Four-Point Bending Notched-Beam Fatigue Testing of Geosynthetic-Reinforced Asphalt Beams

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STATE OF NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

RESEARCH & DEVELOPMENT

Four-Point Bending Notched-Beam Fatigue Testing of Geosynthetic-Reinforced Asphalt Beams

FINAL REPORT

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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	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
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	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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16. Abstract

Four-point bending notched-beam fatigue tests were conducted on eight geosynthetic-reinforced asphalt beams fabricated previously as part of the reflective cracking study under Project RP2021-07. The eight specimens comprised three beams reinforced with paving composite #2 (PC#2), three with paving grid (PaG), one with paving mat (PM), and one with paving fabric (PF). These beams had been stored under laboratory conditions for approximately two years prior to testing. Fatigue tests were performed in constant actuator displacement–control mode at a frequency of 10 Hz and a temperature of 23°C. Failure was defined as the peak point on the tensile stress × cycle versus cycle curve, and results are presented as on-specimen tensile strain (ε_{os}) versus number of cycles to failure (N_f).

Two datasets were excluded from the primary analysis. One dataset corresponds to the PC#2 specimen tested at 300 με, for which environmental chamber control was interrupted due to depletion of the nitrogen supply. The second excluded dataset involves the PM specimen, which reached the test termination limit of 2,000,000 cycles without failure. These excluded datasets are provided in Appendix B.

Overall, the beams tested in this study exhibited shorter fatigue lives than those tested previously in Project RP2021-07. This reduction is attributed primarily to aging of the asphalt beams during the two-year storage period. The relationship between ε_{os} and N_f was established using combined data from Project RP2021-07 and the current study, and the resulting regression coefficients are reported.

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LIST OF ABBREVIATIONS

Item	Definition
AC	Asphalt concrete
NBFT	Notched beam fatigue test
N_f	Number of cycles to failure
PaG	Paving Grid
PC#1	Paving Composite #1
PC#2	Paving Composite #2
PF	Paving Fabric
PG	Performance grade
PM	Paving Mat
RAP	Reclaimed asphalt pavement
ε_{act}	Actuator tensile strain at the beam bottom
ε_{os}	On-specimen tensile strain at the beam bottom
ε_{int}	Interlayer tensile strain

EXECUTIVE SUMMARY

Four-point bending notched-beam fatigue tests were conducted on eight geosynthetic-reinforced asphalt beams fabricated previously as part of the reflective cracking study under Project RP2021-07. The eight specimens comprised three beams reinforced with paving composite #2 (PC#2), three with paving grid (PaG), one with paving mat (PM), and one with paving fabric (PF). These beams had been stored under laboratory conditions for approximately two years prior to testing. Fatigue tests were performed in constant actuator displacement–control mode at a frequency of 10 Hz and a temperature of 23°C. Failure was defined as the peak point on the tensile stress × cycle versus cycle curve, and results are presented as on-specimen tensile strain (ε_{os}) versus number of cycles to failure (N_f).

Two datasets were excluded from the primary analysis. One dataset corresponds to the PC#2 specimen tested at 300 με, for which environmental chamber control was interrupted due to depletion of the nitrogen supply. The second excluded dataset involves the PM specimen, which reached the test termination limit of 2,000,000 cycles without failure. These excluded datasets are provided in Appendix B.

Overall, the beams tested in this study exhibited shorter fatigue lives than those tested previously in Project RP2021-07. This reduction is attributed primarily to aging of the asphalt beams during the two-year storage period. The relationship between ε_{os} and N_f was established using combined data from Project RP2021-07 and the current study, and the resulting regression coefficients are reported.

CHAPTER 1. BACKGROUND

Reflective cracking remains a significant challenge in asphalt overlays, leading to premature pavement failure. Geosynthetic interlayers are often applied with AC overlays to reduce reflective cracking because placement is simple, products are widely available, and costs remain modest. Geosynthetics are intended to provide reinforcement, stress relief, and waterproofing. Reinforcement requires a geosynthetic with a modulus higher than the surrounding asphalt, and crack growth is redirected along the interlayer. Stress-relief products have low stiffness, and strain is stored under low stress. Waterproofing is achieved through tack coat impregnation, and water permeability decreases when the geosynthetic is fully saturated. Overall performance is governed by installation quality, overlay thickness control, and compaction quality control (*1*).

In the previous studies, Projects RP 2019-19 and RP 2021-07, four-point bending notched beam fatigue test (NBFT) and Digital Image Correlations (DIC) technique were used to characterize the reflective cracking resistance and debonding potentials of asphalt concrete specimens reinforced with different geosynthetic interlayers (*2*, *3*). Five geosynthetic product types were used in the study, including paving composite #1 (PC#1), paving composite #2 (PC#2), paving mat (PM), paving grid (PaG), and paving fabric (PF). Research efforts in RP 2021-07 resulted in a step-by-step procedure for predicting the life of geosynthetic-reinforced pavements under real-life conditions using existing pavement condition data, such as falling weight deflectometer (FWD) and crack survey data. Several methodologies were developed to support this prediction procedure, including:

- laboratory measurement of crack resistance of geosynthetic-reinforced asphalt beam specimens using the four-point bending notched beam fatigue test,
- determination of dynamic modulus of damaged asphalt layers in existing pavements,
- prediction of tensile strain at the bottom of asphalt overlay using simulated FWD deflection parameters, and
- prediction of damage index for the traffic and environmental conditions of the project in question.

The developed procedure was calibrated using Pavement Management System data from five routes selected among NCDOT's interlayer projects. The calibrated procedure was verified using the pavement design and condition survey data from the US 1 sections at Moore County near Aberdeen (*3*).

The accuracy of the proposed prediction procedure depends on the relationship between fatigue life and tensile strain at the bottom of asphalt overlay, which is shown in the following equation:

$$N_f = k_1 \left(\frac{1}{\varepsilon_t} \right)^{k_2} \quad (1)$$

where

N_f = number of cycles to failure, representing crack resistance,
k_1, k_2 = regression coefficients, and

ε_t = tensile strain in microns.

This relationship is depicted in Figure 1 and the regression coefficients (k_1 and k_2) and R^2 values are summarized in Table 1. Figure 1 clearly demonstrates the geosynthetic reinforcements' ability to increase the fatigue life regardless of the geosynthetic product type. However, the accuracy of the fatigue life increase is somewhat questionable due to the scatter in the data, which is reflected in low R^2 values in some cases. The predictive procedure developed from RP 2021-07 uses equation (1) with k_1 and k_2 values in Table 1; therefore, it is desirable to improve the R^2 values with additional tests.

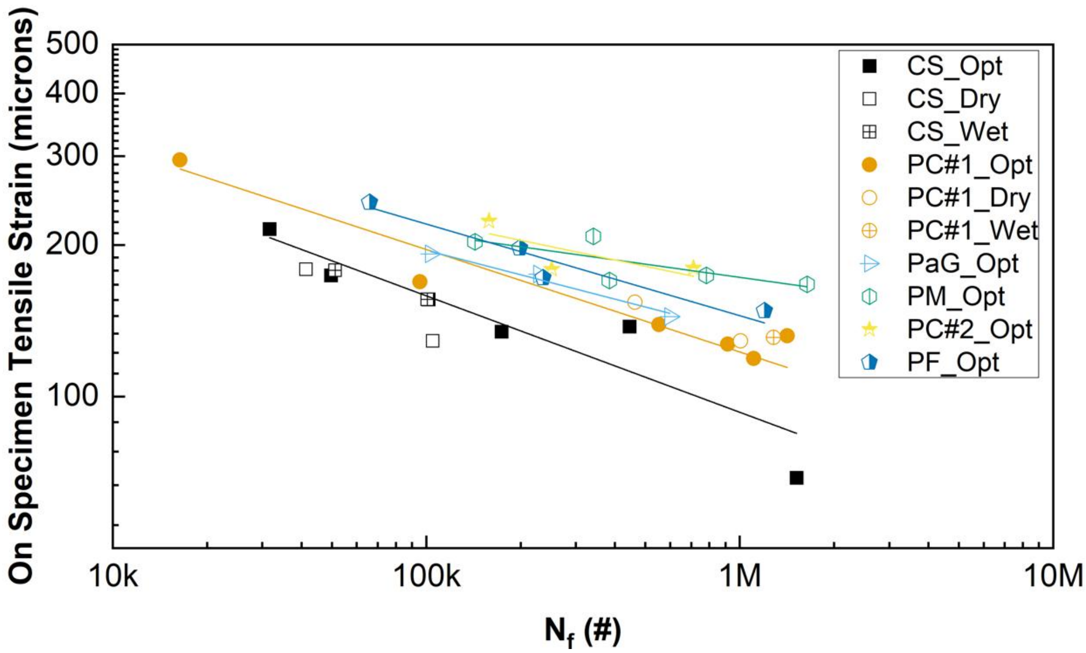


Figure 1. On-specimen tensile strain versus fatigue life for unreinforced (CS) and reinforced beam specimens (*3*).

Table 1. Fatigue coefficients and R^2 values of on-specimen tensile strain versus n_f relationship for unreinforced (cs) and reinforced specimens (*3*).

Interlayer Type	CS	PC#1	PaG	PM	PC#2	PF
k_1	5.15×10^{-16}	1.42×10^{-11}	8.82×10^{-19}	5.09×10^{-38}	6.38×10^{-24}	8.03×10^{-16}
k_2	5.35	4.25	6.21	11.50	7.72	5.49
R^2	0.78	0.90	0.95	0.42	0.1	0.89

Eight geosynthetic-reinforced asphalt beams fabricated previously as part of the reflective cracking study under Project RP 2021-07 were left untested in the previous project due to time shortage. The eight specimens comprised three beams reinforced with PC#2, three with PaG, one with PM, and one with PF. These beams had been stored under laboratory conditions for approximately two years prior to testing. This report describes the testing of these eight specimens and summarizes the test results.

CHAPTER 2. TEST RESULTS AND DISCUSSION

Four-point bending notched-beam fatigue tests were conducted on the eight geosynthetic-reinforced asphalt beams in constant actuator displacement–control mode at a frequency of 10 Hz and a temperature of 23°C. Three strain terms were used in the NBFTs based on the tensile response of a beam. Actuator tensile strain (ε_{act}) at the beam bottom was calculated from actuator displacement, on-specimen tensile strain (ε_{os}) at the beam bottom was calculated from on-specimen displacement measured by an LVDT, and interlayer tensile strain (ε_{int}) was calculated from on-specimen displacement. The relationship ε_{int} = (1/3) ε_{os} was applied, and ε_{int} represents the strain of interest for field overlay interpretation. The initial strain for each NBFT was defined as ε_{os} measured at the 50th loading cycle. Failure was defined as the peak point on the tensile stress × cycle versus cycle curve, and results are presented in the relationship between the initial ε_{os} and N_f. Appendix A presents typical NBFT response plots, including tensile stress versus number of loading cycles, ε_{os} versus number of loading cycles, and tensile stress × cycle versus number of loading cycles.

Two datasets were excluded from the primary analysis. One dataset corresponds to the PC#2 specimen tested at 300 με, for which environmental chamber control was interrupted due to depletion of the nitrogen supply. The second excluded dataset involves the PM specimen, which reached the test termination limit of 2,000,000 cycles without failure. These excluded datasets are provided in Appendix B.

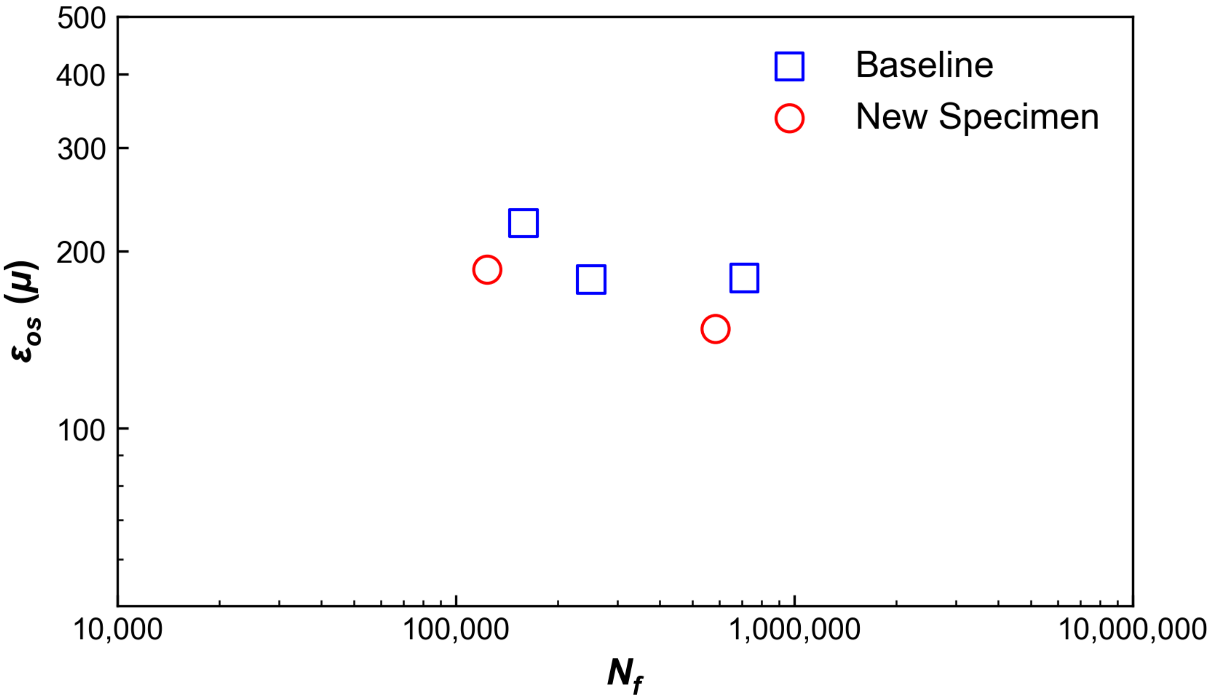
Table 2 reports ε_{int}, ε_{os}, and N_f for each of the applied ε_{act} for each beam. The ε_{os} versus N_f trend remained lower than the data from the RP 2021-07 project, as shown in Figure 2. An in-depth investigation was conducted on the data to find the reason(s) for the shorter fatigue life from the newly tested specimens. It was concluded that the additional aging during two years of storage embrittled the beam specimens and caused the shorter fatigue life. Table 3 summarizes the k_1 and k_2 values for the original data from the RP 2021-07 project, for the new data, and for the pooled data that include both original and new data.

Table 2. Failure life based on stress × N failure definition for geosynthetic-reinforced beam specimens.

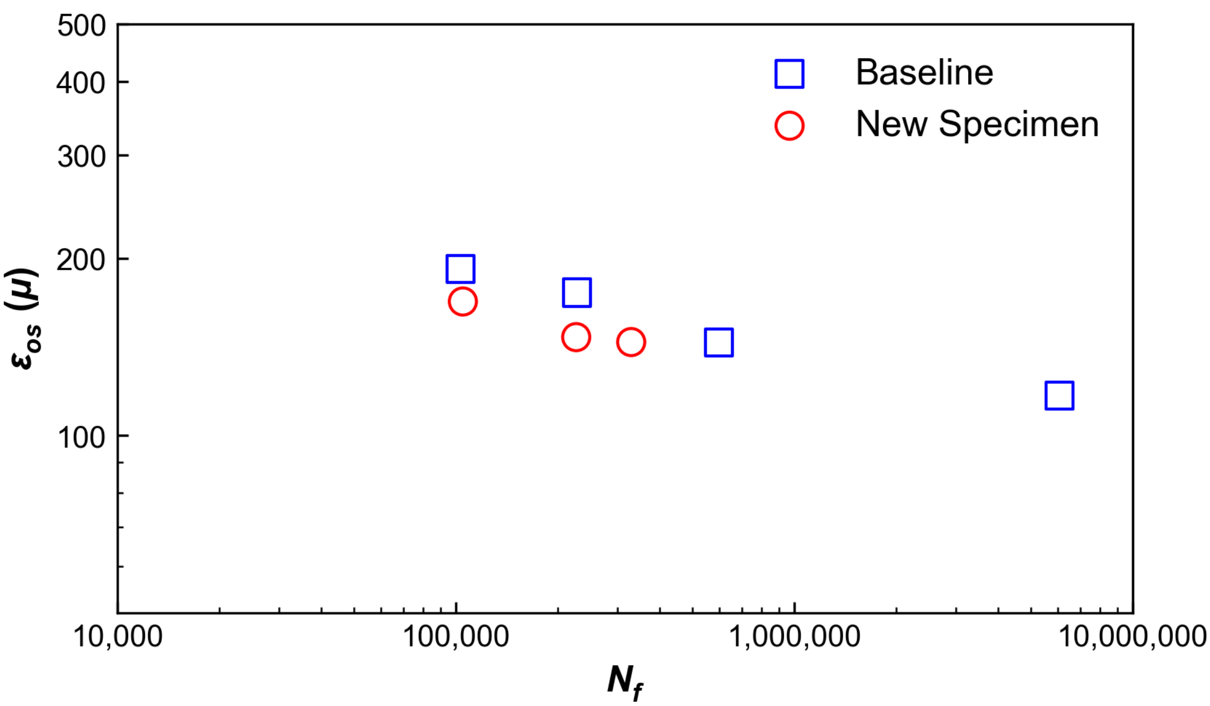
ε_{act}		375 μ	325 μ	300 μ	285 μ
PC#2	ε_{os} (ε_{int})	186 μ (62 μ)			148 μ (49 μ)
	N_f	124,000			586,000
PaG	ε_{os} (ε_{int})	169 μ (56 μ)	147 μ (49 μ)	144 μ (48 μ)	
	N_f	105,000	227,000	330,000	
PF	ε_{os} (ε_{int})			158 μ (53 μ)	
	N_f			248,000	

Table 3. Original and updated fatigue coefficients and R^2 values of on-specimen tensile strain versus N_f relationship for tested specimens.

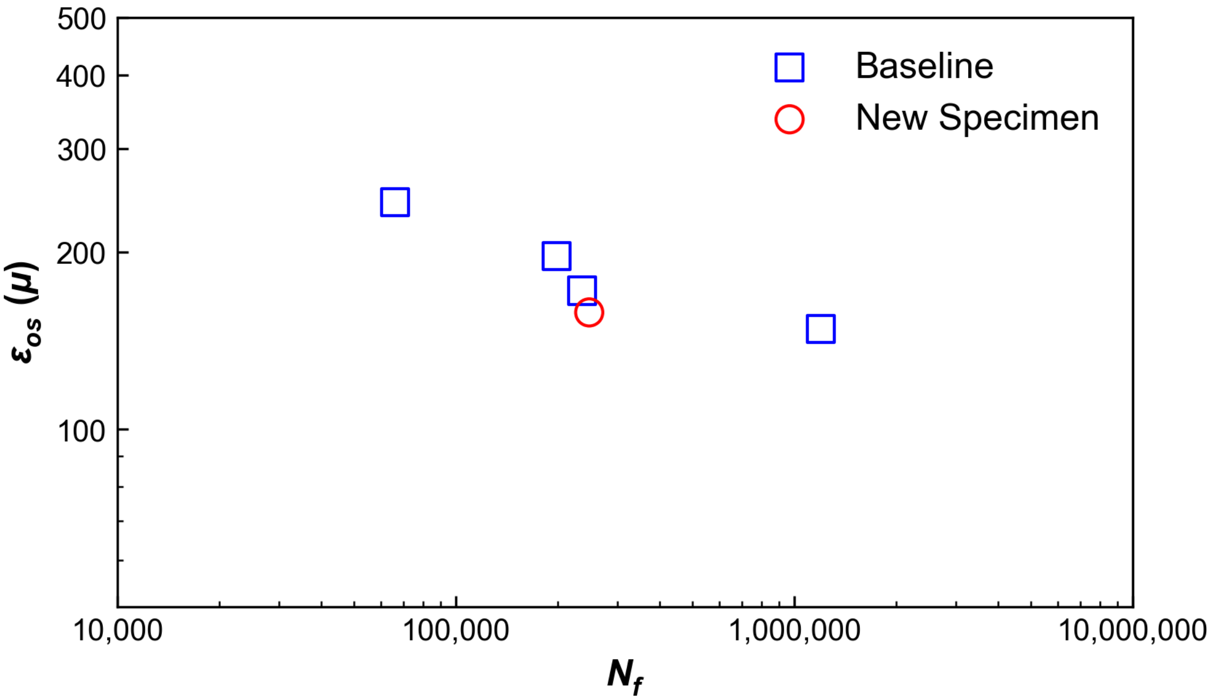
Type	CS	PC#1	PaG			PM	PC#2			PF	
	RP 2021-07	RP 2021-07	RP 2021-07	New	Pooled	RP 2021-07	RP 2021-07	New	Pooled	RP 2021-07	Pooled
k_1	5.15×10^{-16}	1.42×10^{-11}	8.82×10^{-19}	1.47×10^{-20}	1.59×10^{-24}	5.09×10^{-38}	6.38×10^{-24}	1.30×10^{-20}	4.03×10^{-8}	8.03×10^{-16}	9.62×10^{-13}
k_2	5.35	4.25	6.21	6.59	7.70	11.50	7.72	6.70	3.44	5.49	4.65
R^2	0.78	0.90	0.95	0.95	0.81	0.42	0.1	1	0.4232	0.89	0.78


500
400
300
200
100
ε_{os} (μ)
10,000
100,000
1,000,000
10,000,000
N_f
Baseline
New Specimen

A. PC#2.


500
400
300
200
100
ε_{os} (μ)
10,000
100,000
1,000,000
10,000,000
N_f
Baseline
New Specimen

B. PaG.



C. PF.

Figure 2. On-specimen tensile strain versus fatigue life.

CHAPTER 3. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Overall, the beams tested in this study exhibited shorter fatigue lives than those tested previously in Project RP2021-07. This reduction is attributed primarily to aging of the asphalt beams during the two-year storage period. The relationship between ε_{os} and N_f was established using combined data from Project RP2021-07 and the current study, and the resulting regression coefficients are reported.

Recommendations

It is recommended that the fatigue coefficients reported in Table 7-1 of the Project RP2021-07 final report be used for the evaluation of asphalt overlay with different geosynthetic interlayers. This recommendation is due to the fact that the asphalt beams tested in this project were apparently aged due to the two years of storage time.

CHAPTER 4. IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

The Materials and Tests Unit of the NCDOT will be the primary users of the outcomes of this project. The developed guidelines and predictive models with measured fatigue coefficients in the Project RP2021-07 offer a comprehensive and practical approach to enhancing performance of pavements reinforced by geosynthetic interlayers, extending service life, and optimizing maintenance and rehabilitation for NCDOT. The findings of this research will be communicated to the NCDOT in the form of this report.

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2. Kim, Y. R., N. Sudarsanan, and L. G. Xue. *Development of Geosynthetic Pavement Interlayer Improvements*. Publication FHWA/NC/2019-19. North Carolina Department of Transportation, Research and Development Unit, Raleigh, NC, 2022.
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APPENDIX A – TYPICAL NBFT OUTPUT PLOTS

Appendix A provides representative plots from a typical NBFT. The appendix includes including tensile stress versus cycles, ε_{os} versus cycles, and tensile stress × cycle versus cycles, as shown in Figure 3 to Figure 6.

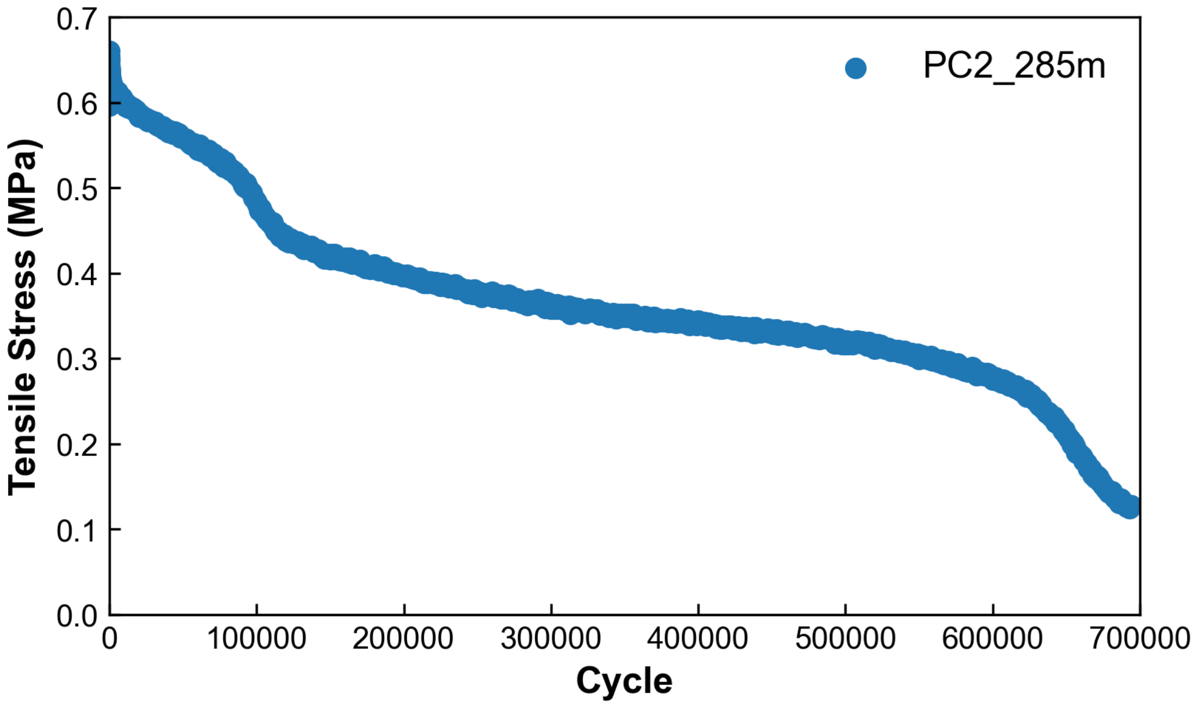

Figure 3. NBFT tensile stress vs. cycle.

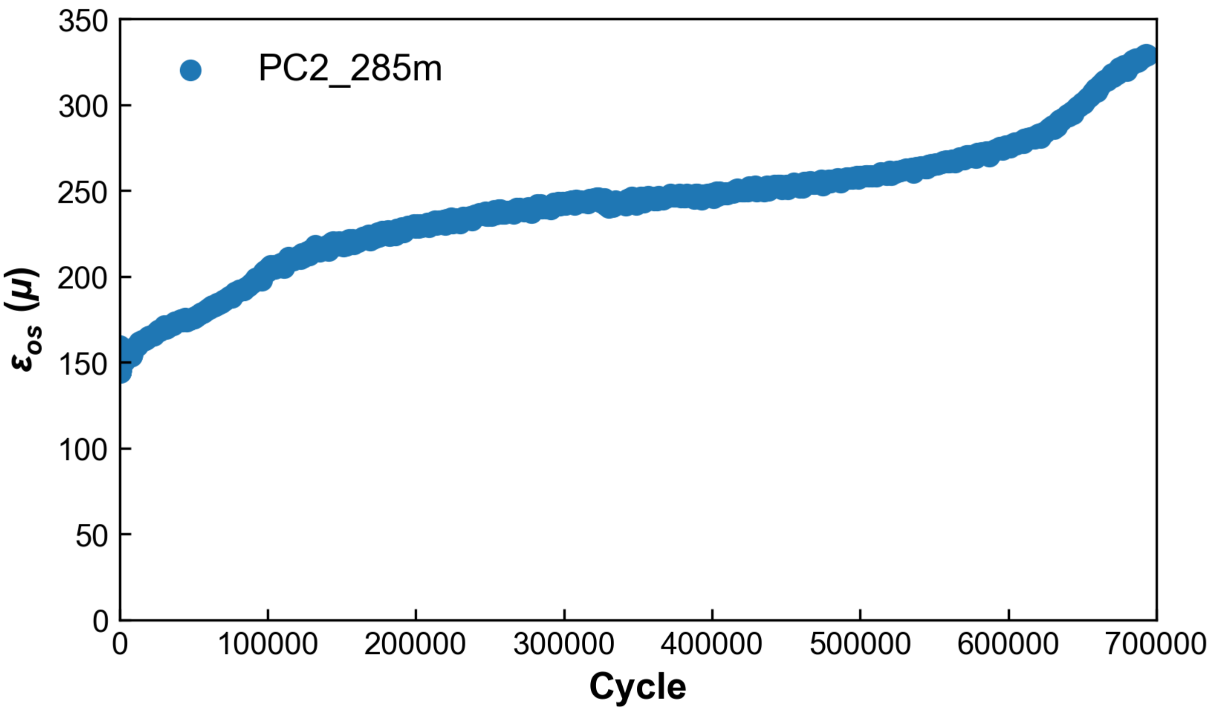

Figure 4. NBFT on-specimen tensile strain vs. cycle.

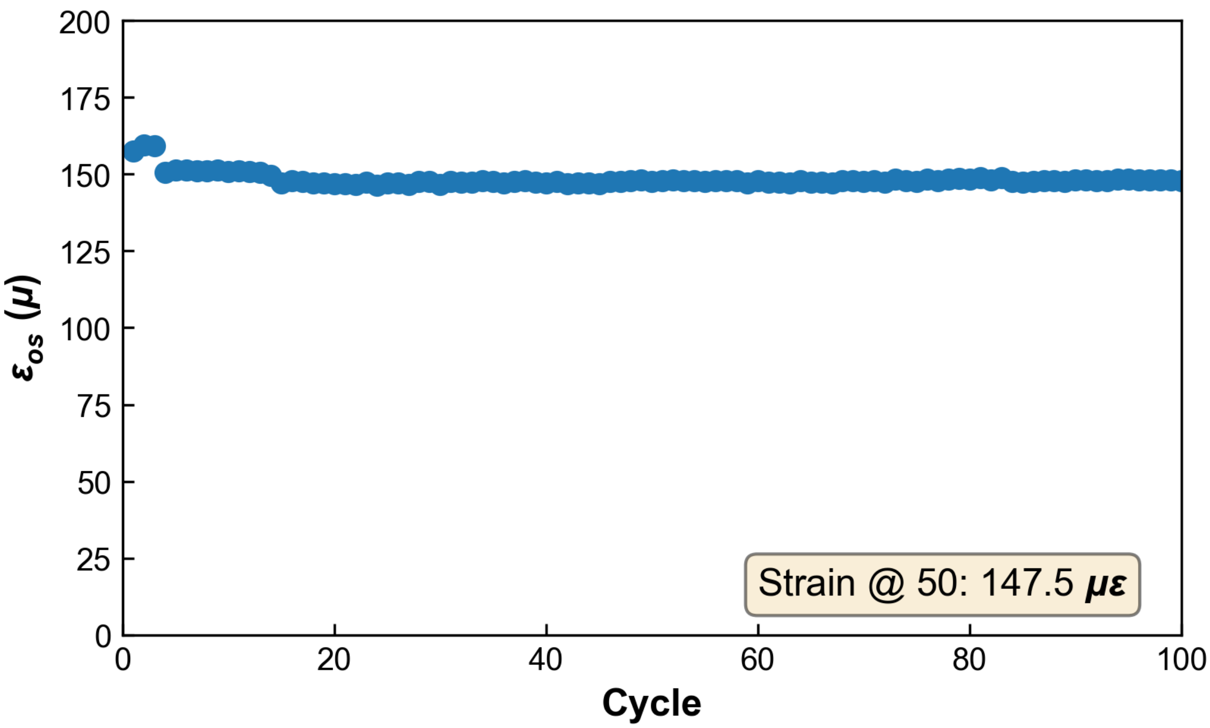

Figure 5. NBFT on-specimen tensile strain at 50th cycle.

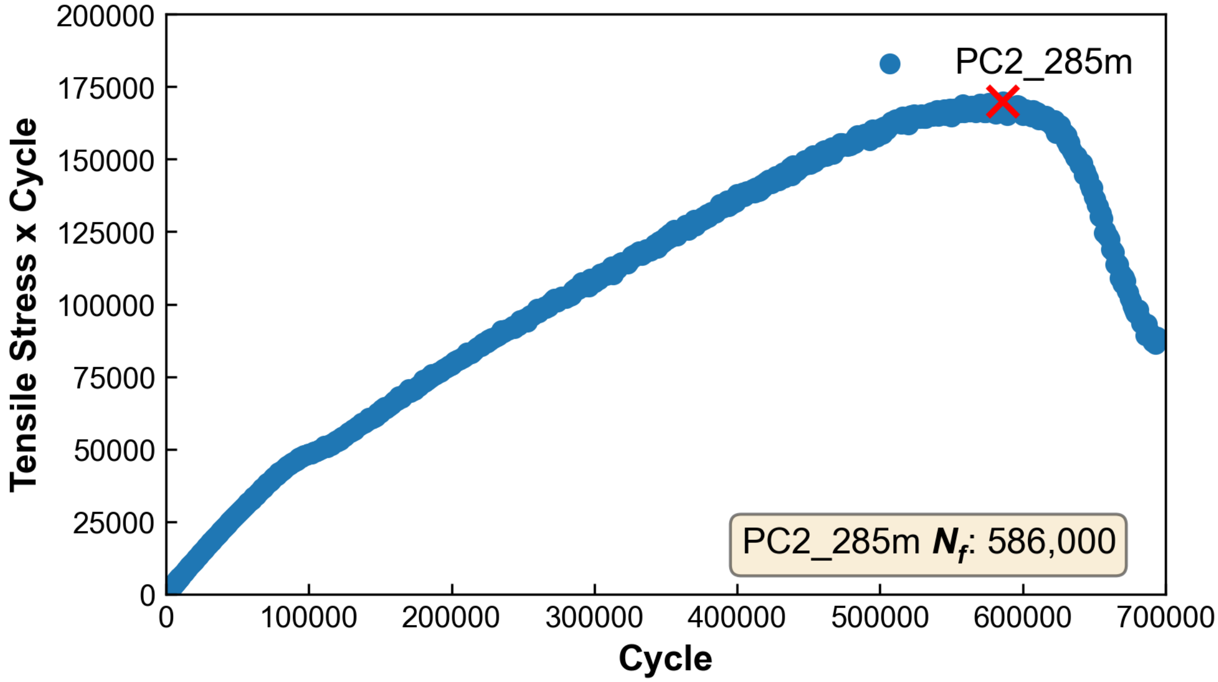

Figure 6. NBFT change in 'stress × N' with number of cycles.

APPENDIX B – NBFT RESULTS NOT INCLUDED IN THE ANALYSIS

Appendix B documents two datasets excluded from the main analysis. Excluded data include PC#2 results at 300 με, as shown in Figure 7, affected by loss of environmental chamber control after nitrogen depletion, and testing continued at ambient temperature. Excluded data also include a PM specimen that reached 2,000,000 cycles without failure at the test termination limit, as shown in Figure 8.

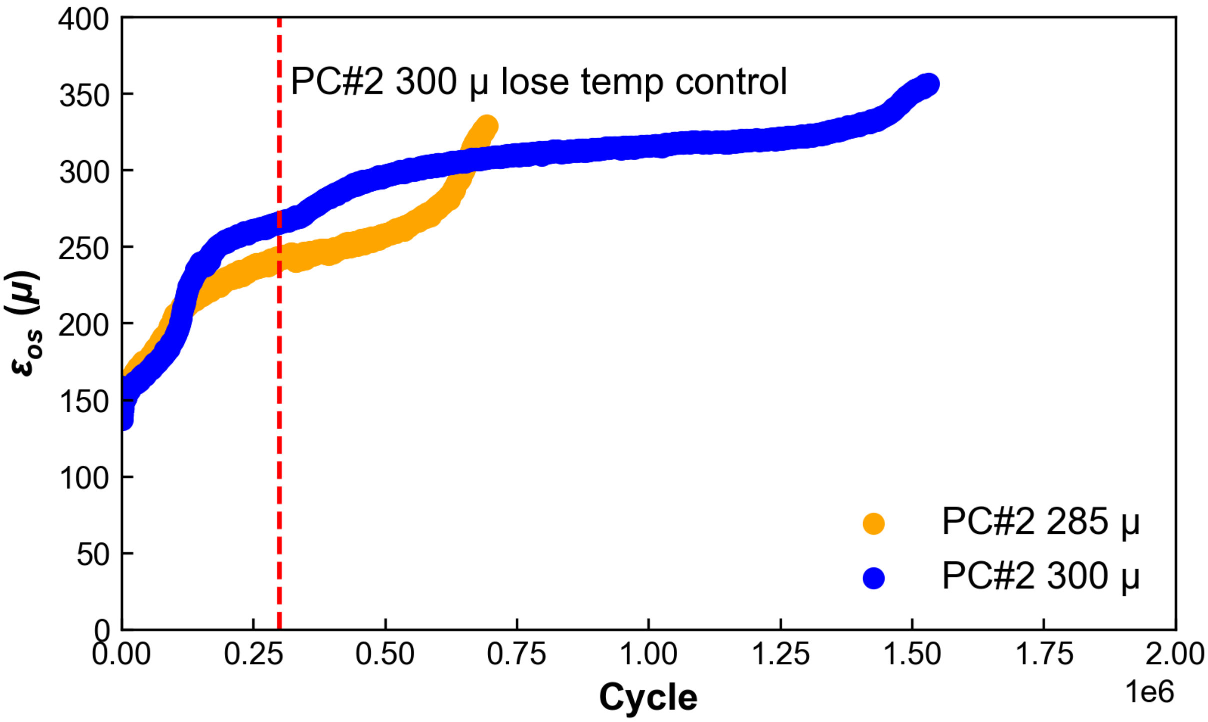

Figure 7. PC#2 on-specimen tensile strain comparison.

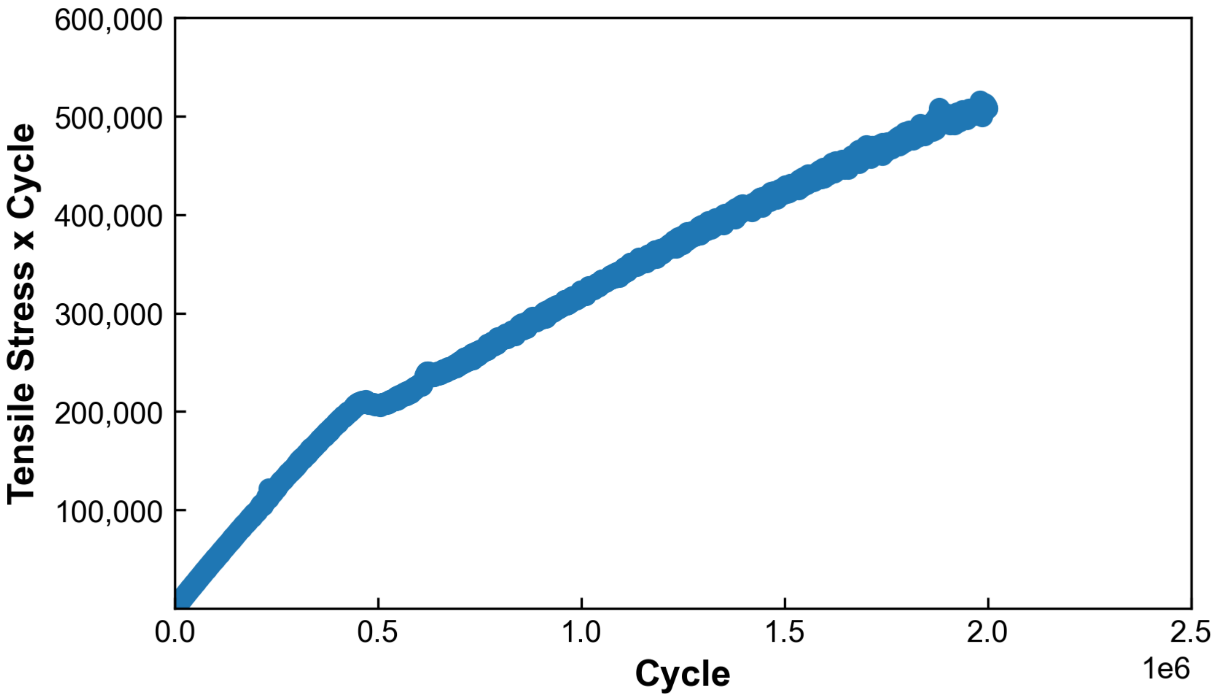

Figure 8. PM change in ‘stress × N’ with number of cycles.