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LABORATORY AND COMPUTATIONAL MECHANICS-BASED FRAMEWORK FOR THE ANALYSIS AND DESIGN OF COLD RECYCLED PAVEMENT LAYERS

PhD dissertation

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Abstract

Cold recycling technologies are increasingly popular rehabilitation techniques for asphalt pavements. These technologies allow construction of new pavement layers with minimal addition of heat and minimal need for transporting the material. In fact, the mixtures are usually prepared in mobile plants or directly in place. The products obtained through the use of cold recycling technologies are called Bituminous Stabilized Materials (BSM). BSM are considered partially-bonded materials since they have mechanical characteristics which are in between fully bonded materials, such as Hot-Mix-Asphalt (HMA) or cemented materials, and unbounded materials, such as crushed aggregates. Their mechanical response is simultaneously dependent on testing temperature and applied confining pressure and the main concern related to those materials in the field is the accumulation of permanent deformation under traffic loading application. Nonetheless, BSM are often assumed to have a linear elastic response in pavement design and analysis.

In this research study, three different mechanical characterization methods for BSM are evaluated. Indirect Tensile Strength (ITS) test and, shear strength and resilient modulus tests in triaxial configuration were performed in the laboratory in order to identify the best suited approach to measure elastic and plastic global properties for BSM. Tests in triaxial configuration showed the ability to fully capture the plastic behavior of the tested mixtures and for this reason were selected as characterization method for the study. Triaxial shear strength (TSS) and resilient modulus (TMR) tests were performed subjecting the material to different lateral confining pressures and to different temperature conditions. This approach characterized the material response under a three-dimensional stress state and under a wide range of realistic temperature scenarios. On the basis of those results, a constitutive model for BSM was adopted. Laboratory reaction force-displacement curves from TSS tests were matched with three-dimensional finite element elastoplastic model simulations in order to extract local elastic and plastic constitutive properties for the material. The local properties calibrated and validated in this stage of research were subsequently used as input parameters in multilayer elastoplastic pavement models for pavement structural response evaluation. Different structural solutions with and without BSM as base layer of pavement were initially simulated in order to determine the ability of BSM as an alternative to traditional granular base layers in terms of rutting accumulation. Afterwards, scenarios with different pavement layer temperatures were simulated and elastoplastic analysis was compared to the traditional linear elastic analysis. Number of allowable load repetitions before fatigue and rutting failure were calculated respectively on the basis of horizontal strains at the bottom of HMA and vertical strains on top of subgrade taken from the model simulation results. The finite element model was then

updated to consider a realistic temperature distribution with depth and consequently use temperature dependent material properties. As last step, considerations on the impact of BSM curing stage on overall plastic response of the pavement structure were made. BSM mechanical properties were estimated at different curing days basing on laboratory results and equations found in the literature. Different structural solutions were simulated before the HMA overlay placement and trends of plastic deformation accumulation on the pavement surface were calculated during the BSM curing period (typically first fourteen days after construction).

The research study indicated the importance of considering elastoplastic models for partially-bonded and unbounded materials in the design and analysis of pavement structures. In addition, it was shown that the effect of temperature on BSM mechanical response cannot be neglected for an accurate pavement evaluation. In terms of curing, the simulations predicted a similar behavior of the pavement structure in between seven and fourteen days after construction. This information needs to be further investigated with field and laboratory testing. The possibility of overlaying the BSM and re-opening the roadway to traffic at an earlier curing stage could result in significant savings on cost.

Overall, this dissertation presents a framework for the analysis and design of BSM based on laboratory tests and computational mechanics analysis which could be adopted for future studies. In addition, this work gives a contribution for the improvement of current methods for pavement design and analysis including considerations on plasticity, indirect confining pressure effects and realistic temperature distribution with depth.

Table of Contents

Appendix

List of Figures

List of Tables

1 Introduction

1.1 Background

Cold recycling technologies allow recovery and re-use of up to 100% of the milled material from an existing asphalt pavement without significant addition of heat. In addition, there is often minimal need for transporting the material since the mixture is usually prepared on site or through the use of mobile plants. For those reasons, cold recycling technologies are one of the most sustainable rehabilitation techniques, both from environmental and economic perspectives. The low production temperatures and the minimal need for transportation result in low CO_2 emissions during preparation and construction. In addition, the oil consumption is drastically reduced with respect to other traditional rehabilitation techniques. The product obtained through the use of cold recycling technologies is called Bituminous Stabilized Material (BSM). These type of materials are considered to be partially-bonded materials, which means that they have characteristics which are in between fully bonded materials, such as Hot-Mix-Asphalt (HMA) and cemented materials, and unbounded materials, such as crushed aggregates. The reason for this is that the asphalt binder content in BSM is lower than the one used to prepare HMA and even in the case where cement is used as additive in the mix, its introduction is always limited to very low application rates. This particular composition causes the material to have mechanical characteristics which are simultaneously temperature and confining pressure dependent.

1.2 Motivations

The principal motivations for this research are:

1. BSMs are partially-bonded and heterogeneous materials with mechanical properties which are simultaneously temperature and confining pressure dependent. For this reason, there is need to identify a specific mechanical characterization method.

2. Mechanical response of BSM pavement layers is usually assumed to be linear elastic in current design and analysis methods. Nonetheless, the predominant mode of failure for BSM is accumulation of permanent deformation. For this reason, there is need to collect information on material plastic response.

3. Limited exploration of constitutive models to fully characterize and describe BSM behavior under different conditions, such as different lateral confining pressures

application and different temperature scenarios has been conducted to date, this needs to be expanded.

4. Curing stage of BSM can affect the overall pavement structure response in terms of permanent deformation accumulation under traffic loading applications before HMA overlay placement. For this reason, there is need to quantify the evolution of BSM mechanical properties with curing time and evaluate how it reflects on the overall pavement response.

1.3 Objectives

The principal objectives of this research study are:

1. Verify that tests in triaxial configuration are a better suited characterization method for BSM with respect to ITS.
2. Effect of BSM composition (in terms of asphalt stabilizing agent and additives) on mechanical properties.
3. Assess the influence of temperature and confining pressure on material mechanical response.
4. Develop a framework to experimentally characterize BSMs.
5. Collect enough information on material elastic and plastic behavior in order to develop a constitutive model and understand its behavior when used as a base layer in pavement structures.
6. Evaluate the effects of BSM curing stage on plastic response of overall pavement structure before HMA overlay placement.

1.4 Overall research approach

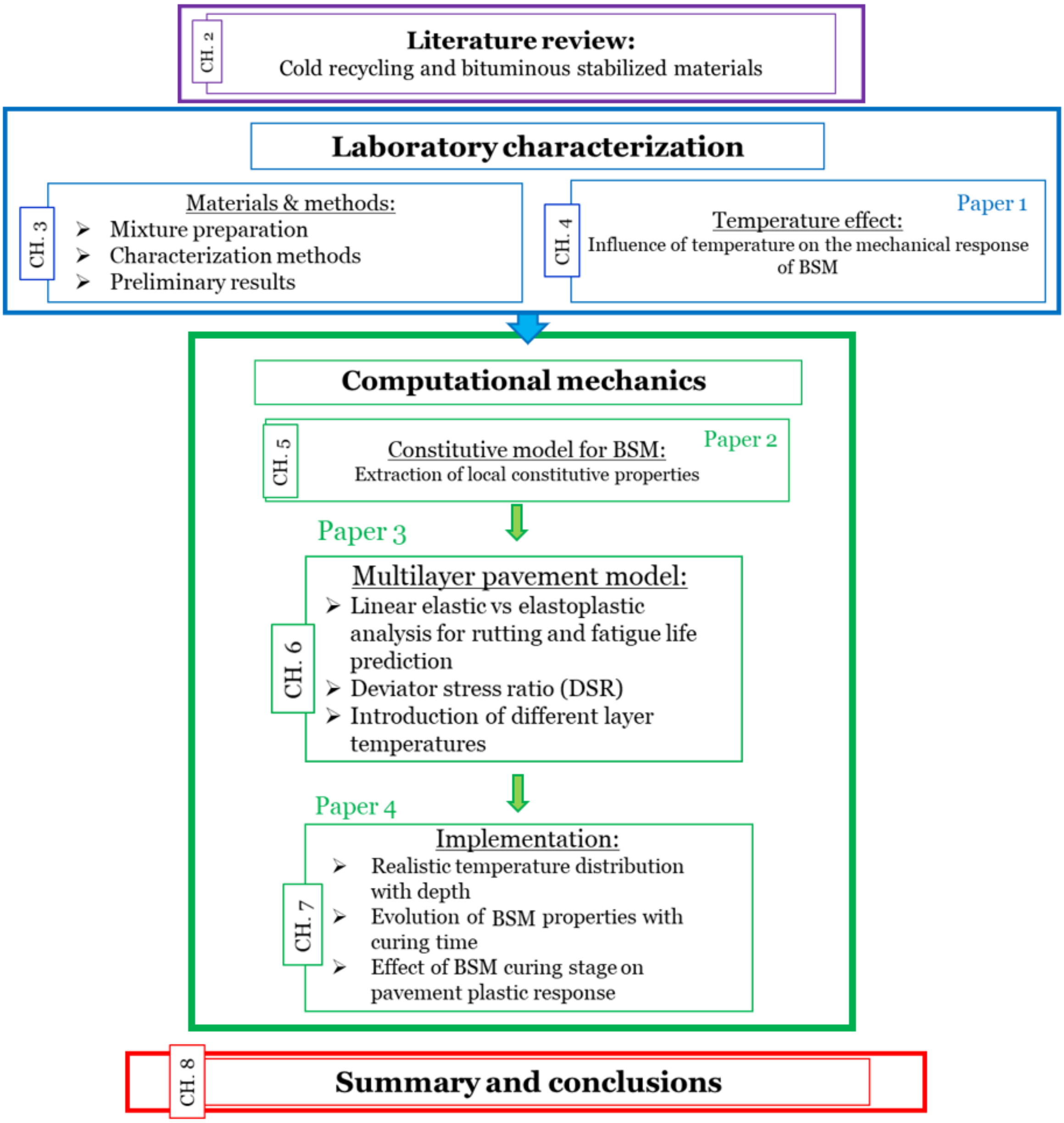

Figure 1.1 Overall research approach and dissertation structure

The overall research approach was organized in two main sections: the first one includes all the laboratory characterization efforts, the second one focuses on the computational mechanics aspect and includes all the numerical simulations.

1.5 Organization of the dissertation

This doctorate dissertation is organized in 9 chapters as indicated in Figure 1.1. A short summary of each chapter is provided in this section and full manuscripts are either attached as appendices to this document or have been discussed within the thesis under designated chapter number and title.

Chapter 1 is intended to give a general introduction on the research topic and show motivations, objective and research approach.

Chapter 2 is an extended literature review on topics such as Reclaimed Asphalt Pavement (RAP), cold recycling technologies and BSM.

Chapter 3 introduces all the materials used in the study, the laboratory equipment that was used and the type of tests which were performed for the mechanical characterization portion. In addition, the preliminary results in terms of ITS, TSS and TMR are shown.

Chapter 4 focuses on the effect of temperature on mechanical response of BSM. The variations of global elastic and plastic properties such as resilient modulus, cohesion and internal friction angle with temperature are assessed.

Chapter 5 is the first chapter of the computational mechanics portion. A three-dimensional elastoplastic model for TSS test simulation is designed and the reaction force-displacement curves from the laboratory are matched with the simulations for different mixtures and under three different confining pressures. In addition, the local elastic and plastic constitutive properties for the materials are extracted.

Chapter 6 introduces the two-dimensional axisymmetric finite-element elastoplastic model which was developed for pavement evaluation. In addition, comparisons are made in between linear elastic analysis and elastoplastic analysis to evaluate the effect of the inclusion of plasticity on overall pavement response under the different temperature scenarios. Deviator Stress Ratio (DSR) is also used as a parameter to evaluate the BSM layer ability to withstand traffic loading application.

Chapter 7 is intended to give an idea of the effect of curing stage of cold recycled layers on the overall plastic response of the pavement structure under traffic loading applications. The trend of variation of elastic modulus and cohesion is estimated on the basis of tests and equations found in the literature and simulations are run for the first fourteen days after construction before HMA overlay placement. In addition, a realistic temperature distribution with depth is implemented in the model in order to adjust material properties at the different locations with respect to pavement surface.

Chapter 8 gives a brief summary of the study and discusses all the conclusions that can be draw from the conducted research. In addition, the possible future extensions for the study are listed.

Details of research efforts and corresponding results and discussion from Chapters 4 thru 8 of this dissertation are in form of peer-reviewed journal manuscripts. A brief synopsis of the work from these manuscripts are provided as body of these chapters. The current status of these five papers is indicated in Table 1.

Table 1. Status of the technical papers.

Chapter	Paper	Journal	Status	Contribution to the Objectives
4	Influence of Temperature on Global and Local Elastoplastic Properties of Bituminous Stabilized Material	Road Materials and Pavement Design	To be submitted (manuscript prepared)	Direct contributions to objective 1,2,3,4
5	Elasto-Plastic Model for Bitumen Stabilized Materials using Triaxial Testing and Finite Element Modelling	RILEM International Symposium on Bituminous Materials conference proceedings	Published	Direct contributions to objective 4, 5
6	Temperature dependent plasticity response in the design and analysis of pavements with cold in-place recycled layer	Construction and Building Materials	To be submitted (manuscript prepared)	Direct contributions to objective 5
7	Influence of curing stage and temperature distribution on plastic response of cold recycled pavement layers	Journal of Materials in Civil Engineering	To be submitted (manuscript prepared)	Direct contributions to objective 6

2 Overview of Asphalt Pavement Cold Recycling and Bituminous Stabilized Materials

This chapter contains an overview on cold recycling technologies and bituminous stabilized materials. Different available rehabilitation techniques are shown and both the In-Place (CIR) and Central Plant (CCPR) technologies are described. In addition, an overview on BSM mix design and curing process is described.

2.1 Cold recycling technologies

Cold recycling technologies allow to recover and re-use up to 100% of the milled material from an existing asphalt pavement without any addition of heat. Generally, this is combined with a minimal need for transporting the material since the mixtures are usually prepared on site or in mobile plants. Since production temperatures are very low and the need for transportation is minimal, cold recycling technologies can guarantee very low CO_2 emissions and oil consumption as can be seen in Figure 2.1.

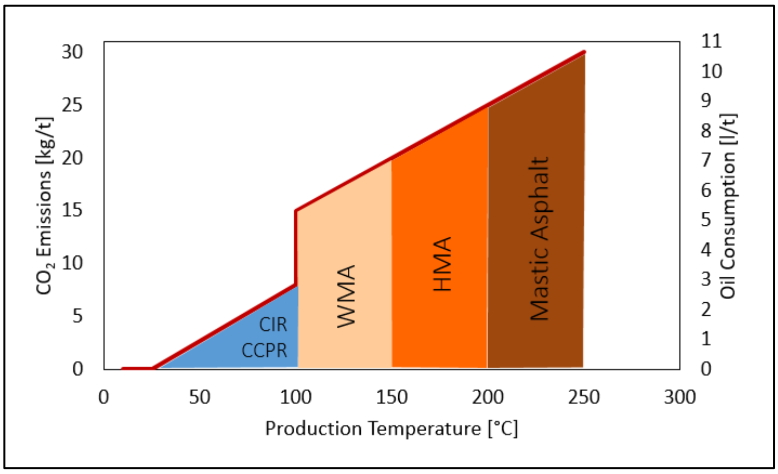

Figure 2.1 CIR and CCPR production temperatures with comparison to other technologies.

According to the recycling processes and mixing temperature, recycling methodologies can be classified as hot recycling and cold recycling. Compared with hot recycling technology, cold recycling has superior advantages in terms of environmental and economic sustainability, and safety. Hot recycling includes hot in-place recycling (HIR) and hot central-plant recycling (HCPR) while, according to construction technology, rehabilitation depth and processing place, in-place recycling technologies involve three methodologies: cold in-place recycling (CIR), cold central plant recycling (CCPR) and full depth reclamation (FDR) [1].

2.1.1 Cold in-place recycling (CIR)

According to the reclamation depth, there are two types of recycling methods: partial-depth recycling and full-depth reclamation (FDR). Though FDR is also conducted in situ, CIR only refers to partial depth. The terms FDR is used to describe technologies which can reach deeper layers in the pavement structure such as base or sub-base layers and consequently are able to address major structural distresses in the pavement structure. CIR techniques address distresses which are solely related to the HMA superficial layers, such as:

- Rutting phenomena involving only asphalt layers;
- Top-down cracking or thermal cracking (longitudinal or transverse cracking);
- Oxidized and raveled surface layers;
- Alligator cracking (fatigue cracking);
- Remove the cracking network in superficial layers;

As a partial-depth recycling method, CIR is mostly used for constructing base courses which are going to be overlaid with HMA layers.
This process is usually carried out by using a series of multi-functional recycling trains and the range of processing depth ranges from 65 to 125 mm, an example of recycling train setup can be found in Figure 2.2 and Figure 2.3.

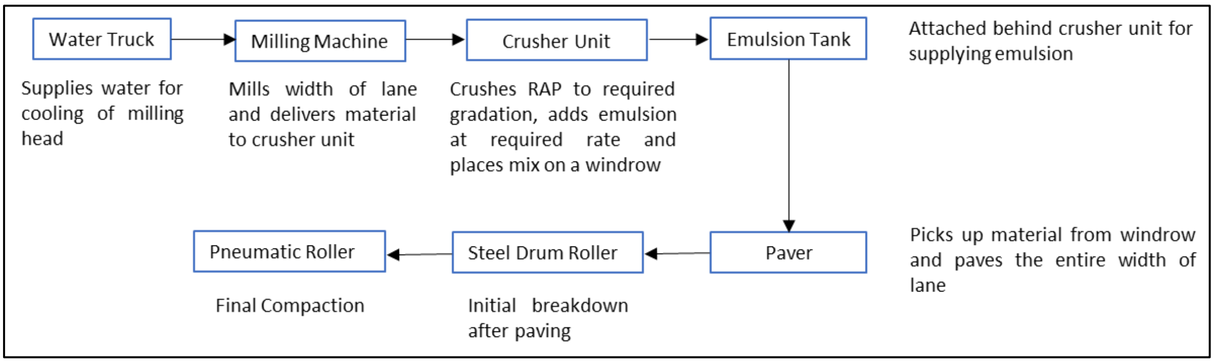

Figure 2.2 CIR train setup scheme

Figure 2.3 CIR train setup on field operations.

The steps in CIR typically consist of: preparation of construction area (including preliminary milling operations to remove the most superficial and oxidized portion of HMA), milling of the existing asphalt pavement, addition of stabilizing agents (foamed or emulsified asphalt) and fillers or active fillers (mineral filler, cement, hydrated lime, etc.), laydown, compaction, and new HMA overlay placement [2].
All of the aforementioned procedures are carried out almost simultaneously in CIR as can be seen in Figure 2.4.

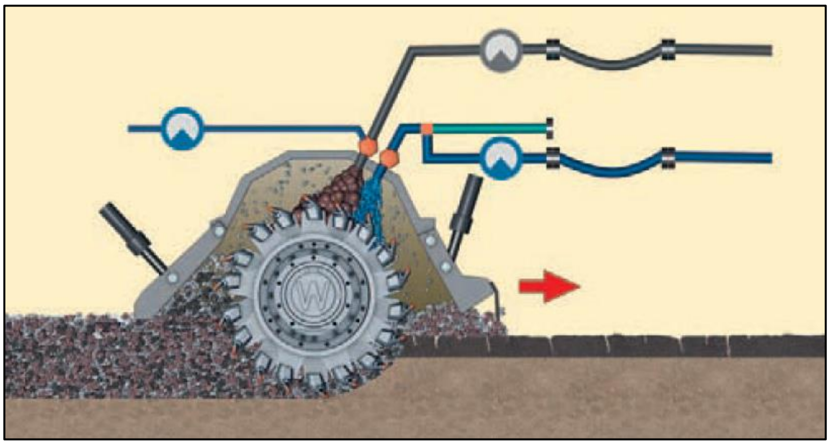

Figure 2.4 Scheme of recycler performing CIR [55].

The train setup is meant to contemporarily mill the existing asphalt pavement while injecting water for compaction and asphalt stabilizing agent in the form of foamed or emulsified asphalt. In addition, when mineral filler or active filler is intended to be used in the mix design, it is sprayed on the pavement surface before the recycler.

The reason why a CIR layer is normally covered by a HMA overlay is to protect it from water ingress and traffic abrasion and to obtain a sounder pavement structure with adequate superficial texture [3].

Some research studies have shown the significance of the environmental benefits of CIR when compared with hot recycling method. It was evaluated that the energy consumption to produce pavement layers through the use of CIR technologies is approximately 20% of the one following traditional rehabilitation methods.

In Figure 2.5, it is shown how CIR technologies, when compared with traditional HMA, allows to save 62% in virgin aggregates usage and reduce the emissions of 52%, 61% and 54% in terms of greenhouse gas, sulfur dioxide and nitric oxide/nitrogen dioxide, respectively.

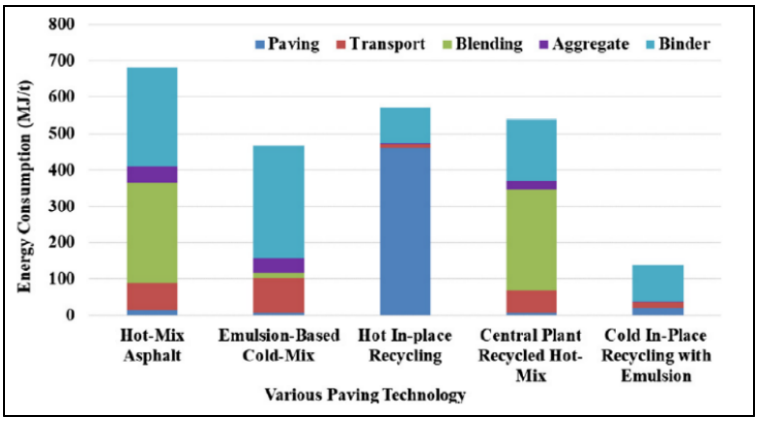

Figure 2.5 Energy consumption of different rehabilitation technologies [4].

Even though CIR method has many significant benefits, there are still some limitations that restrict the popularization of this technology. One of the main imitations is related to the poor available knowledge in terms of mixture internal behavior and mechanical response to traffic loading, which is of upmost importance for the accurate use of mechanistic-based pavement design methods [4].

2.1.2 Cold central plant recycling (CCPR)

CCPR can be conducted in a central traditional plant or using a mobile plant. When the recycling process takes place not directly on the field, the damaged asphalt pavement is milled off and stockpiled in the plant. Subsequently, asphalt binder, fillers and water are added, and the mixture goes back to the field where it is laid and compacted. In this case, the constructor has better control over the composition of the mixture in terms of water content and milled material gradation. Figure 2.6 shows a mobile plant setup for cold mobile plant recycling operations.

Figure 2.6 CCPR with mobile plant setup.

The recycled materials can be crushed to designed size before mixing operations with stabilizing agents, additives and water. Subsequently, the conventional HMA wearing course will be paved on top of cold recycled layer [5 to 7].
Similarly to CIR, CCPR also has the advantages of cost reduction, environmental sustainability and low energy consumption.

2.1.3 Full-depth reclamation (FDR)

In FDR technology the recycling process is the same as CIR and it is conducted completely in situ [8 to 10]. The main difference is that asphalt layers are milled and consequently mixed together with part of base layer or even sub-base layers. Nonetheless, the product obtained with FDR is still considered to be a bituminous stabilized material (BSM) with mechanical characteristics similar to the mixtures obtained through CIR technologies. In addition, FDR can address deeper structural distresses, such as rutting involving base and sub-base layers and cracking propagation coming from underneath HMA, producing a high strength subgrade layer. The reclaiming machines and multi-functional recycling trains are used in FDR process with a milling depth ranging from 100 to 300 mm [11 and 12].

2.2 Bituminous stabilized materials

BSMs are considered to be partially-bonded materials since their mechanical behaviour is in between fully bonded materials and completely unbounded materials. As can be seen from Figure 2.7, the virgin asphalt binder content of BSM is lower than the one used in HMA mixtures. In addition, even in the case where cement is used as active filler, it is introduced in a very low application rate. Usually, the cement content is a BSM does not exceed 1% by weight of dry aggregates which is much lower than in cemented or cement-treated materials preparation.

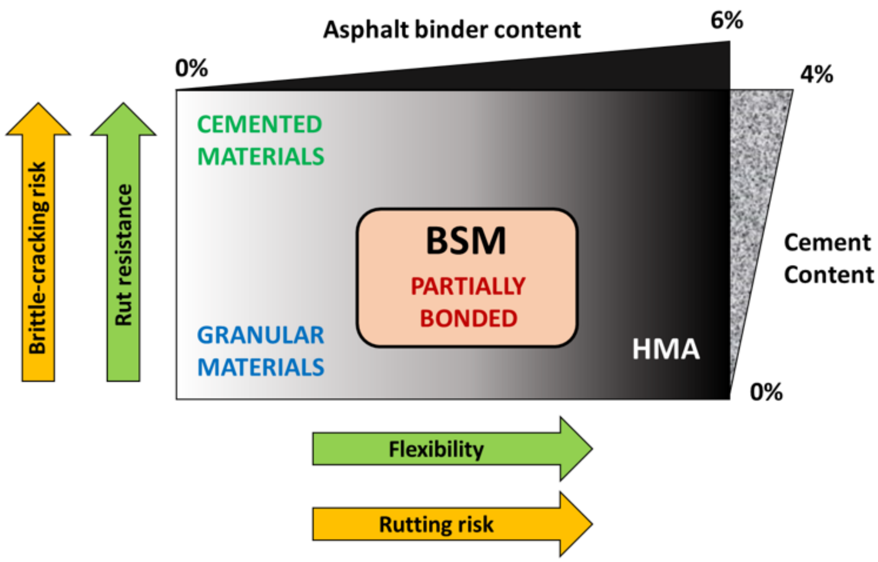

Figure 2.7 Scheme partially-bonded materials.

BSM can guarantee a better flexibility with comparison to granular materials, but at the same time they have a higher potential for rutting distress development. In fact, the main concern related to cold recycled layers is believed to be accumulation of permanent deformation under traffic loading application.

2.3 Cold recycled mixtures components

Cold recycled mixture are composed by Reclaimed Asphalt Pavement (RAP), asphalt stabilizing agent in the form of foamed or emulsified asphalt, fillers such as mineral filler and active fillers such as cement or hydrated lime and water for compaction. Because of the complex composition of the final cold recycled mixtures, the performance of rehabilitated pavement highly depends on the properties and dosage of its components, primarily from RAP gradation, stabilizing agent application rate and active filler type and amount.

2.3.1 Reclaimed asphalt pavement

Typical factors influencing the quality of RAP to be used in cold recycling operations include moisture content, asphalt binder content and condition and RAP aggregate gradation (Figure 2.7). Since the temperature production for cold recycled mixtures are very low, there is no significant reactivation of the asphalt binder in the RAP. For this reason, the primary focus when considering RAP material for cold recycling application should be on aggregate gradation. RAP aggregate gradation depends on multiple factors such as depth and speed of milling operations, type of teeth used on the recycler drum, type of asphalt mixture that is being milled and condition of the existing asphalt material in terms of level of ageing and oxidization [13 to 18].

Figure 2.8 Reclaimed asphalt pavement after milling operations

2.3.2 Stabilizing agents and active fillers

2.3.2.1 Asphalt stabilizing agents

The two commonly used asphalt stabilizing agents are foamed and emulsified asphalt. Both can be adopted as stabilizers for cold recycled mixtures and they confer to the final mixtures similar mechanical properties. The main difference is that while foamed asphalt creates a multitude of punctual adhesive mastics dispersed into the matrix of the mixture (Figure 2.8), emulsified asphalt creates a more homogeneous coating of the RAP aggregates (Figure 2.9).

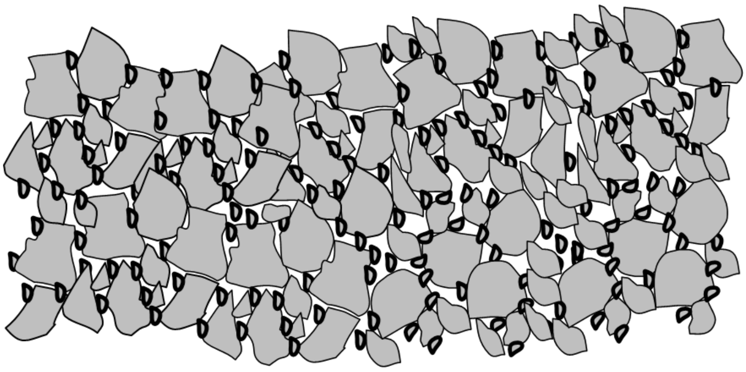

Figure 2.9 Foamed asphalt punctual mastics dispersed in the mixture

Figure 2.10 Emulsified asphalt coating RAP particles.

The thickness of the asphalt binder film created by the asphalt emulsion on top of RAP aggregates is very thin when compared to the one provided by the asphalt binder in HMA mixtures. This is the reason why the final product of stabilization with emulsified asphalt still has characteristics of a partially-bonded material and not of a continuously-bonded material. In general, the amount of asphalt binder used in cold recycled mixtures does not exceed 2-3% by weight of dry RAP aggregates [19 to 31].

The main differences in between cold recycled mixtures prepared with foamed asphalt and the ones prepared using emulsified asphalt are:

- In the mixtures prepared with foamed asphalt, the carriers of the asphalt binder are the fine particles in the mix. In the mixtures prepared with emulsified asphalt, the water in the emulsion and the added water for compaction are the carriers of the asphalt binder.

- Mixtures prepared with emulsified asphalt need longer curing time since the emulsion needs to break and set on the RAP aggregates.

- The water used for the foaming process is not considered in the calculation of the Optimal Moisture Content (OMC) for compaction. The water for compaction in mixtures prepared with emulsified asphalt needs to be adjusted basing on the amount of emulsion and amount of water in the emulsion.

Nonetheless, as mentioned earlier, the final product obtained with both the asphalt stabilizing agents is similar in terms of mechanical characteristics.

2.3.2.2 Active fillers

The term active filler is used to identify those fillers which are able to chemically alter mixture properties. This definition includes materials such as cement, hydrated lime, calcium oxide and fly ash. Active fillers have a completely different micro-structure when compared to mineral filler as can be seen in Figure 2.11.

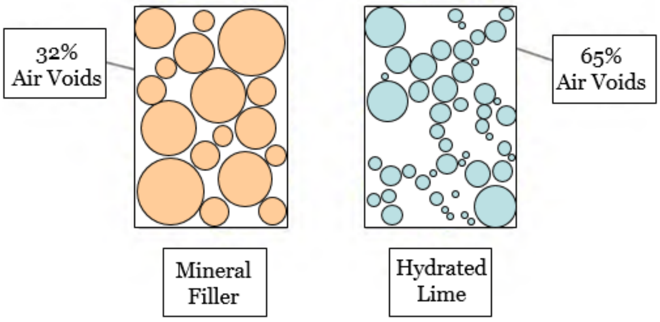

Figure 2.11 Difference in the micro-structure between mineral filler and hydrated lime.

The higher voids content in active fillers and the chemical reactions that are triggered by the contact of those materials with water can have different effects on the final recycled mixture, such as:

- Improve adhesion of the asphalt binder to the aggregates;

- Improve dispersion of the asphalt binder in the mix;

- Increase stiffness & strength gain of mix;

- Accelerate curing of compacted mix.

In general, it can be said that small amounts of active filler application can significantly increase final strength and strength gain of the mixture without affecting the flexibility of the cold recycled layer. When considering cement as active filler, there are higher concerns related to loss in deformability of the material. For this reason, the application rate for cement is usually limited to 1% by weight of dry RAP aggregates while hydrated lime can be introduced in higher amounts [32 to 51].

2.4 BSMs mix design procedure

To produce a cold recycled layer with necessary quality and consistency to serve as a structurally sound base layer in pavement structures, an optimal formulation for the mix needs to be identified. This means that the quality of the different components needs to be evaluated and a correct thickness to be recycled needs to be selected.

The design of a cold recycled mixture requires considerations on volumetric and compaction characteristics as well as mechanical and durability properties. The mix design procedure aims to determine the potential of the material in terms of structural performance, which needs to be evaluated with laboratory testing. In addition, other fundamental considerations that have to be made are in terms of availability of materials, for example type of stabilizing agents or fillers that can be supplied, and in terms of costs. The amount of asphalt binder contributes significantly to the final production cost and therefore it is important to optimize its application rate [52 to 56].

2.5 Curing process in cold recycled mixtures

The main factors are identified as most impacting the BSM mixture curing process are: time, temperature, humidity, wind, rainfall/precipitation, component materials and construction features. As mentioned earlier, considerations of curing stage of the material are of paramount importance, mainly when emulsified asphalt is selected as stabilizing agent for the preparation of BSM. It is important to evaluate the mechanical characteristics of the recycled pavement layer in the days immediately after construction in order to select an optimal time for reopening the rehabilitated pavement structure to traffic or overlay the recycled layer with HMA wearing course [57 to 70].

The main three factor affecting the curing level of the mix and consequently the mechanical properties of the layer are:

- Evaporation of moisture;
- Emulsion breaking;

- Hydration of chemical additives such as active fillers.

This is the reason why curing temperature, rainfalls and atmospheric humidity have a high influence on strength gain of the mixtures. As mentioned earlier, active fillers can help in having a better control over the moisture content in the mixture and in enhancing mechanical properties in the early stage after construction. In addition, cold recycling operations are usually carried out in summer season and in a very narrow time window in order to have adequate environmental conditions for mixing operations, compaction and mainly subsequent curing process.

3 Materials and methods

This chapter contains an overview on materials used for the study, laboratory equipment needed and preliminary results from mechanical characterization of cold recycled mixtures. In addition, the elastoplastic model which was developed to describe BSM mechanical behavior is introduced and the multilayer pavement model used for numerical simulation of the pavement structure under traffic loading is described.

3.1 Materials

Four different mix designs were followed for specimen preparation as can be seen in Table 2.1.

Table 2. Mix designs of cold recycled mixtures tested in the laboratory.

RAP	95%	95%	95%	95%	95%
Mineral Filler	4%	3%	2%	1%	0%
Hydrated Lime	**1%**	**2%**	**3%**	**4%**	**5%**
Asphalt Emulsion	3.3%	3.3%	3.3%	3.3%	3.3%
Residual asphalt binder	2%	2%	2%	2%	2%

A neutral pH emulsion with 60% of residual bitumen and a neat asphalt binder 50/70 penetration grade was used for the preparation of the specimens. The RAP used for the designed BSM had a 4.3% average amount of aged asphalt binder content and came from uncovered stockpiles from milling operations on local roadways in northern Italy. Gradation curve for the RAP material can be seen in Figure 3.1.

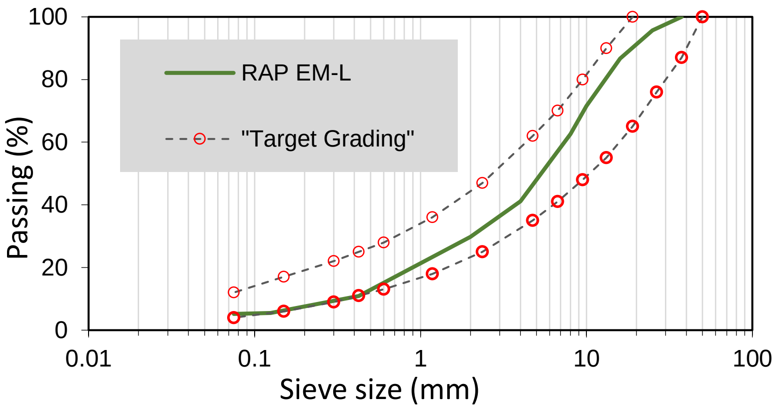

Figure 3.1 RAP gradation.

3.2 Mixing and compaction equipment and specimen preparation

The equipment that was used for specimen preparation consisted of a laboratory mixer of 30 kg capacity and a vibrating hammer for compaction. Both the aforementioned machines can be seen in figure 3.2. The components are mixed together at room temperature for 10 minutes total. At first, RAP and filler are mixed together, subsequently water is added and finally the emulsified asphalt is added.

Figure 3.2 Laboratory mixer and vibrating hammer.

The vibrating hammer was specifically designed by Wirtgen for the compaction of BSM. It provides a type of compaction which is more representative of what's occurring in the field. The functioning consist in applying pressure on the top surface of the material in the compaction mold while vibrating it. This compaction method allows to deal with the water in the mixture and prevent excess pore pressure generation. In addition, the final product after compaction has characteristics which are very similar to what is obtained on field through the use of roller compactors.

There are several approaches that can be followed for curing process of BSM specimens. In some cases the specimens are stored in the laboratory at room temperature and in other cases in the oven at temperatures that can range from 30 to 50 deg. C. In addition, the specimens can be cured without any confinement (free-surface curing) or applying an impermeable lateral confinement over the side surface of the specimens.

In this research study the type of curing methodology selected was 28 days free-surface curing in the laboratory at room temperature.

3.3 Indirect Tensile Strength (ITS)

ITS test are the currently utilized methodology for design and analysis of cold recycled mixtures. The test is performed on specimens of 150 mm diameter and approximately 95 mm height. The specimens can be compacted with the vibrating hammer in two equal layers or using a SuperPave Gyratory Compactor (SGC) in just one layer. The test is performed in displacement control and the reaction force is recorded during the test until failure of the specimen. On the basis of displacement and reaction force, the stress-strain curves are plotted in order to identify the peak tensile strength for the material. Usually, the test is performed on dry specimens and wet specimens (saturated for 24 hours in a water bath) in order to evaluate the moisture sensitivity of the mixture. Test specimen and test setup can be seen in Figure 3.3 [71 to 73].

Figure 3.3 ITS specimens and test setup.

The main limitations related to ITS tests is that they are usually performed exclusively at the reference temperature of 25 deg. C which means they do not provide information on the temperature-dependency of the mechanical response of the material. In addition, the only outcome from this type of test is a stress-strain curve until failure, which does not allow to calculate any global plastic property for the material. As mentioned earlier, the cracking risk is not the main concern in BSM mixtures. The primary failure mode for those type of materials is believed to be accumulation of permanent deformation, thus there is need to collect information on plastic response of the material to predict its performance in terms of rutting accumulation under traffic loading applications.

3.4 Triaxial shear strength and resilient modulus tests

A simplified TSS test for cold recycled mixtures was developed by Mulusa et al. in 2009. This test is a monotonic test performed very similarly to the geotechnical triaxial test. The main difference is in the testing setup and equipment used. The cold recycled specimens used in this type of characterization have dimensions of 150 mm in diameter and 300 mm height and they are usually compacted in five equal layers.

The simplified testing procedure consists in inserting the material into a mould equipped with an inflatable plastic membrane. A metal disk is then placed on top of the specimen and a monotonic displacement is applied in a vertical direction until shear failure of the material. The plastic membrane allows to apply different confining pressures to the test specimen up to 200 kPa [74 to 78].

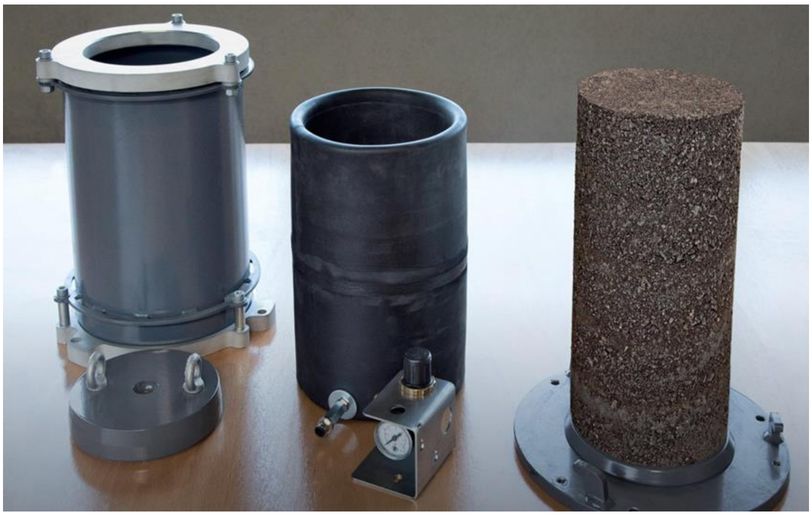

Figure 3.4 Specimen for triaxial testing and testing mold.

The output obtained for the test is a reaction-force displacement curve until shear failure of the test specimen. On the basis of those results it is possible to calculate global plastic properties for the material on the basis of Mohr-Coulomb failure envelope as explained in details next.

For each test specimen the applied failure load ($P_{a,f}$) is recorded in order to calculate the applied failure stress ($\sigma_{a,f}$) using equation 1.

$$\sigma_{a,f} = \frac{P_{a,f}}{A} \cdot 10^{-3} \qquad \text{Eq. 1}$$

Where A is the end area of the cylindrical specimen at the beginning of the test.

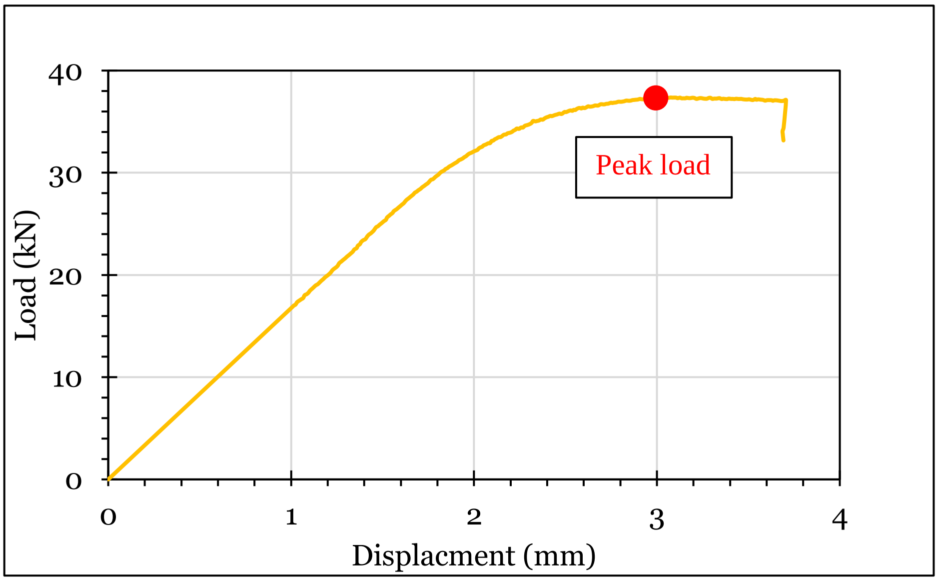

Figure 3.5 Results from triaxial test with identification of peak load.

In a second step, the major principal stress at failure ($\sigma_{1,f}$) is calculated following equation 2.

$$\sigma_{1,f} = \sigma_{a,f} + \sigma_{dw} \qquad \text{Eq. 2}$$

Where σ_{dw} is the pressure resulting from dead weight of top disk and loading ram.

The relationship between the major principal stress at failure and the confining stress (σ_3) is described in equation 3.

$$\sigma_{1,f} = A \cdot \sigma_3 + B \qquad \text{Eq. 3}$$

Where:

$A = \frac{1+sin\varphi}{1-sin\varphi}$ and $B = \frac{2 \cdot C \cdot cos\varphi}{1-sin\varphi}$

Values A and B can be determined by performing a linear regression analysis on the combinations of major principal stress at failure and confining stress. Values of internal friction angle (φ) and cohesion (C) for the material can be accordingly calculated.

The main advantage of using a triaxial test configuration for cold recycled mixture mechanical characterization are:

- Subject the material to a realistic three-dimensional stress state.
- Assess the influence of confining stress on shear capacity of the material.
- Calculate global plastic properties for the material (cohesion and internal friction angle).

In addition, it is easy to perform the test at different temperatures in order to evaluate its effect on plastic response of the material.

Using the same triaxial test equipment is also possible to run resilient modulus tests in order to collect information on the elastic response of the material and its variation with temperature and applied confining stress. A customized AASHTO T307-99 (2017) as shown in Table 3.1 can be adopted.

Table 3. TMR test procedure.

σ_3	σ_1	**Force**	**Cycles**
0 kPa	100 kPa	1.8 kN	110
100 kPa	200 kPa	3.5 kN	110
200 kPa	400 kPa	7 kN	110

The last 10 cycles on 110 cycles of loading application are analyzed, the stress applied over the average recoverable strain in the last 10 cycles is used to estimate the resilient modulus for the material.

3.5 Mohr-Coulomb model for elastoplastic materials

The Mohr-Coulomb failure criterion was utilized to describe the share failure envelope for BSM. The Mohr-Coulomb criterion assumes that failure is governed by the maximum shear stress and that this failure shear stress depends on the normal stress. This can be represented by the Mohr's circle for states of stress at failure in terms of the maximum and minimum principal stresses as can be seen in Figure 3.5 [78].

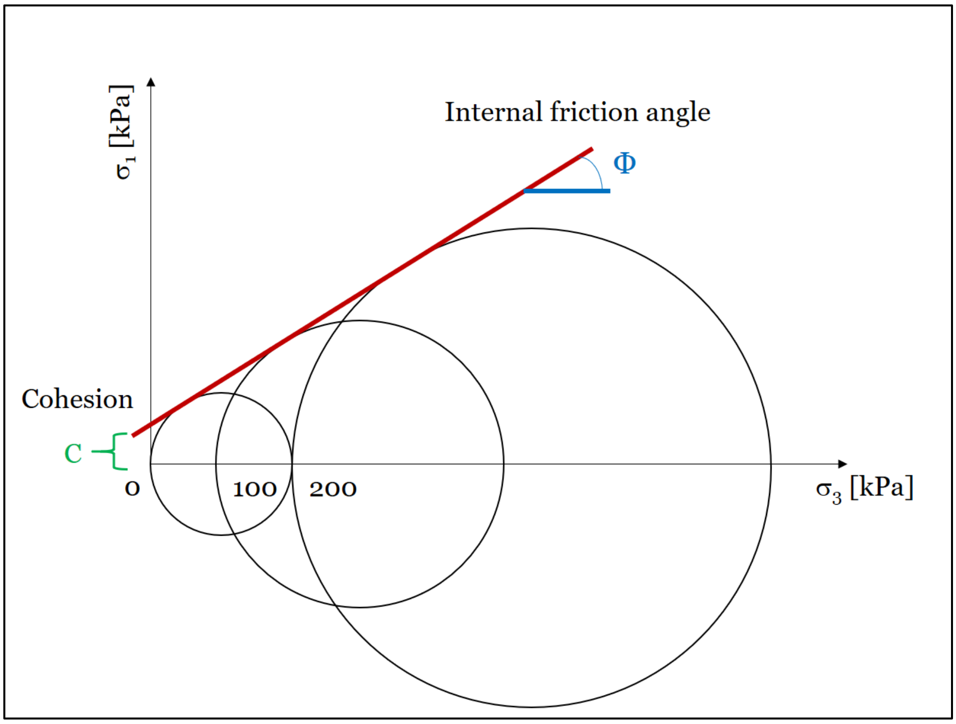

Figure 3.6 Mohr-Coulomb failure envelope.

The equation for Mohr-Coulomb criterion can be written as:

$$\tau = \quad c - \quad \sigma \ tan\phi \qquad \text{Eq. 4}$$

As flow rule, the model utilized in this study considers a flow potential with a hyperbolic shape in the meridional stress plane and has no corners in the deviatoric stress space. This flow potential is completely smooth and provides a unique definition of the direction of plastic flow.

Hyperbolic plastic potential function:

$$G = \sqrt{\left(\epsilon \bar{\sigma}|_0 \tan \psi\right)^2 + q^2} - p \tan \psi \qquad \text{Eq. 5}$$

Where:

- G is the flow potential.
- Є is a parameter referred to as the eccentricity that defines the rate at which the function approaches the asymptote.

The eccentricity used was 0.1 because dilation angle was assumed to be constant under all confining pressure stress values. This means that the flow potential tends to a straight line. The flow rule is non-associated, which means that the stiffness matrix is not symmetric.

3.6 Preliminary results

In this sub-chapter, all the results obtained with ITS and TSS tests are presented. The results can be found also in the journal paper "Use of calcium oxide as active filler for bituminous stabilized materials" under publication process in the Road Materials and Pavement Design journal [79].

The results in terms of ITS (average between three tested specimens), are shown in Figure 3.7.

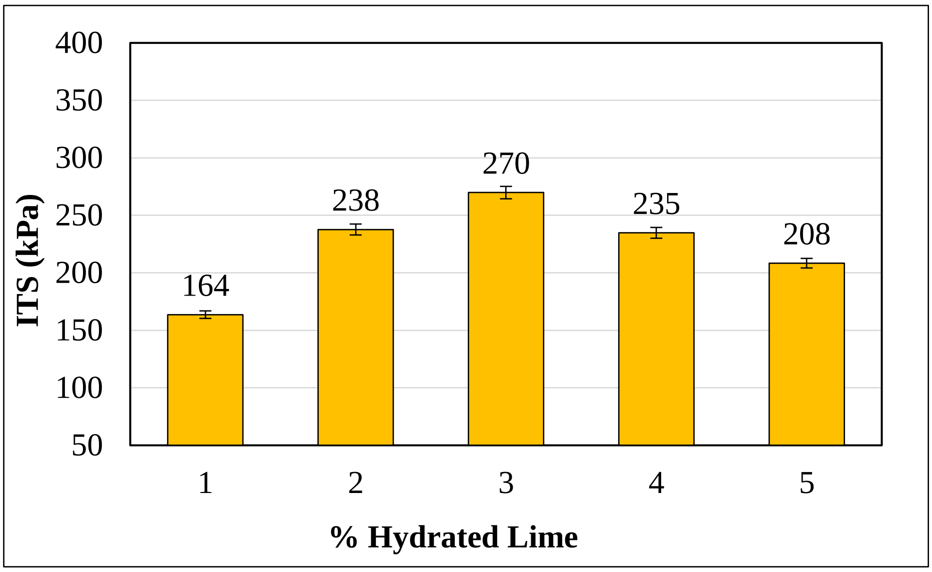

Figure 3.7 ITS preliminary results.

The main outcomes from ITS results are listed next:

- The maximum value of ITS is reached when 3% hydrated lime is added to the mixture.
- High presence of fines in the mixture (over 3%) seems to affect ITS value.
- No information on constitutive plastic properties of the material can be collected from those results.

The results in terms of internal friction angle and cohesion calculated from triaxial shear strength tests are shown in Figure 3.8 and Figure 3.9.

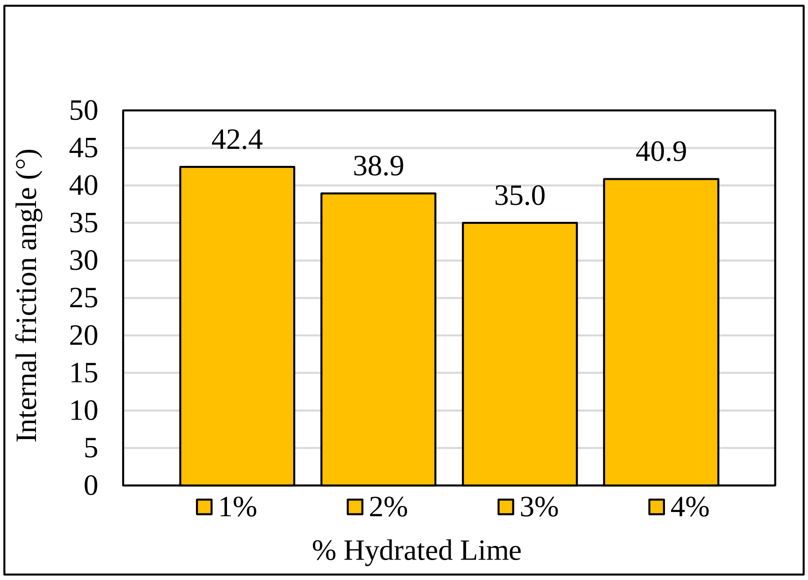

Figure 3.8 Internal friction angle preliminary results.

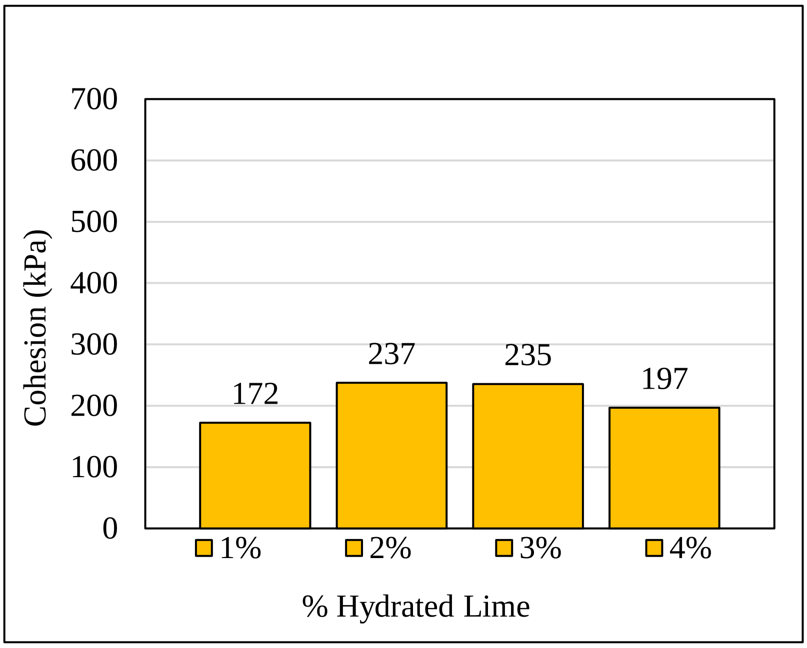

Figure 3.9 Cohesion preliminary results.

The main outcome from TSS tests are listed next:

- Hydrated lime does not have a major impact on global plastic properties of the material.

- Internal friction angle is controlled by RAP aggregates particle-to-particle contact and potentially by RAP gradation. Its value is not influenced by the amount of hydrated lime that is introduced in the mixture.
- Information to describe the plastic behavior of the material were collected following this type of characterization method.

The general conclusion on the basis of the results shown above is that TSS tests, and more in general tests in triaxial configuration, are a better suited characterization method for BSM. As mentioned earlier, the need of fully understand the plastic behavior for those materials and calculate plastic constitutive properties is of paramount importance in order to make accurate prediction on material rutting performance under traffic loading application.

3.7 Multilayer Pavement Model

In this sub-chapter, the multilayer pavement model developed for pavement evaluation is presented. The details about the model and the preliminary results can be found also in the journal paper "Rutting performance analysis for Pavements with Bituminous Stabilized Mixtures as Base Layers" published in the proccedings of the International Symposium on Bituminous Materials conference (December 2020).

The developed two-dimensional finite element model for pavement evaluation can be seen in Figure 3.10.

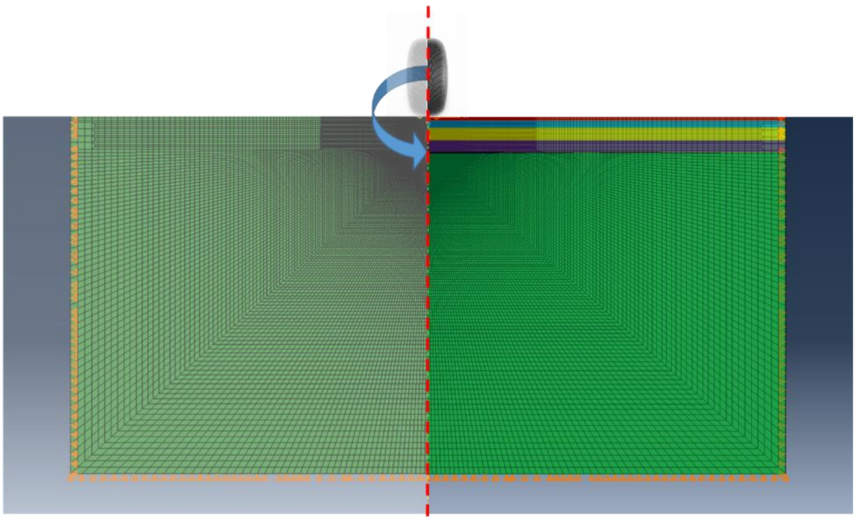

Figure 3.10 Multilayer pavement model.

The model is an axisymmetric model of dimensions 4 m width and 4 m depth. Traffic loading was applied on the surface of the pavement with a tire pressure magnitude of 1 MPa. Friction was considered in between the different layers and the reference cross section was composed by two different lifts of HMA material, a BSM layer, a granular base layer composed of crushed aggregates and subgrade.

While the HMA layers were considered linear elastic materials in all the simulations, plasticity was introduced for all the sub-surface layers. The input values for BSM were taken from the validation and calibration that is described in Chapter 5 (Paper 2).

Up to eight different structural solutions were simulated in order to compare the mechanical performance of rehabilitated pavement structures with the use of cold recycling technologies to the one of traditional pavement structures with only granular base layer.

The four simulated structural solutions can be seen in Figure 3.11.

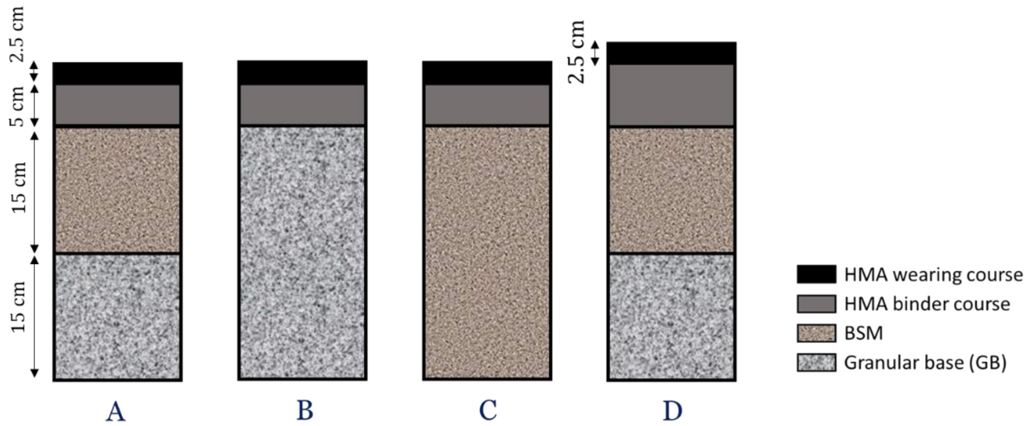

Figure 3.11 Structural solutions.

The results shown in figure 3.12 are in terms of number of loading application on surface before permanent deformation reached 20 mm depth. 20 mm is generally identified as limit for rutting accumulation on the pavement surface, after this threshold is reached the pavement undergoes rehabilitation or reconstruction process.

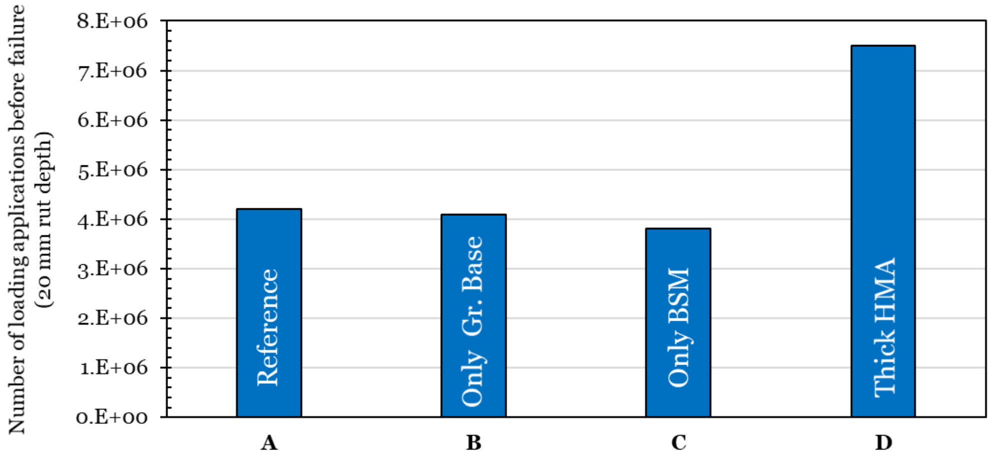

Figure 3.12 Results from numerical simulations of pavement structures in terms of permanent deformation on surface.

In general from those preliminary results it can be seen how asphalt layer thickness has a major impact on rutting performance of the overall pavement structure. Also, it is clear how the structure with only BSM and the one with only granular base show comparable rutting performance. In addition, if solutions A and B are compared it can be seen that replacing 15 cm of granular base with BSM results in the same or increased service life of the pavement structure.

4 Influence of Temperature on Global and Local Elastoplastic Properties of Bituminous Stabilized Material (Paper 1, Appendix A)

The content of this chapter of dissertation is in form of a peer-reviewed journal article. Manuscript for the article is provided in the appendix (Paper 1) to this dissertation. Significance of this article within the overall scope of this dissertation is described next and it serves as a direct contribution to objectives 1, 2, 3 and 4.

4.1 Summary and Significance to Dissertation

This research study has been focusing on the influence of temperature on global and local plastic and elastic properties for BSM. A selected reference mixture prepared with emulsified asphalt and hydrated lime was tested in the laboratory following the triaxial mechanical characterization method described in Chapter 3. TSS and TMR tests were run in the laboratory subjecting the material to three different lateral confining pressures of 0, 100 and 200 kPa under three different temperature conditions of 10, 25 and 40 deg. C. Through the use of Mohr-Coulomb failure envelope, it was possible to calculate global plastic properties for the mixture in terms of cohesion and internal friction angle. Subsequently, local elastic and plastic constitutive properties were extracted through the use of a three-dimensional finite element model which is going to be presented in Chapter 5. As first outcome, the repeatability, accuracy and suitability to different temperature scenarios of triaxial mechanical characterization method was verified. The analysis conducted also indicated that cohesion and elastic modulus are two temperature dependent properties for BSM. In addition, the trend of variation of elastic modulus and cohesion with temperature was shown. In terms of internal friction angle, consistent results were obtained under all the different temperature scenarios, confirming that this parameter is dependent RAP aggregate gradation and particle-to-particle contact more than on the composition of the mixture or the testing temperature. The results obtained allowed to have a better understanding of material mechanical elastic and plastic response under a three-dimensional stress state and realistic temperature range. The calculated local properties were subsequently used in multilayer pavement models for pavement evaluation as it is going to be shown in Chapters 6, 7 and 8.

5 Elasto-Plastic Model for Bitumen Stabilized Materials using Triaxial Testing and Finite Element Modelling (Paper 2, Appendix B)

The content of this chapter of dissertation is in form of a peer-reviewed journal article. Manuscript for the article is provided in the appendix (Paper 2) to this dissertation. Significance of this article within the overall scope of this dissertation is described next and it serves as a direct contribution to objective 4.

5.1 Summary and Significance to Dissertation

This research study focused on the design of a plasticity-based constitutive model for BSM. A three-dimensional elastoplastic finite element model was designed for the simulation of TSS tests.

In a first stage, all the boundary conditions were considered and implemented in the model in order to have a realistic simulation of the laboratory test. Subsequently, a mesh refinement study was conducted until convergence of the results. The laboratory reaction force-displacement curves were then matched with numerical simulations at all the three different lateral confining pressures of 0,100 and 200 kPa. This calibration procedure allowed to extract the local constitutive properties for the material in terms of elastic modulus, cohesion and internal friction angle.

In conclusion, the designed model was able to predict material behavior when subjected to different lateral confining pressure. In addition, the overall research study gives an insight on elastoplastic properties variation for different BSM mixtures with different asphalt binder content. The parameters calibrated and validated with this study were used as input parameters in a multilayer pavement model simulation in order to predict rutting behavior in terms of permanent deformation accumulation on surface under traffic loading application as it is shown in the following Chapters.

6 Temperature dependent plastic response in the design and analysis of pavement structures with cold in-place recycled layer (Paper 3, Appendix C)

The content of this chapter of dissertation is in form of a peer-reviewed journal article. Manuscript for the article is provided in the appendix (Paper 3) to this dissertation. Significance of this article within the overall scope of this dissertation is described next and it serves as a direct contribution to objective 5.

6.1 Summary and Significance to Dissertation

This paper focused on the introduction of plasticity and temperature dependency of BSM and HMA mechanical properties in the design and analysis of rehabilitated pavement structures. The research was conducted using the two-dimensional multilayer pavement model described in the Chapter 3.

In this research study, different constant temperatures throughout the pavement structure and different layer temperature combinations were simulated. The elastic and plastic properties for BSM and HMA were adjusted for each simulation depending on the selected temperature for the layers. In addition, for each scenario the elastoplastic analysis results were compared with linear elastic simulations in order to isolate and quantify the effect of plasticity. The output parameters from simulation results in terms of horizontal strains at the bottom of HMA and vertical strains on top of subgrade were used to calculate maximum allowable repetition of traffic loading applications before rutting and fatigue failure.

The analysis showed that linear elastic and elastoplastic analysis lead to significantly different rutting and fatigue life prediction. Also, it was shown how considering different temperatures and different temperature combinations can have an important effect on overall pavement structure response. As a last step, Deviator Stress Ratio (DSR) was used as parameter for BSM layer evaluation. It was shown how the DSR value gets affected by the temperature of the layer and by its thickness. The model was subsequently implemented with a realistic temperature distribution with depth as it is going to be described in Chapter 7.

7 Influence of curing stage of bituminous stabilized layers on pavement structure elastoplastic response (Paper 4, Appendix D)

The content of this chapter of dissertation is in form of a peer-reviewed journal article. Manuscript for the article is provided in the appendix (Paper 4) to this dissertation. Significance of this article within the overall scope of this dissertation is described next and it serves as a direct contribution to objective 6.

7.1 Summary and Significance to Dissertation

The previously described two-dimensional multilayer pavement model was used in this research study focusing on BSM curing level effect on the overall mechanical response of the pavement structure.

Initially, a function able to consider a realistic temperature distribution with depth was introduced in the model. In this way, the model was able to automatically adjust material elastic and plastic properties at the different locations from the pavement surface. Subsequently, simulations of traffic loading applications were run for the first 14 days after construction operations and before HMA overlay placement on top of BSM. The variation of cohesion and elastic modulus at the different curing levels were estimated on the basis of equations and laboratory tests results taken from the literature. Results in terms of permanent deformation accumulation of the surface under tire loading application were obtain through the simulations. Different structural solutions with different BSM layer types and thicknesses were simulated and compared.

The main outcome has been that in most of the scenarios no significant difference could be seen in terms of permanent deformations on surface in between 7 and 14 days. Also, it was shown how a thicker BSM layer could help limiting rutting accumulation in the early stage of curing and more in general how the evolution in rutting potential depends on the structure of the pavement and not only from material properties.

8 Summary and conclusions

8.1 Summary

Mixtures of BSM were tested in the laboratory following two characterization methods: ITS and TSS. The triaxial configuration was identified as the better suited characterization method in order to identify fundamental elastic and plastic properties for the material. Subsequently, TSS and TMR tests were performed on BSM while subjecting the material to a multitude of different conditions, such as different lateral confining pressures and different temperature conditions. This laboratory effort allowed to calculate global elastic and plastic properties and their variation with testing conditions. At this stage, the research was implemented with a computational mechanics portion in order to develop a constitutive model for BSM. Initially, a three-dimensional elastoplastic model was developed for TSS test simulation. The laboratory reaction force-displacement curves form the laboratory were matched with the simulations in order to extract local elastic and plastic constitutive properties for different BSM mixtures. Those calibrated and validated local properties were subsequently used as input parameters in elastoplastic multilayer pavement models for pavement evaluation. At first, the ability of BSM to guarantee comparable service life in terms of rutting was verified. This was done comparing the results in terms of accumulation of permanent deformation on surface in between structural solutions including BSM as base layer and others with only traditional granular base layers. Secondarily, results in terms of maximum allowable number of traffic loading applications before rutting and fatigue failure of the pavement structure were compared in between linear elastic-based and elastoplastic-based analysis. This was done using different constant temperatures throughout the pavement structures and also introducing different temperatures for the different layers. With this portion, the significant difference in terms of pavement service life calculation caused by the introduction of plasticity and layer temperatures was shown. In conclusion, functions able to consider a realistic temperature distribution with depth in the pavement structure were implemented in the model. This was done so that the model could adjust material properties in the different location basing on the distance from the pavement surface. The evolution of elastic modulus and cohesion with curing time were estimated for BSM on the basis of equations and test results available in literature. Simulation of traffic loading applications were run for the first 14 days before HMA overlay application. The trend of accumulation of permanent deformation on the surface at different curing stages of the material was shown and different structural solutions compared. It was concluded that on the basis of the simulations no major changings can be seen in between the pavement response at 7 and 14 days after construction. In addition, it was shown how the rutting potential in terms of permanent deformation accumulation on the surface depends on the pavement structure and BSM layer thickness and not exclusively on material mechanical properties.

8.2 Conclusions

The main conclusions based on the research completed to date are listed below:

- The use of elastoplastic models for partially-bonded materials is important to fully understand their mechanical behavior.
- BSM when used as a base layer can improve the overall rutting performance of the pavement structure.
- The analysis conducted provides mechanistic analysis to support the use of in-place recycled BSM.
- The framework presented in this study can be adopted for future BSM pavement layer design.
- Linear elastic and elastoplastic analysis lead to significantly different rutting and fatigue life prediction.
- Temperature distribution with depth in the pavement structure has an important effect on the overall pavement response.
- BSM mechanical response at different curing stages of the material suggested that no major changings happen in between seven and fourteen days after construction.
- The rutting potential in the early stage of curing process depends on the pavement structure and BSM layer thickness and not only on material mechanical properties.

8.3 Possible future extensions

The main possible future extensions from this research study are listed below:

1. Verify cohesion and elastic modulus trends for BSM mixtures with laboratory TSS and TMR tests at different curing stages of the material.
2. Verify the trend of permanent deformation accumulation for BSM with curing time with experimental pavement test section.
3. Analyze the effect of temperature on BSM mechanical properties when cement is added to the mixture instead of hydrated lime.

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APPENDIX A Paper 1 (Chapter 4)

Influence of Temperature on Global and Local Elastoplastic Properties of Bituminous Stabilized Material

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Influence of Temperature on Global and Local Elastoplastic Properties of Bituminous Stabilized Material

Bituminous stabilized materials (BSM) are often defined as partially bounded materials since the bitumen content is usually limited to 2% by weight of mix. Nonetheless, temperature susceptibility cannot be neglected when dealing with a material containing bitumen. Therefore, the purpose of this research study was to analyse the influence of test temperatures on mechanical properties of a BSM prepared with bituminous emulsion and hydrated lime. Triaxial shear tests were performed at different temperatures and different confining pressures to obtain the force-displacement curves of BSM (global response). Finite element simulation models were developed for the triaxial shear tests, the global responses from laboratory tests were used as objective functions in finite element models to extract stress-state and temperature dependent local elasto-plastic mechanical properties. It was found that both cohesion in BSM decreases when the test temperature is increased; in addition, the finite element simulation showed that local cohesion is not a constant parameter, but it is closely related to the intensity of the applied lateral confining pressure. As expected, internal friction angle was minimally dependent on temperature.

Keywords: Bituminous Stabilized Materials; Triaxial Shear Test; Finite Element Modeling; Mohr-Coulomb theory; Cohesion; Confining Pressure.

1 Introduction

Bituminous stabilized materials (BSM) are commonly used in cold recycling technologies with three different methodologies: cold in-place recycling (CIR), cold central-plant recycling (CCPR) and full depth reclamation (FDR) [1]. Reclaimed Asphalt Pavements (RAP) and a bituminous stabilizer, such as bituminous emulsion or foamed bitumen, primarily compose those materials, along with mineral or active fillers. In the last few years, many studies have been conducted to determine mechanical properties of BSM but little information was collected on the influence of temperature on their properties, specifically for non-linear constitutive properties. A typical BSM contains around 2% addition of new bitumen by weight of total mixture; although this is less than half of the typical bitumen in Hot Mixed Asphalt (HMA), it can be hypothesised that the mechanical properties of BSM are susceptible to temperature changes, partly due to newly added bitumen and partly due to aged bitumen in RAP. Recent research by Pires et al. [2] supports the hypothesis with respect to effect of temperature on bitumen activity of RAP.

In current pavement design procedures, the mechanical property of BSM that is often taken into consideration is stiffness, or capacity of the material to link stresses and strains. In service, the dominant failure mechanism for the BSM layers within pavement structure is often due to permanent (plastic) deformation; thereby rutting behaviour is of primary interest, while fatigue cracking is not believed to be a main concern for BSM [3]. The permanent deformation causing rutting type of failure is related to plastic flow of the material; for this reason, its shear capacity at different temperatures was evaluated following a geo-mechanics approach. The macroscopic (specimen scale) mechanical behaviour for cohesive granular materials in terms of shear failure limits are usually estimated with the Mohr-Coulomb theory; triaxial shear tests are performed at different confining pressures to determine the macroscopic strength parameters (cohesion and friction angle) [4]. In the specific case of a partially bounded material, surface interactions between particles are altered by the presence of the mastic, or film, created by bitumen and filler in between RAP particles. A second hypothesis for this study was that the physico-chemical bond generated by the mastic affects the cohesion of the material, making it a temperature- and stress-dependent parameter. Therefore, a finite element elastoplastic model was used to simulate laboratory results (force-displacement measurements) and extract local mechanical properties of the material under different conditions. Stress-dependency considerations are of primary importance since the BSM in the pavement structure is subjected to different levels of confining pressures, which depend on the depth of the layer, the magnitude of applied loads on pavement surface and movement of load along pavement surface [5].

2 Materials and Methods

2.1 Mix Design and Specimen Preparation

The BSM was prepared using RAP with a bitumen content of 4.3%, RAP was obtained from milling operations in northern Italy (its size gradation is shown in Figure 1), traditional limestone filler, hydrated lime with 92% calcium hydroxide content and bituminous emulsion as stabilizing agent. The bituminous emulsion used was a neutral pH experimental emulsion containing 60% neat PEN50/70 penetration grade bitumen and the residual bitumen from emulsion was designed to be 2% by weight of dry RAP and filler. The optimum fluid content (OFC) for compaction was determined using the modified AASHTO T-180 [6] test on the dry material (RAP and fillers), resulting in a content of 5.2% by dry aggregates weight. The OFC includes both emulsion and added water during mixing process as they both act as lubricants for BSM [7]. All the details for the BSM mix design can be found in Table 1.

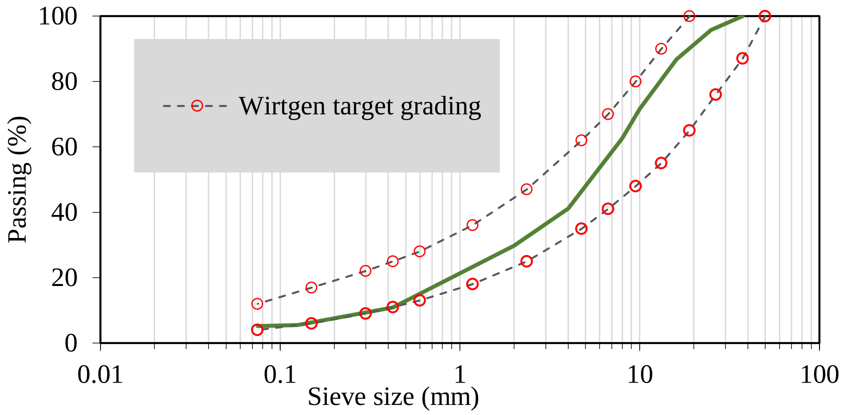

Figure 1. Size gradation of RAP material used for BSM preparation.

Table 1. BSM mix design information.

RAP	Limestone Filler	Hydrated Lime	Residual Bitumen from Emulsion	OFC
95%	3%	2%	2%	5.2%

Specimens for triaxial shear test were prepared using a twin-shaft compulsory mixer with a 30 kg mixing capacity. A total of 360 kg of material was used to prepare 30 specimens of 300 mm height and 152 mm diameter; the specimens were compacted in 5 lifts using a vibrating hammer, a compaction energy of 23 J was applied for 30 seconds using 2.25 kg of material for each lift. The specimens were then stored in the laboratory at constant temperature of 25°C for a curing period of 28 days without any lateral confinement.

2.2 Triaxial Shear Tests

The monotonic confined compression test, or simple triaxial shear test [8, 9], was used to determine the shear properties of the BSM. Three replicates were tested for each confining pressure (0 kPa, 100 kPa, 200 kPa) at each temperature (10°C, 25°C, 40°C).

Figure 2. Simple triaxial shear test set-up

Prior to testing, the specimens were conditioned for 24 hours at the selected test temperature; in addition, the climatic chamber of the test machine was set at the same temperature 2 hours before testing. The tests were performed in displacement control with a constant displacement of 3 mm/minute until complete failure of the test specimen. During the test, the induced reaction force was recorded. The simple triaxial shear apparatus is only applicable to monotonic triaxial testing to obtain cohesion and friction angle values. In addition, it is possible to calculate the monotonic stiffness of the material, also called tangent modulus, which provides an indication of resilient response of the material.

3 Results

3.1 Laboratory Force-Displacement Curves

Figures 2 to 4 present the laboratory measured force-displacement curves; the plots include all the replicates at each temperature and at each confining pressure. The displacement here are line-load displacement values measured at the loading head of the universal testing machine.

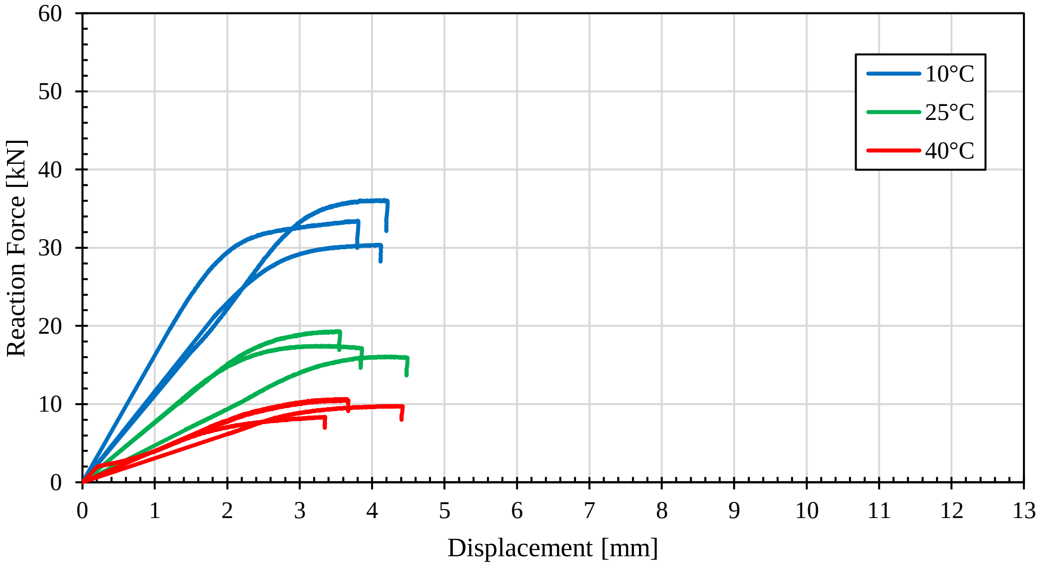

Figure 3. Laboratory Reaction Force-Displacement curves with no lateral confining pressure applied.

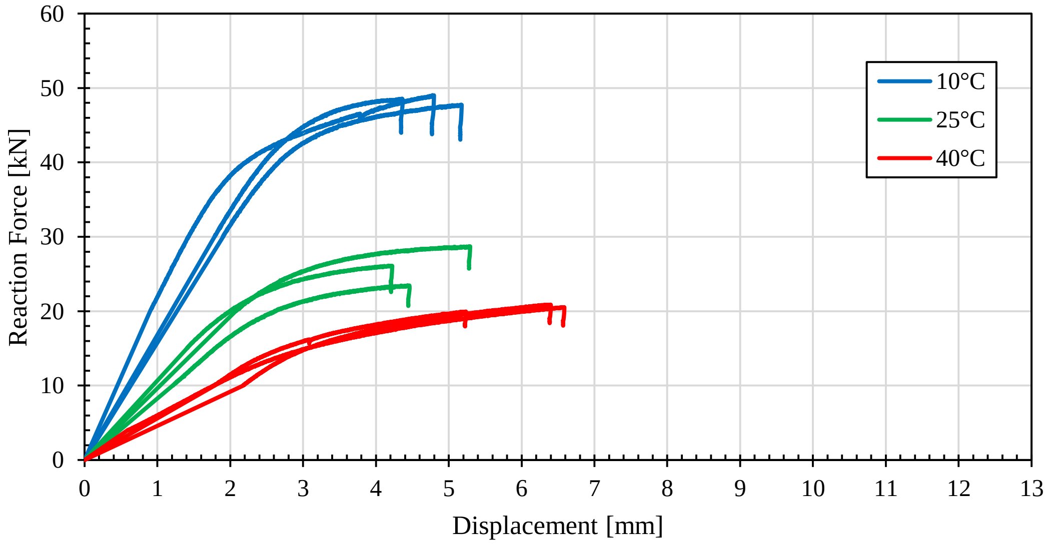

Figure 4. Laboratory Reaction Force-Displacement curves with 100 kPa lateral confining pressure applied.

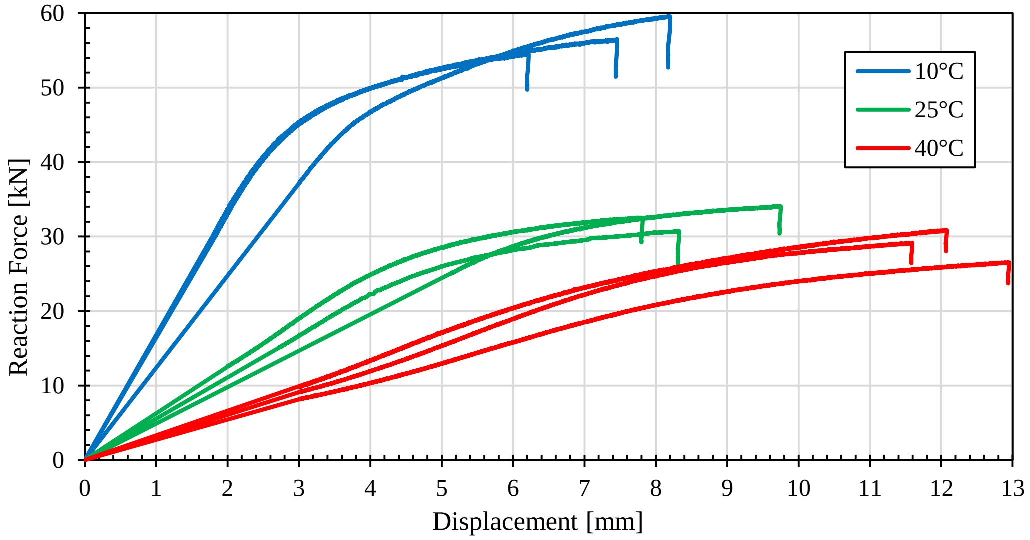

Figure 5. Laboratory Reaction Force-Displacement curves with 200 kPa lateral confining pressure applied.

The replicates show consistent results under each testing condition. When temperature is decreased the initial linear (resilient) response of the material increases in slope, it should be noted that this temperature dependent stiffening effect is not linearly proportional to temperature change (as is case with most viscoelastic materials). In addition, the onset of plastic deformation occurs at higher reaction forces and smaller deformations with decreasing temperatures. As hypothesized, the material displays stiffer behaviour at low temperatures. As can be seen from Figure 2 to 4, under all the different conditions other than 40°C with 200 kPa lateral confining pressure, it was possible to capture the differentiation between the initial linear (elastic) and plastic portion of the response. At higher temperature of 40°C and a relatively high confining pressure of 200 kPa, the material flow is expected to have initiated before application of vertical pressure, thus resulting in absence of clear linear response portion. For this reason, that specific set of results were not considered for simulation and for extraction of local elastoplastic constitutive properties.

3.2 FE Model fitting curves

A 3D finite element elastoplastic model of triaxial shear test (developed by authors [10]) was used for the simulation of the laboratory triaxial shear tests. A representative Reaction Force-Displacement curve was selected from the three replicates at each lateral confining pressure and temperature. To select the curve to be considered for simulation, the replicate curves at each condition were approximated using a bilinear representation (secant representing initial elastic behaviour and tangent to latter part of lab result representing plastic response). Subsequently, average tangents for both the elastic and plastic portions were plotted to obtain a reference bilinear representation for each condition. In Figure 5 to 7, the selected curve from the three replicates under each condition is shown and plotted together with the corresponding simulated results (shown after achieving closest match to objective functions by changing constitutive properties) from the simulation of the elastoplastic triaxial shear test model.

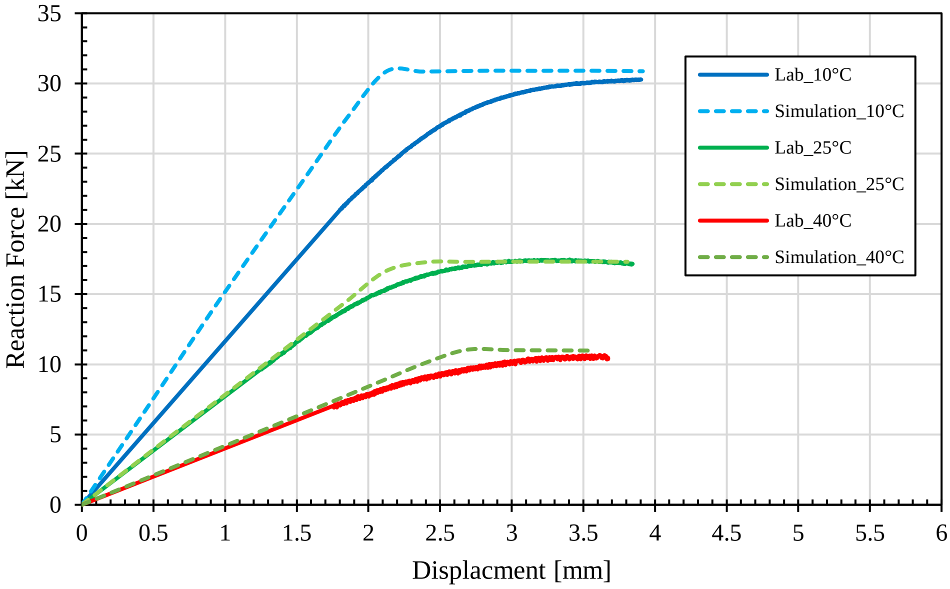

Figure 6. Laboratory selected curves and elastoplastic model fitting curves with no lateral confining pressure.

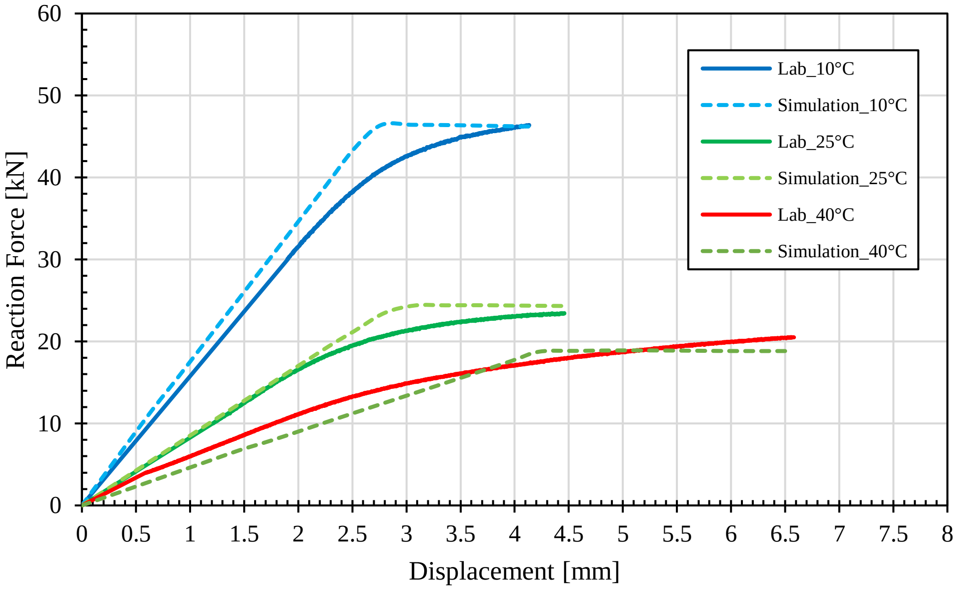

Figure 7. Laboratory selected curves and elastoplastic model simulation curves with 100 kPa lateral confining pressure.

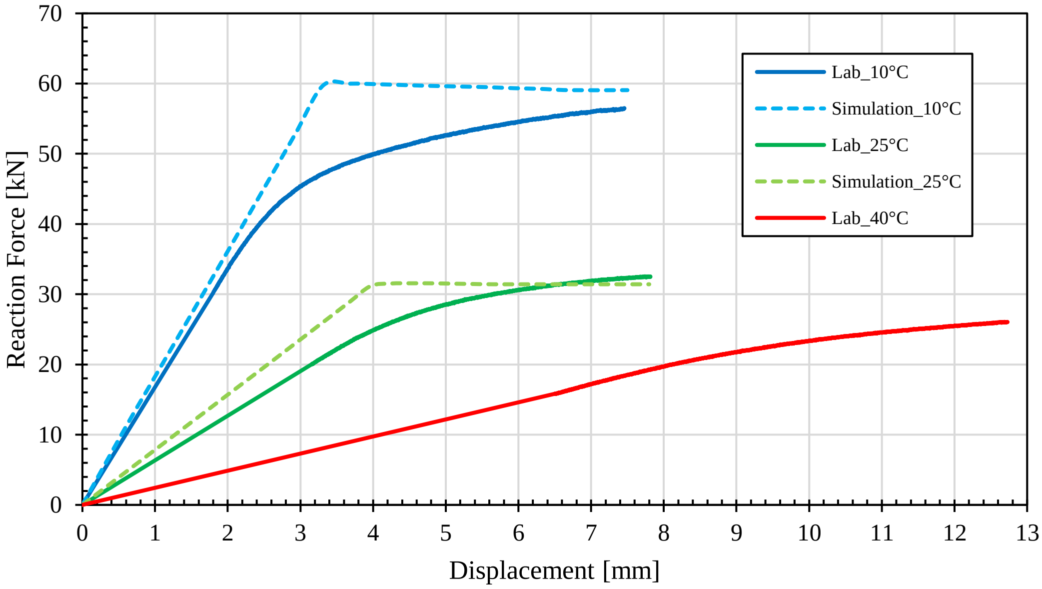

Figure 8. Laboratory selected curves and elastoplastic model fitting curves with 200 kPa lateral confining pressure.

As can be seen from the previous figures, the model was sensitive to confining pressure and temperature changes, it was able to capture the elastic portion of the response and the plasticity occurring in the material under the different conditions; however, the laboratory responses and the fitting curves are not perfectly superposed. This difference is caused by the limitations with respect to current choice of constitutive model that does not capture the transition region between linear response and plastic flow.

3.3 Laboratory results and finite element model simulation comparison

In Table 2, global mechanical properties a determined using force-displacement data from the laboratory testing and local mechanical properties obtained from inverse analysis using finite element model simulation are compared.

Table 2. Comparison in between laboratory measured properties (LAB) and properties from finite element simulation without confining pressure applied (FE).

Parameter		**Temperature [°C]**		
		10	**25**	**40**
Elastic Modulus [MPa]	Global (Lab)	223	112	61
	Local (FEM)	250	130	70
Cohesion [kPa]	Global (Lab)	370	240	125
	Local (FEM)	500	280	180
Friction Angle [°]	Global (Lab)	45	38	42
	Local (FEM)	30	30	30

It should be noted that the global elastic moduli values in Table 2 were estimated using calculation of engineering stress and average specimen strain from force-displacement data within the initial linear portion. Authors fully acknowledge that use of a dedicated test with on-specimen strain measurement, such as resilient modulus test, would have been a better alternative, however due to limitations on laboratory operations, this was not possible. Poisson's ratio measurements are also unavailable for these tests, for the purposes of finite element simulations its value was kept constant at 0.35 for all the conditions. Plastic properties from laboratory tests were calculated using Mohr-Coulomb failure envelope, where the slope of the tangent to the failure stresses at different confining pressures represents the internal friction angle and the intercept with the ordinates axis represents the cohesion of the material. The friction angle from the simulations was found to be constant for all the conditions, regardless of the laboratory calculated values at different temperatures and confining pressures. In Figure 8 and 9, elastic modulus and cohesion variations are presented, those plots are going to be discussed in the subsequent section.

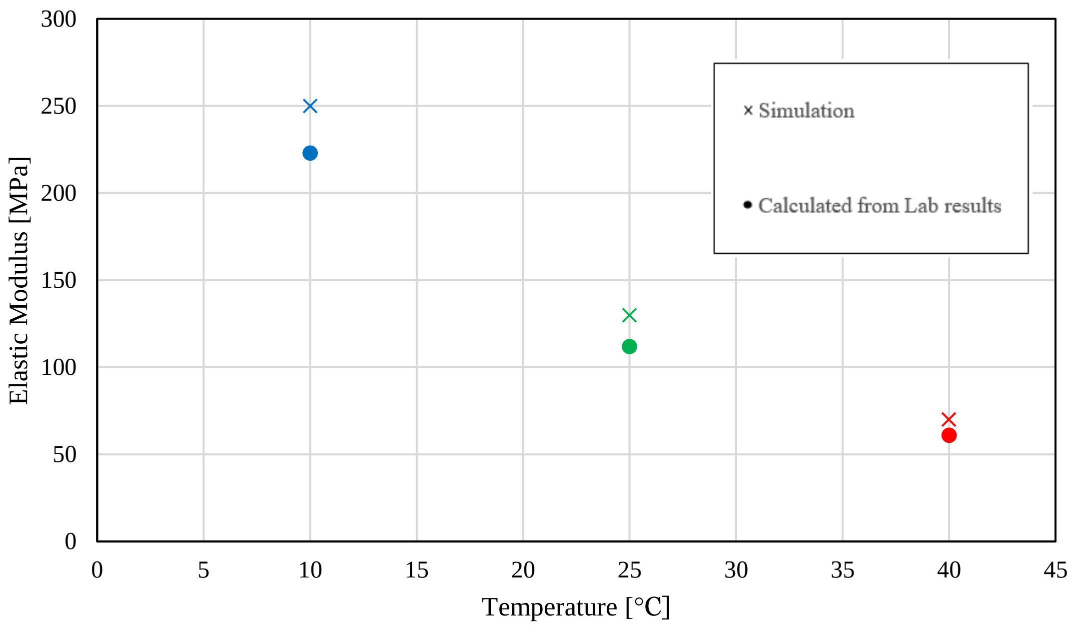

Figure 9. Elastic modulus variation with temperature.

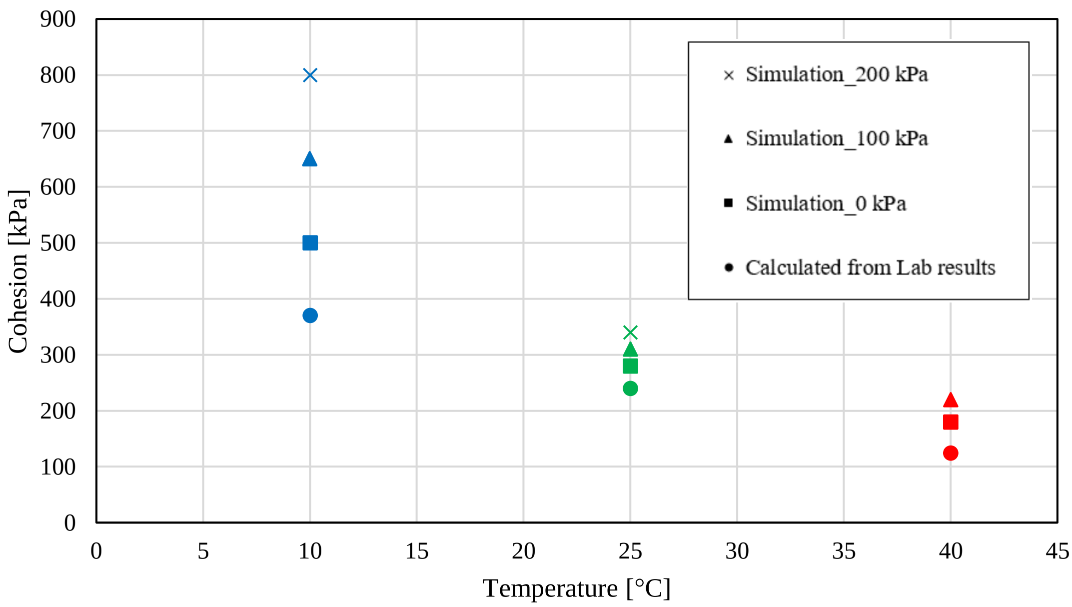

Figure 10. Cohesion variation with temperature and lateral confining pressure.

4 Discussion

4.1 Variation of mechanical properties with temperature

The local properties obtained from simulations were always larger in magnitude with respect to the laboratory measured global properties, this happened under all temperature conditions. In addition, from figure 8 and 9, it is possible to see how both elastic modulus and cohesion vary non-linearly with temperature; this verifies the first hypothesis made for this study: since the moisture content after the curing period of 28 days is believed to be almost insignificant and the aged bitumen coating RAP particles should not be affected in this range of temperatures, the variation of the mechanical properties reflects the influence of temperature on the bituminous mastic in the BSM mixture. In addition, these findings show how BSMs perform differently from unbound materials, in fact, mechanical properties of unbound materials are not affected by temperature changes, and while for partially bounded materials like BSM it is important to keep into consideration temperature effects both on elastic modulus and cohesion properties.

4.2 Cohesion and stress-dependency

In Figure 9, it is shown how the local cohesion value from the model simulations increases with lateral confining pressures. This supports the second hypothesis for this research study: local cohesion is not a stress-state independent property for partially bounded materials.
There are two possible explanation for the cohesion variation with applied pressure:

(1) The adhesion of the bituminous mastic to RAP particles is improved by applied lateral pressure. From a micromechanical point of view, the pressure applied on the material could improve the bonding or adhesion between the particles.
(2) The presence of bitumen in the mix makes the material stress-dependent, in contrast to granular materials in which no bituminous stabilising agents are present.

One last consideration has to be made on the test itself: the simple triaxial shear test utilized in this research study was designed to be performed at 25°C. With an experimental approach it has been adopted to test the material also at low and high temperatures without adjusting the setup, this could explain the higher variability of cohesion at different confining pressure at high and low temperature with respect to the intermediate one.

5 Conclusions

A reference BSM prepared with bituminous emulsion and hydrated lime was subjected to triaxial tests at different temperatures and different lateral confining pressures. Subsequently, the results obtained from the laboratory tests and the mechanical properties calculated from the experimental responses were compared to the simulations obtained from an elastoplastic finite element model. An inverse analysis approach was adopted to match global responses in form of load-displacement curves from laboratory measurements with simulated global response from 3D finite-element model. This was done in order to assess the impacts of temperature effects on elastoplastic mechanical properties of BMS and explore the stress-dependency of the local cohesion for bitumen based partially bounded materials.

The main conclusions on the basis of the previous discussion and results are:

- Friction Angle, as a fundamental plasticity property for partially bounded material, has significant impact on the post-plasticity behaviour of the material. Results from the present work demonstrate that the value of this parameter is driven primarily by aggregate interlocking, which depends on gradation, and has minimal impacts from temperature or stress-state.
- Elastic modulus for partially bounded materials is temperature-dependent.
- Both macroscopic and local cohesion are temperature-dependent parameters, which is expected due to temperature sensitivity of bitumen, which is primary contributor to cohesion in BSM.
- Local cohesion is found to be stress-dependent property for partially bounded materials. An explanation for this dependency can be provided through physical observation of thin films and clusters of asphalt emulsion and filler that exists between RAP particles, such films and clusters under the action of varying confinement provides a varying degrees of adhesive capacity. Secondly, the non-continuous bituminous films and clusters have stress-dependent mechanical response due to their own stress dependent behaviour.

In conclusion, this work demonstrates how BSM mechanical properties are temperature dependent and that plasticity is a fundamental factor to be taken into consideration for partially bounded materials analysis and design; consequently, triaxial tests need to be performed to have a better understanding of the material. This research study is going to be implemented to show the effect of including plasticity and temperature-dependency for BSM layers in multilayer pavement structures design, mainly in terms of rutting resistance. It is believed from the results obtained from this research that neglecting plasticity along with temperature- and stress-dependency of BSM layers can lead to an overestimated service life of the pavement structure. Future extensions of this work are needed to validate the observations made in this paper, some extensions include, use of wider range of materials, exploring more sophisticated plasticity constitutive models, and assessing impacts of BSM constitution (such as, varying amounts of emulsion and active fillers) on global and local elastoplastic properties.

6 References

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APPENDIX B Paper 2 (Chapter 5)

Elasto-Plastic Model for Bitumen Stabilized Materials using Triaxial Testing and Finite Element Modelling

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Elasto-Plastic Model for Bitumen Stabilized Materials using Triaxial Testing and Finite Element Modelling

Abstract. Cold recycling with BSMs is becoming a very common technique, nevertheless there are minimal constitutive models available that can fully characterize their mechanical response in pavement systems.

The aim of this research project was to identify the intrinsic material properties through a finite element simulation of triaxial tests performed in laboratory for BSMs with different mix designs. The main differences between the mechanical behaviors of BSM with respect to foam bitumen content (1.5% and 3%) are determined. All mixes discussed herein contained same active filler amount of 1.5% Portland cement.

The triaxial tests were performed on cylindrical specimens at different confining pressures (0, 100, 200 kPa) in a displacement control configuration (3 mm/min). The triaxial tests at the different confining pressures were simulated using a 3D finite element model to determine plasticity parameters. The input values for an elasto-plastic model (Young's modulus, Poisson's ratio, cohesion, friction angle and dilatation angle) have been calibrated to match experiment results with simulations, mainly in terms of strain and stress levels corresponding to onset of plastic deformation.

The parameters obtained by these simulations are very useful to predict the rutting behavior of bituminous stabilized materials in a multilayer pavement structure. This study provides an insight on how bitumen content affects constitutive BSMs properties.

Keywords: Cold Recycling; Modeling; Finite Elements; Bitumen Stabilized Materials; BSM; Triaxial Test.

1 Introduction

The purpose of this research study was to create a model for BSMs able to describe material responses to mechanical loading conditions. To achieve this objective, laboratory tests were run in order to estimate intrinsic material properties. Those properties were then calibrated in such a way as to match experimental results. As a last step the model has been validated subjecting the material to different boundary conditions, this to verify that it was able to predict material behaviour.

2 Laboratory tests

2.1 Mixtures Design

Bitumen Stabilized Materials are generally designed with Reclaimed Asphalt Pavement (RAP), fillers or active fillers, water and foamed bitumen or bituminous emulsion. In this study the BSMs were prepared with a RAP coming from milling maintenance in north Italy, foamed bitumen (FB) and a combination of fine minerals and cement for the filler portion. All the percentages in the Table 1 are referred to the total weight of the mixture.

Table 4. Mix Designs

Mixture ID	RAP	Mineral filler	Cement	FB	Water
BSM_A	93 %	5.5 %	1.5%	1.5 %	3 %
BSM_B	93 %	5.5 %	1.5%	3 %	3 %

2.2 Laboratory Methodology

The mixtures have been prepared using a bitumen foaming machine and a twin-shaft pug-mill mixer. The RAP was first mixed with the fillers, in a second step the water was added and finally the bitumen was sprayed into the mixture while keeping the mixer running. Five triaxial specimens for every mixture were then compacted using a vibrating compactor, the specimens were compacted in 5 different layers using a compaction time of 30 seconds with an impact energy of 23 J [1]. To promote adhesion a scratcher was used to create a rough surface between the different layers while compacting. The amount of material used for every layer was designed in order to obtain a final height of 300 mm and the mould diameter was of 152 mm.

2.3 Triaxial test setup

The specimens obtained were tested in a triaxial configuration, the specimen holder used is equipped with an inflatable rubber membrane able to apply a lateral confinement to the specimens during the test. A constant displacement rate of 3 mm/min was applied to the loading head of the MTS until specimen's failure, first with no confining pressure and then with 100 kPa and 200 kPa lateral uniform confining pressure. Those values of confining pressure were selected to evaluate material behaviour in the pavement structure, where base materials are subjected to high indirect confining pressure caused by tire load application on the pavement surface.

2.4 Resilient Modulus Testing

A set of BSM_A specimens were tested with a customized AASHTO TP46-94 procedure to determine the Resilient Modulus of the material [2] and have an estimate of the Modulus of Elasticity (E) in a triaxial configuration. The test was run at three different lateral confining pressures and the pressure applied on the top was adjusted each time to keep a constant ratio of $\sigma_1/\sigma_3 = 2$. The last 10 cycles on 110 cycles of loading application were then analysed, the stress applied over the average recoverable strain in the last 10 cycles was used to estimate the Modulus of Elasticity (E).

Table 5. Resilient modulus test

σ_3	σ_1	Force	Cycles	MR
0 kPa	100 kPa	1.8 kN	110	210 MPa
100 kPa	200 kPa	3.5 kN	110	263 MPa
200 kPa	400 kPa	7 kN	110	341 MPa

The recoverable strains were calculated using the outputs coming from the MTS, no strain gauges or displacement transducers were used on the specimen. For this reason, the results can be considered just as a rough estimate of the MR value. Further investigation is needed to determine accurate values, for example performing MR tests in IDT configuration with gauges on the specimens.

3 Finite element elastoplastic model

3.1 ABAQUS Model creation

The 3D model for the BSM was created using ABAQUS software [3], a specimens of 300 mm height and 152 mm diameter was designed, then the boundary conditions for the test were defined. The center of the bottom base was fully fixed (displacements and rotations not allowed in any direction), the displacement for the whole base was not allowed in the Z-axis and for the top base was set a uniform displacement of 3 mm/min. To simulate the confining pressure given by the rubber membrane in the case of 100 kPa and 200 kPa lateral confinement, a uniform distributed load on the lateral surface was applied, this load was set to start being applied 10 seconds before the displacement of the top base. After a mesh refinement process, hexahedral meshes were selected for the model with average element size 10 mm for each of the three dimensions.

3.2 Model Calibration

In this step the inputs for the model were calibrated basing on the global properties of the material obtained from laboratory tests.

The output data obtained from the experimental tests analysis were Friction Angle and Cohesion through the Mohr-Coulomb criterion [4], Modulus of elasticity (E) was estimated from the Resilient Modulus test output and the density of the specimen was measured. The test without confining pressure was simulated adjusting the input values until the output curve from ABAQUS was matching the experimental curve from the laboratory.

Table 3. Unconfined local properties for ABAQUS

ID	Density	E	ν	φ	c
BSM_A	1.93E-009 tonne/mm^3	230 MPa	0.4	31°	450 kPa
BSM_B	1.93E-009 tonne/mm^3	105 MPa	0.4	31°	340 kPa

Table 4. Calibration BSM_A

ID	*ν*	φ	c
BSM_A Lab	NC	37°	475 kPa
BSM_A ABAQUS	0.4	31°	450 kPa

Table 5. Calibration BSM_B

ID	*ν*	φ	c
BSM_B Lab	NC	33°	346 kPa
BSM_B ABAQUS	0.4	31°	340 kPa

3.3 Model Validation

To validate the model, lateral uniform confining pressures of 100 kPa and then 200 kPa were applied keeping the input values constant. This procedure was adopted to assess if the model was able to simulate material behaviour also in case of different boundary conditions. The 3D Finite Element Model is shown in Figure 1. The Cohesion and the Modulus of Elasticity had to be slightly increased when adding the confining pressure to the model as explained in the next paragraph.

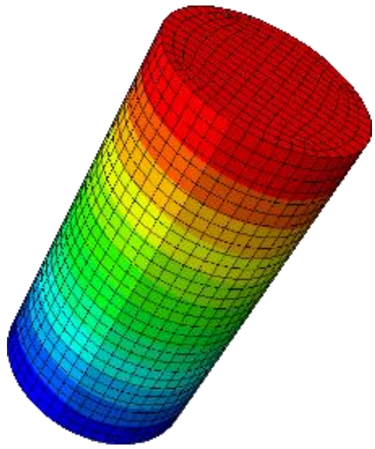

Fig. 13. 3D finite element Elasto-Plastic model

3.4 Hardening effect and Cohesion variation

In both cases the Modulus of Elasticity (E) values had to be increased when adding a confining pressure to the modeled specimen. In the case of BSM_A the E value was increased of 15% every 100 kPa of increment in confining pressure. As can be seen from Fig.2 the values used for the model matched reasonably well with the laboratory results from Resilient Modulus test in triaxial configuration.

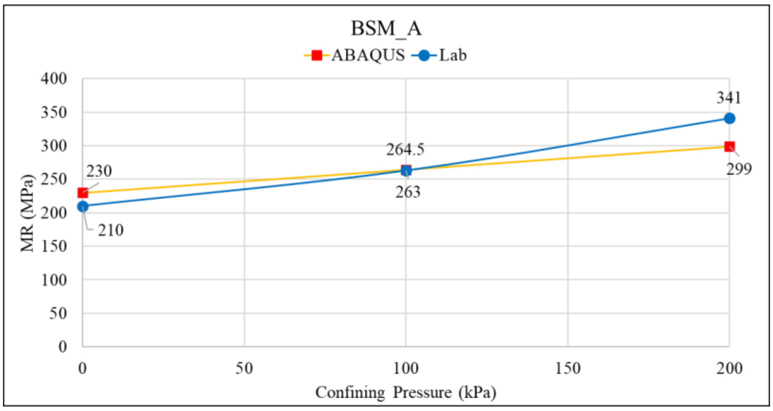

Fig. 2. Modulus used for the model vs Modulus estimated from laboratory results.

In the case of BSMA_B the Modulus of Elasticity had to be increased of 30% for every 100 kPa of incrementation in confining pressure. Those behaviors are due to the stress hardening effect, the material under increased applied stress exhibits less deformation and therefore greater stiffness or resilient modulus [5]. Also, the Cohesion value in the BSM_A was increased of a 15% every 100 kPa increment in confining pressure and of a 10% in the BSM_B.

4. Results

4.1 ABAQUS curves vs Laboratory curves

The curves obtained with the finite element simulation were plotted together with the real curves obtained in the laboratory for the three different conditions (Figure 3).

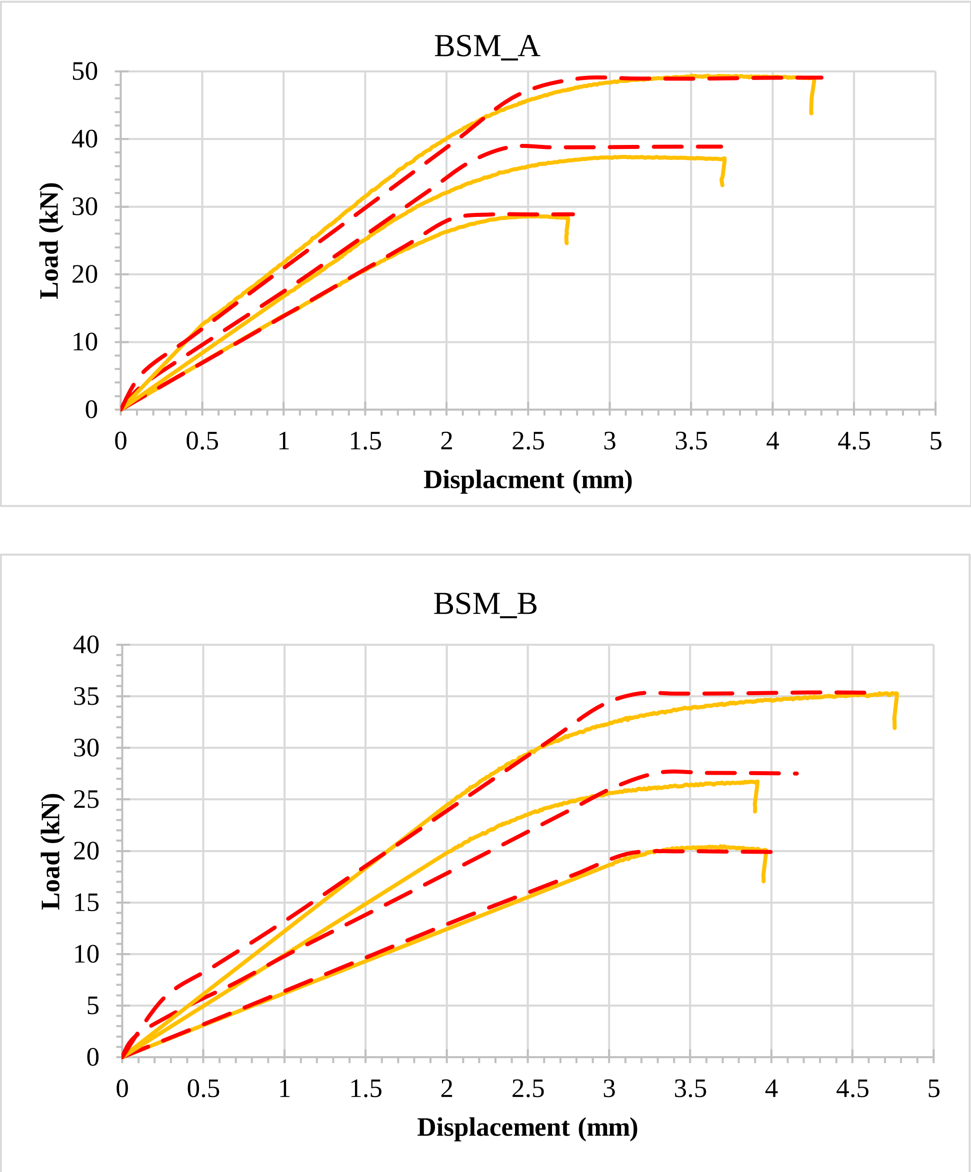

Fig. 3. ABAQUS simulation (red) vs laboratory curves (yellow). Confining pressure applied is 0 kPa for the lower curve, 100 kPa for the middle one and 200 kPa for the higher curve.

It is evident that there is almost no difference in terms maximum load and maximum displacement where plasticity takes over in between the model and laboratory curves, also the slope of the elastic part is matching perfectly with the experiment results. The model is able to accurately capture material's behaviour in the laboratory for both the mixtures.

5. Conclusion

The model is able to predict materials' behaviour when subjected at different confining pressures, it provides an insight on elasto-plastic properties variation for different bitumen contents and under different boundary conditions.

The parameters calibrated and validated with this study have then been used in a multilayer pavement model simulation in order to be able to predict rutting behaviour under traffic loading application.

The different results obtained at different lateral confining pressures are interesting because the material on field is subjected to an indirect confining pressure that is dependent on the depth where the layer is located in the multilayer structure, so the parameter in the multilayer model can be adjusted basing on the BSM position in the structure.

The idea is to implement this study in the future simulating other materials with different active filler content, bitumen content and with other types of components like lime or bituminous emulsion, with the final aim of collecting a database of materials' properties based on different mixture composition.

The properties calibrated and validated following the same procedures used in this study will be useful to implement pavement design software with plasticity information for different BSM designs.

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APPENDIX C Paper 3 (Chapter 6)

Temperature dependent plastic response in the design and analysis of pavement structures with cold in-place recycled layer

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Temperature dependent plastic response in the design and analysis of pavement structures with cold in-place recycled layer

Abstract. Cold In-Place Recycling (CIR) allows the existing asphalt pavement layer to be recycled directly on site. The mixture that is generated through this rehabilitation process usually includes approximately 2% new added asphalt binder (added as emulsified or foamed asphalt); for this reason, these mixtures are often considered as partially bonded materials. The objectives of this research were to demonstrate the importance of incorporating plasticity behavior and the effects of temperature on mechanical properties of CIR in the design of pavements with CIR layers. A 2D axisymmetric finite element model was designed using ABAQUS software. The model was verified for elastic and elastoplastic responses using layered elastic software JULEA and finite element pavement analysis software ILLIPAVE, respectively. Different temperature distributions and three pavement structures were subjected to the same loading applications and their responses were compared to determine the regions and pavement types where plasticity behavior of CIR layers is most critical. In addition to traditional asphalt pavement design responses (tensile strain in HMA layer and vertical strains on subgrade), this study adopted the Deviator Stress Ratio for CIR layers as a critical rutting potential response. Comparisons of critical pavement responses from the ABAQUS elastoplastic model and corresponding design lives demonstrate that plasticity plays a major role in the pavement structural response to traffic loading, primarily at high temperatures and for thinner pavement structures. The pavement designs that do not include the plasticity response in subsurface layers may overestimate design lives by more than 50%.

Keywords: Cold In-Place Recycling; partially bonded materials; finite element modeling; elastoplastic model; temperature distribution.

1 Introduction

Cold In-Place Recycling (CIR) is an increasingly popular rehabilitation technique; it allows the surface layers of the pavement structure to be recycled with minimum energy usage to heat materials (unlike traditional hot recycled of RAP in asphalt mixtures) and without need for transporting in-situ materials. This technique is recognized in road construction for its environmental, economic and structural benefits [1]. The milled material from the existing pavement is directly mixed on site with an asphalt stabilizer, either asphalt emulsion or foamed asphalt, and in some cases with active fillers [2]. The mixture that is generated by CIR process is a partially bonded material containing a relatively low amount of new asphalt binder, usually up to 2% of weight of total mixture.

Many studies focusing on characterization of CIR mechanical properties have been conducted [3, 4]; the main findings show the importance of distinguishing cold recycled materials from fully bonded materials like Hot Mixed Asphalt (HMA) and unbound materials like crushed aggregates. The presence of a relatively high amount of new asphalt binder in the CIR mixture, along with the addition of active fillers such as cement or lime, creates a different mechanical response in comparison to unbound materials generally used for base layers. The presence of asphalt stabilizing agents causes the CIR material to have characteristics closer to HMA in terms of temperature susceptibility, while its failure mechanism is governed by similar principles to the ones of unbound aggregates. Kavussi and Modarres [5] studied the effect of temperature on cold recycled mixtures mechanical properties, the mixtures characterized in this study were prepared with RAP, asphalt emulsion and different percentages of cement. It was demonstrated that when no cement is present in the mix design or the application rate is limited to less than 3%, the temperature susceptibility of the material plays a major role in the elastic response and in terms of fatigue behavior.

The first hypothesis for this research study was that the plastic behavior needs to be considered for pavement analysis and design and that plasticity coming from the CIR layer and its temperature susceptibility cannot be neglected. In current pavement design procedures, the main property of CIR that is taken into consideration is stiffness, or capacity of the material to carry load; in reality, the dominant failure mechanism for this type of pavement layer is permanent deformation from plastic behavior [6]. Constitutive properties for plastic materials, such as cohesion and internal friction angle, can be determined with triaxial tests at different confining pressures, following the failure criterion of Mohr-Coulomb theory. Mechanical properties of CIR materials at different test temperatures were taken from a previous laboratory study; in that research study, the effect of temperature on mechanical properties of a CIR mixture prepared with asphalt emulsion and hydrated lime was determined [7]. Based on the findings from this previous laboratory study, it was also hypothesized that the effect of temperature on the contributions of CIR to overall pavement structural capacity needs to be incorporated, specifically for plastic response of the material. Neglecting temperature dependent plastic response can result in significantly under or over-designed pavement structures.

To evaluate the study hypotheses, a 2D multilayer axisymmetric elastoplastic model was developed using ABAQUS finite element software; the cross-section for the model was designed based on an actual highway, MN-30 in Stevens County, Minnesota. The model was at first validated for elasticity and plasticity and then implemented with a function able to adjust material properties based on layer temperatures. In this way, it was possible to analyze different scenarios and determine the effect of plasticity on pavement response under different temperature conditions. For HMA, granular base and subgrade layers, the mechanical properties were determined from MnPAVE software [8] and the HMA layer is the only layer that was considered purely elastic in all the analysis. The effect of temperature on mechanical properties was considered just for the HMA and CIR layers, in the unbound crushed aggregates and subgrade layers the temperature effect was considered negligible and moisture variations effects were omitted. Pavement structures with thinner and thicker cross-sections with respect to the reference structure were simulated and comparisons made between elastic and elastoplastic solutions. All of those responses where then converted to number of allowable repetitions before fatigue and rutting failure of the pavement structure and the Deviator Stress Ratio (DSR) for the CIR layer [9] was calculated on the basis of the principal stresses from the elastoplastic simulations.

2 Methods

2.1 Finite Element Model Design

Multilayer pavement structure

A finite element model was designed based on a CIR construction project that took place on MN-30 in Stevens County, Minnesota. Post rehabilitated pavement with CIR and a surface course (HMA) was simulated using ABAQUS software, the details of pavement structure can be found in Table 1. The CIR mixture is composed of RAP containing 4.3% aged bitumen, 2% Residual Bitumen (RB) coming from a neutral pH emulsion (60% neat 50/70 penetration grade bitumen) and hydrated lime (HL). The HL used in this study had a 92% calcium hydroxide content and was introduced in the mixture as an active filler.

TABLE 1 Multilayer structure cross-section and materials description

MnDOT TH30 CIR Project [Stevens County; District 7]		
Layer	**Description**	**Thickness [mm]**
HMA	12.5 mm nominal maximum aggregate size, Binder: PG58-34	75
CIR	2% RB + 2% HL	75
Granular Base	MnDOT Class 6	250
Subgrade	Silty Loam	Semi-infinite

ABAQUS model design

The 2D axisymmetric model was designed with dimensions of 6 m width and 6 m depth, the decision for model domain was made on the basis of a model extent analysis that allowed identification of the necessary minimum dimensions to avoid artifact effects coming from the boundary conditions. The elements used to build the model are 4 node quadrilateral axisymmetric explicit elements, their dimensions were varied using an one-way graded transition approach resulting in smaller element sizes in the area close to the applied load as can be seen in Figure 1.

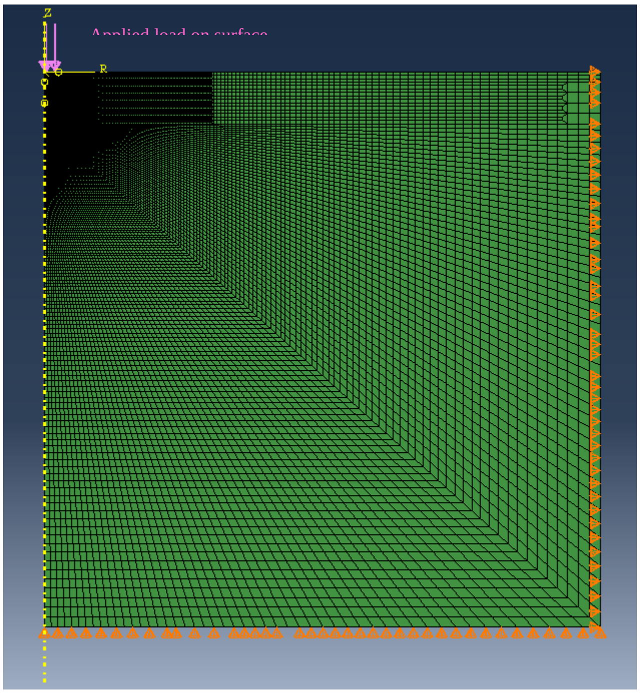

FIGURE 1 Multilayer pavement structure ABAQUS model

A circular tire load was modelled using a 1 MPa pressure over 10 cm radius (corresponding to a 63 kN axle weight). All the layers were considered as fully bonded. A load application of 1 second was considered with a gaussian distribution reaching the peak at 0.5 second. For the elastic validation, a static general analysis was performed and, after plasticity was introduced, the analysis type was changed to dynamic explicit. Lastly, a function able to adjust material mechanical properties based on the layer temperature was introduced for HMA and CIR. Five different temperature scenarios were simulated for this study, in the first three scenarios the temperature was considered uniform throughout the whole pavement structure. Simulated temperatures include, a low temperature of 10 °C, an intermediate temperature of 25 °C and a high temperature of 40 °C. The reason for this selection was to have a representation of different climatic regions; the assumption of having subsurface layers at 10 °C and 40 °C was done in order to have extreme scenarios that would facilitate a complete view of the response trend of the pavement. To have a more realistic representation of an on-site temperature distribution in the pavement, two more scenarios were added. In those models, just HMA layer temperature was varied using 10 °C and 40 °C, while all the other layer were considered at a constant temperature of
25 °C.

Layer Properties

Layer properties are shown in detail in Table 2. The property for HMA, granular base and subgrade were taken from MnPAVE software with the exception of cohesion and friction angle for subgrade; average mechanical properties for silty loam subgrade were taken from a research study by Koloski et al. [10]. The mechanical properties for the CIR layer were obtained from triaxial shear and resilient modulus tests conducted in a previous laboratory study [6]. The air void content for the CIR mixture was 14.3% at the time of testing. All the tests were run after 28 days of curing at room temperature; therefore, the free moisture content in the material was considered to be negligible and consequently not considered.

TABLE 2 Mechanical properties of pavement layers at different temperatures

Layer	Temperature [°C]	Elastic Modulus [MPa]	Poisson's ratio	Cohesion [MPa]	Friction Angle [°]	Density [kg/m³]
HMA	10	3395	0.30	N/A	N/A	2400
	25	1004	0.41	N/A	N/A	
	40	500	0.43	N/A	N/A	
CIR	10	250	0.40	0.180	30	1970
	25	130	0.40	0.280	30	
	40	70	0.40	0.500	30	
Granular Base (MnDOT Class 5)	10, 25, 40	138.5	0.40	0.042	40	2080
Subgrade (Silty Loan)	10, 25, 40	30	0.45	0.015	24	1840

2.2 Model Verification

The model was verified following two steps: first, linear elastic behavior was simulated for all pavement layers with moduli values corresponding to a constant reference temperature of 25 °C throughout the whole pavement structure; the pavement response from ABAQUS model was then compared to the LEA software JULEA. Subsequently, plasticity response was introduced in all the sub-surface layers (CIR, aggregate base, and subgrade)using a constant temperature of 25 °C. The results predicted from the ABAQUS elasto-plastic model were compared with the nonlinear finite element software ILLIPAVE [11]. Three parameters were selected for comparison to verify the model predictability: horizontal strain at the bottom of HMA layer and vertical stress and vertical strain at the top of the subgrade layer. All the results shown in this section are corresponding to the locations directly under the center of the tire at different depths.

Linear elastic model verification

For the linear elastic verification just elastic modulus (E) and Poisson's ratio were used and all the layers were considered as fully bonded. The results for the elastic verification are shown in Table 3.

TABLE 3 Elastic response verification

	LEA	ABAQUS Elastic	Difference [%]
Horizontal Strain at bottom of HMA	1.01E-03	9.83E-04	-2.61
Vertical Strain on top of subgrade	1.23E-03	1.21E-03	-1.60
Vertical Stress on top of subgrade [MPa]	35.92E-03	37.20E-03	3.57

The model was considered reliable for the elastic response, with relatively small differences between the values of critical pavement responses.

Elastoplastic model verification

All the layers were considered as fully bonded. Cohesion and internal friction angle properties were introduced in the ABAQUS model and within ILLIPAVE at the constant reference temperature of 25 °C for the whole structure. All the layers except the HMA were modeled as materials with an elastic- plastic type of behavior. The Mohr-Coulomb model adopted in this study utilizes the material cohesion and internal friction angle values in combination with the principal stresses dictate the plasticity yield conditions. The plastic strain accumulation is on the basis of the Mohr-Coulomb flow rule where plastic strain is calculated using a hyperbolic plastic potential function proposed by Menetrey and William [12]. Due to rate dependency as well as material response non-linearity, the ABAQUS simulations were conducted as a dynamic explicit analyses. The results for the elastoplastic verifications are shown in Table 4.

TABLE 4 Elastoplastic response verification

	ILLIPAVE	ABAQUS Elastoplastic	Difference [%]
Horizontal Strain at bottom of HMA	9.79E-04	1.04E-03	+5.96
Vertical Strain on top of subgrade	1.35E-03	1.36E-0.3	+0.41
Vertical Stress on top of subgrade [MPa]	39.30E-03	41.35E-03	+4.97

The elastoplastic ABAQUS model gave consistent results with ILLIPAVE software and therefore was considered reliable for predicting elastoplastic pavement response.

3 Results and discussion

In this section all the results obtained from the different simulations are presented. Initially, the focus is on the pavement response under the three different constant temperature scenarios. Comparisons are made between structures with different layer thicknesses both in terms of horizontal strains at the bottom of HMA layer and vertical strain at the top of subgrade, and of maximum allowable loading repetitions before fatigue and rutting failure of the pavement. Subsequently, the two additional scenarios with only HMA layer temperature variation are introduced and the responses from those simulations are compared to the previous cases. Lastly, the focus is moved to the CIR layer response, in this case the DSR is adopted as the critical response; this was done to evaluate the material's rutting potential and DSR was calculated for the CIR layer under all the above mentioned scenarios.

3.1 Plasticity effect at different temperatures

The results with assumption of constant temperature throughout pavement structure are presented in Figures 2 and 3. The strains shown are those under the center of the tire over the 1s loading period.

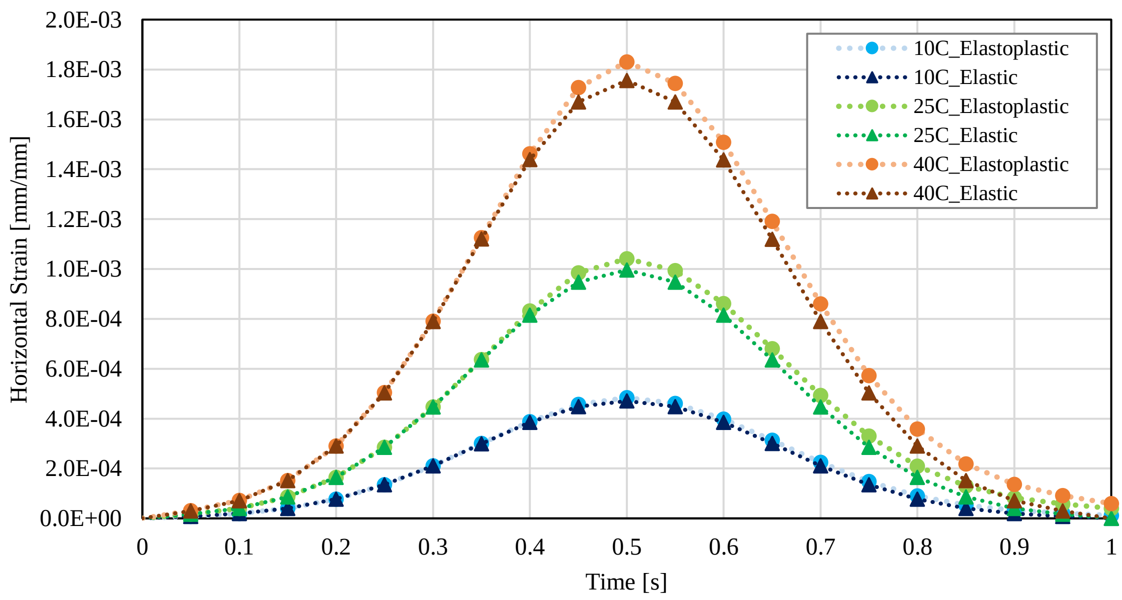

FIGURE 2 Horizontal Strains at bottom of HMA: Elastoplastic model vs Elastic model

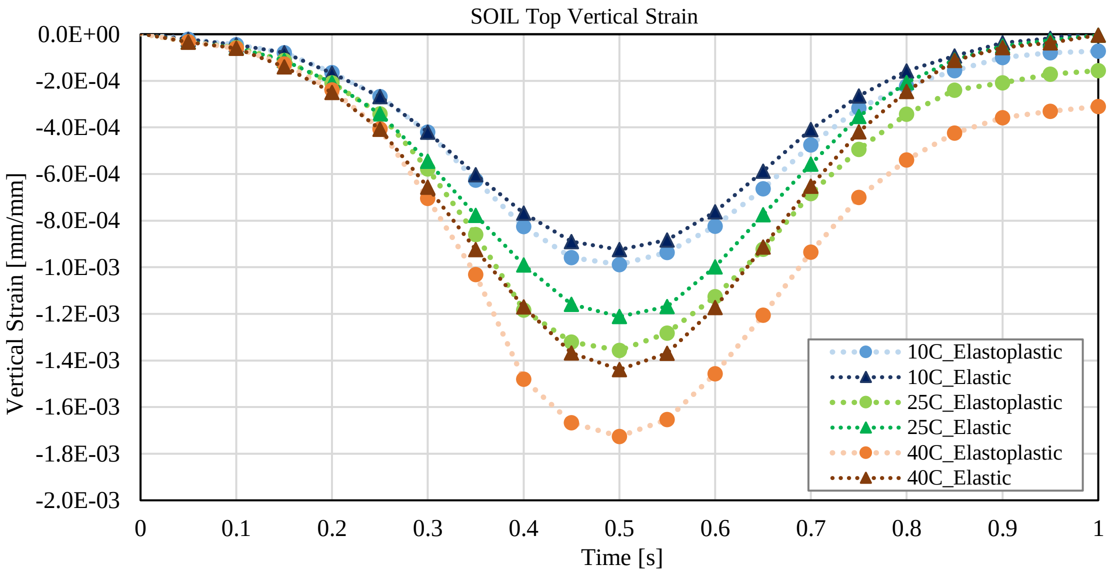

FIGURE 3 Vertical Strains on top of Subgrade: Elastoplastic model vs Elastic model

The consideration of plasticity in subsurface layers results in higher peak strains overall, with a larger impact on vertical strain at the top of the subgrade and a minor impact on horizontal strain at the bottom of the HMA layer. The effect of plasticity (both peak strain and residual strain) is more apparent when the temperature is increased. This is due to lower values cohesion for of CIR at high temperatures and subsequently the material undergoes plastic strains at a lower stress magnitude. Furthermore, at higher temperatures the elastic modulus of HMA layer reduces, which also results in increased stresses within subsurface layers.

3.2 Comparisons of different pavement structures

In addition to the previous three scenarios, another two pavement structures with different cross-sections were considered, this was done in order to evaluate the influence of layer thicknesses on plastic response of the pavement structure. In Table 5, the three different structures are described. For the thin structure simulations were conducted for 10 °C and 25 °C pavement temperatures whereas for the thick structure, simulations for 25 °C and 40 °C pavement temperatures were performed. It is expected that this partial factorial approach is sufficient to assess the hypotheses posed in this paper.

TABLE 5 Pavement structures simulated

Layer	Thin pavement	Reference (MN-30)	Thick pavement
HMA	38 mm	75 mm	100 mm
CIR	50 mm	75 mm	100 mm
Granular Base	100 mm	250 mm	300 mm
Subgrade	Semi-infinite	Semi-infinite	Semi-infinite

The horizontal strains at the bottom of HMA layer and vertical strain on top of subgrade layer were used to calculate the allowable number of loading repetitions before fatigue and rutting failure of the pavement structure. The maximum strains calculated with the elastic and elastoplastic simulations were used as input in the MnPAVE transfer functions for fatigue (equation 1) and rutting (equation 2), the results of these analysis are shown in Table 6.

$$N_F = \quad C_F K_{F1} \varepsilon_h^{K_{F2}} E^{K_{F3}} \qquad (1)$$

$$N_R = \quad C_R K_{R1} \varepsilon_v^{K_{R2}} \qquad (2)$$

Where:

N_F = allowed repetitions for fatigue

C_F = correction factor: 0.433

K_{F1} = 1.2

K_{F2} = -3.291

K_{F3} = -0.854

N_R = allowed repetitions for rutting

C_R = correction factor: 1.39

K_{R1} = 0.0261

K_{R2} = -2.35

E = Elastic modulus of HMA layer

ε_h = maximum horizontal strains at bottom of HMA layer

ε_v = maximum vertical strain on top of subgrade layer

TABLE 6 Comparisons of pavement life in terms of rutting and fatigue (dominant distress is indicated) for Elastic (E) and Elastoplastic (EP) simulations for different pavement structures and temperatures scenarios.

Temperature [°C]	**Structure**	**Model Type**	**N_F**	**Difference between Elastic and Elastoplastic for N_F [%]**	**N_R**	**Difference between Elastic and Elastoplastic for N_R [%]**
10	Thin	E	176,883	-64.56	**22,392***	-47.62
		EP	62,669		**11,727***	
	Reference	E	636,085	-8.57	**488,902***	-14.34
		EP	581,568		**418,770***	
25	Thin	E	102,999	-75.75	**12,037***	-54.14
		EP	24,971		**5,519***	
	Reference	E	**153,113***	-13.26	260,081	-24.01
		EP	**132,808***		197,623	
	Thick	E	**301,954***	-0.81	728,816	-20.56
		EP	**299,497***		578,926	
40	Reference	E	**42,644***	-12.04	172,783	-35.02
		EP	**37,507***		112,265	
	Thick	E	**77,276***	-0.60	483,395	-27.49
		EP	**76,806***		350,481	

*****dominant distress controlling pavement life.

For all scenarios, the number of allowable load repetitions is overestimated by the elastic solution. The effect of elastoplastic response for subsurface layers is more significant in pavement life prediction for thinner pavement structures. The thin pavement structure at low temperature still shows a considerable difference between the elastic and elastoplastic solution, illustrating that considering just elasticity for the design of lower volume roadways could lead to a significant overestimate of the allowable traffic before failure. In the case of thick structures, there are minimal differences in terms of fatigue life while rutting life is overestimated without consideration of plasticity (20% at intermediate temperature). Therefore, the plasticity effect is important to consider for rutting life evaluation in all situations, but may not be necessary for fatigue life evaluation of thick structures.

Plasticity effect comparison with different temperature distributions

The finite element model was extended with a function able to adjust mechanical properties of HMA and CIR materials on the basis of the temperature of the layer. Two scenarios were added to the simulations to isolate the effect of the HMA layer mechanical properties at different temperatures; in the first scenario the HMA temperature was set at 10 °C while keeping the CIR at 25 °C, in the second one the temperature of the HMA was set at 40 °C and the CIR one was again kept constant at 25 °C. The responses in terms of horizontal strains at the bottom of the HMA and vertical strains on top of the subgrade are shown in Figures 4 and 5.

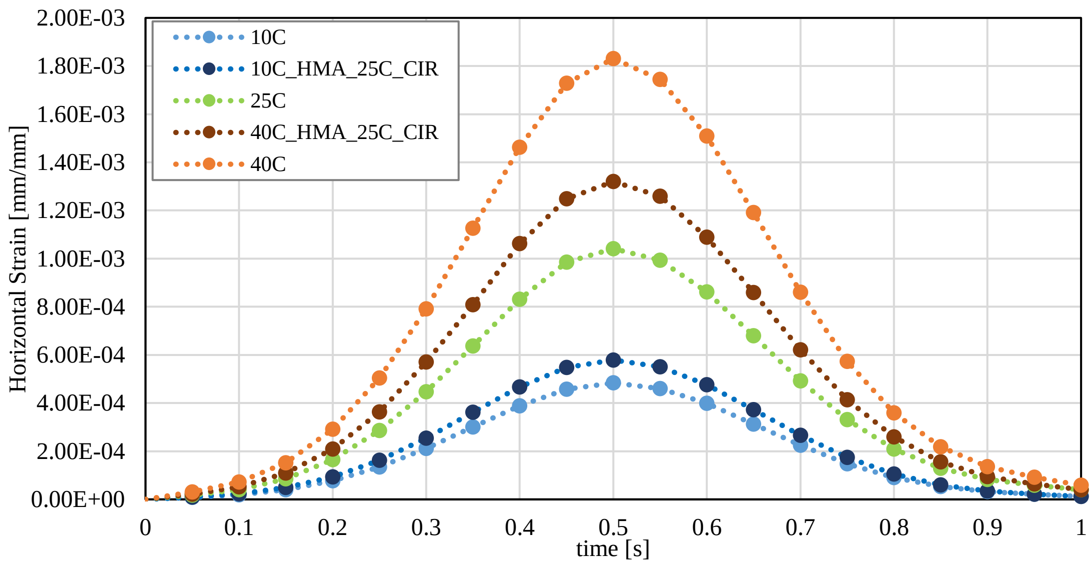

FIGURE 4 Horizontal Strains at bottom of HMA for different scenarios

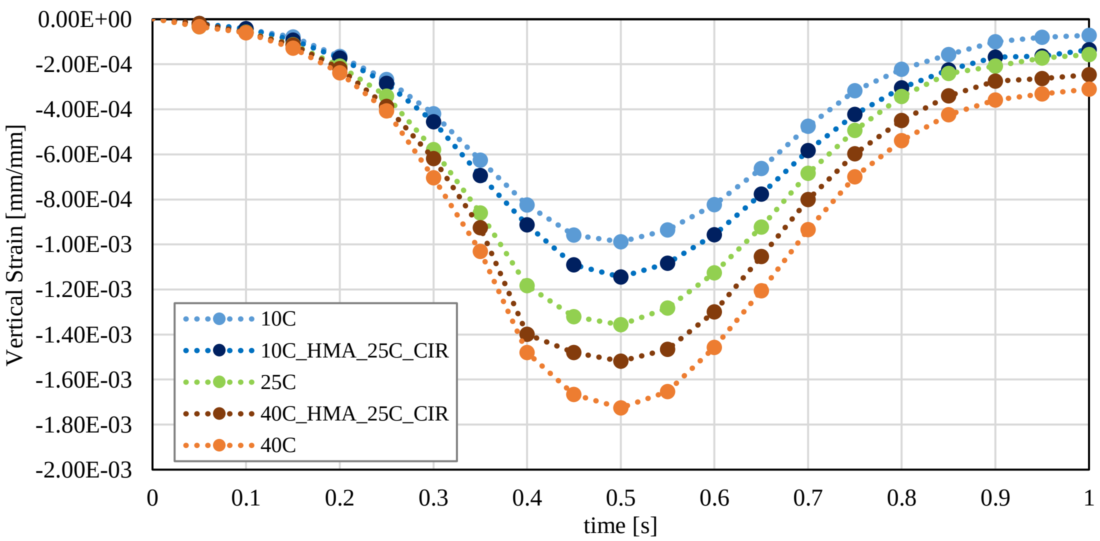

FIGURE 5 Vertical Strains on top of Subgrade for different scenarios

In Table 7, all the responses are converted into maximum number of allowable repetitions for fatigue and rutting based on the transfer functions presented earlier (Equations 1 and 2). The differences in predicted pavement lives are shown with respect to the 25 °C constant temperature scenario.

TABLE 7 Pavement lives from elastoplastic simulations with temperature combinations (dominant distress is indicated)

HMA Temperature [°C]	CIR Temperature [°C]	N_F	Difference between Reference and Other Cases N_F [%]	N_R	Difference between Reference and Other Cases N_R [%]
10	10	581,568	77.16	**418,770***	52.80
10	25	322,442	58.81	**299,177***	33.94
25 (Reference)	25 (Reference)	**132,808***	0	197,623	0
40	25	**109,909***	-17.24	152,167	-23.00
40	40	**37,507***	-71.75	112,265	-43.19

*dominant distress controlling pavement life.

The results from the elastoplastic simulations show how the effect of temperature variation of HMA and CIR layer have a major impact on the response of the pavement. At low temperatures, both HMA elastic layer and CIR elastoplastic layer are stiffer and in addition, the cohesion value for the CIR layer is higher. This leads to a calculation of a high number of repetitions for both fatigue and rutting failure with respect to the reference scenario. The exact opposite is observed when the temperature is increased, in the structure at 40 °C both HMA and CIR have lower elastic modulus and the cohesion for CIR material is lower; consequently, the response in terms of horizontal and vertical strain is higher, leading to a smaller number of loading application before failure. The importance of consideration of pavement temperature within elastoplastic pavement analysis to determine critical responses and corresponding design lives is clearly evident in the results presented herein. In addition, the table shows how the failure of the pavement is controlled by rutting in the first two scenarios, while for the other three scenarios with higher HMA temperature, fatigue is the controlling mechanism of failure. This is caused by the dependency of the transfer function for fatigue (Eq 1) on the elastic modulus value of HMA, which for the low temperature of 10 deg. C is much higher than at the other two temperature conditions. HMA and CIR are the only two layers modeled as temperature depended materials, this causes those two layers to behave in a more rigid manner at low temperatures and consequently transfer higher stresses underneath causing the unbound base layer and the subgrade to accumulate more plastic deformation; on the other hand, when temperature is increased, HMA and CIR layers experience more deformation and this causes the horizontal strains at the bottom of HMA to be higher.

CIR response under different temperature conditions

In the following section, the CIR response for all the scenarios is isolated from the rest of the structure. A deviator stress ratio (DSR) concept is utilized to make comparisons of the CIR rutting performance within pavement structure. The DSR concept has been developed in South Africa and is proposed to be used as a structural design tool for pavements rehabilitated with CIR [13, 14]. The DSR concept follows the triaxial shear strength concept, whereby principal stresses in pavement CIR layer are used to determine maximum deviator stress invariant acting within the CIR layer and this value is compared against corresponding deviator stress from triaxial laboratory tests at similar principal stress state. The calculation of DSR based on the principal stresses extracted from the elastoplastic simulation are made using equation (3).

$$DSR = \frac{\sigma_1 - \sigma_3}{\sigma_{1,f} - \sigma_3} \qquad (3)$$

Where:

$$\sigma_{1,f} = \frac{(\mathbf{1} + \boldsymbol{sin}\ \phi)\sigma_3 + 2\ C\ \boldsymbol{cos}\ \phi}{(\mathbf{1} - \boldsymbol{sin}\ \phi)} \qquad (4)$$

σ_1 = Peak value of major principal stress in the CIR layer (kPa)

σ_3 = Minor principal stress in the CIR layer corresponding to peak major principal stress (kPa)

$\sigma_{1,f}$ = Major principal stress at failure (kPa)

C = Cohesion value of CIR material (kPa)

ϕ = Friction angle value of CIR material (°)

The results for deviator stress ratio (expressed as percentage) are shown in Table 8 for the various pavement structure and temperature scenarios.

TABLE 8 Deviator Stress Ratio for CIR layer in the different structures and temperatures scenarios.

HMA Temperature [°C]	CIR Temperature [°C]	Structure	DSR [%]
10	10	Thin	33%
		Reference	16%
10	25	Reference	21%
25	25	Thin	49%
		Reference	36%
		Thick	8%
40	25	Reference	61%
40	40	Reference	65%
		Thick	11%

Based on research by Jenkins et al. [14], the maximum allowable DSR for CIR layer is 35% for a design reliability of 95% (Highways with heavy traffic); for a design reliability of 80-90% it is of 40% (Arterials with moderate traffic). Thin structures at intermediate temperatures and the reference structure at high temperatures do not meet this threshold. This shows the importance of evaluating CIR layer responses at temperatures higher than 25 °C and that the thickness of the HMA overlay is of fundamental importance for limiting the stress concentration in the CIR. The DSR can be evaluated only through elastoplastic simulations and triaxial shear testing on the CIR material; the maximum and minimum principal stress values can be correctly calculated for this type of material only if plasticity is considered. This illustrates the importance of implementing the current material characterization procedure for the analysis and design of pavement structures with CIR layers. The DSR values for thicker pavement structures are relatively low, including at high temperatures; therefore, elastoplastic simulations for thicker pavements (specifically with thicker CIR layers) may not be necessary.

4 Conclusions

An elastoplastic multilayer 2D axisymmetric model was designed using ABAQUS software; critical pavement responses were verified for the elastic and elastoplastic analysis using existing pavement analysis software. The model developed in this study was subsequently used to simulate different scenarios, both in terms of temperature and pavement structure. The differences between the elastic solution and the elastoplastic solution were calculated to show the importance of including plasticity in pavement design and analysis. Lastly, the CIR response was evaluated through the use of the deviator stress ratio for all scenarios to show the need for evaluating CIR material mechanical properties at different temperatures and the effect of HMA overlay thickness on stress levels in the CIR layer.

Based on the analysis conducted, the main conclusions from this research study are as follows:

- The plasticity effect needs to be considered for pavement design and analysis; this can be done introducing cohesion and friction angle properties for the partially bounded and unbounded layers.
- The effect of temperature on mechanical properties of CIR material are not negligible; this means that elastic modulus and cohesion properties need to be evaluated in the laboratory under different temperature conditions.
- Rutting and fatigue life calculations based on linear elastic simulations can lead to an overestimated life for the pavement structure. The inclusion of plasticity is most important for thinner (HMA and CIR layers under 75 mm thickness such as in low volume roadways) pavement structures and primarily in warmer regions (where the CIR layers may approach temperatures of 40 °C for a significant portion of the year).
- The thickness of the HMA overlay is of fundamental importance for limiting the stress concentration in the CIR layer. Use of DSR as a design parameter to determine suitable overlay thickness is recommended.

The results from this research study show how consideration of plasticity should be implemented in design and analysis in order to obtain more realistic evaluation of fatigue and rutting resistance of rehabilitated flexible pavement structures with CIR. In addition, it gives insight to the response of the CIR layer under different scenarios, identifying which are the main factors affecting longevity of the pavement structure. Future work that is being considered includes: introduction of viscoelastic response for the HMA layer, assessment of pavement responses under different vehicle types and using additional cross-sections, introduction of different CIR types and evaluation of the effect of curing level on CIR response.

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APPENDIX D Paper 4 (Chapter 7)

Influence of curing stage and temperature distribution on plastic response of cold recycled pavement layers

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Influence of curing stage and temperature distribution on plastic response of cold recycled pavement layers

Abstract. Cold recycling technologies are extensively utilized rehabilitation techniques for asphalt pavements. Mainly when emulsified asphalt is utilized as stabilizing agent in the mix, considerations have to be made on the level of curing of the material. Curing time after compaction is needed for the emulsion to break in its two components, for the asphalt binder to set on the RAP aggregates and for the moisture to evaporate from the mixture. In addition, when active fillers are used, curing time is important for completing the chemical reactions. During curing process, the material undergoes a process of strength gain and it is of fundamental importance to assess the evolution of mechanical properties with time in order to establish the best timing for HMA overlay application and re-opening to traffic of the rehabilitated roadway section. In this research study, simulations for a rehabilitated pavement structure with BSM were run at different curing stages after construction. This was done in order to evaluate pavement response to traffic loading application in terms of accumulation of permanent deformation on the surface during curing process. A multilayer two-dimensional elastoplastic axisymmetric model was used for the study. This model was implemented with functions able to consider a realistic temperature distribution with depth and consequently adjust material properties in the different locations with respect to the surface. Different structural solutions with different types of BSM layers were simulated and the main outcome has been that no major difference was seen in between the results obtained at 7 and 14 days after construction. In addition, it was shown how a thicker recycled layer allows to limit permanent deformation accumulation on surface and consequently how the rutting potential does not only depend on material characteristics but also on the pavement structure.

Keywords: Cold In-Place Recycling; finite element modeling; elastoplastic model; curing time; strength gain.

1 Introduction

Cold recycling technologies are considered some of the most sustainable rehabilitation technologies, both from economic and environmental prospectives. The product obtained through the use of those techniques is called bituminous stabilized material (BSM). BSMs have mechanical characteristics which are in between fully bonded materials, such as HMA and cemented materials, and unbounded materials such as crushed aggregates. In previous studies [1, 2] it was shown how the primary concern related to BSM is accumulation of permanent deformation under traffic loading application. For this reason, it is important to evaluate both elastic and plastic constitutive properties for the material. Mainly in the case when emulsified asphalt is used as stabilizing agent, another fundamental factor to keep into consideration is curing process of the mixture. After the emulsified asphalt is mixed together with the other components, the emulsion starts breaking into the two phases of water and asphalt binder. Once the breaking process is completed, additional time is needed for the emulsion to set onto RAP aggregates and for the water to evaporate. The main factors affecting curing time needed for the mixture before HMA overlay application and consequent re-opening to traffic are: temperature, exposure to rainfalls and wind and composition of the mixture [3, 4]. In fact, in order to accelerate BSM strength gain, active fillers such as cement or hydrated lime are commonly added to the mixture. During curing process, both elastic and plastic properties evolve with time, which means that the strength gain affects contemporarily the elastic portion of material response and its cohesiveness. In this study, simulations were run at different curing levels of the material for two different BSM mixtures in order to assess their response to traffic loading application. All the simulations were run prior to HMA overlay placement, in the specific at 1, 3, 5, 7 and 14 days after construction. Different structural solutions in terms of BSM layer thickness were considered and the results were compared in terms of permanent deformation accumulation on the surface caused by traffic loading application. In general, this research study gives an insight on how to consider BSM plastic response in the early stage of curing and how to integrate it into models for pavement design and analysis.

2 Methods

2.1 Temperature distribution

As first step, a temperature distribution function was identified for the pavement structure. Usually cold recycling operations are carried out during summer season and the main concern regarding accumulation of plastic deformation in BSM is associated with warm weather. For this reason, a reference scenario with an average seasonal air temperature of 27 deg. C was selected.

The temperature distribution was calculated using the following equation [5]:

$$T_P = T_A\left(1 + \frac{1}{z+4}\right) - \frac{34}{z+4} + 6 \qquad \text{Eq. 1}$$

Where:

TP = average seasonal pavement temperature (deg. F)

TA = average seasonal air temperature (deg. F)

z = depth at which temperature is predicted (in.)

In Figure 1, the calculated temperature equation with depth is shown and 0 mm corresponds to the surface of the pavement.

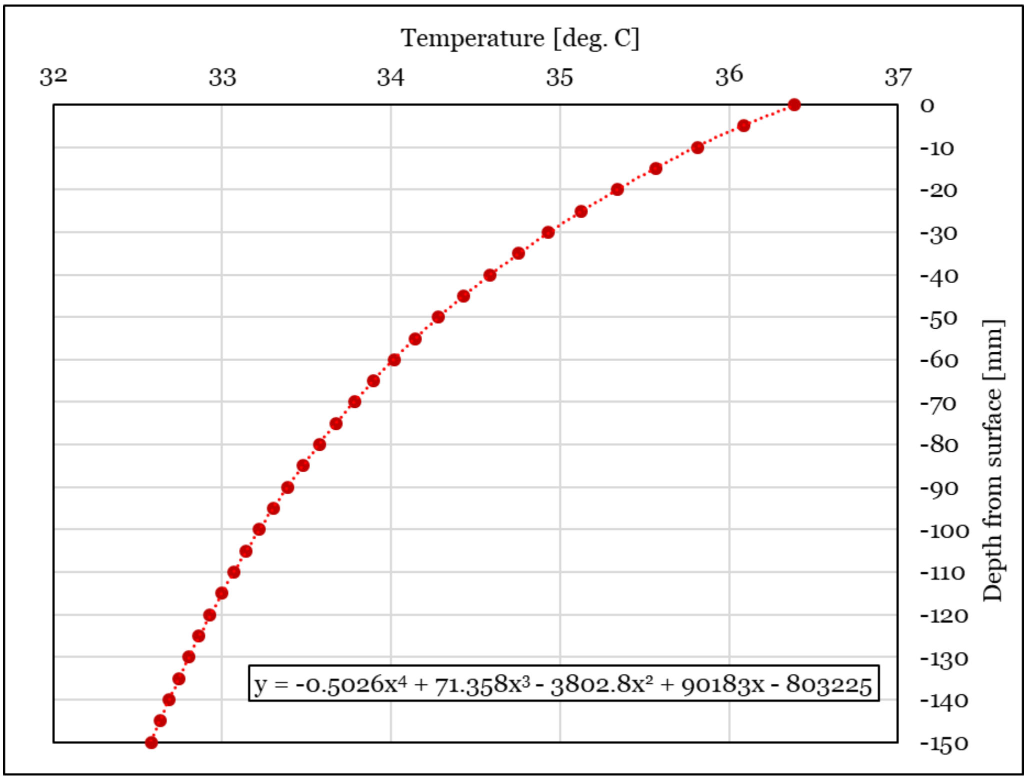

Figure 1. Temperature distribution with depth implemented in the model considering an air temperature of 27 deg. C.

As mentioned in the introduction, all the structural solutions analyzed in this study did not include HMA overlay. Consequently, the temperature distribution in Figure 1 is exactly the one that was considered throughout the BSM layer. In addition, BSM layer was the only layer were temperature dependency was considered for the simulations. Granular base and subgrade layers were assumed to be at a constant temperature of 25 deg. C throughout their whole thickness.

2.2 Elastoplastic properties variation

In order for the model to adjust BSM mechanical properties with depth, it was necessary to input equations able to describe their variation with temperature. In a previously published research study by the authors [6], triaxial shear strength tests and resilient modulus tests in triaxial configuration were performed under different temperature conditions and applying different lateral confining pressures. With the aforementioned laboratory campaign, it was possible to identify elastic properties of the material and plastic properties in terms of cohesion and internal friction angle on the basis of Mohr-Coulomb failure envelope. In addition, elastic modulus and cohesion were identified as temperature dependent properties in BSM. The variation of those two properties with temperature was assessed in a range of temperatures in between 10 and 40 deg. C. Two BSM mixtures were taken into consideration, both of those mixtures were prepared with 2% residual asphalt binder from emulsified asphalt and respectively 1% and 2% hydrated lime content by weight of dry Reclaimed Asphalt Pavement (RAP) aggregates.

Variation of elastic modulus and cohesion for the two BSM mixtures can be seen in Figure 2 and 3.

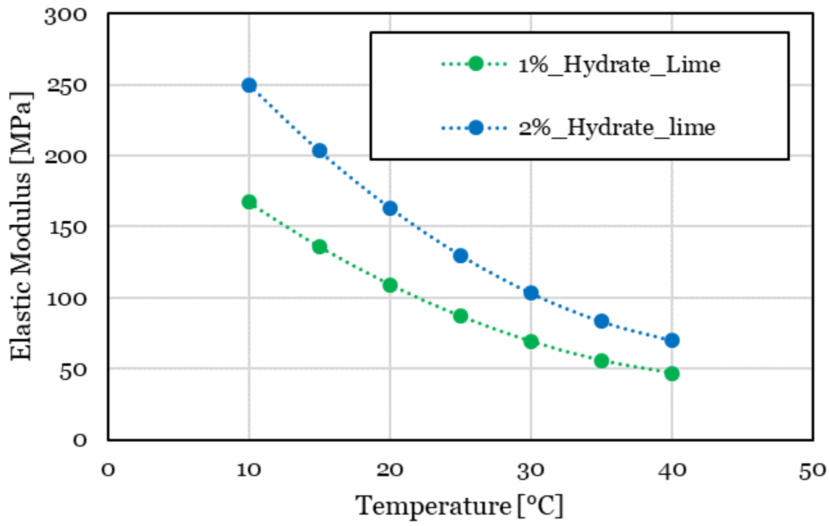

Figure 2. Variation of elastic modulus with temperature for BSM.

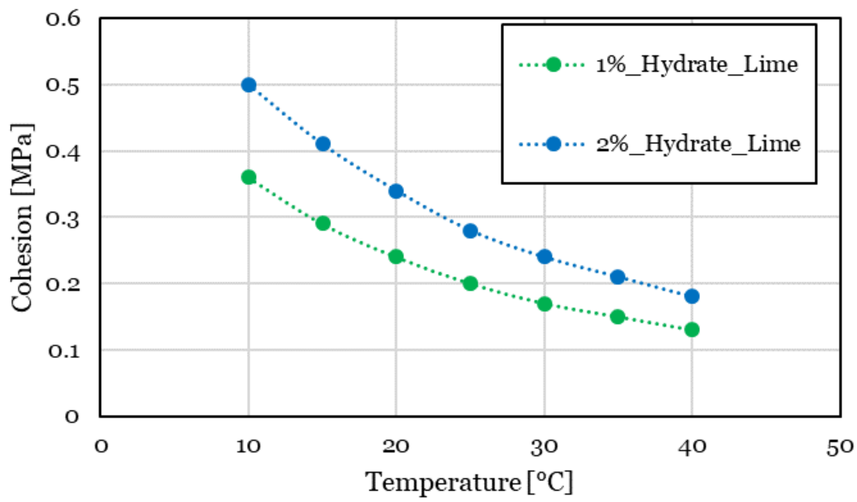

Figure 3. Variation of cohesion with temperature for BSM.

From Figures 2 and 3, it can be seen how the testing temperature has a major impact on elastic and plastic response of the material. The two material properties which were instead considered constant and independent from temperature on the basis of the laboratory results were Poisson's ratio and internal friction angle, which were respectively considered as 0.4 and 31°.

2.3 Evolution of elastic modulus and cohesion with curing time

The evolution of both elastic modulus and cohesion during BSM curing process were estimated on the basis of previous research studies [7 and 8] found in the literature. All the available results from the test campaigns were relative to specimens which were fully cured in the laboratory at room temperature for 28 days. The values in terms of elastic modulus and cohesion at the fully cured stage were considered as reference point to back-calculate the evolution trend down to the first day after construction. This was done in a range of temperatures in between 10 and 40 deg. C as can be seen in Figure 4 and 5.

The evolution of elastic modulus was calculated on the basis of an equation developed in a research study on BSM by Kuna et al. [7].

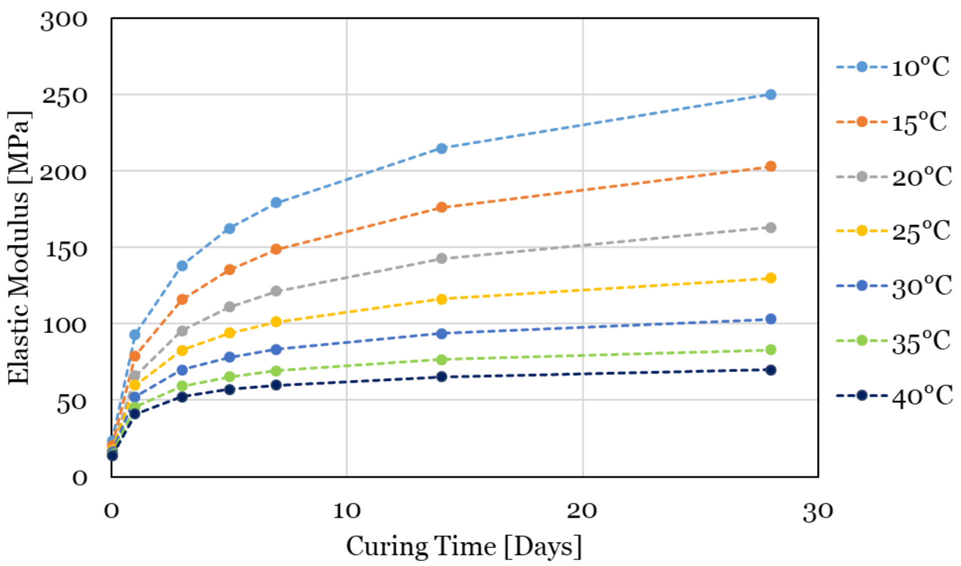

Figure 4. Evolution of elastic modulus with curing time for the mixture with 2% hydrated lime active filler content.

The evolution in terms of cohesion for the material was calculated on the basis of a trend identified in a research study on BSM by Gandi et al. [8].

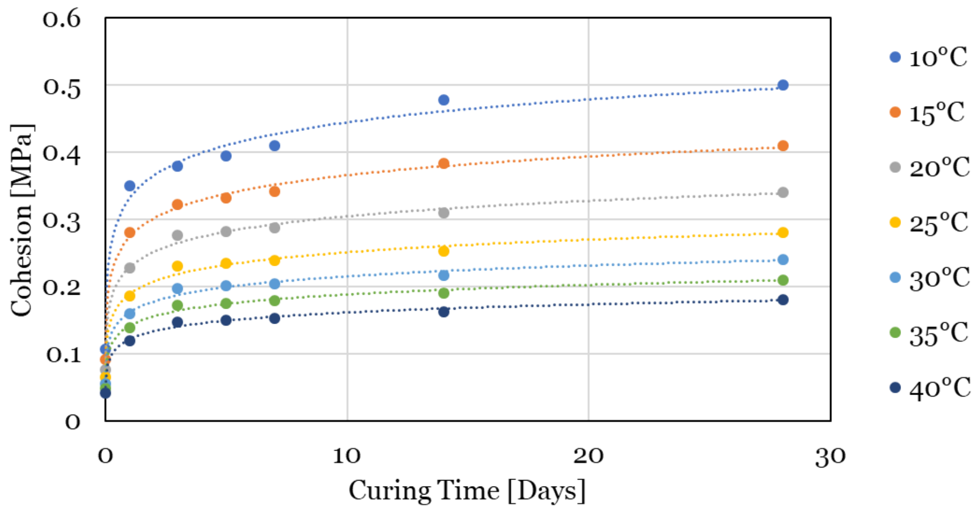

Figure 5. Evolution of cohesion with curing time for the mixture with 2% hydrated lime active filler content.

This estimate for the material mechanical properties evolution with time, allowed the model to adjust elastic modulus and cohesion values each time on the basis of which day after construction was going to be simulated. In addition, knowing the variation of those two properties with temperature at all stages, permitted to always recalibrate mechanical properties in each node of the finite element model with respect to the specific temperature at each depth.

2.4 Elastoplastic model used for simulations

The model that was used for the simulations is an elastoplastic two-dimensional axisymmetric multilayer model developed by the authors in a previously published research study [9]. In this model, all the layers were considered fully bonded at the interface and all the materials were considered to give a purely elastic-purely plastic type of response under loading application. All the materials were modeled following the Mohr-Coulomb theory. In the specific of the BSM mixtures, a study was conducted by the authors to verify the suitability of the material to be modeled following the aforementioned theory [10]. While Mohr-Coulomb failure envelope was utilized to identify plasticity occurring in the materials, a flow rule considering a completely smooth flow potential with a unique definition of the direction of plastic flow was utilized to describe the accumulation of plasticity during plastic flow [11].

As mentioned earlier, the only layer which was modeled as a temperature dependent material was the BSM layer, all the other layers were considered to be at a constant temperature of 25 deg. C. A tire applying a pressure of 1 MPa was designed on the surface, representing an axle load of 62.8 kN. The duration of loading application was set to be of 0.1 second with a rest period of 0.9 second representing a vehicle speed of indicatively 30 km/h.

2.5 Structural solutions considered

All the structural solutions considered were composed by a BSM layer, a granular base layer and subgrade. The three different simulated structural solutions can be seen in Table 1, the only variation is in terms of BSM layer thickness and type.

Table 1. Structural solutions considered for the simulations.

Layer	**Thin pavement**	**Reference (MN-30)**	**Thick pavement**
BSM (1% HL and 2% HL)	50 mm	75 mm	100 mm
Granular Base	250 mm	250 mm	250 mm
Subgrade	Semi-infinite	Semi-infinite	Semi-infinite

3 Results

All of the results that are shown in this paragraph are in terms of permanent deformation caused by the transit of one axle of 62.8 kN on the surface of the BSM layer. It is important to underline that the permanent deformation obtained on the surface is a combined effect of all the permanent deformations happening in each single layer of the pavement structure. The same type of simulation was performed at 1, 3, 5, 7 and 14 days after construction and before HMA overlay placement. This was done in order to isolate the response of BSM layer at the different curing stages.

The results obtained with this research study are shown in Figure 6 and 7.

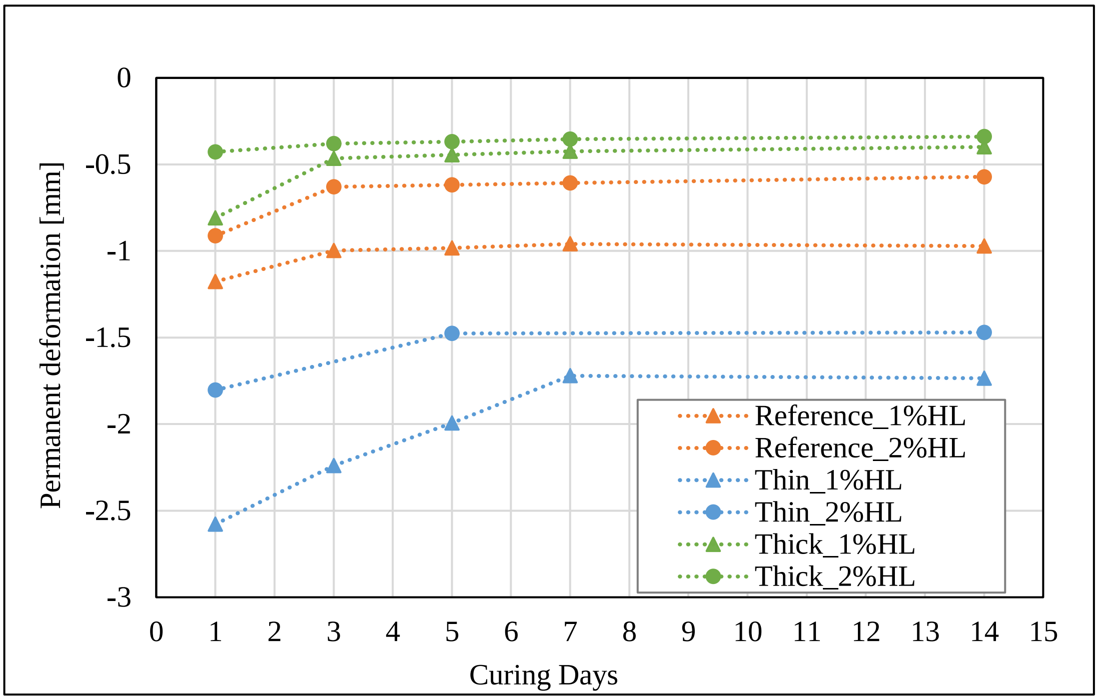

Figure 6. Permanent deformation on surface at different curing stages and for different structural solutions and different BSM mixtures.

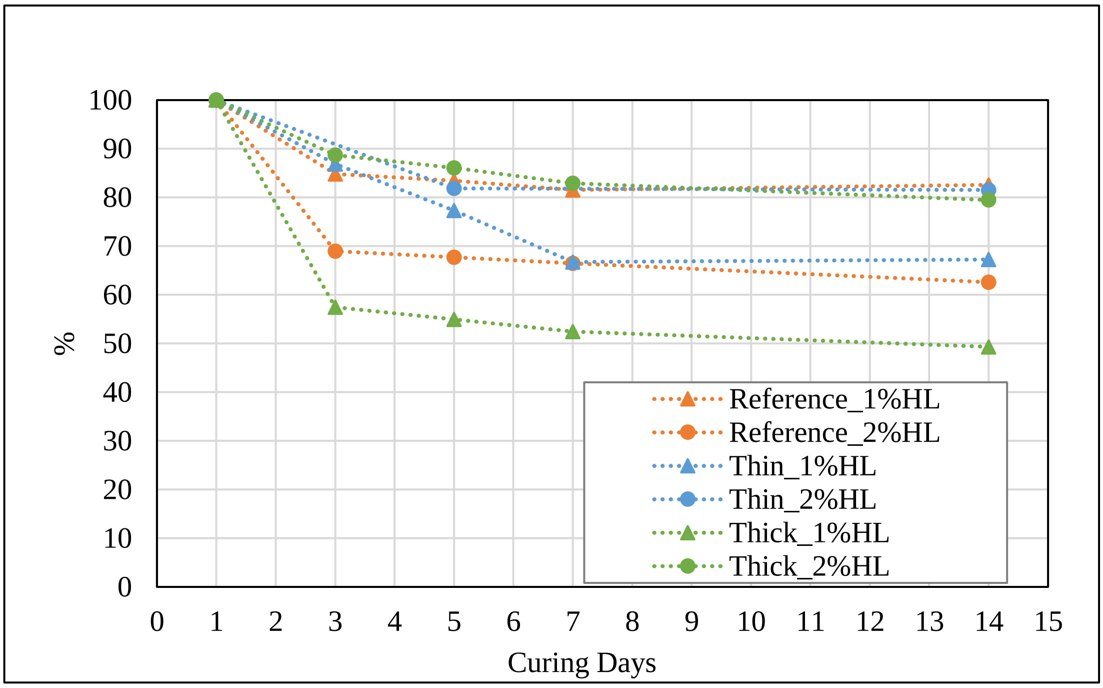

Figure 7. Normalized values for permanent deformation on surface.

It Figure 6, it can be noticed how the thickness of BSM layer has an effect on the total permanent deformation caused by the loading application on the surface. This might be related to the enhanced ability of thicker BSM layer to reduce the stress transferred to the underlying layers. In fact, granular base layer and subgrade are characterized by lower values of cohesion and elastic modulus, which translate in a higher susceptibility to plastic deformation accumulation. In addition, it is clear how in most of the simulated scenarios the permanent deformation which is obtained at 5, 7 or 14 days on surface is not significantly different. This is an outcome which needs to be furtherly investigated since the possibility of an early re-opening of a rehabilitated pavement structure to traffic could lead to considerable saving on costs. Furthermore, it can be seen how the BSM mixture prepared with 2% hydrated lime content has the ability to better resist to permanent deformations with respect to the mixture with 1% hydrated lime content.

4 Conclusions

The main conclusions from the research study are listed below:

- In most of the scenarios, there is no significant difference in terms of permanent deformations on surface in between 7 and 14 days.
- A thicker BSM structure is able to limit permanent deformation accumulation on the surface basing on simulations results.
- The evolution in rutting potential in terms of permanent deformations does not only depend on material properties but also on pavement structure.

The future plans for this research study are to verify the trend of evolution for both cohesion and elastic modulus during curing process with laboratory testing in triaxial configuration. In addition, the permanent deformation evaluated through model simulations on the surface at different curing stages needs to be verified with field testing on experimental sections. In terms of modeling, it would be interesting to try the effect of using other type of mixtures, for example prepared with cement instead of hydrated lime as active filler and also evaluate pavement response under other air temperature conditions.

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