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Evaluation of Maintenance and Rehabilitation Treatments on Long-Term Asphalt Pavement Performance

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ABSTRACT

This paper aims to evaluate the impact of maintenance and rehabilitation treatments on long-term asphalt pavement performance using the data collected in the Specific Pavement Studies: SPS-3 and SPS-5 of the Long-Term Pavement Performance (LTPP) program. Pavement performance indicators include fatigue cracking, longitudinal cracking, rutting, and roughness. The SPS-3 concentrates on the effect of four maintenance treatments include: thin overlay, slurry seal, crack seal, and chip seal. The SPS-5 concentrates on rehabilitation methods like overlay thickness (51 and 127mm), asphalt overlay materials (recycled hot mix asphalt (HMA) compared with virgin mix), and pre-overlay treatments (with or without milling). All of the research sites were wet and dry with no freeze as each of them had a climate that was exactly similar to Egypt's. Statistical methods such as boxplot, average long-term effectiveness increment, annual variation, and paired t-test were used. According to maintenance, the results indicated that chip seal and thin overlay had the greatest impact on long-term cracking improvements. Long-term roughness and rutting improvements were best achieved with a thin overlay. In terms of fatigue cracking and roughness, the effectiveness of crack sealing was the worst. For rehabilitation, the results showed that recycled had no influence on fatigue cracking for thin overlays. As expected, the use of recycled was found to be effective in decreasing the rutting and roughness potential of thick overlays. The climate had no obvious impact on the development of rutting while wet climates provided higher fatigue cracking and longitudinal progress for recycled sections.

Keywords: *maintenance; rehabilitation; LTPP; long term performance; cracking.*

1. Introduction

Pavement rehabilitation and maintenance activities typically constitute a significant portion of the budget of any highway agency worldwide [1]. In addition to the money needed to build new roads and infrastructure, there will be an increase in annual maintenance operations that use additional resources. As a result, there is a growing need for more ideal maintenance and rehabilitation (M&R) program that strike a balance between costs and performance [2]. Maintenance is commonly defined as work done to extend the life of a roadway's service life. Rehabilitation is the process of adding new surface material or performing any other actions needed to restore an existing roadway to a structurally or operationally suitable state. The pavement structure could be completely removed and replaced as part of rehabilitation program [3]. Pavement deterioration may lead to pavement distresses such as rutting, cracking, roughness, and other kinds of road distress. Such distresses can lead to a variety of difficulties, particularly in developing countries such as Egypt. Pavement surface conditions have an influence on traffic safety, operating speed, maneuverability, driver comfort, and service volume [4]. To overcome the distresses associated with materials, traffic, and environmental conditions, years of maintenance and rehabilitation are required [5].

The LTPP program was established in 1987. This program collected data on a variety of performance parameters, particular conditions of influence variables, preventive maintenance treatment (PMT) implementation timing, and identifying pavement distress. In addition, it consists of general pavement studies (GPS) and specific pavement studies (SPS) [6]. The LTPP SPS-3 experiment was designed to evaluate the effectiveness of PMTs on flexible pavements as well as the best time to apply them. There are four types of PMTs: thin overlay, slurry seal, chip seal, and crack seal [7]. The SPS-5 experiment was created to examine the impact of flexible pavement rehabilitation options. A total of eighteen projects were built in the United States (U.S.) and Canada for SPS-5. Each project includes eight test sections with varying overlay thicknesses, pre-overlay treatment procedures, and material types. Also, it includes a control section with no overlay and treatment for reference. The control section is known also as the core 9 section [8].

Previous studies utilized several statistical methods such as paired t-test and cumulative frequency distribution to discuss the impact of the above-mentioned four types of PMTs on pavement performance using LTPP SPS-3 experiments. It was found that thin overlay is the most effective one, followed by chip seals and slurry seals [9]. Another study used statistical analysis such as Friedman test and Box-Whisker plot to assess the effect of each treatment on pavement performance. The results found that thin overlay and chip seal are the effective treatment choices for most design conditions with regard to fatigue cracking. In most design conditions, thin overlay performs better than other treatments in terms of rutting and, in some cases, in terms of roughness [10]. Among the four most prevalent preventive treatments, chip seal and thin overlay both present significant effectiveness in preventing fatigue cracking, longitudinal cracking, and transverse cracking. But thin overlay still outperformed chip seal in rutting resistance [11]. Scatterplot, cumulative frequency distribution, average long-term effectiveness increment, and paired-samples t-test were used to study the effectiveness of the PMTs in moderating pavement distress. The findings indicated that thin overlay and crack seal provided the best and worst PMTs for each performance, respectively [6]. In order to clarify how many variables, such as pretreatment roughness condition, pretreatment surface condition, and various other parameters on the performance of PMTs were discussed using a logistic regression model [1].

It should be noted that various researchers had used the LTPP SPS-5 data. Analysis of variance (ANOVA) showed that overlay age had the greatest impact on the overall pavement performance. Overlays with reclaimed asphalt pavement (RAP) had higher distresses and roughness than overlays without RAP. However, this difference was not significant for rutting and international roughness index (IRI). With the exception of rutting, thick overlays outperformed thin overlays. Milling before rehabilitation reduced IRI and transverse cracking but had little impact on longitudinal cracking [12]. ANOVA and paired t-tests were utilized to discuss the impact of rehabilitation treatments on pavement performance. The findings indicated that overlays with recycled mixes performed as well as overlays with virgin mixes in terms of IRI, rutting, block cracking, and raveling. Except for rutting, thicker overlays evolved pavement performance [13]. The plot charts and paired t-tests results indicated that the usage of RAP-containing mixes, overlay thickness, and pre-overlay treatment procedure all had interacting impacts. The unwanted performance of RAP-containing mixes was predicted with a reasonably thin (51 mm) overlay and minimum pre-overlay preparation [14].

Despite the fact that a great number of research studies on maintenance and rehabilitation treatments have been done, the particular experience continues to play a dominant role in a specific application. This study investigated the specific application conditions for various treatments and proposes effective suggestions for the purpose of the improved utilization and implementation effectiveness for each treatment. It is usually difficult to choose the optimal treatment from the guidelines. More attention should be put into determining the effectiveness of maintenance and rehabilitation treatments with respect to the specific existing pavement distress.

The overall aim of this research was to examine the impact of maintenance and rehabilitation treatments on pavement performance indicators using data from LTPP SPS-3 and SPS-5 experiments. The reason for choosing SPS-3 and SPS-5 experiment sites was taken in order to simulate the climate of Egypt.

2. Research objectives

In order to achieve the main aim of this research the following objectives were set:

- To investigate the impact of maintenance and rehabilitation treatments on pavement performance using data from the LTPP SPS-3 and SPS-5 experiments.
- To identify significant pavement performance indicators and assess the impact of each treatment on pavement performance.
- To use areas that simulate the climate of Egypt to assess the effects of climatic factors (wet vs. dry).
- To perform statistical analyses on the data collected as an outcome of the use of various variables like as (treatment type and climatic factors). For this objective, the boxplot and average long-term effectiveness increment, annual variation, and paired-samples t-test were used.

3. Data selection and preparation

According to the Köppen climate classification system, one of the most extensively used methods for climate categorization, Egypt has a hot desert climate [15]. The climate is generally relatively dry across the country, with the exception of the northern Mediterranean coast, which receives winter rainfall. Egypt's climate is defined by a lack of rain and high

heat throughout the summer months, while midday temperatures are somewhat moderated on the northern coast. According to that, Egypt's climate is classified as not freeze and dry throughout the country, and not freeze/wet around the northern Mediterranean coast [5].
For a similar Egypt climate, there are 26 LTPP SPS-3 sites used in this study. At each site, four maintenance treatments (thin overlay, slurry seal, crack seal, and chip seal) were applied to the pavement sections with an average length of 700ft and an average width of 24ft along with a control section. With respect to rehabilitation, there are 8 LTPP SPS-5 sites used in this study. Each site includes 8 test-sections (4 using virgin materials and 4 using recycled HMA mix) constructed and operated under the same conditions.

3.1. Selecting data from the SPS-3 experiment

In general, the LTPP SPS-3 intends to assess the effectiveness of PMTs and determine the optimal application timing of PMTs. Meanwhile, it includes a total of 81 sites and 431 sections spread across the United States and Canada, providing significant high-quality data for PMTs. The core SPS-3 experiment involves a control section and four maintenance treatments, as listed in Table (1) [16].

Table 1- SPS-3 core experimental sections [16].

Test section number	Treatment
310	Thin overlay
320	Slurry seal
330	Crack seal
340	Control
350	Chip seal

26 SPS-3 sites were employed in this study. Each site consists of one control section, four treatment sections, and one GPS-1 or GPS-2 section for sections without control section. The treated sections contained thin overlay, slurry seal, crack seal, and chip seal, against no PMTs in the control section. The climatic and traffic conditions in the control and treatment conditions were identical. Of these sites, 14 sites had no control section, while an adjacent GPS section can act as a control section. According to the Egyptian climate, all sites in this research were classified as not freeze and dry throughout the country, and not freeze/wet around the northern Mediterranean coast. The distribution of the number of sites, available in LTPP SPS-3 for evaluating the long-term impact of PMTs, according to different pavement performance indicators is shown in Figure (1).

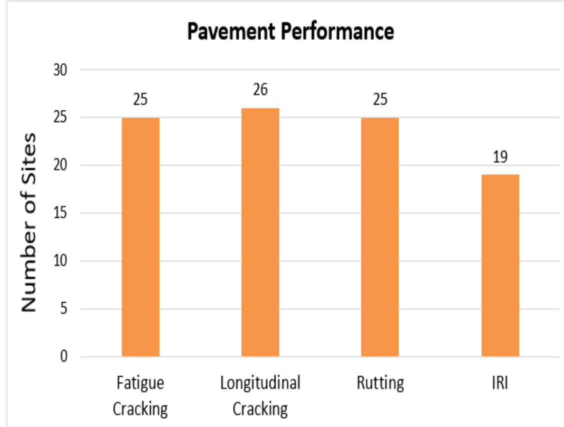

Figure 1- Number of effective sites with different pavement performance indicators in LTPP SPS-3.

3.2. Selecting data from the SPS-5 experiment

Four test sites from the LTPP database (SPS-5) with climates similar to Egypt were chosen for this investigation. Table (2) contains descriptions of the pavement sections investigated in this study. Table (3) shows the selected sites from various states. Each site includes eight sections to explain the impact of overlay thickness (51 and 127mm), asphalt overlay materials (recycled HMA compared with virgin mix), and pre-overlay treatments (with or without milling).

Table 2- Core experimental sections of SPS-5 [17].

SHRP ID	Overlay Type
0501	Control (no treatment)
0502	Thin overlay (51 mm) (recycled HMA)
0503	Thick overlay (127 mm) (recycled HMA)
0504	Thick overlay (virgin)
0505	Thin overlay (virgin)
0506	Thin overlay (virgin, with milling)
0507	Thick overlay (virgin, with milling)
0508	Thick overlay (recycled, with milling)
0509	Thin overlay (recycled, with milling)

Table 3- The chosen sites from the LTPP data.

climate	Site Name	Construction Year
Not freeze/wet climate	Georgia	1993
	Texas	1991
Not freeze/dry climate	Arizona	1990
	California	1992

4. Data analysis methodology

The following calculation was used to construct a weighted average index to indicate the overall performance of the sections over the years for maintenance sections only [6], [10]:

$$WD = \frac{\sum_{i=0}^{n-1} (D_i + D_{i+1}) * \frac{P_{i+1}}{2}}{\sum_{i=0}^{n} P_{i+1}}$$

where:

- WD = indicates the weighted average long-term performance, which is the distress throughout the full survey period.
- i = is the survey number (i = 0 denotes first measurement after the treatment).
- Di = is the distress value measured at the i^{th} survey
- P_{i+1} = is the period (in years) between survey i and survey i+1
- n = is the total number of surveys for the section

Four methods were used to perform the analysis, as follows:

Average long-term effectiveness increment

The first analysis used in this study was the average method to show an average weighted distress change over the service period of the treatment, the average long-term effectiveness of PMTs was defined and measured as [6]:

$$EI_{avg} = \frac{\sum_{i=1}^{N} (WD_{post.j} - WD_{cont.j})}{N}$$

where:

- EI_{avg} = represents the average increase in long-term effectiveness
- N = represents total number of available sites
- J = denotes the number of sites
- $WD_{post,\ j}$ = represents weighted distress of treated sections after the treatment at j site
- $WD_{cont,\ j}$ = denotes weighted distress of control sections at j site.

Box-whisker plot

The second analysis method used in this study is box-whisker plot to evaluate the effectiveness of maintenance and rehabilitation. The lower and higher quartiles are represented by the box's edges, while the median is represented by the center line. The whisker marks the minimum and maximum limits of the distress [10]. Box Plot elements are illustrated in Figure (2). The lower quartile, median, and higher quartile can be determined using the following methods [18]:

- Step 1: Sort the data on a primary attribute.
- .Step 2: Calculate the Median
- Step 3: Calculate the Quartiles.
  Quartiles: Q1 (25th %), Q3 (75th %)
  Inter-quartile range: IQR = Q3 – Q1
  Five number summary: min, Q1, M, Q3, max
  Boxplot: ends of the box are the quartiles, median is marked, whiskers, and plot outlier individually
- Step 4: Calculate the Outlier:
  More than 1.5 x IQR.

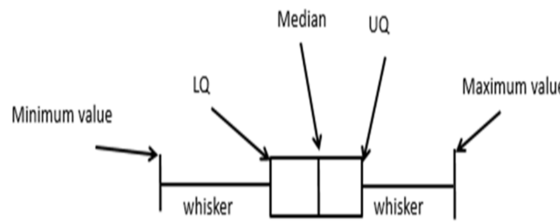

Figure 2- Boxplot elements [18].

Paired-sample t-test

The third analysis method used in this study is paired-sample t-test to measure the difference between the progress of each studied distress (such as crakes, rutting, and roughness) utilizing the SPSS program for both maintenance and rehabilitation [19]. According to maintenance, if the p-value is less than 0.05 of any treatment for certain distress so that the performance of this treatment is significant and better than other treatments [6]. For rehabilitation, it is necessary to compute the difference between recycled and virgin observations (Recycled - Virgin) in order to test the null hypothesis that the true mean difference is zero. Therefore, recycled section performs better than virgin section if the t-value for particular distress has a negative sign. The t-test can be calculated from the following equations [5]:

$$T = \frac{\text{Mean diff.}}{SE}$$

where:

- Mean diff. = is the mean of the difference between sections
- SE = is the standard error of the mean difference

$$SE = \frac{Sd}{\sqrt{n}}$$

- Sd = is the standard deviation
- n = is the number of sections

Annual variation

The fourth analysis method used in this study is annual variation to highlight the impact of the several aspects on performance relating to rehabilitation. Because the number of monitored years varied among the states studied, the annual variation of distress was used as an assessment metric and was measured as [20]:

$$\text{Annual variation} = \frac{(\text{End value} - \text{Starting value})}{\text{N}}$$

where:

- Starting value = is the first survey after the treatment
- End value = is the last survey after the treatment
- N = is the number of years

5. Results and Discussion

5.1. Maintenance

Three of the statistical methods that were described in Section 4 were used to completely examine the long-term impact of PMTs on pavement performance. They are average long-term effectiveness increment, boxplot, and paired-samples t-test. To evaluate the overall performance of various treatments, data from the LTPP SPS-3 program on fatigue cracking, longitudinal cracking, rutting, and roughness were used.

5.1.1. Fatigue cracking

Figure (3) shows the average long-term effectiveness of various PMTs on fatigue cracking. It was found that thin overlay and chip seal were the most effective. Additionally, it was indicated that crack sealing did not prevent fatigue cracking.

Figure (4) illustrates the box-whisker plot of weighted distress index for fatigue cracking. In comparison to slurry seal, crack seal, and control section, thin overlay and chip seal had decreased fatigue cracking quantities. Chip seal had a slightly lower median than thin overlay. Moreover, chip seal also had the smallest min-max range. Slurry seal-treated sections demonstrated lower weighted average fatigue cracking than crack seal and control sections. Over the monitored period, crack seal appeared to be less effective in preventing the progression of fatigue cracking.

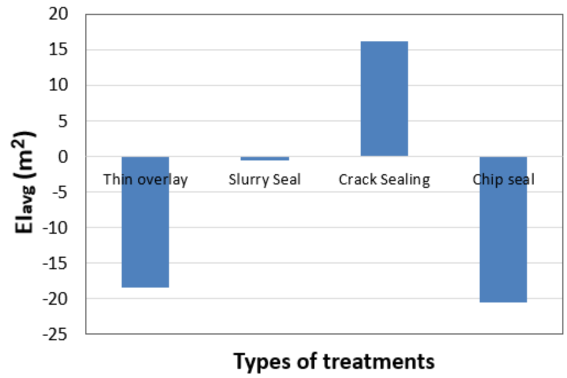

Figure 3- Average long-term effectiveness increment of various PMTs on fatigue cracking.

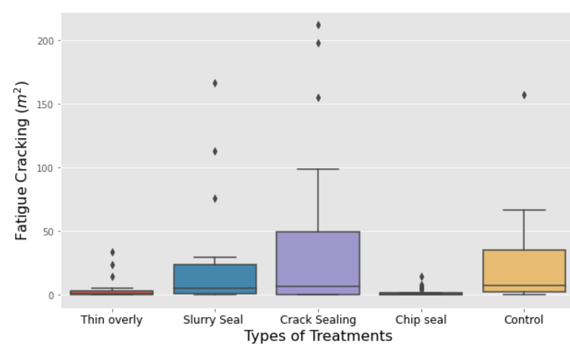

Figure 4- Weighted average fatigue cracking; median min-max chart.

The results of paired t-test for fatigue cracking were shown in Table (4). Thin overlay and chip seal had p-values less than 0.05, indicating that their improving effectiveness on fatigue cracking was significant. However, because the p-value was more than 0.05, the efficiency of the crack seal and slurry seal was insignificant. Furthermore, these findings were consistent with the average long-term effectiveness increment and the box-whisker plot.

5.1.2. Longitudinal cracking

According to Figure (5), the thin overlay, slurry seal, and chip seal were all efficient at improving longitudinal cracks, but the crack seal was ineffective

Table 4- Paired t-test results for fatigue cracking.

Paired variables		Paired Differences					t	df	Statistical sig. (P-values)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Control - Thin overlay	18.48	33.47	6.69	4.66	32.29	2.76	24	0.011
Pair 2	Control - Slurry seal	0.52	46.82	9.36	-18.81	19.84	0.06	24	0.956
Pair 3	Control - Crack sealing	-16.23	59.38	11.88	-40.74	8.28	-1.37	24	0.184
Pair 4	Control - Chip seal	20.49	34.22	6.84	6.36	34.61	2.99	24	0.006

by using average long-term effectiveness of various PMTs on longitudinal cracking.

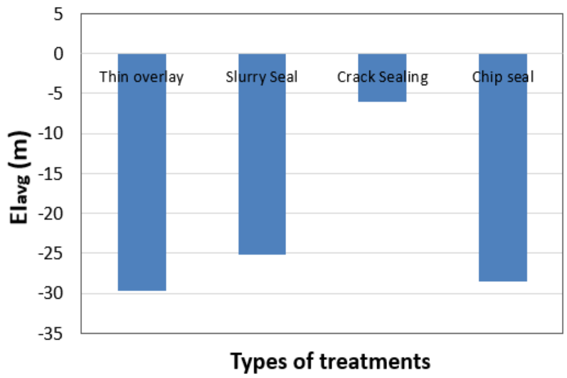

Figure 5- Average long-term effectiveness increment of various PMTs on longitudinal cracking.

The results of box-whisker plot of weighted distress index for longitudinal cracking were shown in Figure (6). Thin overlay had a slightly lower median than slurry seal and chip seal. Thin overlay had the smallest min-max range. Crack seal appeared to be less effective in reducing longitudinal cracking over time.

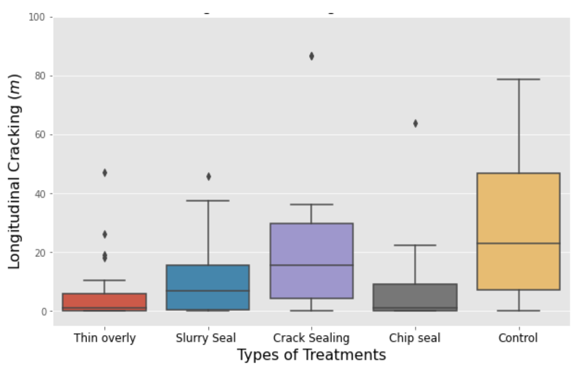

Figure 6- Weighted average longitudinal cracking; median min-max chart.

The results of paired t-test for longitudinal cracking were shown in Table (5). It was found that p-values for thin overlay, chip seal, and slurry seal were lower than 0.05, meaning that their improved effectiveness on longitudinal cracking was significant. However, the effectiveness of crack seal was non-significant due to p-values higher than 0.05.

5.1.3. Rutting

Figure (7) shows the average long-term effectiveness of various PMTs on rutting. It was found that a minimum EI_{avg} exists for thin overlay compared with the other three treatments, meaning that this treatment had the best and most significant effectiveness. Chip seal had a high EIavg, indicating that chip seal had poor effectiveness on rutting.

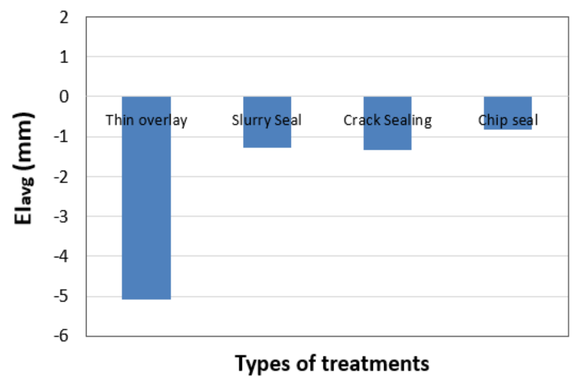

Figure 7- Average long-term effectiveness increment of various PMTs on rutting.

The results of box-whisker plot of weighted distress index for rutting were shown in Figure (8). Over time, thin overlay proved to be the most effective maintenance solution for preventing rutting. Rather than giving a considerable structural improvement to the pavement area, this form of treatment may have been the most effective at reducing rutting after treatment.

The findings of the paired samples t-test for rutting were shown in Table (6). The p-value for thin overlay was found to be less than 0.05, meaning that the improvement effectiveness on rutting was significant. In addition, these findings were in agreement with the average long-term effectiveness increment and the box-whisker plot.

Table 5- Paired t-test results for longitudinal cracking

Paired variables		Paired Differences					t	df	Statistical sig. (P-values)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Control - Thin overlay	29.67	41.90	8.22	12.75	46.59	3.61	25	0.001
Pair 2	Control - Slurry seal	25.18	42.88	8.41	7.86	42.50	2.99	25	0.006
Pair 3	Control - Crack sealing	6.04	69.41	13.61	-21.99	34.08	0.44	25	0.661
Pair 4	Control - Chip seal	28.47	41.94	8.23	11.53	45.41	3.46	25	0.002

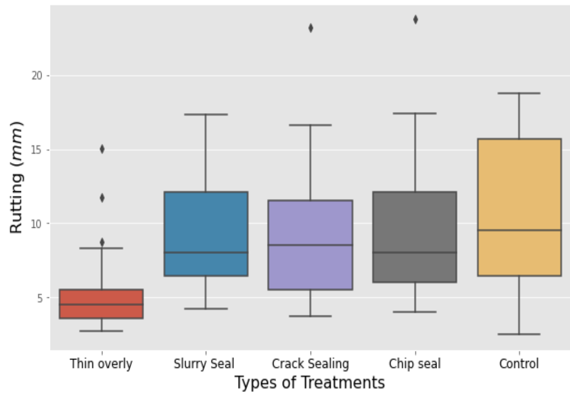

Figure 8- Weighted average rutting; median min-max chart.

5.1.4. Roughness

IRI is one of the primary indications used to determine the best timing and cost-benefit for PMTs, according to previous studies [21]. Figure (9) shows the average long-term effectiveness increment in view of weighted IRI. It was found that the EI_{avg} for thin overlay was minimum, -0.20036 m/km, compared with the other three treatments, indicating that this treatment had the most significant long-term effectiveness on roughness. Slurry seal, crack seal, and chip seal had a positive EIavg, indicating that the three treatments were ineffective against roughness.

Figure (10) shows the findings of a box-whisker plot of the weighted distress index for roughness. The thin overlay had a lower median than the other three treatments. It was discovered that crack seal had a larger median than other treatments, implying that crack seal was less effective in reducing roughness.

The results of paired samples t-test for roughness were shown in Table (7). It was found that p-values for thin overlay, chip seal, and slurry seal were lower than 0.05, meaning that their improved effectiveness on roughness was significant. However, the performance of other treatments was non-significant due to p-values higher than 0.05.

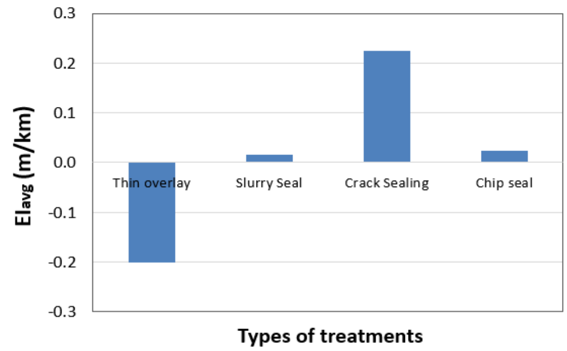

Figure 9- Average long-term effectiveness increment of various PMTs on roughness.

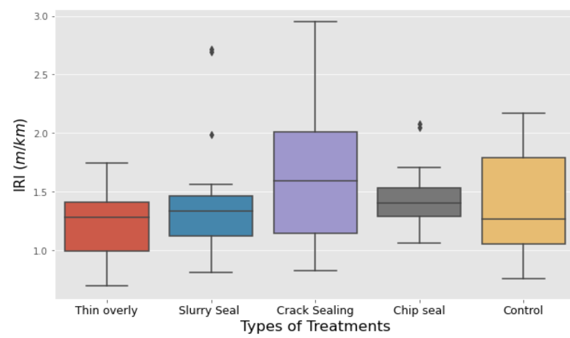

Figure 10- Weighted average roughness; median min-max chart.

In all, the long-term effect of various PMTs in improving various pavement performances was investigated in this research in different sections depending on the previous analysis, as indicated in Table 8.

5.2. Rehabilitation

Three of the statistical methods that were described in Section 4 were used to completely examine the long-term impact of rehabilitation on pavement performance. They are boxplot, annual variation and paired samples t-test. With a view to assessing the effectiveness of various treatments, data on fatigue cracking, longitudinal cracking, rutting, and roughness were gathered throughout the LTPP SPS-5 program.

Table 6- Paired t-test results for rutting.

Paired variables	Paired Differences					t	df	Statistical sig. (P-values)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Pair 1 Control - Thin overlay	5.10	5.21	1.04	2.95	7.25	4.89	24	0.000
Pair 2 Control - Slurry seal	1.27	4.64	0.93	-0.64	3.19	1.37	24	0.183
Pair 3 Control - Crack sealing	1.33	5.27	1.05	-0.84	3.51	1.27	24	0.218
Pair 4 Control - Chip seal	0.82	5.39	1.08	-1.41	3.05	0.76	24	0.455

Table 7- Paired t-test results for roughness.

Paired variables	Paired Differences					t	df	Statistical sig. (P-values)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Pair 1 Control - Thin overlay	0.20	0.41	0.09	0.002	0.40	2.12	18	0.048
Pair 2 Control - Slurry seal	-0.02	0.53	0.12	-0.27	0.24	-0.13	18	0.899
Pair 3 Control - Crack sealing	-0.22	0.60	0.14	-0.51	0.06	-1.64	18	0.118
Pair 4 Control - Chip seal	-0.02	0.39	0.09	-0.21	0.16	-0.27	18	0.790

Table 8- Summary of PMTs' long-term effectiveness.

Pavement perforamance	Preventive maintenance treatments			
	Thin overlay	Slurry seal	Crack seal	Chip seal
Fatigue cracking	S	NS	P	S
Longitudinal cracking	S	G	NS	S
Rutting	S	NS	NS	NS
Roughness (IRI)	S	NS	P	NS

Note: S = significance; G = good; NS = non-significance; P = Poor.

5.2.1. Fatigue cracking

Two sites were considered to evaluate the fatigue cracking development in asphalt overlay over time in a wet/no-freeze climate (Georgia and Texas). Two sites were investigated for the dry/no-freeze climate (Arizona and California). Figures (11 and 12) illustrate the development of fatigue cracking at two dry climate sites and Figures (13 and 14) illustrate the development of fatigue cracking at two wet climate sites. Each figure shows four boxplot charts with eight LTPP SPS-5 pavement sections code (ID) as indicated in Table (2). These four charts represented two overlay thicknesses (51 and 127mm) as well as two pre-overlay curing processes (with or without milling). Each figure highlights two types of materials used in the construction of asphalt overlay mixtures (completely virgin mix and recycled HMA mix).

Figures (11 and 12) illustrate the fatigue cracking in dry climates. It was observed that the recycled sections had a lower median than virgin sections except the recycled section 509 had a higher median than virgin section 506 in Arizona. In California, utilizing virgin mix instead of recycled mix increased the performance of both thin and thick overlays except the recycled section 508 had a lower median than virgin section 507. Figures (13 and 14) illustrate the fatigue cracking in wet climates. It was found that virgin sections had a lower median than recycled sections except the recycled section 508 had a lower median than virgin section 507 in Georgia. For Texas, it was observed that all virgin sections performed better than recycled sections for thin and thick overlays.

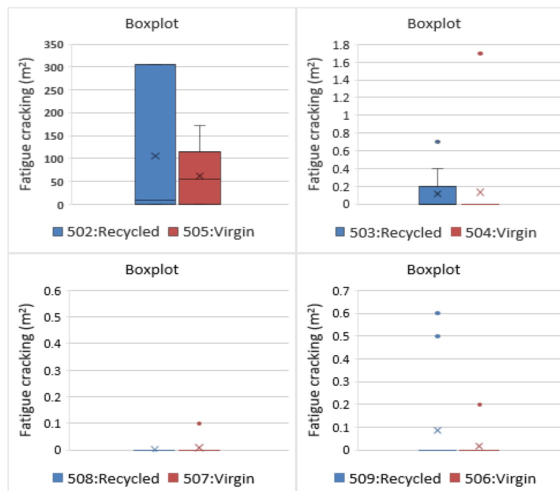

Figure 11- Boxplots for fatigue cracking in Arizona (dry climate).

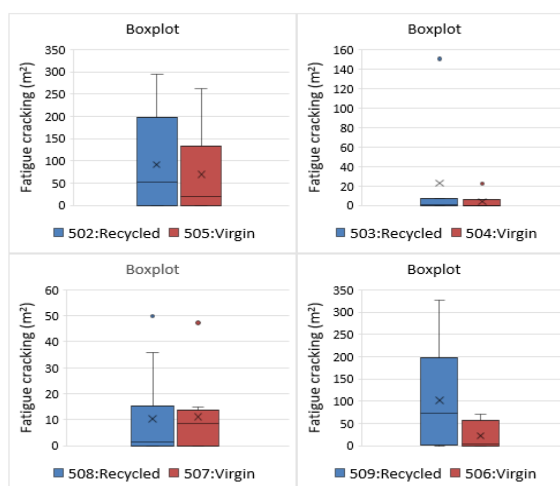

Figure 12- Boxplots for fatigue cracking in California (dry climate).

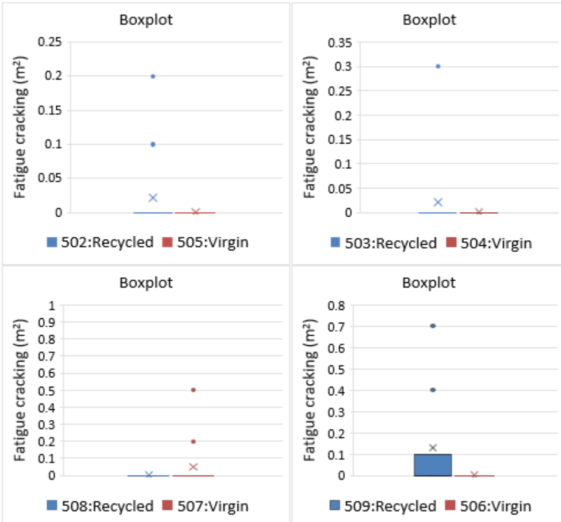

Figure 13- Boxplots for fatigue cracking in Georgia (wet climate).

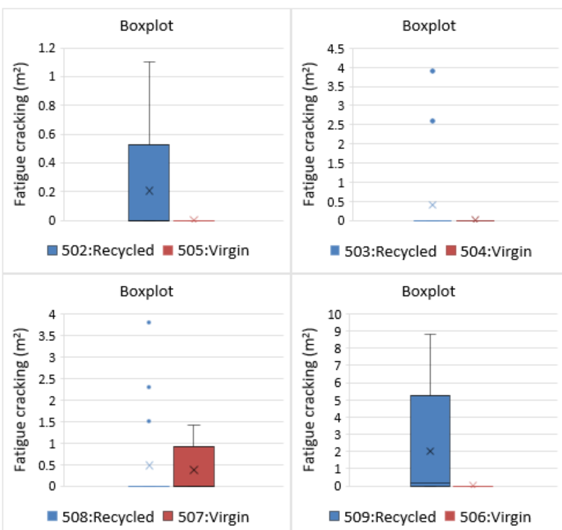

Figure 14- Boxplots for fatigue cracking in Texas (wet climate).

The results of annual variation for fatigue cracking were shown in Figure (15). For dry climates, virgin sections performed significantly better than recycled sections for thin overlays. Furthermore, recycled sections performed significantly better than virgin sections for thick overlays in Arizona. According to California, it was found that mostly virgin sections performed significantly better than recycled sections for thin and thick overlays. According to wet climates, it was observed that the recycled sections showed fatigue cracking improvement lower than virgin sections except the recycled section 508 in Georgia. For Texas, it was found that all virgin sections performed significantly better than recycled sections for thin and thick overlays.

The results of paired samples t-test for fatigue cracking were shown in Table (9). In a dry climate, virgin sections performed insignificantly better than recycled sections in Arizona and California for thinner overlay thickness (51mm). Moreover, with thick overlays, recycled sections performed substantially better than virgin sections. In Georgia and Texas, utilizing virgin mix instead of recycled mix increased the performance of both thin and thick overlays in wet climates with an exception at sections 507 and 508 in Georgia.

5.2.2. Longitudinal cracking

The results of box-whisker plot of longitudinal cracking were shown in Figures (16 to 19). In dry climates, the longitudinal cracking of sections using virgin mix in Arizona appeared to be less serious than that of sections using recycled mix, with the exception of recycled section 508, which appeared to be less serious than virgin section 507 as shown in Figure (16). It was observed that the recycled sections had a lower median than virgin sections in California, it was indicated that recycled sections performed better than virgin sections for thin and thick overlays as shown in Figure (17). For wet climates, it was found that recycled sections performed better than virgin sections for thin overlays, while virgin section 506 performed better for longitudinal cracking when compared to recycled section 509 in Georgia as shown in Figure (18). In Figure (19), it was illustrated that all virgin sections gave a better performance for longitudinal cracking than recycled sections in Texas for both thin and thick overlays.

The results of annual variation for longitudinal cracking were shown in Figure (20). For dry climate, it was illustrated that recycled sections had a higher annual variation for longitudinal cracking than virgin sections but recycled section 508 had a lower annual variation than virgin section 507 in Arizona. According to California, all recycled sections performed better than virgin sections. For wet climate, the results showed that recycled sections performed better than virgin sections such as sections 502 and 508 in Georgia except for sections 503 and 509. For Texas, all virgin sections had a lower annual variation for longitudinal cracking than recycled sections.

The results of paired samples t-test for longitudinal cracking were shown in Table (10). For dry climate, it was observed that mostly recycled sections performed insignificantly worse than virgin sections in Arizona but all recycled sections performed insignificantly better than virgin sections in

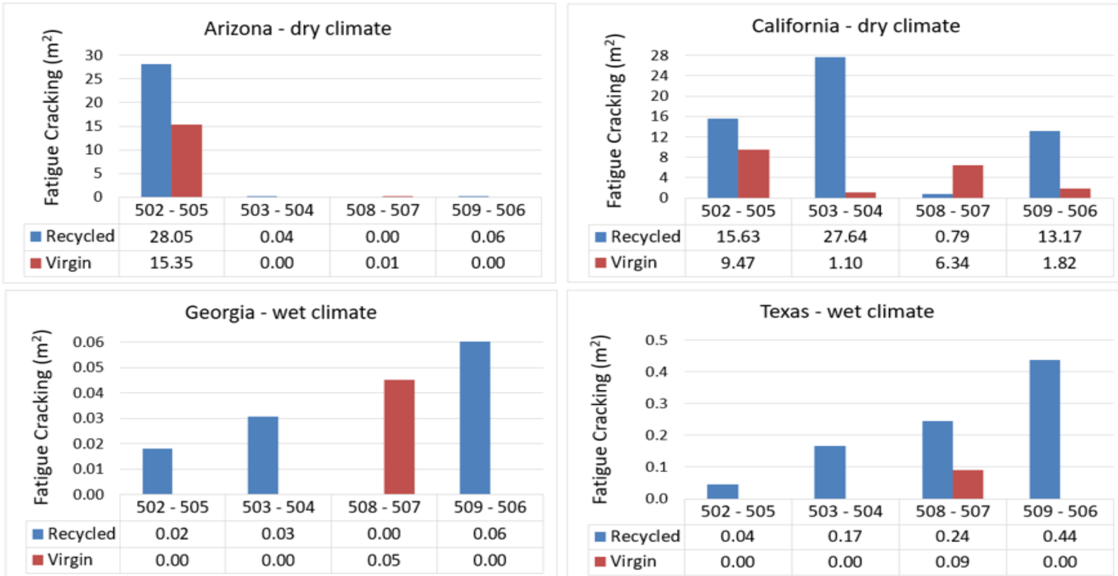

Figure 15- Annual variation of fatigue cracking.

Table 9- Summary of pair-t tests for fatigue cracking.

Climate	Site	Sections	Mean .diff (m^2)	Sd	SE	t-value	df	p-value (α=0.05)	Signi-ficance	Better performance
Dry climate	Arizona	502-505	42.99	95.87	26.59	1.62	12	0.132	Insign.	Virgin
		503-504	-0.02	0.33	0.09	-0.17	12	0.870	Insign.	Recycled
		508-507	-0.01	0.03	0.01	-1.00	12	0.337	Insign.	Recycled
		509-506	0.07	0.22	0.06	1.13	12	0.281	Insign.	Virgin
	California	502-505	21.84	36.40	12.13	1.80	8	0.110	Insign.	Virgin
		503-504	18.77	56.01	21.17	0.89	6	0.409	Insign.	Virgin
		508-507	-0.75	21.28	6.73	-0.11	9	0.914	Insign.	Recycled
		509-506	79.77	88.92	29.64	2.69	8	0.027	Sign.	Virgin
Wet climate	Georgia	502-505	0.02	0.06	0.01	1.39	13	0.189	Insign.	Virgin
		503-504	0.02	0.08	0.02	1.00	13	0.336	Insign.	Virgin
		508-507	-0.05	0.14	0.04	-1.34	13	0.205	Insign.	Recycled
		509-506	0.13	0.26	0.07	1.82	13	0.092	Insign.	Virgin
	Texas	502-505	0.21	0.38	0.09	2.18	15	0.046	Sign.	Virgin
		503-504	0.41	1.14	0.28	1.43	15	0.173	Insign.	Virgin
		508-507	0.11	0.73	0.18	0.58	15	0.570	Insign.	Virgin
		509-506	2.03	3.42	0.86	2.37	15	0.032	Sign.	Virgin

California. For wet climate and according to non-milled sections, it was illustrated that virgin section 505 performed worse than recycled section 502 for thin overlay. Otherwise, virgin section 504 performed better than recycled section 503 for thick overlay. With respect to milled sections, it was indicated that recycled section 508 performed better than virgin section 507 for thick overlay. Otherwise, virgin section 506 performed better than recycled section 509 for thin overlay. All virgin sections performed significantly better than recycled sections in Texas.

5.2.3. Rutting

Figures (21 and 22) show the overlay rutting performance in dry climates in Arizona and California respectively. As shown in Arizona, it was concluded that virgin sections performed better than recycled sections for thin overlays without pre-overlay treatments. Furthermore, recycled section 508 performed better than virgin section 507 for thick overlays with pre-overlay treatments. For California, it was found that all virgin sections performed worse than recycled sections for thin and thick overlays except the recycled section 502 had a higher median

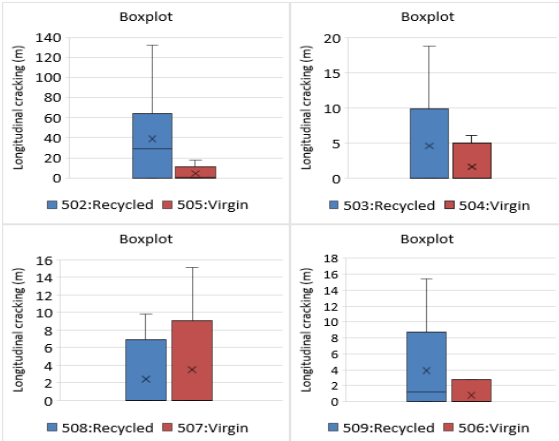

Figure 16- Boxplots for longitudinal cracking in Arizona (dry climate).

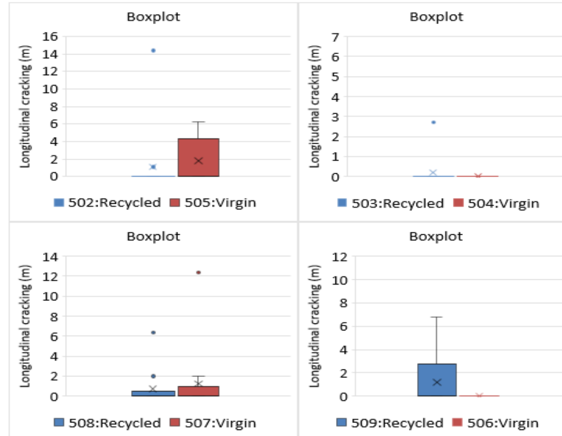

Figure 18- Boxplots for longitudinal cracking in Georgia (wet climate).

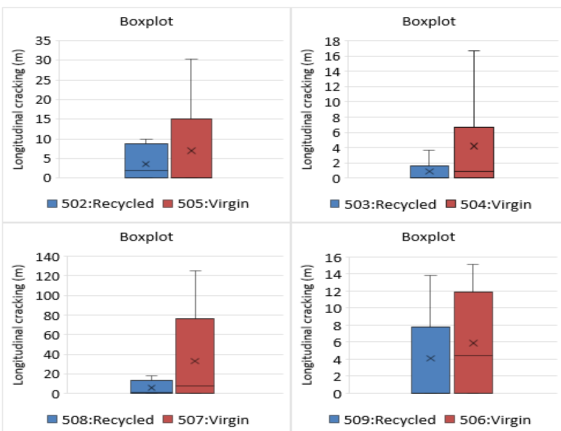

Figure 17- Boxplots for longitudinal cracking in California (dry climate).

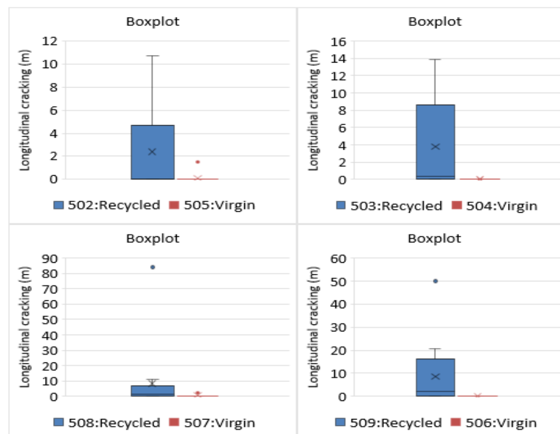

Figure 19- Boxplots for longitudinal cracking in Texas (wet climate).

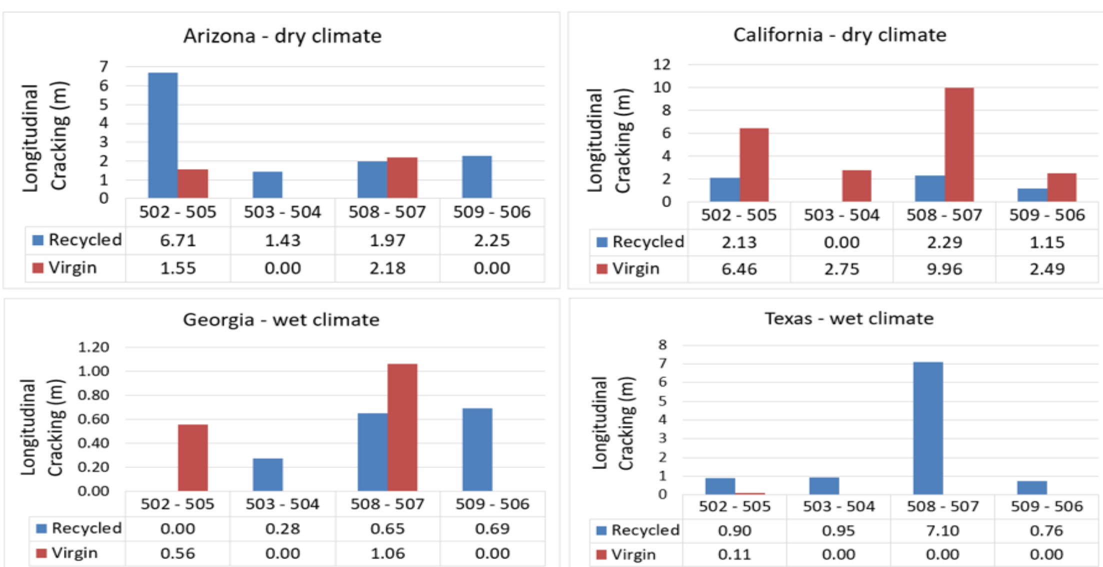

Figure 20- Annual variation of longitudinal cracking.

Table 10- Summary of pair-t tests for longitudinal cracking

Climate	Site	Sections	Mean .diff (m)	Sd	SE	t-value	df	p-value (α=0.05)	Signi-ficance	Better performance
Dry climate	Arizona	502-505	34.32	42.89	17.51	1.96	5	0.107	Insign.	Virgin
		503-504	3.01	6.72	2.54	1.19	6	0.280	Insign.	Virgin
		508-507	-1.07	7.31	2.76	-0.39	6	0.712	Insign.	Recycled
		509-506	3.10	5.94	2.24	1.38	6	0.216	Insign.	Virgin
	California	502-505	-3.41	9.36	3.120	-1.09	8	0.306	Insign.	Recycled
		503-504	-3.30	6.18	2.34	-1.41	6	0.207	Insign.	Recycled
		508-507	-27.47	39.54	12.51	-2.20	9	0.056	Insign.	Recycled
		509-506	-1.80	8.12	2.71	-0.67	8	0.525	Insign.	Recycled
Wet climate	Georgia	502-505	-0.68	4.86	1.30	-0.52	13	0.610	Insign.	Recycled
		503-504	0.19	0.72	0.19	1.00	13	0.336	Insign.	Virgin
		508-507	-0.49	1.92	0.51	-0.96	13	0.354	Insign.	Recycled
		509-506	1.180	2.13	0.57	2.07	13	0.059	Insign.	Virgin
	Texas	502-505	2.29	3.67	0.95	2.42	14	0.030	Sign.	Virgin
		503-504	3.80	5.24	1.35	2.81	14	0.014	Sign.	Virgin
		508-507	7.75	21.30	5.50	1.41	14	0.181	Insign.	Virgin
		509-506	8.64	13.60	3.51	2.46	14	0.027	Sign.	Virgin

than virgin section 505 without pre-overlay treatments. Figures (23 and 24) show the overlay rutting performance in wet climates in Georgia and Texas respectively. It was found that virgin sections performed better than recycled sections for thin overlays, but recycled sections acted better than virgin sections for thick overlays in Georgia. For Texas, it was illustrated that all recycled sections had lower median rutting than virgin sections for both thin and thick overlays. The pre-overlay treatments had no obvious effect on performance, with recycled areas performing better.

The results of annual variation for rutting were shown in Figure (25). For dry climate, the annual variation for rutting utilizing recycled mixture was greater than that in the section using virgin mixture except section 508 in Arizona. Recycled sections had a lower annual variation for rutting than virgin sections except for section 502 in California. For thin overlays in wet climates, virgin sections performed substantially better than recycled sections. However, recycled sections performed better than virgin sections for thick overlays in Georgia. For both thin and thick overlays in Texas, it was shown that all recycled sections had a lower annual variation for rutting than virgin sections. Furthermore, these findings were consistent with the box-whisker plot.

The statistical analysis of paired samples t-test of rutting development was shown in Table (11). For dry climate, it was observed that mostly virgin sections performed significantly better than recycled sections in Arizona, despite that pre-overlay treatment before rehabilitation showed that the performance of recycled milled sections against rutting was significantly better than virgin sections in California. For wet climates, virgin sections performed significantly better than recycled sections for thin overlays. However, recycled sections performed insignificantly better than virgin sections for thick overlays in Georgia. For both thin and thick overlays whether with or without milling, it was demonstrated that all recycled sections performed much better than virgin sections in Texas.

5.2.4. Roughness

The results of box-whisker plot of IRI were shown in Figures (26 to 29). In dry climates, sections with recycled mixture had lower median IRI values than the sections with virgin mixture except section 502 in Arizona. However, sections with virgin mixture had higher median IRI values than the sections with recycled mixture except for sections 504 and 506 in California. In wet climate, it was observed that mostly virgin sections had lower median IRI values than recycled sections and milled sections with recycled mixture had the highest median IRI value in Georgia. For both thin and thick overlays in Texas, it was shown that all recycled sections had lower median IRI values than virgin sections.

Figure (30) illustrated the annual variation for IRI. For dry climates, virgin sections had lower annual variation for IRI than recycled sections for thin overlays. However, recycled sections had lower annual variation for IRI than virgin sections for thick overlays in Arizona. Mostly virgin sections had lower

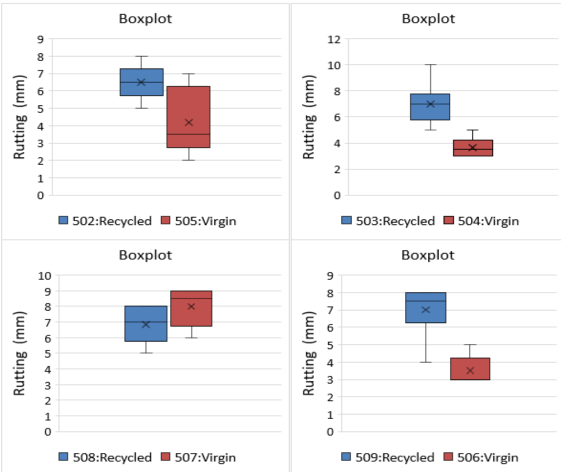

Figure 21- Boxplots for rutting in Arizona (dry climate).

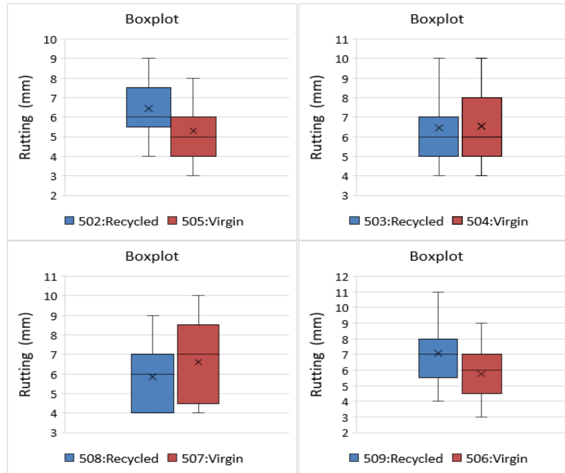

Figure 23- Boxplots for rutting in Georgia (wet climate).

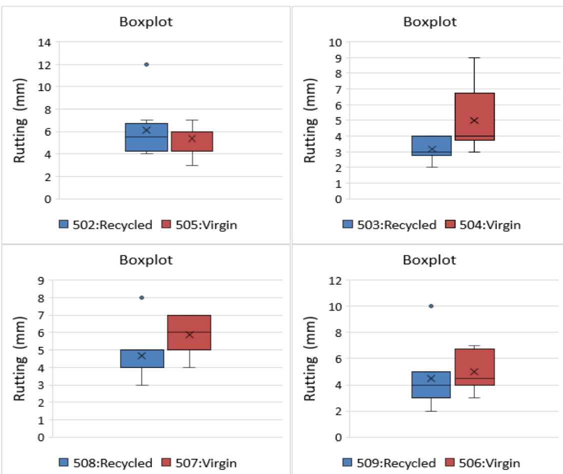

Figure 22- Boxplots for rutting in California (dry climate).

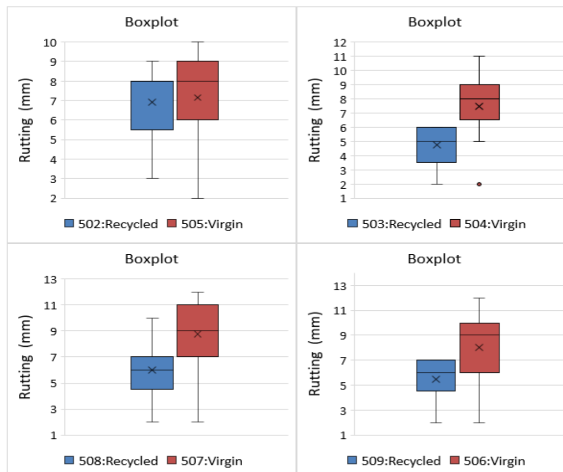

Figure 24- Boxplots for rutting in Texas (wet climate).

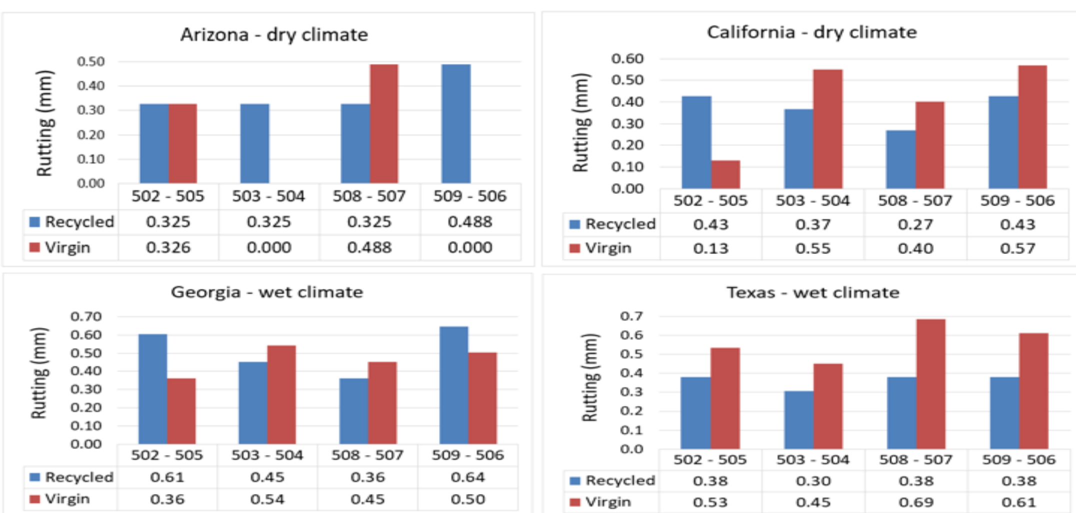

Figure 25- Annual variation of rutting.

Table 11- Summary of pair-t tests for rutting.

Climate	Site	Sections	Mean .diff (mm)	Sd	SE	t-value	df	p-value (α=0.05)	Signi-ficance	Better performance
Dry climate	Arizona	502-505	2.33	1.86	0.76	3.07	5	0.028	Sign.	Virgin
		503-504	3.33	1.63	0.67	5.00	5	0.004	Sign.	Virgin
		508-507	-1.17	0.75	0.31	-3.80	5	0.013	Sign.	Recycled
		509-506	3.50	1.38	0.56	6.22	5	0.002	Sign.	Virgin
	California	502-505	0.75	2.25	0.80	0.94	7	0.378	Insign.	Virgin
		503-504	-1.83	1.60	0.65	-2.80	5	0.038	Sign.	Recycled
		508-507	-1.22	0.97	0.32	-3.77	8	0.005	Sign.	Recycled
		509-506	-0.50	1.51	0.54	-0.94	7	0.381	Insign.	Recycled
Wet climate	Georgia	502-505	1.15	0.80	0.22	5.20	12	0.000	Sign.	Virgin
		503-504	-0.08	0.86	0.24	-0.32	12	0.753	Insign.	Recycled
		508-507	-0.77	1.24	0.34	-2.25	12	0.044	Sign.	Recycled
		509-506	1.31	1.32	0.37	3.58	12	0.004	Sign.	Virgin
	Texas	502-505	-0.23	1.01	0.28	-0.82	12	0.427	Insign.	Recycled
		503-504	-2.69	1.49	0.41	-6.50	12	0.000	Sign.	Recycled
		508-507	-2.77	1.74	0.48	-5.74	12	0.000	Sign.	Recycled
		509-506	-2.54	1.33	0.370	-6.88	12	0.000	Sign.	Recycled

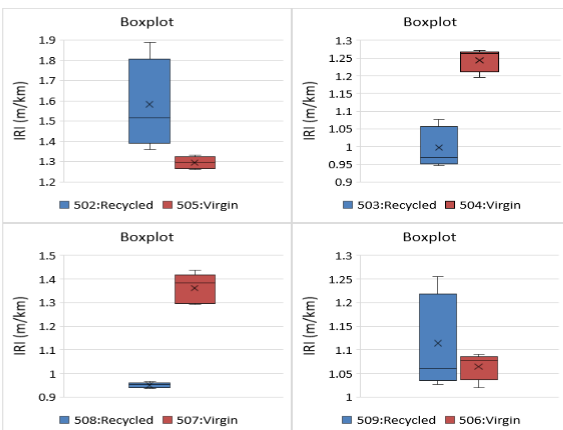

Figure 26- Boxplots for roughness in Arizona (dry climate).

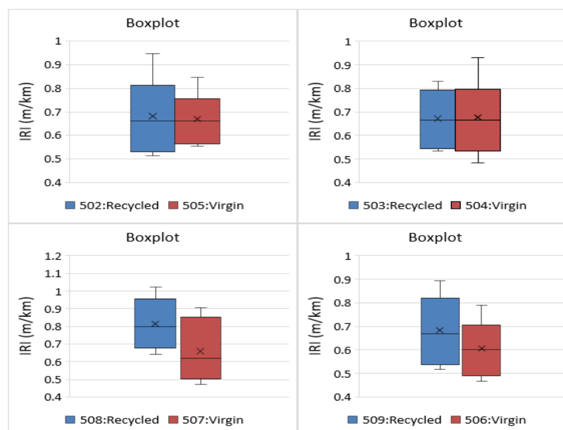

Figure 28- Boxplots for roughness in Georgia (wet climate).

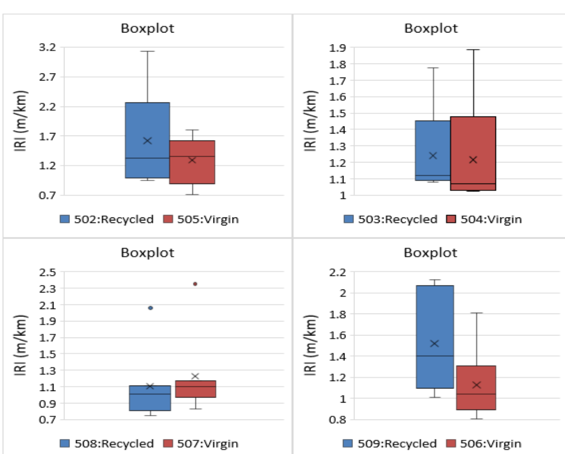

Figure 27- Boxplots for roughness in California (dry climate).

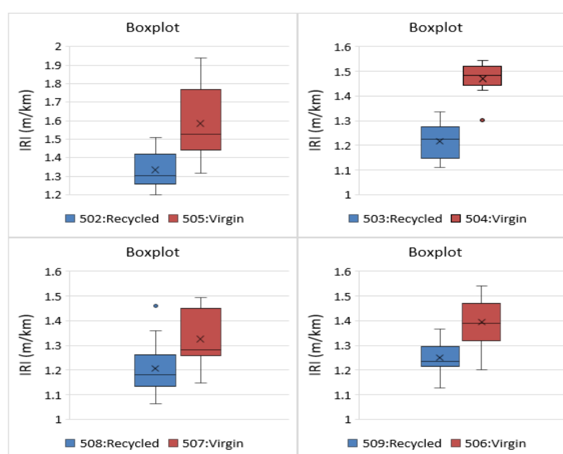

Figure 29- Boxplots for roughness in Texas (wet climate).

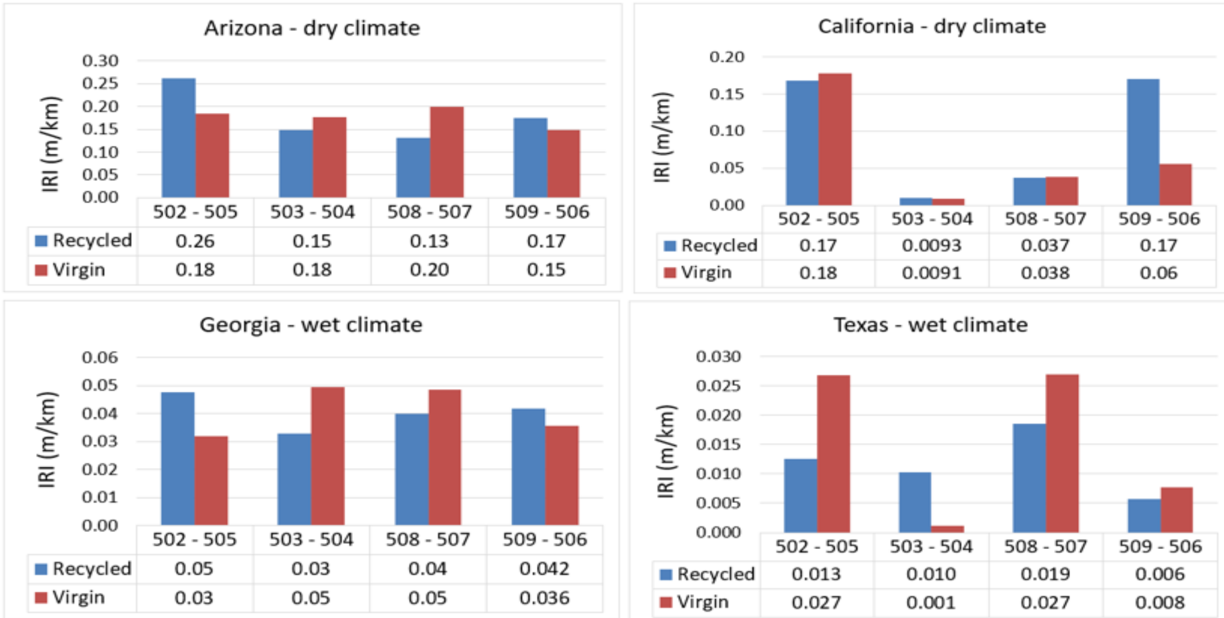

Figure 30- Annual variation of roughness.

annual variation for IRI than recycled sections except sections 505 and 507 in California. With respect to wet climates, it was shown that recycled sections had a lower annual variation for IRI than virgin sections for thick overlay. otherwise, virgin sections had a lower annual variation for IRI than recycled sections for thin overlay in Georgia. According to Texas, it was found that mostly recycled sections had a lower annual variation for IRI than virgin sections for both thin and thick overlays except section 503.

The results of paired samples t-test for IRI were shown in Table (12). For dry climate, it was found that virgin sections performed significantly better than recycled sections for thin overlays, but recycled sections performed significantly better than virgin sections for thick overlays in Arizona. In California, it was shown that mostly recycled sections performed worse than virgin sections except for section 508. For wet climates, it was found that mostly virgin sections performed better than recycled sections except for section 504 in Georgia. According to both thin and thick overlays in Texas, it was shown that all recycled sections performed better than virgin sections. In addition, these findings were mostly in agreement with the box-whisker plot and annual variation.

On the whole, as shown in Table (13), the long-term impact of various rehabilitation treatments in improving various pavement performances was investigated in this research in different sections based on the previous analysis.

6. Conclusions and recommendations

This research was conducted to investigate the impact of flexible pavement maintenance and rehabilitation treatments on pavement performance. Pavement performance indicators included fatigue cracking, longitudinal cracking, rutting, and roughness. The chosen sites of this study were wet and dry, with no freezing. Statistical techniques were applied such as boxplot and average long-term effectiveness increment, annual variation, and paired-samples t-test. The outcomes of this study added to the knowledge gathered from the previous studies. The following conclusions were taken from the analyses:

1. Fatigue cracking: According to maintenance, it was found that thin overlay and chip seal were the most effective. Furthermore, it was discovered that the effectiveness of crack seal on fatigue cracking was not obvious. With respect to rehabilitation, virgin sections performed better than recycled sections in dry climates for thinner overlay thickness (51mm). Otherwise, with thick overlays, recycled sections performed substantially better than virgin sections. Using virgin mix improved the performance of both thin and thick overlays in wet climates.

2. Longitudinal cracking: According to maintenance, thin overlay, slurry seal, and chip seal were all effective at improving longitudinal cracking however, the crack seal was useless. With respect to rehabilitation, recycled sections performed better than virgin sections, especially for thick overlays in dry climates. Mostly virgin sections performed better

Table 12- Summary of pair-t tests for roughness.

Climate	Site	Sections	Mean .diff (m/km)	Sd	SE	t-value	df	p-value (α=0.05)	Signi-ficance	Better performance
Dry climate	Arizona	502-505	0.29	0.20	0.09	3.25	4	0.031	Sign.	Virgin
		503-504	-0.25	0.04	0.02	-14.67	4	0.000	Sign.	Recycled
		508-507	-0.41	0.06	0.03	-16.55	4	0.000	Sign.	Recycled
		509-506	0.05	0.09	0.04	1.22	4	0.290	Insign.	Virgin
	California	502-505	0.33	0.62	0.25	1.30	5	0.250	Insign.	Virgin
		503-504	0.02	0.08	0.03	0.70	4	0.523	Insign.	Virgin
		508-507	-0.12	0.09	0.03	-3.58	6	0.012	Sign.	Recycled
		509-506	0.39	0.27	0.11	3.57	5	0.016	Sign.	Virgin
Wet climate	Georgia	502-505	0.01	0.05	0.02	0.60	7	0.566	Insign.	Virgin
		503-504	-0.01	0.04	0.02	-0.28	7	0.785	Insign.	Recycled
		508-507	0.15	0.05	0.02	9.61	7	0.000	Sign.	Virgin
		509-506	0.08	0.04	0.02	5.24	7	0.001	Sign.	Virgin
	Texas	502-505	-0.25	0.11	0.03	-8.86	13	0.000	Sign.	Recycled
		503-504	-0.25	0.08	0.02	-12.20	13	0.000	Sign.	Recycled
		508-507	-0.12	0.12	0.03	-3.71	13	0.003	Sign.	Recycled
		509-506	-0.14	0.10	0.03	-5.23	13	0.000	Sign.	Recycled

Table 13- Summary of the long-term effectiveness of rehabilitation treatments.

Pavement perforamance	Dry climate				Wet climate			
	Thin overlay		Thick overlay		Thin overlay		Thick overlay	
	non milling	milling	non milling	milling	non milling	milling	non milling	milling
Fatigue cracking	V	V	V , R	R	V	V	V	V , R
Longitudinal cracking	V , R	V , R	V , R	R	V , R	V	V	V , R
Rutting	V	V , R	V , R	R	V , R	V , R	R	R
Roughness (IRI)	V	V	V , R	R	V , R	V , R	R	V , R

than recycled sections in specific milled thin and thick overlays in wet climates.

3. Rutting: According to maintenance, the most effective way to avoid rutting was to apply thin overlay. This type of treatment was found to be the most effective at decreasing rutting. With respect to rehabilitation, in dry climates, mostly virgin sections performed better than recycled sections in specific thin overlays. However, recycled sections performed better than virgin sections, especially for milled thick overlays. Mostly recycled sections performed better than virgin sections in specific thick overlays in wet climate.

4. Roughness: According to maintenance, it was found that thin overlay had the most significant long-term effectiveness on roughness. Slurry seal, crack seal, and chip seal were ineffective against roughness. With respect to rehabilitation, virgin sections performed better than recycled sections in dry climates for thin overlays. However, with thick overlays, mostly recycled sections performed better than virgin sections. Mostly recycled sections performed better than virgin sections in specific thick overlays in wet climates.

The conclusions of this study may provide guidelines for the application of maintenance and rehabilitation treatment decision-making. However, the effect of many variables such as pavement materials, constructions, environmental and traffic conditions on long-term effectiveness is a more significant subject that attracts researchers. In view of that, greater research into this subject is needed to give complete recommendations for maintenance and rehabilitation decision-making.

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