LABORATORY COMPARISON OF SOLVENT-LOADED AND SOLVENT-FREE EMULSIONS

Interim Report

SPR #391

Oregon Department of Transportation

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SPR PROJECT #391

by

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16. Abstract

Asphalt emulsions have been widely used in highway construction and maintenance since the 1920s, initially as dust palliatives and spray applications. More recently, they have been used in more diverse paving applications such as base and surface course mixes, surface treatments and maintenance activities. The Oregon Department of Transportation (ODOT) uses nearly 450,000 Mg (500,000 t) of cold mix, i.e., emulsified asphalt concrete (EAC), for construction and maintenance at a cost of approximately $10 million per year. For safety, environmental and economic reasons, the use of emulsions is likely to increase dramatically in the next ten years. The decrease in highway funding and the public's heightened environmental awareness demand innovative technology for roads of the 21st century. Recognizing the opportunities inherent in this challenge, some commercial enterprises have already developed solvent-free alternatives. Preliminary laboratory testing of solvent-free emulsions in standard dense- and open-graded EAC mixes indicated that mechanical properties are comparable to or exceed those of conventional solvent-loaded emulsions. Accordingly, the objective of this research was to quantify the difference between conventional solvent-loaded and solvent-free EAC as measured by indirect tensile strength.

Two aggregates typically used in ODOT Regions 4 and 5 were combined with three asphalt emulsions: a conventional CMS-2S and two commercially produced solvent-free emulsions. The results from this laboratory study are extremely promising. Specimens made with solvent-free emulsions had consistently greater indirect tensile strengths than did those made with conventional solvent-loaded emulsions. Furthermore, specimens made with the solvent-free emulsions achieved that strength gain more rapidly. Minor problems with the solvent-free emulsion consistency, i.e., uniformity, were encountered, but are considered an artifact of the production process rather than a problem with the material. Given the obvious effects on mixing, coating, adhesion and strength properties, this product consistency problem should be addressed prior to field trials, the logical extension of this very promising laboratory study. To that end, experiment designs for additional laboratory testing and field trials have been proposed.

The results of this and subsequent research could reduce, if not entirely eliminate the use of volatile solvents in EAC, yielding both economic and environmental benefits. Elimination of volatile solvent minimizes the fire hazard enhancing worker safety during manufacture of the emulsion and construction of the pavement section. Two-fold environmental benefits are expected with the use of solvent-free emulsions: improved air quality because of the elimination of volatile fumes; and reduction in the possibility of ground water contamination.

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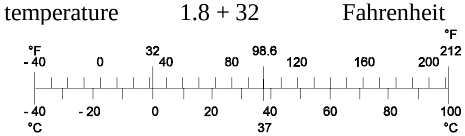
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
In	Inches	25.4	Millimeters	Mm
Ft	Feet	0.305	Meters	M
Yd	Yards	0.914	Meters	M
Mi	Miles	1.61	Kilometers	Km
		AREA		
in^2	Square inches	645.2	millimeters	mm^2
ft^2	Square feet	0.093	meters squared	M^2
yd^2	Square yards	0.836	meters squared	M^2
Ac	Acres	0.405	Hectares	Ha
mi^2	Square miles	2.59	kilometers squared	Km^2
		VOLUME		
fl oz	Fluid ounces	29.57	Milliliters	ML
Gal	Gallons	3.785	Liters	L
ft^3	Cubic feet	0.028	meters cubed	m^3
yd^3	Cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
Oz	Ounces	28.35	Grams	G
Lb	Pounds	0.454	Kilograms	Kg
T	Short tons (2000 lb)	0.907	Megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	Millimeters	0.039	inches	in
m	Meters	3.28	feet	ft
m	Meters	1.09	yards	yd
km	Kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	Hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	Liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	Grams	0.035	ounces	oz
kg	Kilograms	2.205	pounds	lb
Mg	Megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement

(4-7-94 jbp)

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DISCLAIMER

LABORATORY COMPARISON OF SOLVENT-LOADED AND SOLVENT-FREE EMULSIONS

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1.0 INTRODUCTION

1.1 BACKGROUND

Asphalt emulsions have been widely used in highway construction and maintenance since the 1920s, initially as dust palliatives and spray applications. More recently, they have been used in more diverse paving applications such as base and surface course mixes, surface treatments and maintenance activities *(Asphalt Institute)*. Annually, the Oregon Department of Transportation (ODOT) uses nearly 450,000 Mg (500,000 t) of cold mix, ie. emulsified asphalt concrete (EAC), for construction and maintenance at a cost of approximately $10 million.

Emulsions typically contain asphalt cement, water, and emulsifying agent in the following approximate proportions: 65-70%, 30-35%, and 2-3%, respectively. The CMS-2S emulsion widely used in ODOT Regions 4 and 5 (eastern Oregon) typically contains about 9% volatile solvent. Solvents are included in emulsions to facilitate mixing and enhance aggregate coating. For engineering, environmental and economic reasons, the use of emulsions is likely to increase dramatically in the next ten years. The decrease in highway funding and the public's heightened environmental awareness demand innovative technology for roads of the 21st century. Recognizing the opportunities inherent in this challenge, some commercial enterprises have already developed solvent-free alternatives.

Preliminary laboratory testing of these solvent-free emulsions in standard dense- and open-graded emulsified asphalt concrete mixes indicates that mechanical properties are comparable to or exceed those of conventional solvent-based emulsions. Field evaluation of solvent-free emulsions has only recently begun in Western Europe and South America, but appears promising *(Majeska 1996; Leahy 1997; Leahy and Majeska 1997)*. One commercial entity has developed a medium-to-slow set solvent-free emulsion that consists of an alkyl polyamine. Alkyl polyamine is a cationic surfactant that enhances the emulsion's adhesion and resistance to water. Another commercial entity has developed a similar emulsion, which contains fatty and rosin acids, and lignin. These compounds are derived from by-products of the pulp and paper industry.

1.2 OBJECTIVES

The purpose of this research is to determine the suitability of solvent-free emulsions in terms of pavement performance. The specific focus is on the laboratory and field performance of typical emulsified asphalt concrete mixes used primarily in ODOT Regions 4 and 5. Cold mix pavements in Regions 4 and 5 are generally open-graded and covered with a chip seal for traffic and snow plow protection.

The results of this study could reduce the amount of volatile solvents used in emulsified asphalt concrete, yielding economic and environmental benefits. Elimination of volatile solvents minimizes the fire hazard and enhances worker safety during manufacture of the emulsion and at pavement construction. Environmental benefits in terms of air quality are expected because of the elimination of volatile fumes. Given the heightened environmental awareness of the government agencies and the driving public, the use of solvent-free technology could enhance Oregon's already positive image as an environmentally progressive state.

1.3 HYPOTHESIS

The hypothesis for the research is as follows: for open-graded emulsion asphalt concrete (EAC) mixes, solvent-free emulsions produce material properties that meet or exceed those of conventional solvent-loaded emulsions.

2.0 EXPERIMENT DESIGN

This research attempted to quantify the difference between conventional solvent-loaded and solvent-free EAC as measured by indirect tensile strength. Two aggregates typically used in ODOT Regions 4 and 5 were combined with three asphalt emulsions. The aggregates, henceforth referred to as "Fredrick Butte" and "Burns Junction," were described by ODOT personnel as basalt and basaltic andesite, respectively. The Frederick Butte aggregate was from a private, non-commercial quarry and was considered good quality. The source of the Burns Junction aggregate was an ODOT-owned quarry; the aggregate was considered marginal quality. The asphalt emulsions used in this research were as follows: a conventional solvent-loaded CMS-2S provided by Chevron, and two solvent-free emulsions, one each provided by Westvaco and Akzo Nobel.

2.1 MIX DESIGN

A preliminary step of the research was to determine the optimum emulsion content for the samples. In this experiment, the job mix formula (JMF) determined by Oregon Department of Transportation (ODOT) was the starting point. The aggregate gradations, mix design data, and final JMF for an open-graded emulsified asphalt concrete are shown in Tables 2.1 and 2.2.

According to ODOT personnel, the CMS-2S emulsion used for the Frederick Butte and Burns Junction projects was produced by Idaho Asphalt. The average solvent content for the Frederick Butte and Burns Junction projects was 8.8% and 9.1%, respectively. Typically, CMS-2S emulsions contain approximately 9 to 12% solvent. As to mix design, ODOT selects the design emulsion content based on the following criteria: index of retained strength ≥ 40%; and aggregate coating ≥ 90%.

Table 2.1: Final Job Mix Formula Gradations

Burns Junction Job Mix Formula Gradation				Fredrick Butte Job Mix Formula Gradation		
Sieve Size		% Passing		Sieve Size		% Passing
1¼"	32 mm	100		1¼"	32 mm	100
1"	25.4 mm	100		1"	25.4 mm	100
¾"	19 mm	98		¾"	19 mm	99
½"	12.5 mm	75		½"	12.5 mm	81
¼"	6.3 mm	27		¼"	6.3 mm	24
#10	2 mm	3		#10	2 mm	2
#40	0.425 mm	2		#40	0.425 mm	1
#200	0.075 mm	1.4		#200	0.075 mm	0.9

Table 2.2: ODOT Mix Design and Optimum Emulsion Content

	Sample ID	Sample Description	% Emulsion by Wt. of Dry Aggregate	% H_2O by Wt. of Dry Aggregate	Average Height (in)*	Mass in Air (g)	Gmb	Load (lb)*	Compressive Strength (lb/in^2)*	Index of Retained Strength
ODOT Mix Design: Burns Junction Solvent-Loaded (CMS-2S)										
8.5% oil distillate	1	Unconditioned	4.0	1.5	4.33	1686.3	1.897	945	75	17
	2	Conditioned	4.0	1.5	4.33	1684.6	1.895	160	13	
	3	Unconditioned	5.0	1.5	4.31	1699.7	1.921	1135	90	24
	4	Conditioned	5.0	1.5	4.31	1693.7	1.914	270	21	
	5	Unconditioned	6.0	1.5	4.29	1713.7	1.945	1083	86	41
	6	Conditioned	6.0	1.5	4.28	1709.8	1.946	445	35	
	7	Unconditioned	7.0	1.5	4.31	1723.7	1.948	1225	97	38
	8	Conditioned	7.0	1.5	4.27	1722.0	1.964	463`	37	
6.5% oil distillate	1	Unconditioned	4.0	1.5	4.36	1673.8	1.870	1393	111	14
	2	Conditioned	4.0	1.5	4.37	1672.5	1.864	197	16	
	3	Unconditioned	5.0	1.5	4.37	1682.0	1.875	1483	118	15
	4	Conditioned	5.0	1.5	4.35	1684.1	1.885	217	17	
	5	Unconditioned	6.0	1.5	4.34	1697.0	1.904	1160	92	32
	6	Conditioned	6.0	1.5	4.35	1701.2	1.905	375	30	
	7	Unconditioned	7.0	1.5	4.31	1706.9	1.929	1207	96	30
	8	Conditioned	7.0	1.5	4.31	1708.6	1.931	366	29	
ODOT Mix Design: Fredrick Butte Solvent-Loaded (CMS-2S)										
4.5 % oil distillate	31	Unconditioned	4.0	1.0	3.76	1680.6	2.177	1712	136	24
	32	Conditioned	4.0	1.0	3.77	1680.3	2.171	410	33	
	33	Unconditioned	5.0	1.0	3.74	1692.2	2.204	1670	133	29
	34	Conditioned	5.0	1.0	3.74	1690.2	2.201	482	38	
	35	Unconditioned	6.0	1.0	3.74	1699.8	2.213	1652	131	61
	36	Conditioned	6.0	1.0	3.73	1701.8	2.222	1010	80	
	37	Unconditioned	7.0	1.0	3.73	1709.0	2.231	1704	136	62
	38	Conditioned	7.0	1.0	3.74	1692.2	2.204	1057	84	

Asphalt Data	% Emulsion by Wt. of Dry Aggregate	% H_20 by Wt. of Dry Aggregate	Max Specific Gravity (Gmm)
Burns Junction Optimum Emulsion Content			
Wearing Course	5.9	1.5	2.398
Base Course	5.9	1.5	2.398
Fredrick Butte Optimum Emulsion Content			
Wearing Course	5.4	1.5	2.745
Base Course	5.4	1.5	2.745

* To convert to metric: Multiply inches by 25.4 to find millimeters. Multiply pounds by 0.454 to find kilograms. Multiply lb/in^2 by 0.0007031 to find kg/mm^2.

Comparable results for the ODOT Mix Design were obtained in the Oregon State University (OSU) lab. Specifically, eight specimens were fabricated and tested in accordance with ODOT TM 313: Method of Test for Compressive Strength of Emulsified Asphalt Mixtures. The results from the testing are reported in Table 2.3.

The various values shown in the table were calculated using equations 2-1 through 2-6.

$$\textbf{Geometric Gmb} = \frac{\dfrac{M_d}{(\pi d^2/4)(H_{avg})}}{\gamma_{H_2O}} \tag{2-1}$$

$$\textbf{Parafilm Gmb} = \frac{M_d}{M_{para} - M_w - [(M_{para} - M_d)/0.9]} \tag{2-2}$$

$$\textbf{\% Air Voids (Geometric)} = \frac{Gmm - Gmb_{geom}}{Gmm} \cdot 100 \tag{2-3}$$

$$\textbf{\% Air Voids (Parafilm)} = \frac{Gmm - Gmb_{para}}{Gmm} \cdot 100 \tag{2-4}$$

$$\textbf{Compressive Strength} = \frac{Load}{(\pi d^2/4)} \tag{2-5}$$

$$\textbf{Index of Retained Strength} = \frac{Strength_{conditioned}}{Strength_{unconditioned}} \tag{2-6}$$

where
- M_d = Mass of dry sample
- M_{para} = Mass of sample in air parafilmed
- M_w = Mass of sample submerged in water parafilmed
- H_{avg} = Average height of sample (in)
- Gmm = Maximum Theoretical Specific Gravity
- Gmb_{geom} = Bulk Specific Gravity (geometric method)
- Gmb_{para} = Bulk Specific Gravity (parafilm method)
- d = Diameter of sample (in)
- γ_{H_2O} = Unit weight of water

Table 2.3: OSU Lab Mix Design Confirmation

Sample ID	Sample Description	Mass in Air (g)	Average Height (in)*	Mass with Parafilm (g)	Mass w/ Parafilm in H_20	Geometric Gmb	Parafilm Gmb	% Air Voids (Geometric Gmb)	% Air Voids (Parafilm)	Load (lb)*	Compressive Strength (psi)*	Index of Retained Strength (%)
Mix Design: Burns Junction Solvent-Loaded (CMS-2S)												
1	Unconditioned	1539.7	4.130	1547	680.5	1.810	1.794	24.4	25.1	814	65	43
2	Conditioned	1529.9	4.145	1537.1	698.1	1.793	1.841	25.1	23.1	346	28	
3	Unconditioned	1542.9	4.117	1549.8	703.1	1.820	1.839	24.0	23.2	850	68	42
4	Conditioned	1545.0	4.111	1550.6	696.1	1.825	1.821	23.8	23.9	360	29	
Mix Design: Fredrick Butte Solvent-Loaded (CMS-2S)												
1	Unconditioned	1759.7	4.144	1767.4	911.7	2.062	2.077	24.9	24.3	787	63	55
2	Conditioned	1747.4	4.087	1754.5	906.7	2.076	2.080	24.4	24.2	432	34	
3	Unconditioned	1757.2	4.101	1764.6	912.1	2.081	2.081	24.2	24.2	791	63	58
4	Conditioned	1754.7	4.091	1762.2	915.1	2.083	2.092	24.1	23.8	457	36	

* To convert to metric: Multiply inches by 25.4 to find millimeters. Multiply pounds by 0.454 to find kilograms. Multiply lb/in^2 by 0.0007031 to find kg/mm^2.

A comparison of the indices of retained strength confirmed the ODOT Mix Design. For the Fredrick Butte aggregate, ODOT recorded an index value of 61% for an optimum emulsion content of 6.0%. This was confirmed by the average OSU lab value of 56.5% for the 5.4% emulsion. The ODOT design recorded a bulk specific gravity of 2.218 while the OSU lab value averaged at 2.082. Also, the specimen heights obtained by ODOT averaged 9.42 mm (0.371 in) shorter than the OSU lab values. It is likely that the higher specific gravity and shorter specimens resulted in the ODOT design obtaining higher compressive strengths, in some cases nearly twice those obtained in the OSU lab. Although ODOT obtained higher strengths, the indices of retained strength were comparable.

The ODOT mix design reported an index of retained strength value of 41% for the Burns Junction aggregate with 6.0% emulsion content. The OSU lab value reported an index value of 42.5% with a 5.9% emulsion content, which confirmed the mix design. The compressive strengths obtained in the OSU lab were slightly less than those recorded by ODOT, but this can be explained by the discrepancies in both the bulk specific gravity and height of the specimens. However, the discrepancies for the Burns Junction aggregate were less than those of the Fredrick Butte aggregate.

2.2 ORIGINAL RESEARCH

A paired experiment was conducted to compare the strength characteristics of EAC made with solvent-free and conventional solvent-loaded emulsions. The conventional solvent-loaded emulsion served as the control for the experiment. The experiment design for this study originally required 180 cylindrical specimens measuring 102 mm (4 in) in diameter and 63.5 mm ± 4 mm (2.5 in ± 0.16 in) in height. The original experiment design was constructed so that six replicate samples would be fabricated for each aggregate source, emulsion type, and cure time. During the experiment, a potential problem was found in the Westvaco solvent-free emulsion when mixing with the Burns Junction aggregate. The emulsion appeared to have a different consistency, and therefore, ten additional samples were tested (See Table 2.4). This was done to check the emulsion consistency from batch to batch.

Table 2.4: Experiment Design

		Fredrick Butte Aggregate					Burns Junction Aggregate				
Ambient Cure Time Before Testing (days)		1	7	14	30	60	1	7	14	30	60
Number of Samples in Each Cure Time	Solvent-Loaded	6	6	6	6	6	6	6	6	6	6
	Westvaco Solvent-Free	6	6	6	6	6	8	8	8	8	8
	Akzo Nobel Solvent-Free	6	6	6	6	6	6	6	6	6	6

2.2.1 Sample Preparation

The batched aggregate was combined with water and emulsion at room temperature, and mixed by hand until the aggregate was fully coated. The mixture was spread evenly in a flat bottom pan to cure, also at room temperature. Each aggregate-emulsion combination was cured in a 25°C (77°F) air bath until the emulsion “broke,” a term used to describe the moment the water begins to separate from the asphalt particles. The loose mix cure times for each aggregate-emulsion combination are shown in Table 2.5.

Table 2.5: Loose Mix Cure Times

	Loose Mix Cure Time (hours:minutes)	
	Frederick Butte	**Burns Junction**
Solvent-Loaded	24:00	24:00
Westvaco Solvent-Free	2:20	1:15
Akzo Nobel Solvent-Free	3:00	2:00

After curing in the loose mix form, samples were compacted as outlined with ODOT TM 313. A steel compaction mold with an inside diameter of 100 mm (4 in) was used to mold the specimens. Approximately half of the mixture was poured into the mold and rodded 25 times with a thin spatula. The remaining portion of the mixture was poured into the mold and again rodded 25 times to ensure proper compaction and to prevent segregation. After a follower was placed on top of the mixture, the mold was placed between the load platens of the test machine so that the load was applied axially. A leveling load of 855 kg (1,885 lbs) was applied and held for 15 to 20 seconds. Then the load was increased to 17,146 kg (37,800 lbs) within 30 seconds, and held static for two minutes to complete the compaction. After compaction, the samples were extracted from the molds, placed on glass plates in a 60°C (140° F) oven, and allowed to cure for 24 hours.

Following the oven cure, samples were removed from the oven and allowed to cool. The geometric bulk specific gravity of each sample was determined. Air void content was computed using the theoretical maximum specific gravity and the geometric bulk specific gravity.

2.2.2 Test Procedures

For confirmation of the EAC design, cylindrical specimens (102 mm diameter × 102 mm height (4 in × 4 in)) were tested for axial compressive strength. Since direct tensile strength is much more widely used in mix design as a relative measure of strength, this parameter was deemed more appropriate for use in this research.

Each sample was subjected to an indirect tensile strength test as outlined in AASHTO T283 *(1993)*. To determine the indirect tensile strength, a specimen was removed from the 25°C (77°F) air bath and placed between the steel loading strips of the test machine (MTS). The steel loading strips were milled with a 102 mm (4 in) radius that matched the radius of the specimen. The specimen was placed so that the test load would be applied through the diameter as shown in Figure 2.1.

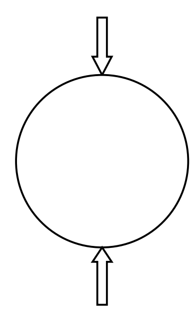


Figure 2.1: Load Application

The test load was then applied at a constant rate of 51 mm/minute (2 in/minute) until the specimen formed a vertical crack. A plotter receiving data from the MTS load cell generated a load-time curve. The load applied to the specimen was recorded on the Y-axis of the plotter while time was recorded on the X-axis. The indirect tensile strength was computed as shown in equation 2-7:

$$\mathbf{S_t = \frac{2P}{\pi td}} \tag{2-7}$$

where S_t = tensile strength
P = maximum load
t = specimen thickness
d = specimen diameter

Test results are summarized in the following chapter.

3.0 RESULTS

The complete data and a summary are included in Tables 3.1 through 3.6, and are shown graphically in Figures 3.1 and 3.2. Typical data reflecting replicate variability are shown in Figures 3.3a - 3.3f. An example of large variability and an example of small variability are shown for each aggregate-emulsion combination. Summaries of the variability as a function of curing time are shown in Figures 3.4 and 3.5. Data from all the specimens were used in the formulation of these figures.

The summary table on each data sheet contains two calculations for standard deviation. The numbers under the ‘Standard Deviation’ heading were determined using the ‘n-1’ or ‘nonbiased’ method. This formula assumes that the arguments are a sample of some larger population. The ‘Standard Deviation P’ column corresponds to the standard deviation of the population. This formula assumes that the arguments are the entire population, which conforms to the conducted experiment. Values for both methods of calculating standard deviation are given to demonstrate that they are not significantly different despite the small sample size. The coefficient of variation was calculated using the standard deviation of the population.

Table 3.1: Fredrick Butte Solvent-Loaded Data

FB SOLVENT LOADED Gmm	Sample 1	Sample 2
Mass Sample (g)	1504.7	1525.9
Mass Pync + H_2O (g)	6199.7	6199.7
Mass Pync+H_2O+Sample (g)	7156.2	7169.7
Gmm	2.745	2.745
	Avg Gmm	**2.745**

EXPERIMENT SPECIMEN KEY	
F	Fredrick Butte
B	Burns Junction
S	Solvent Loaded
W	Westvaco
A	Akzo Nobel

Cure Time (days)	Average Load (lb)	Average ITS (psi)	Maximum ITS (psi)	Minimum ITS (psi)	Standard Deviation	Standard Deviation P	CV (%)
1	220	14	15	14	0.5	0.4	3
7	250	16	19	14	2.1	1.9	12
14	223	14	16	12	1.5	1.3	9
30	294	19	23	12	3.9	3.6	19
60	319	21	23	18	1.9	1.7	8

Sample ID	Ambient Cure Time (days)	Height (in)*				Average Height (in)*	Mass in Air (g)	Geometric Gmb	% Air Voids (Geometric Gmb)	Load (lb)*	Indirect Tensile Strength (psi)*	Notes
F S 1-1	1	2.450	2.435	2.431	2.451	2.442	1038.2	2.065	24.8	221	14	
F S 1-2	1	2.442	2.456	2.461	2.442	2.450	1045.5	2.072	24.5	223	15	
F S 1-3	7	2.442	2.427	2.430	2.451	2.438	1045.3	2.082	24.1	243	16	
F S 1-4	7	2.417	2.432	2.444	2.430	2.431	1044.5	2.087	24.0	285	19	
F S 1-5	14	2.430	2.426	2.428	2.430	2.429	1044.5	2.089	23.9	189	12	Tested @27.5 °C
F S 1-6	14	2.452	2.439	2.444	2.462	2.449	1046.5	2.075	24.4	201	13	Tested @27.5 °C
F S 1-7	30	2.469	2.456	2.457	2.458	2.460	1045.9	2.065	24.8	290	19	
F S 1-8	30	2.441	2.441	2.434	2.456	2.443	1040.0	2.067	24.7	272	18	
F S 1-9	60	2.451	2.450	2.460	2.453	2.454	1048.6	2.075	24.4	299	19	
F S 1-10	60	2.441	2.441	2.464	2.447	2.448	1044.2	2.071	24.5	305	20	
F S 2-1	1	2.450	2.405	2.444	2.440	2.435	1045.8	2.086	24.0	227	15	
F S 2-2	1	2.442	2.443	2.451	2.445	2.445	1046.1	2.077	24.3	224	15	
F S 2-3	7	2.426	2.428	2.433	2.427	2.429	1047.1	2.094	23.7	257	17	
F S 2-4	7	2.445	2.449	2.443	2.445	2.446	1045.1	2.075	24.4	284	18	
F S 2-5	14	2.440	2.453	2.452	2.445	2.448	1042.9	2.069	24.6	244	16	
F S 2-6	14	2.445	2.440	2.442	2.441	2.442	1046.6	2.081	24.2	219	14	
F S 2-7	30	2.444	2.450	2.449	2.435	2.445	1044.1	2.074	24.4	191	12	
F S 2-8	30	2.444	2.452	2.442	2.449	2.447	1046.9	2.078	24.3	305	20	
F S 2-9	60	2.441	2.441	2.444	2.442	2.442	1048.4	2.085	24.0	336	22	
F S 2-10	60	2.449	2.426	2.439	2.440	2.439	1048.8	2.089	23.9	281	18	Failed in air bath
F S 3-1	1	2.455	2.435	2.434	2.440	2.441	1044.5	2.078	24.3	218	14	
F S 3-2	1	2.459	2.457	2.437	2.443	2.449	1045.1	2.072	24.5	208	14	
F S 3-3	7	2.440	2.455	2.454	2.447	2.449	1040.9	2.064	24.8	218	14	
F S 3-4	7	2.453	2.455	2.471	2.470	2.462	1045.5	2.062	24.9	213	14	
F S 3-5	14	2.437	2.457	2.461	2.447	2.451	1043.7	2.068	24.7	240	16	
F S 3-6	14	2.474	2.466	2.472	2.469	2.470	1037.2	2.039	25.7	242	16	
F S 3-7	30	2.441	2.446	2.437	2.432	2.439	1042.3	2.075	24.4	345	23	
F S 3-8	30	2.466	2.461	2.450	2.452	2.457	1045.4	2.066	24.7	363	23	
F S 3-9	60	2.444	2.442	2.437	2.436	2.440	1038.8	2.068	24.7	355	23	
F S 3-10	60	2.429	2.421	2.436	2.431	2.429	1033.1	2.065	24.8	337	22	

*To convert to metric: Multiply inches by 25.4 to find millimeters. Multiply pounds by 0.454 to find kilograms. Multiply lb/in^2 by 0.0007031 to find kg/mm^2.

Table 3.2: Fredrick Butte Westvaco Solvent-Free Data

FB WESTVACO Gmm	Sample 1	Sample 2
Mass Sample (g)	1537.2	1530.4
Mass Pync + H_2O (g)	6199.1	6199.1
Mass Pync+H_2O+Sample (g)	7175.9	7170.2
Gmm	2.743	2.736
	Avg Gmm	**2.740**

EXPERIMENT SPECIMEN KEY	
F	Fredrick Butte
B	Burns Junction
S	Solvent Loaded
W	Westvaco
A	Akzo Nobel

Cure Time (days)	Average Load (lb)	Average ITS (psi)	Maximum ITS (psi)	Minimum ITS (psi)	Standard Deviation	Standard Deviation P	CV (%)
1	488	33	36	25	4.2	3.9	12
7	583	40	44	36	2.5	2.3	6
14	603	41	44	38	2.1	1.9	5
30	594	40	46	35	3.5	3.2	8
60	748	51	62	45	6.7	6.1	12

Sample ID	**Ambient Cure Time (days)**	**Height (in)***				**Average Height (in)***	**Mass in Air (g)**	**Geometric Gmb**	**% Air Voids (Geometric Gmb)**	**Load (lb)***	**Indirect Tensile Strength (psi)***	**Notes**
F W 1-1	1	2.363	2.361	2.355	2.365	2.361	1047.5	2.154	21.4	492	33	
F W 1-2	1	2.347	2.351	2.358	2.355	2.353	1050.0	2.167	20.9	527	36	
F W 1-3	7	2.352	2.353	2.374	2.351	2.358	1053.9	2.171	20.8	591	40	
F W 1-4	7	2.359	2.358	2.365	2.344	2.357	1053.6	2.171	20.8	534	36	
F W 1-5	14	2.335	2.340	2.344	2.351	2.343	1051.0	2.179	20.5	646	44	
F W 1-6	14	2.367	2.370	2.373	2.377	2.372	1056.5	2.163	21.0	601	40	
F W 1-7	30	2.366	2.366	2.370	2.354	2.364	1046.8	2.150	21.5	600	40	
F W 1-8	30	2.349	2.370	2.358	2.358	2.359	1053.8	2.169	20.8	625	42	
F W 1-9	60	2.342	2.346	2.343	2.338	2.342	1053.5	2.184	20.3	911	62	Tested at 22.5 °C
F W 1-10	60	2.362	2.356	2.352	2.355	2.356	1055.8	2.176	20.6	826	56	Tested at 22.5 °C
F W 2-1	1	2.350	2.350	2.363	2.356	2.355	1038.3	2.141	21.8	529	36	
F W 2-2	1	2.340	2.340	2.344	2.344	2.342	1040.6	2.158	21.2	528	36	
F W 2-3	7	2.330	2.332	2.338	2.338	2.335	1039.0	2.161	21.1	570	39	
F W 2-4	7	2.335	2.333	2.332	2.338	2.335	1026.4	2.135	22.1	568	39	Damaged
F W 2-5	14	2.308	2.316	2.335	2.314	2.318	1046.3	2.192	20.0	618	42	
F W 2-6	14	2.341	2.337	2.340	2.335	2.338	1039.7	2.159	21.2	579	39	
F W 2-7	30	2.342	2.340	2.350	2.341	2.343	1044.3	2.164	21.0	561	38	
F W 2-8	30	2.350	2.347	2.348	2.345	2.348	1041.9	2.155	21.3	522	35	
F W 2-9	60	2.340	2.339	2.342	2.354	2.344	1040.1	2.155	21.3	661	45	
F W 2-10	60	2.320	2.316	2.312	2.325	2.318	1044.6	2.188	20.1	659	45	
F W 3-1	1	2.330	2.330	2.301	2.330	2.323	1016.3	2.125	22.4	363	25	Damaged, emulsion not mixed well?
F W 3-2	1	2.333	2.332	2.323	2.340	2.332	1037.7	2.161	21.1	486	33	
F W 3-3	7	2.317	2.337	2.357	2.336	2.337	1042.8	2.167	20.9	594	40	
F W 3-4	7	2.332	2.342	2.331	2.317	2.331	1047.3	2.182	20.3	641	44	
F W 3-5	14	2.335	2.343	2.346	2.343	2.342	1048.2	2.174	20.7	559	38	
F W 3-6	14	2.342	2.340	2.350	2.352	2.346	1053.1	2.180	20.4	613	42	
F W 3-7	30	2.348	2.343	2.349	2.367	2.352	1055.5	2.179	20.4	590	40	
F W 3-8	30	2.342	2.335	2.320	2.314	2.328	1054.6	2.200	19.7	667	46	
F W 3-9	60	2.362	2.352	2.342	2.360	2.354	1054.9	2.176	20.6	708	48	
F W 3-10	60	2.353	2.348	2.342	2.346	2.347	1055.7	2.184	20.3	721	49	

*To convert to metric: Multiply inches by 25.4 to find millimeters. Multiply pounds by 0.454 to find kilograms. Multiply lb/in^2 by 0.0007031 to find kg/mm^2.

Table 3.3: Fredrick Butte Akzo Nobel Solvent-Free Data

FB AKZO NOBEL Gmm	Sample 1	Sample 2
Mass Sample (g)	1525.8	1531.5
Mass Pync + H_2O (g)	6199.4	6199.4
Mass Pync + H_2O+Sample (g)	7175	7177.1
Gmm	2.773	2.765
	Avg Gmm	**2.769**

EXPERIMENT SPECIMEN KEY	
F	Fredrick Butte
B	Burns Junction
S	Solvent Loaded
W	Westvaco
A	Akzo Nobel

Cure Time (days)	Average Load (lb)	Average ITS (psi)	Maximum ITS (psi)	Minimum ITS (psi)	Standard Deviation	Standard Deviation P	CV (%)
1	473	32	34	29	1.8	1.7	5
7	500	34	36	32	1.5	1.4	4
14	540	37	41	33	2.5	2.3	6
30	546	37	39	34	2.0	1.8	5
60	598	40	41	39	1.1	1.0	2

Sample ID	Ambient Cure Time (days)	Height (in)*				Average Height (in)*	Mass in Air (g)	Geometric Gmb	% Air Voids (Geometric Gmb)	Load (lb)*	Indirect Tensile Strength (psi)*	Notes
F A 1-1	1	2.359	2.365	2.373	2.368	2.366	1045.8	2.146	22.5	508	34	
F A 1-2	1	2.375	2.368	2.371	2.366	2.370	1046.8	2.145	22.5	474	32	
F A 1-3	7	2.352	2.355	2.360	2.353	2.355	1051.1	2.167	21.7	482	33	
F A 1-4	7	2.350	2.354	2.349	2.346	2.350	1050.9	2.172	21.6	491	33	
F A 1-5	14	2.361	2.364	2.365	2.358	2.362	1048.2	2.155	22.2	491	33	
F A 1-6	14	2.341	2.348	2.353	2.334	2.344	1050.0	2.175	21.5	541	37	
F A 1-7	30	2.345	2.348	2.345	2.364	2.351	1050.4	2.170	21.6	582	39	
F A 1-8	30	2.348	2.351	2.357	2.349	2.351	1050.0	2.169	21.7	573	39	
F A 1-9	60	2.369	2.379	2.369	2.352	2.367	1049.3	2.152	22.3	592	40	
F A 1-10	60	2.350	2.354	2.342	2.333	2.345	1031.2	2.136	22.9	611	41	
F A 2-1	1	2.332	2.370	2.365	2.355	2.356	1048.1	2.161	22.0	450	30	
F A 2-2	1	2.348	2.336	2.356	2.362	2.351	1049.9	2.169	21.7	434	29	
F A 2-3	7	2.360	2.352	2.363	2.370	2.361	1050.5	2.160	22.0	476	32	
F A 2-4	7	2.348	2.338	2.350	2.378	2.354	1052.4	2.171	21.6	532	36	
F A 2-5	14	2.360	2.353	2.360	2.353	2.357	1047.7	2.159	22.0	603	41	
F A 2-6	14	2.355	2.358	2.353	2.361	2.357	1051.3	2.166	21.8	530	36	
F A 2-7	30	2.361	2.372	2.405	2.370	2.377	1046.6	2.138	22.8	510	34	
F A 2-8	30	2.340	2.350	2.350	2.361	2.350	1052.4	2.174	21.5	541	37	
F A 2-9	60	2.386	2.358	2.351	2.387	2.371	1049.8	2.151	22.3	603	41	
F A 2-10	60	2.367	2.370	2.356	2.373	2.367	1052.0	2.159	22.0	605	41	
F A 3-1	1	2.355	2.361	2.361	2.362	2.360	1044.7	2.150	22.4	498	34	
F A 3-2	1	2.354	2.335	2.328	2.338	2.339	1047.8	2.176	21.4	474	32	
F A 3-3	7	2.380	2.363	2.351	2.386	2.370	1050.6	2.153	22.3	524	35	
F A 3-4	7	2.338	2.338	2.372	2.352	2.350	1047.3	2.164	21.9	496	34	
F A 3-5	14	2.350	2.360	2.371	2.356	2.359	1050.9	2.163	21.9	524	35	
F A 3-6	14	2.356	2.357	2.347	2.345	2.351	1049.4	2.167	21.7	552	37	
F A 3-7	30	2.358	2.356	2.360	2.354	2.357	1049.0	2.161	22.0	548	37	
F A 3-8	30	2.342	2.345	2.361	2.355	2.351	1048.1	2.165	21.8	522	35	
F A 3-9	60	2.357	2.365	2.365	2.360	2.362	1048.7	2.156	22.1	572	39	
F A 3-10	60	2.353	2.325	2.327	2.364	2.342	1046.1	2.169	21.7	606	41	

*To convert to metric: Multiply inches by 25.4 to find millimeters. Multiply pounds by 0.454 to find kilograms. Multiply lb/in^2 by 0.0007031 to find kg/mm^2.

Table 3.4: Burns Junction Solvent-Loaded Data

BJ SOLVENT LOADED Gmm	Sample 1	Sample 2
Mass Sample (g)	1492.7	1490.3
Mass Pync + H_2O (g)	6197.8	6197.8
Mass Pync+H_2O+Sample (g)	7066.4	7066.1
Gmm	2.392	2.396
	Avg Gmm	**2.394**

EXPERIMENT SPECIMEN KEY	
F	Fredrick Butte
B	Burns Junction
S	Solvent Loaded
W	Westvaco
A	Akzo Nobel

Cure Time (days)	Average Load (lb)	Average ITS (psi)	Maximum ITS (psi)	Minimum ITS (psi)	Standard Deviation	Standard Deviation P	CV (%)
1	266	17	20	13	2.7	2.5	15
7	326	20	26	18	3.2	2.9	14
14	356	22	26	17	3.0	2.7	12
30	451	28	30	26	1.5	1.4	5
60	497	31	33	29	1.7	1.6	5

Sample ID	Ambient Cure Time (days)	Height (in)*				Average Height (in)*	Mass in Air (g)	Geometric Gmb	% Air Voids (Geometric Gmb)	Load (lb)*	Indirect Tensile Strength (psi)*	Notes
B S 1-1	1	2.556	2.557	2.553	2.563	2.557	960.7	1.824	23.8	323	20	
B S 1-2	1	2.547	2.546	2.537	2.545	2.544	962.7	1.838	23.2	307	19	
B S 1-3	7	2.557	2.562	2.562	2.558	2.560	965.4	1.831	23.5	425	26	
B S 1-4	7	2.558	2.570	2.558	2.556	2.561	964.9	1.830	23.6	326	20	
B S 1-5	14	2.561	2.562	2.577	2.561	2.565	960.1	1.817	24.1	355	22	
B S 1-6	14	2.562	2.561	2.588	2.588	2.575	962.5	1.815	24.2	370	23	
B S 1-7	30	2.554	2.558	2.566	2.567	2.561	960.3	1.821	23.9	471	29	
B S 1-8	30	2.537	2.545	2.551	2.550	2.546	961.6	1.834	23.4	457	29	
B S 1-9	60	2.570	2.571	2.560	2.569	2.568	965.8	1.827	23.7	474	29	
B S 1-10	60	2.559	2.561	2.560	2.558	2.560	965.0	1.831	23.5	537	33	
B S 2-1	1	2.536	2.543	2.552	2.551	2.546	958.7	1.829	23.6	270	17	
B S 2-2	1	2.563	2.562	2.571	2.566	2.566	956.4	1.810	24.4	246	15	
B S 2-3	7	2.568	2.570	2.568	2.573	2.570	963.1	1.820	24.0	309	19	
B S 2-4	7	2.566	2.575	2.582	2.574	2.574	962.4	1.815	24.2	285	18	
B S 2-5	14	2.574	2.546	2.558	2.554	2.558	959.0	1.821	24.0	425	26	
B S 2-6	14	2.542	2.544	2.544	2.552	2.546	959.7	1.831	23.5	364	23	
B S 2-7	30	2.582	2.586	2.590	2.587	2.586	958.4	1.800	24.8	433	27	
B S 2-8	30	2.538	2.538	2.535	2.529	2.535	965.2	1.849	22.8	479	30	
B S 2-9	60	2.560	2.558	2.558	2.561	2.559	960.4	1.822	23.9	511	32	
B S 2-10	60	2.545	2.548	2.548	2.555	2.549	961.1	1.831	23.5	460	29	
B S 3-1	1	2.551	2.551	2.559	2.560	2.555	960.3	1.825	23.8	240	15	
B S 3-2	1	2.562	2.577	2.555	2.561	2.564	963.4	1.825	23.8	210	13	
B S 3-3	7	2.553	2.550	2.550	2.554	2.552	963.3	1.833	23.4	297	19	
B S 3-4	7	2.554	2.576	2.566	2.570	2.567	964.8	1.825	23.7	312	19	
B S 3-5	14	2.560	2.557	2.551	2.556	2.556	961.8	1.827	23.7	350	22	
B S 3-6	14	2.550	2.540	2.545	2.550	2.546	961.5	1.834	23.4	274	17	
B S 3-7	30	2.549	2.554	2.555	2.549	2.552	962.3	1.831	23.5	443	28	
B S 3-8	30	2.551	2.562	2.556	2.556	2.556	963.0	1.829	23.6	420	26	
B S 3-9	60	2.546	2.530	2.527	2.532	2.534	960.3	1.840	23.1	504	32	
B S 3-10	60	2.546	2.539	2.549	2.550	2.546	965.6	1.842	23.1	495	31	

*To convert to metric: Multiply inches by 25.4 to find millimeters. Multiply pounds by 0.454 to find kilograms. Multiply lb/in^2 by 0.0007031 to find kg/mm^2.

Table 3.5: Burns Junction Westvaco Solvent-Free Data

BJ WESTVACO Gmm	Sample 1	Sample 2
Mass Sample (g)	1547.7	1521.2
Mass Pync + H_2O (g)	6199.1	6199.1
Mass Pync+H_2O+Sample (g)	7096.8	7082.5
Gmm	2.381	2.385
	Avg Gmm	**2.383**

EXPERIMENT SPECIMEN KEY	
F	Fredrick Butte
B	Burns Junction
S	Solvent Loaded
W	Westvaco
A	Akzo Nobel

Cure Time (days)	Average Load (lb)	Average ITS (psi)	Maximum ITS (psi)	Minimum ITS (psi)	Standard Deviation	Standard Deviation P	CV (%)
1	614	39	42	36	2.1	1.9	5
7	683	43	45	42	1.1	1.0	2
14	728	46	49	41	2.8	2.6	6
30	782	49	53	46	2.6	2.4	5
60	846	54	57	51	2.5	2.3	4

Sample ID	Ambient Cure Time (days)	Height (in)*				Average Height (in)*	Mass in Air (g)	Geometric Gmb	% Air Voids (Geometric Gmb)	Load (lb)*	Indirect Tensile Strength (psi)*	Notes
B W 1-1	1	2.517	2.513	2.517	2.525	2.518	966.6	1.864	21.8	623	39	Emulsion consistency of milk-shake. Cured 2.5hr prior to compaction, appeared excessively stiff when compacted.
B W 1-2	1	2.521	2.521	2.525	2.528	2.524	972.4	1.871	21.5	584	37	
B W 1-3	7	2.536	2.524	2.528	2.538	2.532	974.3	1.869	21.6	670	42	
B W 1-4	7	2.510	2.511	2.520	2.511	2.513	976.4	1.887	20.8	712	45	
B W 1-5	14	2.513	2.515	2.518	2.517	2.516	972.5	1.877	21.2	780	49	
B W 1-6	14	2.505	2.510	2.504	2.507	2.507	969.8	1.879	21.2	744	47	
B W 1-7	30	2.511	2.508	2.511	2.520	2.513	979.5	1.893	20.6	844	53	
B W 1-8	30	2.530	2.533	2.531	2.540	2.534	975.4	1.870	21.5	759	48	
B W 1-9	60	2.513	2.508	2.512	2.511	2.511	973.7	1.883	21.0	798	51	
B W 1-10	60	2.518	2.508	2.518	2.512	2.514	974.2	1.882	21.0	837	53	
B W 2-1	1	2.497	2.488	2.490	2.492	2.492	961.1	1.873	21.4	639	41	Fresh bottle of emulsion consistency of chocolate syrup. Cured 1.5hr prior to compaction, appeared slightly over-cured.
B W 2-2	1	2.495	2.496	2.505	2.500	2.499	964.0	1.873	21.4	629	40	
B W 2-3	7	2.516	2.512	2.518	2.525	2.518	971.4	1.874	21.4	697	44	
B W 2-4	7	2.508	2.513	2.509	2.500	2.508	968.7	1.876	21.3	659	42	
B W 2-5	14	2.485	2.480	2.491	2.487	2.486	969.8	1.895	20.5	713	46	
B W 2-6	14	2.508	2.507	2.501	2.500	2.504	973.7	1.888	20.8	700	44	
B W 2-7	30	2.504	2.504	2.505	2.513	2.507	968.0	1.875	21.3	813	52	
B W 2-8	30	2.505	2.510	2.519	2.519	2.513	971.1	1.876	21.3	779	49	
B W 2-9	60	2.508	2.498	2.496	2.505	2.502	975.2	1.893	20.6	898	57	
B W 2-10	60	2.519	2.515	2.516	2.515	2.516	970.5	1.873	21.4	840	53	
B W 3-1	1	2.495	2.498	2.500	2.501	2.499	964.0	1.874	21.4	611	39	Fresh bottle of emulsion consistency of chocolate milk. Cured 1.4hr prior to compaction , appeared sufficiently cured.
B W 3-2	1	2.539	2.515	2.513	2.505	2.518	963.0	1.857	22.1	563	36	
B W 3-3	7	2.505	2.529	2.523	2.522	2.520	967.2	1.864	21.8	689	44	
B W 3-4	7	2.562	2.538	2.520	2.520	2.535	967.8	1.854	22.2	684	43	
B W 3-5	14	2.505	2.491	2.500	2.500	2.499	969.0	1.883	21.0	758	48	
B W 3-6	14	2.541	2.554	2.547	2.550	2.548	968.6	1.846	22.5	659	41	
B W 3-7	30	2.548	2.516	2.538	2.524	2.532	967.7	1.856	22.1	781	49	
B W 3-8	30	2.526	2.529	2.548	2.534	2.534	967.8	1.854	22.2	731	46	
B W 3-9	60	2.524	2.513	2.526	2.520	2.521	962.7	1.855	22.2	805	51	
B W 3-10	60	2.542	2.524	2.553	2.545	2.541	970.0	1.854	22.2	851	53	

Table 3.5: Burns Junction Westvaco Solvent-Free Data (continued)

Sample ID	Ambient Cure Time (days)	Height (in)*				Average Height (in)*	Mass in Air (g)	Geometric Gmb	% Air Voids (Geometric Gmb)	Load (lb)*	Indirect Tensile Strength (psi)*	Notes
B W 4-1	1	2.505	2.501	2.504	2.502	2.503	963.8	1.870	21.5	661	42	Fresh bottle of emulsion consistency of chocolate milk. Cured 1.4hr prior to compaction , appeared sufficiently cured.
B W 4-2	1	2.510	2.494	2.502	2.497	2.501	965.5	1.875	21.3	604	38	
B W 4-3	7	2.505	2.494	2.491	2.492	2.496	969.7	1.887	20.8	691	44	
B W 4-4	7	2.490	2.486	2.501	2.494	2.493	968.5	1.887	20.8	665	42	
B W 4-5	14	2.498	2.513	2.510	2.500	2.505	971.0	1.882	21.0	773	49	
B W 4-6	14	2.491	2.498	2.499	2.494	2.496	970.6	1.889	20.7	697	44	
B W 4-7	30	2.537	2.531	2.534	2.553	2.539	968.8	1.853	22.2	748	47	
B W 4-8	30	2.494	2.496	2.491	2.489	2.493	970.7	1.891	20.6	804	51	
B W 4-9	60	2.515	2.523	2.532	2.526	2.524	969.2	1.865	21.8	907	57	
B W 4-10	60	2.483	2.489	2.483	2.482	2.484	969.4	1.895	20.5	834	53	

*To convert to metric: Multiply inches by 25.4 to find millimeters. Multiply pounds by 0.454 to find kilograms. Multiply lb/in^2 by 0.0007031 to find kg/mm^2.

Table 3.6: Burns Junction Akzo Noble Solvent-Free Data

BJ AKZO NOBEL Gmm	Sample 1	Sample 2
Mass Sample (g)	1530.3	1534.8
Mass Pync + H_2O (g)	6199.1	6199.2
Mass Pync + H_2O+Sample (g)	7094.3	7095.1
Gmm	2.410	2.402
	Avg Gmm	**2.406**

EXPERIMENT SPECIMEN KEY	
F	Fredrick Butte
B	Burns Junction
S	Solvent Loaded
W	Westvaco
A	Akzo Nobel

Cure Time (days)	Average Load (lb)	Average ITS (psi)	Maximum ITS (psi)	Minimum ITS (psi)	Standard Deviation	Standard Deviation P	CV (%)
1	525	33	36	30	2.7	2.5	7
7	570	36	40	33	2.3	2.1	6
14	660	42	44	38	2.4	2.2	5
30	704	44	47	40	2.9	2.7	6
60	715	45	48	40	3.1	2.8	6

Sample ID	**Ambient Cure Time (days)**	**Height (in)***				**Average Height (in)***	**Mass in Air (g)**	**Geometric Gmb**	**% Air Voids (Geometric Gmb)**	**Load (lb)***	**Indirect Tensile Strength (psi)***	**Notes**
B A 1-1	1	2.509	2.530	2.518	2.504	2.515	960.7	1.855	22.9	576	36	
B A 1-2	1	2.527	2.512	2.534	2.510	2.521	961.5	1.852	23.0	535	34	
B A 1-3	7	2.504	2.502	2.503	2.493	2.501	961.3	1.867	22.4	587	37	
B A 1-4	7	2.518	2.526	2.520	2.517	2.520	964.0	1.857	22.8	564	36	
B A 1-5	14	2.510	2.507	2.507	2.510	2.509	963.1	1.864	22.5	654	41	
B A 1-6	14	2.525	2.524	2.524	2.523	2.524	961.1	1.849	23.1	599	38	
B A 1-7	30	2.521	2.528	2.518	2.513	2.520	962.6	1.855	22.9	752	47	
B S 1-8	30	2.519	2.540	2.543	2.523	2.531	963.3	1.848	23.2	634	40	
B A 1-9	60	2.515	2.518	2.510	2.509	2.513	965.7	1.866	22.4	727	46	
B A 1-10	60	2.522	2.527	2.519	2.510	2.520	962.6	1.855	22.9	640	40	
B A 2-1	1	2.521	2.503	2.513	2.546	2.521	957.5	1.845	23.3	477	30	
B A 2-2	1	2.500	2.495	2.501	2.495	2.498	961.8	1.870	22.3	522	33	
B A 2-3	7	2.504	2.504	2.515	2.500	2.506	961.0	1.862	22.6	523	33	
B A 2-4	7	2.553	2.514	2.555	2.530	2.538	960.5	1.838	23.6	546	34	
B A 2-5	14	2.496	2.514	2.492	2.488	2.498	959.2	1.865	22.5	657	42	
B A 2-6	14	2.510	2.500	2.504	2.508	2.506	963.3	1.867	22.4	651	41	
B A 2-7	30	2.550	2.519	2.520	2.520	2.527	962.3	1.849	23.1	707	45	
B A 2-8	30	2.511	2.495	2.504	2.519	2.507	962.8	1.865	22.5	722	46	
B A 2-9	60	2.508	2.512	2.514	2.502	2.509	963.8	1.865	22.5	688	44	
B A 2-10	60	2.509	2.510	2.513	2.511	2.511	961.8	1.860	22.7	764	48	
B A 3-1	1	2.505	2.520	2.506	2.515	2.512	963.8	1.864	22.5	563	36	
B A 3-2	1	2.526	2.531	2.532	2.528	2.529	959.0	1.841	23.5	478	30	
B A 3-3	7	2.515	2.505	2.513	2.503	2.509	961.3	1.861	22.7	627	40	
B A 3-4	7	2.537	2.517	2.525	2.520	2.525	961.9	1.850	23.1	572	36	
B A 3-5	14	2.526	2.517	2.508	2.515	2.517	962.3	1.857	22.8	699	44	
B A 3-6	14	2.529	2.528	2.517	2.521	2.524	958.8	1.845	23.3	702	44	
B A 3-7	30	2.516	2.520	2.516	2.518	2.518	961.4	1.854	22.9	668	42	
B A 3-8	30	2.518	2.506	2.512	2.515	2.513	962.5	1.860	22.7	739	47	
B A 3-9	60	2.513	2.521	2.510	2.523	2.517	960.3	1.853	23.0	707	45	
B A 3-10	60	2.501	2.513	2.510	2.515	2.510	960.7	1.859	22.7	764	48	

*To convert to metric: Multiply inches by 25.4 to find millimeters. Multiply pounds by 0.454 to find kilograms. Multiply lb/in^2 by 0.0007031 to find kg/mm^2.

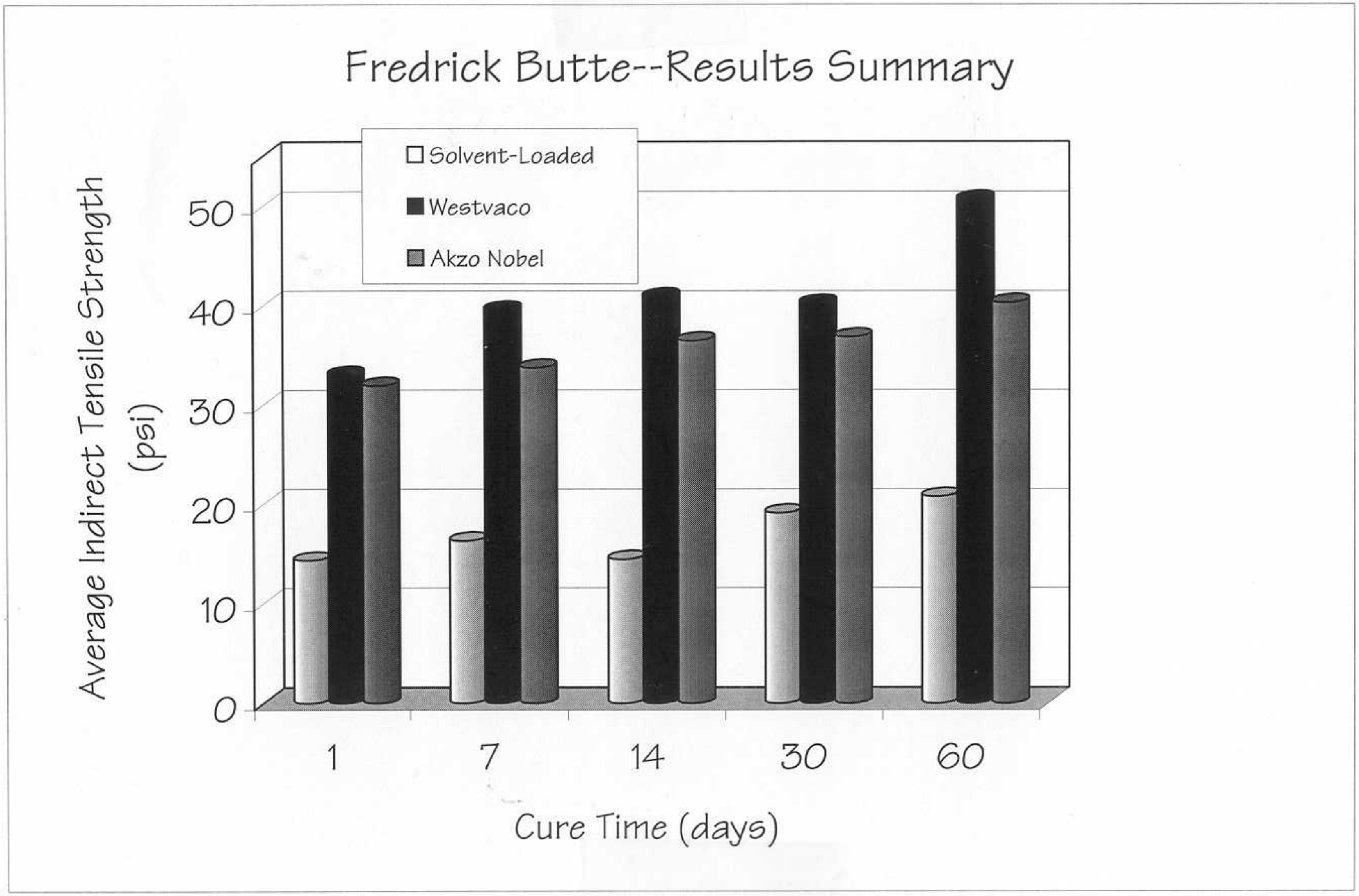


Figure 3.1: Fredrick Butte Experiment Summary

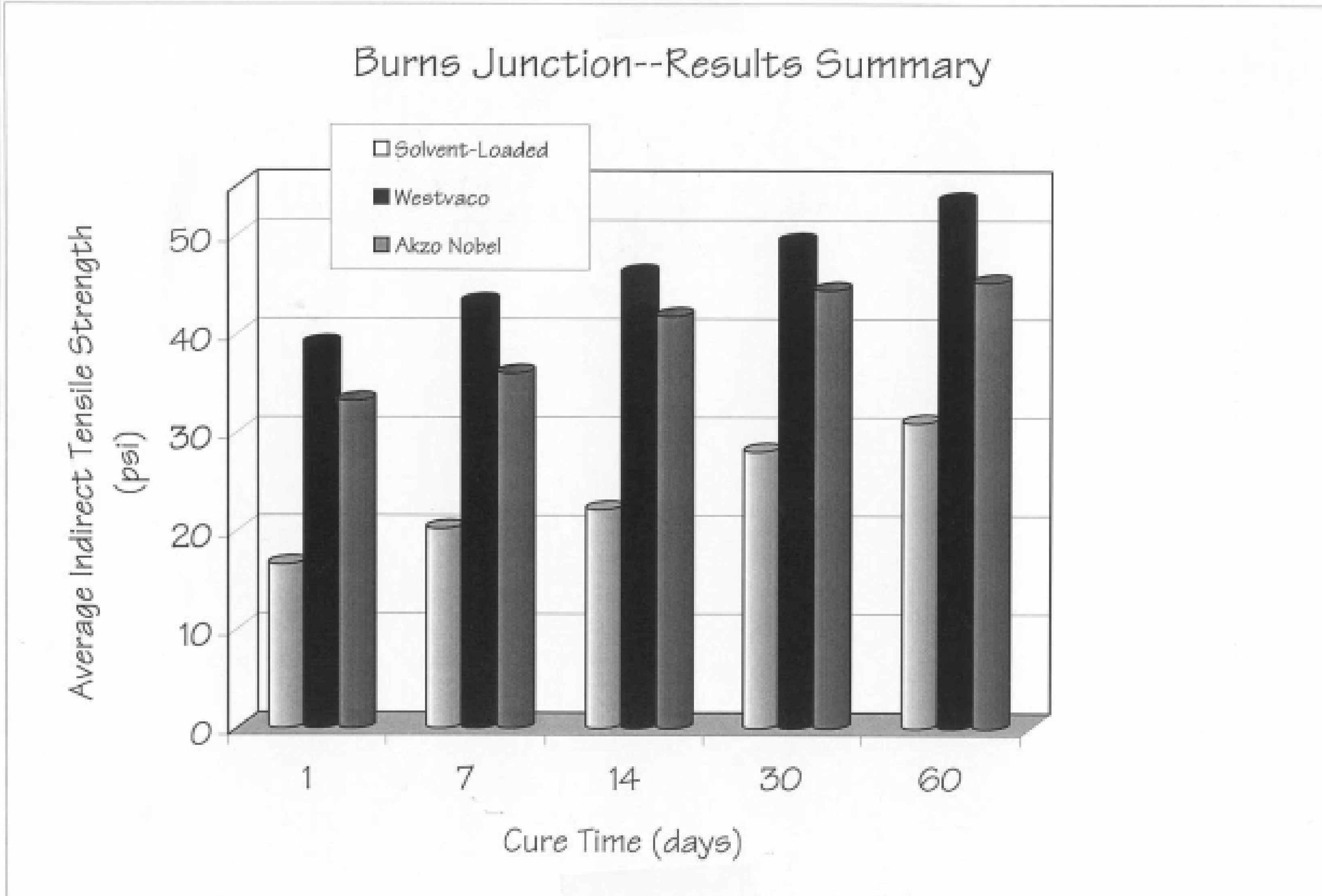
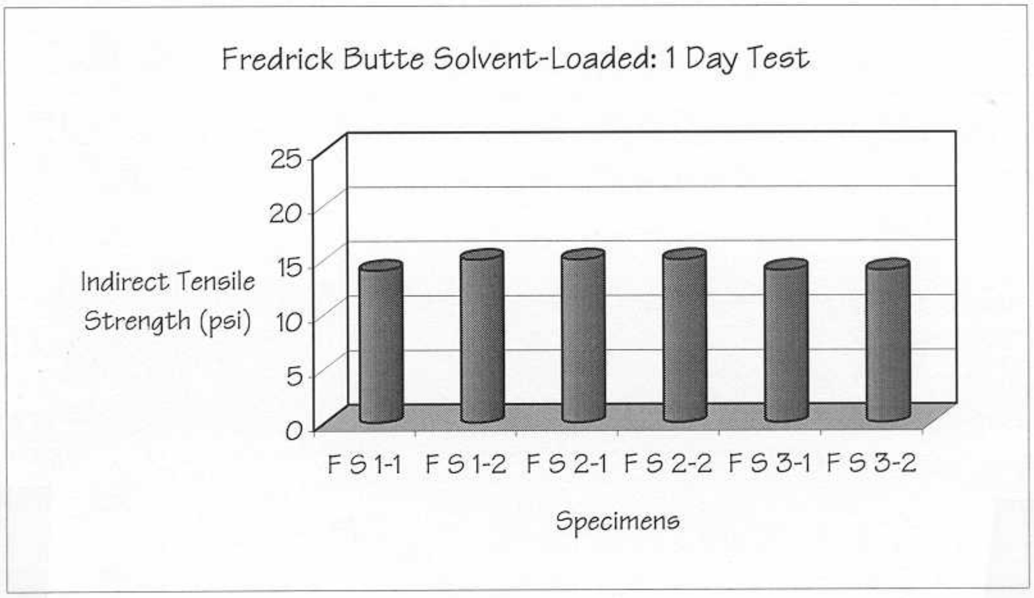


Figure 3.2: Burns Junction Experiment Summary



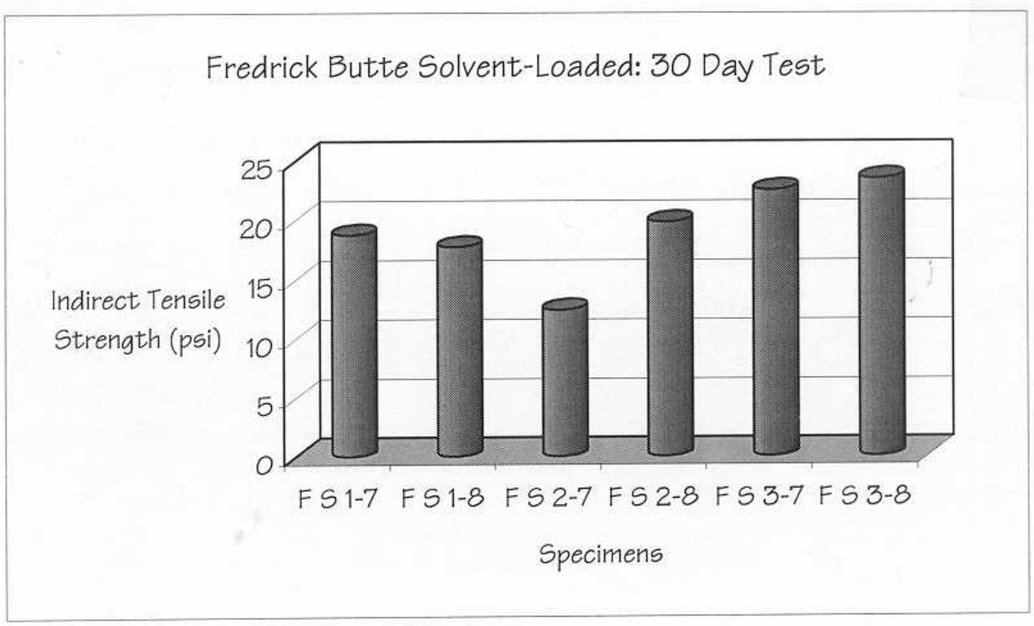
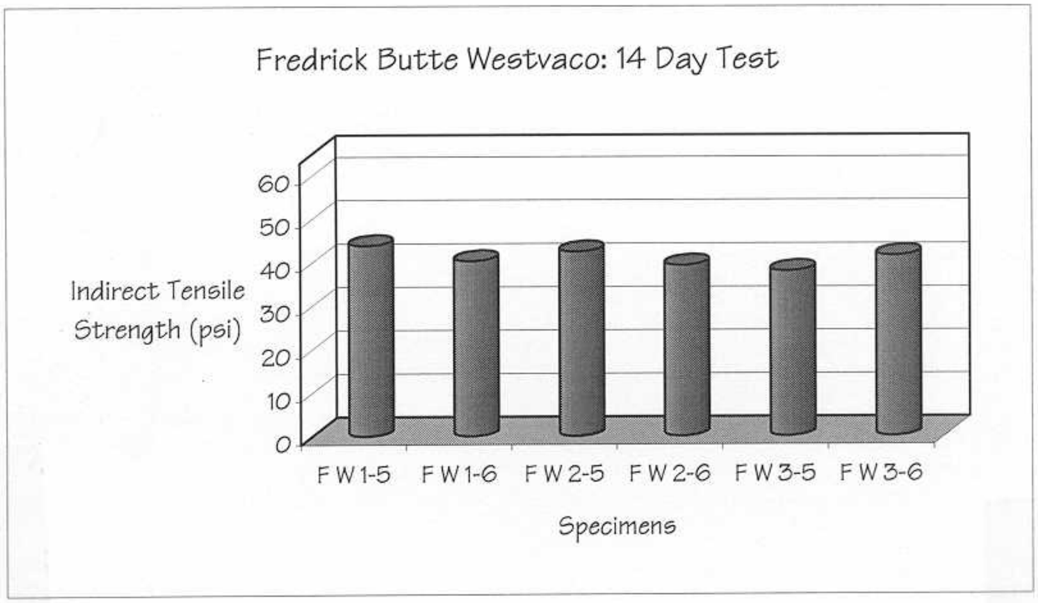


Figure 3.3a: Replicate Variability



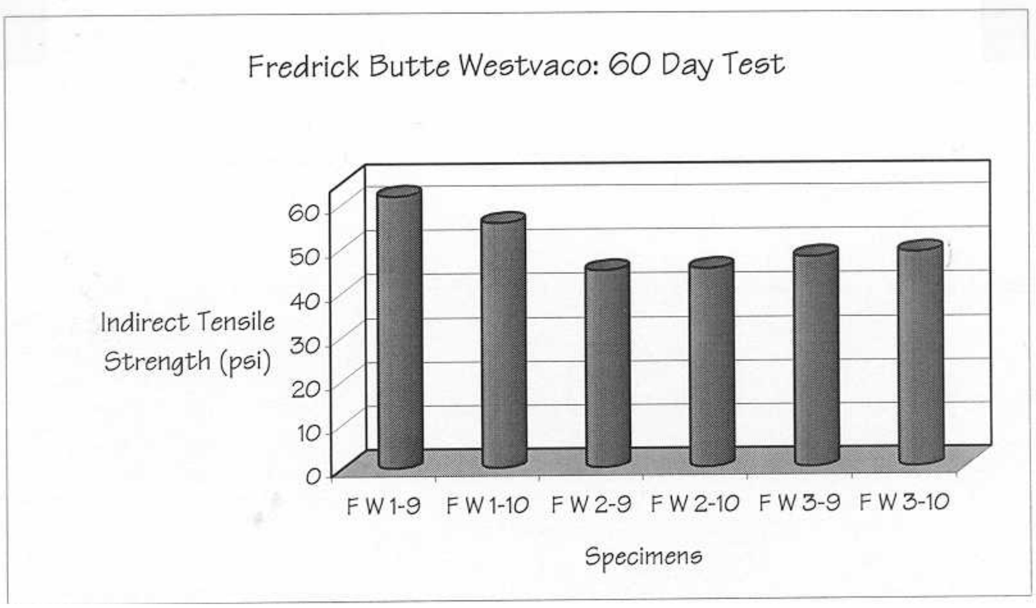
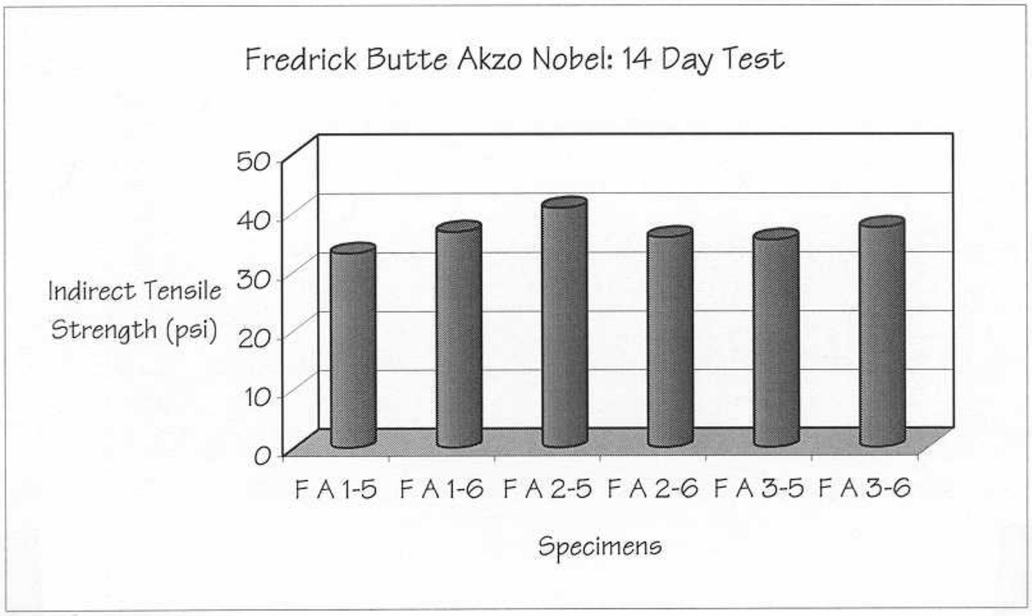


Figure 3.3b: Replicate Variability



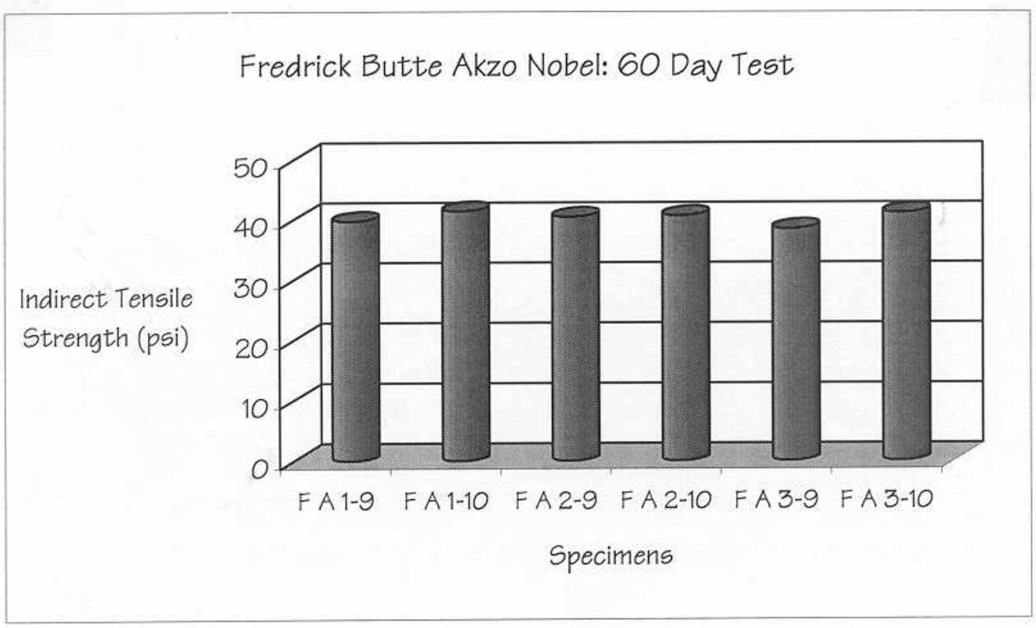
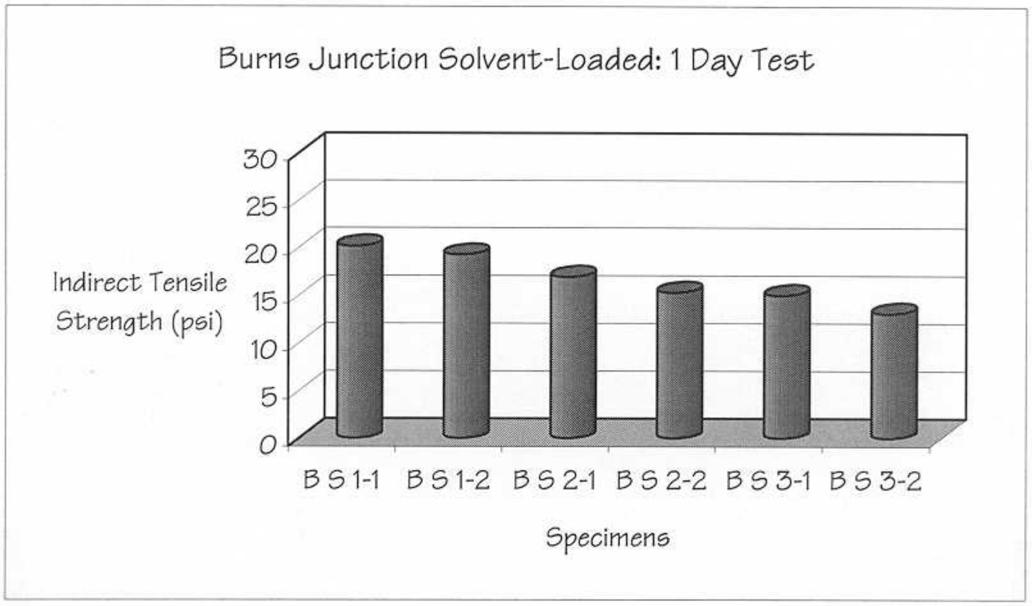


Figure 3.3c: Replicate Variability



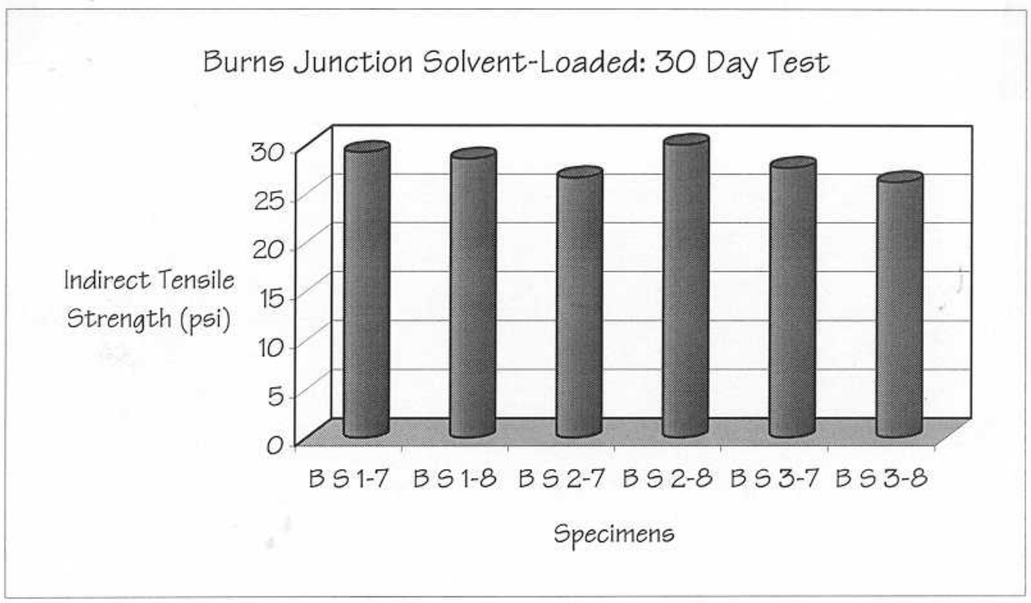
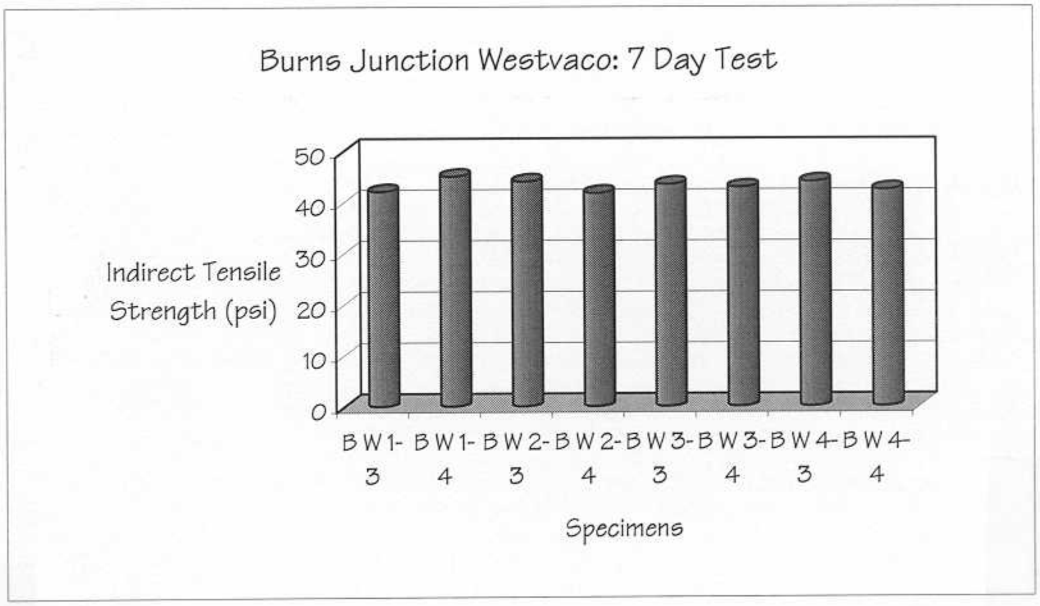


Figure 3.3d: Replicate Variability



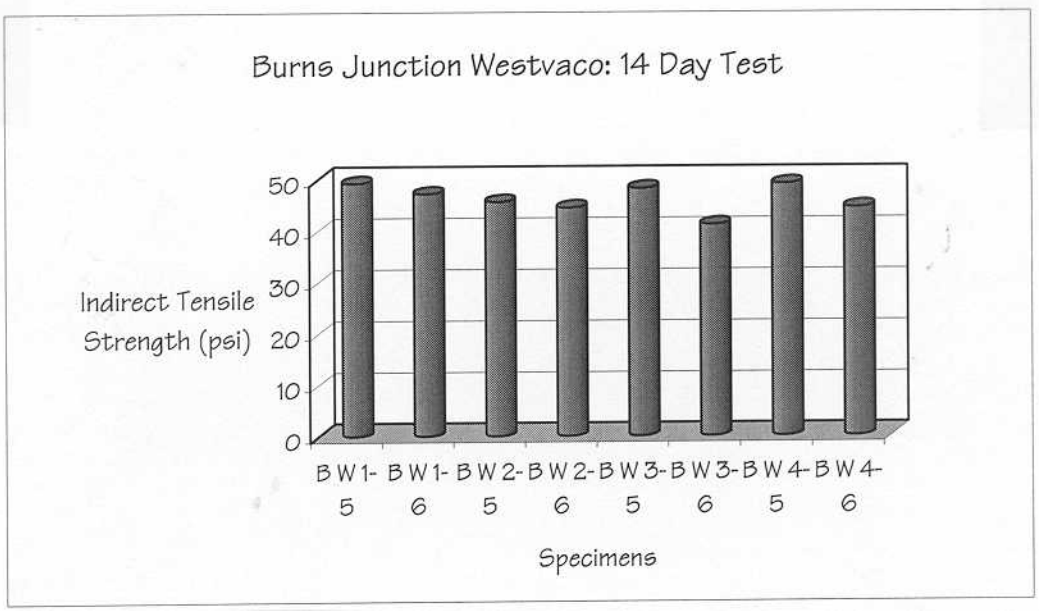
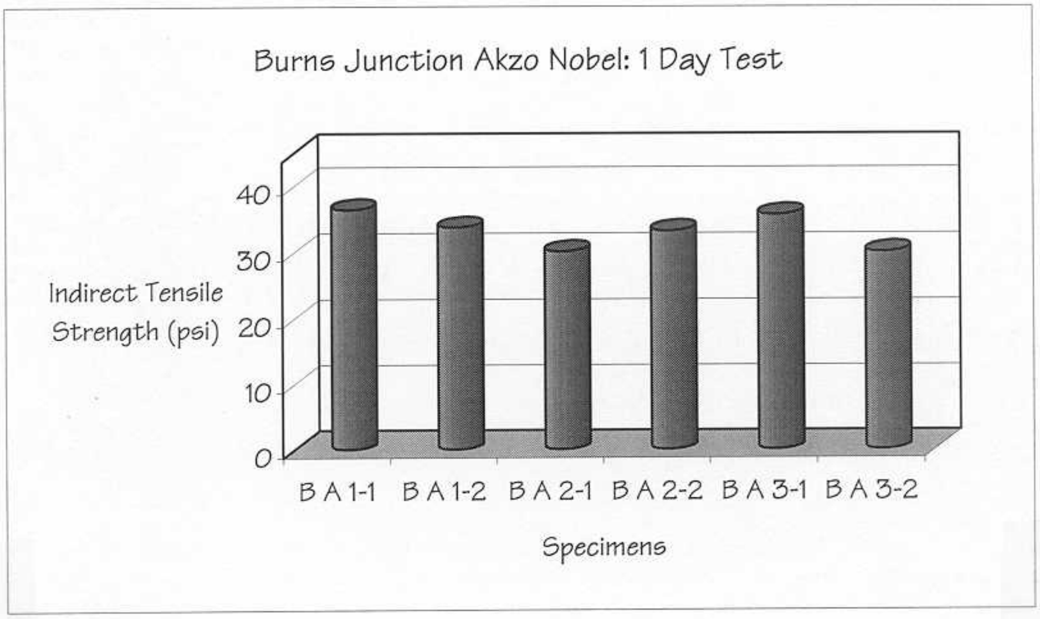


Figure 3.3e: Replicate Variability



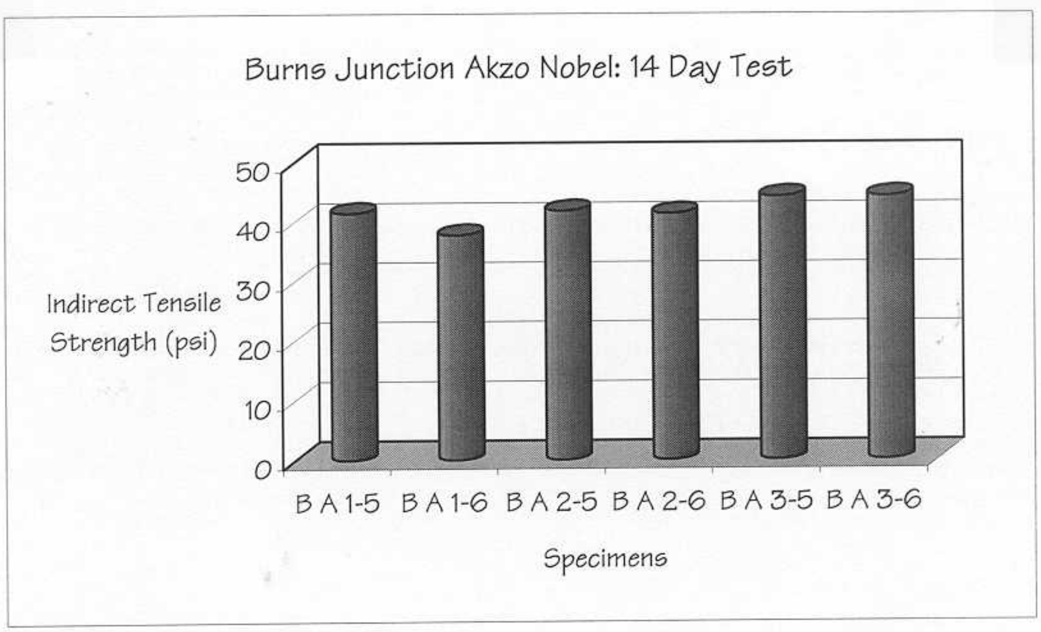


Figure 3.3f: Replicate Variability

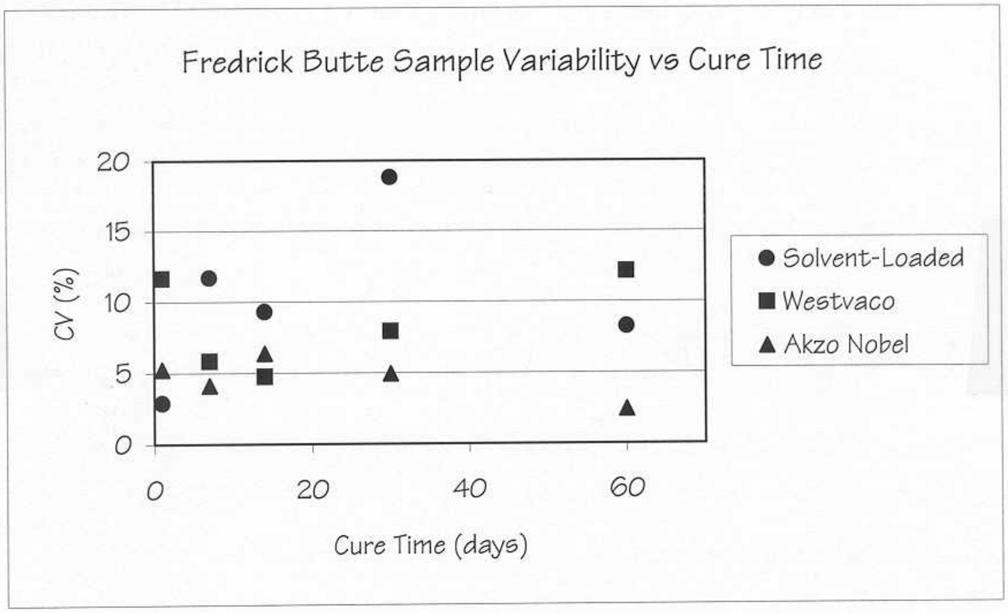


Figure 3.4: Fredrick Butte Sample Variability vs. Cure Time

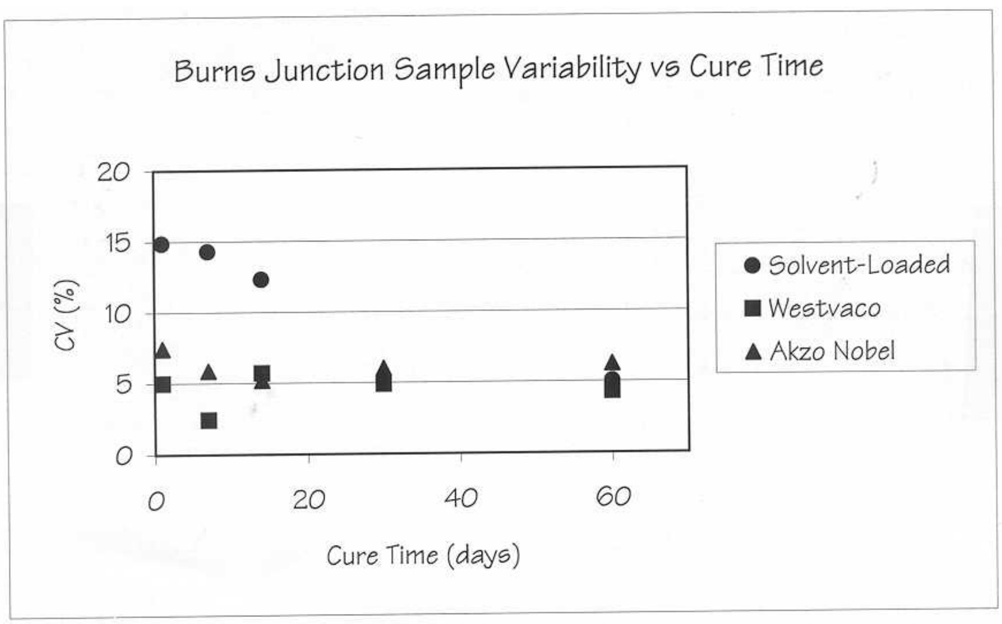


Figure 3.5: Burns Junction Sample Variability vs. Cure Time

3.1 OVEN TEST

An additional experiment was conducted to quantify the effects of the length of the oven cure on final tensile strength. Thirty-six samples were prepared as outlined in ODOT TM 313 and tested for indirect tensile strength in accordance with AASHTO T283 *(1993)*. Eighteen samples were made with the solvent-loaded emulsion and eighteen with the Westvaco solvent-free emulsion. All samples were made with the Burns Junction aggregate. Samples were tested in 24-hour increments from a 2-day oven cure to a 7-day oven cure. The experiment design is outlined in Table 3.7.

The results for this experiment are shown in Tables 3.8 and 3.9 and are graphically represented in Figure 3.6. The standard deviation was calculated using the standard deviation of the population method.

Table 3.7: Oven Test Experiment Design

Oven Cure (days)	Number of Solvent-Loaded Samples	Number of Westvaco Solvent-Free Samples
1	values from original experiment	values from original experiment
2	3	3
3	3	3
4	3	3
5	3	3
6	3	3
7	3	3

Table 3.8: Oven Test Data – Solvent-Loaded

OVEN TEST
Burns Junction Solvent Loaded Samples

BJ SOLVENT LOADED Gmm	Sample 1	Sample 2
Mass Sample (g)	1492.7	1490.3
Mass Pync + H_2O (g)	6197.8	6197.8
Mass Pync+H_2O+Sample (g)	7066.4	7066.1
Gmm	2.392	2.396
	Avg Gmm	**2.394**

KEY	
X	Oven Test
F	Fredrick Butte
B	Burns Junction
S	Solvent Loaded
W	Westvaco

Sample ID	Oven Cure (days)	Mass in Air (g)	Height (in)				Average Height (in)	Geometric Gmb	% Air Voids (Geometric Gmb)	Load (lb)	Indirect Tensile Strength (psi)	Average Load (lb)	Avg Indirect Tensile Strength (psi)	Standard Deviation P
B S 1-1	1	960.7	2.556	2.557	2.553	2.563	2.557	1.824	23.8	323	20			
B S 1-2	1	962.7	2.547	2.546	2.537	2.545	2.544	1.838	23.2	307	19			
B S 2-1	1	958.7	2.536	2.543	2.552	2.551	2.546	1.829	23.6	270	17	266	17	2.5
B S 2-2	1	956.4	2.563	2.562	2.571	2.566	2.566	1.810	24.4	246	15			
B S 3-1	1	960.3	2.551	2.551	2.559	2.560	2.555	1.825	23.8	240	15			
B S 3-2	1	963.4	2.562	2.577	2.555	2.561	2.564	1.825	23.8	210	13			
X B S 1	2	959.1	2.542	2.541	2.548	2.545	2.544	1.831	23.5	508	32			
X B S 2	2	959.9	2.529	2.545	2.544	2.542	2.540	1.835	23.3	414	26	420	26	4.4
X B S 3	2	955.9	2.550	2.542	2.560	2.549	2.550	1.820	24.0	337	21			
X B S 4	3	957.9	2.560	2.577	2.558	2.546	2.560	1.817	24.1	488	30			
X B S 5	3	957.9	2.565	2.569	2.580	2.587	2.575	1.806	24.5	443	27	487	30	2.3
X B S 6	3	956.0	2.550	2.543	2.546	2.549	2.547	1.823	23.9	529	33			
X B S 7	4	958.7	2.565	2.560	2.567	2.577	2.567	1.813	24.2	556	34			
X B S 8	4	962.4	2.575	2.579	2.592	2.579	2.581	1.811	24.4	505	31	530	33	1.4
X B S 9	4	956.8	2.555	2.550	2.543	2.534	2.546	1.825	23.8	528	33			
X B S 10	5	949.5	2.589	2.587	2.604	2.578	2.590	1.781	25.6	559	34			
X B S 11	5	959.5	2.565	2.575	2.566	2.566	2.568	1.814	24.2	493	31	510	31	2.1
X B S 12	5	955.0	2.596	2.600	2.586	2.603	2.596	1.786	25.4	478	29			
X B S 13	6	957.7	2.572	2.557	2.572	2.559	2.565	1.813	24.3	510	32			
X B S 14	6	958.6	2.571	2.573	2.578	2.579	2.575	1.808	24.5	599	37	591	37	4.0
X B S 15	6	955.0	2.549	2.563	2.531	2.546	2.547	1.821	23.9	663	41			
X B S 16	7	957.0	2.548	2.547	2.571	2.548	2.554	1.820	24.0	695	43			
X B S 17	7	958.6	2.585	2.591	2.580	2.573	2.582	1.803	24.7	673	41	702	43	1.7
X B S 18	7	955.8	2.583	2.585	2.570	2.575	2.578	1.800	24.8	738	46			

Table 3.9: Oven Test Data – Westvaco Solvent-Free

OVEN TEST
Burns Junction Westvaco Solvent Free Samples

BJ WESTVACO Gmm	Sample 1	Sample 2
Mass Sample (g)	1547.7	1521.2
Mass Pync + H_2O (g)	6199.1	6199.1
Mass Pync+H_2O+Sample (g)	7096.8	7082.5
Gmm	2.381	2.385
	Avg Gmm	**2.383**

KEY	
X	Oven Test
F	Fredrick Butte
B	Burns Junction
S	Solvent Loaded
W	Westvaco

Sample ID	**Oven Cure (days)**	**Mass in Air (g)**	**Height (in)**				**Average Height (in)**	**Geometric Gmb**	**% Air Voids (Geometric Gmb)**	**Load (lb)**	**Indirect Tensile Strength (psi)**	**Average Load (lb)**	**Avg Indirect Tensile Strength (psi)**	**Standard Deviation P**
B W 1-1	1	966.6	2.517	2.513	2.517	2.525	2.518	1.864	21.8	623	39	608	39	1.8
B W 1-2	1	972.4	2.521	2.521	2.525	2.528	2.524	1.871	21.5	584	37			
B W 2-1	1	961.1	2.497	2.488	2.490	2.492	2.492	1.873	21.4	639	41			
B W 2-2	1	964.0	2.495	2.496	2.505	2.500	2.499	1.873	21.4	629	40			
B W 3-1	1	964.0	2.495	2.498	2.500	2.501	2.499	1.874	21.4	611	39			
B W 3-2	1	963.0	2.539	2.515	2.513	2.505	2.518	1.857	22.1	563	36			
X B W 1	2	961.1	2.508	2.512	2.505	2.510	2.509	1.860	21.9	738	47	800	51	2.9
X B W 2	2	964.9	2.529	2.510	2.535	2.515	2.522	1.858	22.0	821	52			
X B W 3	2	963.5	2.495	2.505	2.492	2.510	2.501	1.871	21.5	842	54			
X B W 4	3	970.5	2.538	2.564	2.540	2.545	2.547	1.850	22.3	902	56	861	54	3.9
X B W 5	3	968.5	2.538	2.553	2.554	2.514	2.540	1.852	22.3	779	49			
X B W 6	3	961.7	2.492	2.485	2.500	2.494	2.493	1.873	21.4	904	58			
X B W 7	4	964.2	2.507	2.532	2.521	2.509	2.517	1.860	21.9	965	61	987	62	4.1
X B W 8	4	969.5	2.535	2.532	2.524	2.529	2.530	1.861	21.9	925	58			
X B W 9	4	967.7	2.502	2.527	2.490	2.514	2.508	1.873	21.4	1070	68			
X B W 10	5	965.2	2.540	2.529	2.505	2.515	2.522	1.858	22.0	983	62	1026	64	2.9
X B W 11	5	966.0	2.577	2.542	2.567	2.534	2.555	1.836	23.0	1003	63			
X B W 12	5	967.4	2.553	2.530	2.508	2.545	2.534	1.854	22.2	1091	69			
X B W 13	6	963.7	2.503	2.501	2.498	2.507	2.502	1.870	21.5	1010	64	995	63	2.3
X B W 14	6	967.0	2.520	2.527	2.524	2.545	2.529	1.857	22.1	951	60			
X B W 15	6	962.9	2.507	2.511	2.500	2.509	2.507	1.865	21.7	1025	65			
X B W 16	7	967.8	2.542	2.532	2.534	2.552	2.540	1.850	22.4	937	59	952	60	1.4
X B W 17	7	965.8	2.513	2.522	2.516	2.525	2.519	1.862	21.9	981	62			
X B W 18	7	965.8	2.518	2.512	2.525	2.538	2.523	1.859	22.0	938	59			

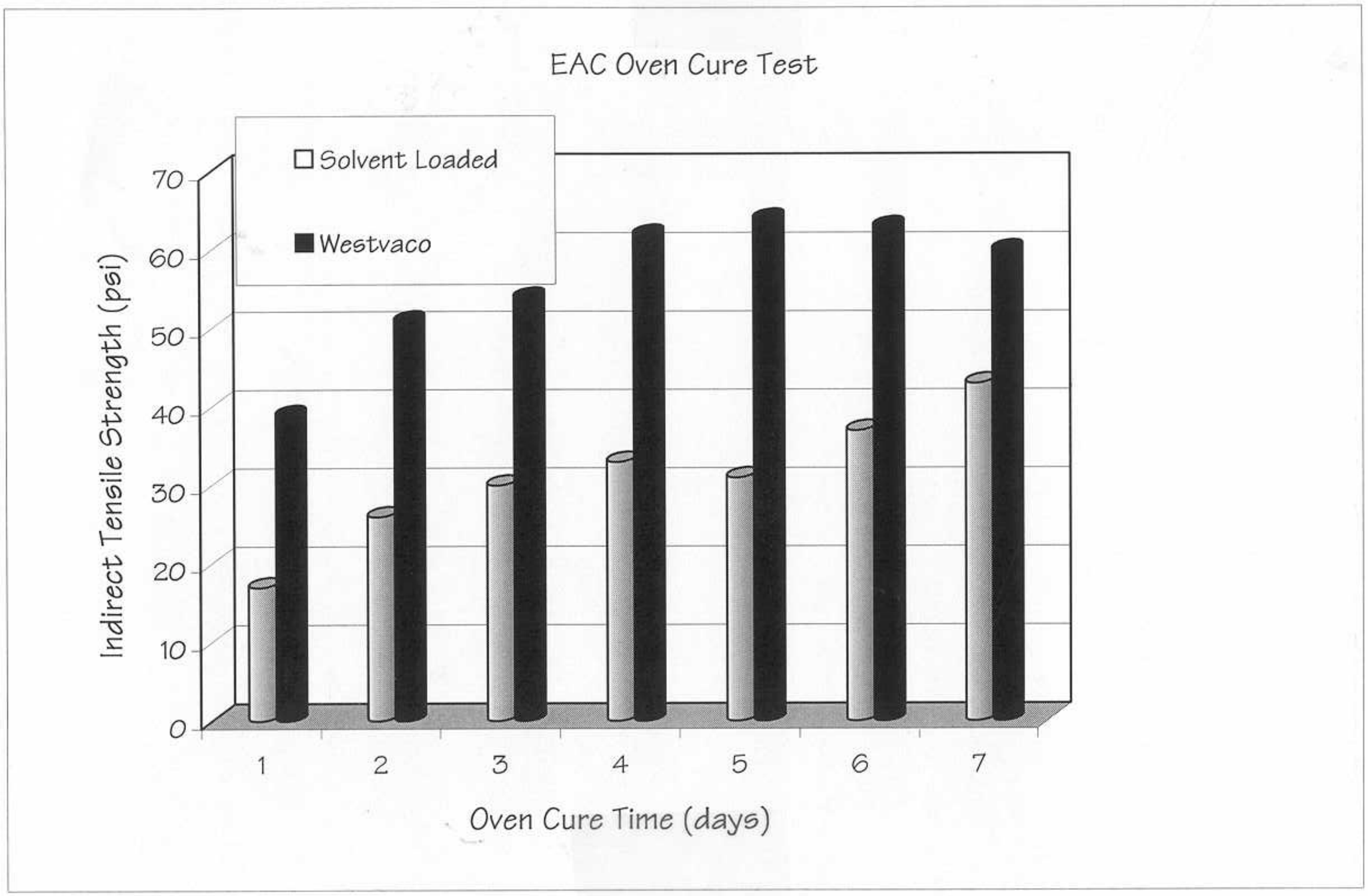


Figure 3.6: Oven Test Summary

3.2 STATISTICAL ANALYSIS: t-TESTS

To ascertain if the means of the indirect tensile strengths between the conventional and solvent-free emulsions were statistically different, t-tests were performed. A t-test was conducted for each of the following combinations: solvent-loaded versus Westvaco solvent-free, solvent-loaded versus Akzo Nobel solvent-free, and Westvaco solvent-free versus Akzo Nobel solvent-free emulsions. The t-tests were performed for both the Fredrick Butte and the Burns Junction aggregates for each of the cure times (1, 7, 14, 30, and 60 days). It is assumed that the populations have normal distributions, and the tests are two-tailed and conducted at the 5% significance level.

To complete the t-tests, equal population variance must first be checked. This is done by looking at the ratio of the two sample variances and comparing this value to an F distribution. The hypothesis is that the populations have equal variance, or H_0: $\sigma_1^2 = \sigma_2^2$. If the ratio of variances (with the larger variance in the numerator) is greater than the critical F value, $F_\alpha(\nu_1,\nu_2)$, then the hypothesis is rejected and the sample variances are unequal.

Once equal or unequal variance is established, a t-test can be performed. The hypothesis for all of the t-tests is that the means of the populations are not different, or H_0: $\mu_1-\mu_2 = 0$. If the absolute value of the t-statistic obtained from the t-test is greater than the t-critical value, then the hypothesis is rejected and the population means are not equal. The results of the t-tests are shown in Table 3.10 for the main experiment, and Table 3.11 for the Oven Test.

Table 3.10: t-Tests

KEY	
F	Fredrick Butte
B	Burns Junction
S	Solvent-Loaded
W	Westvaco
A	Akzo Nobel

Cure Time (days)	Variance of FS	Variance of FW	Ratio of Variance	F Distribution (critical value)	Equal Variance?	Absolute Value t-statistic	t critical	Means Different?
t-Test FS vs FW								
1	0.17	14.83	86.34	5.05	no	10.82	2.57	yes
7	3.63	5.33	1.47	5.05	yes	17.43	2.228	yes
14	1.80	3.78	2.10	5.05	yes	25.06	2.228	yes
30	12.96	10.14	1.28	5.05	yes	9.84	2.228	yes
60	2.93	37.74	12.87	5.05	no	10.51	2.447	yes
t-Test FS vs FA								
1	0.17	2.80	16.28	5.05	no	22.85	2.447	yes
7	3.63	1.93	1.88	5.05	yes	16.57	2.228	yes
14	1.80	5.40	2.99	5.05	yes	18.37	2.228	yes
30	12.96	3.32	3.91	5.05	yes	9.84	2.228	yes
60	2.93	0.96	3.04	5.05	yes	22.18	2.228	yes
t-Test FW vs FA								
1	14.83	2.80	5.30	5.05	no	0.6	2.365	no
7	5.33	1.93	2.76	5.05	yes	4.86	2.228	yes
14	3.78	5.40	1.43	5.05	yes	3.27	2.228	yes
30	10.14	3.32	3.06	5.05	yes	2.06	2.228	no
60	37.74	0.96	39.11	5.05	no	3.73	2.570	yes
t-Test BS vs BW								
1	6.06	3.79	1.60	3.97	yes	16.09	2.179	yes
7	8.34	1.10	7.57	3.97	no	16.63	2.447	yes
14	7.44	6.94	1.07	3.97	yes	13.88	2.179	yes
30	1.91	5.82	3.04	4.88	yes	16.96	2.179	yes
60	2.43	5.32	2.19	4.88	yes	18.62	2.179	yes
t-Test BS vs BA								
1	6.06	6.08	1.00	5.05	yes	10.69	2.228	yes
7	8.34	4.46	1.87	5.05	yes	9.88	2.228	yes
14	7.44	4.71	1.58	5.05	yes	9.1	2.228	yes
30	1.91	7.10	3.72	5.05	yes	12.22	2.228	yes
60	2.43	7.96	3.28	5.05	yes	10.12	2.228	yes
t-Test BW vs BA								
1	3.79	6.08	1.60	3.97	yes	4.54	2.179	yes
7	1.10	4.46	4.05	3.97	no	5.65	2.262	yes
14	6.94	4.71	1.48	4.88	yes	3.07	2.179	yes
30	5.82	7.10	1.22	3.97	yes	3.36	2.179	yes
60	5.32	7.96	1.50	3.97	yes	5.87	2.179	yes

Table 3.11: Oven Test t-Tests

Cure Time (days)	Variance of FS	Variance of FW	Ratio of Variance	F Distribution (critical value)	Equal Variance?	Absolute Value t-statistic	t critical	Means Different?
OVEN TEST: t-Test BS vs BW								
1	6.25	3.24	1.93	5.05	yes	16.09	2.228	yes
2	19.36	8.41	2.30	19.00	yes	6.6	2.776	yes
3	5.29	15.21	2.88	19.00	yes	7.46	2.776	yes
4	1.96	16.81	8.58	19.00	yes	9.72	2.776	yes
5	4.41	8.41	1.91	19.00	yes	12.79	2.776	yes
6	16.00	5.29	3.02	19.00	yes	8.07	2.776	yes
7	2.89	1.96	1.47	19.00	yes	10.51	2.776	yes

4.0 DISCUSSION & CONCLUSIONS

4.1 COMPACTION METHOD SELECTION

During the development of the experiment, two methods of sample compaction were considered, static and gyratory. Static compaction, as outlined in ODOT TM 313, has long been accepted in emulsion mix design. Gyratory compaction has recently begun to replace static and other compaction methods because it more closely models actual field compaction. Samples were prepared using a gyratory compactor to determine if this method would produce acceptable EAC specimens. The specimens produced by the gyratory compactor failed to reach a density that would allow them to remain intact during the curing time. Even with the compaction effort set to the highest common standard of 600 kPa (12,531 psf) and 150 gyrations, all the samples fell apart during curing. Two samples were compacted at 1000 kPa (20,885 psf) and 100 gyrations and these too failed while curing. It was determined that the gyratory compaction method was not suitable for the experiment. Accordingly, the static compaction method was used and presented no problems. All specimens were prepared according to ODOT TM 313. A summary of the gyratory compaction data is shown in the appendix.

4.2 SOLVENT-FREE EMULSION CHARACTERISTICS

Despite the positive properties of the solvent-free emulsions, there were some problems with some of the batches sent to the OSU lab. The Westvaco solvent-free emulsion sent in May 1999 had the consistency analogous to that of fudge. This batch of emulsion was only used in preliminary planning and testing phases. The second batch of Westvaco emulsion that the OSU lab received (June 1999) was 'broken' upon arrival. The third batch of Westvaco emulsion (July 1999) was the consistency of a thin milkshake. This was the emulsion used in all of the testing reported.

The first batch of Akzo Nobel solvent-free emulsion received (July 1999) was already 'broken.' The second batch, received in August 1999, was the consistency of water and was the emulsion used in all of the testing. As noted in Table 3.5, the solvent-free emulsion mixtures also cured more quickly than the solvent-loaded emulsions.

4.3 CONCLUSIONS

The results from the experiment support the hypothesis stated earlier. Both Westvaco and Akzo Nobel solvent-free emulsions produced material properties that met or exceeded conventional solvent-loaded emulsions. The t-tests performed proved that the means of the solvent-loaded specimens and the solvent-free specimens are statistically different (see Tables 3.10 and 3.11). The indirect tensile strength test results showed that Westvaco had a maximum average strength of 352 kPa (51 lb/in^2) for the Fredrick Butte aggregate and 372 kPa (54 lb/in^2) for the Burns Junction aggregate. Akzo Nobel had a maximum average strength of 276 kPa (40 lb/in^2) for the Fredrick Butte aggregate and 310 kPa (45 lb/in^2) for the Burns Junction aggregate. The solvent-loaded emulsion had a maximum average strength of 148 kPa (21 lb/in^2) for the Fredrick Butte aggregate and 214 kPa (31 lb/in^2) for the Burns Junction aggregate. The higher strengths achieved by the solvent-free emulsions versus the solvent-loaded emulsions, as a percent difference, are shown in Table 4.1.

Table 4.1: Strength Difference – Solvent-Free vs. Solvent-Loaded

	Avg 60-Day Strength, kPa (lb/in^2)	% Difference
	Fredrick Butte Aggregate	
Westvaco Solvent-Free	352 (51)	59
Solvent-Loaded	148 (21)	
Akzo Nobel Solvent-Free	276 (40)	48
Solvent-Loaded	148 (21)	
	Burns Junction Aggregate	
Westvaco Solvent-Free	372 (54)	43
Solvent-Loaded	214 (31)	
Akzo Nobel Solvent-Free	310 (45)	31
Solvent-Loaded	214 (31)	

As shown by the data presented in Chapter 3, specimens made with solvent-free emulsions had indirect tensile strengths that met or exceeded those made with conventional solvent-loaded emulsions. The maximum indirect tensile strengths were measured after the maximum curing time of 60 days. As shown previously in Figures 3.1 and 3.2, the indirect tensile strength of specimens made with the solvent-loaded emulsion never exceeded that made with the solvent-free emulsions, regardless of curing time.

Data from the limited experiment described in Section 3.1 is instructive with regard to the relationship between oven curing time and rate of strength gain. The maximum average indirect tensile strengths for EAC made with the solvent-loaded and solvent-free emulsions were 296 kPa (43 lb/in^2) and 441 kPa (64 lb/in^2), respectively. The strength of the solvent-free specimens peaked at five days of oven curing whereas the solvent-loaded specimens continued to gain strength beyond that time. Still, the strength of the solvent-loaded EAC never exceeded that of the solvent-free EAC.

Variability of indirect tensile strength for replicate test samples, as shown in Figures 3.3 to 3.5, was greater for the Westvaco emulsion than for the Akzo Nobel emulsion, a reflection of the emulsion inconsistency. This inconsistency in the emulsion is attributed to the small size of the production batch, i.e., 3.8 L (1 gal). It is very likely that full-scale production would yield a more consistent product. Elsewhere, the replicate test variability, as described by the coefficient of variation was typically lower for the solvent-free emulsion than for the solvent-loaded emulsion: about 5 to 8% and 15 to 18%, respectively.

The results of this research are very promising: specimens made with solvent-free emulsions had consistently greater indirect tensile strengths and achieved that strength gain more rapidly than did specimens made with the conventional solvent-loaded emulsion. Moreover, solvent-free emulsions make for a safer work environment as they minimize the fire hazards associated with conventional solvent-loaded emulsions. Also, solvent-free emulsions eliminate the potential for groundwater contamination.

5.0 RECOMMENDATIONS

Although the laboratory test results are promising, additional laboratory testing and field validations are necessary to validate the hypothesis previously stated herein. The field-testing should include construction of both control and experimental sections at each selected location.

5.1 CONSISTENCY TESTING

As noted previously, there was a perceptible difference in consistency between individual batches for both the Westvaco and Akzo Nobel emulsions. Given the obvious effects on mixing, coating, adhesion and strength properties, it is imperative that this matter be addressed prior to field trials.

Regardless of the size of the production batch, standardized laboratory testing is recommended to ensure product consistency, i.e., uniformity, and storage stability. To that end, the following tests are recommended: viscosity (Saybolt Furol); and settlement or storage stability. Assuming that subsequent laboratory testing yields positive results, and the authors feel confident that this will be the case, field trials are the logical extension to this research. Table 5.1 shows the proposed experiment design for the additional laboratory testing.

Table 5.1: Recommended Laboratory Testing

Batch size for each solvent-free emulsion** • Three independent 4 L (1 gallon) samples • Split each 4 L sample: 1 L sent to each lab for testing	**Testing Lab**		
	ODOT	**Lab 1**	**Lab 2**
Testing (triplicate test samples from each 1 L container)			
• Saybolt Furol viscosity (9 samples total)	X	X	X
• Settlement or storage stability (9 samples total)	X	X	X
** Westvaco and Akzo Nobel			
It is proposed that emulsions be manufactured with assistance/oversight provided by Westvaco and Akzo Nobel staff.			

5.2 MIX DESIGN CONSIDERATIONS

The mix designs for the field validation sections should be done using standard ODOT procedures. Results should be compared to the control section mix designs. The indirect tensile strength for both the control and experimental mixes should also be tested. At a minimum, tests should be done at one, seven, 14 and 30-day cure times. The results will establish a strength gain trend for comparison to the in-place (core) test results. Table 5.2 presents the proposed experiment design for the field trials.

Table 5.2: Proposed Field Trials

<table>
<tr><th>Project Location</th><th>Number of Projects</th><th>Materials Sampling and Testing for Control and Experimental Sections</th></tr>
<tr><td>Region 4</td><td>2</td><td rowspan="2">• Sample solvent-free and solvent-loaded emulsions at construction site (three 1 L (1 quart) samples of each)
• Conduct viscosity tests (triplicate measurement of each sample)
• Extract 5 field cores (100 mm diameter (4 in)) after EAC compaction at each time interval (24 hr,7 days, 2 months, 6 months, and 12 months) from both control and experimental sections
• Seal cores in air tight bag/container
• Within 24 hr of field coring, conduct indirect tensile strength test as outlined in AASHTO T283
• Monitor pavement performance, i.e., visual distress survey at regular interval (time or traffic)</td></tr>
<tr><td>Region 5</td><td>2</td></tr>
<tr><td colspan="3">• It is recommended that the experimental section of solvent-free EAC (approximately 1.6 km (1 mi) in length) be placed contiguous with or parallel to the control section of conventional solvent-loaded CMS-2S.
• It is recommended that the EAC lift thickness be a minimum of 50 to 75 mm (2 to 3 in).
• It is recommended that the locations for materials sampling and performance monitoring be clearly marked within both the control and experimental sections.
• It is recommended that the solvent-free emulsion and the CMS-2S be produced by the same manufacturer using the same base asphalt to reduce the number of variables for comparison.</td></tr>
</table>

5.3 CONSTRUCTION MONITORING CONSIDERATIONS

Construction of the experimental and control sections shall be monitored by research personnel. Information to be collected includes:

- Pavement condition prior to treatment.
- Weather conditions during construction.
- Construction issues related to handling and mixing the materials. Problems related to pumping and storing should be monitored.
- Construction issues related to placing the materials. Problems related to trucking, laydown, and compaction should be documented.
- Traffic impacts – behavior of the mixes under initial traffic.
- Any adjustments made to compensate for problems include adjustments to address poor coating, if necessary.

Following construction, the sections will also be monitored for an additional 18 months to document performance. Cores will be taken as noted in Table 5.2 and distress surveys will be performed.

6.0 REFERENCES

AASHTO T283: Resistance of Compacted Bituminous Mixture to Moisture Induced Damage. Standard Specification for Transportation Materials and Methods of Sampling and Testing. Sixteenth Edition. American Association of State Highway and Transportation Officials. 1993. pp 905-907.

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APPENDIX

GYRATORY TRIALS

GYRATORY TRIALS

KEY	
F	Fredrick Butte
B	Burns Junction
L	Solvent Loaded
X	Solvent Free

Sample ID	Type of Curing	Length of Cure hrs (loose)	Air Cure hrs (compacted)	Number of Gyrations	Notes
B L 1	Air Bath	24	1	100	Fell apart in oven
B L 2	Air Bath	24	14	100	Partially fell apart in oven
B L 3	Open Air	24	14	100	Partially fell apart in oven, worse than B L 2
B L 4	Open Air	24	12	100	About 10 g fell off in oven.
F L 1	Open Air	24	1	150	Held together better, still not stiff enough. 150 gyrations reduced height by additional .5 mm
F L 2	Open Air	30	1	100	Compacted at 30 hrs instead of 36 hrs. Fell apart after bulking.
B L 5	Air Bath	30	24	100	50 g fell off when top paper taken off before oven cure. Did not bulk BL5
B L 6	Air Bath	30	24	100	~30 g fell off when top paper taken off right out of oven.
F L 3	Air Bath	30	24	100	~20 g fell off when top paper taken off right out of oven.
F L 4	Air Bath	30	24	100	Paper kept on 1.5 hrs after out of oven--held together better.
F L 5	Air Bath	24	24	100	They all fell apart. The 48 didn't feel much different from the 24. Positioning in the air bath and number of samples in the air bath apparently have a big influence on how the sample cures. The paper was taken off before oven cure.
F L 6	Air Bath	30	24	100	
F L 7	Air Bath	36	24	100	
F L 8	Air Bath	48	24	100	
B X 1	Air Bath	4	~2	100	Fell apart in oven
B X 2	Air Bath	4	~2	100	
F X 1	Air Bath	4	~2	100	30-40 g fell off in oven
F X 2	Air Bath	4	~2	100	
B L 7	Air Bath	48	24 no oven	100	Changed Pine to 800 kPa. This didn't help, we are changing to using the Tinius for compaction.
B L 8	Air Bath	48	24 no oven	100	1000 kPa
F L 9	Air Bath	48	24 no oven	100	800 kPa
F L 10	Air Bath	48	24 no oven	100	1000 kPa