value	Stiffness (MPa)
BP11-66	58-22	0.079	9576
SP095 11-24	70-22	0.121	11720
SP095 11-71	70-22	0.122	10538
SP125 09-120	64-22	0.122	11716
SP125 10-117	58-28	0.138	6898
SP125 10-45	70-22	0.125	10372
SP125 11-11	70-22	0.107	9526
SP125 11-13	64-22	0.111	6720
SP125 11-14	70-22	0.126	11580
SP125 11-34	64-22	0.082	7528
SP125 11-37	64-22	0.080	8424
SP190 10-25	64-22	0.109	7386
SP190 11-32	64-22	0.072	7930
SP190 11-33	64-22	0.090	7822
SP190 11-72	70-22	0.108	9480
SP250 11-26	64-22	0.142	9366
SP250 11-41	64-22	0.106	7950

In an attempt to find a property that would set the mixtures apart, the dry appearance of some of the mixtures was recalled. When RAP was first introduced into mixtures, NCHRP Report No. 452 was used for guidance. A method to estimate the aggregate bulk specific gravity (G_{sb}) was suggested by calculating the effective specific gravity (G_{se}) from the maximum theoretical specific gravity (G_{mm}) of the mixture. This results in a slightly inflated value for G_{sb} in some cases and it may be greatly exaggerated in others. While this is adequate for less than 20% RAP in the mixture, it can lead to an inflated value for the mixture VMA when higher amounts of RAP are incorporated. The G_{sb} of the virgin aggregate was compared to the G_{se} of the RAP aggregate. The plot of the G_{sb} difference vs. m-value didn't show much of a correlation (Figure 4). The mixtures mixed in the laboratory didn't seem to be consistent with the plant mixed mixtures. These were removed from the data along with the mixture with PG 58-28. The correlation now appeared to be good using the virgin/RAP difference as can be seen in Figure 5. An R-squared value of 0.66 indicates a moderately good correlation of the data. Removing the same mixtures from the data did not appear to change the correlation in the other properties as discussed earlier. Based on this, the VMA was recalculated with the virgin aggregate G_{sb} for the mixtures with the highest difference which happened to be from the US 50 project comparing mixtures with different binders and additives. The average drop in VMA due to the G_{sb} difference is about 1%. Typically, a 1% increase in VMA will result in a 0.3 to 0.4% increase in the binder content. An increase in the virgin binder content of the US 50 mixtures would mitigate some of the cold temperature susceptibility that the RAP and RAS binders introduced.

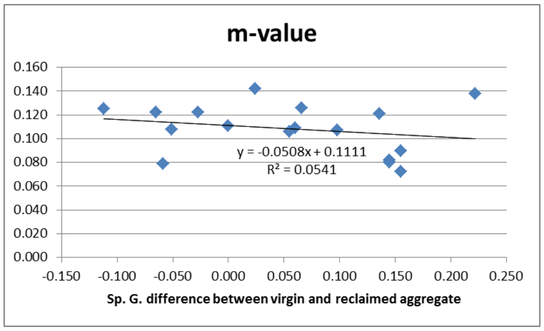


Figure 4

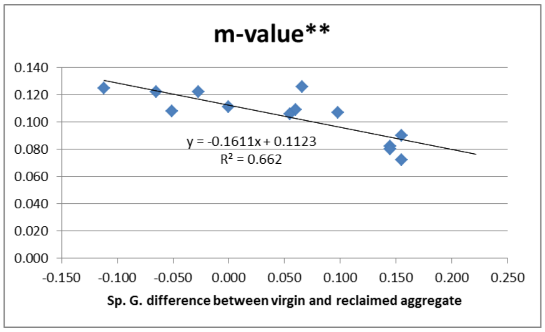


Figure 5

Another mixture parameter provided by the BBR data is creep compliance. Creep compliance is calculated from the inverse of creep stiffness. Higher creep compliance is an indicator of resistance to cracking. Creep compliance curves can then be input into the MEPDG. A comparison of the US 50 mixtures is shown in Figure 6. These represent PG 64-22 Grade H and mixtures with PG 64-22 with hydrated lime and shingles. All mixtures contain RAP. It is interesting to note the RAS mixtures have the largest creep compliance values. For comparison, the high and low values from a 2008 MoDOT study on creep compliance are shown as "IDT Study." The data for the study was performed at -10C and the creep compliance values are calculated to match the time intervals of the BBR data. It is unknown whether the difference is in the test method or an actual difference in the mixtures.

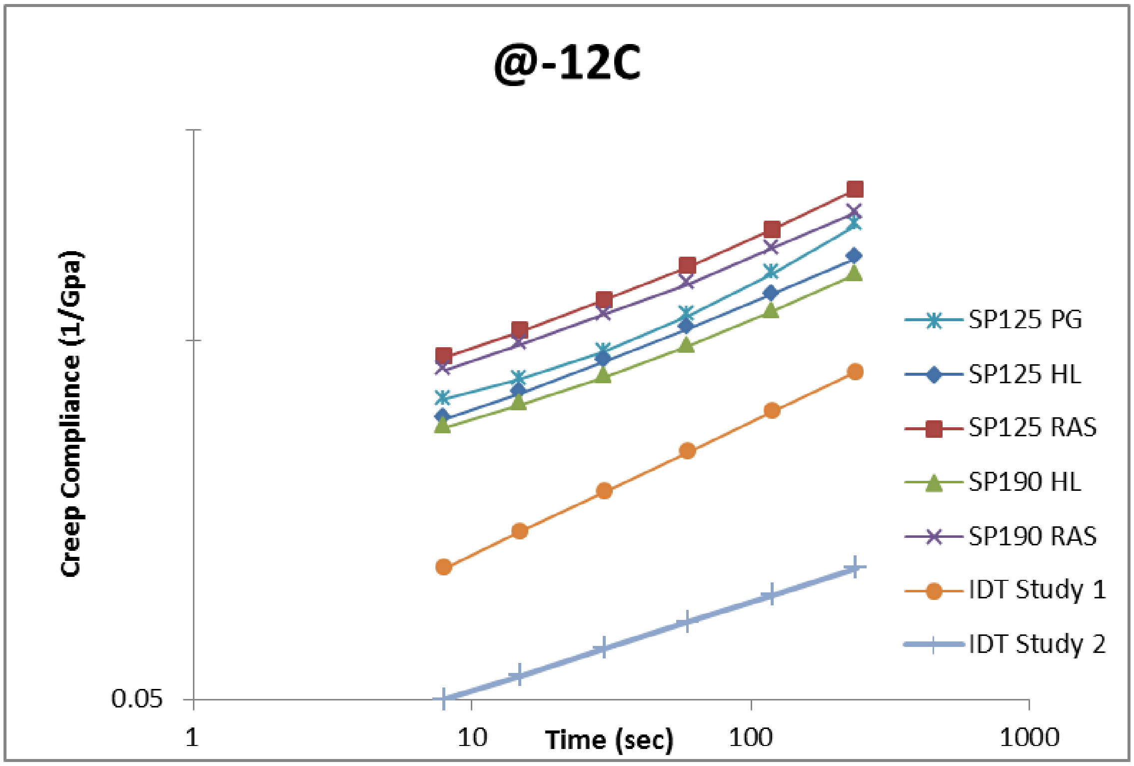


Figure 6

It appears mixture testing with the BBR is viable for ranking mixtures by their predicted cold temperature characteristics. Cold temperature evaluations of surface mixtures are a key component of the mix design process that has been missing. While variability of beams in individual mixtures seemed to be excessive, removing a few obvious outliers resulted in consistent trends in the data. This should be reduced by having a more secure means to hold specimens while cutting. It was no surprise to find that having a temperature compliant binder is important. This study highlighted that for mixtures to be resistant to cold temperature cracking the volume of binder is equally important.

Recommendations from this study are as follows:

1. Evaluate these mixtures in the field to see if thermal cracking resistance is consistent with the test results.
2. Compare aged specimens with field conditions by collecting samples from projects performing well and performing poorly after 3 to 5 years in service.
3. Use G_{sb} of virgin aggregate for RAP in lieu of G_{se} unless other compelling data can be supplied, i.e. design data for RAP mixture when placed.
4. Consider adopting NCAT recommendation of increasing virgin asphalt content 0.1% for every 10% RAP binder in mixture or use PG XX-28 binders in mixtures. This could be modified for RAS by adding 0.1 % for every 2% RAS.

References

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Romero, P., Ho, C., VanFrank, K. *Development of Methods to Control Cold Temperature and Fatigue Cracking for Asphalt Mixtures.* Utah Department of Transportation, May, 2011.

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APPENDIX

			@-12C, 60 sec.								
ID	**Mix ID**	**Pbev/Pb**	**m-value**	**s**	**RAP**	**RAS**	**GTR**	**PG**	**SPECIAL**	**Binder**	**Sampled From**
112RJH010	SP125 10-117	65%	0.138	6898	17	3		58-28		ConocoPhillips, KC	Plant Sample from TSR specimens.
117ERL049	SP125 11-13	100%	0.111	6720			10	64-22	GTR	Coastal	Plant Sample from TSR specimens.
117LJK062	SP250 11-41	68%	0.106	7950	16	3		64-22	LG	APAC, Daystar	Plant Sample from TSR specimens.
116B3B109	SP125 09-120	69%	0.122	11716	17	3		64-22	LP Mix, WMA	ConocoPhillips	Plant Sample from TSR specimens.
116J6C060	SP125 11-14	91%	0.126	11580	10			70-22	LP Mix	ConocoPhillips	Plant Sample from TSR specimens.
114GTS082	SP190 10-25	81%	0.109	7386	20			64-22	LG	ConocoPhillips, KC	Plant Sample from TSR specimens.
119DWM047	SP095 11-71	87%	0.122	10538	15			70-22	LG	Coastal	Plant Sample from TSR specimens.
119DWM041	SP190 11-72	89%	0.108	9480	10			70-22	LG	Coastal	Plant Sample from TSR specimens.
	SP095 11-24	76%	0.121	11720	27			70-22	LG	ConocoPhillips, KC	Mix Design Verification.
	BP11-66	52%	0.079	9576	27	3		58-22	50 Gyration, WMA	ConocoPhillips	Mix Design Verification.
	SP250 11-26	75%	0.142	9366		5		64-22	LG	Coastal	Mix Design Verification.
10MFO0017	SP125 10-45	61%	0.125	10372	10	5		70-22	LP Mix,WMA	ConocoPhillips	Rte. 47, Franklin RAS and PG 70-22.
11MFO0035	SP125 11-11	72%	0.107	9526	28			70-22	LG	ConocoPhillips, KC	US 50, Morgan/Pettis PG, Hydrated Lime and RAS
11MFO0042	SP190 11-33	67%	0.090	7822	18	3		64-22	LG	ConocoPhillips, KC	US 50, Morgan/Pettis PG, Hydrated Lime and RAS
11MFO0044	SP190 11-32	74%	0.072	7930	25			64-22	LG - 1% HL	ConocoPhillips, KC	US 50, Morgan/Pettis PG, Hydrated Lime and RAS
11MFO0046	SP125 11-34	68%	0.082	7528	20	3		64-22	LG	ConocoPhillips, KC	US 50, Morgan/Pettis PG, Hydrated Lime and RAS
11MFO0052	SP125 11-37	74%	0.080	8424	28			64-22	LG - 1% HL	ConocoPhillips, KC	US 50, Morgan/Pettis PG, Hydrated Lime and RAS

Report No. UT-10.08 Development of Methods to Control Cold Temperature and Fatigue Cracking for Asphalt Mixtures, Appendix A - Determine sample average, x, and standard deviation, σ. If $\sigma > 15\%\ x$, then determine outlier. Outlier is 2 σ from mean.

	SP095 11-24				PG 70-22	27% RAP	
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
G	0.151	n	0.152	0.010	0.023	0.172	6.22
L	0.160	n				0.132	6.33
M	0.138	n					6.22
O	0.162	n					6.27
X	0.151	n					6.09
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
G	11400	n	9198	1289	1380	11776	12.14
L	8860	n				6620	12.63
M	9170	n					12.55
O	8270	n					12.10
X	8290	n					12.13
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
F	0.129	n	0.121	0.022	0.018	0.165	6.45
K	0.127	n				0.077	6.36
N	0.123	n					6.38
T	0.142	n					6.43
Y	0.084	n					6.47
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
F	11900	n	11720	773	1758	13266	12.09
K	11800	n				10174	12.73
N	12400	n					12.82
T	12100	n					12.09
Y	10400	n					12.05
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
A	0.104	n	0.072	0.020	0.011	0.112	6.26
B	0.049	n				0.032	6.26
C	0.070	n					6.63
E	0.062	n					6.31
J	0.076	n					6.34
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
A	14100	n	13200	980	1980	15160	12.43
B	13100	n				11240	12.04
C	14300	n					12.10
E	12300	n					12.47
J	12200	n					12.45

	SP125 10-45				PG 70-22	10% RAP	5% RAS
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
4	0.166	n	0.157	0.008	0.024	0.173	6.67
11	0.154	n				0.141	6.35
13	0.159	n					6.43
24	0.145	n					6.58
26	0.160	n					6.27
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
4	8610	n	8194	1360	1229	10914	13.04
11	8190	n				5474	12.86
13	8360	n					13.05
24	9780	n					13.08
26	6030	n					12.90
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
10	0.125	n	0.1252	0.010	0.019	0.145	6.21
12	0.121	n				0.105	6.33
21	0.111	n					6.36
22	0.132	n					6.38
28	0.137	n					6.30
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
10	7780	n	10366	2342	1554.9	15050	12.90
12	9020	n				5682	12.36
21	12200	n					12.86
22	9430	n					12.13
28	13400	n					12.05
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
2	0.106	n	0.095	0.009	0.014	0.113	6.47
5	0.085	n				0.077	6.30
6	0.098	n					6.56
7	0.098	n					6.42
16	0.087	n					6.51
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
2	13700	n	11556	1412	1733	14380	12.94
5	11900	n				8732	12.93
6	10900	n					12.87
7	9880	n					12.97
16	11400	n					13.07

	SP125 09-120				PG 64-22	17% RAP	3% RAS
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
32	0.180	n	0.189	0.006	0.028	0.201	6.68
35	0.185	n				0.177	6.18
38	0.192	n					6.55
41	0.192	n					6.49
48	0.196	n					6.26
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
32	8480.0	n	8250	1306	1238	10862	12.79
35	8220.0	n				5638	12.94
38	7000.0	n					12.79
41	10300.0	n					12.99
48	7250.0	n					12.23
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
31	0.145	n	0.122	0.028	0.018	0.178	6.30
34	0.135	n				0.066	6.54
37	0.101	n					5.92
40	0.083	n					6.69
46	0.145	n					6.28
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
31	15000.0	n	11646	3137	1746.9	17920	12.05
34	13600.0	n				5372	12.95
37	7940.0	n					12.46
40	8690.0	n					12.79
46	13000.0	n					12.95
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
30	0.055	n	0.072	0.012	0.011	0.096	6.51
33	0.073	n				0.048	6.45
36	0.070	n					6.40
39	0.088	n					5.62
43	0.076	n					6.71
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
30	8380	n	10520	1640	1578	13800	12.84
33	9720	n				7240	12.31
36	10600	n					12.95
39	11100	n					12.21
43	12800	n					13.02

	SP125 11-14				PG 70-22	10% RAP	
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
51	0.164	n	0.173	0.029	0.026	0.231	6.38
54	0.194	n				0.115	6.36
58	0.191	n					6.36
64	0.126	n					6.48
71	0.189	n					6.48
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
51	8740.0	n	7524	1949	1129	11422	12.44
54	7370.0	n				3626	12.65
58	7550.0	n					12.65
64	4420.0	n					12.55
71	9540.0	n					12.44
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
53	0.128	n	0.1262	0.013	0.019	0.152	6.43
57	0.121	n				0.100	6.56
60	0.146	n					6.40
63	0.111	n					6.39
68	0.125	n					6.25
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
53	12000.0	n	11580	736	1737	13052	12.58
57	10300.0	n				10108	12.47
60	11600.0	n					12.41
63	12000.0	n					12.38
68	12000.0	n					12.81
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
49	0.061	n	0.078	0.014	0.012	0.106	6.40
52	0.069	n				0.050	6.31
59	0.077	n					6.49
62	0.093	n					6.37
70	0.092	n					6.41
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
49	8060	n	11232	2107	1685	15446	12.68
52	10200	n				7018	12.21
59	12100	n					12.40
62	12500	n					12.33
70	13300	n					12.72

	SP190 10-25				PG 64-22	17% RAP	3% RAS
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1A	0.164	n	0.151	0.024	0.023	0.199	6.24
2A	0.136	n				0.103	6.67
3A	0.115	n					6.68
4A	0.171	n					6.85
5A	0.167	n					6.59
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1A	6670.0	n	6268	867	940	8002	12.71
2A	5780.0	n				4534	12.63
3A	5090.0	n					12.76
4A	6440.0	n					12.77
5A	7360.0	n					12.63
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6A	0.129	n	0.109	0.014	0.016	0.137	6.51
7A	0.091	n				0.081	6.15
8A	0.103	n					6.70
9A	0.109	n					7.01
10A	0.111	n					6.20
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6A	7320.0	n	7386	1586	1107.9	10558	12.77
7A	5460.0	n				4214	12.84
8A	6470.0	n					12.71
9A	8040.0	n					12.73
10A	9640.0	n					12.59
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11A	0.117	n	0.132	0.014	0.020	0.160	6.89
12A	0.141	n				0.104	6.33
13A	0.117	n					6.53
14A	0.135	n					6.29
15A	0.148	n					7.01
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11A	10900	n	11606	2424	1741	16454	12.73
12A	9230	n				6758	12.75
13A	11300	n					12.46
14A	10900	n					12.66
15A	15700	n					12.89

	SP125 11-13				PG 64-22 w/ 10% GTR 0% RAP		
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1K	0.189	n	0.190	0.013	0.028	0.216	6.29
2K	0.174	n				0.164	6.49
3K	0.189	n					6.67
4K	0.21	n					6.61
5K	0.187	n					6.44
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1K	5620.0	n	5758	981	864	7720	12.37
2K	6900.0	n				3796	12.58
3K	6290.0	n					12.54
4K	5720.0	n					12.50
5K	4260.0	n					12.54
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6K	0.073	n	0.111	0.024	0.017	0.159	6.47
7K	0.106	n				0.063	6.66
8K	0.113	n					6.52
9K	0.13	n					6.72
10K	0.131	n					6.77
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6K	4650.0	n	6720	1608	1008	9936	12.48
7K	7970.0	n				3504	12.54
8K	8430.0	n					12.68
9K	7040.0	n					12.70
10K	5510.0	n					12.57
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11K	0.065	n	0.087	0.013	0.013	0.113	6.45
12K	0.09	n				0.061	6.48
13K	0.099	n					6.30
14K	0.092	n					6.60
15K	0.089	n					6.55
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11K	8080	n	9126	1769	1369	12664	12.46
12K	9190	n				5588	12.46
13K	11800	n					12.62
14K	9470	n					12.86
15K	7090	n					12.81

	BP11-66				PG 58-22	27% RAP	3% RAS
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1P	0.126	n	0.115	0.016	0.017	0.147	6.05
2P	0.089	n				0.083	6.58
3P	0.122	n					6.59
4P	0.126	n					6.70
5P	0.113	n					6.50
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1P	12100	n	8824	2045	1324	12914	12.47
2P	7230	n				4734	12.59
3P	6970	n					12.27
4P	8930	n					12.45
5P	8890	n					12.25
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6P	0.091	n	0.0792	0.008	0.012	0.095	6.27
7P	0.077	n				0.063	6.56
8P	0.074	n					6.11
9P	0.072	n					6.37
10P	0.082	n					6.52
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6P	8190	n	9576	1697	1436.4	12970	12.44
7P	11600	n				6182	12.19
8P	11200	n					12.34
9P	8050	n					12.69
10P	8840	n					12.22
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11P	0.069	n	0.076	0.012	0.011	0.100	6.18
12P	0.077	n				0.052	6.48
13P	0.071	n					6.86
14P	0.096	n					6.58
15P	0.067	n					6.08
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11P	14500	n	14700	2308	2205	19316	12.43
12P	17100	n				10084	12.81
13P	11800	n					12.11
14P	13200	n					12.66
15P	16900	n					12.62

	SP250 11-26				PG 64-22	5 % RAS	
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1N	0.115	n	0.149	0.022	0.022	0.193	6.49
2N	0.163	n				0.105	6.41
3N	0.139	n					6.29
4N	0.157	n					6.37
5N	0.169	n					6.38
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1N	9110	n	6924	2156	1039	11236	13.04
2N	3380	n				2612	13.31
3N	7530	n					13.11
4N	7850	n					13.98
5N	6750	n					13.42
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6N	0.134	n	0.1418	0.018	0.021	0.178	6.58
7N	0.169	n				0.106	6.41
8N	0.119	n					6.05
9N	0.147	n					6.28
10N	0.14	n					6.53
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6N	7770	n	9366	1717	1404.9	12800	13.05
7N	10200	n				5932	13.41
8N	10800	n					13.11
9N	10800	n					12.95
10N	7260	n					13.30
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11N	0.111	n	0.097	0.019	0.014	0.135	6.45
12N	0.105	n				0.059	6.52
13N	0.067	n					6.38
14N	0.111	n					6.50
15N	0.089	n					6.49
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11N	12600	n	12280	1016	1842	14312	13.15
12N	11200	n				10248	13.06
13N	11200	n					13.25
14N	13200	n					12.98
15N	13200	n					12.94

	SP095 11-71				PG 64-22	17% RAP	3% RAS
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1O	0.134	n	0.173	0.023	0.026	0.219	6.23
2O	0.183	n				0.127	6.29
3O	0.189	n					6.39
4O	0.19	n					6.39
5O	0.169	n					6.52
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1O	3360.0	n	5448	1390	817	8228	12.23
2O	5360.0	n				2668	12.26
3O	6910.0	n					12.58
4O	6500.0	n					12.55
5O	5110.0	n					12.12
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6O	0.106	n	0.122	0.017	0.018	0.156	6.97
16O	0.103	n				0.088	6.46
8O	0.121	n					6.44
9O	0.138	n					6.27
10O	0.14	n					6.41
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6O	13700.0	n	10538	2010	1580.7	14558	12.09
16O	9930.0	n				6518	12.39
8O	8310.0	n					12.40
9O	11000.0	n					12.28
10O	9750.0	n					12.14
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11O	0.081	n	0.106	0.016	0.016	0.138	6.06
12O	0.115	n				0.074	6.06
13O	0.107	n					6.24
14O	0.104	n					6.86
15O	0.124	n					6.34
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11O	9790	n	12398	1658	1860	15714	12.07
12O	14300	n				9082	12.66
13O	13100	n					12.30
14O	12200	n					12.34
15O	12600	n					12.59

	SP190 11-72				PG 70-22	10% RAP	
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1Q	0.231	n	0.199	0.025	0.030	0.249	6.34
2Q	0.16	n				0.149	6.35
3Q	0.202	n					6.44
4Q	0.205	n					6.60
5Q	0.199	n					6.35
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1Q	4120.0	n	6808	1811	1021	10430	12.13
2Q	8640.0	n				3186	12.53
3Q	7540.0	n					12.30
4Q	5870.0	n					12.26
5Q	7870.0	n					12.19
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6Q	0.092	n	0.108	0.018	0.016	0.144	6.01
7Q	0.101	n				0.072	6.51
8Q	0.095	n					6.60
9Q	0.137	n					6.26
10Q	0.115	n					6.77
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6Q	13300.0	n	9480	2576	1422	14632	12.22
7Q	6680.0	n				4328	12.82
8Q	8130.0	n					12.26
9Q	10700.0	n					12.11
10Q	8590.0	n					12.59
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11Q	0.094	n	0.101	0.045	0.015	0.191	6.87
12Q	0.109	n				0.011	6.87
16Q	0	y					6.54
14Q	0.098	n					6.45
15Q	0.101	n					6.44
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11Q	11200	n	11060	5389	1659	21838	13.03
12Q	13700	n				282	13.03
16Q	0	y					12.45
14Q	7740	n					12.45
15Q	11600	n					13.16

	SP250 11-41				PG 64-22	16% RAP	3% RAS
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1L	0.116	n	0.110	0.011	0.017	0.132	6.74
2L	0.095	n				0.088	7.10
3L	0.124	n					6.43
4L	0.104	n					6.91
5L	0.112	n					6.91
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1L	6330.0	n	5756	1081	863	7918	12.99
2L	4210.0	n				3594	13.02
3L	6030.0	n					12.79
4L	5200.0	n					12.79
5L	7010.0	n					12.75
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6L	0.107	n	0.106	0.021	0.016	0.148	6.54
7L	0.125	n				0.064	6.71
16L	0.115	n					6.41
9L	0.071	n					6.97
17L	0.113	n					6.28
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6L	8070.0	n	7950	1421	1192.5	10792	12.94
7L	9220.0	n				5108	13.00
16L	7980.0	n					12.45
9L	5590.0	n					12.83
17L	8890.0	n					12.48
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11L	0.12	n	0.099	0.019	0.015	0.137	6.86
12L	0.113	n				0.061	7.17
13L	0.092	n					7.17
14L	0.071	n					5.87
18L	0.097	n					6.32
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11L	8080	n	11128	2187	1669	15502	12.96
12L	11900	n				6754	13.01
13L	13200	n					13.02
14L	9660	n					12.76
18L	12800	n					12.47

	SP125 11-11				PG 70-22	28% RAP	
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
16M	0.096	n	0.106	0.014	0.016	0.134	6.34
17M	0.088	n				0.078	6.33
3M	0.107	n					6.14
4M	0.118	n					6.16
5M	0.122	n					6.17
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
16M	7000	n	6854	798	1028	8450	13.06
17M	5700	n				5258	13.27
3M	7430	n					13.12
4M	7690	n					13.22
5M	6450	n					13.11
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
18M	0.078	n	0.107	0.017	0.016	0.141	6.11
7M	0.114	n				0.073	6.09
8M	0.123	n					6.18
9M	0.109	n					7.01
10M	0.111	n					6.20
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
18M	9560	n	9526	2765	1428.9	15056	13.01
7M	6490	n				3996	13.05
8M	13900	n					13.17
9M	8040	n					12.73
10M	9640	n					12.59
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
19M	0.055	n	0.063	0.022	0.009	0.107	6.64
12M	0.059	n				0.019	6.25
13M	0.080	n					6.47
14M	0.088	n					6.23
20M	0.031	n					6.17
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
19M	9850	n	10458	3908	1569	18274	13.66
12M	15400	n				2642	13.18
13M	10000	n					13.10
14M	12300	n					13.16
20M	4740	n					13.15

	SP190 11-33				PG 64-22	18% RAP	3% RAS
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1R	0.082	n	0.077	0.023	0.012	0.123	6.57
2R	0.042	n				0.031	6.35
3R	0.067	n					6.43
4R	0.100	n					6.58
5R	0.094	n					6.27
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1R	12000	n	8290	3338	1244	14966	12.66
2R	3250	n				1614	12.86
3R	6990	n					13.05
4R	9970	n					13.08
5R	9240	n					12.90
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6R	0.045	n	0.0896	0.042	0.013	0.174	6.57
7R	0.098	n				0.006	6.70
8R	0.157	n					6.80
9R	0.080	n					6.84
10R	0.068	n					6.92
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6R	3260	n	7822	3708	1173.3	15238	12.66
7R	11100	n				406	13.11
8R	4350	n					13.10
9R	10000	n					13.25
10R	10400	n					12.64
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11R	0.064	n	0.032	0.024	0.005	0.080	6.51
12R	0.050	n				-0.016	6.89
13R	0.015	n					6.47
14R	0.013	n					6.95
15R	0.016	n					6.69
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11R	21400	n	13884	10595	2083	35074	13.19
12R	17900	n				-7306	12.56
13R	24900	n					12.69
14R	1960	n					12.70
15R	3260	n					12.71

	SP190 11-32				PG 64-22	25% RAP	1% HL
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1D	0.153	n	0.132	0.021	0.020	0.174	6.72
2D	0.142	n				0.090	6.10
3D	0.102	n					6.66
4D	0.144	n					6.77
5D	0.121	n					6.75
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1D	10500.0	n	9182	1620	1377	12422	12.71
2D	10100.0	n				5942	12.87
3D	6440.0	n					13.28
4D	9800.0	n					12.97
5D	9070.0	n					13.05
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6D	0.077	n	0.072	0.014	0.011	0.100	6.43
7D	0.077	n				0.044	6.62
8D	0.051	n					6.60
9D	0.090	n					6.52
10D	0.067	n					6.77
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6D	9380.0	n	7930	1794	1189.5	11518	13.09
7D	10100.0	n				4342	13.11
8D	5900.0	n					13.36
9D	7720.0	n					13.12
10D	6550.0	n					13.09
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11D	0.097	n	0.087	0.021	0.013	0.129	6.81
12D	0.096	n				0.045	6.97
13D	0.112	n					6.85
14D	0.063	n					6.85
15D	0.068	n					6.22
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11D	16400	n	16060	1781	2409	19622	12.99
12D	15100	n				12498	13.15
13D	13900	n					13.14
14D	18700	n					13.32
15D	16200	n					13.43

	SP125 11-34				PG 64-22	20% RAP	3% RAS
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1C	0.123	n	0.117	0.025	0.018	0.167	6.76
2C	0.079	n				0.067	6.67
3C	0.139	n					6.53
4C	0.137	n					6.65
5C	0.109	n					6.44
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1C	5860.0	n	6624	1497	994	9618	12.94
2C	4410.0	n				3630	13.18
3C	7150.0	n					13.02
4C	8160.0	n					13.08
5C	7540.0	n					13.06
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6C	0.099	n	0.082	0.034	0.012	0.150	6.40
7C	0.08	n				0.014	6.40
8C	0.109	n					6.32
9C	0.098	n					6.69
10C	0.025	n					6.58
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6C	10100.0	n	7528	3088	1129.2	13704	13.12
7C	5890.0	n				1352	13.15
8C	10100.0	n					12.85
9C	8610.0	n					13.00
10C	2940.0	n					13.16
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11C	0.121	n	0.100	0.013	0.015	0.126	6.58
12C	0.102	n				0.074	6.52
13C	0.093	n					6.66
14C	0.087	n					6.62
15C	0.095	n					6.37
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11C	7060	n	10570	2857	1586	16284	13.09
12C	9090	n				4856	13.21
13C	11900	n					13.18
14C	14600	n					13.37
15C	10200	n					13.60

	SP125 11-37				PG 64-22	28% RAP	1% HL
	-6C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
1G	0.144	n	0.131	0.050	0.020	0.231	6.72
2G	0.152	n				0.031	6.53
3G	0.175	n					6.59
4G	0.045	n					6.57
5G	0.137	n					6.62
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
1G	9390.0	n	7272	3495	1091	14262	12.96
2G	8040.0	n				282	12.79
3G	11400.0	n					12.96
4G	2730.0	n					13.29
5G	4800.0	n					13.07
	-12C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
6G	0.031	n	0.080	0.033	0.012	0.146	6.43
7G	0.085	n				0.014	6.51
8G	0.113	n					6.51
9G	0.067	n					6.72
10G	0.105	n					6.57
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
6G	3070.0	n	8424	3193	1263.6	14810	12.58
7G	10600.0	n				2038	12.90
8G	10400.0	n					12.66
9G	7850.0	n					13.07
10G	10200.0	n					12.73
	-18C						
Beam No.	m-value	Out.	x	σ	15% * x	x +/- 2σ	Thickness
11G	0.089	n	0.080	0.006	0.012	0.092	6.72
12G	0.076	n				0.068	6.80
13G	0.083	n					6.57
14G	0.077	n					6.97
15G	0.076	n					6.68
	Stiffness		x	σ	15% * x	x +/- 2σ	Width
11G	12700	n	11080	2666	1662	16412	12.68
12G	10000	n				5748	12.69
13G	14700	n					12.78
14G	7800	n					12.74
15G	10200	n					13.75