Spring 2018

Evaluation of Cracking Indices for Asphalt Mixtures Using SCB Tests at Different Temperatures and Loading Rates

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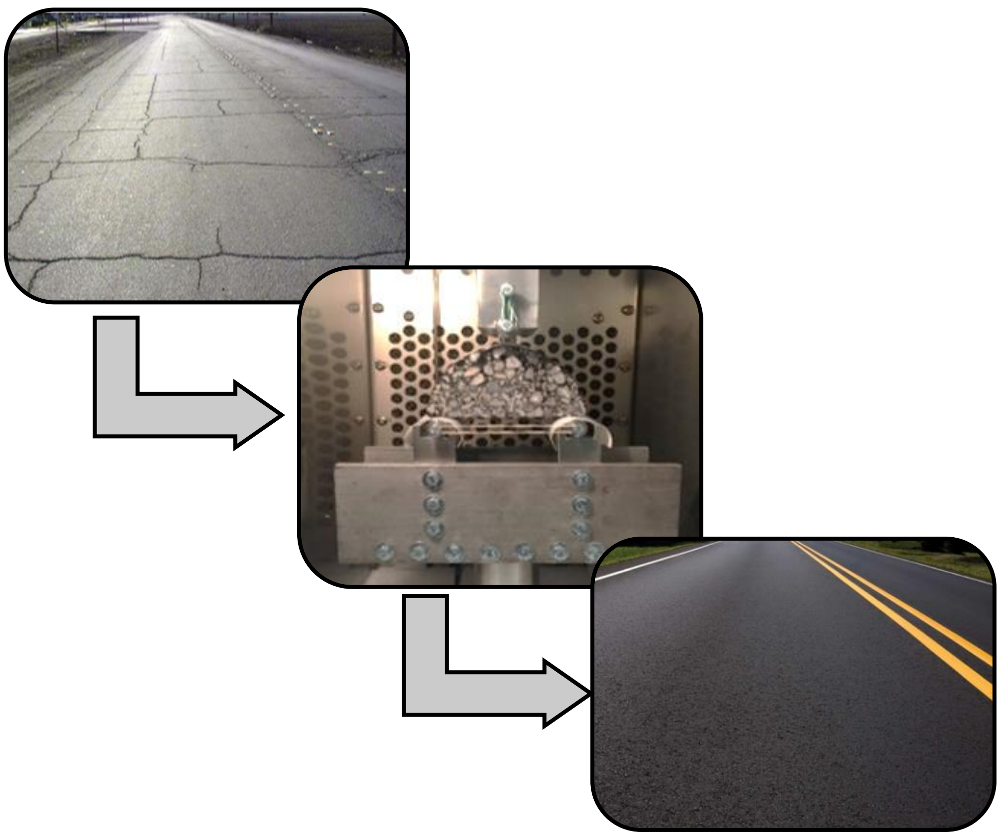

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Honors Thesis
Spring 2018

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ABSTRACT

In recent years, there has been a shift towards implementing performance based pavement specifications (PBPS) to increase reliability of asphalt concrete mixture specifications and enhance service lives of roadways. Several of the performance indices used in PBPS are based on the asphalt mixture fracture tests. There is an increasing need for a better understanding the effects of temperature and loading rate interdependency for fracture properties of asphalt mixtures. The goal of this study is to build upon previous work conducted during a Summer Undergraduate Research Program (SURF) project entitled, "Exploration of Temperature and Loading Rate Interdependency for Fracture Properties of Asphalt Mixtures," as well as to incorporate ongoing research studies at the University of New Hampshire (UNH). There are many proposed fracture indices including Fracture Energy (G_f), Illinois Flexibility Index (FI), Toughness Index (TI), Nflex, and Fracture Strain Tolerance (FST). The objective of this study is to evaluate different fracture indices and their variations with changes in test temperature and loading rates. Results from Semi-Circular Bend (SCB) fracture tests on five asphalt mixtures (from Vermont and Virginia) are being evaluated. All mixtures represent same aggregate maximum sizes and consist of varying amounts of Reclaimed Asphalt Pavement (RAP). Conclusions will be drawn on the effectiveness of each fracture index to distinguish and appropriately rank mixtures as well as on the variations of these indices with changes in test temperature and loading rates. On basis of this study, use of crack mouth opening displacements for fracture index calculations is recommended obtain better distinction of cracking performances between mixtures.

KEYWORDS: SCB, fracture indices, test temperature, loading rate

INTRODUCTION

Every four years, the American Society of Civil Engineering releases a report card scoring America's Infrastructure. The most recent infrastructure report card was released in 2017, with an overall rating of America's infrastructure as a D-. The overall grade is based on several categories such as, drinking water, energy, bridges, transit and roads. The US road network system received a grade of a D. Similar to the national report card, New Hampshire has also adopted the same report card system. In 2017, New Hampshire's received an infrastructure report card score was a C-. Per the NH Infrastructure report card grading system, a C corresponds to mediocre performance with the network in fair to good condition, however it is deteriorating and requires attention. A grade of a D corresponds to infrastructure in poor to fair condition and is generally rated as being below standard and approaching the end of its service life [1, 2]. There is an increasing need to address the aging road network at both the state and national level.

In recent years the asphalt industry is shifting towards a performance based specification system to improve the service life of roads. Developing a greater understanding of fracture performance at low and intermediate temperatures of asphalt concrete mixtures is a critical part of this process. Data acquired for the research conducted as part of the honors thesis study was obtained from a previous project entitled, "Exploration of Temperature and Loading Rate Interdependency for Fracture Properties of Asphalt Mixtures" [3].

Fracture performance testing and cracking related index parameters to evaluate low and intermediate temperature cracking resistance of asphalt mixtures are gaining increased attention. The development cracking indexes using the Semi-Circular Bend (SCB) test has been conducted by several individuals [4, 5, 6, 7, 8] and is currently an ongoing topic of research in the asphalt pavement field.

One of the challenges with cracking tests is the selection of test temperature and loading rate that is appropriate for a given pavement climatic location. Cracking performance testing should be performed at temperatures that resemble those experienced in the field in order to appropriately evaluate mixture performance. Temperature has a significant impact on asphalt binder properties. In general, as temperature decreases asphalt binder modulus and strength increase. Therefore, at a lower testing temperature a mixture will behavior more brittle compared to when tested at a higher temperature it will behavior more ductile. A study conducted by Minnesota Department of Transportation (MNDOT) reported that, "Even at low temperatures asphalt mixtures are complex viscoelastic composite materials that significantly temperature and loading rate dependent" [9].

The goal of this study is to conduct an evaluation of the various cracking indices using output from SCB fracture test which was performed over a range of testing temperatures and loading rate combinations. Analysis consisted primarily of the comparisons of load-displacement curves and the ranking of cracking indices. Specific research objectives included:

1. Evaluate various cracking indices using SCB fracture test conducted over a range of testing temperature and loading rates.
2. Compare effects of using different displacement measurements from lab tests (Line-Load Displacement (LLD) versus Crack Mouth Opening (CMOD) Displacement) on calculated fracture properties.
3. Investigation of the effect of test temperature and loading rate on fracture performance ranking of mixtures.

METHODOLOGY

The SCB test is a relative new testing method to measure fracture energy of asphalt mixtures at intermediate temperatures. For this study, the Illinois method of SCB testing was used in accordance with AASTHO TP 105 [4, 10] test specifications. Figure 1 shows the typical SCB testing set up.

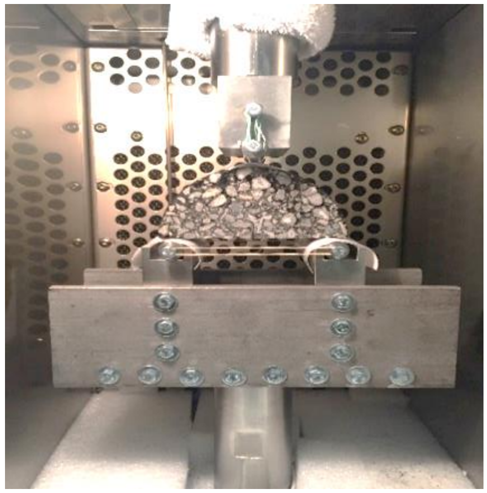


Figure 1: Typical SCB set in environmental chamber of the testing machine.

The scope of this project included five asphalt mixtures from two regional sources, Virginia and Vermont. The percentage of Reclaimed Asphalt Pavement (RAP) varied from 0% to 40% and Superpave performance graded (PG) asphalt binders were used to produce the study mixtures, as shown in Table 1. The high temperature PG grade for the Virginia binders was adjusted in an effort to compensate for the increasing percentage of RAP. All mixtures evaluated in this study have a nominal maximum aggregate (NMA) size of 9.5 mm and were sampled at a hot-mix production plant. Test specimens were fabricated from gyratory compacted specimens prepared on-site without reheating the material.

Table 1: Summary tested mixtures and test parameters (loading rates and temperature).

Mixture		Virginia		Vermont	
Testing Condition		25°C & 50 mm/min		25°C & 50 mm/min	
		13°C & 50 mm/min		13°C & 50 mm/min	
		13°C & 1.86 mm/min		1°C & 50 mm/min	
		13°C & 10 mm/min		1°C & 2 mm/min	
PG	RAP	76-22	0%	52-34	20%
		70-22	20%	52-34	40%
		64-22	40%		

The standard testing temperature is 25°C and line-load displacement rate of 50 mm/min was used. The specification for this test recommends 25°C temperature irrespective of the binder grade. Table 1 summarizes the testing temperatures and loading rates combinations that were used for all mixtures while performing the SCB testing in this study. The selection of testing temperature and loading rate combinations was inferred through the Time-Temperature-

Superposition Principle (TTSP). For each testing condition 3 replicate specimens were tested. The first and second set of testing conditions were conducted at 13°C (12 °C cooler than standard test temperature of 25 °C, which is equivalent to two PG grades) and 25 °C using the standard loading rate of 50 mm/minute. The average Gf was determined at 13°C and 25 °C and the ratio P13/P25 was calculated. This ratio is equivalent to the viscoelastic shift factor assuming the time-temperature superposition principle is valid. Then the dynamic modulus (|E*|) ratio (E*13/E*25) was compared to the P13/P25 ratio to yield the equivalent loading rates at the two temperatures (Figure 2).

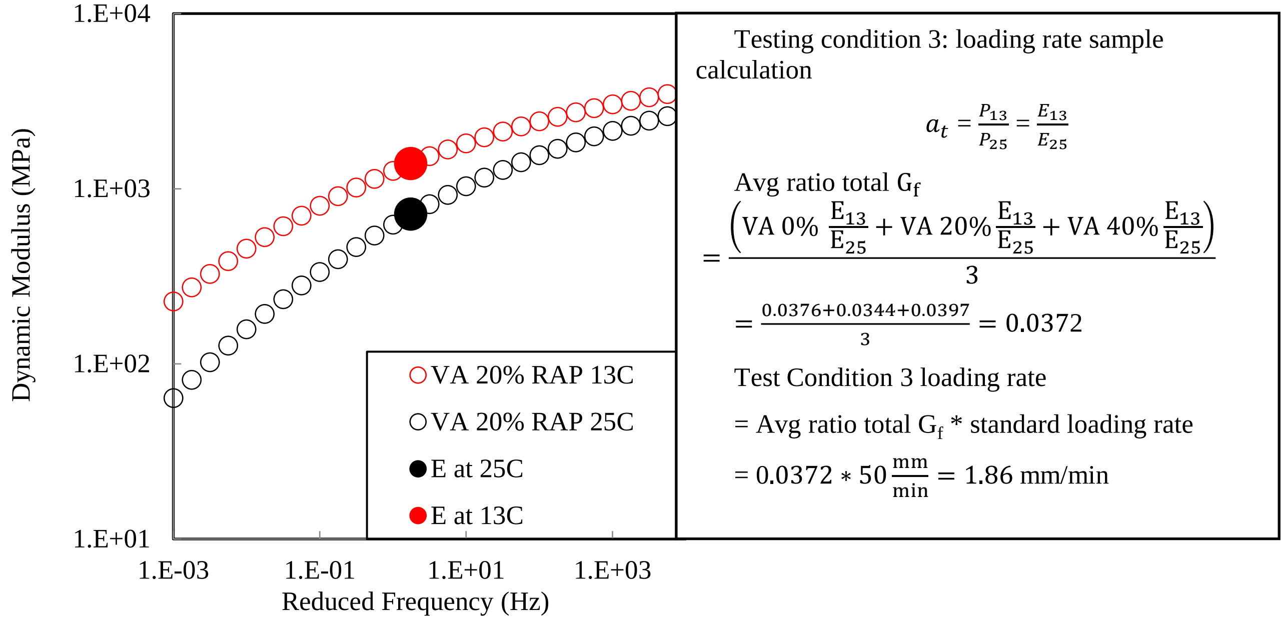
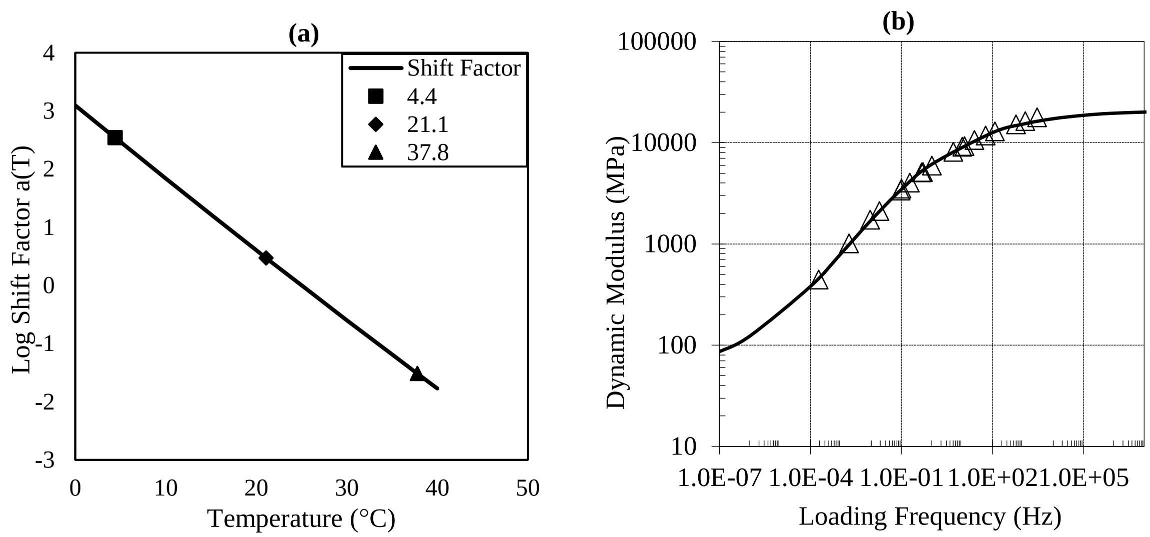


Figure 2: Example of ratio based method to determine trial testing conditions using VA 20% RAP mixture [3].

The average ratio between the two loading rates was multiplied by the original loading frequency (50 mm/min) to obtain the new testing frequency for the third test condition, which was carried out at 13°C. A similar methodology was used for determining testing conditions for the fourth set of replicates. Figures 3 (a) and (b) demonstrate an example of the TTSP shift factor plot and a complex modulus (|E*|) master curve for the Virginia 20% RAP mixture to determine the third set of testing conditions.



(a) TTSP shift factor-temperature plot.

(b) 20% RAP VA Mix master curve.

Figure 3: Example of dynamic modulus data used to determine loading rate for different test temperatures [3].

Outputs from the SCB test include line-load displacement (LLD), crack-mouth opening displacement (CMOD), and load (P). For further comparison, all fracture indices were calculated using both total LLD and CMOD. Figure 4 shows a typical load-displacement curve that is generated from the SCB test output. All load displacement curves for each testing condition by mixture are included in the Appendix.

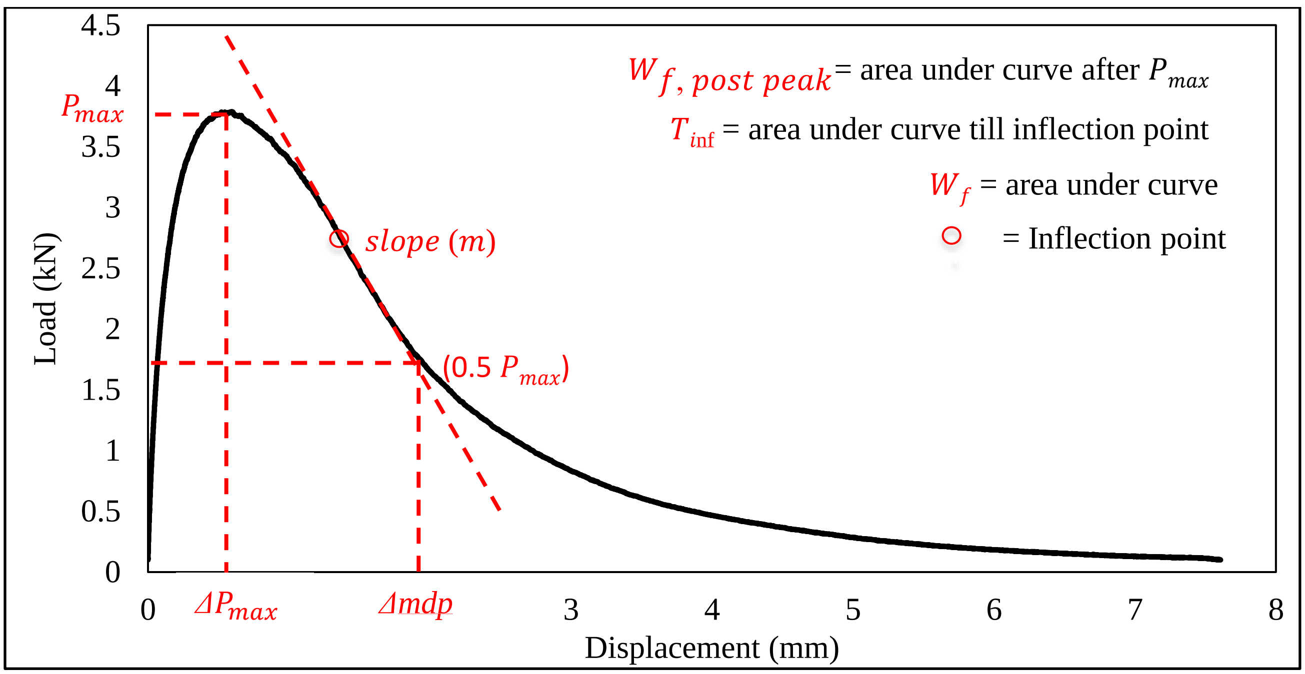


Figure 4: Typical load-displacement curve generated from SCB test.

The cracking indices evaluated in this study included: Fracture Energy (G_f), Illinois Flexibility Index (FI), Toughness Index (TI), Nflex Factor, Fracture Strain Tolerance (FST), and the Cracking Resistance Index (CRI). In the subsequent sections the method to determine each index is briefly describe including the mathematical formula to calculate each index.

Fracture Energy (G_f)

The fracture energy of a given material is defined as the energy needed to create a new unit fracture surface in the body [11]. Equation 1 is used to calculate G_f, which is defined as the area under the load-displacement curve (W_f) normalized by fracture area. The fracture area is the product of the width of the specimen (t) and the ligament length (a).

$$G_f = \frac{W_f}{t * a} \quad (1)$$

Flexibility Index (FI)

Upon calculating G_f, the Flexibility Index can be determined. The Illinois method in accordance with AASTHO TP 105 was utilized to determine FI in this study [10]. One of the main advantages to normalize G_f by another parameter is to better distinguish fracture resistance between mixtures. Different mixture may have very high peak load and steep post-peak softening slopes and vice versa conditions. Therefore, to normalize fracture energies a parameter that considers the shape of post-peak portion may be utilized. In the case of the FI, G_f is normalized by the average post peak slope (m) as shown in Equation 2.

$$FI = \frac{G_f}{|m|} \quad (2)$$

Fracture Strain Tolerance (FST)

Similar to the FI where G_f is normalized by another parameter to better distinguish mixtures, FST utilizes the Fracture Strength (S_f) of specimens to normalize fracture energies. To determine S_f from the SCB geometry, a similar approach that was used for Disk-Shaped Compact Tension (DCT) test in Zhu et al. in combination with ASTM E399-90 was implemented to develop Equation 3 [7, 12]. Fracture strength takes into consideration the peak load as well as the specimen's geometry where (t) is the specimen's thickness, (w) is the specimen's width, and (a) is the ligament length.

$$S_f = \frac{2P_{max}(2w+a)}{t(w-a)^2} \quad (3)$$

FST is then calculated by normalizing fracture energy with S_f as shown in Equation 4.

$$FST = \frac{G_f}{S_f} \quad (4)$$

Cracking Resistance Index (CRI)

Recently developed in 2018 by Kaseer et al., the CRI index is simply calculated by dividing the fracture energy by peak load (Equation 5)

$$CRI = \frac{G_f}{P_{max}} \quad (5)$$

Toughness Index (TI)

Toughness Index is calculated using the post peak G_f rather than the total area under the curve, and multiplying it by the displacement between the peak load (ΔP_{max}) and 50% of the peak load (Δmdp). A scale adjustment factor of 10^{-3} is included in Equation 6.

$$TI = \left(G_{f,post\ peak}\right) * (\Delta mdp - \Delta P_{max}) * 10^{-3} \quad (6)$$

Nflex Factor

Finally, the Nflex Factor that was utilized in this study was adopted from work conducted at the National Center for Asphalt Technology (NCAT) by Yin et al using the Indirect Tensile Test (IDT). Originally, the Nflex Factor was inspired by the Illinois Flexibility Index [13], which relies on the determination of the slope of the inflection point on the post peak curve. Raw data was fitted using a sixth-degree polynomial function, slope calculated at the post peak point of inflection and the area under the load displacement curve up to the inflection point (toughness) was calculated. The Nflex Factor is then simply calculated by diving the toughness by the absolute value of the post peak slope as shown in Equation 7.

$$Nflex\ Factor = \frac{T_{inf}}{|m|} \quad (7)$$

RESULTS AND DISCUSSION

Comparing use of Line-Load Displacement and Crack Mouth Opening Displacement for Calculation of Fracture Indices

Tables 2 and 3 summarize the results for the VA mixtures, while Tables 4 and 5 summarize results for the VT mixtures at the 4 different testing conditions. Within each testing condition, mixtures are ranked from best performers (i.e. most resistant to cracking) in green to worst performers in red.

Table 2: Line-load displacement comparison of VA mixtures for all cracking index at varying test temperature and loading rate combinations (green to red represents best to worst performing).

Virginia Line-Load Displacement							
Testing Condition	**Mixture**	**G_f J/m^2**	**FI**	**TI 10^3**	**Nflex**	**FST**	**CRI**
25°C & 50mm/min	VA 0% RAP	2622	8.18	3.513	1.97	354.99	668.77
	VA 20% RAP	**1976**	5.39	1.827	1.13	281.02	547.21
	VA 40% RAP	**2080**	2.24	0.820	0.52	221.68	410.38
13°C & 50mm/min	VA 0% RAP	1661	**1.00**	0.081	0.05	120.86	235.57
	VA 20% RAP	1109	**1.00**	0.127	0.07	95.47	**176.83**
	VA 40% RAP	1012	**1.00**	0.045	0.04	94.08	**184.13**
13°C & 1.86mm/min	VA 0% RAP	**1700**	8.00	1.904	1.13	269.96	513.32
	VA 20% RAP	1485	2.93	0.764	0.66	243.88	440.36
	VA 40% RAP	**1719**	1.77	0.616	0.36	182.20	346.88
13°C & 10 mm/min	VA 0% RAP	2562	2.39	1.594	**0.77**	248.67	476.66
	VA 20% RAP	1859	1.59	0.445	0.36	196.82	374.34
	VA 40% RAP	1299	1.00	0.028	**0.04**	113.49	225.69

Table 3: CMOD comparison of VA mixtures for all cracking index at varying test temperature and loading rate combinations (green to red represents best to worst performing).

Virginia CMOD Displacement							
Testing Condition	Mixture	G_f J/m²	FI	TI 10^3	Nflex	FST	CRI
25°C & 50mm/min	VA 0% RAP	3855	29.40	16.408	4.80	521.65	982.70
	VA 20% RAP	**2888**	16.41	8.630	1.93	410.64	799.53
	VA 40% RAP	**2384**	6.62	4.623	1.08	253.43	468.67
13°C & 50mm/min	VA 0% RAP	2272	1.78	1.505	0.13	165.21	321.91
	VA 20% RAP	1397	1.79	1.540	0.26	120.80	**223.47**
	VA 40% RAP	1113	1.18	0.833	0.07	102.84	**201.68**
13°C & 1.86mm/min	VA 0% RAP	**2370**	15.22	7.597	2.43	382.38	726.17
	VA 20% RAP	1643	7.35	3.537	1.18	270.78	488.51
	VA 40% RAP	**2194**	5.42	3.683	0.51	233.41	444.99
13°C & 10 mm/min	VA 0% RAP	3256	7.50	8.027	1.80	315.83	605.77
	VA 20% RAP	2001	4.58	2.908	0.52	212.65	404.53
	VA 40% RAP	1211	1.00	0.705	0.05	105.90	210.10

Table 4: Line-load displacement comparison of VT mixtures for all cracking index at varying test temperature and loading rate combinations (green to red represents best to worst performing).

Vermont Line-Load Displacement							
Testing Condition	Mixture	G_f J/m²	FI	TI 10^3	Nflex	FST	CRI
25°C & 50mm/min	VT 20% RAP	**1165**	16.57	2.351	3.80	491.48	886.81
	VT 40% RAP	**1419**	17.70	3.944	4.20	473.53	802.64
13°C & 50mm/min	VT 20% RAP	2072	8.77	2.699	1.85	359.08	663.49
	VT 40% RAP	2050	3.45	1.525	1.09	284.72	522.92
1°C & 50mm/min	VT 20% RAP	1424	1.00	0.208	0.15	135.80	248.28
	VT 40% RAP	1125	1.00	0.049	0.06	114.21	205.13
1°C & 2mm/min)	VT 20% RAP	**1558**	4.09	1.263	0.90	258.66	489.21
	VT 40% RAP	**1571**	1.87	0.736	0.44	192.53	359.55

Table 5: CMOD comparison of VT mixtures for all cracking index at varying test temperature and loading rate combinations (green to red represents best to worst performing).

Vermont CMOD Displacement							
Testing Condition	Mixture	G_f J/m²	FI	TI 10³	Nflex	FST	CRI
25°C & 50mm/min	VT 20% RAP	**1692**	34.60	9.91	8.70	713.73	1287.81
	VT 40% RAP	**1419**	54.43	17.00	9.10	473.53	802.64
13°C & 50mm/min	VT 20% RAP	2964	26.48	9.02	3.45	513.45	949.88
	VT 40% RAP	2610	8.62	7.21	1.55	362.55	665.93
1°C & 50mm/min	VT 20% RAP	1590	2.38	1.86	0.18	155.79	278.97
	VT 40% RAP	1138	1.29	0.75	0.07	115.49	206.92
1°C & 2mm/min)	VT 20% RAP	**2068**	12.77	5.74	2.00	345.71	653.81
	VT 40% RAP	**1911**	5.83	3.55	0.82	234.18	437.28

Effect of Test Temperature and Loading Rate

Asphalt is considered a viscoelastic material meaning it exhibits both a viscous and elastic component when undergoing deformation. Asphalt also exhibits both time and temperature dependent properties in response to loading. Table 6 highlights the effect of test temperature on the six cracking indices from 1 ℃ to 25 ℃ while holding the loading rate constant at 50 mm/min. Only the two mixtures from VT were tested at 1℃, as the fourth combination of test temperature and loading rate for the VA mixtures was focused on investigating the effect of loading rate as temperature was held constant. Table 7 summarizes the effect of varying loading rate while temperature is held constant on the corresponding cracking indices.

Table 6: Effect of test temperature on ranking of mixtures at performed at 25 °C, 13 °C and 1 °C with constant loading rate of 50 mm/min (green to red represents best to worst performing).

Effect of Test Temperature							
Testing Condition	Mixture	G_f J/m²	FI	TI 10³	Nflex	FST	CRI
25°C & 50mm/min	VT 20% RAP	1692	34.60	9.91	8.70	713.73	1287.81
	VT 40% RAP	1419	54.43	17.00	9.10	473.53	802.64
	VA 0% RAP	3855	29.40	16.41	4.80	521.65	982.70
	VA 20% RAP	2888	16.41	8.63	1.93	410.64	799.53
	VA 40% RAP	2384	6.62	4.62	1.08	253.43	468.67
13°C & 50mm/min	VT 20% RAP	2964	26.48	9.02	3.45	513.45	949.88
	VT 40% RAP	2610	8.62	7.21	1.55	362.55	665.93
	VA 0% RAP	2272	1.78	1.50	0.13	165.21	321.91
	VA 20% RAP	1397	1.79	1.54	0.26	120.80	223.47
	VA 40% RAP	1113	1.18	0.83	0.07	102.84	201.68
1°C & 50mm/min	VT 20% RAP	1590	2.38	1.86	0.18	155.79	278.97
	VT 40% RAP	1138	1.29	0.75	0.07	115.49	206.92

Table 7: Effect of loading rate on ranking of mixtures performed at 50 mm/min, 10 mm/min and 1.86 mm/min while holding testing temperature constant at 13 °C (green to red represents best to worst performing).

Effect of Loading Rate							
Testing Condition	Mixture	G_f J/m^2	FI	TI 10^3	Nflex	FST	CRI
13°C & 50mm/min	VT 20% RAP	2964	26.48	9.02	3.45	513.45	949.88
	VT 40% RAP	2610	8.62	7.21	1.55	362.55	665.93
	VA 0% RAP	2272	1.78	1.50	0.13	165.21	321.91
	VA 20% RAP	1397	1.79	1.54	0.26	120.80	223.47
	VA 40% RAP	1113	1.18	0.83	0.07	102.84	201.68
13°C & 10 mm/min	VA 0% RAP	3256	7.50	8.03	1.80	315.83	605.77
	VA 20% RAP	2001	4.58	2.91	0.52	212.65	404.53
	VA 40% RAP	1211	1.00	0.70	0.05	105.90	210.10
13°C & 1.86mm/min	VA 0% RAP	**2370**	15.22	7.60	2.43	382.38	726.17
	VA 20% RAP	1643	7.35	3.54	1.18	270.78	488.51
	VA 40% RAP	**2194**	5.42	3.68	0.51	233.41	444.99

SUMMARY AND CONCLUSIONS

As the asphalt industry shifts towards a PPBS, there is an increasing number of proposed cracking indices to evaluate fracture performance of asphalt mixtures. Understanding the effects of test temperature and loading rate on the performance of mixtures is a critical step in implementation of performance based testing. This study evaluated 6 different cracking indices used to rank the performance of asphalt mixtures. Five different mixtures with varying amounts of RAP and PG grades were tested at 4 different test temperature and loading rate combinations. Key conclusions from this study include:

- Similar ranking of mixtures using line-load versus CMOD displacement. However, the magnitude and distinction between mixtures varies significantly with temperature.

- Post peak slope behaviour has an impact on the ranking of mixtures.

- Consideration to climatic region should be incorporated into selection of appropriate test temperature and loading rate combination for fracture testing.

Recommendations for future work consists of expanding the mixture database and incorporating finite element analysis (FEA) to gain a greater understanding of the effect of temperature on fracture performance. Further study on the development of stresses within the SCB specimen while undergoing loading using the cohesive zone (CZ) model should be conducted to simulate the fracture in asphalt mixtures. By incorporating CZ model into the FEA process, the weakening of material near the crack tip to resist crack initiation and propagation may be capture and analysed further. Validation of mixture performance is also strongly encouraged using field performance data.

ACKNOWLEDGEMENTS

I would like to thank my faculty advisors Dr. Dave and Dr. Daniel for their continued support and guidance throughout my experience at UNH. Acknowledgements are also extended to the Hamel Center for Undergraduate Research, the Materials Research Group and UNH Honors Program.

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APPENDICES

SCB Load-Displacement Curves VA Mixture

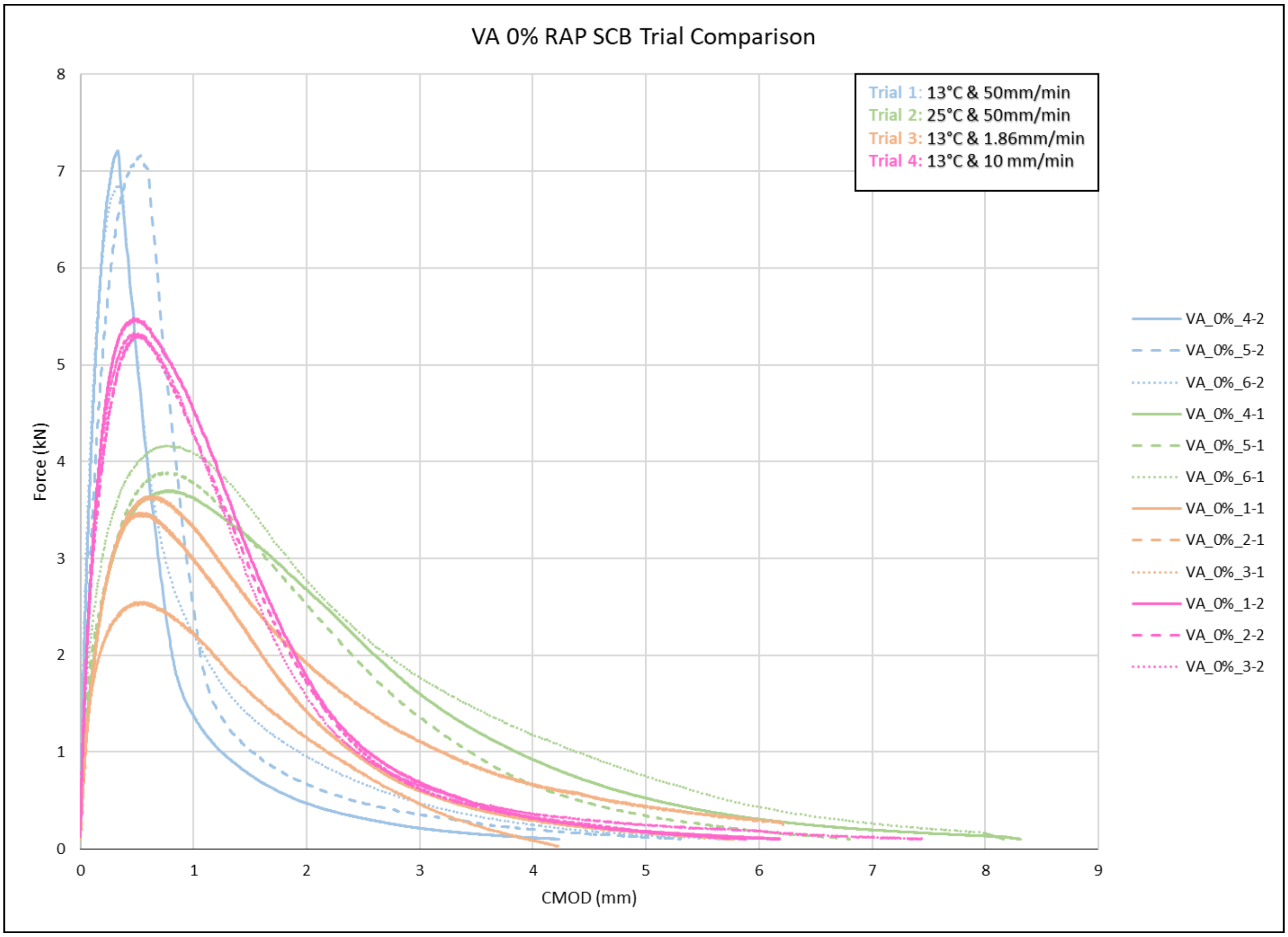

Figure 5: SCB load-displacement curves for VA 0% RAP mixtures.

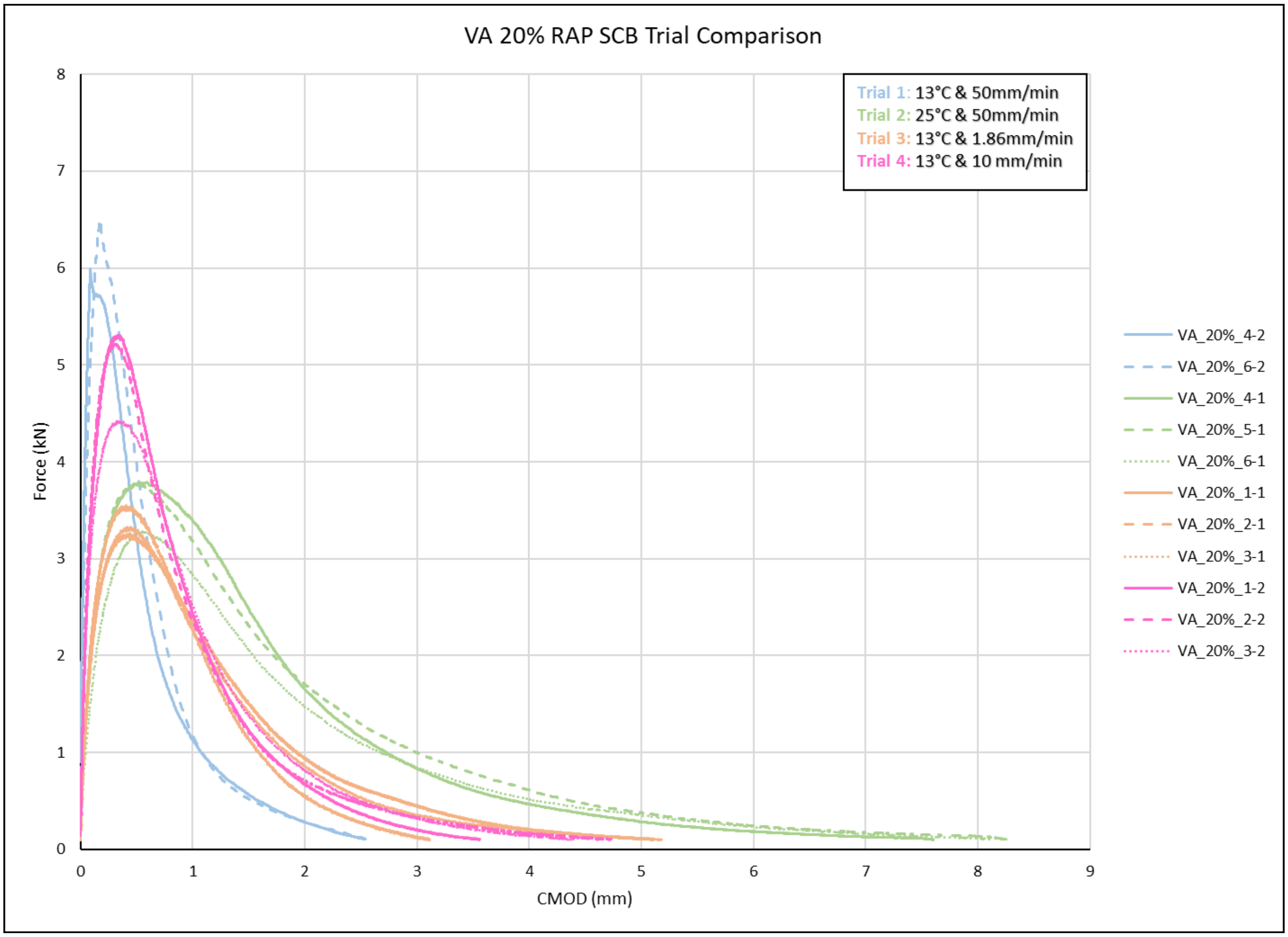

Figure 6: SCB load-displacement curves for VA 20% RAP mixtures.

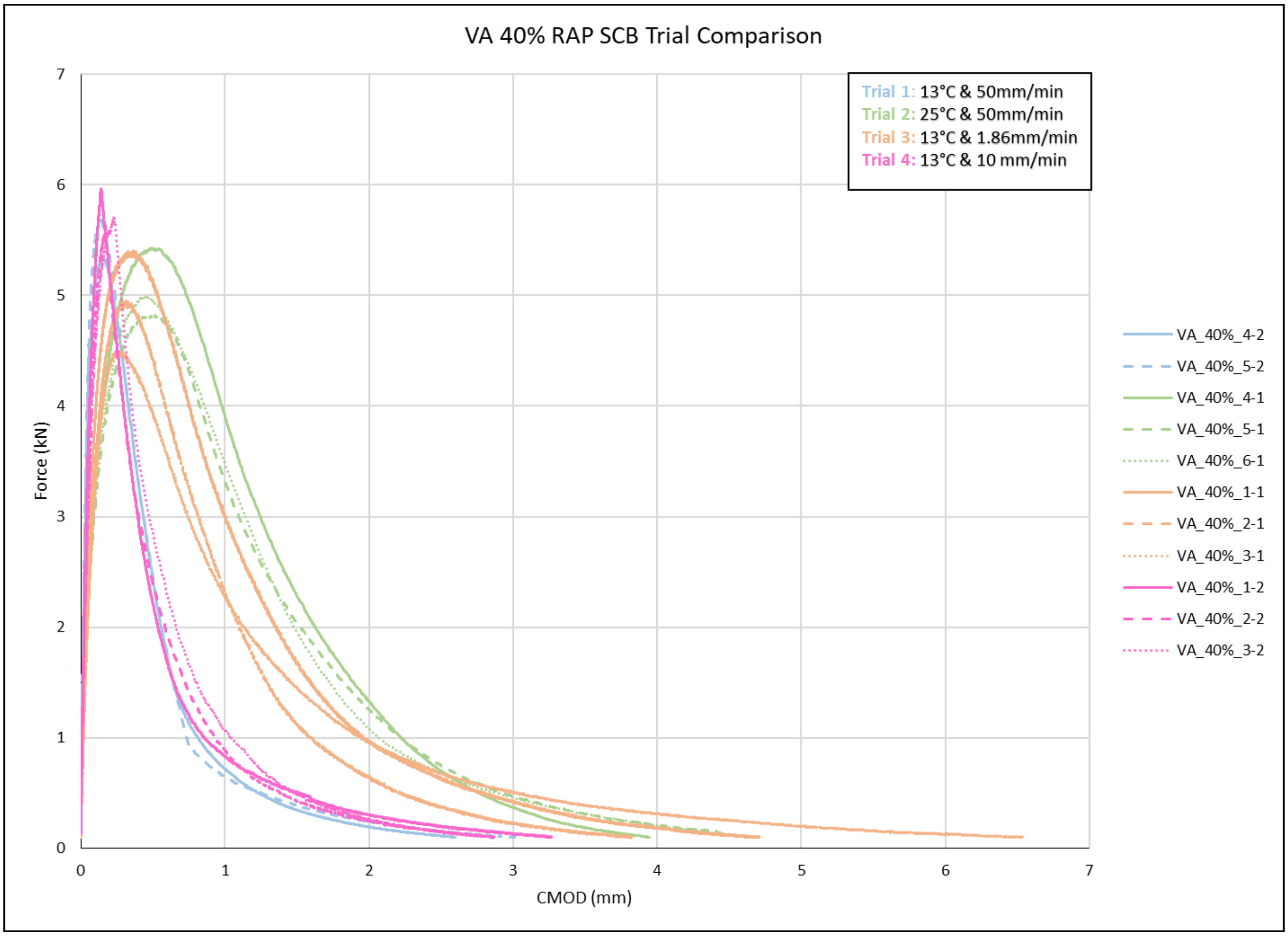

Figure 7: SCB load-displacement curves for VA 40% RAP mixtures.

SCB Load-Displacement Curves VT Mixture

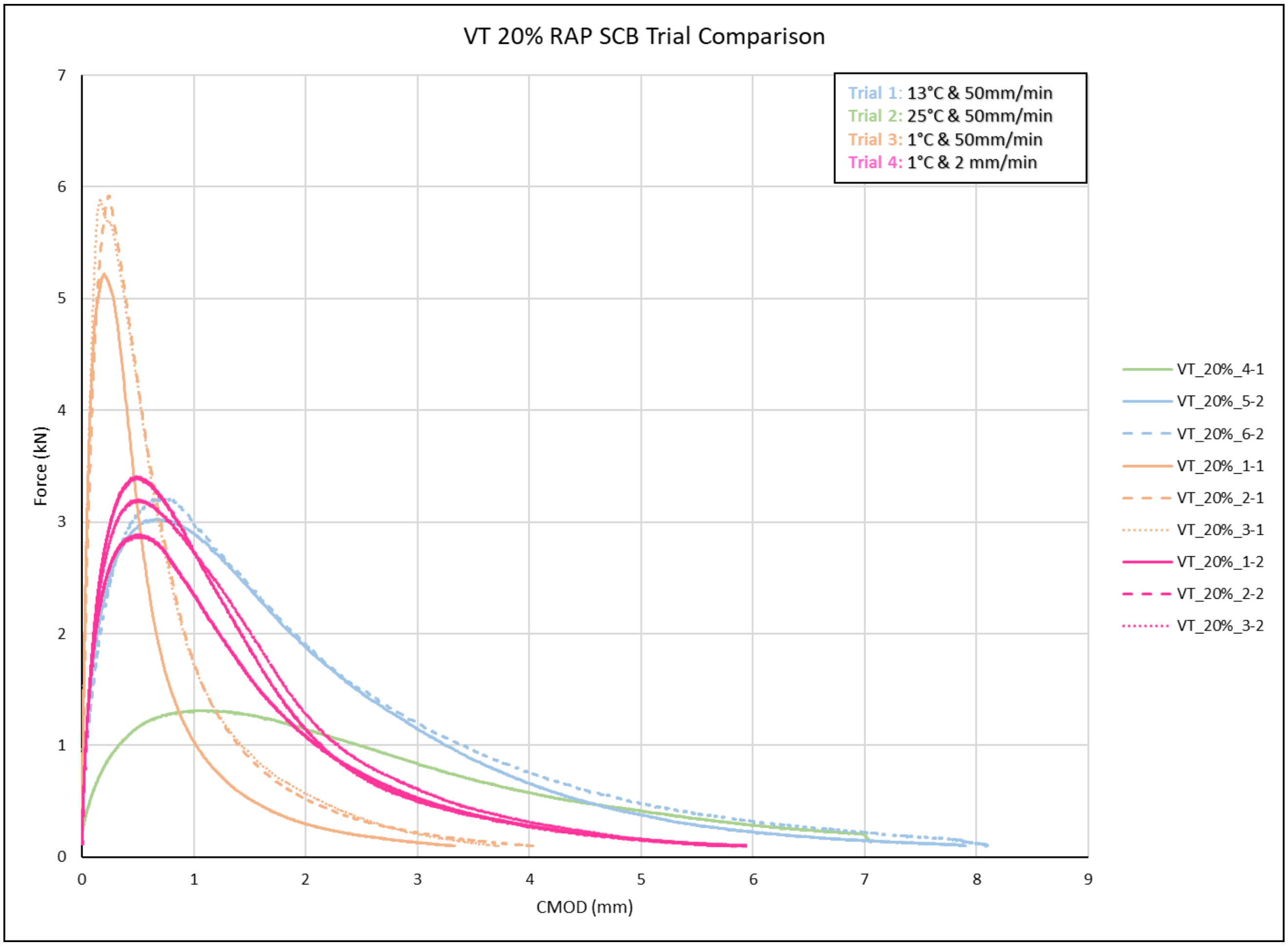

Figure 8: SCB load-displacement curves for VT 20% RAP mixtures.

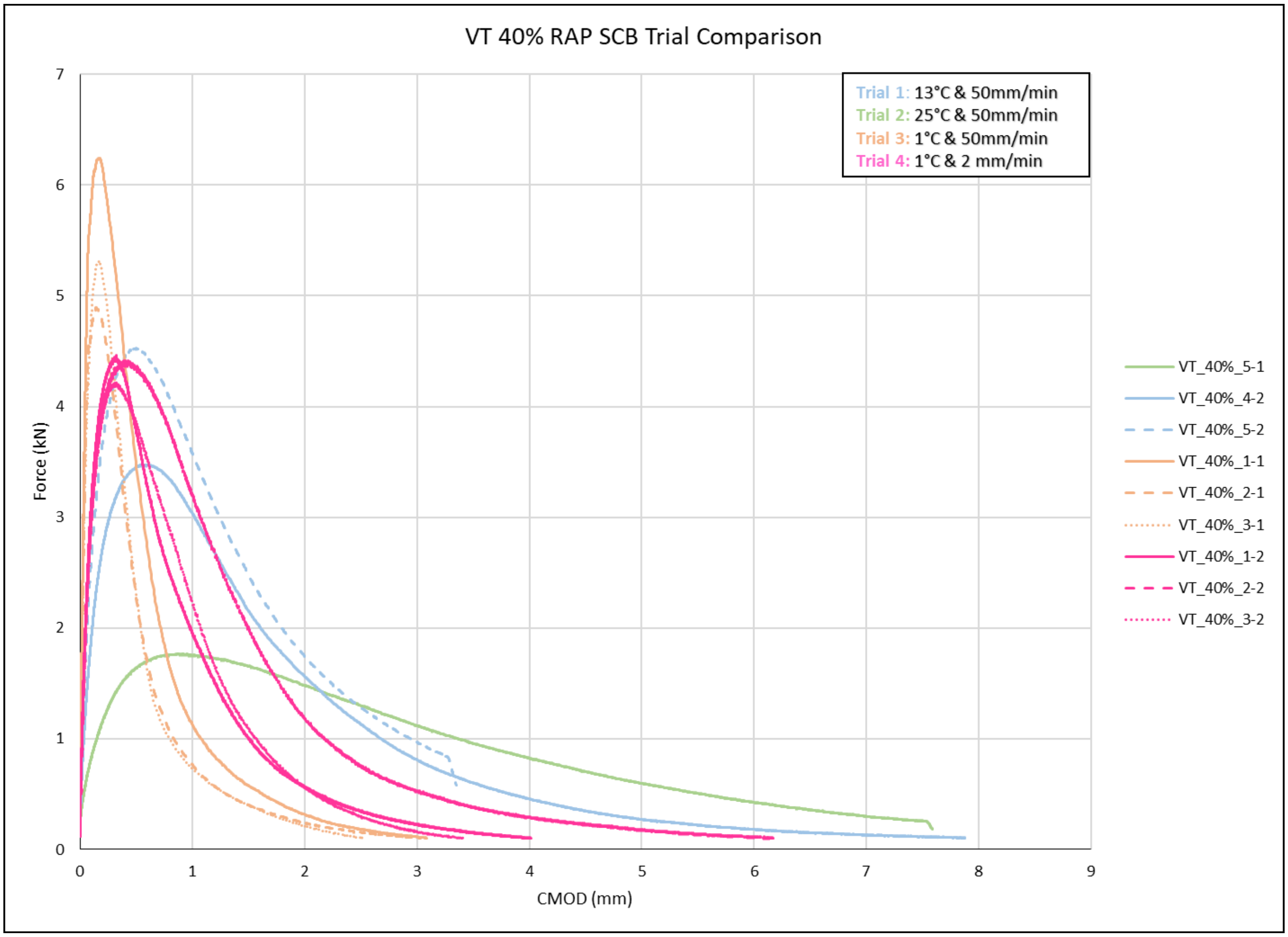

Figure 9: SCB load-displacement curves for VT 40% RAP mixtures.