CDOT Applied Research and Innovation Branch

Evaluating the Structural Properties and Cost-Effectiveness of Graphene-modified Asphalt

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May 2024

Report CDOT-2024-06

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CDOT-2024-06		

4. Title and Subtitle	5. Report Date
Evaluating the Structural Properties and Cost-effectiveness of Graphene-modified Asphalt	May 2024
	6. Performing Organization Code
7. Author(s) Christopher T. Senseney, Joseph L. Tucker	8. Performing Organization Report No.
9. Performing Organization Name and Address University of Colorado Boulder 428 UCB Boulder, CO 80309	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 422.02
12. Sponsoring Agency Name and Address Colorado Department of Transportation Applied Research and Innovation Branch 2829 W. Howard Place Denver, CO 80204	13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the US Department of Transportation, Federal Highway Administration

16. Abstract

Graphene oxide (GO) is a nanoscale material created from graphite. GO has the potential to increase the service life of asphalt binders and asphalt mixtures, but there are concerns about the high cost of GO. The objective of this study is to provide the cost benefit of using GO in neat and SBS modified asphalt binders for a simulated asphalt pavement construction project with estimated long-term engineering performance in Colorado. To accomplish this objective, the asphalt binders with different GO dosages were subjected to a series of laboratory tests to determine the material properties. The results of the lab tests were input into the AASHTOWare Pavement ME software with representative pavement sections to determine pavement design life. The design life, rehabilitation schedule, and cost for the control and the GO binder were evaluated through a life cycle cost analysis. When considering the rutting performance of the pavement, the LCCA results indicated that the current costs of using GO in a neat binder are competitive with a conventional neat binder, while the current costs of using GO in a SBS modified binder are much higher than a conventional SBS modified binder.

17. Keywords	18. Distribution Statement
	This document is available on CDOT's website https://www.codot.gov/programs/research

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Acknowledgements

The authors gratefully acknowledge the support of the personnel from the CDOT Asphalt Program and Bituminous Laboratory, including Vincent Battista, Ericka Stripp, Darcie Lopez, Gregg Stephenson, and Jason Trojan. Additionally, we would like to thank the CDOT Project Manager, Thien Tran, and the CDOT Research Branch Manager, Steve Cohn, for their support.

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Executive Summary

This project aims to study the cost effectiveness of using graphene oxide (GO) as an additive to asphalt binder to increase the longevity of asphalt pavement in the CDOT roadway network. GO is characterized by a two-dimensional, atomically thin, honey-combed lattice structure with polar oxygen-containing groups on the outside of the structure. The large surface area and chemical properties of GO make it compatible and easily mixed with asphalt binders. In this study, different dosages of GO were blended with a non-modified asphalt binder and a SBS modified binder for testing and evaluation.

The execution of this study involved laboratory testing, AASHTOWare Pavement ME design simulations, and life cycle cost analysis (LCCA) of pavement designs with different asphalt pavement mixture scenarios. The asphalt binders with different GO dosages were subjected to a series of laboratory tests in the CDOT asphalt laboratory including the Dynamic Shear Rheometer (DSR), the Rolling Thin Film Oven Test (RTFO), the Pressure Aging Vessel (PAV), and the Bending Beam Rheometer (BBR). The results of the lab tests were input into the AASHTOWare Pavement ME software with representative pavement sections to determine pavement design life. The design life, rehabilitation schedule, and cost for the control and GO binders were evaluated through a LCCA.

Laboratory testing indicated that a 0.05% by mass of binder was the optimum dosage for a neat (non-modified) PG 64-22 binder and 0.2% by mass of binder was the optimum dosage for an SBS modified PG 64-28 binder. The lab results for these binder dosages were input into the AASHTOWare Pavement ME software for a 20-year design life of a simulated highway pavement on I-70 on the eastern plains of Colorado. The software indicated that GO addition had the greatest impact on rutting performance, so rutting was selected as the primary factor to dictate pavement mill and overlay rehabilitation in the LCCA model. The LCCA results showed the cost of using 0.05% GO in a PG 64-22 was approximately equal to the cost of using a conventional PG 64-22 binder. The LCCA also showed the cost of using 0.2% GO in a PG 64-28 binder was approximately $18.6M more than a conventional PG 64-28 binder over the life of the pavement. Future research should consider the low temperature cracking performance of binders with GO addition since that was not evaluated in this study.

Chapter 1: Introduction

With the increased demand and cost of asphalt binder, limited highway maintenance budgets, and the need to reduce greenhouse gas emissions from asphalt production, it is important for engineers and highway agencies to capitalize on new asphalt technologies that might increase pavement longevity. The use of nanomaterials (nanoclays, nanosilica, nano-silicone dioxide, nano zinc oxide, nano titanium oxide, and carbon nanomaterials) in asphalt binder has received significant attention due to these materials' potential to improve performance and durability of asphalt pavement. The types of carbon nanomaterials used in asphalt binder primarily includes carbon nanotubes, graphene oxide (GO), and graphene nanoplatelets. Amongst these carbon nanomaterials, GO has exhibited the most promise in the improvement of asphalt binder properties; however, the high cost of GO incorporated at the necessary scale for roadway asphalt pavement projects could potentially outweigh the benefits [1, 2].

Few studies have evaluated the economics and cost-benefit relationships of nanomaterials in asphalt binder, and even fewer have looked at the economics of GO. Although the dosage of graphene oxide (and most other nanomaterials) in asphalt binder would be relatively low, the production cost of typical nanomaterials is high, which would be the most significant obstacle to implementation of such nanomaterials by the asphalt binder and asphalt mixture supplier industries. The asphalt content and the cost of hot mix asphalt (HMA) varies by region, with the unit price ranging from \$80-\$180 per ton (short ton) in the United States [3], often depending on the inclusion of polymers or other additives in the asphalt binder. Currently, GO costs approximately \$481k to \$1.35M per ton per ton depending on the quality of the product, and GO addition at 0.2% by weight, could increase the HMA unit price to \$150-\$300 per ton. No studies to date have performed a comprehensive life cycle cost analysis (LCCA) of the long-term economics of using GO in asphalt binders.

1.1 Scope and Objectives of Research

This research study included the following tasks:

1. Identify the appropriate dosage of GO to add to asphalt binder based on previously conducted studies.
2. Perform testing on control and GO additive binder samples through a series of laboratory tests to determine material properties at the unaged condition, the placement condition, and the simulated aged condition for the service life of the pavement.
3. Input binder laboratory test results into the AASHTOWare Pavement ME software with a representative pavement section to determine pavement design life and maintenance intervention schedule.
4. Perform a life cycle cost analysis (LCCA) of different GO dosages based on results from AASHTOWare Pavement ME simulations.

Chapter 2: Materials, Experiments, and Methods

2.1. Materials

2.1.1 Asphalt Binder

In this study, PG 64-22 and PG 64-28 binders were utilized since they are among the most common types of binders used on CDOT asphalt pavement projects. The performance grading (PG) system aligns binders with the climate they should be used, where the first number is the average of the seven-day maximum pavement temperature and the second is the minimum pavement design temperature. PG 64-22 is a raw un-modified binder (neat binder), while 64-28 is a Styrene-butadiene-styrene (SBS) modified binder. Binder samples were provided by CDOT and originated from the Suncor oil refinery in Commerce City, Colorado. Asphalt binder is obtained from crude petroleum through a series of refining steps. Asphalt binders are semisolid or solid at room temperature and liquid at high temperature. Different grades of asphalt binders are produced by changing the source of crude oil and altering the refining conditions. Many highway pavements in cold regions are now modified with polymers to extend the performance grade. Accordingly, CDOT currently uses SBS modified binders to improve thermal cracking resistance at colder temperatures.

2.1.2 Graphene Oxide

The GO incorporated in this study was a high surface area graphene oxide in a loose powder form manufactured by ACS Material. The GO was created using the modified Hummer's method where graphite is synthesized into single or few atomic layer sheets in a chemical process with strong oxidizers. The chemical process and oxidizers expand the interlayer structure and add the oxygen functional groups. The GO particles have a lateral size between 1 and 5 μm and a thickness between 0.8 and 1.2 μm. The GO has a carbon content of approximately 51% by weight and an oxygen content of approximately 41% by weight. PG 64-22 samples were mixed with 0.2% by weight and 0.05% by weight to replicate the recommended dosages from similar studies [4]. Raw samples were heated to 160° C, then stirred in a high-speed shear mixer for 45 minutes until completely mixed. Table 1 below shows the sample identification number, PG grade, and dosage of the four GO binder mixtures evaluated in this study.

Table 1 Asphalt binder sample identification numbers for laboratory testing

Sample ID number	Binder grade	% weight GO
1A	PG 64-22	0.2
2A	PG 64-28	0.2
1B	PG 64-22	0.05
2B	PG 64-28	0.05

2.2 Experimentation

2.2.1 Dynamic Shear Rheometer

The Dynamic Shear Rheometer (DSR) test following the AASHTO T 315-20 standard was performed on the control (no GO) and GO modified binders. In the DSR test, a 25 mm diameter binder sample is sandwiched between two oscillating plates that are 1 mm apart. Samples are oscillated at 10 rad/s with the dynamic shear modulus (G*) and phase angle (δ) recorded every 0.2 seconds for a total of 20 times for each temperature setting. For the unaged tests, the temperature begins at a high PG temperature grade then increases by 6 degrees C until the rutting factor (G*/sinδ) is less than 1.0 kPa. For the aged test, the binders are aged in both the rolling thin film oven (RTFO) and pressure aging vessel (PAV) before DSR testing with a smaller 8 mm diameter sample at lower temperatures. The PAV process was conducted for 10 hours at a temperature of 100° C and a pressure of 2.1 MPa. Aged DSR testing comprised a decrease in the temperature until the fatigue cracking factor (G*sinδ) was greater than a threshold value of 5000 kPa. All DSR testing was conducted on an Anton Paar Smart Pave 102e rheometer as shown in Figure 1.

Figure 1 Anton Paar Smart Pave 102e rheometer used for DSR testing at CDOT's Bituminous Lab

2.2.2 Rolling Thin Film Oven (RTFO)

The asphalt binder was first placed in the Rolling Thin Film Oven (RTFO) test to simulate short term aging of the binder, similar to aging experienced during mixing at the plant and placement in the field. The RTFO keeps a constant rolling film of binder moving, while it has dry air blown over top of it for 85 minutes. Once complete, the change in mass of the sample is recorded and compared to mass before the test. The RTFO test was completed in accordance with AASHTO T 240-24.

2.2.3 Pressure Aging Vessel (PAV)

The PAV exposes the binder to accelerated oxidation under pressure, simulating aging during the service life of the binder. Once aged via the RTFO test, the PAV requires the binder to be placed into steel pans and then is held under pressure at 2.1 MPa at a temperature of 100°C for 20 hours. The PAV process was completed in accordance with AASHTO R 28-21.

2.2.4 Bending Beam Rheometer (BBR)

The BBR test following the AASHTO T 313-19 standard was performed on RTFO and PAV aged control and GO modified binders to determine low temperature material properties and resistance to low temperature cracking. In the BBR test, aged binder is formed into 6.25 mm by 12.5 mm by 127 mm beams. The beam is loaded at the midpoint by an initial contact load of 35 mN following by a test load of 980 mN that ramps down to 35 mN. The loading takes place in a temperature bath at -12° and -18° C.

Stiffness is calculated based measured deflection and standard beam properties and is expressed as the creep stiffness S.

2.3 Methods

2.3.1 AASHTOWare Pavement ME Software

After laboratory testing was completed, the binder material properties were input into the American Association of State Highway and Transportation Officials (AASHTO) Pavement ME design software. The software is based on AASHTO's mechanistic-empirical design guide [5] and is a more advanced and sophisticated approach to structural pavement design as compared to traditional empirical methods, such as the 1993 AASHTO Guide for Design of Pavement Structures [6]. The mechanistic part of Pavement ME calculates pavement responses (i.e., stresses, strains, and deflections) under given traffic loads, materials properties, and climate conditions. The empirical part of Pavement ME relates the calculated responses to pavement damage and smoothness based on performance testing of actual pavement sections in the field. In the Pavement ME design simulations, pavement damage is accumulated over the given design life of the pavement. CDOT adopted the AASHTO Pavement ME design procedure in 2014 and is currently using version 2.6 of the software. Initial local calibration of material properties and damage criteria was performed for CDOT in 2013 [7].

The material inputs for Pavement ME are divided into three groups: asphalt mixture, asphalt binder, and asphalt general, and each of these input groups can be categories in three hierarchical levels, namely Level 1, Level 2, or Level 3. Level 1 and 2 designs are intended for high-priority and medium-priority pavements, respectively, and both Level 1 and Level 2 designs require laboratory testing of G^* and δ parameters as binder inputs [8]. The results presented in this paper would be considered a Level 2 design analysis because Level 1 inputs for the asphalt mixture (e.g., dynamic modulus E^*) were not included as part of this study.

2.3.2 Life Cycle Cost Analysis (LCCA)

LCCA is a systematic approach to evaluate the total cost of owning, operating, and maintaining an asset over its entire life span. In the context of highway pavement investment decisions, the analysis often considers all major costs associated the pavement including initial construction, maintenance, rehabilitation, user costs, and environmental costs, and the analysis may consider return on investment from salvage, if there is any return [9]. The usefulness of LCCA is based on the premise that it may be wiser to invest in a higher-quality pavement initially to limit maintenance and reconstruction costs in the future. LCCA could help to minimize overall spending on maintenance and rehabilitation compared to the costlier, more frequent maintenance required for a lower-quality pavement selected initially to save money, often due to budget constraints.

The deterministic and probabilistic approaches are the two common methods of LCCA used in highway pavement investment decisions. In deterministic LCCA, all input values and parameters are treated as known and fixed, and there is no consideration of uncertainty or variability. A probabilistic LCCA uses probability distributions to represent input variables, allowing for a range of possible outcomes. In general, deterministic LCCA provides a more simplified and faster methodology since it does not require probability distributions and multiple iterations. Probabilistic LCCA can provide decision makers a more comprehensive and realistic assessment of the potential variability in costs [10]. In this study, a deterministic LCCA was selected for simplicity and for a lack of accurate statistical data to populate the probabilistic model.

For the deterministic approach, the net present value (NPV) is often used as the economic indicator to compare options. NPV is a discounted monetary value of expected net costs, i.e., costs minus benefits, and is given by Eq. 1:

$$\text{NPV}=\text{Initial Cost}+\sum_{k=1}^{N}\text{Maintenance cost}_k\,[1/(1+i)^{n_k}]-\text{Salvage value}[1/(1+i)^{n_e}] \quad (1)$$

where N is the number of maintenance interventions incurred over the analysis period, i is the discount rate (the percentage figure representing the rate of interest that money can be assumed to earn over the analysis period), n_k is the number of years from initial construction to the k^{th} expenditure, and n_e is the analysis period. Some examples of future maintenance costs incurred over an asphalt pavement lifetime include mill and overlay, crack sealing, and surface treatments. An example cash flow diagram depicting the expenditure and revenue stream for an asphalt pavement is shown in Figure 2.

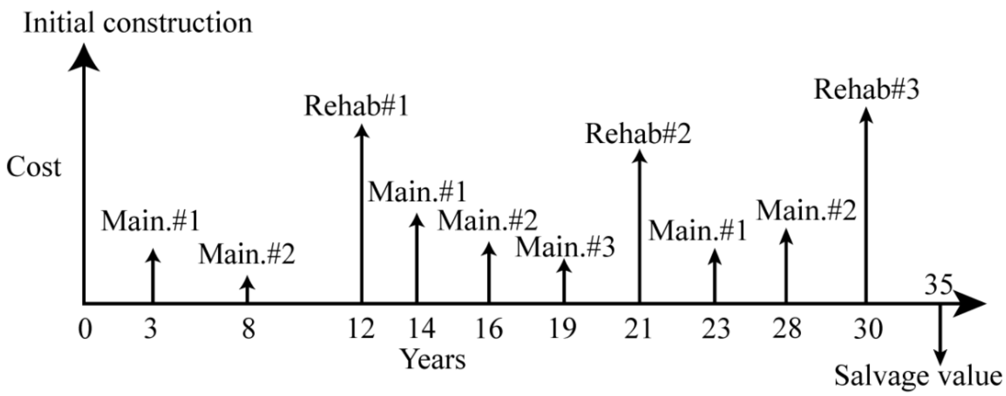

Figure 2 Example cash flow diagram of an asphalt pavement LCCA

Chapter 3: Results and Discussion

3.1 Laboratory Results

3.1.1 Dynamic Shear Rheometer (DSR) Results

The DSR results indicate the effects of GO on rutting performance of unaged binders at high temperatures. Since rutting is a cyclic loading phenomenon, the amount of work dissipated per loading cycle in the DSR test should be minimized to prevent rutting of an asphalt pavement. The rutting factor G*/sinδ, obtained from DSR testing data, is a measure of the ability of a binder to dissipate work. Rutting resistance is maximized when G*/sinδ is maximized. All samples were found to pass the AASHTO M320 criteria of G*/sinδ greater than 1.0 kPa at their higher test temperature of 64°C. The results for samples without GO added can be found in Tables 2 and 3, while the GO modified samples can be found in Tables 4 to 7.

Table 2 Rutting factor results from DSR testing of no GO PG-22 samples

Temp (°C)	G* (kPa)	δ (degrees)	G*/sinδ (kPa)
58	3.15	86.2	3.16
64	1.42	87.5	1.42
70	70	88.6	0.81

Table 3 Rutting factor results from DSR testing of Sample 1A: PG 64-22 with 0.2% GO

Temp (°C)	G* (kPa)	δ (degrees)	G*/sinδ (kPa)
58	4.33	84.0	4.35
64	1.75	86.4	1.75
70	0.83	87.9	0.83

Table 4 Rutting factor results from DSR testing of Sample 1B: PG-22 with 0.05% GO

Temp (°C)	G* (kPa)	δ (degrees)	G*/sinδ (kPa)
58	4.94	84.3	4.97
64	2.19	86.1	2.19
70	1.01	87.5	1.01

Table 5 Rutting factor results from DSR testing of no GO PG 64-28 samples

Temp (°C)	G* (kPa)	δ (degrees)	G*/sinδ (kPa)
58	2.05	71.48	2.16
64	1.12	73.45	1.17
70	0.62	76.21	0.64

Table 6 Rutting factor results from DSR testing of Sample 2A: PG 64-28 with 0.2% GO

Temp (°C)	G* (kPa)	δ (degrees)	G*/sinδ (kPa)
64	2.03	69.98	2.16
70	1.20	71.69	1.26
76	0.57	74.01	0.69

Table 7 Rutting factor results from DSR testing of Sample 2B: PG 64-28 with 0.05% GO

Temp (°C)	G* (kPa)	δ (degrees)	G*/sinδ (kPa)
64	1.82	71.15	1.92
70	1.01	73.05	1.05
76	0.57	75.61	0.59

Samples 1B, 2A, and 2B satisfied the rutting factor G*/sinδ threshold value of 1.0 kPa per AASHTO M320, at or above 70°C. This means that these samples could potentially be re-graded at a higher value than the PG of the unmodified sample. Sample 1B could be re-graded as a PG 70-22, while Samples 2A and 2B can be raised to a PG 70-28. Sample 1A failed at 70°C but passed at 64°C, so it would stay graded at a PG 64-22. This information can help CDOT, other state highway agencies, and civil construction contractors or asphalt binder manufacturers in the future by providing a potential different additive in asphalt binder to raise the higher end of a binder's PG.

In addition to higher PG grading, each of the binders can be compared at the 64°C measuring point and we see that the binders with GO added have between 50% to 80% higher rutting factors than that of the unmodified. From these results, we can conclude that adding the GO raises the rutting factor, making the binder stiffer, and in turn, more resistant to rutting.

In further examination of the GO modified binder DSR data, we can compare the results between similar PG samples. Looking at samples 1A and 1B at 64°C, G* is 1.75 kPa for Sample 1A and is 2.19 kPa for Sample 1B. Sample 1B, with only 0.05% by weight GO, has a larger G* than that of the sample 1A with a larger percentage GO. In other words, the neat binder in our testing protocol benefits more from the lower percentage of GO. This is the opposite of what is seen in the PG 64-28 samples. At 64°C, sample 2A has a G* of 2.038 kPa, while 2B has a G* of 1.82 kPa. Consequently, the SBS modified binder benefits from the higher GO percentage of 0.2% by weight. Both optimal weight percentages are similar to the findings of other studies [4].

Once the unaged samples were tested, the binder was then aged via RTFO and PAV. These PAV samples were then tested once more in the DSR, but this time with a smaller 8mm sample. All samples passed the required fatigue cracking parameter G*sin(δ) criteria of less than 6000 kPa at the required temperature per AASHTO M320, except for 2B which failed at the required temperature of 22°C. No RTFO and PAV samples were tested for the control (no GO) binders. Results for each sample can be found in Tables 8 to 11.

Table 8 PAV aged DSR fatigue cracking parameter results for Sample 1A: 64-22 with 0.2% GO

Temp (°C)	G* (kPa)	δ (degrees)	G*/sinδ (kPa)
22	6291	48.38	4703
19	9810	45.09	6948

Table 9 PAV aged DSR fatigue cracking parameter results for Sample 1B: 64-22 with 0.05% GO

Temp (°C)	G* (kPa)	δ (degrees)	G*/sinδ (kPa)
19	3928	60.91	3432
16	6755	57.21	5679
13	11376	53.06	9093

Table 10 PAV aged DSR fatigue cracking parameter results for Sample 2A: 64-28 with 0.2% GO

Temp (°C)	G* (kPa)	δ (degrees)	G*/sinδ (kPa)
19	3159	48.24	3159
16	6565	45.59	4690
13	10070	42.82	6845

Table 11 PAV aged DSR fatigue cracking parameter results for Sample 2B: 64-28 with 0.05% GO

Temp (°C)	G* (kPa)	δ (degrees)	G*/sinδ (kPa)
25	6164	48.01	4582
22	9368	45.05	6630

3.1.2 Bending Beam Rheometer (BBR) Results

The BBR test is used to evaluate the stiffness and cracking potential of asphalt binder at low temperatures. Since the asphalt binder becomes stiffer with age and becomes more susceptible to thermal cracking, the BBR test is conducted on RTFO and PAV-aged samples. The creep stiffness *S*, is a measure of thermal stresses in the asphalt binder resulting from thermal contraction. The lower the *S*, the better the resistance to thermal cracking. CDOT specifies a maximum *S* of 300 MPa. Table 12 presents the average *S* results from two BBR tests of five of the six binders at -12° C. A BBR test was not able to be conducted on the no GO PG 64-28 binder. It is somewhat concerning that Samples 1A and 2A, with a higher GO content, have a higher creep stiffness, which could indicate that binders with a higher GO content might be more susceptible to low temperature cracking. Low temperature cracking is a historical problem for asphalt pavements in Colorado; therefore, future research would be recommended to study the effects of low temperatures on the performance of GO modified binders.

Table 12 Bending Beam Rheometer (BBR) testing results

Binder sample	Force (mN)	Deflection (mm)	Estimated Creep Stiffness (Mpa)
PG 64-22 no GO	991.0	0.443	181.0
Sample 1A: PG 64-22 with 0.2% GO	986.5	0.395	200.5
Sample 1B: PG 64-22 with 0.05% GO	975.0	0.516	152.5
PG 64-28 no GO	-	-	-
Sample 2A: PG 64-28 with 0.2% GO	998.0	0.386	207.0
Sample 2B: PG 64-28 with 0.05% GO	994.0	0.499	161.5

3.2 Pavement ME Results

CDOT uses AASHTO's Pavement ME software to generate designs for both rigid and flexible pavements. The base design case for this study was developed from CDOT's Pavement ME Design Manual 2021. A ten-mile stretch of Interstate 70 located at the west side of Colorado near the Kansas border between mile markers 417 and 427 was used for the design scenario. Traffic data were retrieved from CDOT's Online Transportation Information System (OTIS) at station 103106. This section of interstate has an Average Annual Daily Traffic (AADT) of 10,000, with 2,850 of those vehicles being combination trucks. Weather data was imported into Pavement ME via a virtual weather station that combines the nearest weather stations to accurately estimate the climate at the project site (CDOT 2021). The pavement design is based on a 20-year design life and the LCCA will be performed over a 40-year span. Each scenario has 10 inches of asphalt cement concrete paved over 10 inches of non-stabilized base. Both layers are placed over a fair to poor strength subgrade with an AASHTO soil classification of A-7-6. The primary Pavement ME design inputs for initial construction are shown in Table 13.

Table 13 Primary Pavement ME design inputs for example I-70 CDOT highway construction project

Parameter	Value
Asphalt thickness	10 in
Asphalt mixture air voids	5.1%
Percent asphalt content per weight of mix	4.5%
Asphalt mixture unit weight	145 pcf
Base course classification	A-1-a (crushed aggregate)
Base course resilient modulus	30,000 psi
Subgrade classification	A-7-6
Subgrade resilient modulus	9495 psi

When a rehabilitation was required in LCCA methodology, a two-inch mill and overlay was placed over the existing pavement. To simulate the rehabilitation in Pavement ME, the existing asphalt layer was reduced from 10 in to 8 in. The existing 8 in pavement layer structural condition was updated to include the fatigue cracking and transverse cracking distress data from the previous Pavement ME evaluation. The rut depth of the existing pavement was set to 0 in for all layers since rutting is effectively removed after milling. The top 2-inch layer of new pavement was given the same properties as the new asphalt in the initial construction. A cross section of the rehabilitated design scenario in Pavement is shown in Figure 3.

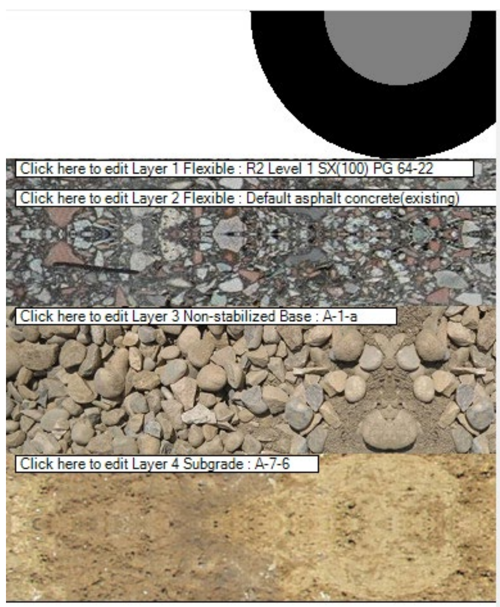

Figure 3 Example rehabilitated pavement cross section for PG 64-22 binder

Since GO addition influenced rutting more significantly than other distresses in our Pavement ME calculations, we selected rutting as the primary factor to dictate pavement repair rehabilitations in our life cycle model. We compared the 0.05% GO binder to the control binder for the PG 64-22 analysis and compared the 0.2% GO binder to the control binder for the PG 64-28 analysis. In the LCCA, when the pavement reached overall rut depth average of 0.4 inches, a rehabilitation was triggered. We assumed a 2-inch mill and overlay would be performed, and the overlay would restore the pavement to nearly the initial rut depth at initial construction. As shown in Figures 3a and 3b, each of the three mixtures starts at the Pavement ME initial rutting level of approximately 0.15 inches. In Figure 4a for the PG 64-22 mix, the no GO mix initially reaches the 0.4-inch threshold at 16.9 years and the 0.05% GO mix reaches it at 25.8 years. In this scenario, the no GO 64-22 mix would require a first mill and overlay at 16.9 years, a second mill and overlay at 29.5 years, and a third mill and overlay at 36.4 years. The 0.05% GO mix would require one mill and overlay. In Figure 4b for the PG 64-28 mix, the no GO mix initially reaches the 0.4-inch threshold at 13.8 years and the 0.2% GO mix reaches it at 19.7 years. In this scenario the no GO 64-28 mix would require a first mill and overlay at 13.8 years, a second mill and overlay at 27.1 years, and a third mill and overlay at 33.3 years. The 0.2% GO mix would require two mill and overlay rehabilitations.

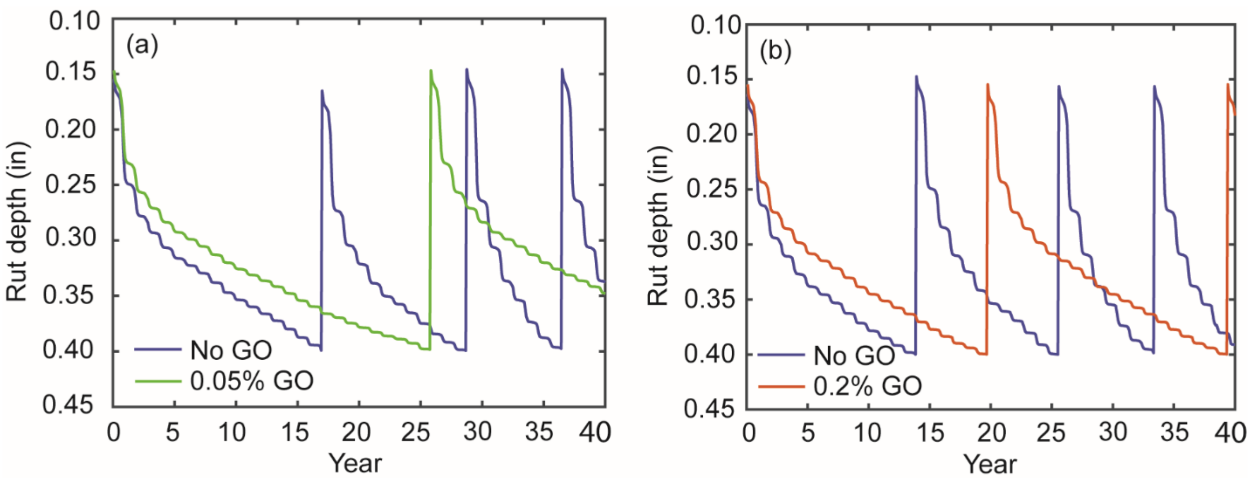

Figure 4 Pavement ME Calculated rutting depth for (a) PG 64-22 and (b) PG 64-28 LCCA scenarios

3.3 Life Cycle Cost Analysis (LCCA) Results

The cost of graphene varies significantly depending on the type and quality of graphene. GO prices are significantly higher than carbon nano tubes and graphene nano-platelets, but the potential improvements of GO for asphalt appear to be more pronounced for GO compared to these carbon nanomaterials. Currently, the unit cost of graphene oxide in large scale production is $481k to $1.35M per ton depending on the quality of the GO [11]. Since highway agencies would want the highest quality material when implementing a new technology such as this, the high end of the range, namely $1.35M per ton was selected for the LCCA. It should be noted the unit cost of the GO used for this study was much higher because it was purchased in a small quantity.

Using the rutting outputs from Pavement ME, a 2-inch mill and overlay rehabilitation was planned whenever the design scenario reached a rut depth of 0.4 inches. Cost data for initial construction was taken from the open source 2022 CDOT cost book database. Seven projects within the last five years were considered to estimate the PG 64-22 paving cost in Colorado. The total cost of PG 64-22 asphalt paving bid items for all the projects was divided by the total quantity paved in tons. This calculation resulted in an average unit cost across the last 5 years of $104.26 per ton for PG 64-22 paving. The same process was completed for projects with PG 64-28 binder. A total of 50 projects over the last 5 years were considered for PG 64-28, and the average unit cost was calculated at $109.27 per ton. With 0.2% GO and 0.05% GO added to PG 64-22 binder, the unit costs increase to $225.76 per ton and $134.63, respectively. With 0.2% GO and 0.05% GO added to PG 64-28 binder, the costs are $230.77 per ton and $139.65, respectively. Average costs for the 2-inch mill and overlay were also computed using CDOT cost book data. Milling costs from the past five year and above 5000 square yards were considered since small milling projects would have artificially inflated the milling unit cost. A total of 61 projects were considered in calculating the average unit cost for milling of $3.50 per square yard. For the GO mixes, the cost of GO was added to the cost of the two-inch overlay.

Combining the costs and rutting data from the previous presented, a life cycle cost analysis can be calculated for both 40-year lifetime scenarios. For sample 1B with 0.05% GO, NPV was calculated to be $24,413,218, which is a $188,503 cost savings from using the control PG 64-22 binder. Table 14 shows the LCCA results for the no GO PG 64-22 binder and Table 15 shows the LCCA results for the 0.05% GO PG 64-22 binder. For sample 2A with 0.2% GO, NPV was calculated to be $45,869,928, which is a $18,629,869 increase over the control PG 64-28 binder. Table 16 shows the LCCA results for the no GO PG 64-28 binder and Table 17 shows the LCCA results for the 0.2% GO PG 64-28 binder.

Table 14 LCCA results for control (no GO) PG 64-22 binder

Activity	Time (years)	Cost	Inflation	Present Value
Initial construction	0	$16,147,640.95	-	$16,147,641
Rehabilitation #1	16.9	$3,517,844	$297,258	$3,026,303
Rehabilitation #2	28.7	$3,517,844	$504,811	$2,714,451
Rehabilitation #3	36.4	$3,517,844	$640,248	$2,524,822
Total	-	-	-	$24,413,218

Table 15 LCCA results for 0.05% GO PG 64-22 binder

Activity	Time (years)	Cost	Inflation	Present Value
Initial construction	0	20,852,121		20,852,121
Rehabilitation #1	25.8	4,255,592	549,610	3,372,594
Total	-	-	-	$24,224,715

Table 16 LCCA results for control (no GO) PG 64-28 binder

Activity	Time (years)	Cost	Inflation	Present Value
Initial construction	0	$16,923,762	-	$16,923,762
Rehabilitation #1	13.8	$3,639,554	$251,129	$3,220,210
Rehabilitation #2	27.1	$3,639,554	$493,160	$2,850,547
Rehabilitation #3	33.3	$3,639,554	$605,986	$4,245,539
Total	-	-	-	$27,240,059

Table 17 LCCA results for 0.2% GO PG 64-28 binder

Activity	Time (years)	Cost	Inflation	Present Value
Initial construction	0	$35,741,682	-	$35,741,682
Rehabilitation #1	19.7	$6,590,546	$649,169	$5,526,643
Rehabilitation #2	39.3	$6,590,546	$1,295,042	$4,601,604
Total	-	-	-	$45,869,928

Chapter 4 Conclusions

Based on the findings of this study, the following conclusions can be made:

- The optimum dosage of GO for a neat (non-modified) PG 64-22 binder appears to be 0.05% by mass of binder. 0.2% by weight appears to be the optimum dosage for an SBS modified PG 64-28 binder. The 0.05% for neat binders and 0.2% for SBS is consistent with other similar studies [4].
- Adding GO to an asphalt binder increases the complex modulus (G*), stiffening the binder, which can reduce the rate of rutting and extend the life of an asphalt concrete pavement.
- GO can be a cost-effective additive to PG 64-22 asphalt binder over the lifetime of the pavement section, when considering the rutting model in Pavement ME with Colorado local calibration factors. The representative pavement is similar to designs for highways in Eastern Colorado. Further research would be needed to investigate cracking predictive models, low temperature performance, and performance in field conditions.
- The addition of GO to SBS modified binders in Colorado (i.e., PG 64-28) does not appear to have beneficial LCCA cost comparisons when using the rutting model in Pavement ME. However, this should be questioned as the base model for PG 64-28 without GO rutted faster than expected from a similar pavement.

This study has prompted additional ideas for further research into the addition of GO and other forms of graphene to asphalt binders. Full asphalt mixtures with graphene modified binders should be evaluated with asphalt mixture performance tests, including the Accelerated Mixture Performance Test (AMPT), Disk-shaped Compact Tension Test, and Indirect Tension Test. These tests would provide methods for measuring the dynamic modulus (E*) and Flow Number, which can be input into Pavement ME under a Level 1 analysis. Additional studies should evaluate a wide range of binder grades and the low temperature performance of GO modified asphalt binders. These types of additional studies would help inform industry and state highway agencies on the costs and benefits of incorporating graphene in asphalt pavements.

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