PERFORMANCE ANALYSIS OF FLEXIBLE PAVEMENTS WITH BASE LIME

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Abstract

The performance of the pavement is influenced by several factors, such as the pavement structure, materials, traffic, and climate conditions. These factors affect the pavement response, mainly the compressive strain developed at the top of each layer and the tensile strain developed at the bottom of the asphalt concrete layer, resulting in various forms of distresses, such as fatigue cracking. The materials used in the construction of these layers are equally important for the long-term performance of the pavements as well as its structural stability. Aggregates are the most used materials in the construction of base layers in a flexible pavement structure. Moreover, the aggregate used in the base layer provides foundation for the overlying layers and needs to have enough strength, but due to the scarcity of quality materials and the rising demand, base layers are often treated with different types of stabilizing agents. In this study, various mechanistic analyses are performed using the 3-D Move Analysis software to study the effects of lime as a stabilizing agent on fatigue resistance performance. These analyses showed that the use of lime as a stabilizing agent increased the pavement performance up to 48 % for fatigue cracking resistance when compared to untreated base layers. The cost-effectiveness analysis also showed that the use of stabilizing agents would reduce the long-term cost of pavement as compared to untreated bases. The overall cost efficiency of the lime treated base is found to be 1.68 times the untreated base.

Keywords: base treatments, fatigue cracking, mechanistic analysis, finite element analysis, lime, cost efficiency

1 Introduction

Hot mixed asphalt (HMA) pavement consists typically of 3-layers: HMA surface layer, base layer and subgrade. The base layer composed of aggregates is an important layer in terms of structural performance. The load transferred from the surface of the pavement ultimately goes to the base, therefore, there is a great need for the base layer to be strong to handle the variable traffic loads and various climatic conditions (1). Various methods are being utilized for enhancing the strength of the base layer against traffic loading and climate conditions. The multiple layers in the pavement structure are required to withstand the traffic loads and various distress generated. A base layer should be strong and have rigidity to not allow distortion, lateral flow and consolidation. The base course layer is designed to have adequate thickness to reduce the traffic damage over time. (2). A base layer can be made either bounded or unbounded. A bounded layer refers to a base layer where some sort of stabilizing agent or treatments agents is utilized to make the layer more robust and stable. In contrast to bound layer, an unbounded layer does not utilize any kind of external agent and the strength of the base layer is solely depends on the strength of the aggregates. Various kinds of stabilizing agents are utilized in bounded bases such as lime, cement and asphalt.

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The use of these additives is very beneficial in the construction of HMA pavement as they reduce distresses in the pavement structure. Pavement performances are also affected by the environmental conditions. Therefore, a proper study regarding the utilization of these kinds of stabilizers must be made through various mechanistic and cost-effectiveness analyses. The study presented in this paper compares various aspects of utilizing lime treated bases and untreated bases.

2 Literature review

Stabilization is the process of adding a cementing agent to the soil or crushed rock to produce materials that have greater strength than the original unstabilized ones [3,4]. There are two types of base layers generally used in the construction of flexible asphalt pavements, which includes unbound aggregate bases that consists of untreated granular materials and bound aggregate bases that consist of granular material bounded physically or chemically by a stabilizing agent (e.g., cement, asphalt emulsion or foamed asphalt [3]. The use of a stabilized base results in an increased performance of base layer with a greater stability and proper aggregate interlock. Johnson [5] studied the use of lime on bases and subgrades to increase its performance. The study found that poor subgrade and base materials can be modified to a significant level if appropriate quantities of the lime were used. The finished base was also found to be waterproof if lime was used. A study was performed by Azadegan et al. on the performance evaluation of lime and cement treated base layers in the unpaved road [6]. It was found that there bearing capacity of the base layer increased, and similarly, stiffness of subgrade and base layer should have a corresponding value. In a report submitted to the National Lime Association, the utilization of lime-stabilized layer in mechanistic-empirical pavement design is described [7]. It was basically focused on utilizing the lime stabilized layer as a structural component of the pavement system. Different issues and steps needed to be considered when incorporating lime stabilized layers in the pavement design are exclusively discussed. Mixture design and material testing were essential components. Moreover, economic benefits from the utilization of lime treated layer was an important finding from the study.
In addition to the structural benefits of the treated base layers of pavement, various economic savings are obtained [5, 7]. Koroma studied the life cycle cost analysis of pavement sections containing treated open-graded bases and compared them to traditional dense-graded untreated bases using predicted performance of the MEPDG [8]. Treated open-graded bases were found to have higher life cycle cost.
The various studies presented above showed that the addition of additive or using base treatments resulted in a great impact on the pavement structural capacity and its life. These studies have clearly provided analysis related to the strength, but the long-term impact on the cost and benefit are rarely described. This paper quantifies the recurring cost using mechanistic-empirical analysis based on bottom-up fatigue cracking for lime treated base in pavement structures.

3 3-D study objective

Base treatments are one of the most important construction practices to increase the overall pavement performance in addition to their potential long-term cost-effectiveness benefits. Various stabilizing materials are utilized for base treatments. This study focuses on the use of lime as stabilizing agent. Lime treated base was considered in determining the improved pavement performance using mechanistic analysis, which then was utilized to investigate the cost-effectiveness of such treatments using two different binder grades at four different traffic speeds.

4 3-D move mechanistic analysis

One of the One of the most powerful software packages in the design of flexible pavements is referred to as the 3-D Move Analysis. Complex surface loading, such as multiple loads and non-uniform tire pavement contact stress, are handled by the program with the continuum finite layer approach [9]. Advanced applications of the software include estimation of damage under-off-road farm vehicles and estimation of pavement performance at the intersection. This study utilized the 3-D Move Analysis software to the utmost level to find the performance of the flexible pavement base when it accounts for the bottom-up fatigue cracking for two different grade of binder and three different temperatures with two different base sections of untreated and lime treated.

This research used the HMA properties determined in the National Cooperative Highway Research Program (NCHRP) 9-44 A (10). The test results used in this study are the results presented in the project report NCHRP Report 762. The values required in the 3-D Move Analysis, such as dynamic modulus |E*|, phase angle (ø), and fatigue regression coefficient are derived from the same research project. The research effort of the NCHRP 9-44 A included the characterization of different PG asphalt binders. This study considered two PG asphalt binders which are PG 64-22 and PG 76-16. The corresponding regression coefficient k1, k2 and k3 of the generalized fatigue model of PG 64-22 are 0.000558, 3.876197 and 0.875271, respectively. Similarly, for PG 76-16 asphalt binder, the fatigue regression coefficients k1, k2 and k3 are 0.000558, 3.876197 and 0.875271, respectively [10].

5 Mechanistic Analysis of Bottom-Up Fatigue Cracking

Among the various types of the distress conditions in flexible pavements, bottom-up fatigue cracking is one of the major forms of distress. Bottom-up fatigue cracking is a series of interconnected cracks developed in the surface of the HMA surface or base under repeated traffic loading. Crack initiates at the bottom of the asphalt layer and propagates towards the surface of the pavement. The mechanistic performance of base layer under various treatments, such as lime is expected to perform better. Figure 1 shows the bottom-up fatigue cracking performance of two different types of mixtures, one with binder grade PG 64-22 and the other one with PG 76-16 under three different speeds of 40, 72, and 104 kilometre per hour.

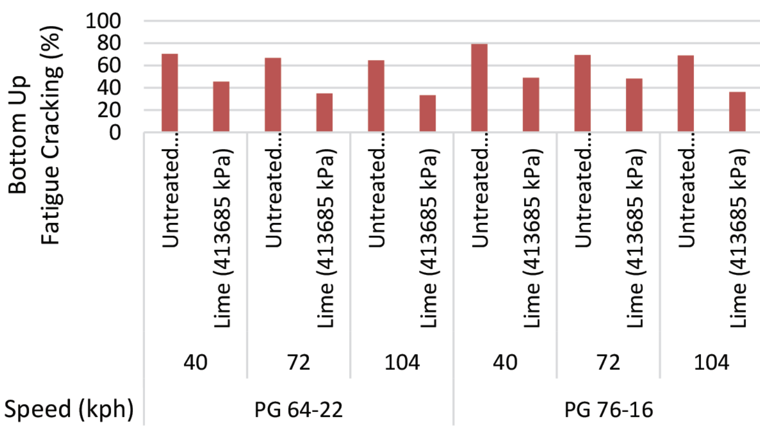

Figure 1 Bottom-up fatigue performance of pavement with lime treated base

It can be observed from Figure 1 that treated base layers had superior fatigue cracking resistance as compared to untreated sections. Lime treatment had the low predicted fatigue cracking. It can also be noticed that pavement structures with stiffer asphalt binder grade (PG 76-16) are more susceptible to fatigue cracking than softer asphalt binder grade (PG 64-22). The fatigue cracking of both PG 64-22 and PG 76-16 asphalt binders decreases as the traffic speed increases due to the viscoelastic nature of asphalt pavements where pavement structures act as a strong material under high loading frequency (high traffic speed) whereas it acts as a weak material under low loading frequency (low traffic speed).
In order to mathematically quantify the performance of base treatments with regard to their improved fatigue cracking resistance, a Fatigue Cracking Reduction Percentage (FCRP) was calculated as Eq. (1).

$$\text{FCRP} = \frac{\text{Fatigue cracking for untreated base section} - \text{fatigue cracking of treated base section}}{\text{Fatigue cracking for untreated base section}} \cdot 100\% \quad (1)$$

Table 1 shows the calculated FCRP for all structures illustrated in Figure 1. All presented lime treated bases at different traffic speeds and binder grades had a highest FCRP of 48 %. This indicates that lime base treatment has better performance than the untreated bases.

Table 1 Bottom-Up Fatigue Cracking Performance of lime treated base

Binder Grade	Speed Limit [km/h]	Base treatment	Bottom-Up Fatigue Cracking [%]	Fatigue Cracking Reduction Percentage (FCRP)
PG 64-22	40	Untreated (172369 kPa)	70.38	N/A
		Lime (413685 kPa)	45.54	35.29
	72	Untreated (172369 kPa)	66.82	N/A
		Lime (413685 kPa)	34.84	47.86
	104	Untreated (172369 kPa)	64.56	N/A
		Lime (413685 kPa)	33.32	48.39
PG 76-16	40	Untreated (172369 kPa)	79.27	N/A
		Lime (413685 kPa)	48.99	38.20
	72	Untreated (172369 kPa)	69.37	N/A
		Lime (413685 kPa)	48.29	30.39
	104	Untreated (172369 kPa)	68.88	N/A
		Lime (413685 kPa)	36.19	47.46

*N/A relates to original untreated base layer

6 Cost-effectiveness analysis of base treatments

Cost-effectiveness analysis plays an important role to determine the performance versus the cost of using different base treatment applications. In this study, cost-effectiveness analysis was conducted for lime treated bases in terms of its improved fatigue resistance as compared to untreated bases. Eq. (2) is the mathematical representation of the estimated cost-effectiveness of base treatments in terms of bottom-up fatigue cracking:

$$\text{Cost-effectiveness of base treatments in terms of fatigue} = \frac{\text{Undamaged Area of Pavement due to Bottom-up fatigue cracking}}{\text{Cost per mile of the pavement}} \quad (2)$$

Upon determining the cost-effectiveness of each base treatment, cost-effectiveness ratio can also be determined as Eq. (3):

$$\text{Cost} - \text{Effectiveness Ratio} = \frac{\textit{Treated Cost Effectiveness}}{\textit{Unteated Cost Effectiveness}} \quad (3)$$

6.1 Remaining undamaged pavement condition

By the end of the design life of 20 years, the remaining undamaged surface area of pavement due to bottom-up fatigue cracking can be estimated as the total surface area (1.600m*3.66m) minus the predicted bottom-up fatigue cracking as shown in Table 2.

6.2 Cost per mile of pavement

To estimate the cost of each base treatment and compare it to the untreated base, the cost of one ton of each of the base treated layer was calculated given the fact the unit price for aggregates, lime is $22, $220.61 per ton, respectively [11]. In this analysis, lime treatments were added to the base aggregates at a rate of 2 % by weight of the aggregates. This leads to the cost of base layer calculated as the following (assuming that the cost of plant and equipment are same for all types of bases):

- 1 Ton of Untreated Base Layer: $22/ton
- 1 Ton of Lime Treated Base: 2 % of $220.71/ton+ 98 % of $22/ton=$25.98/ton

For 8 inches of base layer thickness, the required quantity is calculated as width (3.66 m) × length (1600 m) × thickness (0.2 m) × density (2472.42 kg / m^3) = 2895.7 tons. Therefore, the cost required for paving with the given base and treatments can be calculated as:

- Cost to pave 1.6 km of untreated base case= $ 63,705
- Cost to pave 1 mile of lime treated base case= $ 75,229

6.3 Cost - effectiveness of lime base treatment in terms of bottom-up fatigue cracking

Based on the calculated remaining undamaged area of pavement due to bottom-up fatigue cracking and the cost per one mile of each base-treatment, cost-effectiveness for lime treated bases in terms of bottom-up fatigue cracking were calculated based on equation 2. Overall results are shown in Table 2.
The cost-effectiveness analysis of the base treatment in terms of bottom-up fatigue cracking shows that the use of base treatment is more economical compared to untreated bases. It can be noticed that the use of lime treatment has cost-effectiveness in comparison to untreated bases at different traffic speeds using both asphalt binder grades. The cost-effectiveness ratio of all base treatments is found to be higher using stiffer asphalt binder and for higher traffic speed cases (Table 2).

Table 2 Cost- Effectiveness of Lime Base Treatments for Bottom-Up Fatigue Cracking

Binder Grade	Speed Limit [km/h]	Base Treatment	Remaining undamaged surface area [m²]	Cost to pave 1.6 km ($)	Cost-Effectiveness (using Eq. (2))	Cost-Effectiveness Ratio (using Eq. (3))
PG 64-22	40	Untreated (172369 kPa)	1743.53	63705	0.027	N/A
		Lime (413685 kPa)	3205.70	75229	0.043	1.56
	72	Untreated (172369 kPa)	1953.09	63705	0.031	N/A
		Lime (413685 kPa)	3835.54	75229	0.051	1.66
	104	Untreated (172369 kPa)	2086.12	63705	0.033	N/A
		Lime (413685 kPa)	3925.01	75229	0.052	1.59
PG 76-16	40	Untreated (172369 kPa)	1220.24	63705	0.019	N/A
		Lime (413685 kPa)	3002.62	75229	0.040	2.08
	72	Untreated (172369 kPa)	1802.98	63705	0.028	N/A
		Lime (413685 kPa)	3043.82	75229	0.040	1.43
	104	Untreated (172369 kPa)	1831.83	63705	0.029	N/A
		Lime (413685 kPa)	3756.07	75229	0.050	1.74
Overall Cost-Effectiveness Ratio of Lime Treated Base						1.68

*N/A relates to original untreated base layer

7 Conclusions and recommendations

The purpose of this study was to conduct a mechanistic comparative analysis between treated and untreated bases in order to evaluate bottom-up fatigue cracking resistance. The base treatment considered in this study was lime treatment. In addition, cost-effective analysis was performed to investigate if such treatment was worthwhile considering their cost versus their improved field performance. Based on both mechanistic and cost-effectiveness analyses, the following conclusions are drawn:

- In terms of bottom-up fatigue cracking performance, treated base layers had superior fatigue cracking resistance as compared to untreated sections. Lime treated base had 48 % higher FCRP.
- It can also be concluded that pavement structures with stiffer asphalt binder grade (PG 76-16) were more susceptible to fatigue cracking than softer asphalt binder grade (PG 64-22). Similarly, fatigue cracking decreased as the traffic speed increased due to the viscoelastic nature of asphalt pavements.
- Cost-effectiveness analysis showed that the use of lime treated base resulted in the highest cost effectiveness considering bottom-up fatigue cracking. The overall cost-effectiveness ratio of lime was 1.68 times the untreated base for the bottom-up fatigue cracking.

Therefore, it can be concluded that the use of base treatments could potentially contribute to an overall improved fatigue cracking resistant pavement structures. In addition, such treatments present improved cost-efficiency in base construction practices. Furthermore, this research reports the preliminary mechanistic and cost-effectiveness analysis of various base treatments based on the Texas Department of Transportation (TXDOT) practices, hence, further study based on other countries practices along with other form of distresses such as rutting and reflective cracking can lead to a geographically diverse verification of the above-mentioned analysis.

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