Life Cycle Cost Analysis of FORTA-FI Fiber-Reinforced Asphalt Concrete Pavement

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Submitted to

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February 5, 2015

ASU NATIONAL CENTER of EXCELLENCE for SMART INNOVATIONS

ARIZONA STATE UNIVERSITY

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Executive Summary

Fiber based asphalt pavement technologies generally require a larger initial investment than conventional asphalt concrete. However, benefits in long-term performance reduce the overall cost of the project when examined over its entire life cycle. A Life Cycle Cost Analysis (LCCA) at a discount rate of 4% shows a present net worth **savings of between 24.0 and 36.9%** with the FORTA-FI fibers depending on how it is used and the analysis period considered. The analysis described also shows that the savings can result in a dollar value difference of between **$74,131 and $78,049 per lane/mile** over a 50 year analysis period or between **$62,499 and $75,751** over a 40 year analysis cycle. Annualizing these costs yields a difference between **$2,909 and $3,633 per lane/mile/yr**.

The important details from this analysis are:

- The estimates of performance for both the fiber-reinforced and conventional pavements were carried out using Mechanistic Empirical Pavement Design Guide (MEPDG).
- The pavement structural design was selected so that a pavement using conventional asphalt concrete would exhibit a balanced performance with respect to rutting and fatigue cracking under the climate condition of Phoenix, Arizona.
- One conventional asphalt concrete scenario and two different fiber scenarios were evaluated; 1) the fiber mixture was used in the same initial design as the conventional asphalt concrete and 2) the initial design of the pavement using the fiber mixture had a reduced thickness. The analysis assumed that all fiber-reinforced sections were rehabilitated with fiber-reinforced mixtures and the conventional section was rehabilitated with conventional asphalt concrete mixtures. The fiber reinforced cases showed net worth reductions of at least 33% (for 50 year analysis with 4% discount rate).
- The MEPGD material inputs of the fiber-reinforced asphalt concrete mixture using 1 lb/ton fiber dosage were based on the average results from multiple laboratory studies. The alligator cracking distress model was calibrated for the fiber-reinforced mixture, while the rutting distress model was left the same as the conventional mixture knowing that the fiber-reinforced mixtures are regularly showing better resistance of rutting than the conventional rutting. The moduli of the fiber-reinforced mixtures were increased by 30% based on laboratory studies from five different asphalt concrete mixtures.
- The parameters for the LCCA were established from state practices, Federal Highway Administration guidance, literature, local cost information, and engineering judgment.
- Analysis was completed using 30, 40, and 50 year performance windows and with different discount rates to consider the different LCCA standards in use.
- A premium of $10/ton was given for the fiber-reinforced asphalt concrete. This premium was considered in all cost calculations so that any calculated cost benefits are inclusive of the additional material cost from the fiber-reinforcement.
- Following national convention user costs (costs of delays, increased vehicle maintenance, impacts from pavement roughness on fuel consumption, etc.) were omitted from this analysis. In light of the impact of increased maintenance activities on these costs it is expected that this analysis results in a **conservative assessment of the true life cycle cost benefits of FORTA-FI** and that the actual achieved cost difference would be greater than what is reported here.

Prediction of Pavement Performance Using MEPDG

The pavement performance of the control and the 1 lb/ton fiber–reinforced mixture was predicted using the Mechanistic Empirical Pavement Design Guide (MEPDG) (Version 1.1). State and local practices for life cycle cost analysis (LCCA) vary, and to comprehensively evaluate the technology for all interested parties a total simulation period of 50 years was first devised. LCCA was the carried out for analysis periods of 30, 40, and 50 years and for discount rates of 3, 4, and 5%. Two main distresses were considered in this analysis; total rutting and bottom-up fatigue cracking (alligator cracking). The MEPDG simulations were conducted with respect to Arizona State calibration. For the fiber-reinforced pavement, the alligator cracking distress prediction model was calibrated to increase the fiber-reinforced pavement resistance against alligator cracking by three times compared to the conventional pavement (concluded based on the average laboratory performance of 12 fiber studies). The dynamic modulus $|E^*|$ values used for the fiber-reinforced pavement simulations were also increased by 30% which is the average increase in the modulus due the use of FORTA-FI fibers based on the results obtained from five FORTA studies. The rutting prediction model for the fiber-reinforced pavement was kept the same as the conventional pavement as there is not enough data to calibrate the model for fiber reinforced mixture. Table 1 shows the conventional and the fiber-reinforced $|E^*|$ values used in the MEPDG simulations where the $|E^*|$ values of a typical 19-mm conventional dense graded mixture was used and then was increased by 30% for the fiber-reinforced mixture. Table 2 shows the MEPDG inputs for both conventional and fiber-reinforced pavements.

Preliminary MEPDG simulations were conducted on a conventional pavement section so that the pavement would yield a balanced performance with respect to rutting and fatigue cracking. This section was designed to be as close as possible to the failure criteria of rutting or alligator cracking after 15 years from the initial construction. The total rutting failure criteria was 0.75 inch and the alligator failure criteria was 20% of the pavement area. After the initial analysis period, MEPDG simulations were again conducted on the rehabilitated conventional pavement section for additional time periods of interest up to 50 years. In each of these additional simulations the initial traffic was adjusted to account for the expected growth. The MEPDG simulations were then conducted on the fiber-reinforced pavement using two different scenarios; 1) same initial design as the control (referred to as simply fiber-reinforced) and 2) reduced initial thickness to produce a similar pavement performance as the control (referred to as fiber-reinforced-thin construction). The future traffic for each simulation period was predicted using 4.0% compound traffic growth rate. Figure 1 and Figure 2 showed a comparison of predicted total rutting and alligator cracking respectively for conventional and fiber-reinforced pavements. It is observed that the rutting performance of the fiber-reinforced pavement is slightly better than the conventional pavement, and the alligator cracking performance of the fiber-reinforced pavement is substantially better than the conventional pavement. Table 3 includes a summary of the MEPDG simulations for conventional and fiber-reinforced pavements.

Table 1 $|E^*|$ Values for Conventional and Fiber-Reinforced Mixtures

	Freq. Hz	Dynamic Modulus, ksi	

Temperature, °F		Fiber-Reinforced	Conventional	Modular Ratio
14	25	7,877	6,059	1.30
	10	7,263	5,587	1.30
	5	7,150	5,500	1.30
	1	6,478	4,983	1.30
	0.5	6,208	4,776	1.30
	0.1	5,474	4,212	1.30
40	25	5,448	4,191	1.30
	10	5,235	4,027	1.30
	5	4,931	3,793	1.30
	1	4,165	3,204	1.30
	0.5	3,822	2,940	1.30
	0.1	3,064	2,357	1.30
70	25	2,935	2,258	1.30
	10	2,557	1,967	1.30
	5	2,288	1,760	1.30
	1	1,672	1,287	1.30
	0.5	1,440	1,108	1.30
	0.1	987	759	1.30
100	25	1,313	1,010	1.30
	10	1,063	818	1.30
	5	891	685	1.30
	1	575	442	1.30
	0.5	468	360	1.30
	0.1	306	235	1.30
130	25	503	387	1.30
	10	382	294	1.30
	5	321	247	1.30
	1	225	173	1.30
	0.5	203	156	1.30
	0.1	168	130	1.30

Table 2 Inputs of MEPDG Simulations

Traffic Data

Initial two-way Annual Average Daily Truck Traffic (AADTT)		2,500
Number of lanes in design direction		2
Percent of trucks in design direction (%)		50
Percent of trucks in design lane (%)		80
Operational speed, mph		60
Traffic Growth Factor		Comp. 4%
Climate Data		
Weather Station		Phoenix Airport, PHX
Latitude (degrees.minutes)		33.26
Longitude (degrees.minutes)		-111.59
Elevation, ft		1106
Depth of water table, ft		20
Mean annual air temperature, ºF		73.25
Pavement Section Data		
Layer 1	Material type	Asphalt concrete
	Initial Layer thickness, in	4.0 or 3.5
	Reference temperature, °F	70
Layer 2	Unbound Material	Crushed Gravel
	Thickness, in	8
	Modulus, psi	25,000
	Plasticity Index, PI	1
	Liquid Limit, LL	6
Layer 3	Unbound Material	A-6
	Modulus, psi	14,500
	Plasticity Index, PI	16
	Liquid Limit, LL	33

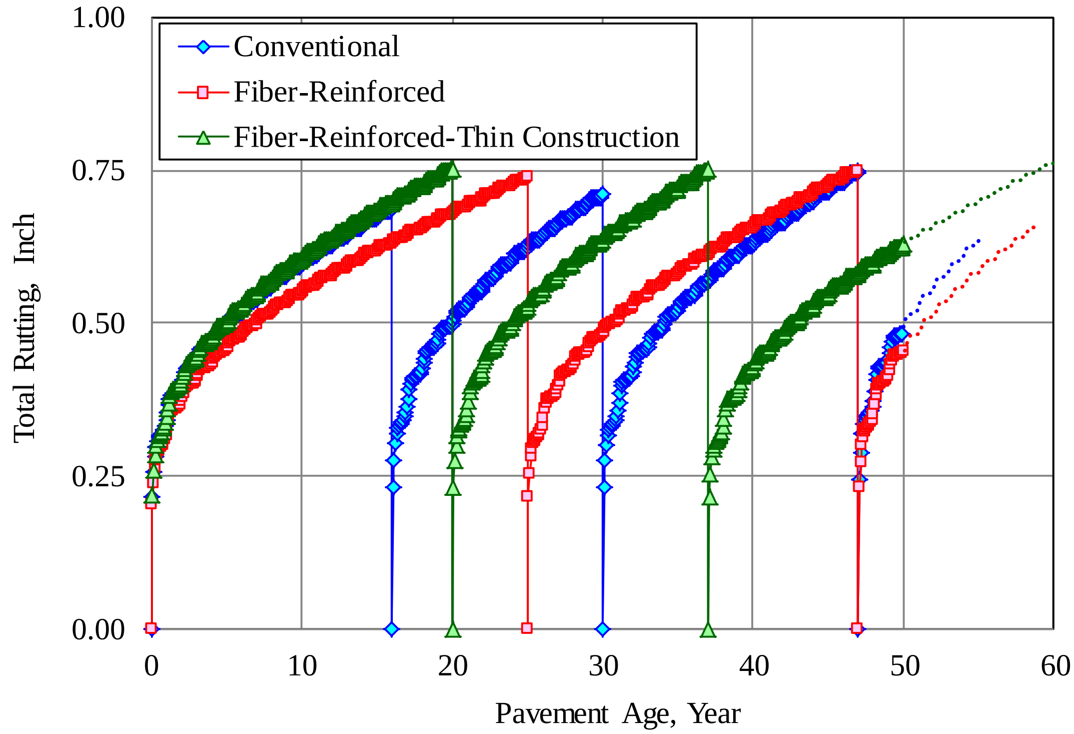

Figure 1 |*E**| Prediction of Total Rutting for Conventional and Fiber-Reinforced Pavements.

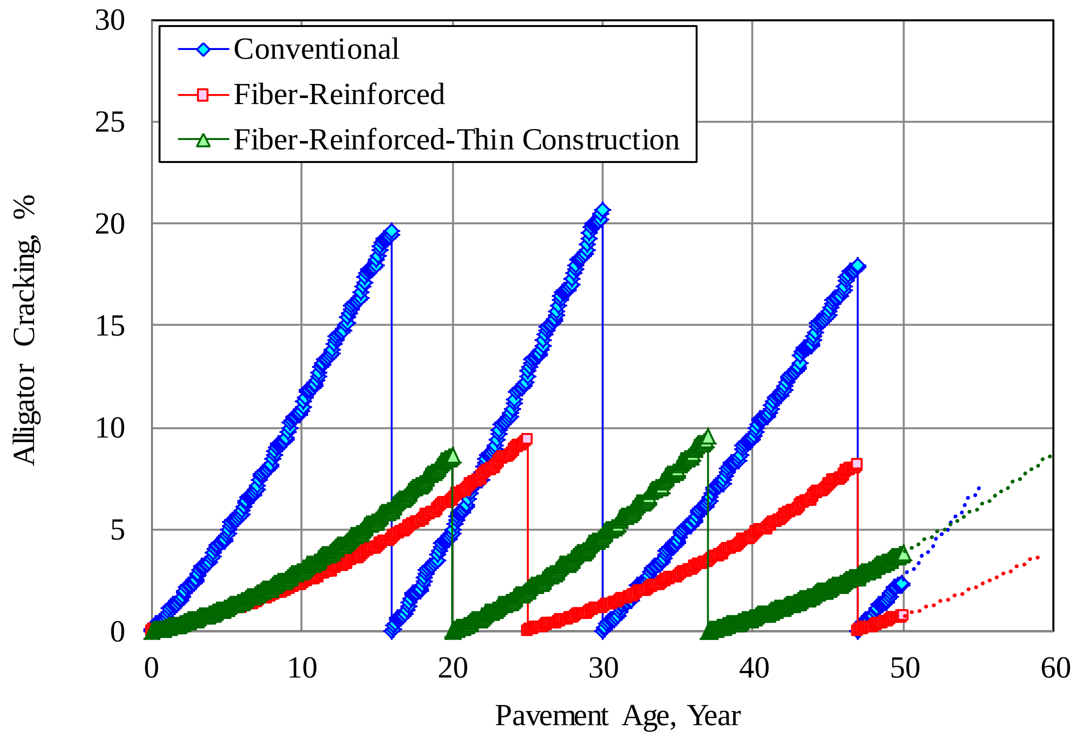

Figure 2 |*E**| Prediction of Alligator Cracking for Conventional and Fiber-Reinforced Pavements.

Table 3 Summary of MEPDG Simulations for Conventional and Fiber-Reinforced Pavement

Simulation Stage	Parameter	Conventional	Fiber-Reinforced	Fiber-Reinforced-Thin Construction
First	Simulation Period (Years)	0-16	0-25	0-20
	AADT at End	4,700	6,700	5,500
	Rutting at End, inch	0.69	0.74	0.75
	Alligator Cracking at End, %	19.7	9.40	8.70
Second	Simulation Period	17-30	26-47	21-37
	AADT at End	8,100	15,800	11,000
	Rutting at End, inch	0.72	0.75	0.75
	Alligator Cracking at End, %	20.7	8.20	9.60
Third	Simulation Period	31-47	48-50	38-50
	AADT at End	15,800	17,800	17,800
	Rutting at End, inch	0.75	0.46	0.63
	Alligator Cracking at End, %	18.0	0.72	3.80
Fourth	Simulation Period	48-50	N/A	N/A
	AADT at End	17,800		
	Rutting at End, inch	0.49		
	Alligator Cracking at End, %	2.40		
Extended Surface Life after 50 Years, year (For salvage calculation)		11 (out of 14)	14 (out of 17)	9 (out of 22)

Rehabilitation Strategy

The following decisions are made for the rehabilitation plan for both conventional and fiber-reinforced pavements:

- Crack seal is applied at 4% and 12% alligator cracking;
- Patching is applied at 8% and 16% alligator cracking;
- Milling and asphalt concrete overlay are performed when total rutting is close to 0.75 inch or total fatigue cracking is close to 20%;
- The milling is 2.0 inches deep if the cracking at the time of the overlay is above 15% and 1.0 inch deep if the fatigue cracking is less than 15%;
- Conventional sections are overlaid with conventional asphalt and fiber-reinforced sections are overlaid with fiber-reinforced asphalt; and
- The AC overlay thickness is adjusted (in 0.5 inch increments) based on traffic levels at the time of the rehabilitation so that the predicted life of the overlay is never less than 15 years.

Based on the maintenance decisions, the rehabilitation activities for conventional, fiber-reinforced, and fiber-reinforced thin construction pavements are shown in Figure 3 through Figure 5 respectively.

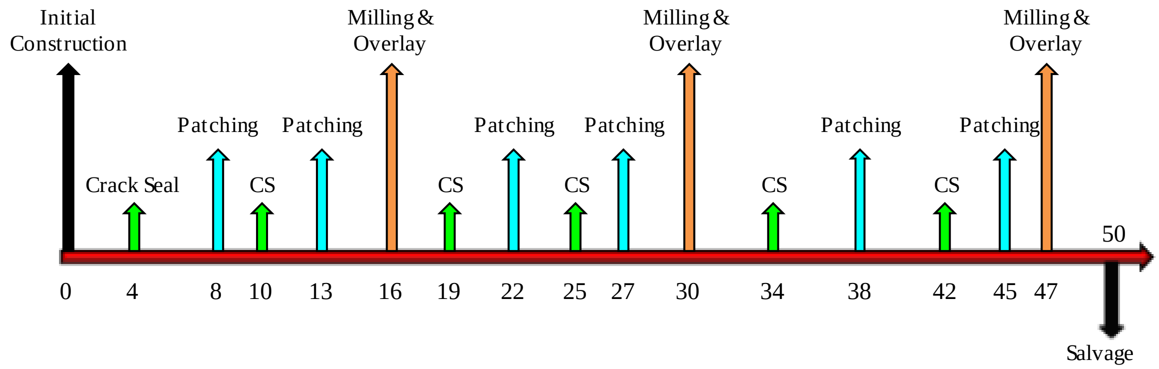

Figure 3 Rehabilitation Activities for Conventional Pavement.

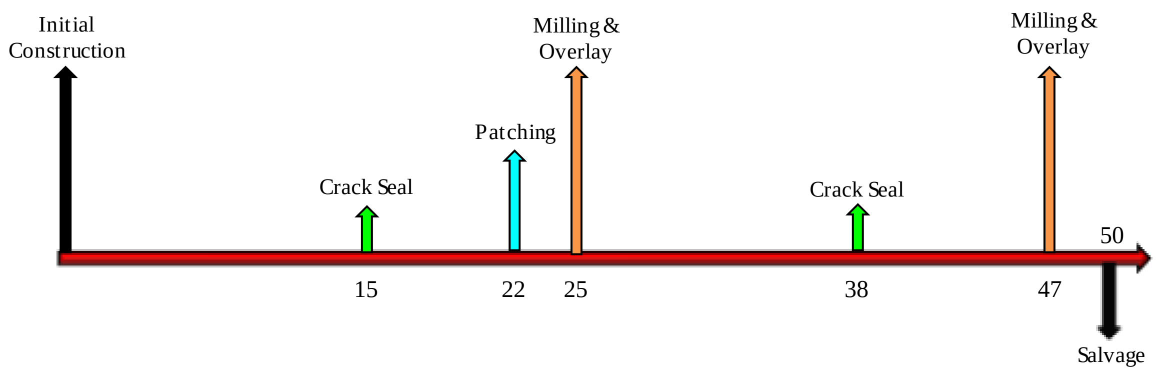

Figure 4 Rehabilitation Activities for Fiber-Reinforced Pavement.

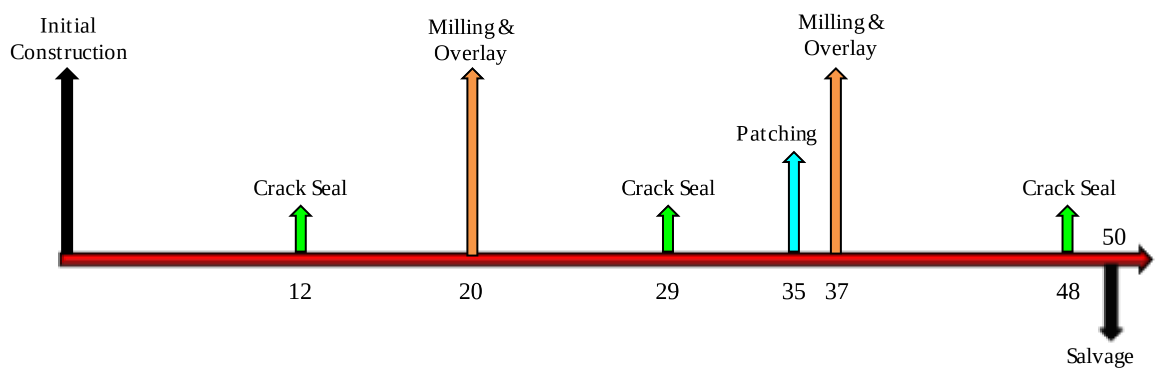

Figure 5 Rehabilitation Activities for Fiber-Reinforced-Thin Construction Pavement.

LCCA Analysis

Updated costs for the applied rehabilitation activities were obtained according to Arizona State. The costs of the different construction and rehabilitation items are summarized in Table 4. The LCCA is conducted considering only one lane/mile for both conventional and fiber-reinforced pavements. The salvage value was determined based on the extended pavement service life after the LCCA period. The patching area was calculated by taking 33% of the cracked area and assuming one third of the alligator cracking area has severe cracks. The crack sealing length was estimated assuming there is one main fatigue crack under each wheel path and one transverse crack repeated every 15 ft. Following general LCCA convention, the engineering, staging, and construction costs for the initial construction are not considered since they would be essentially the same for all alternatives. However, since the timing of overlays would not be consistent between all alternative the cost for overlay includes the materials cost as well as estimates for staging, traffic control, and other costs in addition to the materials. The premium for fiber materials is included in only the materials portion of this estimate. Table 5 through Table 7 includes a summary of LCCA results of conventional and fiber-reinforced pavements respectively for the 50 year analysis period. Costs are assessed using both the Net Present Worth (NPW), Equation (1), and the Equivalent uniform Annualized Cost (EAC), Equation (2), methods. The net present worth converts all costs during the life cycle to current year dollars whereas the equivalent uniform annualized method distributes the costs over the life time (accounting for the time-value of money). Discount rates of 3-5% were used, which represent the conventionally suggested rates for LCCA. Results from all of the analysis cases are summarized in Table 8 and Table 9, as the difference in the PWC or EAC between the conventional and fiber mixes. In all cases the benefits of FORTA-FI are clear.

$$NPW = InitialCost + \sum_{j=1}^{N} R_j \left[\frac{1}{(1+i')^n} \right] - SalvageValue \left[\frac{1}{(1+i')^n} \right] \tag{1}$$

$$EAC = PWC \left[\frac{i'(1+i')^n}{(1+i')^n - 1} \right] \tag{2}$$

Where,

i'	=	discount rate
n	=	year of expenditure
R_j	=	rehabilitation expenditure (single cost expenditure)

Table 4 Costs of Construction and Rehabilitation Items

Item	Unit	Cost/Unit, $
Conventional Asphalt Mix	ton	60.0
Fiber-Reinforced Asphalt Mix	ton	70.0
Crack Sealing	linear foot	0.35
Patching	ft^2	2.6
Milling	yd^2/inch	0.75
Asphalt Concrete Overlay	yd^2/inch	6.4
Fiber-Reinforced Overlay*	yd^2/inch	7.0

*Unit cost figured applying $10/ton extra to material component of regular asphalt overlay cost.

Table 5 Summary of LCCA for Conventional Pavement, 4% discount rate, (Lane/Mile)

Activity	Time, year	Unit	Unit Cost, $	Quantity	Total Cost, $	Present Worth, $
Initial Construction	0	ton	60	1,584	95,040	95,040
Crack Sealing	4	ft	0.35	580	203	174
Patching	8	ft^2	2.6	1,670	4,342	3,173
Crack Sealing	10	ft	0.35	580	203	137
Patching	13	ft^2	2.6	1,670	4,342	2,608
Milling of 2 inches	16	yd^2	1.5	7,040	10,560	5,638
Overlay of 2.5 inches	16	yd^2	16	7,040	112,640	60,139
Crack Sealing	19	ft	0.35	580	203	96
Patching	22	ft^2	2.6	1,670	4,342	1,832
Crack Sealing	25	ft	0.35	580	203	76
Patching	27	ft^2	2.6	1,670	4,342	1,506
Milling of 2 inches	30	yd^2	1.5	7,040	10,560	3,256
Overlay of 3 inches	30	yd^2	19.2	7,040	135,168	41,675
Crack Sealing	34	ft	0.35	580	203	54
Patching	39	ft^2	2.6	1,670	4,342	941
Crack Sealing	43	ft	0.35	580	203	38
Patching	45	ft^2	2.6	1,670	4,342	743
Milling of 2 inches	47	yd^2	1.5	7,040	10,560	1,671
Overlay of 3 inches	47	yd^2	19.2	7,040	135,168	21,395
Salvage	50	ton	60	2,022	-121,346	-17,075
Net Present Worth, $						***223,116***
EAC, $						***10,386***

Table 6 Summary of LCCA for Fiber-Reinforced Pavement, 4% discount rate (Lane/Mile)

Activity	Time, year	Unit	Unit Cost, $	Quantity	Total Cost, $	Present Worth, $
Initial Construction	0	ton	70	1,584	110,880	110,880
Crack Sealing	15	ft	0.35	580	203	113
Patching	22	ft^2	2.6	1,670	4,342	1,832
Milling of 1 inches	25	yd^2	0.75	7,040	5,280	1,981
Overlay of 2 inches	25	yd^2	14	7,040	98,560	36,972
Crack Sealing	38	ft	0.35	580	203	46
Milling of 1 inches	47	yd^2	0.75	7,040	5,280	836
Overlay of 2 inches	47	yd^2	14	7,040	98,560	15,600
Salvage	50	ton	70	1,957	-136,969	-19,273
Net Present Worth, $						***148,985***
EAC, $						***6,935***

Table 7 Summary of LCCA for Fiber-Reinforced-Thin Construction Pavement, 4% discount rate (Lane/Mile)

Activity	Time, year	Unit	Unit Cost, $	Quantity	Total Cost, $	Present Worth, $
Initial Construction	0	ton	70	1,386	97,020	97,020
Crack Sealing	12	ft	0.35	580	203	127
Milling of 1 inches	20	yd^2	0.75	7,040	5,280	2,410
Overlay of 1.5 inches	20	yd^2	10.5	7,040	73,920	33,736
Crack Sealing	29	ft	0.35	580	203	65
Patching	35	ft^2	2.6	1,670	4,342	1,100
Milling of 1 inches	37	yd^2	0.75	7,040	5,280	1,237
Overlay of 1.5 inches	37	yd^2	10.5	7,040	73,920	17,319
Crack Sealing	48	ft	0.35	580	203	31
Salvage	50	ton	70	810	-56,700	-7,978
Net Present Worth, $						***145,067***
EAC, $						***6,753***

Table 8 Summary of LCCA Results for NPW and EAC Methods for Control versus Fiber-Reinforced Pavement.

Analysis Period (years)	Discount Rate (%)		
	3	4	5
Difference in NPW ($/Lane/Mile)			
30	52,925	40,950	31,887
40	78,533	62,499	49,667
50	96,720	74,131	57,146
Difference in EAC ($/Lane/Mile/yr)			
30	2,057	1,906	1,747
40	3,052	2,909	2,721
50	3,759	3,451	3,130
% Difference in NPW			
30	28.9	24.0	20.0
40	34.5	30.5	26.6
50	38.0	33.2	28.7

Table 9 Summary of LCCA Results for NPW and EAC Methods for Control versus Fiber-Reinforced-Thin Construction Pavement.

Analysis Period (years)	Discount Rate (%)		
	3	4	5
Difference in NPW ($/Lane/Mile)			
30	63,025	52,898	44,652
40	93,541	75,741	61,827
50	98,007	78,049	62,924
Difference in EAC ($/Lane/Mile/yr)			
30	2,449	2,462	2,446
40	3,636	3,526	3,387
50	3,809	3,633	3,447
% Difference in NPW			
30	34.4	31.0	27.9
40	41.0	36.9	33.1
50	38.5	35.0	31.6

Conclusion

Based on the 50 year analysis period and the 4% discount rate, the following conclusions can be made:

1. The addition of the FORTA-FI fiber at 1 lb/ton dosage and following the same initial design reduces the net present worth cost by $74,131 per lane/mile (a reduction of 33.2%).
2. The addition of the FORTA fiber at 1 lb/ton dosage and including a reduced initial design thickness reduces the net present worth cost by $78,049 per lane/mile (a reduction of 35.0%).
3. The savings in the net present worth due to the fiber usage is anticipated to increase if the user cost is considered due to the lower rehabilitation activities rate of the fiber-reinforced pavement compared to the control pavement. That means the user delays in case of the fiber-reinforced pavement is much less compared to the conventional pavement.

Similar conclusions at different advantage levels are found for other analysis periods and discount rates. The smallest calculated LCCA benefit is 20.0% and this occurs at the highest discount rate. The conclusion, that Fiber-Reinforced mixtures can constitute a substantial life cycle cost advantage, exists for all analysis periods and discount rates studied. The reduced thickness scenario provides slightly greater benefit than the same initial design scenario. However, the difference is small (1-8%), which is within the estimated error of salvage value approximations. It is our conclusion that in terms of life cycle costs the two fiber scenarios are equivalent.