Transactions on Engineering and Computer Science

Research| Vol 1 Iss 2

Long Term Performance of Asphalt Overlays in Flexible Pavement Rehabilitation

Ahmed Ebrahim Abu El-Maaty*[1], Alaa Bahaa El-Dein Fathy[1] and Saad Abd El-Karim El-Hamrawy[1]

[1] All the authors are with the Faculty of Engineering, Civil Department, Menoufia University, Egypt

***Corresponding author:** Ahmed Ebrahim Abu El-Maaty, Faculty of Engineering, Civil Department, Menoufia University, Egypt; Tel: 002-01097038811; E-mail: maaty5000[AT]yahoo.com

Received: July 20, 2020; **Accepted**: August 15, 2020; **Published:** August 23, 2020

Abstract

Reusing asphalt pavement (RAP) has been utilized in producing new bituminous mixes for last several years and has turned into a popular topic in pavement organizations. However, worries from its behavior in the field have been still standing. The main objective of this research is investigating the long-term performance of asphalt overlays containing RAP in flexible pavement rehabilitation using data from Long Term Pavement Performance (LTPP) program. Many variables are considered such as overlay thickness (51, 127mm), asphalt overlay materials (raw mixtures compared with mixtures including 30% RAP), climate (wet, dry) and pre-overlay curing that means pavement surface handling before rehabilitation by low or heavy grinding. In this article, data from 4 sites were taken to perform analysis where each site consists of 8 sections (4 sections with raw materials and another 4 sections using 30%RAP). These sites were selected due to their similar climate to Egypt. Five performance indicators were chosen including fatigue cracking, longitudinal cracking, transverse cracking, rutting, and roughness. Two statistical analyses were performed on extracted data to determine the priority in performance and the significance in variation. The first analysis was using paired t-tests and p-values while the second was the analysis of variance (ANOVA). The results of field observations indicated that the RAP sections achieved similar/ better performance as compared with raw sections except for rutting development which increased at using RAP. Moreover, RAP addition in thicker overlay provided lower fatigue cracking progress while thinner overlay for RAP sections provided lower longitudinal cracking development. The pre-overlay handling didn't appear any noticeable difference in fatigue, longitudinal and transverse cracking development. The climate had no obvious effect on fatigue and transverse cracking progress while dry climate provided higher longitudinal cracking and roughness progress for RAP sections. Statically, the variation in pre-overlay curing (from low to heavy) had the highest statistical effect on fatigue and transverse cracking, while rutting and roughness progresses weren't clearly affected by variation in climate, thickness or surface curing before rehabilitation. According ANOVA test, the variation in climate from wet to dry had a significant statistical effect on reducing fatigue cracking and increasing longitudinal cracking.

Keywords: ***Rehabilitation; Asphalt overlay; Long term performance; RAP; Cracking; Rutting.***

Citation: El-Maaty AEA, Fathy AB, and El-Hamrawy SAK. Long term performance of asphalt overlays in flexible pavement rehabilitation. Trans Eng Comput Sci. 2020;1(2):111.

1. Introduction

1.1 Background

Deterioration of the pavement may contribute to pavement distresses which then causes several problems especially in developing countries such as Egypt. The most common distress types occurring in the Egyptian roads are rutting, cracking, roughness, etc. Thus, continuous rehabilitation is needed for successive years to overcome the distresses related to materials, traffic and environmental conditions. The most effective mean for pavement rehabilitation is using overlays [1,2]. Continues destruction of flexible pavements provides huge amounts of solid remnants. With decreasing of landfill areas, raw aggregates and asphalt, the recycling of asphalt pavement wastes has turned into an important issue around the world in the last years [3]. Despite of that, the long-term performance of hot asphalt mixtures containing reclaimed asphalt pavement (RAP) has not been satisfactorily investigated yet. These investigations are extremely helpful in evaluating the life cycle assessment of pavements including RAP [4]. The Long-Term Pavement Performance (LTPP) program in the United States (U.S.) and Canada gathered and analyzed information over a long period (approximately 20 years) and produced the factors affecting pavement performance such as materials, climatic, traffic loads, building parameters and rehabilitation treatments [5,6]. The Specific Pavement Studies Experiment 5 (SPS-5) was prepared to investigate the impacts of overlay rehabilitation through observing the growth of cracks, plastic deflection or rutting, and roughness [7].

Thence, an amount of long-term performance information was collected and analyzed in this research from 4 sites (SPS-5) that selected according to their climate, which similar to the Egyptian environment. Each site is including 8 test sections (4 using raw materials and 4 using 30%RAP) constructed and operated under the same conditions. The main objective of this study is evaluating the long-term performance of asphalt overlays utilizing 30% RAP material as compared with using only raw materials. Moreover, the overlay thicknesses of 51 and 127 mm representing as a thin and a thick thickness respectively are investigated. Rehabilitation with and without grinding of the standing surface is also considered. The five performance indicators (deteriorations groups) which are chosen for this study are containing fatigue cracking, longitudinal cracking, transverse cracking, rutting, and roughness.

1.2 Literature review

In the latest years, many researches and studies investigated the efficiency of different maintenance handlings. Hongren and coauthors [8] analyzed the efficiency of deterrent maintenance handlings of asphalt pavements using data from the LTPP data (specific pavement study 3 (SPS-3)). The handlings contained chip seal, thin asphaltic overlay, crack seal and slurry seal. The selected performance indicators were fatigue cracking, (IRI), longitudinal cracking, rutting and transverse cracking. The results showed that chip seal and thin overlay were the only effective methods in delaying cracking of fatigue. Lower overlay thickness was the only active method in delaying long-run roughness, longitudinal cracking, rutting, and transverse cracking. Sites with poor surface state suffer faster from long-run longitudinal cracking and roughness. Moreover, Jia and coauthors [9] investigated the long run validation of deterrent maintenance on pavement behavior utilizing (SPS-3) in LTPP. A new structure was setup to estimate pavement treatment status. Weighted deterioration was considered to characterize long-term behavior. The results showed that the crack seal and thin overlay are the best and worst maintenance means. While Amarasiri and coauthors [10] evaluated the efficiency of various maintenance treatments under many pavement states, traffic volumes and climates. Relationships were established to evaluate the longitudinal cracking appears in each maintenance technique (slurry seal, thin overlay, crack seal and chip seal). The dissections used the wet-freeze climate to predict the long-run pavement behavior according to longitudinal cracking information from LTPP. Generally, chip seal was the most active curing method followed by slurry seal and then low overlay thickness and crack seal come and then finally untreated section respectively.

Other few pervious researches concentrated on using different types and thicknesses of asphaltic overlays as a maintenance method. Yuhong [11] compared the long-run effectiveness of bituminous overlays utilizing virgin mixtures and mixtures of 30% of RAP. Information used for comparison was collected from 18 SPS-5 sites beneath, the long-term pavement performance (LTPP) program. The results indicated that there were reactive impacts between the using of mixtures containing RAP, thickness of overlay, and pre-overlay handling method. With comparatively thin overlay (51 mm) and low pre-overlay handling, unwanted performance of RAP mixtures was predictable. On the contrary, with comparatively higher overlay thickness (127 mm) and high pre-overlay handling, RAP mixtures surpassed virgin mixtures in roughness and rutting. The performance of RAP mixtures was confirmed to be driven by their main properties, the decreased cracking impedance and high stiffness. Randy and coauthors [12] studied flexible overlaid pavement performance with and without RAP. They investigated the effect of location, period from construction in years, thickness of overlay, and milling of the current pavement on the performance of the overlays. The results showed that the overlays mixtures containing 30% RAP were performed as well as virgin overlays mixtures for block cracking, International roughness index (IRI), raveling and rutting. Lower overlays thicknesses showed better pavement performance, unless for rutting. Curing before rehabilitation reduced transverse cracking; fatigue cracking and IRI however increased rutting. Regis and coauthors [13], studied long-run performance of RAP blended compared with raw asphaltic overlays. The impacts of area environment, thickness of overlay, and surface curing before rehabilitation were studied. Information from the SPS-5 sections of the LTPP program was utilized. Asphaltic overlay performance was observed through estimating fatigue cracking, rutting and roughness. The whole flexible pavement effectiveness of the overlaid parts was predicted from the analysis of deformation data. The results clarified that the most of RAP mixtures had a statistic performance equals to virgin bituminous mixes. The statistical parity of deformations proposed that overlays containing RAP can supply structural refinement, equal to virgin asphalt overlays.

Mei [14] evaluated the long-term behavior of asphalt pavement included reclaimed asphalt pavement (RAP) using the data taken from (SPS-5). The results clarified that the both longitudinal and alligator cracking were affected the impairment of the long-run behavior of flexible pavement obviously. The rutting provided an important effect on the goodness of the bituminous pavement more than the cracks. The addition of RAP up to 30% provided comparable behavior according to measurements of longitudinal cracking, IRI and transverse cracking. RAP sections achieved lower rutting as compared with virgin asphalt mixtures. Gong and coauthors [15] studied the field behavior of RAP sections of (SPS-5) through LTPP database. It was showed that RAP had slight impacts on roughness, transverse cracking and longitudinal cracking. Utilizing RAP was useful in decreasing the rutting of higher overlays thicknesses. For RAP and raw bituminous overlays, higher overlays thicknesses achieved better behavior than lower thicknesses in all performance indicators unless rutting. Pre-overlay handlings techniques and subgrade sorts were the most important variables impacting roughness and fatigue cracking. Moreover, the primary pavement surface state provided significant impacts on fatigue cracking. Mohamed and coauthors [16] investigated the impact of pavement service life and thickness on the roughness value using LTPP data for achieving mathematical relations between the roughness and the thickness of pavement, traffic volumes, service period, type of subgrade and climatic conditions. The results provided that the impact of thickness on the service period can be ignored for weak traffic, dry climate, and moderate temperature.

Generally, previous researches that studied rehabilitated pavement in long-run have been carried out using the LTPP database. Their results concluded that the long-term performance indicators such as cracking, plastic deflection or rutting and roughness have not changed significantly at using different overlay types (raw & RAP) and different pre-overlay handlings (low & heavy) [17,18]. Although the previous studies provided helpful outputs, the potential reacting impacts between overlay thickness and surface curing before rehabilitation have not been studied thoroughly. Moreover, the performance of asphalt overlays including RAP has not been highlighted clearly [8].

2. Methodology

2.1 Selecting Data from LTPP

According to Köppen climate classification, which is one of the most widely climate classification systems that first published by the German-Russian climatologist Wladimir Köppen [19], Egypt basically has a hot desert climate. The climate is in general extremely dry all over the country except on the northern Mediterranean coast which receives rainfall in winter. In addition to scarcity of rain, extreme heat during summer months is also a general climate feature of Egypt although daytime temperatures are more moderated along the northern coast. Based on that, the climate of Egypt is classified as not freeze and dry all over the country, and not freeze/wet at the northern Mediterranean coast. Data extracted from long term pavement performance (LTPP) program include comprehensive information about the test sections and all measurements recorded such as overlay construction date, climate, traffic, distresses, records for these distresses at periodic visits made to gather different performance data from the test sections, and event description of rehabilitation method.

As aforementioned, the explanations and analysis are executed using the data obtainable for SPS-5, which contains 197 test sections from 17 locations. For this research, the practical observations of pavement performance for (SPS-5) were taken from LTPP database including four variables: overlay thickness, type of materials (Raw & RAP), climate (wet & dry) and pre-overlay curing (pavement surface handling before rehabilitation by low or grinding). Data in the observation unit contains deterioration registrations for fatigue cracking, longitudinal cracking, transverse cracking, average rutting depths and global roughness index. Each deterioration group own three intensity levels low, medium, and high. The amounts utilized for this study were the sum of the three levels. Four test sites from LTPP database (SPS-5) were selected due to their climates that similar to Egypt. Table 1 illustrates the selected sites from different states. Each site contained 8 sections to clarify the effect of overlay thickness (thin or thick), pre-overlay curing (low or heavy grinding of the standing pavement before rehabilitation) and overlay materials types (raw material only or combined with 30%RAP) on their long-term performance. Each section is 152.4 m long and 3.66 m wide. Table 2 shows descriptions for the pavement sections studied in this research.

Table 1: The Selected Sites From LTPP Database (SPS-5).

Not freeze/wet climate		Not freeze/dry climate	
Site Name	**Overlay Construction Year**	**Site Name**	**Overlay Construction Year**
Alabama	1991	Arizona	1990
Maryland	1992	New Mexico	1996

Table 2: Descriptions for the Selected Pavement Sections (SPS-5).

Thickness of Overlay	**Thin thickness (51mm)**			
Pavement surface curing before rehabilitation	No/low grinding		Heavy grinding	
Section number (ID)	505	502	506	509
Materials types	Raw	RAP	Raw	RAP
Thickness of Overlay	**Thick thickness (127mm)**			
Section number (ID)	504	503	507	508
Materials types	Raw	RAP	Raw	RAP

2.2 Analyzing of data

After selecting data, the long-term performance of asphalt overlay is analyzed using comparisons between the different studied parameters such as overlay thickness, surface curing before rehabilitation and material types. The effects of these parameters are evaluated on each deterioration group considered in this study. The first analysis used in this study is by collecting and plotting the extracted data for each investigated parameter on one graph to illustrate the potential variation.

The second analytical method used in this study is the paired-sample t-test to measure the difference between the progress of each studied distress (such as crakes, rutting and roughness) for RAP and raw sections at the same conditions utilizing SPSS program by deducting the deterioration values of the raw section from the values for RAP section [11]. The t-test sign provides thoughts on variance between the long-term performance of raw and RAP when used in asphalt overlay. Thus, if the t-value has a negative sign for a certain distress, hence the performance of RAP section is better than raw section [20]. T-test can be calculated through the following equations [20]:

$$T = \text{Mean diff.}/SE \qquad (1)$$

$$\text{SE}= \frac{Sd}{\sqrt{n}} \qquad (2)$$

Where: Mean diff. is the mean of difference between RAP and virgin sections, SE is the standard error of the mean difference, Sd is the standard deviation and n is the number of sections using RAP and virgin mixtures together.

Using t value and degree of freedom (df = n-1), the P-value can be determine as a significance index (α) for the difference between RAP and raw sections performances. Traditionally, the cut-off value to reject the null hypothesis (α) is 0.05, when no significant difference exists. Thus, the difference between RAP and raw sections becomes significant when ($\alpha<0.05$) [12].

The third analytical method used is analysis of variance (ANOVA) which provides a statistical procedure interested with comparing means of many samples [21,22]. This method was potential because the measurements at each site were completed on the same date for all elected sections. Furthermore, all sections in each location own the same characteristics such as (pavement layers properties, traffic volumes, and climate features). Thus, the pavement behavior allocation with the passage of time was considered a reduplicated measure, and the directions assorted by design features, were construed together for each location at a time. The outputs from the ANOVA tests for each location were collected. If no statistical variation was provided, the behavior was considered tantamount between the RAP and raw mixtures.

3 Results and Discussion

3.1 Fatigue cracking

The first deterioration group studied in this research is fatigue cracking which is measured in crack area by (m^2). To study the fatigue cracking development in asphaltic overlay at the long term in wet/not freeze climate, two sites were considered (Alabama and Maryland). For dry/not freeze climate, two sites were considered (Arizona and New Mexico). Figs.1 & 2 show the fatigue cracking developments for two sites representing wet climate. Each Figure illustrates 4 diagrams containing 8 pavement sections code (ID) from LTPP as defined in Table 2. These four diagrams are representing two overlay thicknesses (51 and 127 mm) and two pre-overlay handling methods (No/low grinding and heavy grinding). Each diagram clarifies two materials types used in construction of asphalt overlay mixtures (completely raw and mixed with 30% RAP).

Generally, it can be concluded that with increasing service life of the constructed asphalt overlay, the fatigue cracking development increases pointedly and severely in Alabama especially at terminal observed periods. Moreover, at first, the RAP and raw sections provide fatigue cracking development at the same rate, but in a long-term RAP sections show higher fatigue cracking. Moreover, the difference in fatigue development between RAP and raw sections is rather small at thick overlay thickness (127mm) while this difference becomes larger at thin overlay thickness (51mm). Thus, it can be said that using 30% RAP gives better long-term performance of asphalt overlay according to fatigue cracks development. For second SPS-5 site in wet climate (Maryland), it can be observed that the fatigue performance of RAP and raw sections are almost identical at many points. It is striking that RAP sections show lower fatigue cracking at many points confirming its long-term effectiveness as compared with virgin materials. The pre-overlay curing cases (No/low grinding and heavy grinding) don't have any obvious effect on fatigue development in a long run.

Fig. 3. illustrates the fatigue cracking for two sites representing dry climate. It can be observed that the RAP sections show fatigue cracking development higher than raw sections at the last years of observation in most sections in Arizona

site. The RAP section 509 appears a sudden increased deterioration at the last years of observation as compared with raw section 506. Better result for RAP sections is achieved in New Mexico site (Fig. 4) where they provide fatigue performance identical or even better than virgin materials in long term.

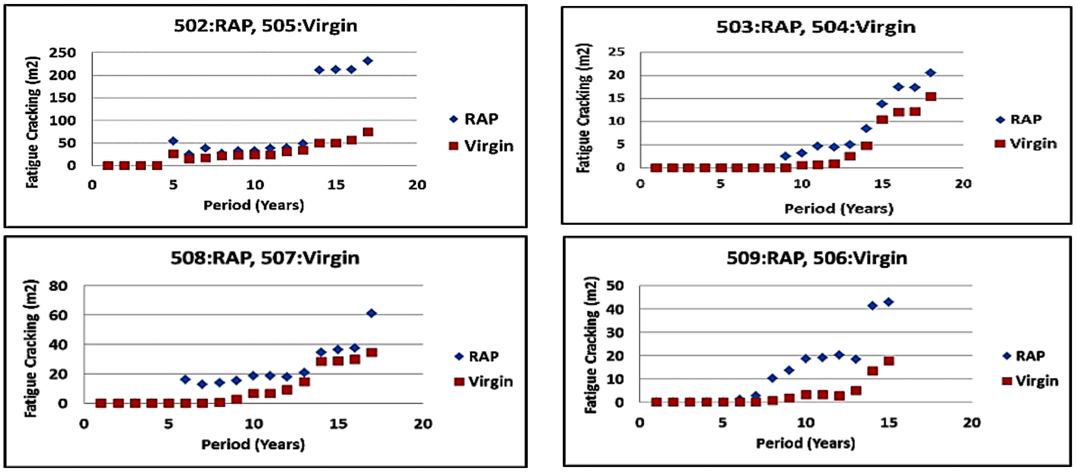


Fig. 1. Fatigue cracking progress in Alabama (wet climate).

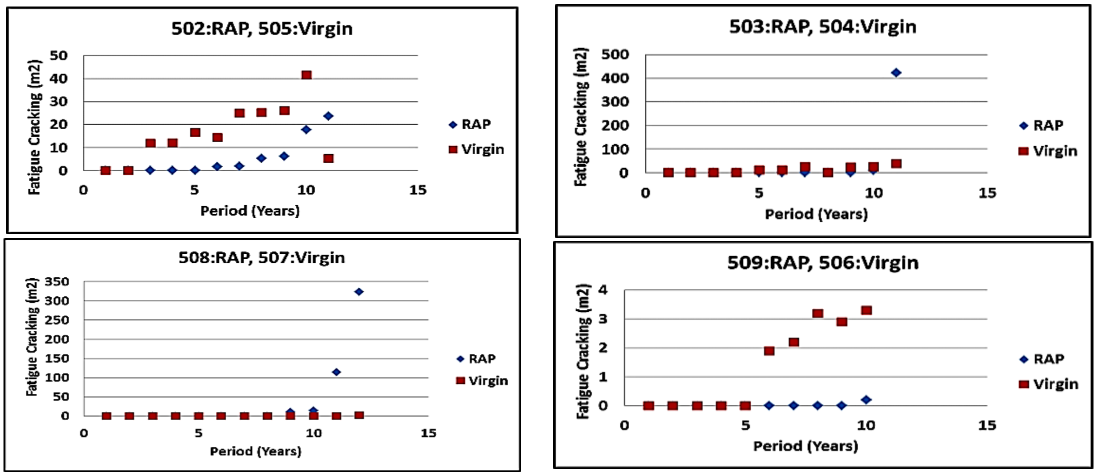


Fig. 2. Fatigue cracking progress in Maryland (wet climate).

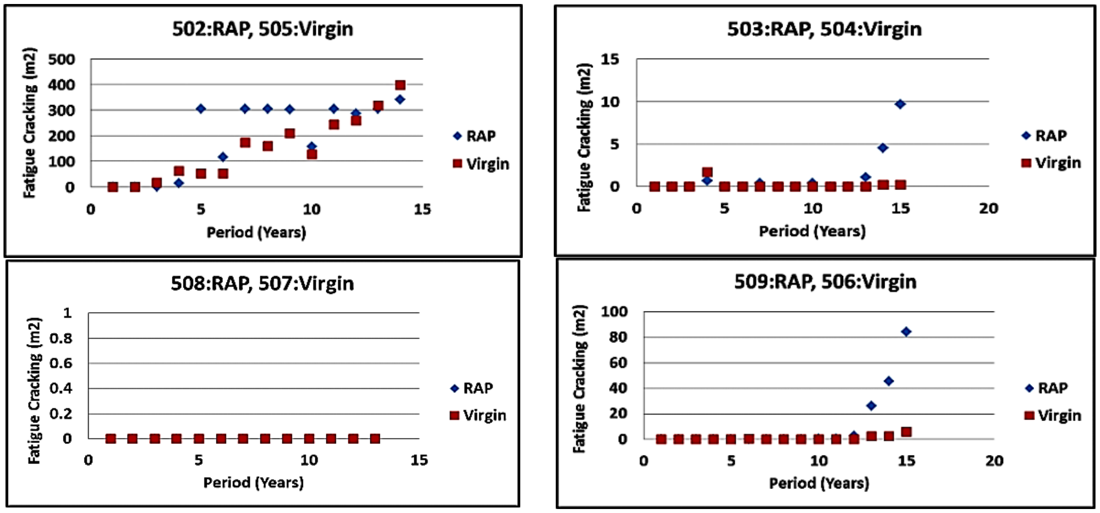


Fig. 3. Fatigue cracking progress in Arizona (dry climate).

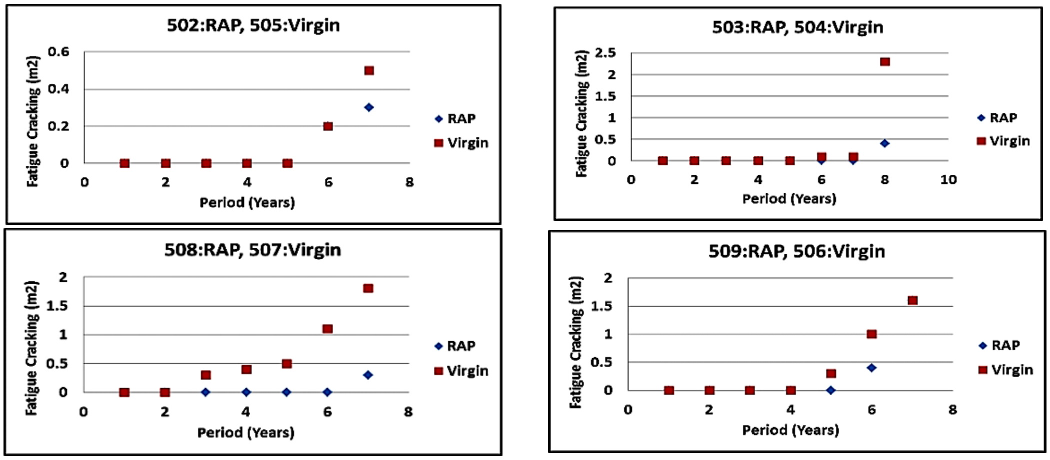


Fig. 4. Fatigue cracking progress in New Mexico (dry climate).

Generally thicker overlay provides better results for RAP sections. The surface grinding before rehabilitation doesn't appear any noticeable difference in fatigue cracking. Most RAP sections perform worse than/identical with raw sections according to fatigue cracking development in long term performance in wet and dry climate especially at terminal observed periods. Table 3 illustrates the t-tests and the P-values for fatigue cracking development. As shown in Table 3, for wet climate, mostly raw sections perform significantly better than RAP sections in Alabama. For thinner overlay thickness (51mm) in Maryland site, RAP sections perform significantly better than raw sections. While for thicker overlay thickness (127mm) in Maryland, raw sections perform insignificantly better than RAP sections. For dry climate, using RAP improves the performance insignificantly in New Mexico, while raw sections provide better performance insignificantly in Arizona. Generally, it can be observed that RAP sections statistically achieve better insignificant performance in dry climate while they obtain worse significant performance in wet climate.

Fig. 3 illustrates the fatigue cracking for two sites representing dry climate. It can be observed that the RAP sections show fatigue cracking development higher than raw sections at the last years of observation in most sections in Arizona site. The RAP section 509 appears a sudden increased deterioration at the last years of observation as compared with raw section 506. Better result for RAP sections is achieved in New Mexico site (Fig. 4) where they provide fatigue performance identical or even better than virgin materials in long term.

Table 3: Paired t-tests and p-values for Fatigue Cracking Development.

Climate	Site	Sections	Mean diff. (m^2)	Sd	SE	t-value	df	p-value (α=0.05)	Significance	Better Perf.
Wet climate	Alabama	502-505	44.68	65.898	15.98	2.796	16	0.013	Sign.	Raw
		503-504	2.12	2.12	0.499	4.241	17	0.001	Sign.	Raw
		508-507	8.36	7.24	1.76	4.757	16	0	Sign.	Raw
		509-506	9.39	9.69	2.501	3.753	14	0.0002	Sign.	Raw
	Maryland	502-505	-11.07	12.74	3.84	-2.88	10	0.016	Sign.	RAP
		503-504	26.89	118.95	35.87	0.75	10	0.471	Insign.	Raw

		508-507	38.28	94.61	27.31	1.402	11	0.189	Insign.	Raw
		509-506	-1.33	1.45	0.46	-2.89	9	0.018	Sign.	RAP
dry climate	**Arizona**	502-505	47.88	85.06	22.73	2.106	13	0.055	Insign.	Raw
		503-504	0.98	2.63	0.679	1.443	14	0.171	Insign.	Raw
		508-507	-0.9	3.49	0.9	-1	14	0.334	Insign.	RAP
		509-506	9.97	22.58	5.829	1.71	14	0.109	Insign.	Raw
	New Mexico	502-505	-0.029	0.0756	0.029	-1	6	0.356	Insign.	RAP
		503-504	-0.26	0.663	0.234	-1.12	7	0.3	Insign.	RAP
		508-507	-0.54	0.562	0.213	-2.55	6	0.043	Sign.	RAP
		509-506	-0.13	0.236	0.089	-1.44	6	0.2	Insign.	RAP

3.2 Longitudinal Cracking

Figs. 5 and 6 illustrate the longitudinal cracking performance of the four SPS-5 pavement sections in Alabama and Maryland respectively representing wet climate. It's clarified that RAP sections give similar or better performance for longitudinal cracking than raw sections in long run especially in two sections (502 in Alabama and 509 in Maryland). The thicker overlay thickness (127mm) provides better results where it shows more rapprochements between RAP and raw sections in favor of RAP sections. Figs. 7 and 8 clarify the longitudinal cracking progress in Arizona and New Mexico respectively representing dry climate. It can be observed that in dry climate, RAP sections perform worse than raw sections such as sections 503 and 508 in Arizona and 509 in New Mexico. Thus, it can be concluded that unlike fatigue cracking, thinner overlay thickness may provide better long-term performance for RAP sections against longitudinal cracking development as shown in section 502 in Arizona. The surface curing before rehabilitation hasn't any obvious effect in longitudinal cracking. Generally, most RAP sections provide better or convergent performance in wet climate and worse performance in dry climate according to longitudinal cracking development. From the statistical analysis shown in Table 4, it can be observed that mostly RAP sections perform significantly worse than raw sections for both wet and dry climates.

Table 4: Paired t-tests and p-values for Longitudinal Cracking Development.

Climate	**Site**	**Sections**	**Mean diff. (m)**	**Sd**	**SE**	**t-value**	**df**	**p-value (α=0.05)**	**Signifi-cance**	**Better Perf.**
Wet climate	**Alabama**	502-505	-4.485	8.709	1.947	-2.3	19	0.033	Sign.	RAP
		503-504	19.9	20.051	4.726	4.21	17	0.001	Sign.	Raw
		508-507	17.05	26.981	6.36	2.68	17	0.016	Sign.	Raw
		509-506	23.256	33.103	8.276	2.81	15	0.013	Sign.	Raw
	Maryland	502-505	86.807	56.76	15.17	5.722	13	0	Sign.	Raw
		503-504	72.907	57.32	15.32	4.759	13	0	Sign.	Raw
		508-507	40.58	58.57	18.52	2.191	9	0.056	Insign.	Raw
		509-506	-130.6	86.85	26.185	-4.99	10	0.001	Sign.	RAP
dry climate	**Arizona**	502-505	-33.27	23.463	7.074	-4.7	10	0.001	Sign.	RAP
		503-504	18.425	40.387	10.097	1.825	15	0.088	Insign.	Raw

		508-507	76.938	70.31	17.577	4.377	15	0.001	Sign.	Raw
		509-506	18.979	24.065	6.432	2.951	13	0.011	Sign.	Raw
	New Mexico	502-505	40.77	32.509	9.384	4.344	11	0.001	Sign.	Raw
		503-504	99.083	76.846	22.184	4.467	11	0.001	Sign.	Raw
		508-507	107.88	108.732	36.244	2.976	8	0.018	Sign.	Raw
		509-506	83.63	55.598	17.582	4.757	9	0.001	Sign.	Raw

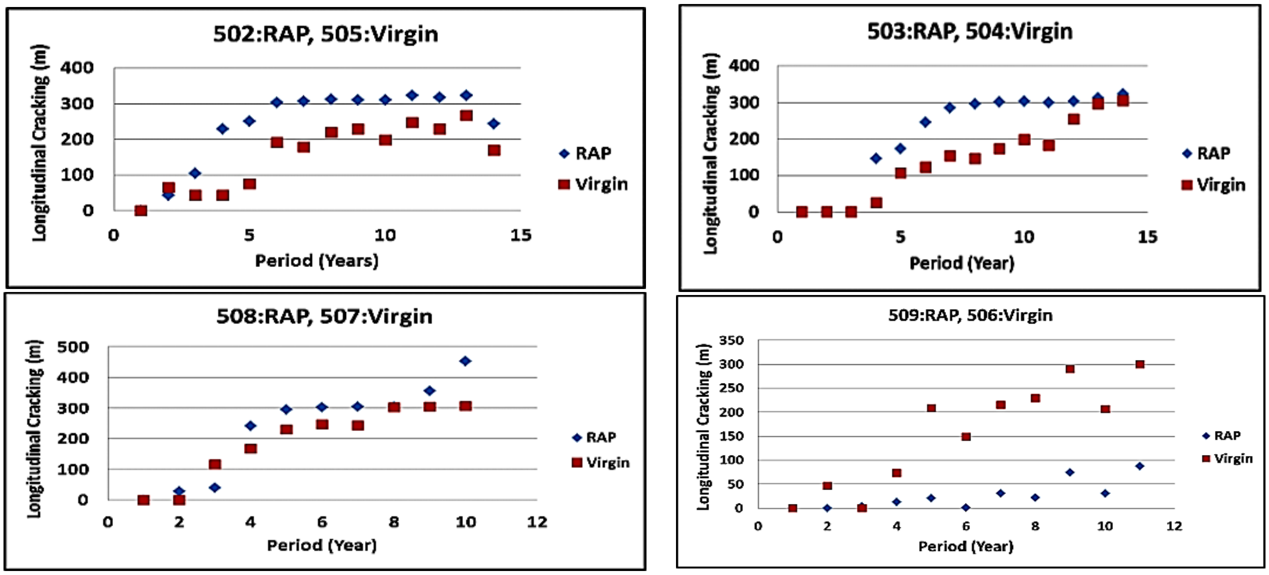


Fig. 5: Longitudinal cracking development in Alabama (wet climate).

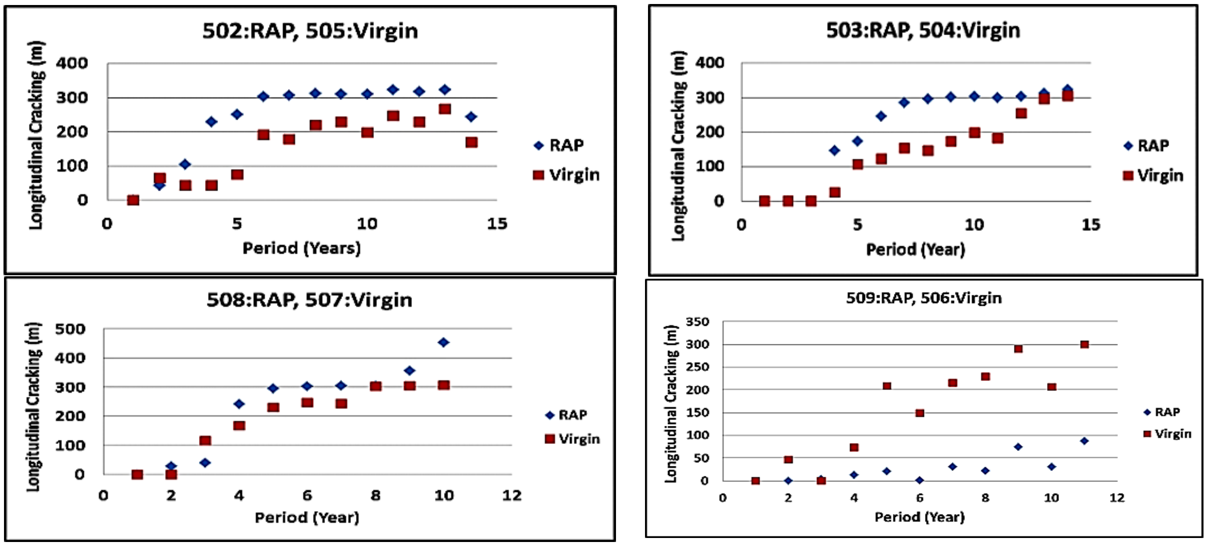


Fig. 6. Longitudinal cracking development in Maryland (wet climate).

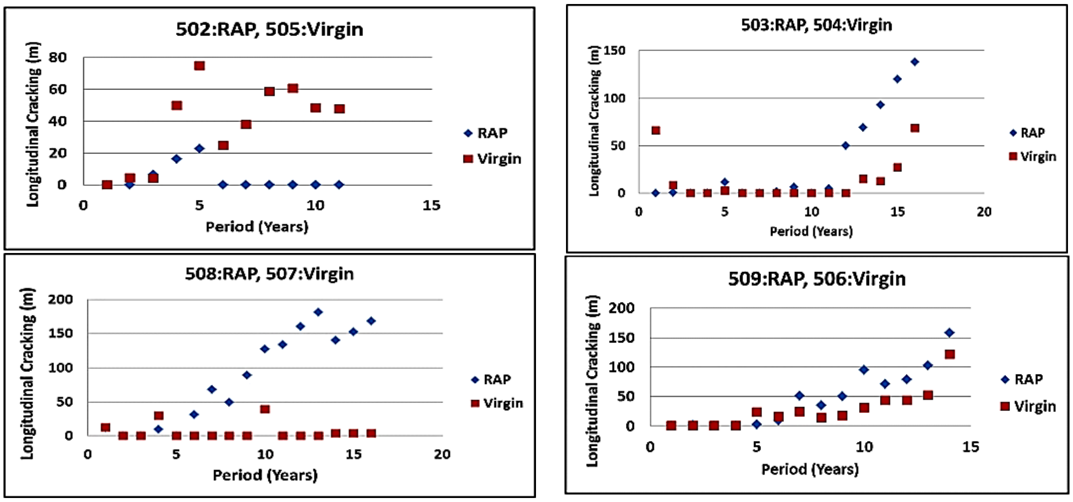


Fig. 7. Longitudinal cracking development in Arizona (dry climate).

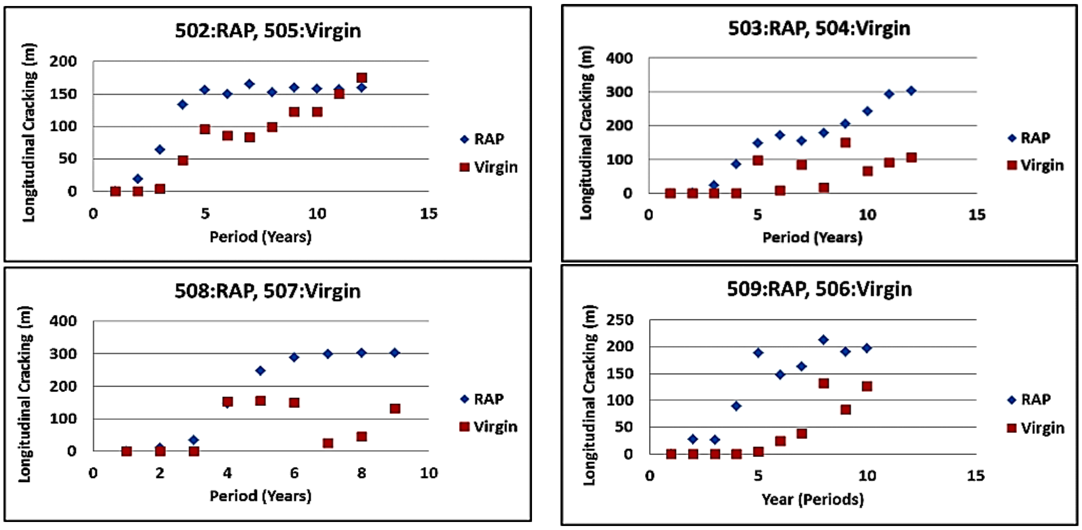


Fig. 8. Longitudinal cracking development in New Mexico (dry climate).

3.3 Transverse cracking

Figs. 9 and 10 show the overlay performance against transverse cracking in Alabama and Maryland respectively representing wet climate. In Alabama sections, initially the RAP and raw sections provide transverse cracking development at the same rate, but in a long term, RAP sections 503 and 509 show extremely higher transverse cracking. RAP sections 502 and 508 in Alabama and Maryland show convergent values with raw sections. RAP section 509 in Maryland provides better performance, where its transverse cracking values are obviously lower than raw sections. For dry climate, the transverse cracking is illustrated in Figs. 11 and 12 for Arizona and New Mexico respectively. In most sections, using RAP provides extremely higher transverse cracking. RAP sections 502 in Arizona and RAP sections 502 and 509 in New Mexico provide convergent values with raw sections. Generally, RAP sections perform worse than or convergent with raw sections according to transverse cracking progress in long term performance in both wet and dry climate. The overlay thickness and pre-overlay curing haven't any obvious effect on transverse cracking development in both wet and dry climate. From the statistical analysis shown in Table 5, it can be shown for wet climate that the RAP sections perform significantly worse than raw sections in Alabama while in Maryland site, the RAP sections show worse performance for thicker sections (127mm) and better performance for thinner sections (51mm). For dry climate, mostly RAP sections perform significantly worse than raw sections against the transvers cracks progress.

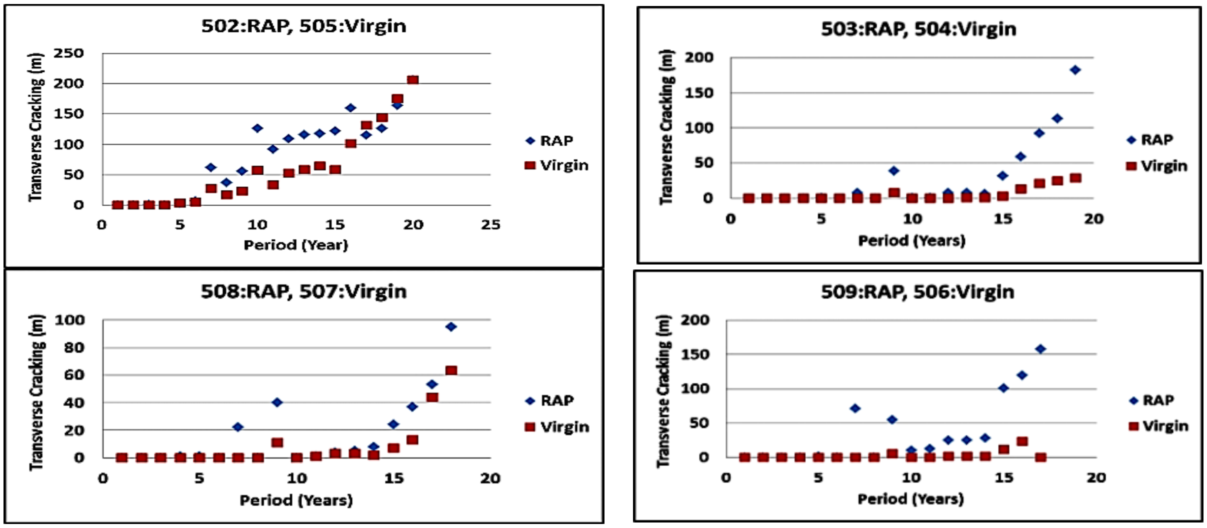


Fig. 9. Transverse cracking progress in Alabama (wet climate).

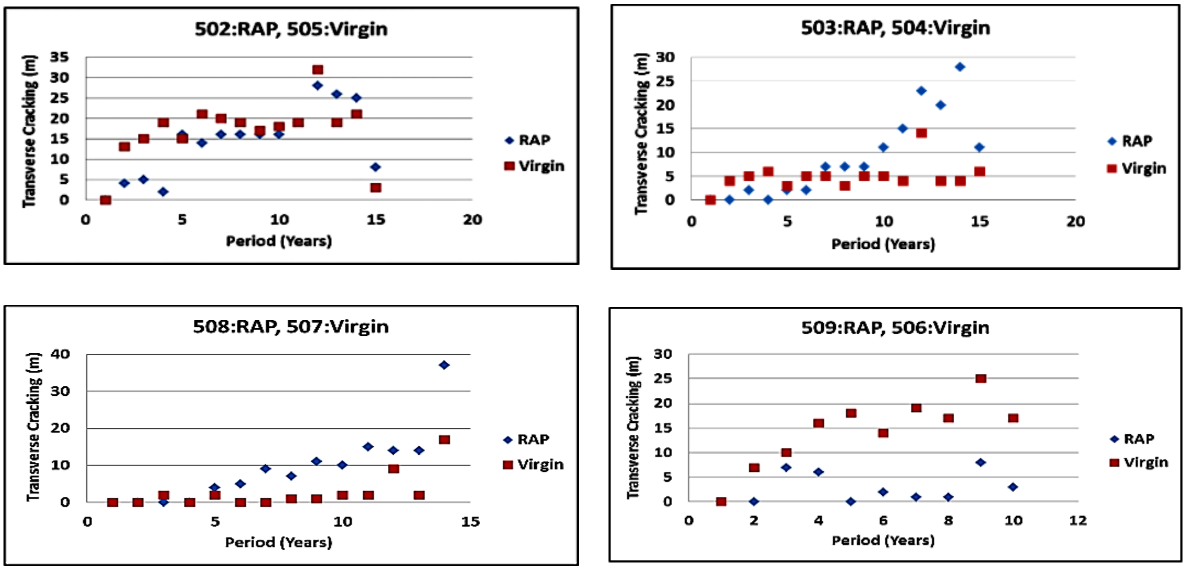
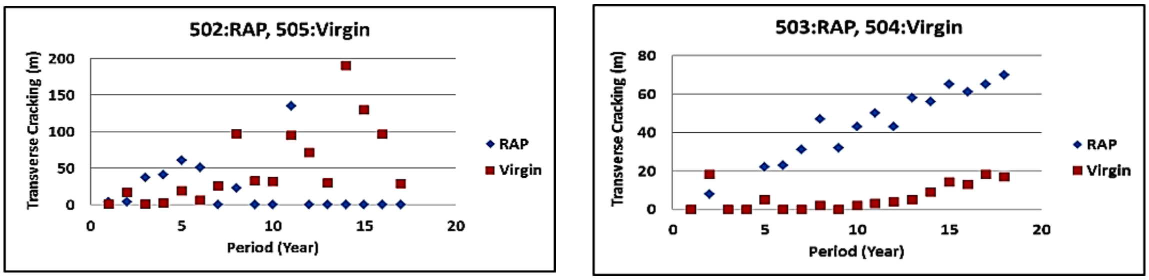


Fig. 10: Transverse cracking progress in Maryland (wet climate).



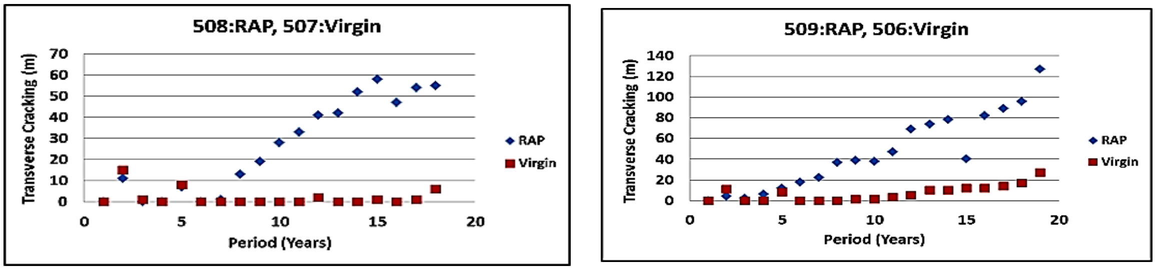


Fig. 11. Transverse cracking progress in Arizona (dry climate).

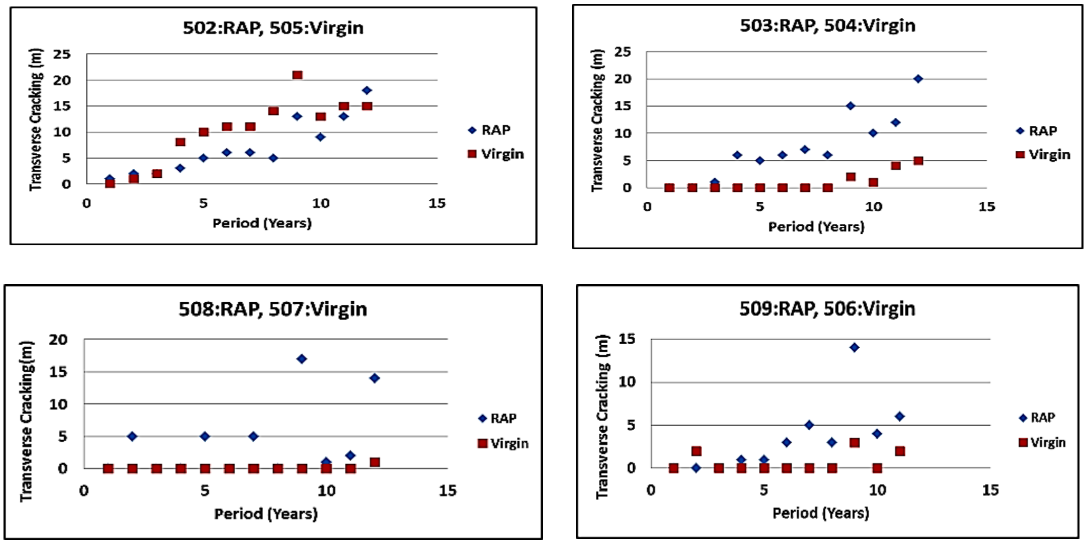


Fig. 12. Transverse cracking progress in New Mexico (dry climate).

Table 5: Paired t-tests and p-values for Transverse Cracking Development.

Climate	Site	Sections	Mean diff. (m)	Sd	SE	t-value	df	p-value (α=0.05)	Significance	Better Perfor.
Wet climate	Alabama	502-505	23.25	30.74	6.87	3.382	19	0.003	Sign.	Raw
		503-504	23.63	40.62	9.32	2.536	18	0.021	Sign.	Raw
		508-507	8	11.34	2.67	2.993	17	0.008	Sign.	Raw
		509-506	32.94	45.49	11.03	2.986	16	0.009	Sign.	Raw
	Maryland	502-505	-2.67	6.26	1.62	-1.65	14	0.121	Insign.	RAP
		503-504	4.13	8.17	2.11	1.96	14	0.07	Insign.	Raw
		508-507	6.29	6.19	1.66	3.797	13	0.002	Sign.	Raw
		509-506	-11.5	6.399	2.02	-5.68	9	0	Sign.	RAP
dry climate	Arizona	502-505	-30.53	66.05	16.02	-1.91	16	0.075	Insign.	RAP
		503-504	31.33	21.15	4.98	6.284	17	0	Sign.	Raw
		508-507	23.72	22.94	5.41	4.386	17	0	Sign.	Raw
		509-506	39.42	31.51	7.23	5.453	18	0	Sign.	Raw
	New Mexico	502-505	-3.17	3.76	1.09	-2.92	11	0.014	Sign.	RAP
		503-504	6.33	4.68	1.35	4.69	11	0.001	Sign.	Raw
		508-507	4	5.61	1.62	2.471	11	0.031	Sign.	Raw

		509-506	2.73	3.47	1.05	2.609	10	0.026	Sign.	Raw

3.4 Rutting

Figs. 13 and 14 clarify the overlay rutting performance in Alabama and Maryland respectively representing wet climate. It can be concluded that the pre-overlay curing has an obvious effect on the performance against rutting where the heavy surface grinding before rehabilitation provides worse performance for RAP sections except section 508 in Maryland. For no/low pre-overlay curing, RAP sections provide rutting values convergent with raw sections. For dry climate sections in Arizona and New Mexico, Fig. 15 shows that using RAP in overlay mixtures provides lower performance for all sections in Arizona except section 508. While Fig. 16 illustrates that using RAP in overlay mixtures shows better/close performance as compared with raw sections for all sections in New Mexico. Generally, it can be observed that the heavy surface grinding before rehabilitation has a clear impact in reducing the long-term performance of RAP sections against rutting in wet climate. While in dry climate, the pre-overlay curing hasn't any clear impact on the performance where RAP sections provide slight worse performance in Arizona and convergent (slight better) performance in New Mexico. Moreover, the overlay thickness hasn't obvious effect on rutting development in both wet and dry climate.

Table 6 illustrates the statistical analysis of the rutting development that emphasizes the previous observations. For wet climate, heavy surface grinding before rehabilitation shows that the performance of RAP sections against rutting is significantly worse than raw sections except section 508 in Maryland. While no/low pre-overlay curing provides convergent/ better performance for RAP sections. For dry climate in Arizona, most RAP sections perform significantly worse than raw sections except section 508, while in New Mexico site, most p-values are greater than 0.05, thus there is no significant difference in rutting performance between RAP and raw overlay sections.

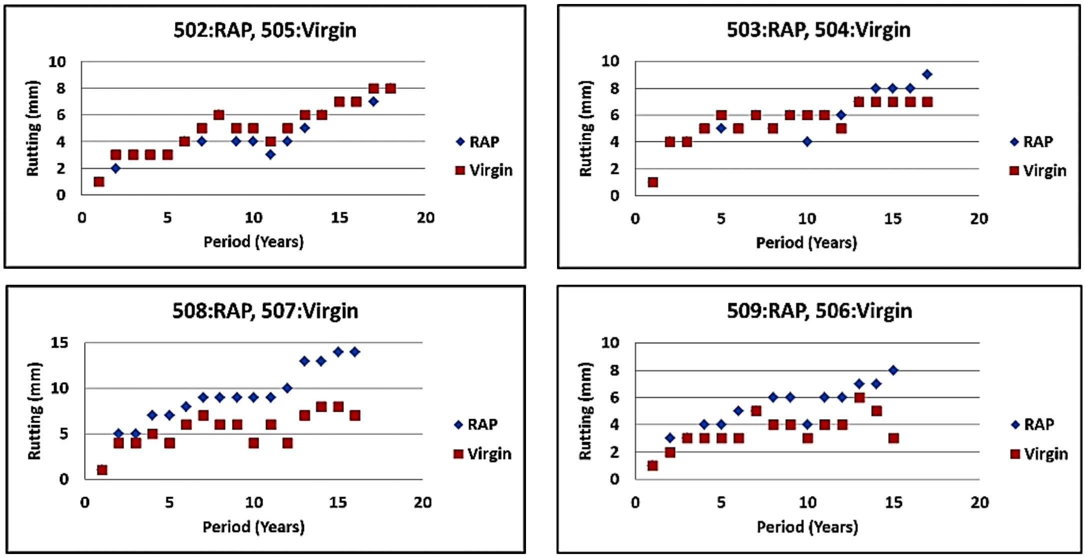


Fig. 13. Rutting development in Alabama (wet climate).

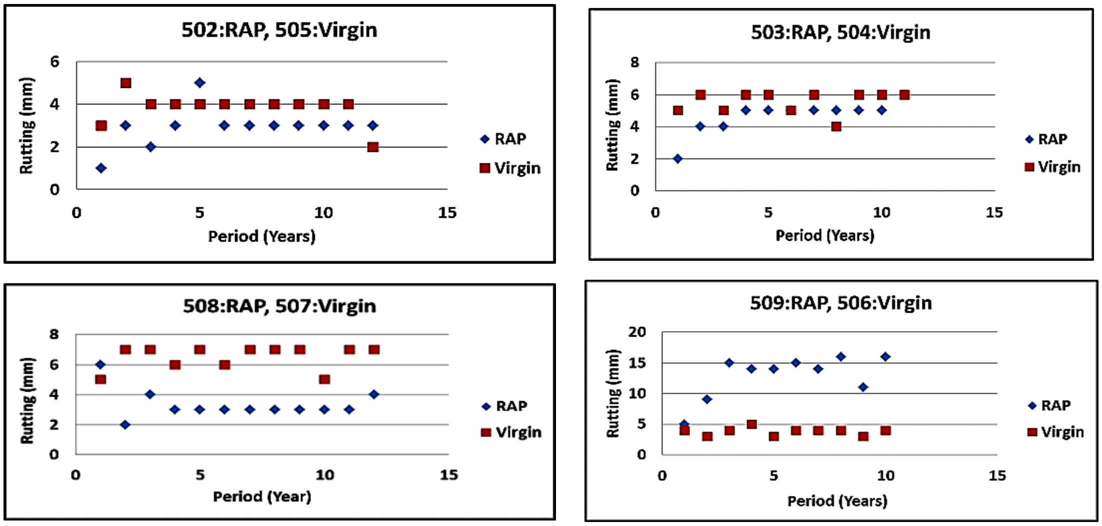


Fig. 14. Rutting development in Maryland (wet climate).

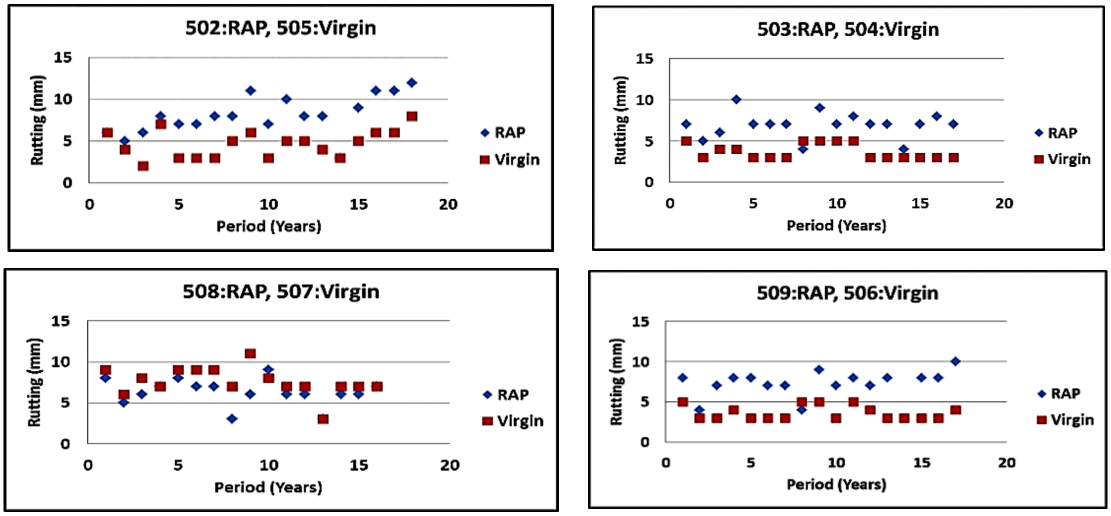


Fig. 15. Rutting development in Arizona (dry climate).

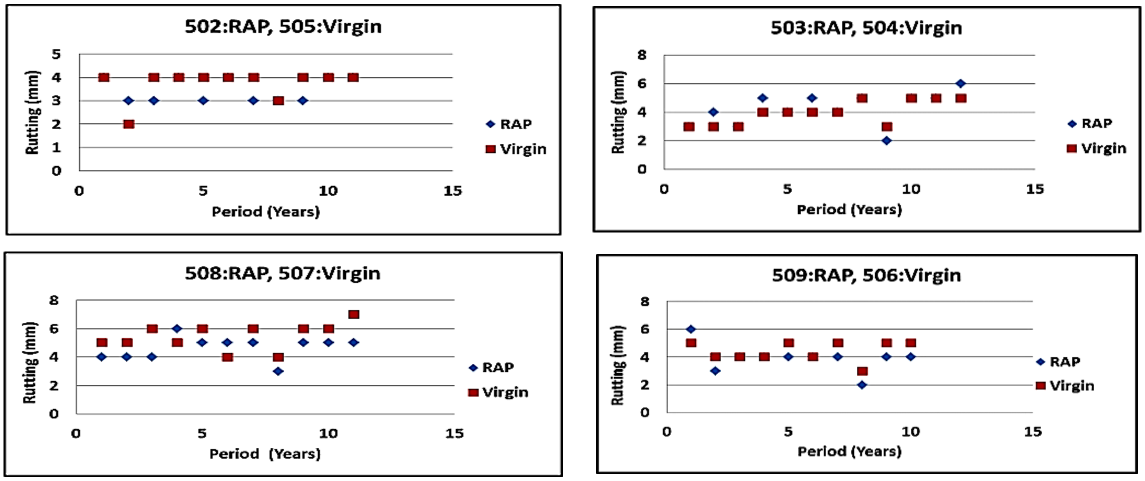


Fig. 16. Rutting development in New Mexico (dry climate).

Table 6: Paired t-Tests and p-values for Rutting Development.

Climate	Site	Sections	Mean diff. (cm)	Sd	SE	t-value	df	p-value (α=0.05)	Signifi-cance	Better Perf.
Wet climate	Alabama	502-505	-0.444	0.5113	0.1205	-3.69	17	0.002	Sign.	RAP
		503-504	0.1765	0.8828	0.2141	0.824	16	0.422	Insign.	Raw
		508-507	3.4375	2.128	0.5320	6.461	15	0.000	Sign.	Raw
		509-506	1.4667	1.246	0.3217	4.559	14	0.000	Sign.	Raw
	Maryland	502-505	-0.917	0.996	0.288	-3.19	11	0.009	Sign.	RAP
		503-504	-0.91	1.04	0.315	-2.89	10	0.016	Sign.	RAP
		508-507	-3.17	1.528	0.441	-7.18	11	0.000	Sign.	RAP
		509-506	9.100	3.414	1.08	8.43	9	0.000	Sign.	Raw
dry climate	Arizona	502-505	3.389	1.7197	0.405	8.360	17	0.000	Sign.	Raw
		503-504	3.176	1.667	0.404	7.856	16	0.000	Sign.	Raw
		508-507	-1.313	1.493	0.373	-3.52	15	0.003	Sign.	RAP
		509-506	3.471	1.875	0.455	7.633	16	0.000	Sign.	Raw
	New Mexico	502-505	-0.273	0.647	0.195	-1.399	10	0.192	Insign.	RAP
		503-504	0.250	0.622	0.179	1.393	11	0.191	Insign.	Raw
		508-507	-0.818	0.982	0.296	-2.764	10	0.020	Sign.	RAP
		509-506	-0.500	0.707	0.224	-2.236	9	0.052	Insign.	RAP

3.5 Roughness

From the most important pavement performance indicator is the roughness which influences both passenger relief and car running effort and thus energy exhaustion. Moreover, roughness is usually utilized in life cycle assessment of pavements. The international roughness index (IRI) is generally used to express roughness of pavement. IRI of 1.5 m/km is considered as the roughness starting [16, 23]. The roughness development in Alabama and Maryland (as wet climate) is as shown in Figs. 17 and 18 respectively. It can be observed that, the development in roughness over the following years for both RAP and raw sections is unnoticeable such as sections 503 and 504 in Maryland, or increases at a slow rate such as sections 502 and 505 in Alabama. On the contrary, in dry climate that illustrated in Figs. 19 and 20, the roughness develops faster yearly for both RAP and raw sections where the difference between them is larger than obtained in wet climate sections. This of course confirms the bad effect of dry climate on roughness progress in long term. The RAP performance is generally wobbly in both wet and dry climate where it can be observed that, mostly low pre-overlay curing provides a converging/better RAP performance against roughness in wet climate and a converging/worse RAP performance in dry climate. Thicker overlay thickness (127 mm) may contribute to more affinity between RAP and raw sections in both wet and dry climate. On the other hand, the pre-overlay curing hasn't any obvious effect on roughness development in long run for both RAP and raw sections. From Table 7 that illustrates the statistical analysis for roughness development, it can be shown that, for wet climate, most RAP sections provide worse long-term performance against roughness in Alabama except section 502, and provides better performance in Maryland except section 509. For dry climate, most RAP sections provide insignificant better or significant worse performance except section 508.

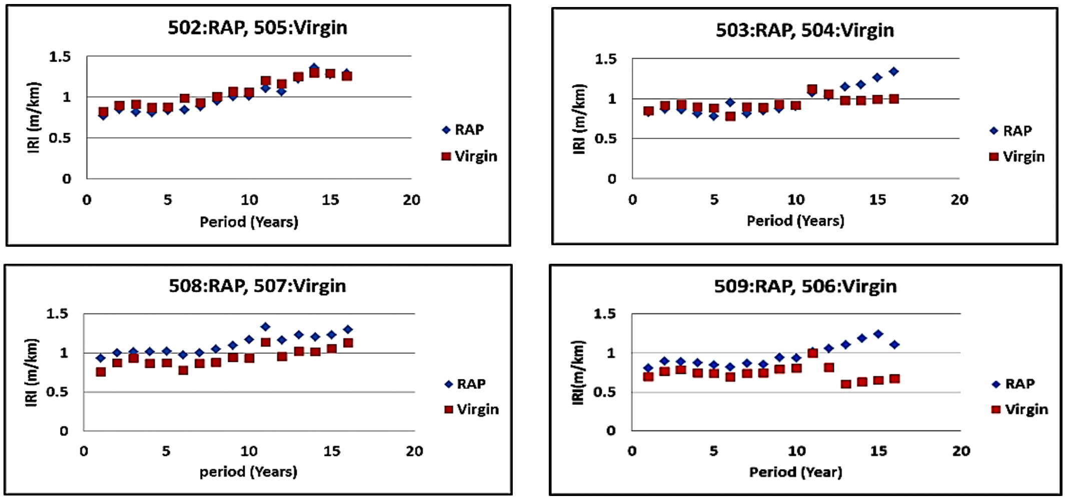


Fig. 17. Roughness progress in Alabama (wet climate).

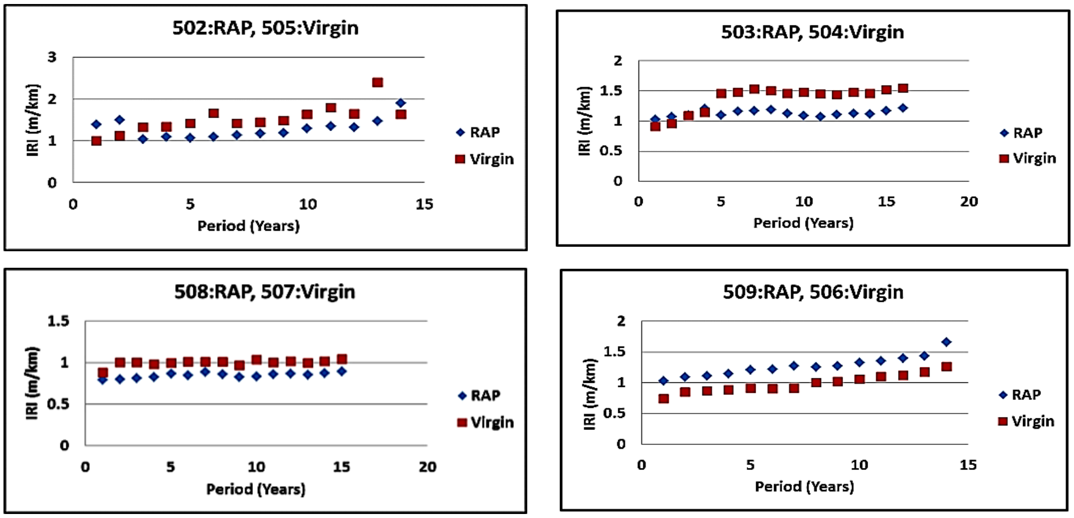
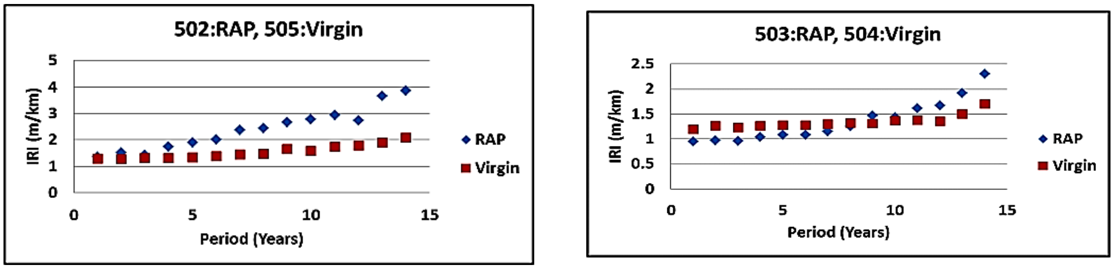


Fig. 18: Roughness progress in Maryland (wet climate).



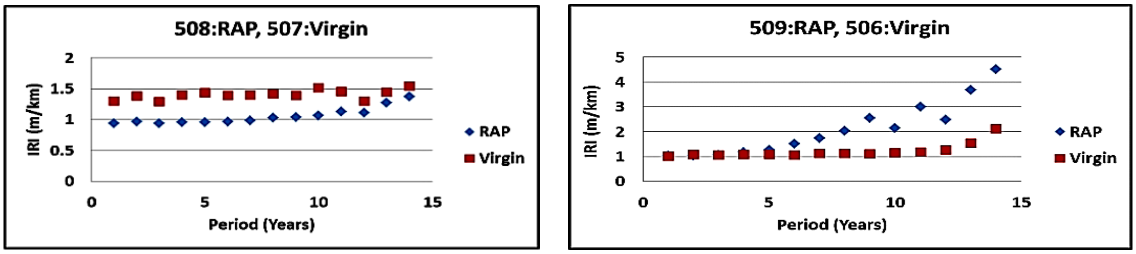


Fig. 19. Roughness progress in Arizona (dry climate).

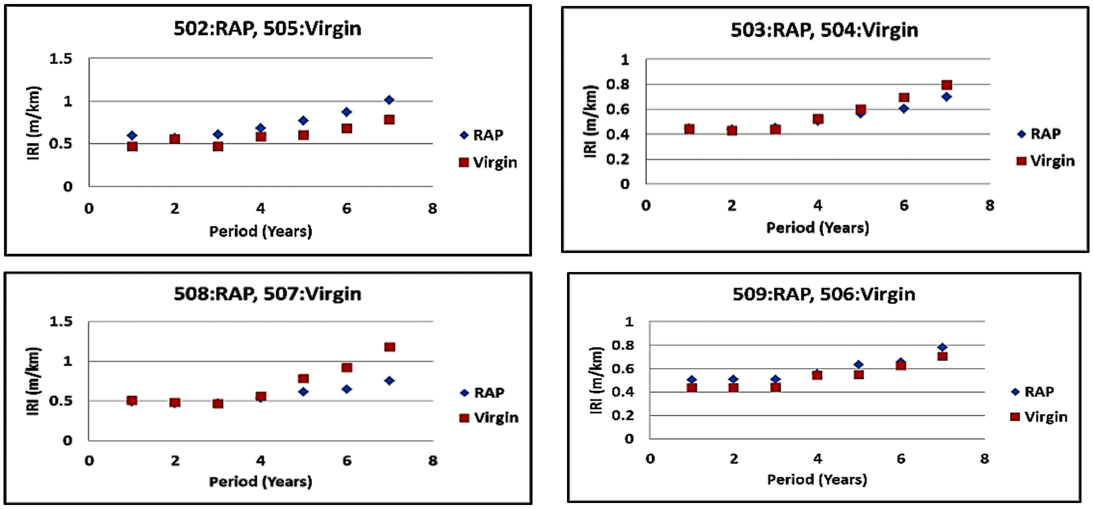


Fig. 20. Roughness progress in New Mexico (dry climate).

Table 7: Paired t-Tests and p-values for Roughness Development.

Climate	Site	Sections	Mean diff. (m)	Sd	SE	t-value	df	p-value (α=0.05)	Signifi-cance	Better Perfor.
Wet climate	Alabama	502-505	-0.048	0.0494	0.0123	-3.901	15	0.001	Sign.	RAP
		503-504	0.0353	0.1419	0.0355	0.996	15	0.335	Insign.	Raw
		508-507	0.1704	0.0386	0.0096	17.683	15	0	Sign.	Raw
		509-506	0.2232	0.186	0.0465	4.799	15	0	Sign.	Raw
	Maryland	502-505	-0.234	0.3603	0.0963	-2.429	13	0.03	Sign.	RAP
		503-504	-0.239	0.1918	0.0479	-4.988	15	0	Sign.	RAP
		508-507	-0.151	0.0301	0.0078	-19.48	14	0	Sign.	RAP
		509-506	0.285	0.0456	0.0122	23.4	13	0	Sign.	Raw
dry climate	Arizona	502-505	0.8434	0.5394	0.1442	5.85	13	0	Sign.	Raw
		503-504	0.0119	0.2903	0.0776	0.154	13	0.88	Insign.	Raw
		508-507	-0.351	0.1057	0.0283	-12.43	13	0	Sign.	RAP
		509-506	0.8706	0.8296	0.2217	3.927	13	0.002	Sign.	Raw
	New Mexico	502-505	0.1387	0.0674	0.0255	5.443	6	0.002	Sign.	Raw
		503-504	-0.029	0.0444	0.0168	-1.738	6	0.133	Insign.	RAP
		508-507	-0.132	0.1643	0.0621	-2.123	6	0.078	Insign.	RAP

		509-506	0.0591	0.0268	0.0101	5.836	6	0.001	Sign.	Raw

4. ANOVA Analysis

ANOVA model was used in this study to measure the magnitude of the variation between sections using mixtures containing 30% RAP and sections using raw materials. Utilizing means of values in ANOVA provides more emphasis to the impact of each variable separately such as overlay thickness, pre-overlay preparation and climate. By using SPSS program, this test can be carried out to produce the means of each distress values as shown in Table 8. RAP mixtures provide worse performance for all indicators in varying proportions according to ANOVA test. The increase ratios in each distress due to using RAP as compared to raw materials that shown in Fig. 21 illustrate that the best RAP performance is achieved in roughness followed by rutting, longitudinal, fatigue and transverse cracking respectively.

Table 8: ANOVA Results Under all Variables.

Distress mean	**RAP**	**Raw**
Fatigue cracking (m^2)	24.8	13.9
Longitudinal cracking (m)	100.8	67.2
Transverse cracking (m)	21.8	11.9
Rutting (mm)	5.7	4.7
Roughness IRI (m/km)	1.1	1.0

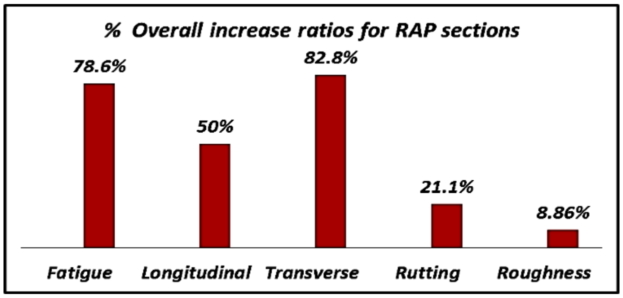


Fig. 21. Overall increase ratios for RAP sections according to ANOVA test.

The effect of climate on each mean distress increase ratios for RAP sections shown in Fig. 22 illustrates that the RAP performance in wet and dry climates is approximately the same for both rutting and roughness. Adding RAP achieves significant better performance against fatigue cracking in dry climate and significant worse performance for longitudinal cracking according to ANOVA test. Figs. 23 and 24 show the impact of overlay thickness and pre-overlay curing respectively. It can be concluded that the RAP sections provide better performance at thinner overlay thickness (51mm) as well as at no/low pre-overlay curing for all distresses. Worse RAP performance is achieved at thicker thickness (127mm) and heavy pre-overlay curing at fatigue and transverse cracking only. According to the three studied variables, it is clear that the variation in pre-overlay curing (from low to heavy) followed by overlay thickness variation (from 51 to 127mm) have the highest statistical effect on fatigue and transverse cracking increasing. While the variation in climate from wet to dry has a significant statistical effect on reducing fatigue cracking and increasing longitudinal cracking. The Rutting and roughness progresses aren't clearly affected by variation in climate, thickness or curing.

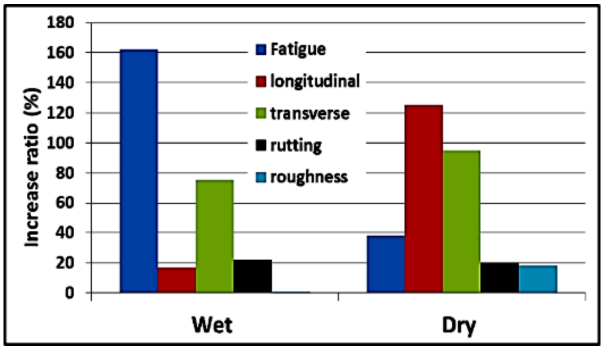


Fig. 22. Climate effect on the increase ratios of RAP sections for each distress according to ANOVA test.

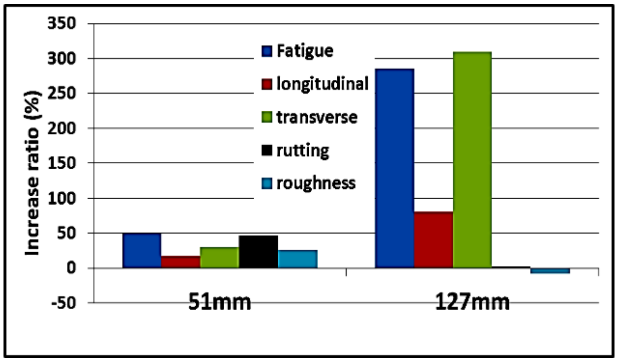


Fig. 23. Overlay thickness effect on the increase ratios of RAP sections for each distress according to ANOVA test.

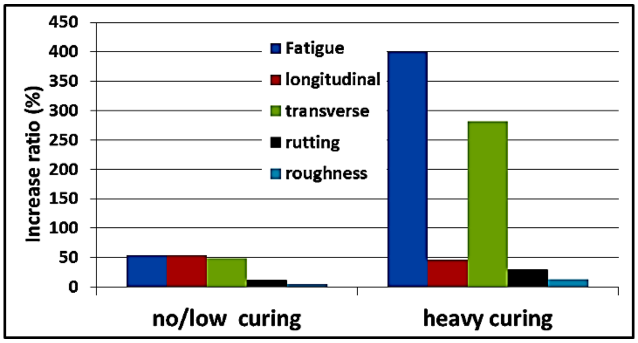


Fig. 24. Pre-overlay curing effect on the increase ratios of RAP sections for each distress according to ANOVA test.

5. Conclusions

In this study, the performance of asphalt overlay including 30% RAP was compared with overlay constructed using raw materials only in long run using LTPP database. Two overlay thicknesses (thin: 51mm and thick: 127mm), two surface curing methods before rehabilitation (no/low and heavy grinding) and two climates (wet and dry/not freeze representing the Egyptian climate) were investigated. The statistical analysis using the paired t-tests, p-values and ANOVA analysis were achieved to determine the priority in performance and the significance in variation. The main conclusions are shown as following:

1. Overlay material types had an obvious effect on the performance of flexible pavement. According to fatigue cracking progress, most RAP sections performed worse than or identical with raw sections in both wet and dry

climates especially at terminal observed periods. For longitudinal cracking, most RAP sections improved the performance of asphalt overlay as compared with raw sections in wet climate, but performed worse than raw sections in dry climate. Considering transverse cracking development, most RAP sections achieved performance worse than or similar to raw sections in both wet and dry climate. According to rutting development, most RAP overlay sections constructed over a heavy grinded surface in wet climate provided higher rutting development in the long term while no/low pre-overlay curing achieved rutting values convergent with raw sections. For roughness development, most RAP and raw overlay sections in wet climate provided an unnoticeable or slightly increase development in long term, while in dry climate, the roughness developed faster for both RAP and raw sections where the difference between them was higher than shown in wet climate. This emphasizes the poor effect of dry climate on roughness progress in long run.

2. Thicker overlay (127mm) for RAP sections provided lower fatigue cracking progress as compared with thinner thickness (51mm). While thinner overlay (51mm) for RAP sections obtained better long-term performance for longitudinal cracking development. According to both transverse cracking and rutting, the overlay thickness didn't have any obvious effect in both wet and dry climate. For roughness development, thicker overlay thickness might contribute to more affinity between RAP and raw sections.

3. The surface grinding before rehabilitation didn't appear any noticeable difference in fatigue, longitudinal and transverse cracking development. According to rutting development in dry climate, the pre-overlay curing had a wobbling impact where they provided slight worse performance in Arizona and convergent (slight better) performance in New Mexico. Considering roughness development, most RAP sections constructed after no/low surface curing achieved converging/better performance in wet climate and a converging/worse performance in dry climate.

4. The second analytical method used in this study was a statistic method using the paired-sample t-test. Generally, RAP sections achieved better insignificant performance against fatigue cracking in dry climate while obtained worse significant performance in wet climate. For longitudinal cracking, it performed significantly worse than raw sections for both wet and dry climates. According to transverse cracking, mostly RAP sections performed significantly worse than raw sections according in dry climate. For rutting progress, the pre-overlay curing provided significant worse performance for most RAP sections in wet climate, while in dry climate, most RAP sections performed significantly worse than or convergent with raw sections. According to roughness development, most RAP sections provided insignificant better or significant worse performance in dry climate.

5. The third analytical method used in this study was ANOVA analysis. According to ANOVA results, RAP mixtures performed worse than raw mixtures especially for transverse, fatigue and longitudinal cracking respectively. The variation in pre-overlay curing (from low to heavy) had the highest statistical effect on fatigue and transverse cracking increasing, while rutting and roughness progresses weren't clearly affected by variation in climate, thickness or surface curing before rehabilitation. The variation in climate from wet to dry had a significant statistical effect on reducing fatigue cracking and increasing longitudinal cracking.

REFERENCES

1. Kang WL, Kathleen W, and Syed. Prediction of performance and evaluation of flexible pavement rehabilitation strategies. J Traffic Transp Eng. 2017;1:178-184.
2. Jan M, Lubos R, and Marian M. Asphalt concrete overlay optimization based on pavement performance models. Adv Mater Sci Eng. 2017;2017: Article ID 6063508.
3. Bryce J, Rada G, and Hicks G. Effect of preservation treatments on pavement performance. In Pavement and Asset Management, CRC Press, 2019;619-626p.
4. FHWA report. Applied research associates, statistical analysis of performance of recycled hot mix asphalt overlays in flexible pavement rehabilitation. FHWA Product Distribution Center, FHWA-HRT-11-051, 2011.
5. Daieiden JF, Simpson A, and Rauhut JB. Rehabilitation performance trends: Early observations from long-term pavement performance (LTPP) specific pavement studies (SPS) (No. FHWA-RD-97-099). Turner-Fairbank Highway Research Center, 1998.
6. Mannan UA and Tarefder RA. Evaluation of long-term pavement performance based on New Mexico LTPP SPS5 data. Second Transportation & Development Congress, 2014, 269-279p.
7. Kathleen T, Carlos E, and Amy L. Performance of flexible pavement rehabilitation treatments in the long-term pavement performance SPS-5 experiment. J Transp Res Rec. 2003;1823:93-101.
8. Hongren G, Qiao D, Baoshan H, et al. Effectiveness analyses of flexible pavement preventive maintenance treatments with LTPP SPS-3 experiment data. J Transp Eng. 2016;142(2):04015045.
9. Jia Y, Dai X, Wang S, et al. Evaluation of long-term effectiveness of preventive maintenance treatments using LTPP SPS-3 experiment data. Constr Build Mater.2020;247:118585.
10. Amarasiri S and Muhunthan B. Evaluating the effectiveness of pavement preventive-maintenance treatments in mitigating longitudinal cracks in wet-freeze climatic zones. J Pavement Eng Part B. 2020;146(2):04020014.
11. Yuhong W. The effects of using reclaimed asphalt pavements (RAP) on the long-term performance of asphalt concrete overlays. Constr Build Mater. 2016;120:335–348.
12. Randy W, Jenna M, Rod T, et al. Use of data from specific pavement studies experiment 5 in the long-term pavement performance program to compare virgin and recycled asphalt pavements. J Transp Res Rec. 2011;1:82-89.
13. Regis L, Hamid S, Manuel A, et al. Performance of recycled hot-mix asphalt overlays in rehabilitation of flexible pavements. J Transp Res Rec. 2010;2155(1):55-62.
14. Mei Z. Exploratory Analysis of long-term performance of pavement using reclaimed asphalt pavement. In Transportation Research Congress: Sustainable, Smart, and Resilient Transportation, Reston, VA: American Society of Civil Engineers, 2017;164-173p.
15. Gong H, Huang B, and Shu X. Field performance evaluation of asphalt mixtures containing high percentage of RAP using LTPP data. Constr Build Mater. 2018;176:118-128.
16. Mohamed R, Khaled A, and Akram S. Investigation of factors affecting pavement roughness. Eng Res J. 2011;132.
17. Harold L, Von Q, Amy L, et al. Rehabilitation of asphalt concrete pavements: Initial evaluation of the SPS-5 experiment. Final Report, Federal Highway Administration, FHWA-RD-01-168, 2006.

18. Fouad B, Hassan S, and Lacy V. Analysis of the long-term pavement performance data for the Idaho GPS and SPS sections. Idaho Transportation Department, 2006.
19. Kottek M, Grieser J, Beck C, et al. World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift. 2006;15(3):259-263.
20. Rosie S. Statistics: 1.1 paired t-tests, Mathematics learning support center, 2004.
21. Eva O, and Oskar O. Methodology and application of one-way ANOVA. Am J Mech Eng. 2013;1:256-261.
22. Christopher M, Susan L, Ralph H, et al. Analysis of influences on as-built pavement roughness in asphalt overlays. Int J Pavement Eng. 2007;4:181-192.

Saad Abd El-Karim El-Hamrawy is currently a Professor of highway and airports engineering with the Department of Civil Engineering, Faculty of Engineering, Menoufia University, Egypt. His research interests include airports, pavement structure and highway geometric design, structure engineering and reinforced concrete buildings.

Ahmed Ebrahim Abu El-Maaty is currently an Associate Professor of highway and airports engineering with the Department of Civil Engineering, Faculty of Engineering, Menoufia University, Egypt. His research interests include pavement structure and highway geometric design, consistency of soil reinforcement, concrete pavement, finite elements analysis, fundamentals of geotechnical engineering and traffic performance analysis. He has published numerous refereed articles in international and professional journals.

Alaa Bahaa El-Dein Fathy was graduated from the Department of Civil Engineering, Faculty of Engineering, Menoufia University, Egypt, in 2017. Her current research interests include pavement structure and highway geometric design, structure engineering, reinforced concrete design and all fields of civil engineering.

Citation: El-Maaty AEA, Fathy AB, and El-Hamrawy SAK. Long term performance of asphalt overlays in flexible pavement rehabilitation. Trans Eng Comput Sci. 2020;1(2):111.