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# Improvement of fatigue and rutting performance with different base treatments

## Abstract

Pavement performance is a key parameter that governs the serviceability of road networks. This performance is heavily influenced by the pavement construction materials such as asphalt binder and aggregates. The use of proper aggregates results in enhanced structural stability and greater long-term performance of pavements. However, due to the rapid construction of roads around the world, aggregates used in the base layer are often treated with various stabilizing agents such as lime and cement. In this study, various mechanistic analyses are performed using the 3-D Move Analysis software to study their effect on rutting and fatigue resistance performance. The analysis showed that the use of stabilizing agents increased the pavement performance up to 96% for fatigue cracking and 34.4% for rutting 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.

**Keywords:** pavements, base layer, stabilizing agents, lime, cement, rutting, fatigue cracking, mechanistic analysis, cost-effectiveness

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**Abbreviations:** HMA, hot mixed asphalt; SFDR, stabilized full depth reclaimed pavement; RAP, reclaimed asphalt pavement; BCS, blended calcium sulfate; IBA, incinerator bottom ash; RI, rhode island; RIDOT, ri department of transportation; MEPDG, mechanical empirical pavement design guide; NCHRP, national cooperative highway research program; FCRP, fatigue cracking reduction percentage; TRRP, total rutting reduction percentage; TXDOT, Texas department of transportation

## 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 need for the base layer to be stiff enough to withstand 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 distresses generated. The base layer must be strong and have rigidity to not allow distortion, lateral flow, nor consolidation. The base course layer is designed to have adequate thickness to reduce traffic damage over time.[2] Additionally, the 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 agent is utilized to make the layer more robust and stable. In contrast to bound layer, an unbound layer does not utilize any kind of external agent, but rather the strength of the base layer solely depends on the strength of the aggregates. Various kinds of stabilizing agents are utilized in bounded bases, such as lime, cement, and asphalt. 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 environmental conditions, therefore, a proper study regarding the utilization of these kinds of stabilizers must be made through various mechanistic and cost-effectiveness analyses.

## 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 un stabilized 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.[3,5,6] The use of a stabilized base results in an increased performance of base layer with a greater stability and proper aggregate interlock. Granular base layers have low elastic modulus values, which requires both asphalt and base layers with higher flexible pavement thickness in order to avoid premature failure due to rutting or fatigue cracking. The construction cost of asphalt layer is higher than the construction cost of other pavement layers.[7] Using treated base layers with higher elastic moduli will reduce the thickness of the pavement layers, decrease construction costs, and conserve natural resources. Various researchers have used various stabilizing agents in HMA pavement, however; the basic purpose of using the stabilizing agent remains the same.

Wang investigated the performance of flexible pavements with stabilized bases. The performance of experimental pavement was observed at the Pennsylvania Transportation Research Facility. Crushed stone, aggregate bituminous concrete, aggregate cement, and aggregate lime- pozzolana were used as base course for the pavement with the loading conditions of 2.4 million 18-kip equivalent axle load. The data were analyzed with respect to the pavement serviceability index and distress conditions of roughness, rutting, and cracking. Various models were developed and evaluated which illustrated an increased pavement performance using stabilizing agents.[8] Similarly, Simpson evaluated the asphalt stabilized layer equivalency factors for use in airfield flexible pavement design.[9] In his research, UFC-3-260-02 guides were used for the design of pavement structure. In the airfield pavement, the use of stabilized base layer has been satisfactory. Johaneck and Dai used stabilized full depth reclaimed pavement (SFDR) for judging the responses and performance at

Minnesota Road Research Facility. Three stabilized sections were made with different ratios of pulverized asphalt concrete to granular base. Engineering emulsions were used as stabilizing agents, but the emulsion content varied between the sections. Responses were measured with strain gauges embedded in the HMA and SFDR layers under the wheel loads. The study concluded that the rutting, cracking, and international roughness index were lower, and the stabilized layer provided greater structural performance.[10] Ogundipe performed a study on the bitumen stabilized granular soils to examine the strength and compaction characteristics of the base layer using 2%, 4% and 6% asphalt contents. It was found that the properties of the granular soil improved when it was stabilized with bitumen.[11] Johnson 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.[12]

Faysal et al.[13] mixed reclaimed asphalt pavement (RAP) with different Portland cement content in order to meet the Resilient modulus requirements of 1947 kPa (300psi) to be used in pavement construction project.[13,14] The test results showed that 4% cement content will meet the minimum strength requirement. In a similar study, but using fly ash for stabilization of the RAP, Saride et al.[15] found that 80 % RAP replacing virgin aggregates can be stabilized with 40% fly ash to meet both the resilient modulus and unconfined strength requirements of base material for low volume roads.[15] Mohammad et al.[16] compared the resilient modulus of lime stone aggregate base with different base treated materials.[16] Blended calcium sulfate (BCS) treated with steel slag and BCS treated with fly ash showed higher resilient modulus values among the investigated materials. Incinerator bottom ash (IBA) is a by-product residual produced by incinerating municipal solid waste. Ahmed et al. found that IBA treatment of crushed limestone produced a better performance as a road base layer in comparison with the untreated limestone in respect of their resilient moduli.[17] In addition to the structural benefits of the treated base layers of pavement, various economic savings are obtained. Francois et al. conducted a study on five field sections located on Route 165 in Rhode Island (RI) which were evaluated as part of a controlled study conducted by RI Department of Transportation (RIDOT) to evaluate long-term field performance using stabilized base. It was found that it is cost-effective to use bases stabilized with Portland cement, geogrids, asphalt emulsions, or $CaCl_2$, over non-stabilized RAP base since the life cycle cost of the untreated RAP base section appeared to be the lowest of all the pavement sections analyzed in the study in terms of predicted performance1. In a recent study, Bodhgire et al.[7] compared cement treated base layer with untreated virgin aggregate layer. They found that the estimated cost for flexible pavement designed with cement treated base layer is 52% lower than that designed using granular aggregates base layer.[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 Mechanical Empirical Pavement Design Guide (MEPDG).[18] Treated open-graded bases were found to have higher life cycle cost. He concluded that pavement sections with treated layer will have to go an extra 30 years without maintenance in order to have identical life cycle costs as those with untreated dense-grade bases. The various studies presented above showed that the addition of additive or using base treatments result 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 and rutting.

## 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 and cement as stabilizing agents. These treatments were 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.

### 3-D move mechanistic analysis

One of the most powerful software packages in the design of flexible pavements is referred to as the 3-D Move Analysis. It was developed at the University of Nevada, Reno under the cooperative agreement with Federal Highway Administrative Agency. 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.[19] Advanced applications of the software include estimation of damage under-off-road farm vehicles and estimation of pavement performance at the intersection. Some of the salient features of the 3-D Move Analysis software are adjustable loading configuration and tire, modelling of 3-D surface stresses, and analyzing non-generic tire and axle configuration. 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 and rutting for two different grade of binder and three different temperatures with four different base sections of untreated, cement treated, lime treated, and asphalt treated. Figure 1 shows the typical section of the flexible pavement considered in this study. This research used the HMA properties determined in the National Cooperative Highway Research Program (NCHRP) 9-44 A.[20] 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. Table 1 shows the dynamic modulus values and phase angle of the PG 64-22 at different temperatures and frequencies. 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.[20] Similarly, for PG 76-16 asphalt binder, the fatigue regression coefficients k1, k2 and k3 are 0.000558, 3.876197 and 0.875271, respectively. Table 2 shows the dynamic modulus and phase angles values of the PG 76-16 asphalt binder.

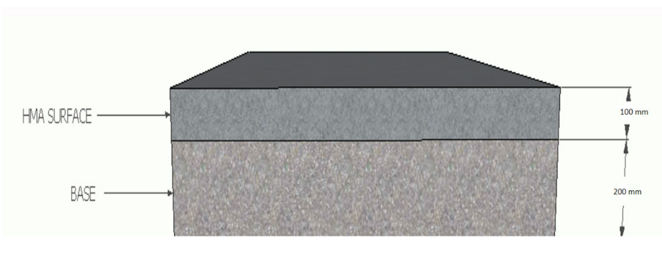


**Figure 1** Pavement structure considered in the study.

**Citation:** Souliman MI, Bastola NR, Zeiada WA. Improvement of fatigue and rutting performance with different base treatments. *Material Sci & Eng.* 2020;4(5):122–129. DOI: 10.15406/mseij.2020.04.00138

**Table 1** Dynamic modulus (E*) and phase angle values for PG 64-22 binder[20]

| | Dynamic modulus (kPa) | | | | | |
|---|---|---|---|---|---|---|
| | **Frequency (Hz)** | | | | | |
| Temp (C) | 0.1 | 0.5 | 1 | 5 | 10 | 25 |
| -10 | 17,243,787 | 19,512,162 | 20,311,954 | 21,980,485 | 22,945,751 | 24,228,176 |
| 5 | 10,328,346 | 13,058,670 | 14,175,620 | 17,092,103 | 18,436,580 | 20,112,006 |
| 22 | 2,654,481 | 3,867,959 | 4,481,592 | 6,219,071 | 7,011,968 | 8,108,234 |
| 38 | 675,686 | 1,020,424 | 1,241,056 | 2,006,374 | 2,482,113 | 3,419,799 |
| 55 | 193,053 | 310,264 | 386,106 | 648,107 | 779,108 | 1,041,108 |
| | Phase angle (ø) (degree) | | | | | |
| -10 | 9 | 8 | 8 | 8 | 8 | 6 |
| 5 | 19 | 16 | 15 | 14 | 14 | 11 |
| 22 | 34 | 30 | 27 | 22 | 20 | 17 |
| 38 | 24 | 25 | 27 | 28 | 28 | 30 |
| 55 | 13 | 15 | 18 | 22 | 25 | 28 |

**Table 2** Dynamic Modulus (E*) and Phase Angle values for PG 76-16 Binder[20]

| **Temp (C)** | **Dynamic modulus (kPa)** | | | | | |
|---|---|---|---|---|---|---|
| | **Frequency (Hz)** | | | | | |
| | 0.1 | 0.5 | 1 | 5 | 10 | 25 |
| -10 | 20,429,165 | 22,945,751 | 24,014,439 | 26,889,552 | 27,772,081 | 29,488,876 |
| 5 | 12,445,036 | 14,734,096 | 15,878,625 | 18,684,791 | 19,608,689 | 21,146,220 |
| 22 | 5,419,279 | 7,604,917 | 8,611,551 | 11,693,508 | 13,134,512 | 14,030,830 |
| 38 | 1,247,951 | 1,778,847 | 2,102,901 | 3,468,063 | 4,136,854 | 5,357,226 |
| 55 | 330,948 | 558,475 | 689,476 | 1,110,056 | 1,344,478 | 1,771,953 |
| | Phase angle (ø) (degree) | | | | | |
| -10 | 7.1 | 9.7 | 10.8 | 11.6 | 11.8 | 12.8 |
| 5 | 9.5 | 12.9 | 14.4 | 15 | 16 | 16.3 |
| 22 | 14.5 | 17.7 | 20.3 | 24.7 | 26.2 | 29.9 |
| 38 | 28.2 | 31.3 | 31.4 | 34.7 | 34.5 | 34 |
| 55 | 31.2 | 27.2 | 26.7 | 22.4 | 20.1 | 19.9 |

## 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 cement, and, lime is expected to perform better. Figure 2 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 25, 45, and 65 miles per hour. It can be observed from Figure 2 that all treated base layers had superior fatigue cracking resistance as compared to untreated sections. Cement treatment had the lowest predicted fatigue cracking followed by lime. 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 frequency loading (high traffic speed) whereas it acts as a weak material under low frequency loading (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 follows:

FCRP=(Fatigue cracking for untreated base section – fatigue cracking of treated base section)/(Fatigue cracking for untreated base section)*100% (1)

Table 3 shows the calculated FCRP for all structures illustrated in Figure 2. All presented cement treated bases at different traffic speeds and binder grades had an average FCRP of 96%, whereas lime treated sections had an average FCRP of 41.3%. This indicates that cement base treatment had the highest performance among studied treatments.

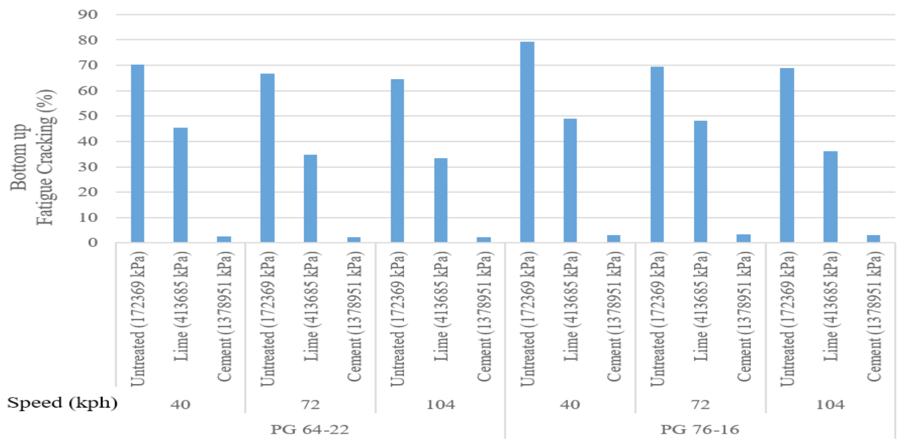


**Figure 2** Bottom-up fatigue performance of the pavement with various base treatments.

**Table 3** Bottom-up fatigue cracking performance of various base treatments

| Binder Grade | Speed limit (kph) | Base treatment | Bottom up fatigue cracking (%) | Fatigue cracking reduction percentage (FCRP) |
|---|---|---|---|---|
| | | Untreated (172369 kPa) | 70.38 | N/A |
| | 40 | Lime (413685 kPa) | 45.54 | 35.3 |
| | | Cement (1378951 kPa) | 2.65 | 96.2 |
| | | Untreated (172369 kPa) | 66.82 | N/A |
| | 72 | Lime (413685 kPa) | 34.84 | 47.9 |
| | | Cement (1378951 kPa) | 2.19 | 96.7 |
| PG 64-22 | | Untreated (172369 kPa) | 64.56 | N/A |
| | 104 | Lime (413685 kPa) | 33.32 | 48.4 |
| | | Cement (1378951 kPa) | 2.17 | 96.6 |
| | | Untreated (172369 kPa) | 79.27 | N/A |
| | 40 | Lime (413685 kPa) | 48.99 | 38.2 |
| | | Cement (1378951 kPa) | 3.19 | 96.0 |
| | | Untreated (172369 kPa) | 69.37 | N/A |
| | 72 | Lime (413685 kPa) | 48.29 | 30.4 |
| | | Cement (1378951 kPa) | 3.25 | 95.3 |
| PG 76-16 | | Untreated (172369 kPa) | 68.88 | N/A |
| | 104 | Lime (413685 kPa) | 36.19 | 47.5 |
| | | Cement (1378951 kPa) | 3.21 | 95.3 |

*N/A relates to original untreated base layer

## Mechanistic analysis of total rutting

Similar to fatigue cracking, rutting is another important type of distress described as a depression in the wheel path of the pavement structure. Rutting accumulates over time from the individual pavement layers (surface, base and subgrade), where the sum of these rutting results in total rutting or surface rutting. Figure 3 shows the total rutting 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 25, 45, and 65 miles per hour. It can be observed from Figure 3 that all treated base layers had superior rutting resistance as compared to untreated sections. Cement treatment had the lowest predicted rutting followed by lime treatment. It can also be noticed that pavement structures with softer asphalt binder grade (PG 64-22) are more susceptible to rutting than stiffer asphalt binder grade (PG 76-16). Total rutting 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 as explained earlier. In order to mathematically quantify the performance of base treatments with regard to their improved rutting resistance, a Total Rutting Reduction Percentage (TRRP) was calculated as follows:

TRRP=(Total rutting for untreated base section – Total rutting of treated base section)/(Total rutting for untreated base section)*100% (2)

Table 4 shows the calculated TRRP for all structures illustrated in Figure 3. All cement treated bases at different traffic speeds and binder grades had an average TRRP of 34.4% whereas lime treated sections had an average TRRP of 16.6. This indicates that cement base treatment had the highest performance among studied treatments in terms of rutting resistance.

**Citation:** Souliman MI, Bastola NR, Zeiada WA. Improvement of fatigue and rutting performance with different base treatments. *Material Sci & Eng.* 2020;4(5):122–129. DOI: 10.15406/mseij.2020.04.00138

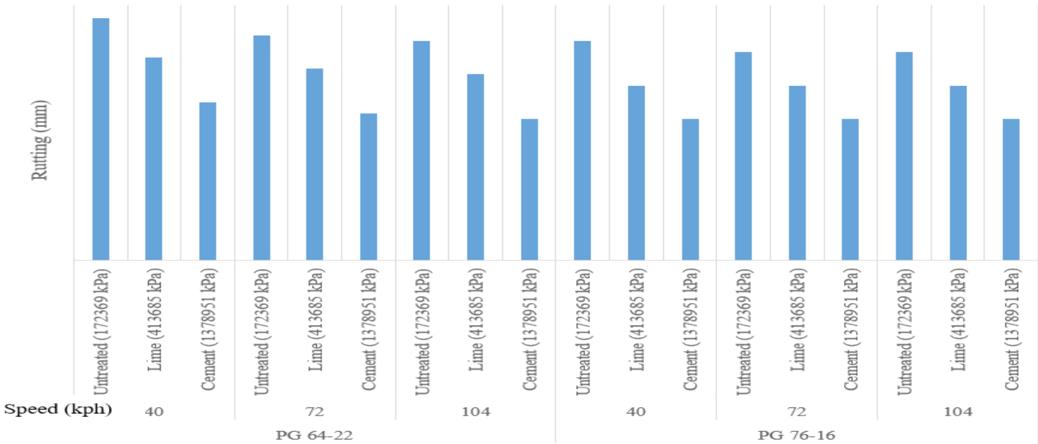


**Figure 3** Rutting performance of pavement with various base treatments.

**Table 4** Rutting performance under various treatments

| Binder Grade | Speed limit (kph) | Base treatment | Total rutting (mm) | Total rutting reduction percentage (TRRP) |
|---|---|---|---|---|
| | | Untreated (172369 kPa) | 10.92 | N/A |
| | 40 | Lime (413685 kPa) | 9.14 | 16.3 |
| | | Cement (1378951 kPa) | 7.11 | 34.9 |
| | | Untreated (172369 kPa) | 10.16 | N/A |
| | 72 | Lime (413685 kPa) | 8.64 | 15.0 |
| | | Cement (1378951 kPa) | 6.60 | 35.0 |
| PG 64-22 | | Untreated (172369 kPa) | 9.91 | N/A |
| | 104 | Lime (413685 kPa) | 8.38 | 15.4 |
| | | Cement (1378951 kPa) | 6.35 | 35.9 |
| | | Untreated (172369 kPa) | 9.91 | N/A |
| | 40 | Lime (413685 kPa) | 7.87 | 20.5 |
| | | Cement (1378951 kPa) | 6.35 | 35.9 |
| | | Untreated (172369 kPa) | 9.40 | N/A |
| | 72 | Lime (413685 kPa) | 7.87 | 16.2 |
| | | Cement (1378951 kPa) | 6.35 | 32.4 |
| PG 76-16 | | Untreated (172369 kPa) | 9.40 | N/A |
| | 104 | Lime (413685 kPa) | 7.87 | 16.2 |
| | | Cement (1378951 kPa) | 6.35 | 32.4 |

*N/A relates to original untreated base layer

## 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 all three different base treatments in terms of their improved fatigue and rutting resistance as compared to untreated bases. The following is the mathematical representation of the estimated cost-effectiveness of base treatments in terms of bottom-up fatigue cracking and rutting:

Cost-effectiveness of base treatments in terms of fatigue =(Undamaged Area of Pavement due to Bottom-up fatigue cracking)/(cost per mile of the pavement ) (3)

Cost-effectiveness of base treatments in terms of rutting =(Undamaged Pavement due to Rutting)/(cost per mile of the pavement ) (4)

Upon determining the cost-effectiveness of each base treatment, cost-effectiveness ratio can also be determined as follows:

Cost-Effectiveness Ratio=(Treated Cost Effectiveness)/(Unteated Cost Effectiveness) (5)

In order to calculate the cost-effectiveness illustrated above, the following two subheadings illustrate the required calculations of both remaining undamaged pavement and the cost per mile of pavement.

## 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 illustrated in Figure 4 (1.600m*3.66m) minus the predicted bottom-up fatigue cracking as shown in Table 3. Similarly, the remaining un-rutted pavement can be estimated as a maximum allowable total rutting of half an inch minus the predicted total rutting as shown in Table 7.

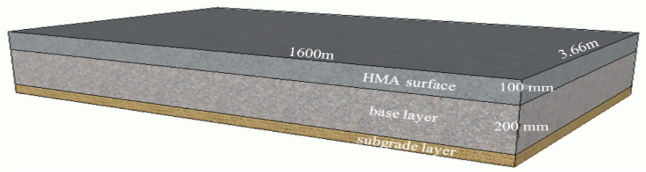


**Figure 4** Pavement structure considered in the study (Dimensions).

## Cost per mile of pavement

In order 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, cement, and lime are $22, $153.69, $220.71 per ton, respectively.[21] The cost based on TXDOT practices is presented for the generalized study. In this analysis, all 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 Cement Treated Base: 2 % of $153.69/ton+ 98% of $22/ton=$24.64/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 as shown in Figure 4, the required quantity is calculated as width (3.66m) × length (1600m) × thickness (0.2 m) × density (2472.42 kg / m3) = 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 1.6 km of cement treated base case= $ 71,349

Cost to pave 1.6 km of lime treated base case= $ 75,229

## Cost- effectiveness of various base treatments 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 all base treatments in terms of bottom-up fatigue cracking were calculated based on equation 3. Overall results are shown in Table 5. The cost-effectiveness analysis of all base treatments in terms of bottom-up fatigue cracking shows that the use of base treatments is more economical compared to untreated bases. It can be noticed that the use of cement treatment has the best cost-effectiveness in comparison to lime treatment 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 5). Table 6 shows the overall cost-effectiveness ratio of all base treatments.

**Table 5** Cost- effectiveness of various base treatments for bottom-up fatigue cracking

| Binder grade | Speed limit (kph) | Base treatment | Remaining undamaged surface area (m$^2$) | Cost to pave 1.6 Km ($) | Cost-effectiveness (using equation 3) | Cost-effectiveness ratio (using equation 5) |
|---|---|---|---|---|---|---|
| PG 64-22 | 40 | Untreated (172369 kPa) | 1743.53 | 63705.00 | 0.03 | N/A |
| | | Lime (413685 kPa) | 3205.70 | 75229.00 | 0.04 | 1.56 |
| | | Cement (1378951 kPa) | 5730.35 | 71349.00 | 0.08 | 2.93 |
| | 72 | Untreated (172369 kPa) | 1953.09 | 63705.00 | 0.03 | N/A |
| | | Lime (413685 kPa) | 3835.54 | 75229.00 | 0.05 | 1.66 |
| | | Cement (1378951 kPa) | 5757.42 | 71349.00 | 0.08 | 2.63 |
| | 104 | Untreated (172369 kPa) | 2086.12 | 63705.00 | 0.03 | N/A |
| | | Lime (413685 kPa) | 3925.01 | 75229.00 | 0.05 | 1.59 |
| | | Cement (1378951 kPa) | 5758.60 | 71349.00 | 0.08 | 2.46 |
| PG 76-16 | 40 | Untreated (172369 kPa) | 1220.24 | 63705.00 | 0.02 | N/A |
| | | Lime (413685 kPa) | 3002.62 | 75229.00 | 0.04 | 2.08 |
| | | Cement (1378951 kPa) | 5698.56 | 71349.00 | 0.08 | 4.17 |
| | 72 | Untreated (172369 kPa) | 1802.98 | 63705.00 | 0.03 | N/A |
| | | Lime (413685 kPa) | 3043.82 | 75229.00 | 0.04 | 1.43 |
| | | Cement (1378951 kPa) | 5695.03 | 71349.00 | 0.08 | 2.82 |
| | 104 | Untreated (172369 kPa) | 1831.83 | 63705.00 | 0.03 | N/A |
| | | Lime (413685 kPa) | 3756.07 | 75229.00 | 0.05 | 1.74 |
| | | Cement (1378951 kPa) | 5697.38 | 71349.00 | 0.08 | 2.78 |

*N/A relates to original untreated base layer

**Table 6** Summary of cost-effectiveness ratio of base treatments for bottom-up fatigue cracking

| Base types | Overall cost-effectiveness ratio |
|---|---|
| Lime Treated | 1.68 |
| Cement Treated | 2.96 |

## Cost-effectiveness of various base treatments in terms of total rutting

Based on the calculated remaining un-rutted pavement and the cost per one mile of each base-treatment, cost-effectiveness for all base treatments in terms of rutting were calculated based on equation 4. Overall results are shown in Table 7. The cost-effectiveness analysis of all base treatments in terms of total rutting shows that the use of base treatments is more economical compared to untreated bases. Similar to the cost-effectiveness in terms of fatigue cracking, it can be noticed that the use of cement treatment has the best cost-effectiveness in comparison to lime treatment 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 7). Table 8 shows the overall cost-effectiveness ratio of all base treatments.

**Table 7** Cost- effectiveness of various treatments for rutting

| Binder grade | Speed limit (kph) | Base treatment | Remaining un-rutted pavement (mm) | Cost to pave 1.6Km ($) | Cost-Effectiveness (using equation 4) | Cost-effectiveness ratio (using equation 5) |
|---|---|---|---|---|---|---|
| PG 64-22 | 40 | Untreated (172369 kPa) | 1.78 | 63,705 | 2.79E-05 | N/A |
| | | Lime (413685 kPa) | 3.56 | 75,229 | 4.73E-05 | 1.69 |
| | | Cement (1378951 kPa) | 5.59 | 71,349 | 7.83E-05 | 2.81 |
| | 72 | Untreated (172369 kPa) | 2.54 | 63,705 | 3.99E-05 | N/A |
| | | Lime (413685 kPa) | 4.06 | 75,229 | 5.40E-05 | 1.35 |
| | | Cement (1378951 kPa) | 6.10 | 71,349 | 8.54E-05 | 2.14 |
| | 104 | Untreated (172369 kPa) | 2.79 | 63,705 | 4.39E-05 | N/A |
| | | Lime (413685 kPa) | 4.32 | 75,229 | 5.74E-05 | 1.31 |
| | | Cement (1378951 kPa) | 6.35 | 71,349 | 8.90E-05 | 2.03 |
| PG 76-16 | 40 | Untreated (172369 kPa) | 2.79 | 63,705 | 4.39E-05 | N/A |
| | | Lime (413685 kPa) | 4.83 | 75,229 | 6.42E-05 | 1.46 |
| | | Cement (1378951 kPa) | 6.35 | 71,349 | 8.90E-05 | 2.03 |
| | 72 | Untreated (172369 kPa) | 3.30 | 63,705 | 5.18E-05 | N/A |
| | | Lime (413685 kPa) | 4.83 | 75,229 | 6.42E-05 | 1.24 |
| | | Cement (1378951 kPa) | 6.35 | 71,349 | 8.90E-05 | 1.72 |
| | 104 | Untreated (172369 kPa) | 3.30 | 63,705 | 5.18E-05 | N/A |
| | | Lime (413685 kPa) | 4.83 | 75,229 | 6.42E-05 | 1.24 |
| | | Cement (1378951 kPa) | 6.35 | 71,349 | 8.90E-05 | 1.72 |

*N/A relates to original untreated base layer

**Table 8** Summary of cost-effectiveness ratio of base treatments for total rutting

| Base types | Overall cost-effectiveness ratio |
|---|---|
| Lime treated | 1.38 |
| Cement treated | 2.07 |

## Conclusions and recommendations

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

I. In terms of bottom-up fatigue cracking performance, all treated base layers had superior fatigue cracking resistance as compared to untreated sections. Cement treatment had the highest average FCRP of 96% whereas lime treated sections had an average FCRP of 41.3%. This indicates that cement base treatment had the highest performance among studied treatments.

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II. Similarly, for total rutting resistance performance, all treated base layers had better rutting resistance as compared to untreated sections. Cement treatment had the highest average TRRP of 34.4% whereas lime treated sections had an average TRRP of 16.6%. This indicates that cement base treatment had the highest performance among studied treatments in terms of rutting resistance.

III. 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). On the other hand, pavement structures with softer asphalt binder tend to be more susceptible to rutting than stiffer asphalt binder grade.

IV. Both fatigue cracking and total rutting decreased as the traffic speed increased due to the viscoelastic nature of asphalt pavements, where pavement structures act as strong material under high frequency loading (high traffic speed) but it acts as a weak material under low frequency loading (low traffic speed).

V. Cost-effectiveness analysis showed that the use of base treatments resulted in the highest cost efficiency in both bottom-up fatigue cracking and rutting resistance. The overall cost-effectiveness ratio of cement, and lime treated bases were 2.96 and 1.68 times the untreated base, respectively for the bottom-up fatigue cracking. Moreover, the overall cost-effectiveness ratio of the cement, and lime treated bases were 2.07 and 1.38 times the untreated base, respectively for the total rutting.

Therefore, it can be concluded that the use of base treatments could potentially contribute to an overall improved fatigue cracking and rutting 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 reflective cracking can lead to a geographically diverse verification of the abovementioned analysis. Similarly, the percentage applications of lime and cement on a particular base layer can lead to a more scientific verification on material level properties such as strain fracture toughness and needs to be studied further.

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## Conflicts of interest

The author declares that there are no conflicts of interest.

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