EVALUATION OF WEARING SURFACE MATERIALS FOR FRP BRIDGE DECKS

Final Report

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by

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16. Abstract

The wearing surface on many fiber reinforced polymer (FRP) composite bridge decks have cracked or delaminated after only a short time in service. Consequently, a set of tests were conducted on four wearing surface products in order to select the material with the best performance with respect to service conditions on an FRP deck. The products were evaluated for tensile strength, failure strain, bond strength, and abrasion resistance. Results were summarized in a ranking matrix, which showed Urefast PF60 should provide the best performance of the products tested.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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EVALUATION OF WEARING SURFACE MATERIALS FOR FRP BRIDGE DECKS

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1.0 INTRODUCTION

Oregon has two state-owned and one county-owned fiber reinforced polymer bridge decks in the state all of which are bascule lift spans. The wearing surfaces on all three bridges have shown poor performance due to cracking and delamination. The delamination problems seem to be related to a bond problem with the non-skid surface layer that is supplied with the deck panels from the manufacturer. However, the cracking problem may in part be due to the inability of the wearing surface material to accommodate the service level strains. Consequently, the Oregon Department of Transportation (ODOT) conducted a set of tests to characterize the tensile properties, abrasion resistance, and bond strength of four candidate wearing surface systems.

Four wearing surface systems were evaluated: Tamms Flexolith, Degussa Degadeck™ Bridge Overlay System, Epoxy Engineered Materials Ceva® Deck 110, and Urefast PF60. Flexolith is an epoxy-based material, Degadeck™ is a methacrylate-based material, Ceva® Deck 110 is an "epoxy blend, elastomeric" material, and Urefast PF60 is a urethane material. The Flexolith and Ceva® Deck systems use aggregate supplied by the manufacturer. For the Degadeck™ and Urefast PF60 materials, Oregon aggregate meeting Oregon Specification 556.12 was used.

A Box-Behnken response surface was developed for the Flexolith, Degadeck™, and Urefast PF60 materials to determine the expected failure strain and tensile strength under representative service conditions. Not enough Ceva® Deck material was available to run a response surface. A response surface provides a mathematical model for responses (in this case, failure strain and tensile strength) as a function of the variables included in the experimental design. The model is only valid over the range of variable values included in the test space.

2.0 PROCEDURE

2.1 TENSILE TESTS

Tensile specimens with a 1 in x 2 in x 4.75 in gage section were made in split aluminum molds as shown in Figure 2.1. Silicone grease was used as a mold release material. The specimens were allowed to cure at ambient laboratory temperature prior to testing.

Figure 2.1: Tensile specimen mold.

Three variables were identified as potentially affecting failure strain and tensile strength: temperature, strain rate, and aggregate content. The high and low values for the variables were selected based on the range in field conditions and the capabilities of the equipment. The values used for the tests are shown in Table 2.1.

Table 2.1: Variable values

	Minimum	Mid-range	Maximum
Temperature (^oF)	15	77.5	140
Strain Rate (in/in/sec)	3.5×10^{-5}	2.65×10^{-3}	5.26×10^{-3}
Aggregate-to-resin volume ratio for Flexolith and Urefast PF60	1	2	3
Aggregate-to-resin volume ratio for Degadeck™ Bridge Overlay System	0	1	2

The Degadeck™ material was tested with 0, 1, and 2 aggregate-to-resin volume ratios because it was not possible to produce specimens with three times the aggregate volume. Because only a small amount of the Ceva® Deck material was available, tests were limited to a strain rate of 2.65×10^{-3} in/in/sec and an aggregate-to-resin volume ratio of 2.

Each specimen was heated in a warming oven or cooled in a freezer for at least 24 hours prior to testing in order to achieve the target temperatures. The specimen was immediately transferred to a Baldwin Satec 600CS testing machine with a 60,000 pound load cell where the specimen was slid into the fixtures as shown in Figure 2.2. The fixtures were designed to pull against the gage shoulder. A Satec P9M extensometer was attached to the specimen, and the test was immediately started. A load and extension curve was generated for each test from which the tensile strength and strain at fracture were calculated. The measurements were used as the responses for the response surfaces which were analyzed using Design Expert® 6.0 by Stat-Ease.

Figure 2.2: Tensile test setup.

2.2 ABRASION TESTS

A Taber® 5150 Abraser with an S-35 tungsten carbide wheel was used to conduct abrasion tests on the wearing surface materials. The specimens, shown in Figure 2.3, were abraded for 10,000 cycles at room temperature, and weight measurements were made after every 1000 cycles. The Urethane PF60 samples were tested for an additional 20,000 cycles with the samples heated to 140°F immediately before each set of 1000 cycles.

Figure 2.3: Abrasion test specimens.

2.3 BOND TEST

The room temperature bond between the wearing surface material and the FRP deck material was measured using a Dillon® Dynamometer Pull Tester. Cylindrical wearing surface specimens 2.44 in in diameter and 0.5 in to 0.75 in thick were cast against sandblasted sections of FRP panels and allowed to fully cure. The threaded steel cylinder of the pull tester was attached to the wearing surface sample as shown in Figure 2.4. The force was increased until the specimens fractured or pulled off of the FRP panels.

Figure 2.4: Bond specimen.

3.0 RESULTS

3.1 TENSILE TESTS

3.1.1 Flexolith

The tensile strengths and failure strains for the set of tensile tests are shown in Table 3.1.

Table 3.1: Tensile results for Tamms Flexolith

Standard order	Temperature (^oF)	Aggregate-to-resin volume ratio	Strain rate (in/in/sec)	Tensile strength (psi)	Failure strain (in/in)
1	15	1	2.65E-03	1384	2.2E-04
2	140	1	2.65E-03	182.3	3.5E-02
3	15	3	2.65E-03	1073	5.5E-04
4	140	3	2.65E-03	182	3.5E-03
5	15	2	3.50E-05	2108	5.5E-04
6	140	2	3.50E-05	1022	3.2E-02
7	15	2	5.26E-03	2344	4.6E-04
8	140	2	5.26E-03	462.7	3.4E-02
9	77	1	3.50E-05	1354	2.3E-02
10	77	3	3.50E-05	696.8	1.2E-03
11	77	1	5.26E-03	1875	2.2E-03
12	77	3	5.26E-03	972.3	6.5E-04
13	77	2	2.65E-03	2151	1.2E-03
14	77	2	2.65E-03	2210	1.4E-03
15	77	2	2.65E-03	2265	1.4E-03
16	77	2	2.65E-03	2238	7.8E-04
17	77	2	2.65E-03	1841	6.4E-04

3.1.1.1 Failure Strain

A linear model in conjunction with transforming the failure strain response with an inverse square root function produced a significant model with insignificant lack-of-fit. The only significant factor was found to be temperature; consequently, aggregate and strain rate were removed from the model. The resulting model (3-1) had a R^2 of 0.74.

$$(\text{Failure strain})^{-1/2} = 55.45 - 0.355 * \text{Temperature} \qquad \textbf{(3-1)}$$

The plot of failure strain as a function temperature is shown in Figure 3.5.

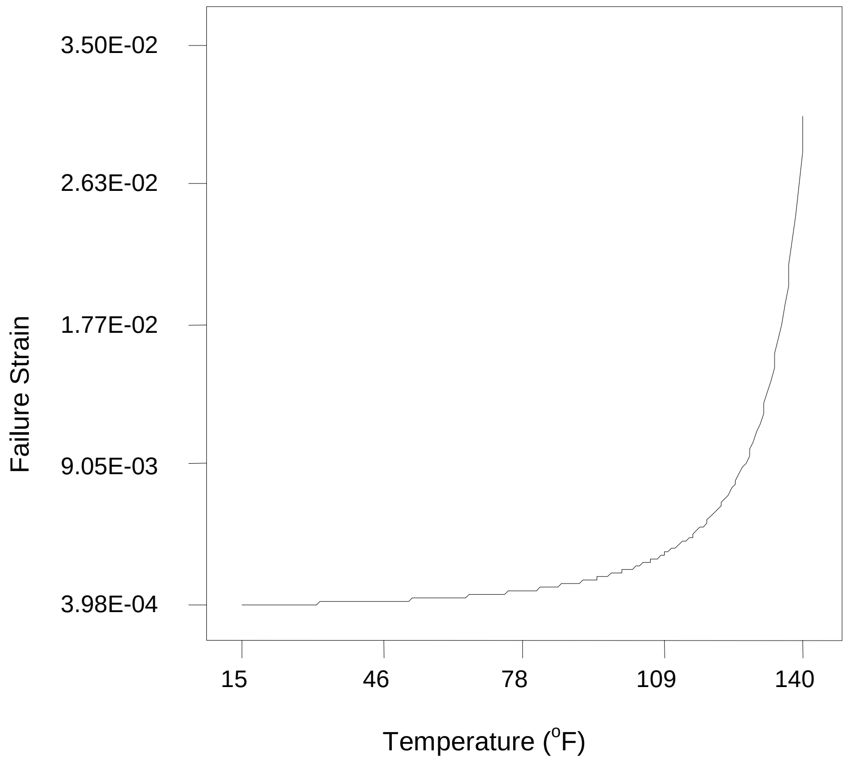


Figure 3.5: Failure strain as a function of temperature for Tamms Flexolith

Based on calculated service strains up to 509 microstrain, the Tamms product could have inadequate ductility in cold weather.

3.1.1.2 Tensile Strength

A quadratic model produced a significant model with insignificant lack-of-fit. Temperature and aggregate content were found to be significant factors. Strain rate, an insignificant factor, was removed from the model. The equation is:

$$\begin{aligned} TensileStrength &= {}^{-}950.71 + 13.356 * Temperature + 3171.24 * AggregateContent \\ &- 0.1515 * Temperature^2 - 851.28 * AggregateContent^2 \end{aligned} \quad \textbf{(3-2)}$$

with an R^2 of 0.88.

As evident in Figure 3.6, an aggregate content of approximately 2-to-1 produced optimum strength over the temperature range tested.

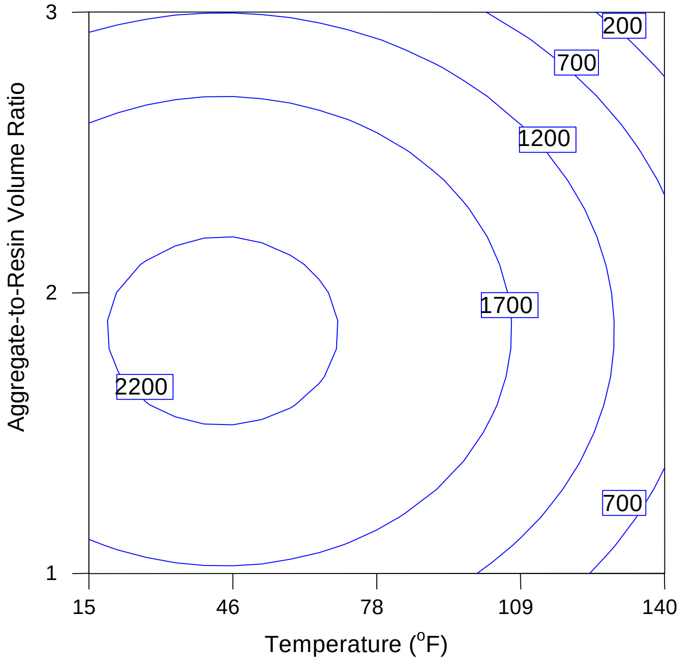


Figure 3.6: Tensile strength contours (psi) for Flexolith.

3.1.2 Degadeck™ Bridge Overlay System

The tensile results are shown in Table 3.2.

Table 3.2: Tensile results for Degadeck™ Bridge Overlay System

Standard Order	Temperature (°F)	Aggregate-to-Resin Volume Ratio	Strain Rate (in/in/sec)	Tensile Strength (psi)	Failure Strain (in/in)
1	15	0	2.65E-03	2130	7.32E-03
2	140	0	2.65E-03	125.1	1.03E-01
3	15	2	2.65E-03	391.9	5.39E-03
4	140	2	2.65E-03	56.21	3.24E-02
5	15	1	3.50E-05	947.4	3.70E-03
6	140	1	3.50E-05	205.1	3.44E-02
7	15	1	5.26E-03	2294	1.25E-03
8	140	1	5.26E-03	210.5	3.34E-02
9	77	0	3.50E-05	330	3.28E-02
10	77	2	3.50E-05	64.3	7.70E-03
11	77	0	5.26E-03	581.5	3.10E-02
12	77	2	5.26E-03	261.9	3.56E-03
13	77	1	2.65E-03	698.3	1.46E-02
14	77	1	2.65E-03	717	1.79E-02
15	77	1	2.65E-03	798.4	2.45E-02
16	77	1	2.65E-03	739.6	2.70E-02
17	77	1	2.65E-03	775.4	2.16E-02

3.1.2.1 Failure Strain

A quadratic mathematical description in conjunction with transforming the failure strain response with a square root function produced a significant model with insignificant lack-of-fit. The significant factors were found to be temperature, aggregate volume ratio, strain rate squared, and an interaction between temperature and aggregate volume ratio. The equation is:

$$(FailureStrain)^2 = 0.0383 + 1.74E-03 * Temperature - 5.43E-03 * Aggregate + 22.3 * StrainRate - 4760 * (StrainRate)^2 - 5.15E-04 * Temperature * Aggregate \quad \textbf{(3-3)}$$

with an R^2 of 0.93.

The contour graphs in Figure 3.7-3.9 show the effect of the variables on failure strain. The lowest failure strain within the test space is 578 microstrain at temperature = 15°F, aggregate-to-volume ratio = 2, and strain rate = 5.26E-03.

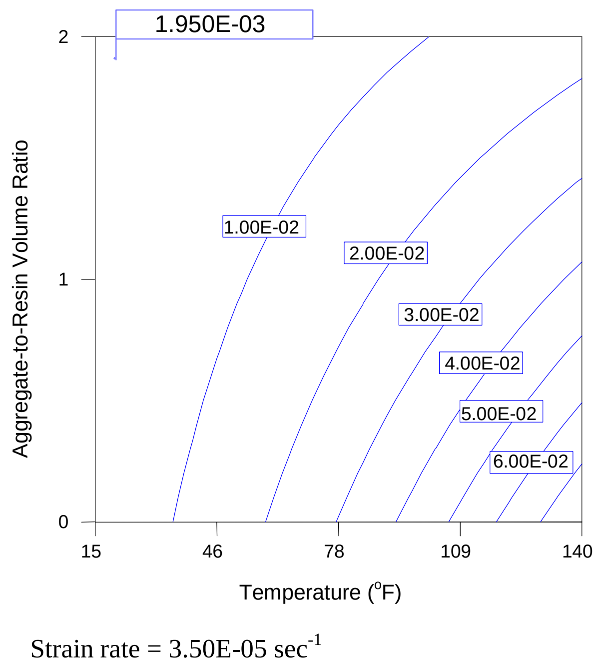
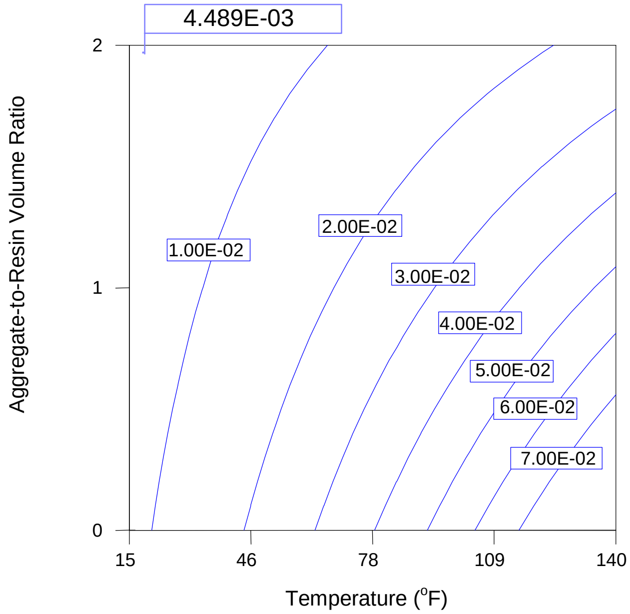
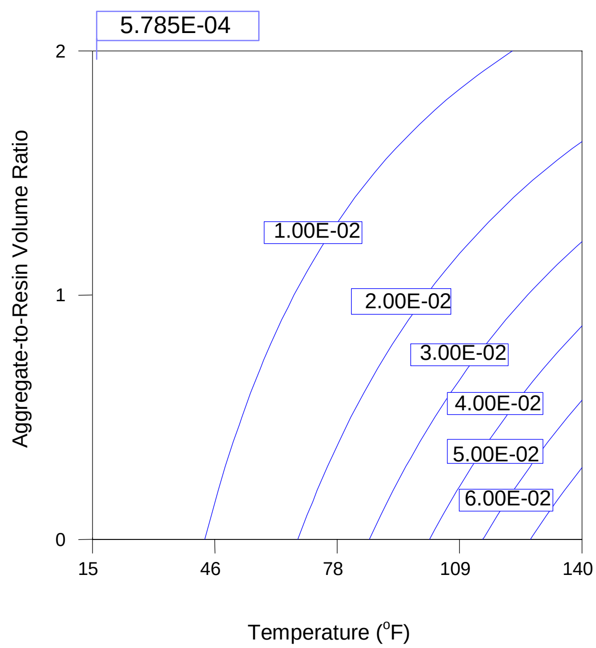


Figure 3.7: Failure strain contours for Degadeck™ Bridge Overlay System at a strain rate of 3.50E-05 sec^{-1}



Strain rate = 2.65E-03 sec^{-1}

Figure 3.8: Failure strain contours for Degadeck™ Bridge Overlay System at a strain rate of 2.65E-03 sec^{-1}



Strain rate = 5.26E-03 sec^{-1}

Figure 3.9: Failure strain contours for Degadeck™ Bridge Overlay System at a strain rate of 5.26E-03 sec^{-1}

3.1.2.2 Tensile Strength

A model with insignificant lack-of-fit was not found.

3.1.3 Urefast PF60

The tensile results are shown in Table 3.3.

Table 3.3: Tensile results for Urefast PF60

Standard Order	Temperature (°F)	Aggregate-to-Resin Volume Ratio	Strain Rate (in/in/sec)	Tensile Strength (psi)	Failure Strain (in/in)
1	15	1	2.65E-03	1695	3.9E-03
2	140	1	2.65E-03	49	4.8E-02
3	15	3	2.65E-03	1262	1.5E-03
4	140	3	2.65E-03	76	3.7E-02
5	15	2	3.50E-05	332	4.7E-03
6	140	2	3.50E-05	76	8.0E-02
7	15	2	5.26E-03	1701	2.1E-03
8	140	2	5.26E-03	104	5.4E-02
9	77	1	3.50E-05	138	1.1E-01
10	77	3	3.50E-05	136	4.8E-02
11	77	1	5.26E-03	553	8.2E-02
12	77	3	5.26E-03	286	5.1E-02
13	77	2	2.65E-03	774	3.4E-02
14	77	2	2.65E-03	807	3.4E-02
15	77	2	2.65E-03	691	4.0E-02
16	77	2	2.65E-03	416	6.9E-02
17	77	2	2.65E-03	436	6.7E-02

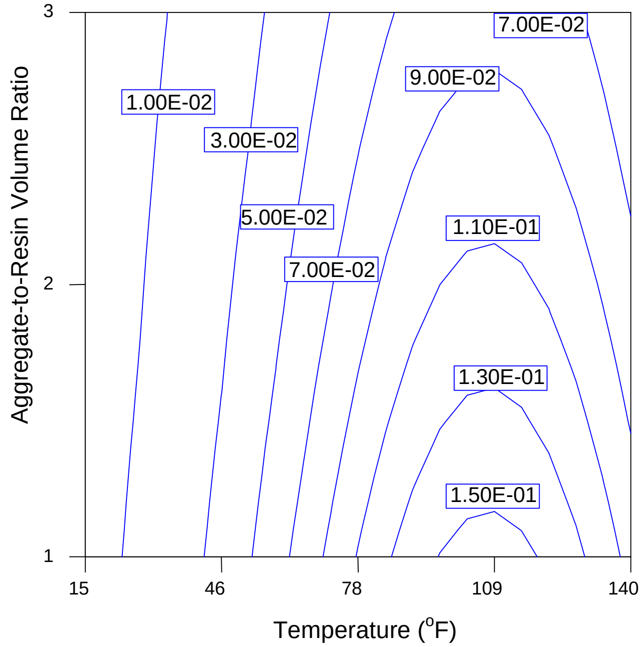
3.1.3.1 Failure Strain

A quadratic mathematical description in conjunction with transforming the failure strain response with a $\log_{10}$ function produced a significant model with insignificant lack-of-fit. The significant factors were found to be temperature, aggregate volume ratio, temperature squared, and strain rate squared. The equation is:

$$\begin{aligned} Log_{10}(FailureStrain) &= {}^{-}2.636 + 0.0368 * Temperature - 0.1368 * AggregateContent \\ &- 155.4 * StrainRate - 1.716E-04 * (Temperature)^2 + 23690 * (StrainRate)^2 \end{aligned} \qquad \textbf{(3-4)}$$

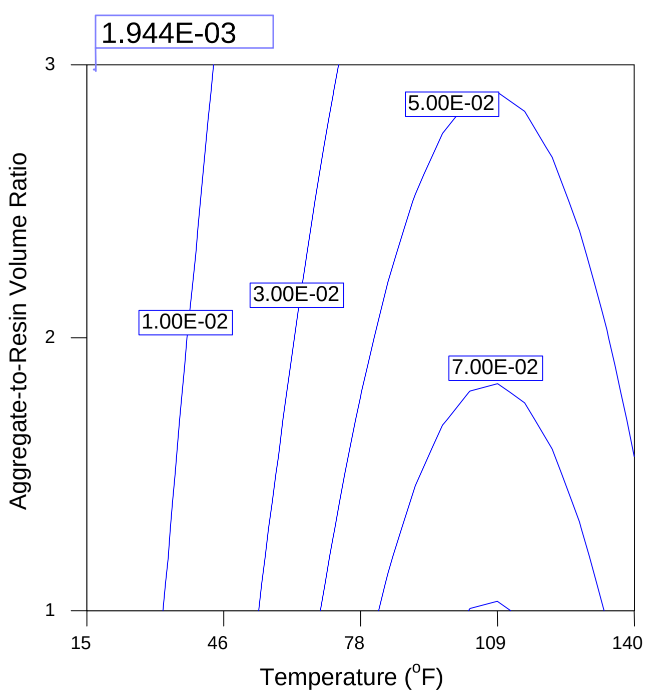
with an R^2 of 0.96.

The contour graphs in Figures 3.10-3.12 show the effect of temperature, aggregate content, and strain rate on the failure strain. The strain rate had little effect on the minimum strain at failure. The lowest failure strain within the test space is approximately 1900 microstrain.



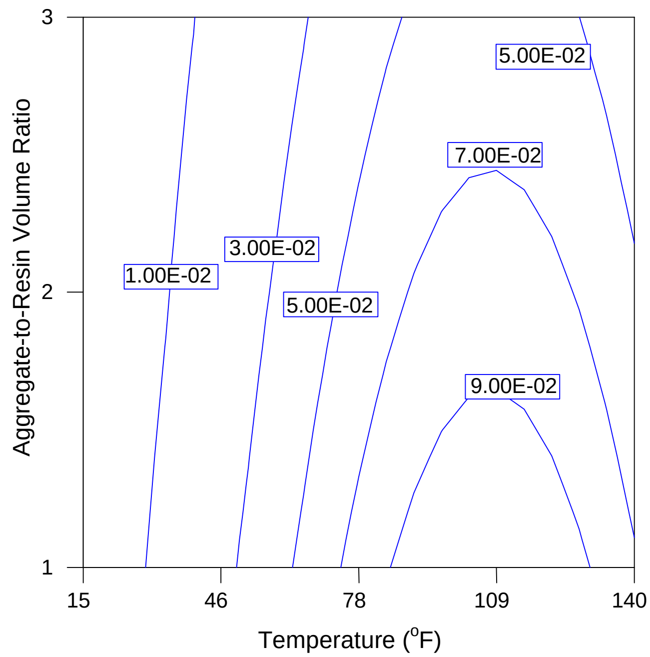
Strain rate = 3.50E-05 sec^{-1}

Figure 3.10: Failure strain contours for Urefast PF60 at a strain rate of 3.50E-05 sec^{-1}



Strain rate = 2.65E-03 sec^{-1}

Figure 3.11: Failure strain contours for Urefast PF60 at a strain rate of 2.65E-03 sec^{-1}



Strain rate = 5.26E-03 sec^{-1}

Figure 3.12: Failure strain contours for Urefast PF60 at a strain rate of 5.26E-03 sec^{-1}

3.1.3.2 Tensile Strength

A quadratic mathematical description in conjunction with transforming the tensile strength response with a $\log_{10}$ function produced a significant model with insignificant lack-of-fit. The significant factors were found to be temperature, strain rate, and strain rate squared. The equation is:

$$Log_{10}(TensileStrength) = 2.87 - 9.23E - 003 * Temperature + 281.5 * StrainRate - 37160 * StrainRate^2 \quad \textbf{(3-5)}$$

with an R^2 of 0.83.

The contour graph in Figure 3.13 shows the effect of temperature and strain rate on tensile strength. The graph shows that strength becomes fairly low at the high temperature end especially at slow strain rate.

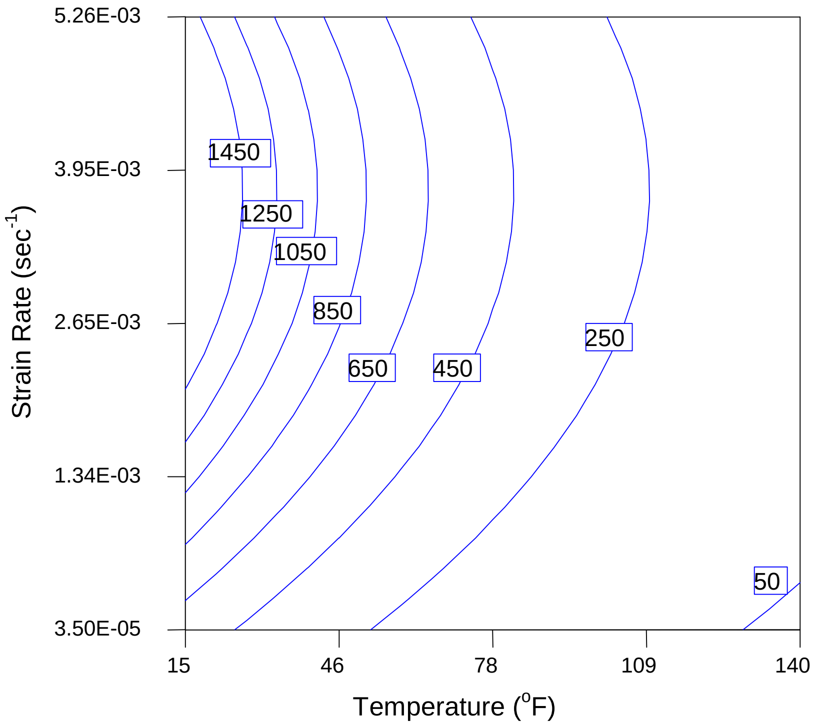


Figure 3.13: Tensile strength contours (psi) for Urefast PF60

3.1.4 Ceva® Deck 110

The tensile results are shown in Table 3.4. An aggregate-to-resin volume ratio of 2 was used for all the tests.

Table 3.4: Tensile results for Ceva® Deck 110

Temperature (°F)	Tensile Strength (psi)	Failure Strain (in/in)
15	585	9.53E-03
15	990	9.23E-03
77	323	3.15E-02
77	242	6.59E-02
140	69	5.72E-02
140	66	4.97E-02

3.2 ABRASION TESTS

The results of the abrasion tests are tabulated in Table 3.5 and shown graphically in Figures 3.14-3.18. The results are useful as a comparison between the four products by comparing the rate of weight loss after the initial break-in period of the first three thousand cycles. The Urefast PF60 showed the best abrasion resistance, while the Flexolith showed the highest rate of wear. Based on the low strength observed in the tensile tests, there was concern that the Urefast PF60 might have poor abrasion resistance on hot days. However, the elevated temperature abrasion resistance for this material was still better than the Flexolith at room temperature.

Table 3.5: Abrasion test results

Cycles on Taber Abraser	Urefast PF60		Flexolith				Degadeck™ Bridge Overlay System				Ceva® Deck 110	
	2:1	3:1	2:1	2:1	3:1	3:1	1:1	1:1	2:1	2:1	2:1	2:1
1000	0.50	0.00	0.30	0.40	0.30	0.30	0.40	0.30	0.50	0.60	0.30	0.10
2000	0.70	0.10	0.50	0.70	0.50	0.70	0.50	0.50	0.60	0.80	0.40	0.10
3000	0.90	0.40	0.60	0.90	0.90	0.90	0.50	0.50	0.60	0.90	0.40	0.10
4000	0.90	0.40	0.80	1.20	1.00	0.90	0.50	0.50	0.70	0.90	0.40	0.20
5000	0.90	0.40	0.80	1.20	1.00	1.00	0.50	0.60	0.80	0.90	0.40	0.20
6000	0.90	0.40	0.90	1.40	1.00	1.10	0.60	0.60	0.80	1.00	0.40	0.20
7000	0.90	0.40	1.10	1.60	1.00	1.10	0.60	0.60	0.90	1.00	0.40	0.20
8000	0.90	0.40	1.10	1.60	1.10	1.10	0.60	0.70	0.80	1.00	0.50	0.20
9000	0.90	0.40	1.10	1.70	1.10	1.10	0.60	0.70	0.80	1.00	0.50	0.30
10000	0.90	0.40	1.20	1.80	1.10	1.20	0.60	0.70	0.90	1.00	0.50	0.30

The table shows cumulative weight loss in grams for various aggregate-to-resin volume ratios. A tungsten carbide S-35 wheel was used.

Cumulative weight loss for Urefast PF60 heated to 140°F before each set of 1000 cycles. The samples were first abraded at room temperature for 10,000 cycles.					
Cycles on Taber Abraser	**2:1**	**3:1**	**Cycles on Taber Abraser**	**2:1**	**3:1**
1000	0.0	0.0	**11000**	0.3	0.1
2000	0.0	0.0	**12000**	0.3	0.2
3000	0.1	0.0	**13000**	0.4	0.2
4000	0.1	0.0	**14000**	0.5	0.2
5000	0.2	0.0	**15000**	0.5	0.2
6000	0.1	0.0	**16000**	0.5	0.2
7000	0.1	0.0	**17000**	0.5	0.2
8000	0.2	0.1	**18000**	0.5	0.2
9000	0.3	0.1	**19000**	0.5	0.2
10000	0.3	0.1	**20000**	0.5	0.2

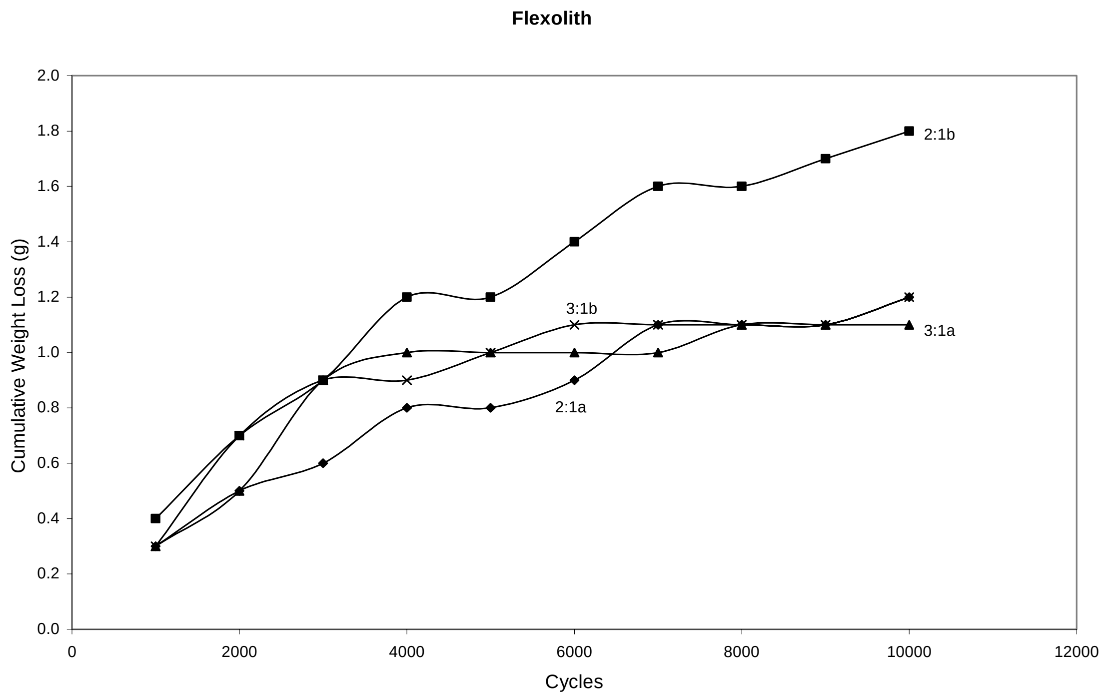


Figure 3.14: Abrasion resistance graph for Flexolith

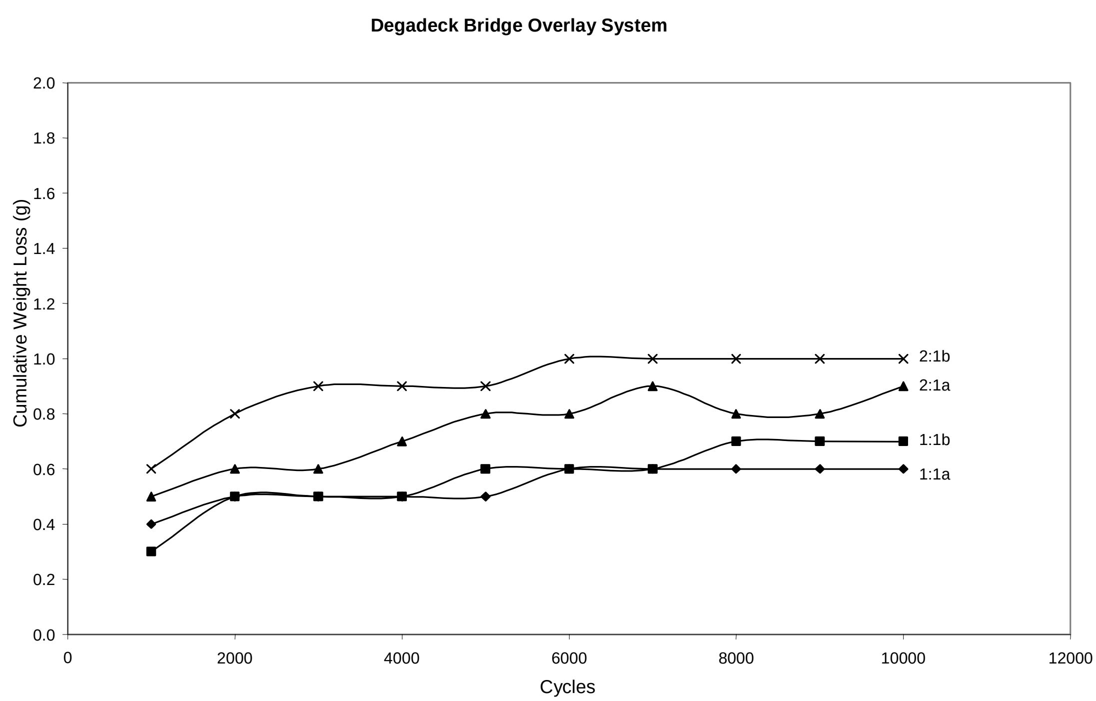


Figure 3.15: Abrasion resistance graph for Degadeck™ Bridge Overlay System

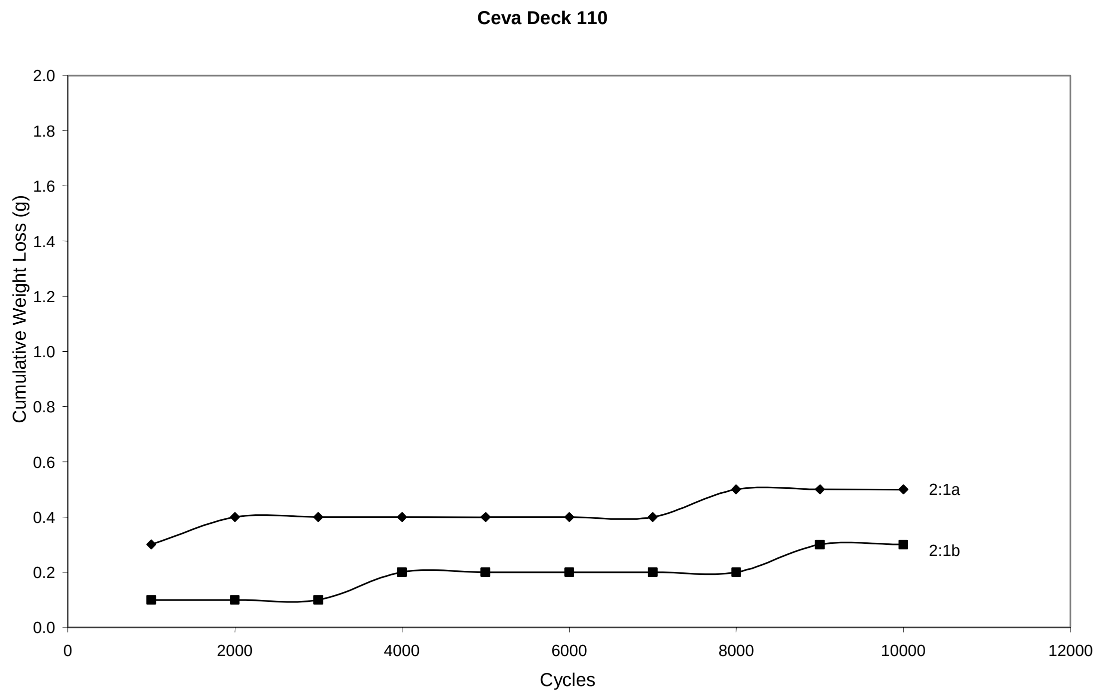


Figure 3.16: Abrasion resistance graph for Ceva® Deck 110

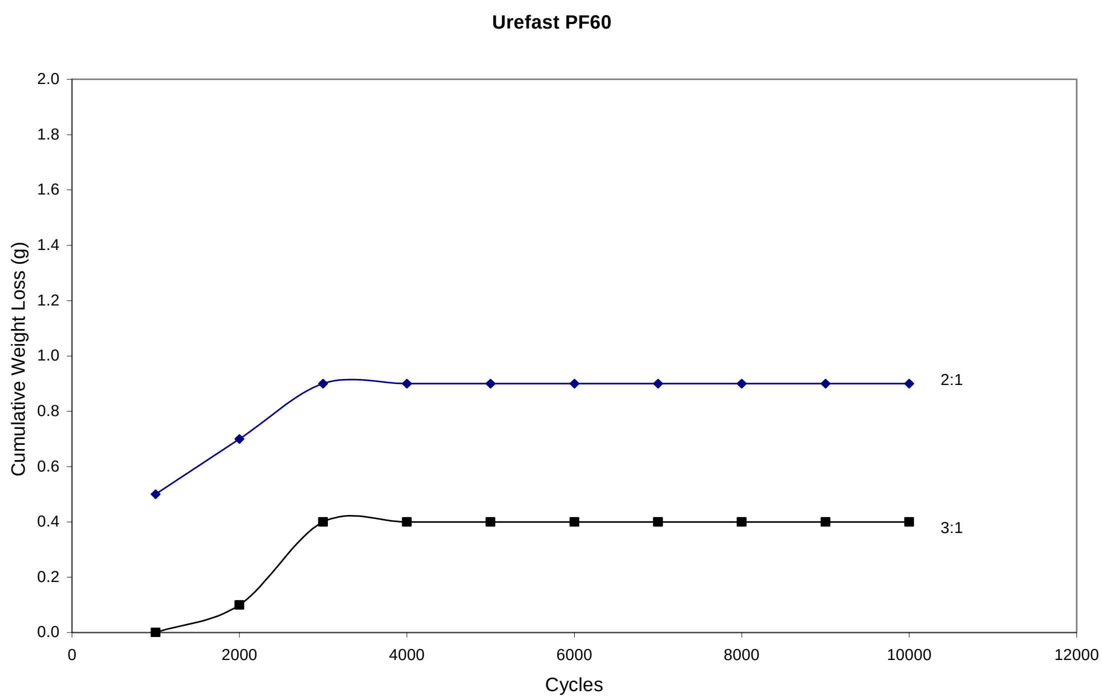


Figure 3.17: Abrasion resistance graph for Urefast PF60

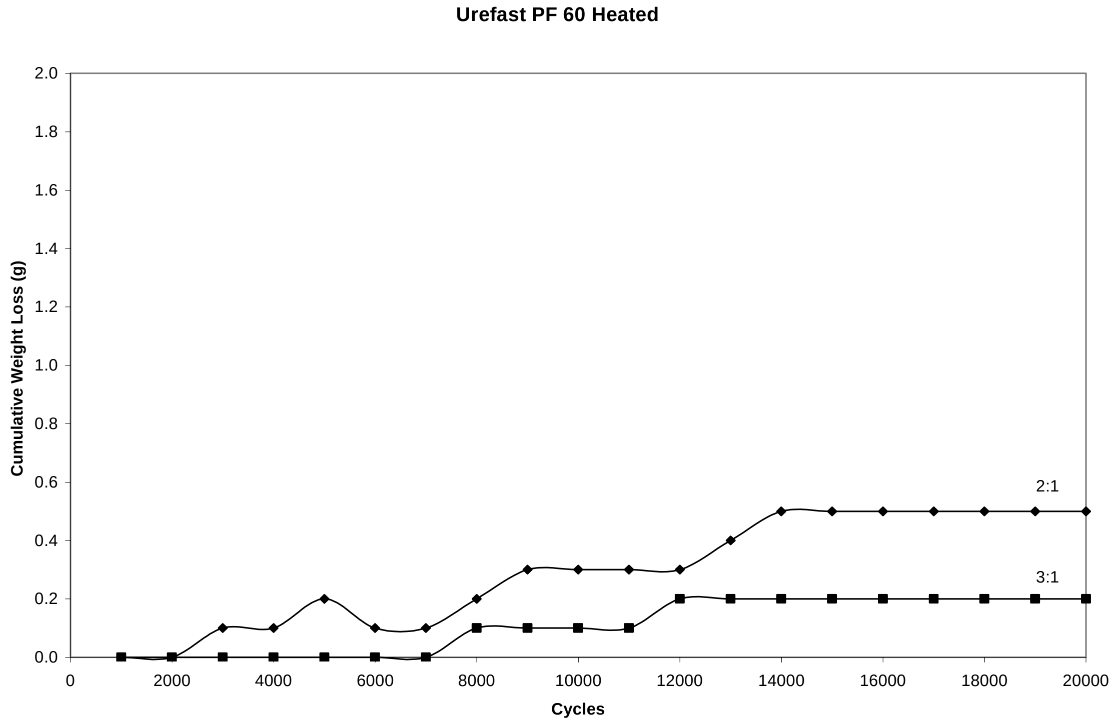


Figure 3.18: Abrasion resistance graph for Urefast PF60 heated

3.3 BOND TESTS

The bond test results for the three products are shown in Table 3.6.

Table 3.6: Bond test results for Urefast PF60, Flexolith, and Degadeck™

Material (aggregate:resin)	Measured Strength (psi)	Failure location
Urefast PF60 (2:1)	428	Interface between the steel cylinder and the sample.
Urefast PF60 (2:1)	514	Interface between the sample and the FRP.
Urefast PF60 (2:1)	359	Interface between the sample and the FRP.
Urefast PF60 (2:1)	428	Interface between the sample and the FRP.
mean = 432		
Flexolith (2:1)	310	Interface between the sample and the FRP.
Flexolith (2:1)	288	Interface between the sample and the FRP.
Flexolith (2:1)	504	Interface between the sample and the FRP.
Flexolith (2:1)	203	Interface between the sample and the FRP.
Flexolith (2:1)	149	Interface between the sample and the FRP.
mean = 291		
Degadeck™ (2:1)	248	Through wearing surface sample.
Degadeck™ (2:1)	316	Through wearing surface sample.
Degadeck™ (2:1)	361	Through wearing surface sample.
Degadeck™ (2:1)	237	Through wearing surface sample.
Degadeck™ (2:1)	352	Through wearing surface sample.
mean = 303		
Degadeck™ (1:1)	587	Interface between the steel cylinder and the sample.
Degadeck™ (1:1)	497	Interface between the steel cylinder and the sample.
Degadeck™ (1:1)	576	Interface between the sample and the FRP.
mean = 553		

4.0 DISCUSSION AND CONCLUSIONS

Based on the test results, the four wearing surface materials were ranked for each of the four test categories as shown in Table 4.1. At the cold temperatures, the Flexolith and Degadeck™ materials exhibited failure strains within the magnitude of service strains expected in the wearing surface of an FRP bridge deck. At the high temperatures, the Degadeck™, Urefast, and Ceva® Deck systems had strengths less than 100 psi. Such low strength could result in wearing surface deformation on hot summer days.

Bond strength comparisons were based on data sets in which the failure was either at the interface between the sample and the FRP or at the interface between the sample and the steel cylinder of the pull tester. The intent of the bond test was not to test the bulk strength of the material; consequently, the Degadeck™ with a 2:1 aggregate-to-resin volume ratio was not considered. Interestingly, the response surface did not show an aggregate effect on the tensile strength of Degadeck™, but the bond tests indicated that there is such an effect. However, considering just the tensile tests at 77°F from the response surface data for Degadeck™, the tensile strength for 1:1 was consistently higher than the tensile strength for 2:1.

The Ceva® Deck material was generally difficult to work with in the laboratory. It was more viscous than the other materials making it difficult to blend in the aggregate and to form the specimens. It also produced a more offensive odor than the other products. Similar complaints about workability and odor have been reported by field highway personnel.

Table 4.1: Ranking matrix for the wearing surface materials

	Flexolith	Degadeck™ Bridge Overlay System	Urefast PF60	Ceva® Deck 110
Failure strain at 15°F	4	3	2	1
Tensile strength at 140°F	1	2	2	2
Abrasion resistance	4	2	1	2
Bond strength	3	1	2	Not tested

1=Best