Universidade Federal do Rio Grande do Sul
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BITUMEN STABILISED MATERIALS IN BASE COURSES: LABORATORY AND FIELD STUDIES OF PERMANENT DEFORMATION AND REFLECTIVE CRACKING

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É melhor tentar e falhar,
que preocupar-se e ver a vida passar;
é melhor tentar, ainda que em vão,
que sentar-se fazendo nada até o final.
Eu prefiro na chuva caminhar,
que em dias tristes em casa me esconder.
Prefiro ser feliz, embora louco,
que em conformidade viver

Martin Luther King

RESUMO

Dias, C. Bitumen Stabilised Materials In Base Courses: Laboratory and Field Studies Of Permanent Deformation and Reflective Cracking. 2023. Tese (Doutorado em Engenharia) – Programa de Pós-Graduação em Engenharia Civil, UFRGS, Porto Alegre.

O uso de camadas granulares estabilizadas com ligantes asfálticos tem aumentado em todo o mundo nas últimas décadas. As razões para escolher estabilizar bases granulares estão relacionadas ao desempenho no campo, que melhora os resultados do custo do ciclo de vida (LCC) e da análise do custo do ciclo de vida (LCCA). Esta tese, composta por três artigos, concentra-se no estudo laboratorial e de campo de resistência, rigidez e deformação permanente de bases granulares tratadas com emulsão asfáltica e, no caso do trecho experimental sobre pavimento rígido, também avaliar a evolução de trincamento. O primeiro artigo apresenta uma revisão da literatura sobre a estabilização de camadas granulares com diferentes tipos de ligantes asfálticos. O segundo artigo avalia, por meio de testes laboratoriais e de campo, o comportamento mecânico dos materiais estabilizados com emulsão, que foram aplicados sobre pavimentos em três trechos com revestimentos asfálticos antigos. Foram realizados ensaios de resistência à tração indireta, triaxiais monotônicos e de carga repetida. Além disso, os módulos de elasticidade in situ foram obtidos por retroanálise de bacias de deflexão. O modelo do TG2 parece subestimar a vida dos pavimentos com camadas de revestimento espessas (> 40 mm). Um modelo relacionando a compactação ao Número N foi obtido, permitindo a previsão da afundamento de trilha de roda. Considerando o desempenho das seções de teste, as misturas mostraram ser eficientes para melhorar a capacidade estrutural, reduzindo também a influência da variação do nível de água no desempenho do pavimento. O terceiro artigo apresenta um estudo de caso de uma base aberta estabilizada com emulsão aplicada como camada anti-reflexão de trincas em reforço asfáltico sobre antigas placas de concreto. O programa experimental incluiu a análise de dados do monitoramento de pavimentos, como deflexões e condição de superfície, a fim de estimar o módulo in situ de cada camada e acompanhar a evolução do afundamento de trilha de roda e do trincamento durante o período de análise. A análise de deflexão demonstrou que as camadas estabilizadas mantiveram sua capacidade estrutural quando usadas como reforço sobre um pavimento rígido.Os resultados novamente sugerem que o modelo sul-africano tende a subestimar a vida útil de pavimentos com misturas abertas com emulsão (CBEM), devido, possivelmente, à dificuldade de obtenção em laboratório de um parâmetro de coesão que represente com acurácia a condição de campo. As principais contribuições dessa tese foram: a) A análise do estado superficial indicou que o pavimento com camada estabilizada com betume aberto apresentou porcentagem de trincamento baixa mesmo após 3 anos de construção, indicando sua eficácia na prevenção de trincamento por reflexão, mesmo quando aplicado sobre um pavimento de concreto fissurado; b) O modelo incluído apresentado no TG2 parece subestimar a vida útil dos pavimentos com camada aberta estabilizada com emulsão, possivelmente devido a dificulade na determinação do parâmetro de coesão durante os testes laboratoriais; c) A adição de cimento e RAP aumentou a coesão da mistura (CETM) em comparação com aquela estabilizada apenas com emulsão (CBEM); d) As camadas estabilizadas com emulsão mantiveram a sua capacidade estrutural, uma vez que não foram observadas deformações elásticas excessivas nem afundamentos no trilho de roda.

Palavras-chave: Bases granulares; estabilização com emulsão, deformação permanente; ensaios de laboratório; monitoramento de pavimentos; reflexão de trincas

ABSTRACT

Dias, C. Bitumen Stabilised Materials In Base Courses: Laboratory and Field Studies Of Permanent Deformation and Reflective Cracking. 2023. Tese (Doutorado em Engenharia) – Programa de Pós-Graduação em Engenharia Civil, UFRGS, Porto Alegre.

The use of the stabilized granular layers with asphalt binders has been increasing all around the world in the last decades. The reasons for choosing to stabilize granular bases are related to their performance in the field that improves the results of the life-cycle cost (LCC) and life-cycle cost analysis (LCCA).This thesis, which consists of three papers, focuses the study of strength, stiffness and permanent deformation behavior, and, in the case of the experimental section over rigid pavement, it also aims to assess the evolution of cracking. The first paper presents a literature review on the stabilization of granular layers with different types of asphalt binders. The second paper evaluate, through laboratory and field tests, the mechanical behavior of Bitumen Stabilized Materials applied as overlay in three section test. Indirect tensile strength, monotonic triaxial, and repeated load triaxial tests were carried out to obtain the necessary mechanical parameters. Besides, in situ moduli were obtained using backanalysis of deflection basins. Using field and laboratory results and the South African TG2 performance model, it was possible to estimate the life of the studied pavements regarding permanent deformation. The TG2 model seems to underestimate the life of pavements with thick (> 40 mm) asphalt layers. A model relating rutting to the number of ESALs was obtained, allowing the prediction of rutting. Considering the test sections' performances, the mixes proved to be efficient to improve structural capacity, also reducing the influence of the water level variation on pavement performance. The third paper presented a study of case of an Open Graded Base Stabilized with Emulsion applied as an anticracking Relief Layer. The experimental program included the analysis of available data from pavement monitoring, such as deflections and surface condition, in order to estimate the in-situ modulus of each layer and follow-up the evolution of rutting and cracking over the analysis period. The deflection analysis demonstrated that the bitumen-stabilized layers retained their structural capacity when used as an overlay on rigid pavement, as there were no signs of excessive elastic deformation or rutting. The findings suggest that the South African model tends to underestimate the lifespan of pavements with open-graded cold bituminous emulsion mixes (CBEM) due to the difficulty of obtaining in the laboratory a cohesion parameter in the laboratory that accurately represents the field condition.. Following are the most meaningful findings of this thesis: a)The analysis of the surface condition indicated that the pavement with the open-graded bitumen stabilized layer exhibited minimal cracking even after 3 years of construction, indicating its effectiveness in preventing reflection cracking, even when applied over a cracked concrete pavement; b) The model included in TG2 South African document seems to underestimate the life of pavements with the studied open-graded bitumen stabilized layer, possibly due to challenges in determining the cohesion parameter during laboratory testing; c) The addition of cement and RAP increased the cohesion of the mix (cement emulsion treated mix, CETM) compared to that stabilized with emulsion only (cold bituminous emulsion mix, CBEM); d) The bitumen stabilized layers kept their structural capacity since neither excessive elastic deformation nor rutting was observed.

Keywords: Granular Bases, Emulsion stabilization, permanent deformation, laboratory test, paveament monitoring, anti-reflective cracking.

SUMÁRIO

LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

AASHTO: American Association of State Highway and Transportation Officials

ARRA: Asphalt Recycling & Reclaiming Association

ASTM: American Society for Testing and Materials

ATPB: Asphalt Treatment Permeable Base

BBF: Binary Blended Filler

BSM: Bitumen Stabilised Materials

CAEM: Cold Asphalt Emulsion Mixtures

CALTRANS: California Department of Transportation

CBEM: Cold Bituminous Emulsion Mixture

CBTM: Cement Bitumen-Treated Materials

CBTM-BE: Cement Bitumen Treated Materials Bituminous Emulsion

CBTM-FB: Cement Bitumen Treated Materials Foam Bituminous

CIPR: Cold in Place Recycling

CRM: Cold Recycled Mixture

CTM: Cement Treated Materials

DCP: Dynamic Cone Penetrometer

DER-SP: Departamento de Estradas de Rodagem do Estado de São Paulo

DNER: Departamento Nacional de Estradas de Rodagem

DNIT: Departamento Nacional de Infraestrutura de Transportes

DSR: Deviator Stress Ratio

EAM: Emulsion Aggregate Mixture

EATB: Emulsified Asphalt Treated Base

ESALs: Number of Equivalent Single Axle Loads

ESG: Environmental and Social and Governance

ETB: Emulsion Treated Bases

FA: Fly Ash

FATB: Foamed Asphalt Treated Base

FDR: Full Depth Reclamation

FEM: Finite Element Modeling

FHWA: Federal Highway Administration

FWD: Falling Weight Deflectometer

GEMs: Granular Emulsion Mixes

GGBS: Ground Granulated Blast Furnace Slag

HATB: Hot Asphalt Treated Base

HMA: Hot Mixture Asphalt

HVS: Heavy Vehicle Simulator

IDT: Indirect Tensile Test

IDTS: Indirect Tensile Strength

ITFT: Indirect Tensile Fatigue Test

ITS: Indirect Tensile Strength

ITSM: Indirect Tensile Stiffness Modulus

ITSR: Indirect Tensile Strength Ratio

LCC: Life Cycle Cost

LCCA: Life Cycle Cost Analysis

LTPP: Long Term Pavement Performance

LWD: Light Weight Deflectometer

M&F: Mill and Fill

MDD: Maximum Dry Density

ME: Mechanistic Empirical

MR: Resilient Modulus

MTO: Ministry of Transportation Ontario

NCHRP: National Cooperative Highway Research Program

OMC: Optimum Moisture Content

OPC: Portland cement

PCI: Pavement Condition Index

PFWD: Portable Falling Weight Deflectometer

RAP: Reclaimed Asphalt Pavement

RLAT: Repeated Load Axial Test

SABITA: Southern African Bitumen Association

SF: Silica Fume

TBF: Ternary Blended Filler

TG2: Technical Guideline

UCS: Unconfined Compressive Strength

UFRGS: Universidade Federal do Rio Grande do Sul

UN: United Nations Organization

1 INTRODUCTION

Due to the growth of commercial traffic in Brazilian roads, both in terms of the number of heavy trucks and the total gross weights and axle loads, there has been an increased necessity to research road pavement layers with higher resistance. If the conventional pavement design is adopted, i.e., asphalt layers over granular layers, the result will be increasingly thicker (close to 20 cm) asphalt layers to prevent premature pavement fatigue failure.

Besides increasing the risk of permanent deformation, the use of thicker asphalt layers results in higher consumption of non-renewable natural resources, depleting quarries and deposits while also increasing energy and fuel consumption. This contradicts the United Nations (UN) objectives related to ESG (Environmental, Social, and Governance) policies.

In addition, granular-based pavements may be susceptible to regional climate-related issues. For example, the Southern Zone of the State of Rio Grande do Sul (RS), Brazil, is characterized by a harsh and rainy winter, raising the water table level, which can lead to excess moisture in the base and subbase layers.

To meet these structural reinforcement needs and reduce susceptibility to damage caused by excess moisture, the implementation of asphalt-treated base layers over existing pavements with reduced structural capacity is an option to be explored.

Besides, open-graded bases treated with asphalt (foamed or emulsion) may also be effective in controlling and mitigating crack reflection when applied over severely cracked rigid or semi-rigid pavements.

In Rio Grande do Sul, open-graded asphalt bases have been experimentally used- in pavement rehabilitation. The particle size distribution used is similar to the Asphalt-Treated Bases of the Department of Highways of the State of São Paulo (ET-DE-P00/026) and the one presented in the 2010 CALTRANS specification for Asphalt-Treated Permeable Bases (ATPB). The main difference between these specifications and the local practice lies in the fact that in Rio Grande do Sul, these mixtures have been prepared using cold-mixing techniques asphalt emulsion.

Three open-graded asphalt base sections were applied as overlays of damaged pavements and have been monitored since construction. Two of these sections belong to heavily trafficked Brazilian Federal Highways (BR-392 and BR-116), being constructed over flexible pavements, in regions with frequent rises of the water table. Additionally, on BR 392 a test section was built over an old rigid pavement, to evaluate its feasibility as mitigating cracking reflection strategy.

Another technique is the stabilization of bases with asphalt emulsion, where crushed stone mixtures, materials from pavement milling (commonly known as RAP, from "reclaimed asphalt pavement") and cement are added. This technique, known as Bitumen Stabilized Materials (BSM), has been used in several countries, including Brazil, in pavement recycling.

BSM exhibits stress-state-dependent properties, and its performance should be measured in terms of permanent deformation. There is no agglomeration of all the aggregates by the asphalt, which makes the behavior of these mixtures similar to that of granular mixtures but with greater cohesion and less sensitivity to humidity.

In 2019, the road concessionaire responsible for the administration of the Pelotas Highway Network, in Rio Grande do Sul State, built a test section on BR 116. The results of the field performance of this mixture have also been monitored since construction. It should be noted that this experimental section was also applied as an overlay to the existing pavements, rather than as a recycling of the surface and base.

At national level, there are no procedures or manuals for the design and performance prediction of pavements containing emulsion-stabilized layers, and methodologies from abroad have been adopted. Therefore, there is an explicit need to contribute to understanding the mechanical behavior of these mixtures by relating long-term monitoring data from test segments to laboratory results and mechanistic performance predictions.

It is worth highlighting the innovative fact that all the aforementioned experimental sections were executed as overlays on existing pavements.

1.1 OBJECTIVES

1.1.1 General objective

The general objective of this research was to study strength, stiffness and permanent deformation behaviour of Bitumen Stabilized Materials constructed in heavily trafficked highways in Southern Brazil. Regarding the BSM layer over rigid pavement, it was also aimed to assess the evolution of cracking.

1.1.2 Specific objectives

In order to attain the general objective, the following activities were addressed:

a) To evaluate the bearing capacity of the experimental pavements through the analysis of stiffness evolution, using field-collected data;

b) To follow the performance of experimental pavements regarding permanent deformation evolution using field-collected data and comparing with that predicted by a Performance Model, included in TG2 South African document;

c) To obtain a Prediction Model for the Evolution of Permanent Deformation (rutting) of Bitumen Stabilized Materials applied as overlays;

d) To evaluate the effectiveness of Open Graded Granular Bases Stabilized with Emulsion to delay reflection cracking in rehabilitated pavements.

1.2 THESIS STRUCTURE

This PhD thesis consists of five chapters. This section summarises the content of each one.

As previously seen, Chapter 1 (Introduction) presents the research theme, states its relevance and lists the research objectives.

Chapters 2 to 4 consist of three journal papers. The thesis author is the main author of all of them. Although these studies have had collaborators, the first author was the only one involved in all parts of the thesis, including planning, testing, analysing and writing. In this thesis presentation version, only the abstracts are included due to copyright issues.

Chapter 2 presents a literature review on the stabilization of granular layers with different types of asphalt binders. It focuses on the following topics: history, analysis of different mixes and structural designs, field behavior, and cost and environmental advantages.

Chapter 3 introduces a published article that evaluates the mechanical properties of Bitumen Stabilized Materials utilized as overlays in three distinct test sections. This evaluation is conducted through a combination of laboratory experiments and field tests.

Chapter 4 presents an article submitted for publication, that presents a case study on the use of an Open Graded Base Stabilized with Emulsion to delay reflection cracking in rehabilitated pavements. It is remarked that the same methodology for performance analyses was used in the papers presented in chapters 3 and 4.

Chapter 5 presents the conclusions of each paper, the contributions to the knowledge and recommendations for further research.

2 AN OVERVIEW OF STABILIZATION OF GRANULAR LAYERS WITH ASPHALT, EMULSION AND FOAM ASPHALT: MECHANICAL PROPERTIES, PERFORMANCE AND ENVIRONMENTAL ASPECTS.

Abstract:

The use of the stabilized granular layers with asphalt binders (hot and cold mixtures) has been increasing all around the world in the last decades. The reasons for choosing to stabilize granular bases are related to their performance in the field that improves the results of the life-cycle cost (LCC) and life-cycle cost analysis (LCCA) when applied as an important tool to achieve the goals of the Environmental and Social and Governance (ESG) program by the United Nations Organization (UN). This paper aims to discuss the behavior of this stabilized material, through an extensive review of the literature on the mechanical properties and performance prediction of such mixtures and their economic and environmental assessment when compared to a conventional pavement rehabilitation technique. The paper highlights that the use of stabilization base layers improves significant benefits, such as Open Treated Base could be used to mitigate the problems associated with high pavement water contents and also, can help to control reflective cracking and Cold mixtures of Bitumen Stabilized Materials (BSM´s) present advantages of less raw materials and fossil fuel consumption and lower carbon footprint due to the improvement on the performance of the pavements..

Keywords:

Open Treated Base, Bitumen Stabilized Materials (BSM), performance, environmental, ESG.

Highlights:

- Anti-reflective cracking bitumen stabilized layer.
- Permanent deformation as model of failure
- Repeated Load and Monotonic triaxial Tests and Indirect Tensile Strength (ITS).
- Life-cycle cost (LCC) and Life cycle cost analysis (LCCA)

3 BITUMEN STABILIZED MATERIALS AS PAVEMENT OVERLAY: LABORATORY AND FIELD STUDY.

Article published in Construction and Building Materials

DOI: https://doi.org/10.1016/j.conbuildmat.2023.130562

Abstract

Bitumen stabilized materials applied as base courses have been used in many countries. In the southern Brazilian State of Rio Grande do Sul, two test sections were built using such mixes (in 2011 and 2015) as overlay asphalt emulsion base courses and have been under monitoring since then. In 2019, a new test section was built to evaluate mixes of granular materials and reclaimed asphalt pavement stabilized with emulsion and Portland cement as overlay base courses. The main objective of the research reported here was to evaluate the mechanical behavior of such materials and to assess their performance in the field during the years after construction. Indirect tensile strength, monotonic triaxial, and repeated load triaxial tests were carried out to obtain the necessary mechanical parameters. The data collected during the monitoring of the test sections were used to analyze the field performance in terms of permanent deformation. Besides, in situ moduli were obtained using backanalysis of deflection basins. The number of equivalent single axle loads (ESALs) for the analysis period was computed using data collected in toll plazas near the test sections. Using field and laboratory results and the South African TG2 performance model, it was possible to estimate the life of the studied pavements regarding permanent deformation. The TG2 model seems to underestimate the life of pavements with thick (> 40 mm) asphalt layers. A model relating rutting to the number of ESALs was obtained, allowing the prediction of rutting of asphalt pavements overlaid by a bitumen stabilized base layer and asphalt wearing courses. Considering the test sections' performances, the mixes proved to be efficient to improve structural capacity, also reducing the influence of the water level variation on pavement performance.

Keywords

Bitumen stabilized material, RAP, cement, base course, overlay, rutting

Highlights

- Crushed aggregates and reclaimed asphalt pavement mixes were stabilized with asphalt emulsion and cement.
- Monotonic and repeated load triaxial tests for bitumen stabilized materials.
- Evaluation of the permanent deformation of bitumen stabilized materials in the field.
- Assessment of deflections and pavement surface condition of bitumen stabilized materials test sections.

4 AN OPEN-GRADED BITUMEN STABILIZED BASE COURSE AS A PAVEMENT OVERLAY ANTI-REFLECTIVE CRACKING SOLUTION.

Article submitted on 10/05/2023 to Transportation Geotechnics

Abstract

The Port of Rio Grande is located in the city of Rio Grande in Rio Grande do Sul, the southernmost state of Brazil. The port terminals are accessed through a section of National Highway BR-392, with an original concrete pavement built in 1975. A few decades later, a layer of asphalt concrete was added on top of the cracked concrete pavement. In 2019, a test section was constructed, which included an open-graded (permeable) cold bituminous emulsion mix (CBEM) base overlaying the existing pavement to reduce crack reflection. The objective of the research presented here was to assess the mechanical behavior of the bitumen-stabilized base and its suitability in delaying crack reflection. The experimental program included the analysis of available data from pavement monitoring, such as deflections and surface condition, in order to estimate the in-situ modulus of each layer and follow-up the evolution of rutting and cracking over the analysis period. The number of equivalent single axle loads (ESALs) was calculated through the data files from the surveys conducted over a three-day period. A mechanistic-empirical (M-E) analysis was conducted using the South African model for bitumen-stabilized materials, and the results were compared with field performance. The deflection analysis demonstrated that the bitumen-stabilized layers retained their structural capacity when used as an overlay on rigid pavement, as there were no signs of excessive elastic deformation or rutting. The findings suggest that the South African model tends to underestimate the lifespan of pavements with open-graded cold bituminous emulsion mixes (CBEM) due to the difficulty of obtaining in the laboratory a cohesion parameter in the laboratory that accurately represents the field condition. The surface condition analysis revealed that the asphalt mix applied over the CBEM base course exhibited low-level cracking after 3 years of construction, indicating that such open-graded mixes are effective in delaying crack reflection.

Keywords

Bitumen stabilized material, open-graded mix, anti-reflective cracking, base course, overlay

Highlights

- Bitumen stabilized overlay as an anti-reflective cracking solution.
- Open-graded aggregates stabilized with asphalt emulsion.
- Structural assessment of a pavement test section with a bitumen stabilized overlay.
- Cracking and rutting of a pavement test section with a bitumen stabilized overlay.

5 CONCLUDING REMARKS

This chapter presents a summary of the conclusions of each article, the main contributions of these thesis and recommendations for further researches.

5.1 CONCLUSIONS

Regarding the characteristics of the mixtures in terms of stiffness and mechanical behavior:

- The Resilient modulus of Open Treated Bases and Bases Stabilized with Emulsion or Foamed Asphalt range from 400 to 2,000 MPa. The resilient modulus (MR) increases as the confining pressure (σ3) and deviatoric stress (σd) increase, exhibiting the same behavior as granular bases. This understanding is important for determine which failure model should be adopted in pavement design;
- The model of failure of these materials is permanent deformation. Therefore, it is recommended to utilize the TG2 Guideline for designing the mixture and pavement projects;
- Open Treated Base could enhance the reflection crack resistance even when applied between a semirigid or rigid base course and an asphalt concrete layer.

Regarding particle size distribution, aggregate shape and type of RAP:

- The size distribution, including the proportion of fines, and the shape of aggregates play a crucial role in determining the performance of the mixture. These characteristics are significant for achieving improved compaction and mechanical interlocking, as well as increasing the specific surface area. This increased surface area allows for better adhesion between the binder and the aggregates. Moreover, fines have an essential function, as they serve as the medium through which the emulsion is dispersed within the mixture, contributing to the overall performance and stability of the material;
- An aged RAP, with a harder bitumen material, provides a better interlocking, improving resistance to permanent deformation in dry conditions. Nevertheless, in soaked conditions, the resistance of permanent deformation becomes poor. A soft bitumen helps

mixes to improve the moisture susceptibility and achieve better results when analyzed in both conditions together (dry and soaked).

Concerning the incorporation of blended fillers, cement, and lime:

- When higher quantities of cement are incorporated into the mixtures, their behavior shifts towards that of cement-stabilized bases, which leads to the need to study the fatigue of these mixtures. Consequently, in such scenarios, it is advised not to categorize these mixtures as asphalt-stabilized bases;
- The use of binary blended filler (BBF) and ternary blended filler (TBF) enhances mix stiffness and significantly reduces its susceptibility to permanent deformation. This kind of filler could replace the cement and lime from the mixture and improve the environmental analysis in terms of LCCA.

Concerning the curing process, water saturation and layer compaction thickness:

- A layer thickness of 15 cm showed the most favorable to achieve better mechanical properties but some concerns must be taken, the mechanistic-empirical function gives a shorter life than the Pavement Number and this must be carefully analyzed;
- Concerning the curing process, higher temperature accelerates water evaporation, and increases the cohesion and friction angle of the mixture, improving the permanent strain of the mixture. This is important to be considered in the planning of the field works;
- When using Open Treated Base, as demonstrated in the ATPB examples, it's crucial to address concerns related to water saturation within the layer. This is because excessive water saturation can lead to a significant reduction in resilient modulus, increased permanent deformation, and a loss of cohesion between aggregates. Therefore, it's important to monitor the content and quality of the binder agent to enhance resistance to water damage.

About LCA and LCCA:

- In terms of environmental impact, since BSM does not require hot mixing, the overall environmental impact is significantly lower than that of the traditional mill and fill, with a reduction in energy consumption and carbon emissions. In addition to environmental

benefits, BSM costs less than a traditional rehabilitation technique in terms of initial and life-cycle costs when analyzed by LCA procedures;

5.2 MAIN CONTRIBUTIONS

This research has advanced the understanding of the mechanical properties and performance behavior based on field data analyses of bitumen-stabilized materials used as overlays. The primary objective was to investigate the strength, stiffness, and permanent deformation behavior of bitumen-stabilized materials in heavily trafficked areas. This was accomplished by evaluating the bearing capacity and comparing the performance of experimental pavements. The comparison involved the evolution of permanent deformation, contrasting it with predictions made by a Performance Model outlined in the TG2 South African document.

Additionally, the study aimed to develop a Prediction Model for the Evolution of Permanent Deformation and to assess the effectiveness of Open Graded Granular Bases Stabilized with Emulsion in delaying reflection cracking in rehabilitated pavements.

The following summarizes the most meaningful findings of this research:

- The open-graded bitumen stabilized layer showed high structural capacity as an overlay on a cracked concrete pavement;
- The analysis of the surface condition indicated that the pavement with the open-graded bitumen stabilized layer exhibited minimal cracking even after 3 years of construction, indicating its effectiveness in preventing reflection cracking, even when applied over a cracked concrete pavement;
- The model included in TG2 South African document seems to underestimate the life of pavements with the studied open-graded bitumen stabilized layer, possibly due to challenges in determining the cohesion parameter during laboratory testing;
- The addition of cement and RAP increased the cohesion of the mix (cement emulsion treated mix, CETM) compared to that stabilized with emulsion only (cold bituminous emulsion mix, CBEM);
- The bitumen stabilized layers kept their structural capacity since no excessive rutting was observed;

- The TG2 model seems to underestimate the life of pavements with thick asphalt wearing courses (> 40 mm);
- A model correlating rutting with the accumulated number of equivalent single axle loads (ESALs) was obtained. It allows rutting estimation of old asphalt pavements overlaid by bitumen stabilized layers and asphalt wearing courses. The model might be interesting for pavement management, although it is only valid for the investigated ranges of ESALs and rutting.

5.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Based on the presented thesis, the following are recommendations for further research:

- Bitumen stabilized layers are effective in mitigating reflective cracking. However, the currently used prediction models may underestimate the life of pavements with these layers. It is also important further studies to analyze how the prediction of crack evolution can be improved, taking into consideration shear stresses, fatigue, and reflection cracking;
- The mechanistic-empirical function presented in TG2 estimates a shorter life than the Pavement Number for layer thickness of 15 cm, but this thickness achieved the most favorable mechanical properties after field compaction. It is important to carry out studies that aim at better aligning performance predictions with better construction procedures;
- As verified in the field, when the asphalt coating layers exceeded 40 mm, the TG2 model seems to underestimate the life of pavements. Future studies are needed to better calibrate such model, especially when BSM is applied over an existing damaged pavement.

6 REFERENCES

AASHTO T307-99. Standard Method for Preparing and Determining the triaxial resilient Modulus of soils. American Association of State Highway and Transportation Officials, 1999.

AASHTO TP 79. Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT). American Association of State Highway and Transportation Officials, 2015.

Akeroyd, F. M. L., and B. J. Hicks. "Foamed bitumen road recycling." Highways 56.1933 (1988): 42-43.

Akeroyd, F. M. "Advances in foamed bitumen technology." Conference on Asphalt Pavements for Southern Africa, 5th, 1989, Manzini, Swaziland. 1989.

Alkins, A. E., Lane, B., & Kazmierowski, T. (2008). Sustainable Pavements: Environmental, Economic, and Social Benefits of In Situ Pavement Recycling. Transportation Research Record, 2084(1), 100–103. https://doi.org/10.3141/2084-11.

Al-Qadi, I.L., et al., 2003. Quantitative field evaluation and effectiveness of fine mix under hot-mix asphalt base in flexible pavements. Transportation Research Record: Journal of the Transportation Research Board, 1823, 133–140.

Anderson, J. R., and Thompson, M. R. (1995). Characterization of Emulsion Aggregate Mixtures. Transportation Research Board 1942, Transportation Research Board, Washington, D.C., 108−117.

Asphalt Academy. TG 2 Third Edition, Technical Guideline: Bitumen Stabilised Materials. A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials. Pretoria, South Africa. 2020.

ASTM D 2166/06. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. American Society for Testing and Materials, 2006.

ASTM D 6931/07. Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures. American Society for Testing and Materials, 2007.

Barbod B, Shalaby A. Laboratory Performance of Asphalt Emulsion Treated Base for Cold Regions Applications. Conference of the Transportation Association of Canada Montreal, Quebec, 2014.

Bejarano, M.O., et al., 2004. Performance of drained and undrained flexible pavement structures under wet conditions test data from accelerated pavement test section 543-drained. Report UCD-ITS-RR-04-6.

Bocci M, Canestrari F, Grilli A, Pasquini E, Lioi D. (2010). Recycling techniques and environmental issues relating to the widening of a high traffic volume Italian motorway. International Journal of Pavement Research and Technology, 3(4), 171–177.

Bocci M, Grilli A, Cadone F, Graziani A. A study on the mechanical behaviour of cement–bitumen treated materials, Constr. Build. Mater. 25 (2) (2011) 773–778. https://doi.org/10.1016/j.conbuildmat.2010.07.007

Bocci M, Grilli A, Cardone F, Ferrotti G. (2012). Full-depth reclamation for rehabilitation of local roads: A case study. International Journal of Pavement Engineering, 15(3), 191–201. https://doi.org/10.1080/10298436.2012.657196

Bocci, M., Grilli, A., Riviera, P., Tolentino, F., and Paglione, S., (2008). Il Riciclaggio a Freddo per l'Ampliamento della Terza Corsia dell'Autostrada A14, Strade & Autostrade, 72(6), pp. 133-140.

Cardone F, Virgili A, Graziani A. (2018). Evaluation of bonding between reclaimed asphalt aggregate and bitumen emulsion composites. Construction and Building Materials, 184, 565–574. https://doi.org/10.1016/j.conbuildmat.2018.07.016

Chen, Yu. Composite specimen testing to evaluate the effects of pavement layer interface characteristics on cracking performance. University of Florida, 2011.

Chun, A. Nazef, E. Offei, J. Greene, and B. Choubane. Effectiveness of crack relief techniques to mitigate reflective cracking in asphalt overlaid concrete pavement. Submitted for presentation and publication at the 2016 Transportation Research Board Annual Meeting.

Collings D., Jenkins K. The long-term behavior of bitumen stabilized materials (BSMs). 10th Conference on Asphalt Pavements for Southern Africa, 2011.

Dal Ben D, Jenkins K J. (2014). Performance of cold recycling materials with foamed bitumen and increasing percentage of reclaimed asphalt pavement. Road Materials and Pavement Design, 15(2), 348–371. http://dxdoi.org/10.1080/14680629.2013.872051

Departamento de Estradas e Rodagem do Estado de São Paulo. ET-DE-P00/025– Pré-Misturado a Frio. São Paulo, 2006.

Departamento de Estradas e Rodagem do Estado de São Paulo. ET-DE-P00/026– Pré-Misturado a Quente. São Paulo, 2006.

Departamento Nacional de Estradas de Rodagem. Avaliação Estrutural dos Pavimentos Flexíveis – Procedimento: DNER 011/1979 - PRO. Rio de Janeiro, 1979.

Departamento Nacional de Estradas e Rodagem. DNER ES-P-106/80 -Pré-Misturado tipo Macadame, IPR, Rio de Janeiro

Departamento Nacional de Estradas e Rodagem. DNER-ES 317/97 –Pavimentação – Pré-misturado a frio. Rio de Janeiro, 1997.

Departamento Nacional de Infraestrutura de Transportes. Avaliação objetiva da superfície de pavimentos flexíveis e semi-rígidos – Procedimento: DNIT 006/2003 - PRO. Rio de Janeiro, 2003.

Departamento Nacional de Infraestrutura de Transportes. Determinação de deflexões utilizando deflectômetro de impacto tipo "Falling Weight Deflectometer (FWD)": DNER-PRO 273/96. Rio de Janeiro, 4 p. 1996.

Departamento Nacional de Infraestrutura de Transportes. Pavimentação – Solos – Determinação do módulo de resiliência – Método de ensaio: DNIT 134/2010 – ME. Rio de Janeiro, 11 p. 2010b.

Dhakal N, Elseifi M A, Zhang Z. Mitigation Strategies for Reflection Cracking in Rehabilitated Pavements – A synthesis. International Journal of Pavement Research and Technology 9 (2016) 228-239.

Dias C R C, Núnez W P, Brito L A T, Johnston M G, Ceratti J A P, Wagner L L, Fedrigo W. Bitumen stabilized materials as pavement overlay: Laboratory and field. Construction and Building Material 369 (2023) 130562.

Dolzycki B, Jaczewski M, Szydlowski C. The long-term properties of mineral-cement-emulsion mixtures. Construction and Building Materials, n° 156, pp 799–808, 2017.

Dołżycki B, Jaskuła P. (2019). Review and evaluation of cold recycling with bitumen emulsion and cement for rehabilitation of old pavements. Journal of Traffic and Transportation Engineering (English Edition), 6(4), 11–323. https://doi.org/10.1016/j.jtte.2019.02.002

F. Ma, W. Dong, Z. Fu, R. Wang, Y. Huang, J. Liu, Life cycle assessment of greenhouse gas emissions from asphalt pavement maintenance: a case study in China, J. Clean. Prod. 288 (2021), 125595.

F.G. Pratico, M. Giunta, M. Mistretta, T.M. Gulotta, Energy and environmental life cycle assessment of sustainable pavement materials and technologies for urban roads, Sustainability 12 (2) (2020) 704.

F.G. Pratico, M. Giunta, M. Mistretta, T.M. Gulotta, Measuring the Sustainability of Transportation Infrastructures Through Comparative Life Cycle and Energy Assessment, New Metropolitan Perspectives: Knowledge Dynamics and Innovation driven Policies Towards Urban and Regional Transition 2 (2021). Volume.

Federal Highway Administration (FHWA), Life-Cycle Cost Analysis Software. Federal Highway Administration, Washington, DC (2011).

Fedrigo W, Núñez W P, Visser A T. (2020). A review of full-depth reclamation of pavements with Portland cement: Brazil and abroad. Construction and Building Materials, 262, 120540. https://doi.org/10.1016/j.conbuildmat.2020.120540

Fu P, Jones D, Harvey J T, Bukhari S A. Laboratory test methods for foamed asphalt mix resilient modulus, Road Mater. Pavement Des. 10 (1) (2009) 187–212. https://doi.org/10.3166/RMPD.10.187-212

Fu P, Steven B D, Jones D, Harvey J T. Relating Laboratory Foamed Asphalt Mix Resilient Modulus Tests to Field Measurements. Road Mater. Pavement Des. 10 (1) (2009) 155-185. https://doi.org/10.1080/14680629.2009.9690186

G. Thenoux, Á. González, R. Dowling, Energy consumption comparison for different asphalt pavements rehabilitation techniques used in Chile, Resour. Conserv. Recycle. 49 (4) (2005) 325–339.

Godenzoni C, Graziani A, Perraton, D. (2017). Complex modulus characterisation of cold-recycled mixs with foamed bitumen and different contents of reclaimed asphalt. Road Materials and Pavement Design, 18(1), 130–150. https://doi.org/10.1080/14680629.2016.1142467

Graziani A, Godenzoni C, Cardone F, Bocci E, Bocci M. An application of the Michaelis–Menten model to analyze the curing process of cold recycled bituminous mixes, International Journal of Pavement Research and Technology, 10(1), 2017, 62-74, https://doi.org/10.1016/j.ijprt.2016.09.002

Graziani A., Mignini C., Bocci E., Bocci M. Complex Modulus Testing and Rheological Modeling of Cold-Recycled Mixtures. Journal of Testing and Evaluation, https://doi.org/10.1520/JTE20180905, 2019.

Grilli A, Graziani A, Bocci M. (2012). Compactability and thermal sensitivity of cement–bitumen-treated materials. Road Materials and Pavement Design, 13(4), 599–617. https://doi.org/10.1080/14680629.2012.742624

Guatimosim F V, Vasconcelos K L, Bernucci L L B, Jenkins K J. Laboratory and field evaluation of cold recycling mix with foamed asphalt, Road Mater. Pavement Des., 19(2), 385-399, (2018), http://dxdoi.org/10.1080/14680629.2016.1261726

Guide to Pavement Technology Part 4D: Stabilised Materials. Edition 2.1 published April 2019. Austroads 2019.

Guo H, Chen S. Numerical simulation of the reflective crack propagation path for Open-graded Large Stone asphalt mixes [C]. 2010 International Conference on Advances in Materials and Manufacturing Processes, ICAMMP 2010, November 6, 2010 - November 8, 2010, 2011: 180-183.

Harvey J, Tsai B, Long F, Hung, D. Asphalt-Treated Permeable Base - Laboratory Testing, Performance, and Predictions. Transportation Research Record 1629, 98-0643; 1998.

Harvey, J., Tsai, B., Long, F., & Hung, D. (1999). CAL/APT Program: Asphalt Treated Permeable Base (ATPB), Laboratory Tests, Performance Predictions, and Evaluation of Caltrans and Other Agencies Experience. Report FHWA/CA/OR-99/09.

He, G.-P., & Wong, W.-G. (2007). Laboratory study on permanent deformation of foamed asphalt mix incorporating reclaimed asphalt pavement materials. Construction and Building Materials, 21(8), 1809–1819.

He, G.-P., & Wong, W.-G. (2008). Effect of moisture on strength and permanent deformation of foamed asphalt mix incorporating RAP materials. Construction and Building Materials, 22(1), 30–40.

Hicks R G, Monismith C L. (1971). Factors influencing the resilient properties of granular materials. Highway Research Record, 345, 15–31.

Hongmei Li, Jiwang Jiang, Qiang Li. Economic and environmental assessment of a green pavement recycling solution using foamed asphalt binder based on LCA and LCCA. Transportation Engineering 13 (2023) 100185.103. https://doi.org/10.3141/2084-11

Horvath, A. A Life-Cycle Analysis Model and Decision-Support Tool for Selecting Recycled Versus Virgin Materials for Highway Applications. Final report for RMRC Research Project No. 23. University of California at Berkeley, Berkeley, Calif., 2004.

ISO, ISO International Standard 14040: Environmental Management – Life Cycle Assessment – Principles and Framework, International Organization for Standardization, Geneva, Switzerland, 2006.

ISO, ISO International Standard 14044: Environmental Management – Life Cycle Assessment – Requirements and Guidelines, International Organization for Standardization, Geneva, Switzerland, 2006.

J. Harvey, J. Meijer, H. Ozer, I.L. Al-Qadi, A. Saboori, A. Kendall, Pavem nt lifecycle assessment framework (2016)

J. Santos, J. Bryce, G. Flintsch, A. Ferreira, B. Diefenderfer. A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. Struct. Infrastruct. Eng. 11 (9) (2015) 1199–1217.

J. Turk, A.M. Pranjic, A. Mladenovic¡, Z. Cotic¡, P. Jurjavc¡ic¡, Environmental comparison of two alternative road pavement rehabilitation techniques: cold-in-place-recycling versus traditional reconstruction, J. Cleaner Prod. 121 (2016) 45–55.

J. Walls III, M.R Smith, Life cycle cost analysis in pavement design-interim technical bulletin (1998).

Kim. J. Jenkins and D. C. Collings, "Combining LCC and energy consumption for enhancing decision making regarding rehabilitation options," in Proceedings of the 10th Conference on Asphalt Pavements for Southern Africa, Drakensberg, South Africa, 2011.

Kim. J. Jenkins, C. E. Rudman, and C. R. Bierman. Delivering Sustainable Solutions through Improved Mix and Structural Design Functions for Bitumen Stabilised Materials. Advances in Materials Science and Engineering Volume 2020, Article ID 7460174. https://doi.org/10.1155/2020/7460174

Kim J. Jenkins & Fenella M. Johns (2021): Reconciling the structural design of bitumen stabilized materials – heuristic versus mechanistic-empirical models, Road Materials and Pavement Design, DOI: 10.1080/14680629.2021.1880963.

Kuchiishi A K, Antão C C D S, Vasconcelos K, Pires J, Araújo O M D O, Bernucci L L B, Lopes R T (2019). Investigation of the matric suction role on the curing mechanism of foamed asphalt stabilized mixes. Road Materials and Pavement Design, 20(sup1), S365–S389. https://doi.org/10.1080/14680629.2019.1589558

Kuchiishi A K, Vasconcelos K, Bernucci L L B, 2019. Effect of mix composition on the mechanical behavior of cold recycled asphalt mixes. International Journal of Pavement Engineering, 22(8), 984-994.

Kuchiishi A K., Andrade L R., Bessa I S., Esteves S F., Vasconcelos K L., Bernucci L. B. Influência da Granulometria nas Propriedades Mecânicas de Misturas Recicladas a Frio Estabilizadas com Emulsão Asfáltica e Cimento Portland. XIX CILA, Congreso Ibero-Latinoamericano del Asfalto, Medellin, 2017.

L. H. Csanyi, Foamed Asphalt in Bituminous Paving Mixes, Highway Research Board Bulletin, Washington, DC, USA, 1957.

L. Yao, Q. Dong, F. Ni, J. Jiang, X. Lu, Y. Du, Effectiveness and cost-effectiveness evaluation of pavement treatments using life-cycle cost analysis, J. Transp. Eng. 145 (2) (2019), 04019006. Part B: Pavements.

Li, P., Liu, J. Characterization of Asphalt Treated Base Course Material - Final Report. Alaska University Transportation Center, 2010.

Liebenberg J J E, Visser A T. (2003). Stabilization and structural design of marginal materials for use in low-volume roads. Transportation Research Record, 1819, 166–172.

Liebenberg J J E, Visser A T. (2004). Stabilization and structural design of marginal materials for use in low-volume roads. Journal of the South African Institution of Civil Engineering, 46(3), 2–8. https://doi.org/10.3141/1819b-21

Loulizi, A., Al-Qadi, I.L., and Elseifi, M., 2006. Difference between in situ flexible pavement measured and calculated stresses and strains. Journal of Transportation Engineering, 132 (7), 574–579.

Lovering W, Cedergren H. Structural Section Drainage, Proceedings of the First International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, University of Michigan, August, 773-784; 1962.

M.I. Giani, G. Dotelli, N. Brandini, L. Zampori, Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling, Resour. Conserv. Recycle. 104 (2015) 224–238.

Meneses J P C, Vasconcelos K, Bernucci L L B, Hajj E. (2021) Compaction methods of cold recycled asphalt mixes and their effects on pavement analysis, Road Materials and Pavement Design, 22(sup1), S154-S179.

Meocci M, Grilli A, Torre F L A, Bocci M., Evaluation of mechanical performance of cement–bitumen-treated materials through laboratory and in-situ testing. Road Materials and Pavement Design, http://dx.doi.org/10.1080/14680629.2016.1213506, 2016.

Mignini C, Cardone F, Graziani A. (2022). Complex modulus of cement-bitumen treated materials produced with different reclaimed asphalt gradations. Materials and Structures, 55, 169. https://doi.org/10.1617/s11527-022-02009-4

Ministry of Transportation Ontario. Pavement Design and Rehabilitation Manual. SDO-90-01. Queen's Printer for Ontario, Toronto, Ontario, Canada, 1990.

Moaveni M, Abuawad I, Hasiba K, Zhang D, Tutumluer E. Characterization of Emulsion Bitumen Stabilized Aggregate Base. 2nd International Conference on Transportation Geotechnics, Sapporo, Japan (2012).

Mondal P G, Kuna K K. (2022). Mix design considerations for foamed bitumen stabilized materials: A review. Construction and Building Materials, 326, 126783. https://doi.org/10.1016/j.conbuildmat.2022.126783.

Mustafa K H, Aziz M M A, Hainin M R, Zaini A A, Warid M N M. A Review on Crack Relief Layer (CRL) in Roads and Highways. Jurnal Teknologi (Sciences & Engineering) 78. 7-3 (2016) 45-52.

Nassar, Ahmed I.; Mohammed, Mahmoud Khashaa; Thom, Nicholas; Parry, Tony (2016). Mechanical, durability, and microstructure properties of Cold Asphalt Emulsion Mixtures with different types of filler. Construction and Building Materials, 114(), 352–363.

Nazarian, S. Design and constructability of 1 emulsion-stabilized bases for full-depth reclamation. TRB 2013 Annual Meeting - Paper revised from original submittal, 2012.

Nokes, W. A., Harvey, J. T., Du Plessis, L., Long, F., & Stolarski, P. J. Caltrans accelerated pavement testing (CAL/APT) program-test results: 1993-1996. In: 8th International Conference on Asphalt Pavements, Seattle (1997), WA. Vol. 2, 1053–1072.

Ojum C, Thom, N. (2017). Effect of binder in recycled asphalt on cold-mix pavements. Proceedings of the Institution of Civil Engineers - Construction Materials, 170(4), 205–210. https://doi.org/10.1680/jcoma.16.00038

Orosa P, Pérez I, Pasandín A R. Evaluation of the shear and permanent deformation properties of cold in-place recycled mixes with bitumen emulsion using triaxial tests. Construction and Building Materials, 328, 127054, 2022 https://doi.org/10.1016/j.conbuildmat.2022.127054

Peifeng Su and Miaomiao Li 2020. Journal of Physics: Conference Series 1549 (2020) 032108. doi:10.1088/1742-6596/1549/3/032108.

Pologruto, M, 2006. Study of in situ pavement material properties determined from FWD testing. Journal of Transportation Engineering, 132 (9), 742–750.

Quick, T. Guthrie W S. Early-Age Structural Properties of Base Material Treated with Asphalt Emulsion. Transportation Research Record: Journal of the Transportation Research Board. No. 2253, Transportation Research Board of the National Academies, Washington D.C., 2011, pp. 40–50. DOI: 10.3141/2253-05.

Recommended Mix Design Guidelines for Cold Recycling Using Emulsified Asphalt Recycling Agent - CR201. Asphalt Recycling & Reclaiming Association (ARRA). 2023.

Recommended Mix Design Guidelines for Full Depth Reclamation (FDR) Using Emulsified Asphalt Stabilizing Agent - FDR201A. Asphalt Recycling & Reclaiming Association (ARRA). 2023.

Review of Structural Design Procedures for Foamed Bitumen Pavements - AP-T188/11. AUSTROADS TECHNICAL REPORT 2011.

Romeo, Elena, et al. "Effect of active fillers on cracking performance of bitumen-stabilised materials." Road Materials and Pavement Design 19.7 (2018): 1563-157

S. Chun, A. Nazef, E. Offei, J. Greene, and B. Choubane. Effectiveness of crack relief techniques to mitigate reflective cracking in asphalt overlaid concrete pavement. Submitted for presentation and publication at the 2016 Transportation Research Board Annual Meeting.

S. M. Acott and P. A. Myburgh, "Design and performance study of sand bases treated with foamed asphalt," Transportation Research Record, vol. 898, pp. 290–296, 1982.

SABITA, ETB. "The Design and Use of Emulsion-Treated Bases: Manual 21." Southem African Bitumen Association, Roggebaai, South Africa (1999).

SABITA, G. E. M. S. "The Design and Use of Granular Emulsion Mixes Manual 14." Southern African Bitumen and Tar Association, Rogge-baai, South, Africa (1993).

SABITA. The Design and Use of Foamed Bitumen Treated Materials, Southern African Bitumen Association, Cape Town, South Africa, 2002.

Santagata, F. A., Bocci, M., Grilli, A., & Cardone, F. (2009). Rehabilitation of an Italian highway by cold-in-place recycling techniques. In Proceedings of 7th international RILEM symposium on advanced testing and characterization of bituminous materials, Rhodes, 27–29 May.

Shuanfa Chen & Yi Jiang (2008) Pavement Reflective Cracking Control with Coarse-Aggregate Asphalt Mix Interlayer, International Journal of Construction Education and Research, 4:3, 200-209, DOI: 10.1080/15578770802494623.

Stimilli, A.; Ferrotti, G.; Graziani, A.; Canestrari, F. (2013). Performance evaluation of a cold-recycled mixture containing a high percentage of reclaimed asphalt. Road Materials and Pavement Design, 14(sup1), 149–161. doi:10.1080/14680629.2013.774752.

T. Wang, C. Kim, J. Harvey, Energy consumption and Greenhouse Gas Emission from highway work zone traffic in pavement life cycle assessment, International Symposium on Pavement Life Cycle Assessment, Davis, California, USA (2014).

Tebaldi G, Dave E V, Marsac P, Muraya P, Hugener M, Pasetto M, Graziani A, Grilli A, Bocci M, Marradi A, Wendling L, Gaudefroy V, Jenkins K, Loizos A, Canestrari F (2014). Synthesis of standards and procedures for specimen preparation and in-field evaluation of cold-recycled asphalt mixes. Road Materials and Pavement Design, 15(2), 272–299. https://doi.org/10.1080/14680629.2013.866707

Terrell, R. L., and Wang, C. K. 1971. Early curing behavior of cement-modified asphalt emulsion mixtures. Association of Asphalt Paving Technologists Proceeding. Vol. 40: pp.108-125.

Tian X, Han H, Zhang Q, Li X, Li Y. Design and Performance of Anticracking Asphalt-Treated Base. Advances in Materials Science and Engineering. Volume 2017, Article ID 2394945, 9 pages. https://doi.org/10.1155/2017/2394945.

Timm, D.H., Turochy, R.E., and Davis, K.P., 2010. Guidance for M-E pavement design implementation. Final Report ALDOT Project 930-685.

Tran, N.H. and Hall, K.D., 2006. An examination of strain levels used in the dynamic modulus Testing. Journal of the Association of Asphalt Paving Technologists, 75, 321–343.

United States Environmental Protection Agency (EPA), Motor Vehicle Emission Simulator (MOVES), Environmental Protection Agency, Washington, DC (2014).

Villwock, J. A. e Tomazelli, L. J. (1995) Geologia Costeira do Rio Grande do Sul. Notas Técnicas, nº 8. CECO/IG/UFRGS. 46p.

W. Zhang, J. Yang, X. Fan, R. Yang, B. Yu, Life-Cycle Cost Analysis of Base Course Using Cold In-Place Recycling: Case Study, Geotech. Spec. Publ. 211 (2011) 4428–4437.

Weir T, White G, Espinosa R. (2022). Review of the design, characterization,and production of foamed bitumen stabilized base courses for pavement construction. Australian Journal of Civil Engineering, 20(2), 308–325. https://doi.org/10.1080/14488353.2021.1974658

Xiao F, Yao S, Wang J, Li X, Amirkhanian, S. (2018). A literature review on cold recycling technology of asphalt pavement. Construction and Building Materials, 180, 579–604. https://doi.org/10.1016/j.conbuildmat.2018.06.006

Xu J, Huang S, Qin Y, Li F. The impact of cement contents on the properties of asphalt emulsion stabilized cold recycling mixs, Int. J. Pavement Res. Technol. 4(1) (2011) 48–55.

Y. Pan, Y. Shang, G. Liu, Y. Xie, C. Zhang, Y. Zhao, Cost-effectiveness evaluation of pavement maintenance treatments using multiple regression and life-cycle cost Analysis. Constr. Build. Mater. 292 (2021), 123461

Zhang Y.; Wang L.; Diefenderfer B. and Zhang W. Modified dynamic modulus test and customized prediction model of asphalt-treated drainage layer materials for M-E pavement design. International Journal of Pavement Engineering, http://dx.doi.org/10.1080/10298436.2015.1019502, 2015.