PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

STIFFNESS EVOLUTION MECHANISM OF RECYCLED MIXES WITH FOAMED BITUMEN AND CEMENT

FELIPE A. HALLES ARÉVALO

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Doctor in Engineering Sciences

Advisor:
GUILLERMO A. THENOUX ZEBALLOS

Santiago de Chile. April, 2013

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ABSTRACT

Deep In Situ Recycling (DISR) of Asphalt Pavements with Foamed Bitumen is a promising rehabilitation technique used massively worldwide since early 1990. Recycled foamed bitumen mixes are constructed using reclaimed asphalt and granular materials, foamed bitumen, active filler and water. Traditionally, characterization of foamed bitumen mixes has been carried out on cured samples, which represents the mix properties after a couple of months since the construction (defined as medium term properties in this document). However, there is not enough information about the mechanical properties of these mixes in the short term, i.e. immediately after construction, nor in the long term, i.e. after a couple of years since the construction and after a large number of traffic loads had been applied. Designers and practitioners need to know this information in order to design the appropriate thickness for the foamed bitumen layer as well as to define mix components, i.e. bitumen and active filler content.

In these mixes the main stabilizing agent is bitumen, so most research has focused on understanding the mix behavior and quantifying mix properties when bitumen is added, as well as establishing a methodology to optimize its content. However, foamed bitumen mixes also use different types of active filler to modify the fine fraction of aggregate gradation, and/or to reduce moisture susceptibility of the mix. While most countries use cement as active filler, others use lime, fly-ash or others. Although the amount of active filler is normally 40% to 80% the amount by weight of bitumen, limited information is available regarding the role and contribution of active fillers on the properties and behavior of the final mix.

In this research work, the strength/stiffness evolution of foamed bitumen stabilized mixes is studied, for the short, medium and long term. In addition, the contribution of the cement in every stage of its service life is studied in detail, since it was identified as one of the main variables affecting strength/stiffness of foamed bitumen mixes. An extensive laboratory programs and in-situ bearing capacity monitoring of foamed bitumen recycled projects were carried out during this research work.

Results indicated that, in the short term, foamed bitumen mixes take a significant portion of time to strengthen; as long as 12 months in normal conditions. If the location is mainly dry, the curing process takes a couple of months. But if the location is wet, subgrade conditions of the road are soaked and drainage conditions of the projects are poor, it is probable that foamed bitumen mix does not lose moisture. In this case, the mix will not strengthen and mechanical properties may not be significantly better than the ones of the reclaimed granular material. Analysis of the long term performance indicated that once a foamed bitumen mix reaches a constant value due to the curing process, the stiffness will decrease or remain constant depending on the stress-level applied to the foamed bitumen layer. If the stress-level is lower than a specific value, the stiffness of the mix will remain constant at a value very close to the initial/maximum stiffness. If the stress-level is greater than a specific value the stiffness of the mix will gradually decrease. Also, the reduction rate of the stiffness will be greater as the stress-level is higher.

The study of the role of cement, including the role of bitumen and the interaction between the two, indicated that cement is as much important as bitumen. While cement increases the strength and stiffness of the foamed bitumen mix significantly in the short and medium term, bitumen gives flexibility and it is the key binder additive for the long term performance.

Finally, this research work provides recommendations for improving the mix design method and a conceptual tool for estimating the long term stiffness of mixes with foamed bitumen and cement.

Keywords: Stiffness evolution, active fillers, foamed bitumen.

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PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

MECANISMO DE EVOLUCIÓN DE LA RIGIDEZ DE MEZCLAS RECICLADAS CON ASFALTO ESPUMADO Y CEMENTO

Tesis enviada a la Dirección de Investigación y Postgrado en cumplimiento parcial de los requisitos para el grado de Doctor en Ciencias de la Ingeniería

FELIPE A. HALLES AREVALO

RESUMEN

El reciclado con asfalto espumado es una promisoria técnica de rehabilitación de pavimentos asfálticos que ha sido utilizada ampliamente a nivel mundial desde 1980. Laa mezclas recicladas con asfalto espumado son preparadas utilizando asfalto reciclado, material granular recuperado, asfalto espumado, filler activo y agua. Tradicionalmente la caracterización de las mezclas con asfalto espumado ha sido realizada en probetas curadas de forma acelerada, lo cual representa las propiedades de las mezclas luego de un par de meses desde su construcción (mediano plazo) período. Sin embargo, no hay suficiente información respecto de las propiedades mecánicas de estas mezclas en el corto plazo, es decir inmediatamente después de la construcción, ni en el largo plazo, es decir después de un par de años y después de que un gran número de cargas de tránsito ha sido aplicado. Los Proyectistas necesitan conocer esta información para poder diseñar apropiadamente los espesores de un pavimento con capas recicladas con asfalto espumado y para definir correctamente con contenidos de asfalto y filler activo que constituyen la mezcla.

En estas mezclas, el principal agente estabilizador es el asfalto y la mayoría de las investigaciones han estado focalizadas en la caracterización de las propiedades de la mezcla cuando este aditivo es incorporado, además de establecer metodologías para optimizar este contenido. Sin embargo las mezclas con asfalto espumado también utilizan algún tipo de filler activo para modificar la fracción fina de la granulometría de la mezcla recuperada y/o para reducir la susceptibilidad mecánica a la presencia de humedad. Mientras la mayoría de los países utilizan cemento como filler activo, otros utilizan Cal, Ceniza Volante u otros. Por otra parte, mientras el contenido de filler activo es entre 40% – 80% de la cantidad en peso del contenido de asfalto utilizado, a la fecha no existe información concreta respecto del rol que el filler activo cumple en las propiedades y comportamiento de las mezclas estabilizadas con asfalto espumado.

En esta investigación, se estudia la evolución de la rigidez y resistencia de estas mezclas a lo largo de toda su vida útil, es decir, en el corto, mediano y largo plazo. Asimismo, se estudia en detalle la contribución del cemento en las propiedades de estas mezclas, dado que es identificado como una de las variables que más afectan las propiedades mecánicas de las mezclas con asfalto espumado.

Los resultados indicaron que en el corto plazo estas mezclas necesitan de una significante cantidad de tiempo para adquirir resistencia, la cual puede llegar a ser tan amplia como 12 meses en condiciones de curado normales. Si la ubicación del proyecto es en áreas secas, entonces el proceso de curado toma solo un par de meses. Sin embargo, si la zona donde se emplaza el proyecto es húmeda y el drenaje es pobre, entonces es probable que la mezcla con asfalto espumado no pierda humedad y por lo tanto no adquiera resistencia. En este caso, las propiedades mecánicas de este tipo de mezclas no serán sustancialmente mejores que las que se obtendrían con el mismo material reciclado sin la adición del asfalto espumado.

Los análisis conducentes a establecer las propiedades de largo plazo indicaron que una vez que las mezclas con asfalto espumado adquieren rigidez, esta se mantendrá constante o disminuirá según el estado de tensiones que tenga la capa. Si el nivel de tensiones es menor que un valor referencial, la rigidez se mantendrá constante a un nivel muy parecido al de la rigidez máxima. Por el contrario si el estado de tensiones es mayor al valor referencial, la rigidez disminuirá conforme la capa estabilizada es sometida a cargas de tránsito. Se pudo establecer que a medida que el estado de tensiones es mayor, más rápido disminuirá la rigidez de la mezcla.

Por otra parte, el estudio del rol que juega el cemento en estas mezclas indicó que el cemento es tan importante como el asfalto espumado en términos de las propiedades de estas mezclas. Mientras el cemento es el principal responsable de proveer resistencia y rigidez a estas mezclas en el corto y mediano plazo, el asfalto es capaz de proveer flexibilidad y durabilidad en el largo plazo. El trabajo conjunto de ambos es el que permite que estas mezclas sean capaces de resistir las cargas de tránsito. Finalmente este trabajo de investigación proporciona recomendaciones concretas respecto al método de diseño de mezclas tradicionalmente utilizado, además de proveer con una herramienta para estimar la rigidez de largo de plazo de mezclas estabilizadas con asfalto espumado y cemento.

Palabras Claves: Evolución de la Rigidez, Asfalto Espumado, Filler Activo.

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1. INTRODUCTION

1.1 Background of the Research

Pavement design is the process of determining the most economical combination of layer thicknesses and material types to enable a pavement structure to carry the design traffic loads, taking into account the properties of the subgrade and climate conditions. Thus, the pavement structure and materials must be designed to dissipate the energy from the applied traffic loading in such a way that stresses and/or strains developed in any layer do not exceed permissible limits during its design service life. This definition is applicable to either new materials or recycled materials.

One of the most promising rehabilitation technologies to recycle deteriorated asphalt pavements is Foamed Bitumen, because it offers positive technical and economic benefits, low impact on environment as well as a rapid construction process in comparison with other rehabilitation techniques. Although its discovery dates from 1956, it began to be used worldwide 15 to 20 years ago and today there are still many uncertainties regarding behavior of these mixes and the effect that some specific variables have on the final mix performance. Foamed Bitumen is referred to as FB in this document.

In these mixes the main stabilizing agent is bitumen, so most research has focused on understanding the mix behavior and quantifying mix properties when bitumen is added. However, to date it is a common practice to use active filler - such as cement or lime - in conjunction with bitumen to improve certain properties of the mix. Although the amount of active fillers is normally 40% to 80% the amount by weight of bitumen, active filler is not included in the mix design procedure and the contribution of these stabilizing agents is not evaluated. When composite materials are used, the contribution of each stabilizing agent must be studied separately in order to understand the effect that each of them have on the properties of the mix.

From the structural point of view, the Strength / Stiffness evolution of the FB mix has not been properly addressed. Evaluation of the mechanical properties of the FB mix in the short term, i.e. during the first days after construction, is not part of any structural design procedure. However, since most of these projects are opened to traffic a few hours after construction, it is necessary to guarantee that the FB layer is capable of dissipating the traffic loads and reaching the structural requirements of the pavement design. In addition, previous researchers have stated that FB mixes do not develop their full strength until most of the mixing moisture has evaporated (Bowering, 1970). Thus it is expected that as more number of days since the construction, the greater should be the strength of the FB mix and thus the ability to resist higher loads once the project is opened to traffic. None of these aspects is included in the mix design analysis, which only uses the Bitumen as variable and mixes are cured before testing, i.e. mixes have been subjected to a process of accelerated loss of moisture and have its maximum strength at the time of testing.

In the long term there is no consensus regarding how to evolve the Stiffness of FB mixes and which are the main variables that affect it. In particular, it has not been established the role that bitumen and cement fulfill in this parameter nor the relative effect of the traffic loads. It is important to note that the value of the stiffness value in the long term is key information to properly design the other layers that compose the pavement structure.

Due to the aforementioned reasons, FB mixes must be evaluated considering the different conditions that will encounter during its life, i.e. from the short to the long term.

As it will be supported in this document, cement plays a fundamental role in the short, medium and long term strength/stiffness of the FB mixes. This is the reason why cement is included as a variable in each stage of this research work.

More details about the information that supports problems mentioned in this section are discussed in further detail in section 2.7 “Research Needs and Opportunities”.

1.2 Objectives and Scope of the Research

The *main objective* of this comprehensive research work is to evaluate and quantify the stiffness evolution of Foamed Bitumen mixes along its service life.

The *second objective* of this research work is to evaluate the contribution of the cement in the behavior and mechanical properties of FB mixes along its service life. The role of the cement is analyzed all across the research work including the first objective.

The *third objective* is to evaluate the relative contribution of other active fillers as well as cement in the mechanical properties of FB mixes. The other active fillers included are lime, CKD and fly-Ash class C. This information should help practitioners in selecting the most appropriate active filler for a specific project.

This research work is focused on Deep in Situ Recycling (DISR) of asphalt pavements, which means that reclaimed materials are composed by recycled asphalt pavement (RAP) and reclaimed granular materials. RAP and reclaimed granular materials have specific properties in terms of gradation, maximum size, plastic index, and crushed particles. In this research work granular materials used are non-plastic. When marginal materials are used, i.e. with plastic index with values more than 4 or 6 and/or high content of fine fraction, then others factors may affect the mix properties and behavior of FB mixes. Details of reclaimed material properties are defined in Chapter 3.

1.3 General Research Methodology

In order to evaluate and quantify the stiffness evolution of Foamed Bitumen mixes along its service life, including the contribution of the main variables defined, this research work was divided in three stages.

At the first stage, a study of the strengthening process (or curing process) of FB mixes was carried out. Therefore, FB mixes were evaluated during the first weeks after construction without using a laboratory methodology to accelerate the curing process, i.e. process in which the material loses its moisture and gains strength (Bowering, 1970).

At the second stage, a study of the role of the cement - and other active fillers - in the mechanical properties of FB mixes was carried out. The research work included the study of mixes without accelerated curing, representing to short-term service life period, as well as cured mixes, which refers to mixes that have been exposed to high controlled temperatures for accelerating the loss of moisture and have acquired its maximum strength/stiffness. Cured mixes represent to the medium-term service life period.

At the third stage, a study of the fatigue behavior was carried out, representing to the long term service life period. This behavior was studied monitoring the stiffness evolution under load cyclic tests and using cured FB mixes.

The contribution of the cement was evaluated on each one of the stages previously described. Details of the curing process used in each case, are discussed in Chapter 3.

1.4 Structure of the Document

Chapter 2 provides a review of the relevant literature, the theory and practices relating to stabilization of recycled materials with FB. In this chapter, the key variables affecting FB mixes are discussed, as well as the aspects concerning the stabilization of materials using active fillers. Mix design procedures and structural performance of FB mixes are also discussed, including the most important variables in the analysis. Finally, based on the discussion carried out in this chapter, the research needs and opportunities are proposed.

Chapter 3 describes the test methods, laboratory procedure, and materials used during this research work.

Chapter 4 presents the research work carried out to study the strengthening process and the stiffness evolution of FB mixes in the early stage as well as the impact of the cement on this service life period.

Chapter 5 presents the research work carried out to evaluate the contribution that active fillers have on mechanical properties of FB materials. Studies conducted at this stage include lime, cement kiln dust (CKD) and fly-ash as well as cement, in order to provide - for engineers and practitioners - a tool for selecting the most appropriate active filler in a particular project.

Chapter 6 presents the research work carried out to evaluate the strength/stiffness evolution of the FB mix in the long-term, due to cyclic traffic loads. With the results obtained at this stage, a conceptual methodology for estimating the long-term stiffness of FB mixes is proposed.

Chapter 7 summarizes main conclusions and presents recommendations for engineering practice and further studies.

1.5 Definitions and Terminology

This study focuses on the Full Depth Recycling (FDR) technique using foamed bitumen (FB) and cement as stabilizing agents. The FDR process reutilizes the complete thickness of the surface layer, i.e. asphalt concrete (AC) or surface treatment (ST), as well as part of the underlying granular bases. Usually, the reclaimed asphalt concrete layer is called RAP (reclaimed asphalt pavement). In this thesis and because materials from both layers are reclaimed (AC plus granular layer), the reclaimed material is called RAG, which means Reclaimed Asphalt Pavement and Granular Materials.

Although many studies have shown that a combination of foamed bitumen and cement as active filler is required to achieve optimum results, most terminology excludes the active filler component. In this document, FDR-FB, defines the Full Depth Recycling (FDR) process of deteriorated asphalt pavements using foamed bitumen (FB) and cement as stabilizing agents. When active filler is not used, it will be explicitly mentioned. Also in this thesis other active fillers were used - lime, CKD and fly-ash - instead of cement. In such cases, the use of other active fillers is explicitly defined.

Glossary of Abbreviations

AC	Asphalt Concrete
CKD	Cement Kiln Dust
EEM	Effective Elastic Modulus
ER	Expansion Ratio
FB	Foamed Bitumen
FDR	Full Depth Recycling
FDR-FB	Full Depth Recycling using Foamed Bitumen and Cement
HMA	Hot Mix Asphalt
ITFT	Indirect Tensile Fatigue Test
ITM	Indirect Tensile Resilient Modulus
ITS	Indirect Tensile Strength
LVDT	Linear Variable Differential Transformer
OMC	Optimum Moisture Content
PUC	Pontificia Universidad Católica de Chile
RAG	Mix of Reclaimed Asphalt Pavement and Reclaimed Granular Materials

RAP	Reclaimed Asphalt Pavement
RM	Resilient Modulus
RMR	Resilient Modulus Retained
RSIE	Ratio between S.Eq and S.Ini
S	Stiffness
S.Eq	Stiffness of Equilibrium
S.Ini	Initial Stiffness
SR	Stress Ratio
ST	Surface Treatment
TSR	Tensile Strength Retained
TxPD	Permanent Deformation Triaxial Test
TxRM	Resilient Modulus Triaxial Test
UCPRC	University of California Pavement Research Center
UCS	Unconfined Compressive Strength

2. LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of the theory and practices that contribute to the current understanding of foamed bitumen (FB) mixes. The literature study was focused on the factors affecting strength, stiffness, flexibility and permanent deformation (as a long-term performance parameter) of FB mixes. Moisture susceptibility and the specific curing process of the FB mixes are discussed. Special emphasis is given to the impact of the active fillers as major components of these mixes in conjunction with bitumen.

The mix design procedure and structural behavior of foamed bitumen mixes are analyzed from the point of view of the concepts discussed in this research study: curing process; active filler influence; short, medium and long term performance.

The first part of this chapter reviews the Full Depth Recycling (FDR) technique used for pavement rehabilitation followed by a description of foamed bitumen (FB) technology as well as benefits of its use. The second part reviews the current mix design procedure of FB mixes and discusses its limitations. Then, a full description of the factors affecting behavior and mechanical properties of FB mixes is presented, followed by a detailed analysis of the influence of the bitumen and active fillers.

Finally, structural behavior considerations are discussed followed by an overview of the research needs and opportunities.

2.2 Full Depth Recycling of Asphalt Pavements Using Foamed Bitumen Stabilization

2.2.1 Pavement Rehabilitation Using Full Depth Reclamation Technique

Pavement rehabilitation consumes a large part of the budget of the Chilean Ministry of Public Works each year in order to preserve the stand of the road network. The service life of pavements normally ranges from 10 to 20 years, which depends on variables affecting the deterioration process and the structural design criteria used. Once the pavement fulfills its service life and preservation actions are no longer effective, it must be reconstructed or structurally rehabilitated using some of the available construction techniques.

Asphalt concrete pavements represent a major part of the road network in Chile as well as many other countries in the world. These pavements are traditionally composed by an asphalt concrete surface layer and granular or stabilized base layers. Hot mix asphalt as overlay has been used traditionally to rehabilitate cracked asphalt concrete pavements. This technique has shown many technical and economical limitations over the years. Reflection of cracks from the underlying asphalt layers up through the overlay in a relatively short period of time may be one of the common failures of this technique.

Full Depth Recycling of deteriorated asphalt pavements (FDR) is a rehabilitation technique that reclaims the existing distressed flexible pavement. The process recycles the existing asphalt concrete layers together with the upper portion of the underlying granular base material. Simultaneously, the process treats the reclaimed material using stabilizing agents (e.g. cement, lime, emulsified or foamed bitumen, or a combination of these), to improve its engineering properties and produce a new base layer. Foamed bitumen has been used worldwide as a stabilizing agent for the FDR technique for twenty years (Asphalt Academy, 2002).

The construction process traditionally used in FB stabilization is conducted using a recycling machine connected to a tank truck, which add the stabilizing agents and water.

Stabilizing agents are added to improve the mechanical properties of the reclaimed material, and water is added to modify the moisture content in order to achieve required densities during the compaction process of the recycled material. Figure 2-1 presents typical equipment used in FDR with foamed bitumen (FDR-FB)

Figure 2-1: Full depth recycling equipment with foam bitumen

The key part of the recycling machine is the mixing chamber, which contains the milling drum that pulverizes the deteriorated pavement, and the injection system that adds the stabilizing agents and water. Active fillers are spreading onto the surface pavement prior to the milling machine. In the chamber, the pulverized material is mixed with the stabilizing agents and water in one single pass of the recycling machine, producing a recycled layer ready to be compacted and shaped using rollers and graders. Figure 2-2 presents a diagram of mixing chamber used in FDR with foamed bitumen.

A typical cross-section of a pavement that has been recycled using foam bitumen is presented in Figure 2-3. On the left side, the figure shows the flexible pavement with the deteriorated asphalt layer. On the right side, the final pavement that has been recycled up to a depth in which part of the granular sub-base and the complete granular base layer have been reclaimed and treated with foamed bitumen in conjunction with the cracked asphalt layer. Over the recycled layer, 5 cm of hot mix asphalt (HMA) or a surface treatment wearing surface may be used. Recycling depth is usually in the range of 15 to 20 cm. The proportion of RAP and granular base material recovered range from 20% to 70% depending on the thickness of the deteriorated asphalt layer.

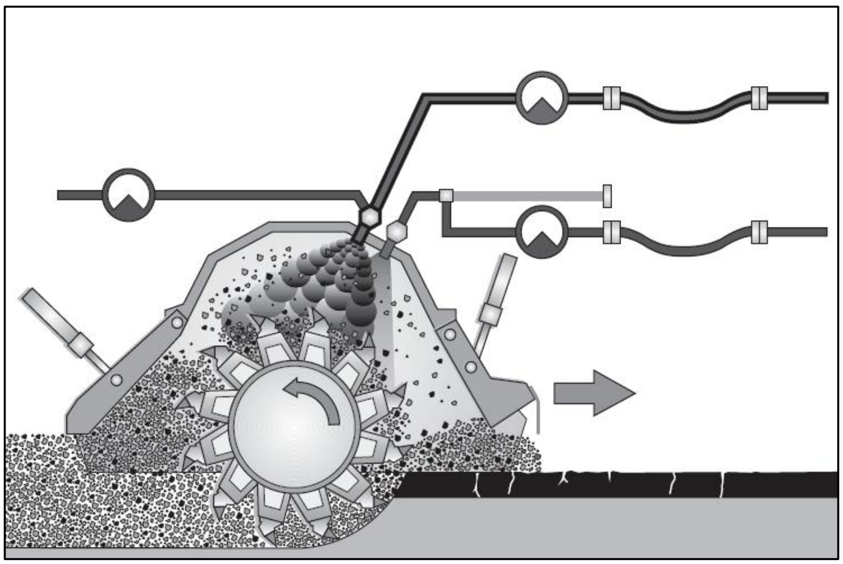


Figure 2-2: Full depth recycling process with foam bitumen (Wirtgen, 1998)

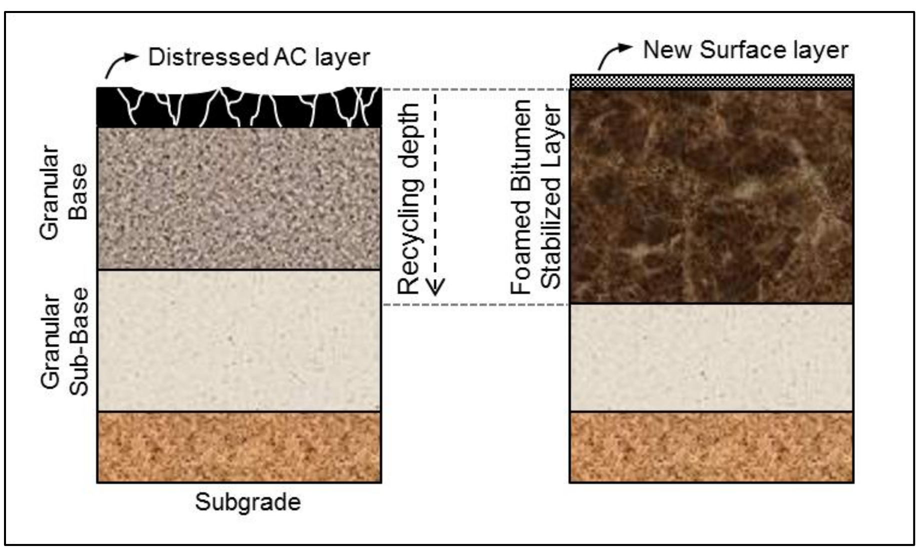


Figure 2-3: Full depth recycling process with foam bitumen

2.2.2 Foamed Bitumen Technology

Foamed bitumen was originally invented by Dr. Ladis Csanyi at the Engineering Experiment Station at Iowa State University around 1956 (Csanyi, 1957; Csanyi, 1960). During the 1960s, Mobil Oil Australia developed methods to improve the production of foamed bitumen as well as mix design procedures. After further developments of the process made by Conoco (Continental Oil Company), this company and Mobil Oil Corp. acquired Csanyi's patent in the late 1960s. Research studies performed in the late 1970s and mid-1980s in Australia, New Zealand, United States, South Africa, France and Germany (Bowering and Martin, 1976; Ruckel et al, 1980; Little et al, 1983; Castedo and Wood, 1983; Brennen et al, 1983), demonstrated benefits of the technology and feasibility of its use as a stabilizing agent for many types of granular materials. Once the Mobil Oil patent expired in 1990, recycled projects using foamed bitumen increased significantly around the world.

Foamed bitumen is produced by injecting a small quantity of cold water, together with compressed air, into hot bitumen in a specially designed expansion chamber. Cold water usually has a mass ratio of 1% to 4% to the bitumen. Bitumen is heated to temperatures between 150 °C and 180 °C.

When water particles make contact with hot bitumen, heat energy from the bitumen is transferred to the water, raising its temperature. Once water reaches the boiling point its state changes from liquid to steam. During this process compressed air is injected into the system, and hot bitumen is temporarily expanded, all together creating thin-filmed bitumen bubbles filled with steam. While bitumen is in a foamed state, it has a very low viscosity, so it may be mixed with RAP and aggregate materials. Figure 2-4 presents the Foam Bitumen Production Process.

During the mixing process, the bitumen bubbles burst, producing tiny bitumen particles that disperse throughout the aggregate by adhering to the finer particles (fine sand and smaller), to form a fairly stiff and stable mastic (Bowering and Martin, 1976). During compaction, the bitumen particles in the mastic are physically pressed against the larger aggregates of the granular material resulting in localized non-continuous bonds called "spot welding". Fine aggregate particles can only be partially coated by bitumen during the foaming process to form the mastic, while a considerable portion of the voids in the aggregate skeleton are filled by fine mineral particles (Jenkins, 2000).

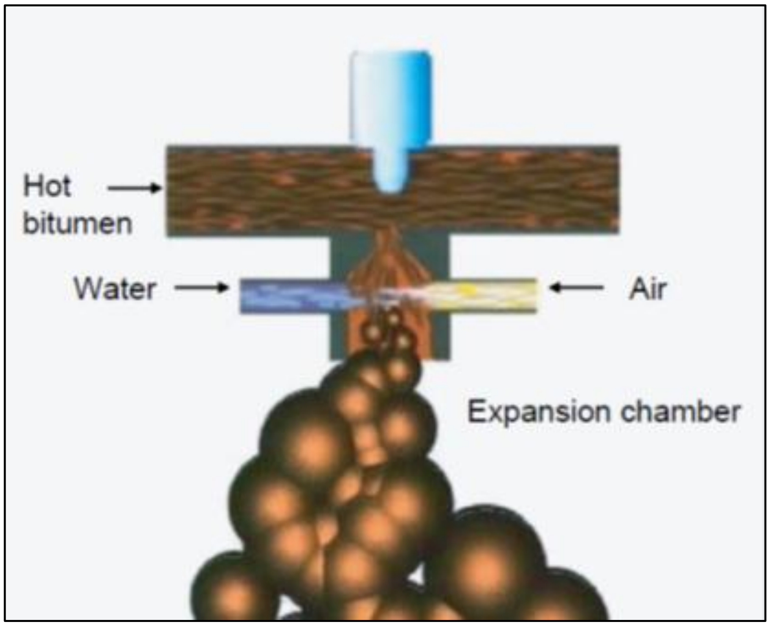


Figure 2-4: Foam bitumen production process (Wirtgen, 2004)

Two primary foaming parameters form the basis of bitumen´s suitability to be used as foamed bitumen, namely a) Expansion ratio and b) Half-life (Asphalt Academy, 2002; Wirtgen, 1998).

- The expansion ratio (ER) is a measure of the viscosity of the foam and will determine how well the bitumen will disperse in the mix. It is calculated as the ratio of the maximum volume of foam relative to the original volume of bitumen.
- The half-life ($\tau_{1/2}$) is a measure of the stability of the foam and provides an indication of the rate of collapse of the foam during mixing. It is calculated as the time taken in seconds for the foam to collapse to half its maximum volume.

Foam with a higher expansion ratio has a larger surface area per unit mass and lower viscosity due to the thinner asphalt film. Thus, it is easier for this type of foam to coat more and finer aggregates; the greater the half-life, the more stable the foam will be. As the foam is more stable, it has more time to blend suitably with the aggregates.

Both parameters are controlled mainly by bitumen temperature and foaming water content (ratio to the mass of bitumen). A higher bitumen temperature and higher content of foaming water creates a greater expansion rate (higher ER), but leads to more rapid subsidence or decay, i.e. a shorter half-life ($\tau_{½}$).

2.2.3 Benefits of FDR-Foamed Bitumen

FDR-FB provides several technical, environmental and economic benefits in comparison with other flexible pavement rehabilitation strategies. These benefits include:

- *Technical:* FDR-FB eliminates the potential of reflective cracking of HMA overlays by pulverizing the cracked underlying asphalt layers.
- *Environmental:* Through recycling and reusing in situ granular material, FDR-FB minimizes the need for extracting (and transporting) virgin aggregates. Additionally, energy consumption is reduced by 20% to 50% compared to the asphalt overlay alternative (Thenoux et al, 2007).
- *Economical*: FDR-FB construction process is constructible using only one lane of the road. Those pavements, when it is structurally feasible, can be re-opened to traffic in a few hours, and consequently the traffic delay caused by construction is also minimized.

Many different researchers have stated benefits of FDR using foamed bitumen in comparison to other stabilizing agents. For example, the FDR-FB process does not involve the emission of volatiles such as in cutback stabilization, nor corrosive dust such as when using lime or cement. Also the curing rate, represented by the loss of water, is quicker than bitumen emulsions so that the gain in strength is faster, thereby allowing a faster re-opening to traffic.

One of the benefits that support the use of bitumen is associated with the loss of flexibility (or increased brittleness) due to exclusive use of cementitious agents. Since this variable is one of the main factors discussed, it will be analyzed further in this document.

2.3 Mix Design Procedures of Foamed Bitumen Mixes

2.3.1 Introduction

Since its discovery, the use of FB has been adopted by many countries with different interpretations of its behavior and performance. Mix design procedures in each country have incorporated the experiences of researchers and practitioners resulting in a variety of proposals for procedures, tests and design criteria.

The main guidelines used for mix design of FB mixes are the ones produced by South African researchers. The first formal document was published by SABITA Ltd & CSIR Transportek by the name of "Foamed Asphalt Mixes -Mix Design Procedure" (Contract Report CR-98/07, 1998). Later, the additional knowledge gained was compiled and published in the *Interim Technical Guideline TG2: The Design and Use of Foamed Bitumen Treated Materials* (Asphalt Academy, 2002). This document was updated and released through the *Technical Guideline: Bitumen Stabilized Materials* (Asphalt Academy, 2009). This last document includes bitumen emulsion treatment as well as foamed bitumen. Another guideline commonly used is the Wirtgen Cold Recycling Manual (1998), which includes a section on FB stabilization, but is also based on the procedure developed by South African researches.

The mix design process with foamed bitumen is particularly challenging because these materials are comprised of numerous and diverse variables. One of the main steps is the classification of the properties of the RAP and reclaimed granular materials to be treated. This research work is focused on recycled pavement, i.e. the properties and gradation of the granular materials to be treated are defined by the pavement material to be treated, and therefore the spectrum of options – in term of granular/reclaimed materials properties - is limited.

2.3.2 Mix Design Criteria

The objective of the mix design process of foamed bitumen recycled materials is to optimize the mix properties for permanent deformation, moisture susceptibility and durability (Asphalt Academy, 2009).

Permanent deformation depends mainly on the properties of the coarse particles and gradation of the whole reclaimed material as well as stabilizing agents (bitumen and active fillers). As it was described in section 2.2.2, FB produces a mastic in conjunction with fine fraction of the RAG (Reclaimed asphalt pavement and granular materials), which coated partially coarse aggregates of the RAG. This mastic increases the cohesion of the recycled material in comparison to untreated granular material, increasing the strength and thus improving permanent deformation properties of the mix (Asphalt Academy, 2002).

Moisture susceptibility is one of the main problems of untreated material, due to the fact that fine fractions of the granular material absorb as much moisture as they can, reducing the ability of fine particles to bond. The inclusion of foamed bitumen droplets in the matrix decreases the proportion of fine particles that become susceptible to the presence of moisture (Asphalt Academy, 2002)

Durability depends mainly on the stabilizing agents; in this case, foamed bitumen and active fillers. Information was not found on methods used to assess the durability of bitumen stabilized mixes. Durability of traditional asphalt concrete mixes is evaluated using different tests with and without aging of the mix or bitumen. Durability of cementitious stabilizing agents is evaluated using dry-wet or thaw-freeze cycle tests (Prusinski and Bhattacharja, 1999; Zhang and Tao, 2008).

Once material classification is covered, the mix design process focuses on defining the optimum bitumen content using mix strength as selection criteria. Traditionally and based on the first design guide manuals (Wirtgen, 1998; Asphalt Academy, 2002), mix design process test four to five mixes with the same active filler content and different FB content, selecting the one with higher strength. Tests are performed on cured samples. Traditional curing processes consider that samples must be kept at 40 °C for 72 hours. Some samples are tested in dry conditions while others are tested after 24 hours in soaked conditions in order to evaluate the moisture susceptibility of FB mixes. No test is used to assess the durability of FB mixes.

The new South African guide (Asphalt Academy, 2009), defines three levels of design depending on the magnitude of design traffic for defining the optimum bitumen content. The first two levels use Indirect Tensile Strength (ITS) testing while the third level uses Resilient Modulus Triaxial testing (TxRM). Figure 2-5 shows an example of the ITS test used for selecting the optimum bitumen content. Dry and soaked results for specimens with 1.5% to 3.5% of bitumen content are depicted in the figure. In this example, 2.6% of bitumen content is selected, based on soaked results.

It must be noted that the active fillers are not considered as a design variable. The new South African guide (Asphalt Academy, 2009) recommends that cement content is limited to 1.0% and should not exceed the bitumen content. No limits are defined for the use of lime or other active fillers.

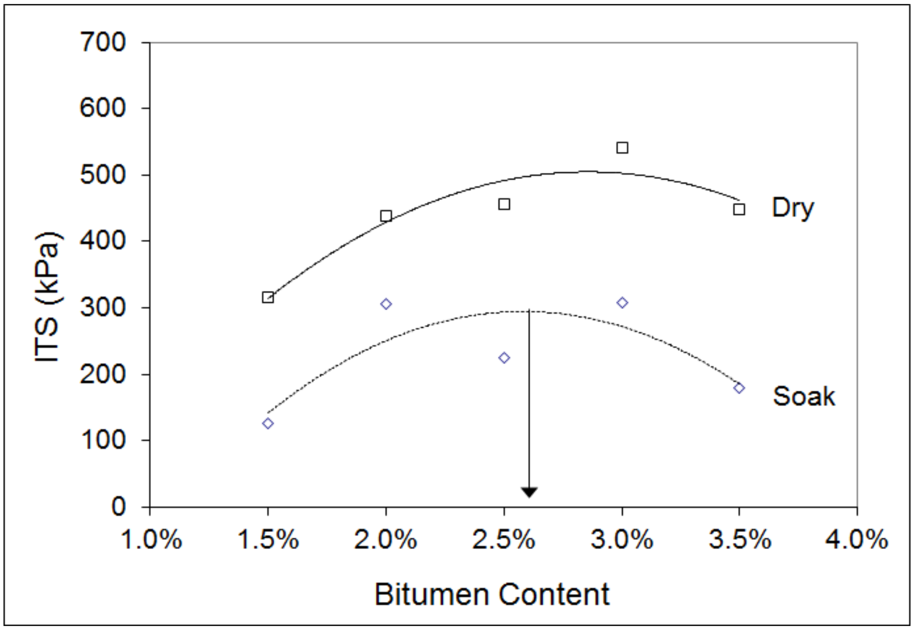


Figure 2-5: ITS test for bitumen content selection

2.4 Variables Affecting Performance and Mechanical Properties of Foam Bitumen Stabilized Mixes

2.4.1 Introduction

Since FB can be used with a great range of granular materials, many approaches have been taken to study its mechanical behavior. Also, for the same reason, the mechanisms of failure are not yet clearly identified.

Nevertheless, it is well accepted that FB mixes have very different characteristics from those of HMA and have similar behavior of unbound granular materials, but with an improved cohesive strength and reduced moisture sensitivity. Strength, resilient modulus and permanent deformation resistance of foamed bitumen mixes are dependent on the stress state (Ebels & Jenkins, 2006; Fu & Harvey, 2007; Jenkins et al 2007), which is a typical behavior of unbound granular materials. On the other hand, foamed bitumen mixes can bear tensile stress (Long & Theyse, 2002; Twagira et al., 2006; Ramanujam & Jones, 2007; Nataatmadja, 2007), which is a typical characteristic of bound materials.

Both approaches have been assumed for FB mix testing and for this reason in the previous literature it is possible to find studies based on resistance to permanent deformation using shear strength, compressive strength and dynamic triaxial tests (Bowering and Martin, 1976; Lancaster et al, 1994; Halles and Thenoux, 2009; Gonzalez et al, 2011), as other well as fatigue tests (Little et al, 1983; Lancaster, 1994).

Studies based on field performance testing and accelerated pavement testing have also reported fatigue alligator cracking in some cases (Chen et al, 2006), and permanent deformation in others (Gonzalez et al, 2009). It is necessary to see that case studies that reported fatigue cracking and rutting correspond to the recycled pavements with asphalt concrete as a surface layer. In this case, the failure mode corresponds to that expected, due to the likelihood of the asphalt concrete layer presenting alligator cracking as a result of cyclic traffic loads. More attention should be given to projects where permanent deformation was identified as the failure mode, since most of those projects used a seal coat as the surface layer and therefore failure observed is directly originated in the FB and underlying layers.

Current approaches establish that if the active filler is relatively low (0 to 1.5% by mass) and the foamed bitumen content is moderate to high (2 to 3.5% by mass), which is the case for most mixes reported in the literature, FB mix can be regarded as a weakly bound asphalt material. If active filler content is high (2 to 3% by mass) and foamed bitumen content is low (less than 2% by mass), FB mix can be regarded as a lightly cemented material. Figure 2-6 depicts the conceptual representation of the behavioral characteristics of flexible pavement construction materials (Asphalt Academy, 2009). In Figure 2-6 is possible to visualize the differences between FB mixes, lightly cemented materials and asphalt concrete in terms of their components.

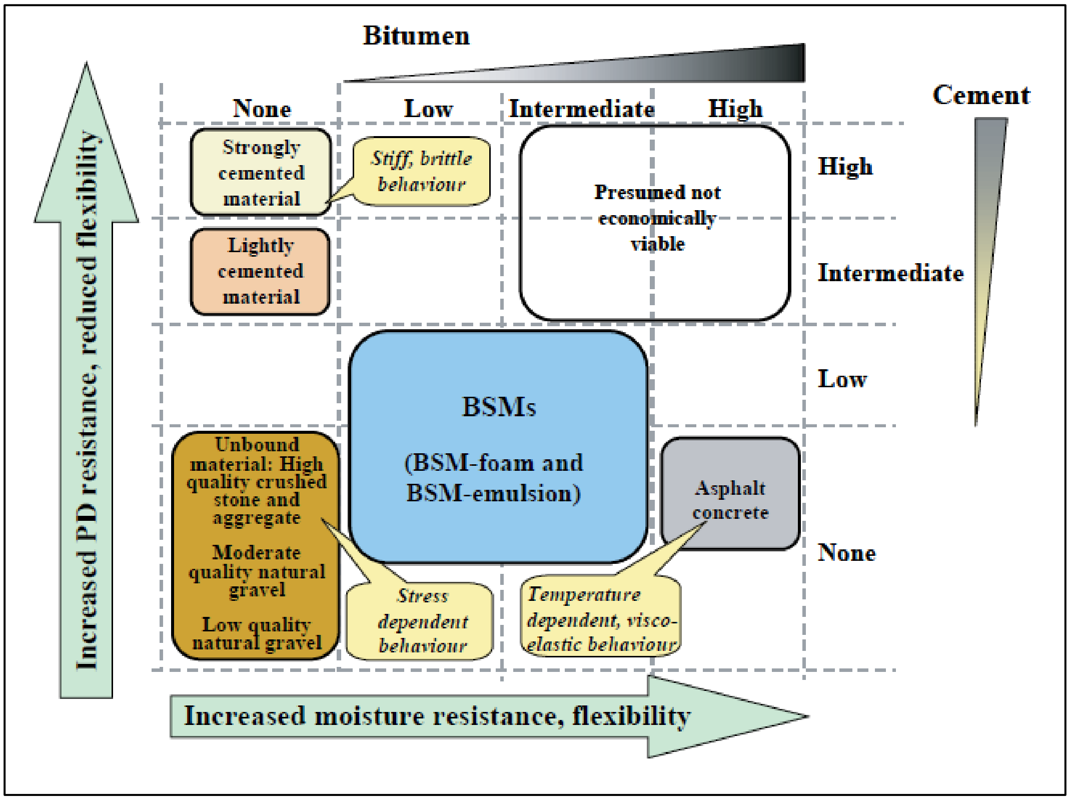


Figure 2-6: Conceptual representation of flexible pavement construction materials (Asphalt Academy, 2009)

2.4.2 Variables Affecting FB Properties

FDR-FB mixes are made of recycled asphalt pavement (RAP), reclaimed granular materials, foamed bitumen, active filler and water. The composition and characteristics of each component all affect the behavior and performance of the FB mix in some way. Due to the presence of bitumen, mechanical properties of FB mixes are affected by temperature, whereas the mechanical response of granular materials is affected by the stress-state and the moisture content in the recycled layer.

This section presents a summary of the main characteristics of each component that affect the properties of the foamed bitumen mixes (FB).

a) RAP and Reclaimed Granular Materials

Gradation and the source of the aggregates are the main parameters that define properties of FB mixes. Foam bitumen may be used with a broad range of reclaimed granular material types, including marginal materials with a high quantity of fine aggregate particles. It is well accepted that the fine fraction of the aggregates, i.e. aggregates passing the 0, 5 mm (#40) and 0,075 mm (#200) sieve, plays a key role in the properties of the FB mixes. And due to FB interacting mainly with the fines fraction of the aggregates, the literature defines a minimum of 4% or 5% of fines passing the 0,075 sieve for use with FB mixes.

The aggregate grading chart developed by Mobil Australia (Akeroyd and Hicks, 1988), presented in Figure 2-7, is commonly used for FB stabilization. The chart proposes three levels of aggregate grading defining “Zone A” as the ideally graded material, which has a range of 5% to 20% of fines passing the 0,075 mm sieve (#200). Despite the foregoing, the grading alone is only a reference and other material properties are also required to provide a more accurate definition. Based on this approach and experience gathered, Bowering and Martin (1976) and later Ruckel et al (1982) proposed a table which recommends optimum bitumen content based on soil type. Optimum bitumen content recommended ranges from 2, 0% in the case of well graded gravel to 6,0% in the case of clayey sand.

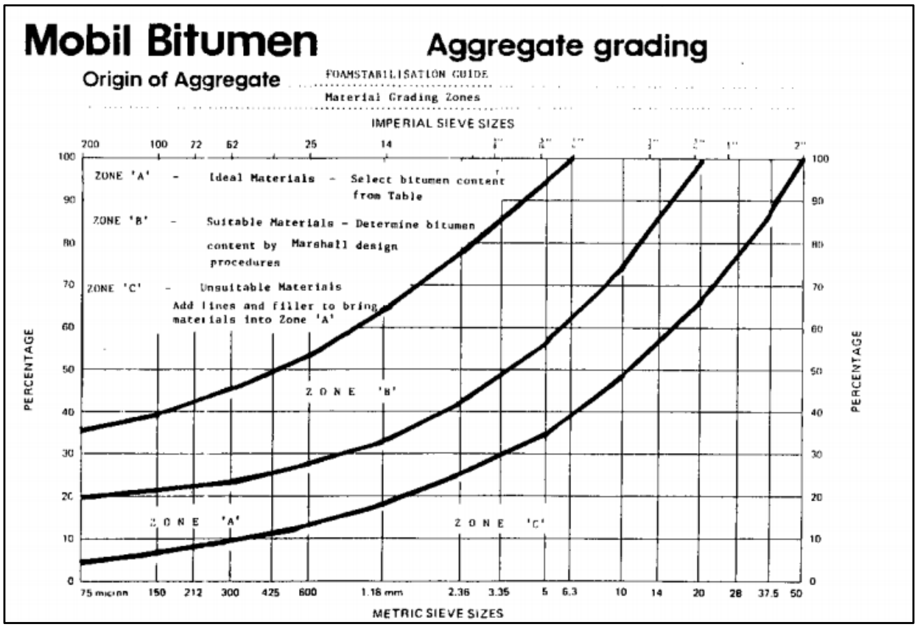


Figure 2-7: Suitability of aggregates for foamed bitumen stabilization by gradation (Akeroyd and Hicks, 1988)

The same researchers (Ruckel et al, 1982) investigated the effect of the fines content on the mechanical properties of FB mixes. They used this parameter to establish a recommended bitumen content range for different fines content (see Table 2-1). Later, this effect was investigated by a comprehensive study developed by the University of California Pavement Research Center (Jones et al, 2008). Results showed that, as long as foamed bitumen content remains constant, as the fines content increases, the resistance of the mixture decreases. This result makes sense when considering the nature of the mixture. The foamed bitumen forms the mastic with the fines of the aggregates, which in turn bind the coarse particles. By incorporating larger content of fines without changing the content of bitumen and/or active filler, the amount of mastic is the same but the mineral filler phase is larger leaving more volume of the total mix without adhesive properties.

Table 2-1: Bitumen content as a function of fines content (Ruckel et al, 1982)

Passing 4.75 mm sieve (%)	Passing 0.075 mm sieve (%)	Foamed Bitumen Content (% of dry aggregates)
< 50	3.0 – 5.0	2.5
	5.0 – 7.5	3.0
	7.5 – 10.0	3.5
	> 10.0	4.0
> 50	3.0 – 5.0	3.0
	5.0 – 7.5	3.5
	7.5 – 10.0	4.0
	> 10.0	4.5

The effect of the coarse aggregates characteristics on the mechanical properties and performance of FB mixes was studied by Jenkins et al. (2007). Results showed better performance of the FB mix in terms of shear parameters for graded crushed rock over the gravel materials.

b) Foamed Bitumen Properties

Although bitumen is a major component of the FB mixes, limited information is available regarding the properties of the bitumen itself and how it affects properties of the FB mixes. The majority of studies available concluded that bitumen with better foaming characteristics tends to achieve better quality FB mixes (Jenkins, 2000; Saleh, 2006). In South Africa, common practices recommend the use of bitumen with penetration values within 80 – 100, although softer bitumen is also used. Harder bitumen is generally avoided due to poor quality foam, leading to poorer dispersion of the bitumen in the mix. Fu et al. (2011) studied three different bitumen sources from different refineries. Results showed that different sources have a significant effect on the strength of the foamed bitumen mixes due to foaming characteristics. It also demonstrated that for the same bitumen, a change of the foaming characteristic will only have minimum impact on the mix properties. It is important to note that these mixes were prepared without any active filler. As a result of this study, it is recommended to evaluate bitumen from different sources in order to select the most appropriate for a specific project.

c) Moisture Content

Moisture content plays an important role in the mixes during the mixing and compaction process as well as curing period and performance over its lifetime. Many studies have reported the effects of mixing moisture on foamed bitumen mix properties using different materials, test procedures and criteria (Lee, 1981; Ruckel et al, 1983; Castedo and Wood, 1983; Jenkins, 2000; Kim and Lee, 2006; Fu et al, 2010). Intuitively, it may be stated that excessive moisture contents in the existing base granular layer could lead to dispersion problems of the foam bitumen during mixing. In this case, fines of the aggregates may tend to agglomerate with high moisture contents, especially with plastic fines. However, this is a major problem of stabilization projects where fines with plastic properties can be found. In recycling projects where good quality granular material is found, agglomeration of the fines are broken apart mainly by the mechanical actions of the recycling machine.

In terms of compaction, the moisture content has a main role because it affects the density of the final mix. Thus, behavior of the FB mix is governed by soil mechanics concepts. Encina (2006) reported from an extensive laboratory test plan that as the density increases, the strength of the FB mix increases as well.

In terms of curing, the moisture content has a key role. Bowering (1970) stated that FB mixes do not develop their full strength until most of the mixing moisture has evaporated. Further studies carried out by Fu et al (2010) validated what had been stated using micromechanics principles. Despite this information, the current mix design methodology (Asphalt Academy, 2009) does not consider this and proposes to carry out the process of selecting the optimum asphalt content only in cured specimens, i.e. when mixes have lost its moisture and acquired its maximum strength. Due to this problem, Ruckel et al (1983) and later, Halles and Thenoux (2009) recommended using a standard based on two levels of curing for mix evaluation: short and medium term. This very important aspect is analyzed in detail during this research.

In service, FB mixes are strongly affected by moisture content. Many studies performed at laboratory level have shown that as the moisture content increases, mechanical properties decrease (strength and stiffness). Field performance evaluation of recycled FB pavements performed by the University of California Pavement Research Center (Jones et al, 2008) concluded that differences in stiffness measured in the wet and dry seasons respectively was as high as 40 percent, which is of a higher relative magnitude than the seasonal variation of subgrade stiffness. Gonzalez et al (2009) reported that it was necessary to introduce water to a full scale experiment - on a FB pavement – in order to cause it to fail.

In conclusion, one of the main recommendations for FDR-FB projects lies with the need to have an adequate drainage system to ensure rapid drying of the FB mixes after construction and to minimize moisture variations in the FB mix in-service.

d) Active Fillers

Although not studied deeply and consistently, the active filler plays a key role in FB mixes. This variable is the main focus of this thesis, so it is analyzed in depth in the next section.

e) Temperature Sensitivity

The temperature affects properties of the FB mixes at three different levels: mixing, compaction and in-service. Its impact on mixing and compaction has been studied widely and is not discussed in this section. Only its impact on in-service mechanical properties is discussed.

Due to the rheological characteristics of the bitumen - as one of the main phases in the matrix – the mechanical properties of FB mixes are temperature-dependent. The temperature sensitivity of HMA and FB mix stiffness are somewhat similar in that they are dependent on the asphalt rheology. However, their micro-structures and the roles of the asphalt binder are different: foamed asphalt mixes have “partial coating of large aggregate with ‘spot welding’ of mix with fines mortar” while HMA has “coating of large aggregate with controlled film thickness” (Jenkins, 2000).

This particular issue has been reported in numerous publications, mainly using the stiffness as parameter. Results have indicated that the stiffness decreases as the temperature increases, as expected. Nataatmadja (2007) reported that the stiffness of FB mixes with bitumen content of 1.5 to 4.2% has a 30 to 44% reduction when the temperature increases from 10 to 40°C. Comparing these results with HMA mixes, Bissada (1987) found that cured FB mixes have higher stiffness values than hot-mix sand asphalt mixes, both tested at temperatures of above 30 °C. Khweir (2007) studied the stiffness of FB mixes using the indirect tensile resilient modulus test for different temperatures. Results showed that stiffness of the cured FB mixes could change as much as 75% when tested at 20 and 25 °C. Fu et al (2007) studied the interaction between temperature and stress-state dependence in FB mix properties and reported that at a higher temperature the FB mix tends to show more “stress-softening” behavior.

It is necessary to state that Fu et al (2007) used FB mixes without active filler while Nataatmadja (2007) and Khweir (2007) used lime or cement as active filler. This is an important issue that is discussed later in the next sections.

f) Stress-State Dependency

In general it is well accepted that the stiffness of FB mixes is sensitive to the stress state of the specimen, especially the bulk stress, which is a typical behavior of weakly bonded granular materials. However, this claim is not completely true, and it will depend whether FB mix also uses or not active filler in conjunction with bitumen.

Jenkins (2000) conducted resilient modulus triaxial tests on mixes with different contents of bitumen and cement. He observed a granular-type behavior in FB mixes without cement (i.e. RM is highly dependent on the stress applied) and also identified three cases in which the stress-dependent behavior of foam mixes becomes less evident or insignificant: the inclusion of cement; FB contents equal or larger than 4%; and specimens that before conducting the resilient modulus tests, were not pre-conditioned with cyclic pulses.

Jenkins (2000) also conducted monotonic triaxial tests on the same mixes. The tests were conducted in a displacement-controlled mode, at different confining pressures and using large (150 x 300mm) specimens. Results showed that the friction angle (ϕ) decreases whilst the cohesion of the FB mix increases with the inclusion of FB. Jenkins also suggested that with the incorporation of only FB (without cement) in a mix, the shear parameters continue to exhibit granular behavior. However, for the tests including 1% cement or more, the foamed mix showed a marked increase in cohesion with a reduction of the value of internal friction to nearly 0°. With these results, Jenkins established that stress dependent behavior is only valid for FB mixes without addition of active filler.

Later, Gonzalez (2009) studied stress dependency of mixes with bitumen and cement using monotonic triaxial test. Results indicated that the addition of FB to mixes with 1.0% cement reduces the angle of internal friction, but conclusive effects on cohesion were not observed (See Figure 2-8). The decrease in the angle of internal friction also indicates that the material is less stress dependent when foam bitumen is added.

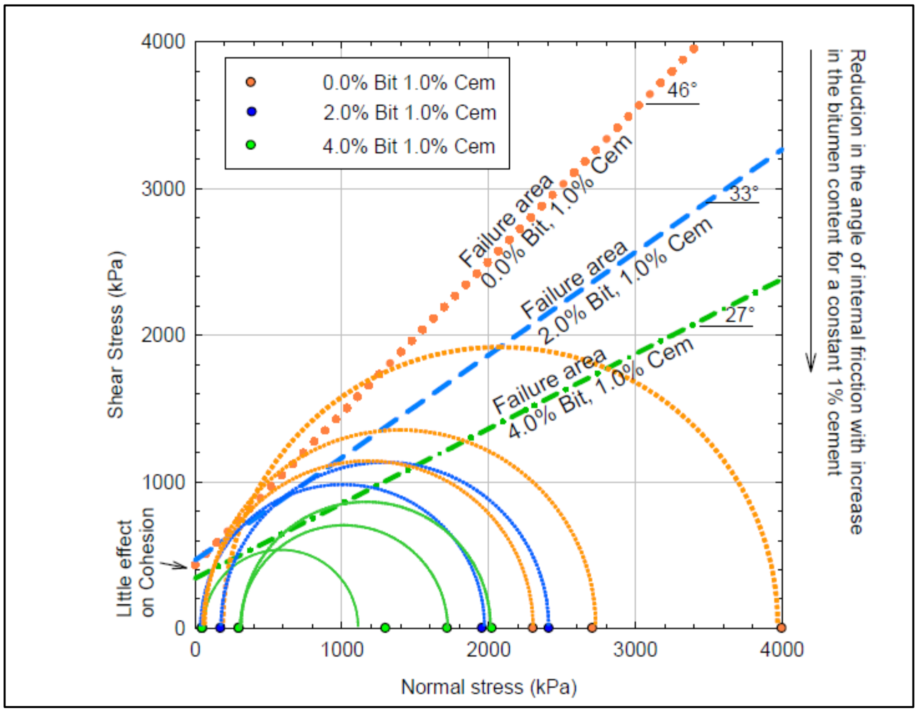


Figure 2-8: Mohr's circles and failure envelopes for FB mixes with fixed 1.0% cement content and 0.0% - 2.0% - 4.0% of bitumen content (Gonzalez, 2009)

2.5 Impact of the Bitumen and Active Fillers on the Properties of Foam Bitumen Mixes

2.5.1 Introduction

Benefits of the use of bitumen on mixes with cement are well accepted and have been also reported in studies with composite material such as cement-asphalt-mortar (Qiang et al, 2011), which is a material used at the non-ballast slab track adopted by the high speed railway industry. The cement asphalt mortar helps to reduce vibration of the structure to meet the requirement of trained high speed running. This material has characteristics of high strength due to cement hydration and high elasticity due to bitumen.

In the literature, the study of the impact of active fillers on the properties of foamed bitumen mixes has rarely been reported. As mentioned in section 2.4, traditional mix design procedure used (Asphalt Academy, 2009) does not consider the active filler as a design variable and recommends that it be used with a maximum content of 1.0%. A greater number of studies can be found on the topic of bituminous emulsion stabilized mixes, where the impact of cement has been studied more extensively. Brown and Needham (2000) studied the beneficial effects of adding cement to bitumen emulsion mixes. The study concluded that the improvements to key properties of cold mix by the addition of cement can be explained by a range of mechanisms, including improved rate of emulsion coalescence after compaction, cement hydration and enhancement of binder viscosity. Later, Montepara and Giuliani (2001) and Oruc et al (2007) stated that addition of cement on bitumen emulsions results in a significant improvement in the stabilized mix. Montepara and Guliani (2001) using diffraction X-RAY analysis, and Oruc et al. (2007) using permanent deformation tests, concluded that cement and bitumen act as a complementary binder instead of working together, i.e. bitumen and cement does not give birth to a new binder.

No information regarding the use of active filler in conjunction with FB mixes was found in the literature before 1994. That year, Lancaster et al. (1994) stated that “if the material is lacking in fines, then an additive such as CWFD (Cement works flue dust) could be used, which should also provide some cementitious bonding within the mix”. They also stated that the amount of cementitious additives should preferably be a maximum of 2% by mass of the mix, to minimize the potential for shrinkage cracks. Before this paper, other researchers only recommend the use of lime as a pretreatment process for stabilizing granular materials with plastic fines (Lee, 1981).

Later, Ramanujam and Jones (2007) raised the need for lime as active filler in the FB mixes in order to: a) flocculate and agglomerate the clay fines in the reclaimed material; b) stiffen the bitumen binder; c) act as an anti-stripping agent to help disperse the FB throughout the material; and d) improve the initial stiffness of the material and increase the early rut resistance of the stabilized material. Based on same trial sections performed in Queensland, Australia, Kendall et al (2000) proved that the use of 2% of cement instead of lime in conjunction with 3,5% of FB, gave better results.

The first edition of the Wirtgen Cold Recycling Manual (1998) incorporated FB as one of the stabilizing agents. This document recommends the use of 1% to 2% of cement in conjunction of FB for recycling projects. The technical guideline of South Africa for design and use of foamed bitumen treated materials (Asphalt Academy, 2002) stated that it is common practice to add a small percentage of active filler to FB mixes to: a) improve resistance to moisture, b) increase stiffness, and c) improve bitumen adhesion. Later, in its second edition document (Asphalt Academy, 2009), stated that FB mixes must not use more than 1% of cement due to the potential for shrinkage cracks. Specific information was not provided about why the cement content cannot be greater than 1.0%. It is only mentioned that the addition of cement triggers the loss of flexibility in the mixture.

Nowadays, it is well accepted that active fillers are used in conjunction with foamed bitumen to a) modify the fine fraction of the aggregates, which serves to improve the dispersion of bitumen in the mix, b) to reduce moisture sensitivity, and c) improve early strength of the mix. However, limited information is available regarding the degree of influence that different types of active fillers have on mechanical properties and long term performance of foamed bitumen mixes.

2.5.2 Foamed Bitumen Content Influence: Previous Studies

Most studies on FB mix properties have been focused on determining the influence of the FB content in the strength properties of the mixes, since it is the decision criteria used in the mix design procedure. While some researchers have reported an increase in strength using one type of laboratory test, others have reported either only a small increase or even a decrease in strength using other types of tests.

Long and Theyse (2002) as well as Frobel and Hallet (2008) evaluated the strength of FB mixes using ITS and UCS tests. Mixes were prepared using 1.0 or 2.0% of cement content and between 2,0 - 4,0% of bitumen content. Both reported that results did not show clear trends, i.e. addition of bitumen does not necessarily increase the strength of the FB mixes. Jones et al. (2008) evaluated mixes with 2% of cement and a range of 2, 0 - 4, 0% of bitumen content (Figure 2-9), obtaining the same conclusions. They stated that the influence of the bitumen on the strength of FB mixes is masked by the presence of cement. In other words, the influence of FB content on the strength of the mixes is very low compared to the influence of the cement.

Long and Theyse (2002) and Long and Ventura (2004) evaluated the strength of FB mixes using the monotonic triaxial test. Mixes were prepared using 1.0% of cement content and various bitumen contents. Both reported that adding FB content reduces the peak axial stress of the mix.

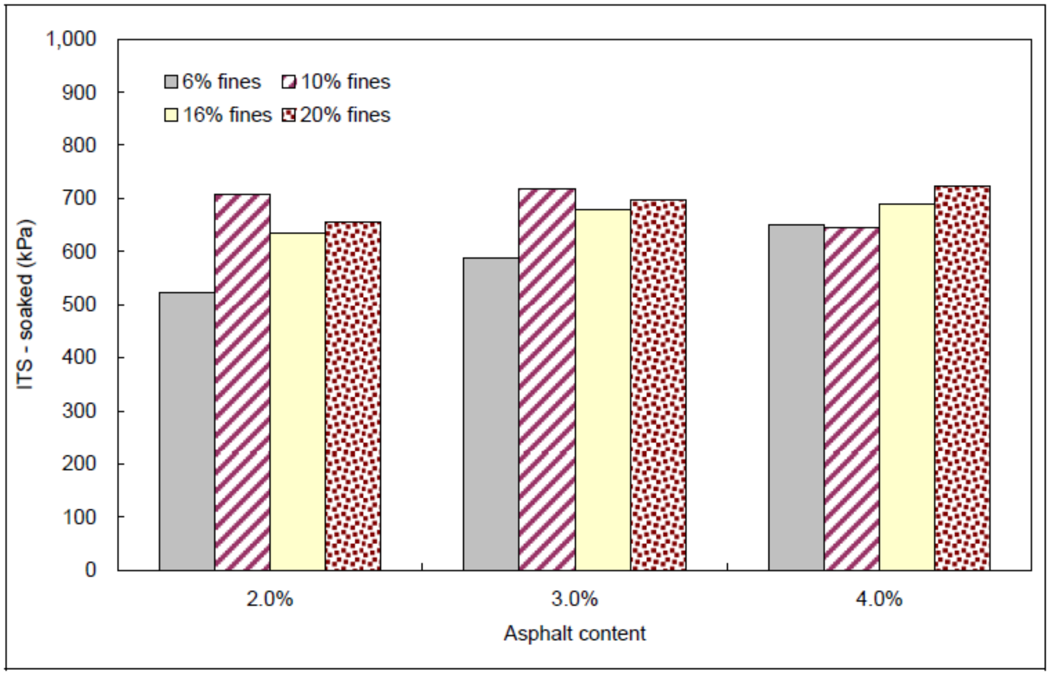


Figure 2-9: Effect of bitumen content on ITS values for fixed cement content of 2% (Jones et al., 2008)

Gonzalez et al. (2009) and Kim et al. (2008) evaluated permanent strain resistance of FB mixes using permanent deformation triaxial tests. Gonzalez et al. evaluated mixes with 1.0% of cement content with various content of bitumen, while Kim et al. evaluated mixes without cement. Both studies reported that as the bitumen content increases, the permanent strain resistance decreases. Kim et al. defined a "flow number" which may indicate the higher rutting susceptibility. As the flow number decreased, the permanent deformation resistance also decreased. They also stated that more specimens failed as the FB content was increased from 1.0% to 3.0%.

All these results are contradictory as the addition of bitumen aims to improve the properties of recycled materials. While the addition of bitumen is positive when comparing the properties of materials with and without asphalt, higher bitumen contents apparently are not beneficial to the strength properties of recycled material. Later, Gonzalez et al (2011) performed accelerated field experiments in order to establish the strength characteristics of FB mix and validate their laboratory results. However, accelerated field experiments showed that the best performance was achieved in those trial sections with more bitumen (2.8% of bitumen and 1.0% of cement). Based on its results they stated that stress conditions in the pavement structure are more complex and laboratory tests are not modeling completely the stress conditions presented in the field.

Due to the restrictions discussed in the above paragraphs, the benefits of the FB content in stabilized mixes have been studied using the concept of strain-at-break, which represents the ability of asphalt to improve the flexibility of the mix (Long and Theyse, 2004). Its results showed that increasing the bitumen content causes the flexibility of the mix to increase. In contrast, an increase in the cement content does not increase the flexibility and in many cases causes a reduction in the flexibility of a mix.

Jones et al. (2008) used the concept of Fracture Energy and Ductility Index for evaluating the effect of the bitumen content on the FB stabilized mixes. They used the ITS test to measure both parameters. *Fracture energy* is defined as the area under the load-displacement curve of an ITS test (Figure 2-10) and is measured in Joules (J). During an ITS test, more than one fracture (crack) can develop under loading though not all will propagate completely through the specimen. Fracture energy can therefore be considered as an index for quantifying the *energy dissipation capacity* of FB treated materials rather than a strict term as used in fracture mechanics. For example, if two specimens made from two different foamed asphalt mixes have the same ITS values after testing, the specimen with a higher fracture energy value can be assumed to be more apt to resist cyclic loads than the specimen with the lower fracture energy value.

The *ductility index* is defined as the fracture energy index (in J) divided by the peak load (in kN) and provides a quantitative indicator of the ductility or tensile deformation resistance of a material. Units are expressed in mm.

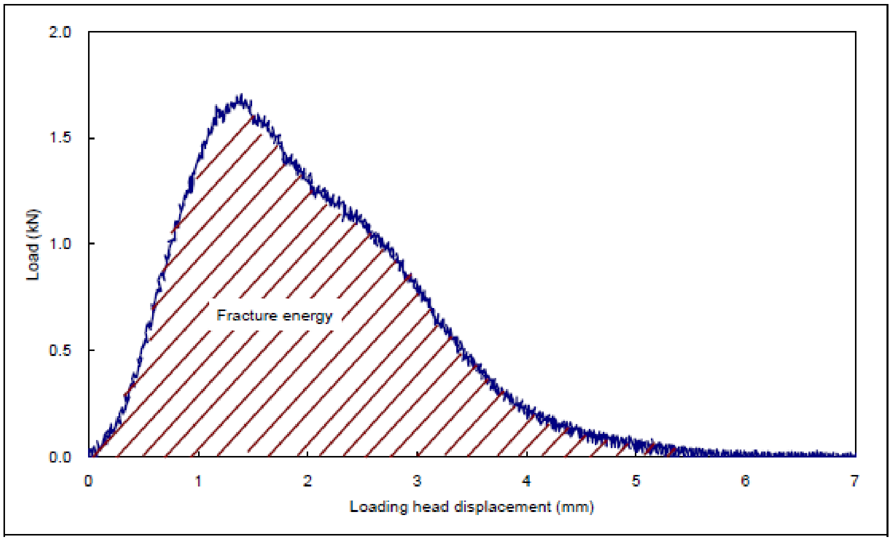


Figure 2-10: Graphic definition of Fracture Energy Index

In the research work carried out by Jones et al (2008), different mixes were prepared using 0.0 – 1.5 – 3.0 and 4.5% of bitumen content without active fillers. Also, three different bitumen sources were used. Results depicted in Figure 2-11 show a clear trend that higher bitumen content is directly related to greater fracture energy.

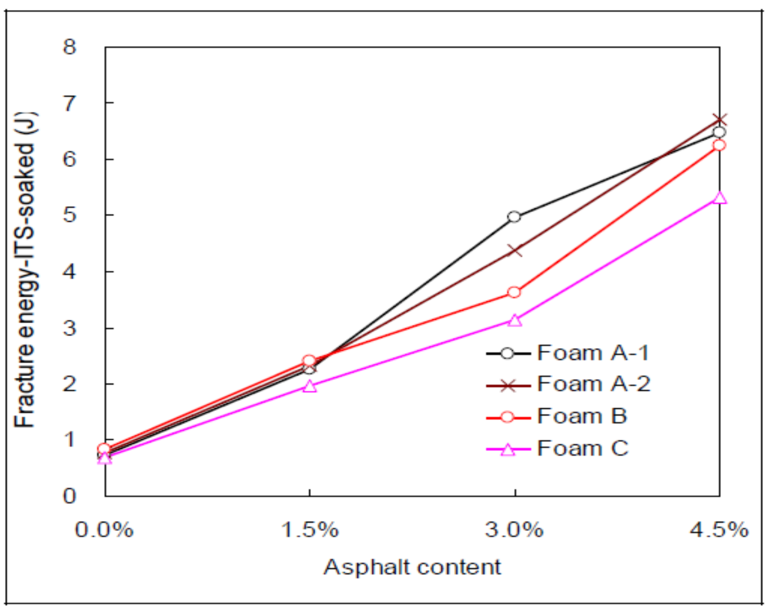


Figure 2-11: Effects of bitumen content on ITS fracture energy (Jones et al, 2008)

2.5.3 Active Filler Content Influence: Previous Studies

Kavussi and Hashemian (2004) studied the ITS of FB mixes with 1.0% and 1.5% of cement, lime and cement-lime compounds, in conjunction with a specific content of FB. Mixes without active fillers were prepared and their optimum binder contents were determined. The effects of adding lime, cement and lime-cement slurries were then analyzed. Reclaimed material tested had maximum dry density of 2.2 ton/m^3, 51% passing #4 sieve, 8% passing #200 sieve and a plasticity index of zero. Samples were tested in dry and soaked conditions. They reported that adding active filler the strength values increased appreciably, but that it makes the mixes quite rigid (with cement stiffening the most), which might not be suitable for paving purposes. Table 2-2 shows results obtained in this study for different combination of cement and lime.

Table 2-2: ITS results for a combination of foam bitumen and active fillers (Kavussi and Hashemian, 2004)

Active Filler	**ITS (kPa)**		**TSR (%)**
	Dry	**Soak**	
1.0% Cement	248	163	66
1.5% Cement	360	220	61
1.5% Lime	343	271	79
0.75% Cement + 0.75% Lime	368	247	67

TSR: Tensile Strength Retained

Hodkinson and Visser (2004) studied the indirect tensile strength (ITS) of FB mixes with 1.5% of cementitious and non-cementitious stabilizing agents with various doses of foamed bitumen or emulsion. Table 2-3 shows the factorial used in this research work. Reclaimed material tested had a maximum dry density of 2.15 ton/m^3, 55% passing #4 sieve, 14% passing #200 sieve and a plasticity index of 7. Samples were tested in dry and soaked conditions.

Table 2-3: Matrix of combinations of cementitious binders, bitumen emulsion and foamed bitumen tested (Hodkinson and Visser, 2004)

Cementitious Binder	Emulsion 2%	Emulsion 3%	Emulsion 4%	Emulsion 5%	Foam 1%	Foam 2%	Foam 3%	Foam 4%
1½% CEM I 42,5	X	X	X	X	X	X	X	X
1½% CEM II AV 32,5	X	X	X	X	X	X	X	X
1½% CEM II BV 32,5	X	X	X	X	X	X	X	X
1½% CEM II AL 32,5	X	X	X	X	X	X	X	X
1½% SLAGMENT	X	X	X	X	X	X	X	X
1½% ROCK FLOUR	X	X	X	X	X	X	X	X
NEAT MATERIAL	X	X	X	X	X	X	X	X

They reported that cementitious stabilizing agents play a major role in the strength of FB and emulsion mixes, while non-cementitious stabilizing agents do not have any influence on them (Figure 2-12). They reported that dry ITS results of the FB mixes were higher than dry ITS results of the emulsion treated material, but no further analysis was done.

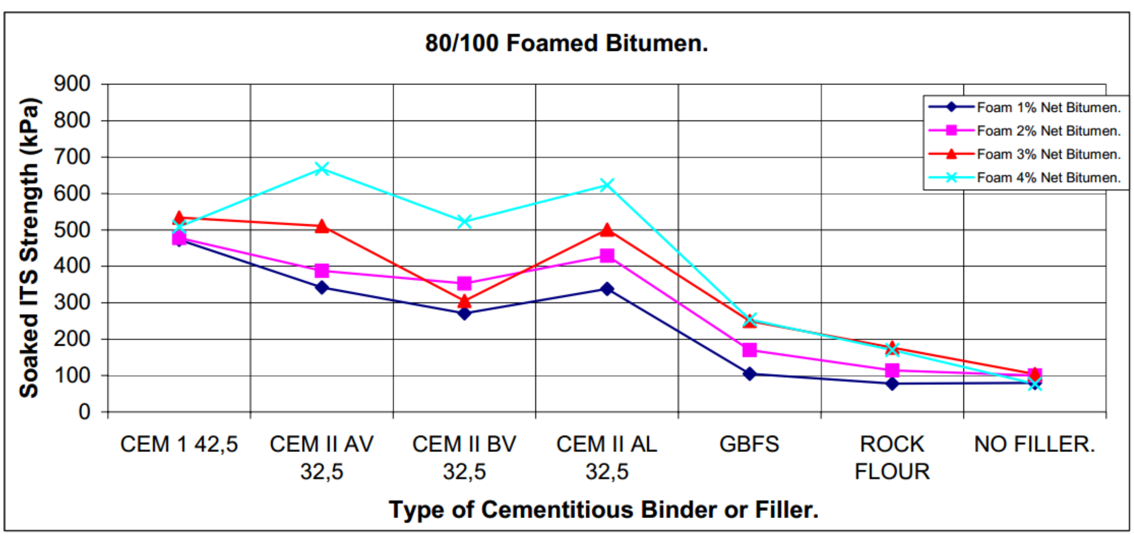


Figure 2-12: Soaked ITS results (Hodkinson and Visser, 2004)

Long and Theyse (2004) used monotonic triaxial tests to calculate the strength of mixes with different contents of cement and bitumen. Figure 2-13 shows the maximum allowable principal stress of six mixes containing different additives and degrees of saturation and relative density. In terms of the active filler content influence, results showed that for mixes with 2.25% of bitumen an increase of the cement content from 1.0 to 2.0% increases the maximum allowable principal stress.

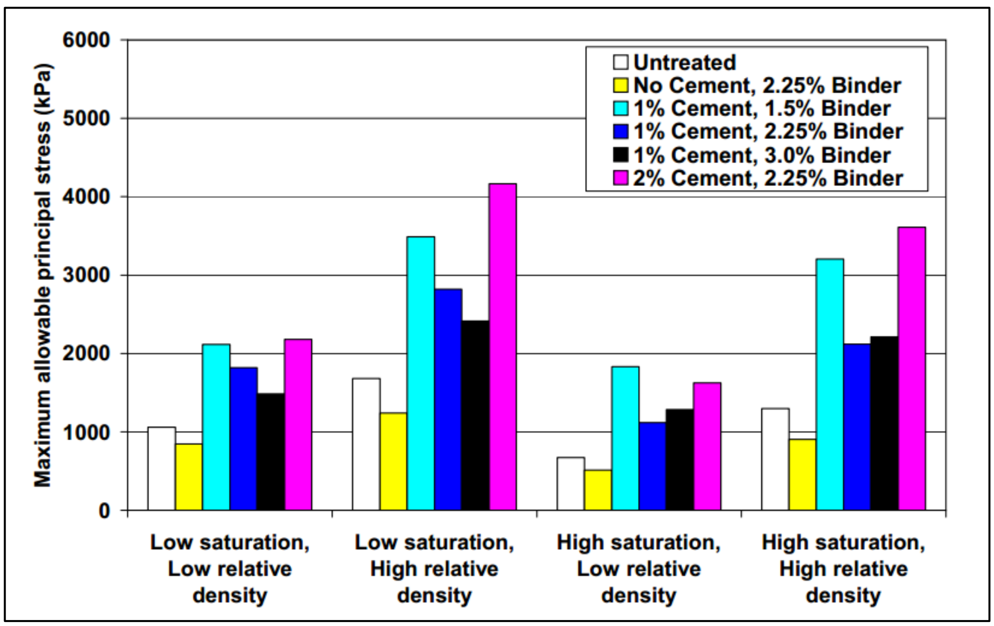


Figure 2-13: Maximum allowable principal stress at various combinations of bitumen and cement (Long and Theyse, 2004)

Montepara and Giuliani (2001) studied cement-bituminous emulsion pastes as well as mortars of monogranular siliceous sand with bituminous emulsion and cement. They performed flexural strength tests using prisms of 40x40x160 mm at different curing times for mortars. They found that higher cement-emulsion ratios produce better results, which is not typical of the traditional cold recycling techniques, due to it possible producing undesired shrinkage. They stated that amounts between 1.0 to 2.0% of cement should be added to bitumen emulsions mixes. They also stated that bitumen that covers the reclaimed aggregates is the weakest structural element of the mix.

Observations of the fracture face produced in the specimens by the flexural test showed that the surface becomes more irregular when emulsion content increases (the mix is less fragile and more ductile). In samples containing bituminous emulsion the breaking was less evident, with no significant crack, and greater strain of the prisms could be noted before breaking (see Figure 2-14). While smaller strength values were obtained, greater ductility with similar fracture energy values was obtained.

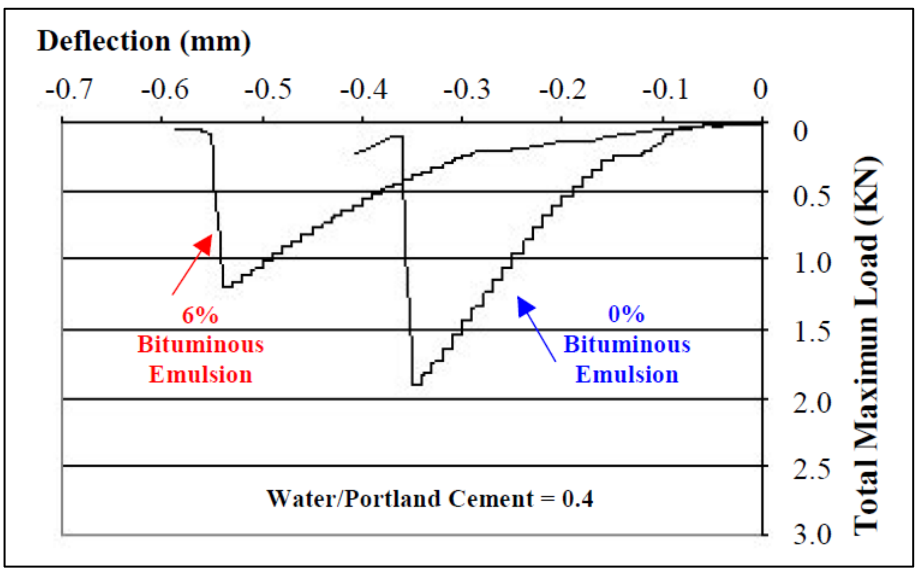


Figure 2-14: Flexural strength test results on cement-bituminous emulsion mortars (Montepara and Guliani, 2001)

2.5.4 Summary

The benefits of using different bitumen contents in reclaimed materials have been studied extensively in mixes stabilized with bituminous emulsions or foamed bitumen. Results obtained when strength and permanent strain resistance of the mixes were evaluated, have not been promising. Most of the researchers have stated that as the bitumen content increases, the strength has not a significant increase nor improves an increase in permanent strain resistance. These results are misleading based on the fact that bitumen is the main binder of the stabilized mix.

The addition of bitumen increases the ductility of the FB mixes, which could lead to an improved long term performance since stabilized layers may be able to resist more cyclic loads. These statements have been inferred from studies using the fracture energy concept.

The benefits of using different cement contents in reclaimed materials have mainly been studied in mixes stabilized with bituminous emulsions. The impact of active fillers on the properties of FB mixes has been rarely reported. Researchers have stated that cementitious stabilizing agents play a major role on the properties of foamed bitumen and emulsion mixes, improving strength and permanent strain resistance. Also, some researchers have warned about potential shrinkage problems when cement content greater than 2.0% are used, without providing testing support.

Regarding the use of active fillers other than cement, there is limited information. The most used is lime when the fines fraction of the reclaimed material has a high plastic index. There is limited experience using different types of active and inactive fillers. The main conclusion is that the use of inactive filler does not give any significant benefits to the stabilized mix in comparison with active fillers.

Today, it is well accepted that active fillers are used in conjunction with foamed bitumen to: a) modify the fine fraction of the aggregates, which serves to improve the dispersion of bitumen in the mix, b) reduce moisture sensitivity (Asphalt Academy, 2009), and c) improve early strength of the mix (Khweir, 2007).

However, limited information is available regarding the degree of influence of the different types of active fillers on the mechanical properties and long term performance of foamed bitumen mixes. Hence, it is very difficult to select the most appropriate active filler (cement, lime or other) for recycling or stabilizing projects, and even more difficult to select the most appropriate active filler content.

2.6 Structural Performance and Design Considerations

Up to date, there is no a globally accepted structural design procedure for foamed bitumen mixes. The most accepted method for the structural design of FB pavements is the one published in the “Interim Technical Guidelines (TG2): The Design and use of Foamed Bitumen Treated Materials” (Asphalt Academy, 2002). This method proposes that FB mixes have two phases of deterioration (Figure 2-15). This proposal is based on laboratory data and accelerated pavement testing performed by Long (2001) on recycled pavements using foamed bitumen and cement as stabilizing agents. As shown in Figure 2-15, the first phase corresponds to a decrease in stiffness of the FB layer until there is a constant stiffness without having a physical manifestation on the pavement layer. The first phase starts after construction and ends after the application of several traffic loads, when the layer reaches a “constant stiffness state”. The period of time to reach this state is defined as the “effective fatigue phase”. The term “equivalent granular state” is used to describe the loss of stiffness of the material, and is comparable to granular materials only in the elastic modulus, and not in the physical composition of the materials (Asphalt Academy, 2002). During the second phase, the material behaves as a granular material, accumulating permanent deformation due to cyclic load applications.

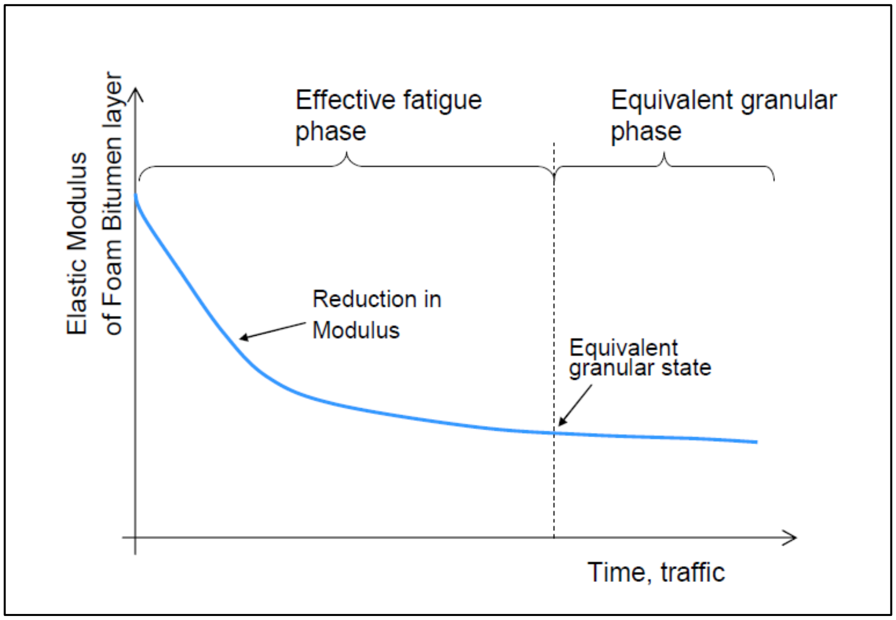


Figure 2-15: Two phases structural behavior model for foamed bitumen mixes (Asphalt Academy, 2002)

This approach is well linked with the FB mix microstructure characterization proposed by previous researchers (Jenkins, 2000; Fu, 2009). The microstructure of a material refers to the microscopic description of its individual constituents. In this case, "FB mix microstructure" refers to the spatial or geometrical configurations of the individual phases of the mix. As described in section 2.2.2, the tiny bitumen particles disperse throughout the aggregate by adhering to the finer particles (fine sand and smaller), forming a fairly stiff and stable mastic that is coated with large aggregates. The structure formed during the mixing and compaction process is conceptually illustrated in Figure 2-16 (Fu, 2009), where different phases can be distinguished: the aggregates skeleton, the "mastic" or bonded fine particles (with bitumen and active filler) and the un-bonded fine particles that partially fill the voids in the skeleton.

Since the bonds formed by stabilizing agents (bitumen and active filler) are not continuous in the microstructure or "spot welded", every single applied stress should break part from those bonds. In the longer term, that situation will produce a decrease in cohesion between particles and therefore a decrease in the FB mix stiffness, supporting evidence identified by Long (2001) in his field studies.

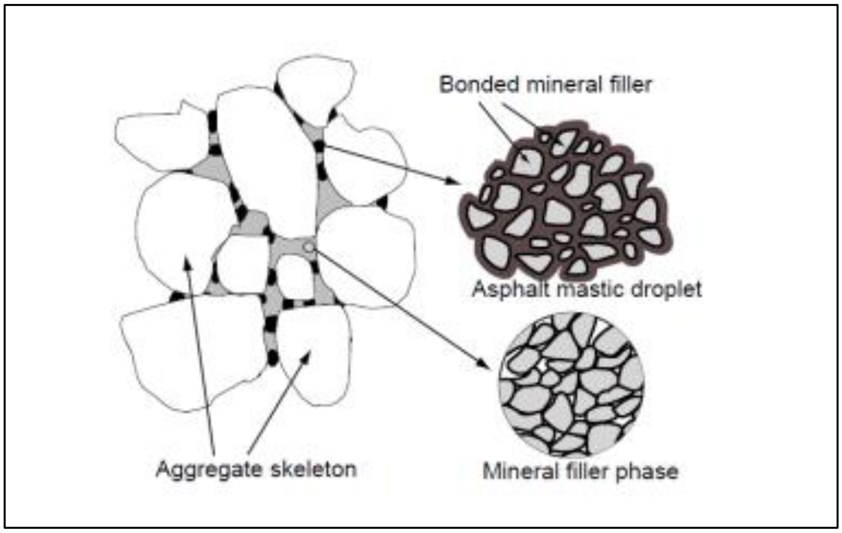


Figure 2-16: Conceptual illustration of microstructure of FB mixes (Fu, 2009)

Based on this background, Long (2001) and Long and Theyse (2002) performed monotonic four-point-beam tests using the strain-at-break concept. This concept is represented by the strain at the point of crack initiation (Figure 2-17) and provides an indication of the fatigue resistance of the material. Beams with a range of bitumen and cement were tested. Results showed that as the bitumen content increases the strain-at-break also increases and as the cement content increases the strain-at-break decreases. The stress-at-break values were also analyzed and, as a global conclusion, it was stated that mixes must contain cement to provide tensile strength and a high foamed bitumen content to provide flexibility.

Unfortunately, beam tests were performed without cyclic loading. In theory, the greater the deformation, the more quickly the bonds formed by the bitumen and cement will break, and therefore the stiffness of the mix will decrease faster.

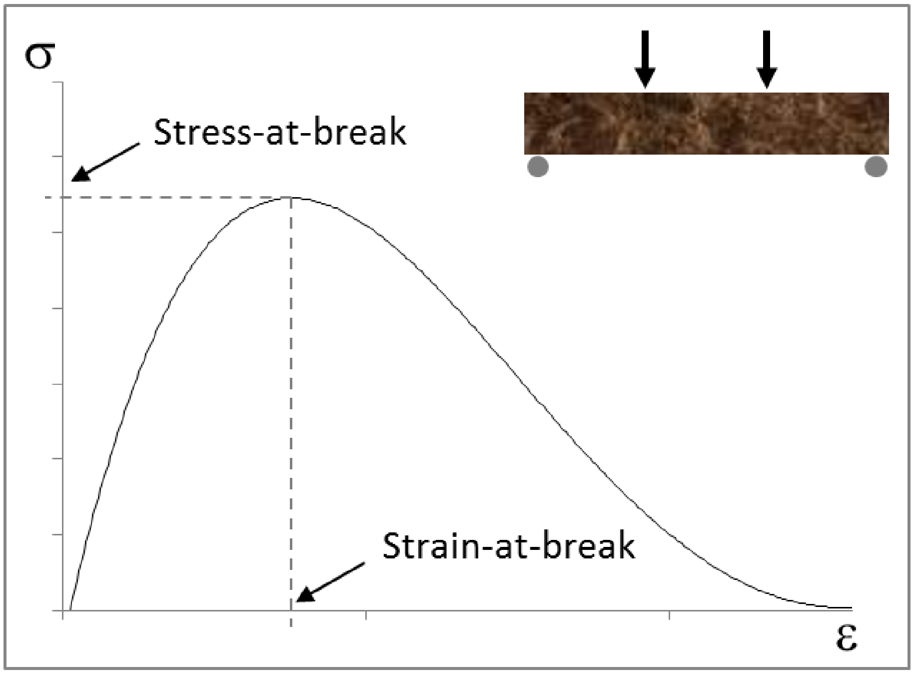


Figure 2.17: Strain-at-break representation on monotonic four-point-beam test

Twagira et al. (2006) performed fatigue tests of FB mixes using the four-point-beam test. They tested mixes with 3.6% of foamed bitumen content with 0.0 and 1.0% of cement content in a 75% crushed rock and 25% RAP milling mix. Strains applied ranged from 120 to 470 micro strains. They tried to relate fatigue results with strain-at-break values for each mix in order to establish some relation between the parameters. Results indicated that the addition of 1.0% of cement increases the fatigue life at higher strains and results in less sensitivity to strain levels. Additionally, results showed that the addition of 1.0% of cement increases the strain-at-break, which is the opposite of what is expected, due to the fact that as the cement content increases, the flexibility decreases. Finally, they stated that strain-at-break test needs further development before it can be considered to provide a reliable link to fatigue performance of cold mixes. While the results are interesting, the factorial analysis carried out is considered insufficient, since they only used one RAP mix and two combinations of bitumen and cement.

2.7 Research Needs and Opportunities

Based on the discussion in this chapter, it is possible to highlight a number of aspects that require further analysis and definition. Many of these aspects are related to the strength and stiffness that FB mixes develop throughout its service life and which are the variables that influence these parameters mostly. The ability to quantify the stiffness of these mixtures in the short, medium and long term, it is essential to perform a structural analysis that allows to define the thickness of the pavement.

One of the main identified problems is related to moisture susceptibility of the FB mixes. The addition of foamed bitumen droplets in the matrix decreases the proportion of fine particles that become susceptible to moisture, but its effect is limited. Therefore, every change of moisture in the vicinity of the layer will affect the moisture content of the FB layer, affecting the in-service strength. This aspect has been widely studied by researchers in cured mixes (Jenkins, 2000; Asphalt Academy, 2002; Fu et al, 2008), which represents conditions of the FB in the medium term. However, there is no clarity regarding to how much moisture affects the mechanical properties of these mixes in the short term, especially during the strengthening process (curing process). Previous researches have stated that FB mixes do not develop full strength until most of the mixing moisture has evaporated (Bowering, 1970). In the case that a project is built in a humid area (i.e. rain, saturated subgrade), the moisture content of the FB layer incorporated during construction process will decrease slowly or even remain constant during a long period of time, slowing down the curing process and affecting the in-service strength of the mix. In this scenario it is expected that, if the curing process does not develop properly, the material will behave as an unbound material, which clearly moves away from the goal of using stabilizing agents. This is an aspect that must be quantified considering that these projects are open to traffic immediately after construction, and therefore the strength and stiffness of these mixes during this period must be defined correctly for structural analysis purpose.

Another problem identified was the need for further analysis for defining the role of active fillers used in FB mixes. As previously mentioned, active filler was first used for improving the fines content of the reclaimed granular materials. Once FB mixes were evaluated, Lancaster et al (1994) stated that the use of active fillers should provide some cementitious bonding within the mix. From that experience, many researchers and practitioners have evaluated FB mix properties using different types of active fillers with different results. Nowadays, the use of active filler is not only recommended to modify the fine fraction of the aggregates, but also for reducing the moisture sensitivity and improving the early strength of the mix. In the first case, the use of active filler reduces the percentage of the fine particles that become susceptible to the presence of moisture. In the second case, active fillers react very quickly with the fine fraction of the reclaimed materials, acquiring strength and therefore giving the early strength to FB mix as required. However, up to date, specific contributions of active fillers have not been quantified. The contribution of the active filler in both aspects must be studied in order to provide to designers and practitioners a tool for selecting the optimum content in the FB mix and for defining the stiffness value for structural design purpose.

There are other aspects related to active fillers that require a comprehensive study. As it was explained in section 2.3.2, current mix design procedures use the strength as design criteria and do not include the active filler as a design variable. This is confusing if we consider results obtained in studies carried out by Hodkinson and Visser (2004) and Kavussi and Hashemian (2004) discussed in section 2.5.3. Both studies stated that the use of cementitious agents increased significantly the strength of the FB mixes compared to the contribution made by the bitumen. All the aspects discussed in this and previous sections, highlight the need for including the active filler in the mix design procedure, or at least, to include some specific – and supported – recommendations for selecting the appropriate active filler content. Additionally, it is well known that different active fillers available, as cement, lime, cement kiln dust, or others, have different effects on properties of treated granular materials. In this sense, it is highly necessary to have some guidance or specific knowledge about the properties of FB mixes when using different types of active fillers.

Finally, it is well known that bonds provided by cementitious agents are strong but brittle in comparison to those provided by bitumen. In this sense, as the active filler increases, the strength increases, but the mix could become brittle which could lead to a poorer long-term performance. On the opposite, it is well accepted that bitumen increases flexibility of the stabilized materials which could lead to better long-term performance. Based on these concepts, long term mechanical properties of FB mixes must be evaluated and defined, not only for quantifying the long term stiffness but also for defining the role of the stabilizing agents.

As a summary, the literature review identified three main topics to be studied, which are part of the objectives of this research work.

- Quantify the strength and stiffness evolution of the FB mixes along its service life, i.e. in the short, medium and long term.
- Define the contribution of the cement in the mechanical properties of FB mixes during all stages of its service life
- Evaluate and compare the contribution of others active fillers in the mechanical properties of FB mixes.

3. MATERIALS, TESTS AND LABORATORY PROCEDURES

3.1 Introduction

This chapter provides details of the materials, laboratory tests and procedures performed in this research work in the laboratory. It must be noted that experiments at laboratory level were carried out in two different locations: University of California Pavement Research Center (UCPRC) and Pontificia Universidad Católica de Chile (PUC).

3.2 Materials

3.2.1 RAG (Reclaimed Asphalt Pavement and Reclaimed Granular Materials)

a) UCPRC laboratory program

The RAG used in UCPRC was collected from California Highway State Route 88 in Amador County. This material was pulverized by recyclers commonly used for Full Depth Recycled (FDR) projects - to a depth of 20 cm - but without addition of FB or Active Fillers. This material contains around 75% recycled asphalt pavement and 25% reclaimed granular base material. One gradation was constituted from the original material by sieving the RAG into four fractions and recombining them for laboratory testing. During this process, 3.5% of fine particles passing 0.075 mm sieve were added to the original RAG using inert baghouse dust collected from an asphalt concrete plant. Table 3-1 shows the main properties of the RAG mix and its gradation is depicted in Figure 3-1 in conjunction with envelopes recommended for “ideal materials” from South African Guidelines (Asphalt Academy, 2002).

Table 3-1: RAG material properties at UCPRC

Maximum Size	19 mm
Material Passing #4 sieve (4.75 mm)	46.6%
Material Passing #40 sieve (0.425 mm)	20.5%
Material Passing #200 sieve (0.075 mm)	10%
Crushed/Fractured Particles	100%
Plasticity Index of fines particles	Non Plastic
Optimum Moisture Content by Modified AASHTO T180	6.0%
Maximum Density as determined by AASHTO T180	2190 kg/m^3

b) PUC laboratory program

The RAG used in PUC was collected from the “Huequén - Los Sauces” recycled project, located near the city of Angol, IX region, Chile. Only the RAP (Recycled asphalt pavement) was pulverized by recyclers to a depth of 10 cm, without addition of FB or active fillers. RAP material was mixed with granular base materials in the laboratory, simulating similar conditions found in traditional FDR projects in Chile. One gradation was constituted from the original material by sieving the RAG into three fractions and recombining them with granular base materials for laboratory testing. Also, inert baghouse dust collected from an asphalt concrete plant was used for correcting the final RAG mix. Table 3-2 shows the main properties of the RAG mix and its gradation is depicted in Figure 3-1.

Table 3-2: RAG material properties at PUC

Maximum Size	19 mm
Material Passing #4 sieve (4.75 mm)	46%
Material Passing #40 sieve (0.425 mm)	13%
Material Passing #200 sieve (0.075 mm)	6%
Crushed/Fractured Particles	100%
Plasticity Index of fines particles	Non Plastic
Optimum Moisture Content by Modified AASHTO T180	6.3%
Maximum Density as determined by AASHTO T180	2187 kg/m^3

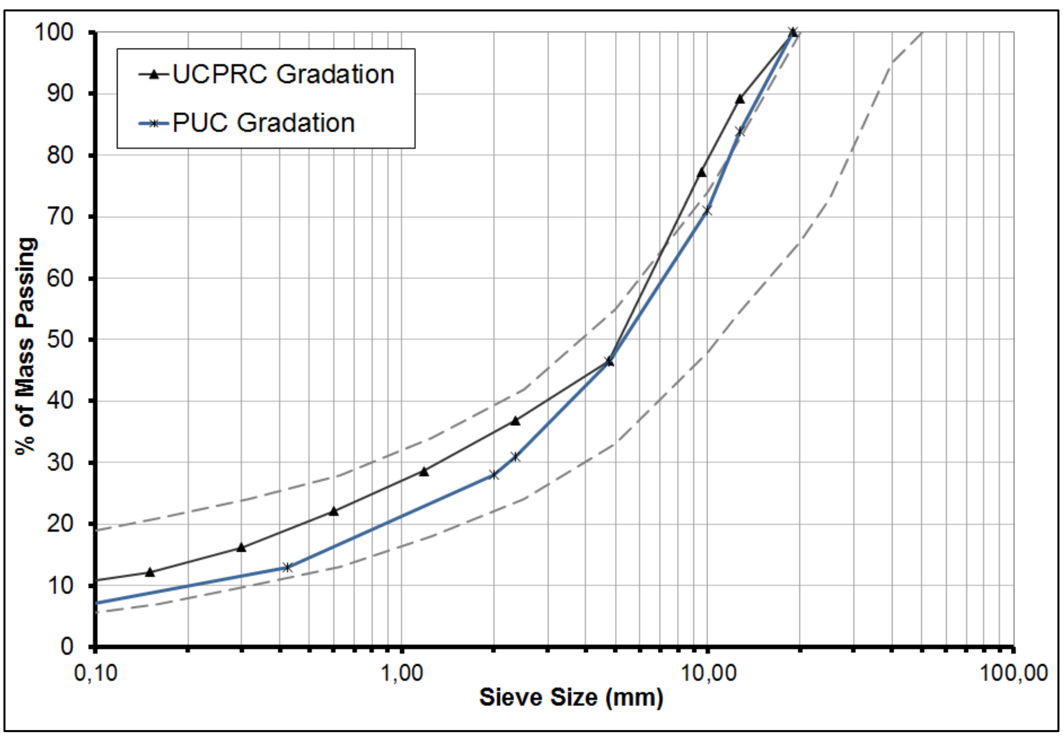


Figure 3-1: Gradation of the RAG used at PUC and UCPRC

3.2.2 Bitumen and Foam Properties

a) UCPRC laboratory program

One grade of bitumen, PG 64-16, was used from a local California refinery. RAG material was foamed using Wirtgen WLB-10 laboratory equipment at 150 °C with 3% of foaming water by mass. The expansion rate was controlled at 17 - 20 points and the half-life was at 23 - 26 seconds. RAG, in terms of temperature and moisture before being mixed, was preconditioned through placing buckets of 15 kg. of material in a controlled room at 30 °C. Mixing temperature was controlled at 25 – 28 °C during the mixing process.

b) PUC laboratory program

A Mobil AC-24 bitumen was used. Table 3-3 presents properties of the bitumen used. RAG material was foamed using Wirtgen WLB-10 laboratory equipment at 165 °C with 2.5% of foaming water by mass. The expansion rate was controlled at 12 – 15 points and the half-life was 10 – 12 seconds. RAG was preconditioned through placing buckets of 20 kg of material at uncontrolled laboratory temperature and relative humidity. Normal values measured during test period range from 18 to 25 °C and from 35 to 55 % of relative humidity.

It must be noted that in UCPRC the half-life of the foam was measured from the time that the nozzles were opened, while in PUC this parameter was measured from when the maximum expansion was achieved.

Table 3-3: Bitumen properties at PUC.

Absolute viscosity at 60 °C, poises		3210
Ductility at 25 °C, 5 cm/min (cm)		> 150
Penetration Index		- 0.9
Flash Point (Cleveland open cup), °C		360
Test on Residue from TFOT	Viscosity at 60 °C, max., poises	9180
	Ductility at 25 °C, min., cm	> 150

3.2.3 Active Fillers

During the research project, portland cement type II was used. At Stage II (refer to section 1.3 General Research Methodology), CKD and lime type S (hydrated) were used as well as fly-ash class C as inert filler, with the aim to compare mechanical properties of foamed bitumen mixes using different active fillers.

3.3 Laboratory Tests

Traditionally, testing of foamed bitumen mixes have been carried out using the Indirect Tensile Strength (ITS), Unconfined Compressive Strength (UCS) test and Cyclic Triaxial Tests. Monotonic Triaxial Test has also been used in many research projects. ITS and UCS are used to assess the strength or admissible maximum stress of FB mixes and are considered conventional tests adopted in practice due to simplicity and low cost. Monotonic triaxial test is normally used in pavement engineering to estimate the peak stress at different confining stresses with the aim of assessing the shear strength parameters of the mix (cohesion and angle of internal friction). Cyclic triaxial test is utilized to study the dynamic response of the mix applying loads that are well below the maximum load at failure, but closer in magnitude to actual loads applied in real pavement structures. Unconfined Compressive Strength (UCS) and the Monotonic Beam tests are also widely used for quantifying strength of FB mixes.

The following section describes some of the above laboratory tests and indicates the ones used in this research.

3.3.1 Indirect Tensile Strength (ITS) Test

Indirect Tensile Strength (ITS) is a standard test that involves monotonic loading of the specimens up to maximum stress or failure (Figure 3-2). The dimensions of the ITS specimens are normally 100 mm in diameter and a nominal height of 63.5 mm (± 5 mm). Specimens of 150 mm in diameter are also used. The ITS specimens are diametrically loaded, inducing a horizontal tensile stress at the center of the specimen. The ITS value is defined as the maximum tensile stress applied to the specimens during the tests. The loading was displacement controlled at a velocity of 50 mm/min. ITS tests were used extensively in stages I and II of this research work (refer to section 1.3).

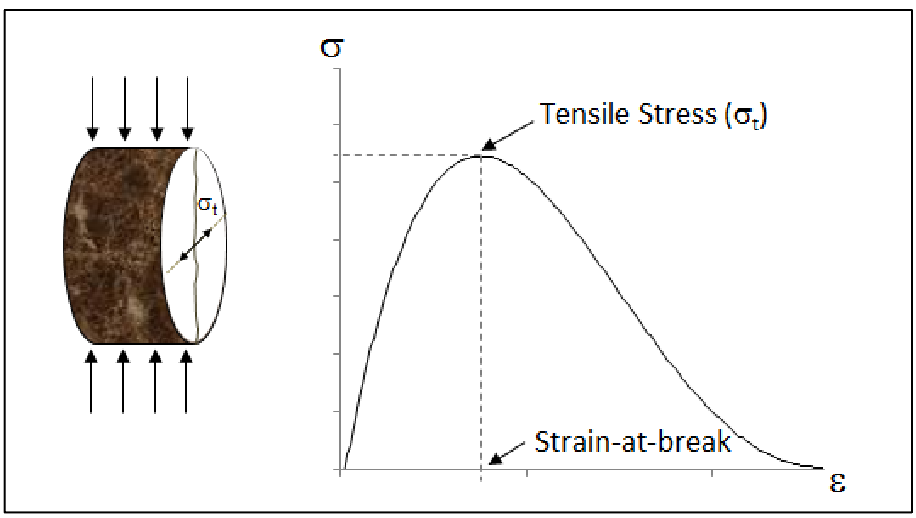


Figure 3-2: ITS test diagram

3.3.2 Monotonic Triaxial Test

Monotonic triaxial tests are conducted on cylindrical specimens applying both vertical and confining stresses (Figure 3-3). The confining stress is kept constant, with increasing vertical stress, at a slow rate, to a point where the specimen reaches its maximum vertical compressive stress. The test is conducted at different confining stresses with the aim of determining the shear strength parameters of the material studied, i.e. cohesion (c) and angle of internal friction (φ). Specimen dimensions are traditionally 150 mm in diameter and 300-mm in height; 100 mm in diameter and 200 mm in height. Monotonic Triaxial Tests were not used in this research work, but results from others researchers were analyzed and used for some tasks.

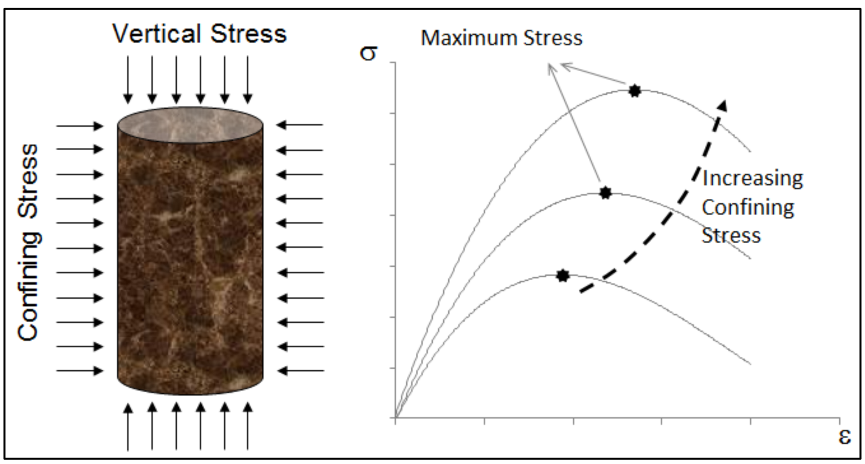


Figure 3-3: Monotonic Triaxial Test diagram

3.3.3 Cyclic Triaxial Test

Cyclic triaxial test uses the same setup of the monotonic triaxial test described previously. In this test, instead of applying a load up to failure, like in the monotonic tests, specimens are subjected to a cyclic load that is usually below failure, in conjunction with different static confining stresses. A typical test setup is shown in Figure 3-4.

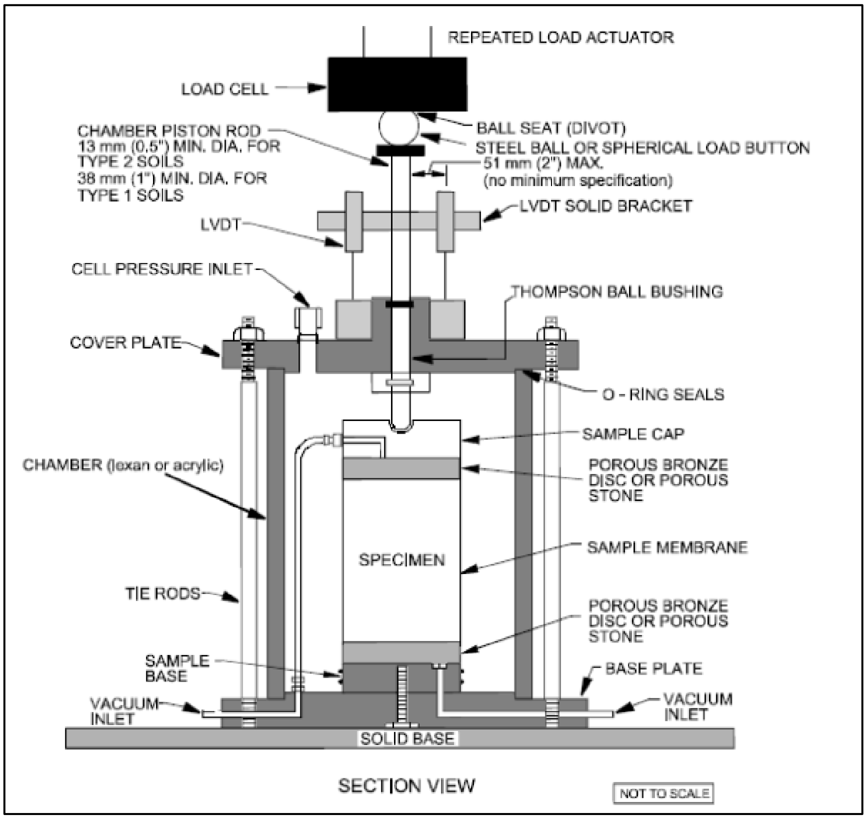


Figure 3-4: Cyclic Triaxial Test setup (FHWA, 1996)

Two types of dynamic triaxial tests are normally conducted: Resilient Modulus (TxRM) and Permanent Deformation (TxPD). In the resilient modulus test, the specimen is loaded to different combinations of confining and deviator stresses, and a limited number of cycles (e.g. 100) is applied at each stress condition. During this test, the elastic or recoverable strain (ε_r, see Figure 3-5) is measured, and the elastic or resilient modulus is calculated using the formula:

$$RM = \frac{\sigma_d}{\varepsilon_r} \qquad \text{(eq. 3.1)}$$

where RM is the resilient modulus, σ_d is the deviator stress and ε_r is the recoverable vertical strain. Figure 3-6 also shows a typical axial strain response under this type of loading, where σ_{cyc} is the magnitude of the deviator stress (σ_d) and σ_c is the contact stress applied during the test

Five confining stress levels, each with three axial stress levels were used. TxRM tests were performed according to AASHTO T307 test protocol.

TxRM tests were used extensively at all stages of this research work. Since the TxRM test is nondestructive, specimens were tested in more than one occasion for evaluating the strengthening process and moisture susceptibility of FB mixes.

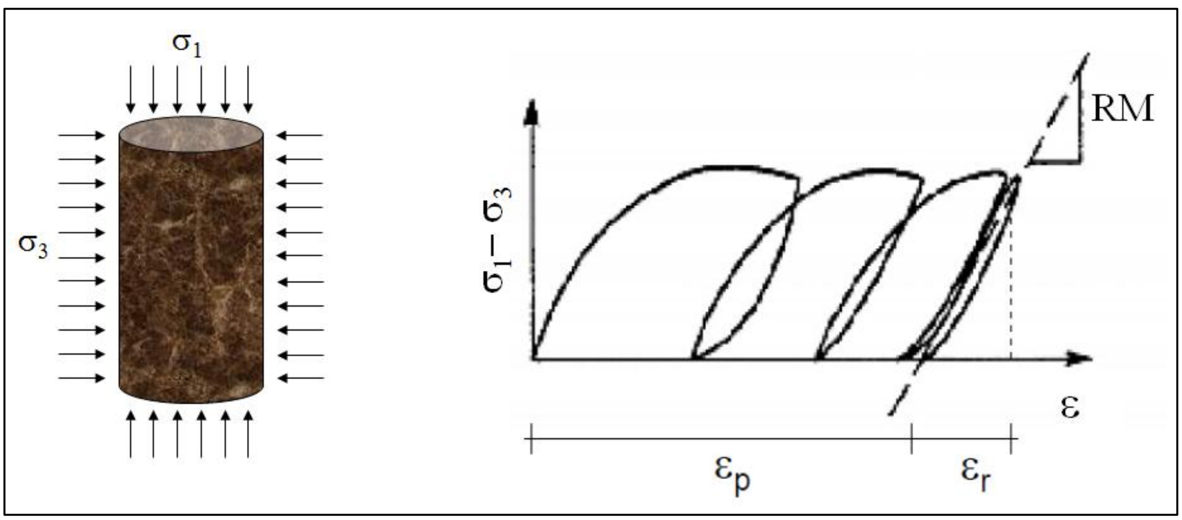


Figure 3-5: Cyclic load applied in Triaxial test

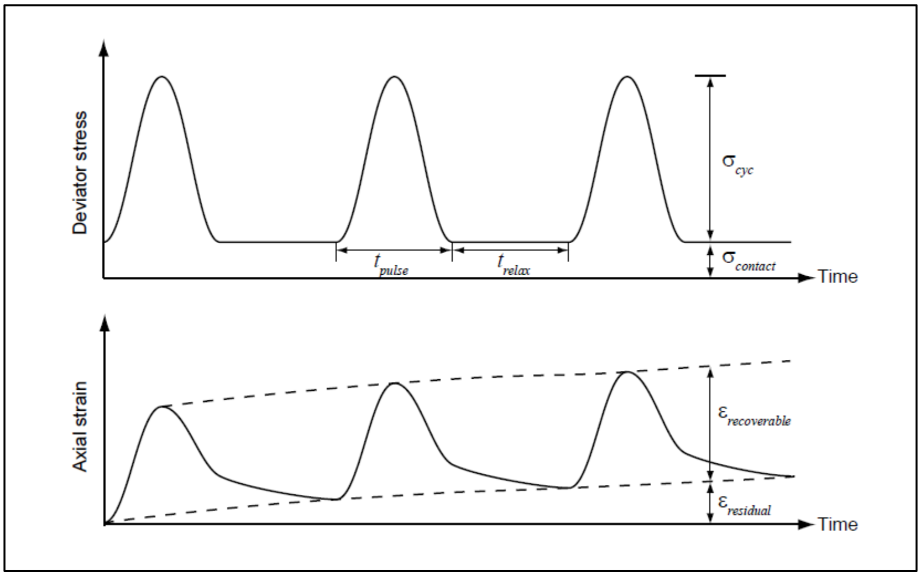


Figure 3-6: Typical axial stress and strain response in TxRM

In the permanent deformation triaxial test (TxPD), a large number of load cycles are applied and the irrecoverable or permanent strain ε_p is recorded ($\varepsilon_{residual}$ in Figure 3-6). TxPD test were used in Stage II of this research work for evaluating the contribution of the cement in the mechanical properties of FB mixes.

3.3.4 Indirect Tensile Fatigue Test (ITFT)

Indirect Tensile Fatigue test uses same setup of the ITS described previously, but in this case the axial stress applied is cyclic. LVDTs are installed diametrically in order to measure the horizontal tensile strains (see Figure 3-7), which is used to calculate the resilient modulus using recoverable strain measured as well as for calculating the fatigue performance of the mix. Specimens of 150 mm in diameter are normally used.

At the Stage III of this research work (refer to section 1.3), ITFT was used for evaluating the long term stiffness evolution of the FB mix under different patterns of stress state. Under a stress controlled test, strains measured were used for calculating the elastic modulus (stiffness) of the mix. Due to the progressive increase in deformations under cyclic loading, using the same stress, stiffness will decrease.

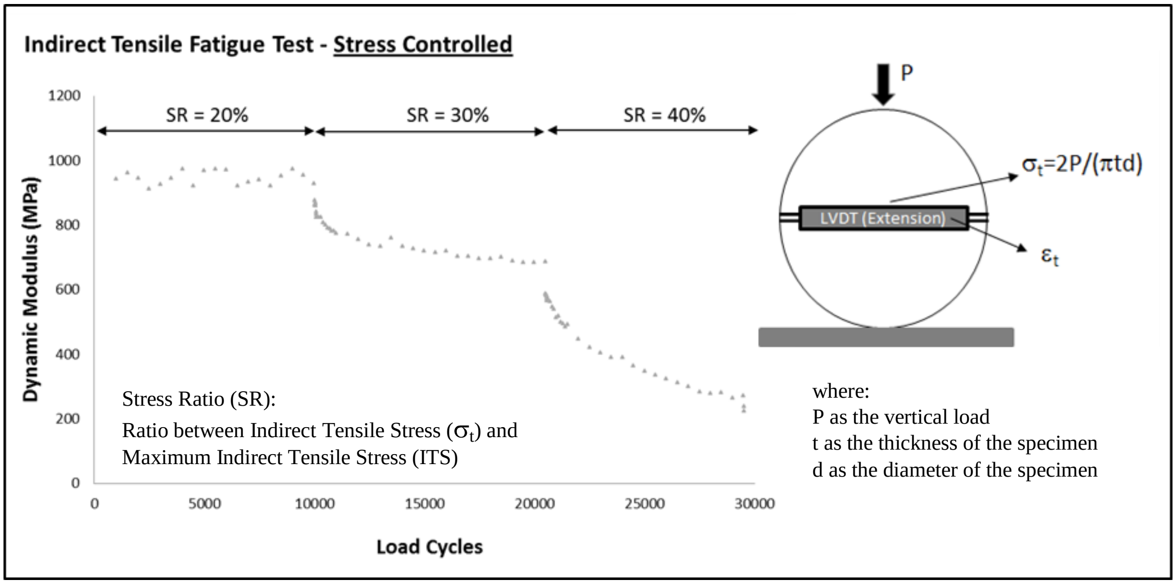


Figure 3-7: Indirect Tensile Fatigue Test setup

3.4 Laboratory Procedures

3.4.1 Mixing Preparation

During mixing preparation the moisture content of the RAG material was strictly controlled and, on average, was close to the 75% of the optimum moisture content (OMC) of the RAG mix. Several Proctor tests were conducted for defining this value.

Foamed bitumen was injected using the Wirtgen WLB 10 laboratory foaming unit and materials were mixed using a twin shaft pugmill mixer. During mix production, RAG materials were mixed in dry with the active fillers, following by the addition of water. After the minimum of one minute of mixing, foamed bitumen was injected while RAG material was being agitated.

3.4.2 Compaction

100 mm ITS specimens were compacted following the Marshall compaction method (Asphalt Institute, 1974). 75 blows per face was the standard compaction effort used. 150 mm ITS specimens were compacted using gyratory compactor equipment. In this case, a specific compaction procedure was used to get the same density on each specimen.

Triaxial specimens with a nominal diameter of 152 mm and a height of 305 mm, were compacted using a modified version of the AASHTO T180 method using 12 lifts of 25.5 mm thick layers, with the mass of each layer calculated based on the 100 percent Modified AASHTO density obtained from the 152 mm ITS specimens.

For some specific tasks, triaxial specimens with a nominal diameter of 100 mm and a height of 200 mm were also used. In this case, similar procedure of the one discussed above was used as a compaction method.

3.4.3 Curing and Water Conditioning

Different curing procedures were used at the different stages of the research work according what was discussed in section 1.3. Table 3-4 shows details of the curing procedures used at these stages. In all cases, specimens were taken out immediately from the molds after compaction and were tested immediately after the curing/conditioning procedure. If for some reason tests were not conducted once required, cured specimens were sealed with plastic until testing.

Table 3-4: Curing procedures used

Curing Procedure Definition	**Water Conditioning**	**Description**
Open to Air	**---**	Specimens were left during different periods of time at ambient temperature open to air. No water conditioning was conducted to these specimens.
Fresh	**---**	Specimens were left 24 hrs at ambient temperature. No water conditioning was conducted to these specimens.
Cured	**Dry**	Specimens were dried in a force draft oven at 40 °C during 72 hrs. No water conditioning was conducted to these specimens
	Soak	Specimens were dried in a force draft oven at 40 °C during 72 hrs. Then, were soaked in a water bath at 25 °C during 24 hrs.

4. ANALISYS OF THE STRENGTHENING (CURING) PROCESS OF MIXES WITH FOAMED BITUMEN AND CEMENT

4.1 Introduction

It is well accepted that FB mixes are very sensitive to moisture variations. This parameter is part of the criteria used in the current mix design guidelines (Asphalt Academy, 2002) for selecting the optimum bitumen content. Studies performed at laboratory and field level, by University of California Pavement Research Center – UCPRC - (Jones et al, 2008), indicated that stiffness of in-service mixes can change as much as 40% between dry and wet seasons.

This property is undesirable, as humidity variations in the field are very common and therefore the stiffness/strength and lifetime of all the structural materials are affected. This effect is very important for quantifying mechanical properties of FB mixes, either in the mix design stage or in-service; Laboratory procedures must be correctly designed for evaluating the mix according to field conditions. If the laboratory procedures does not address correctly the moisture conditions of the mix in-service, then estimations of the mechanical properties as well as life cycle for the FB mix and entire pavement could be significantly inaccurate.

Moisture susceptibility also has a significant impact on the curing process of FB mixes, where curing is the process in which FB material develops strength with time. Some researchers have stated that FB mixes do not develop full strength until most of the mixing moisture has evaporated (Bowering, 1970; Jenkins, 2000). FB materials of projects built in moist ambient should have problems for losing their moisture, having slower curing process and thus more problems to get strength and stiffness. The laboratory procedures must be correctly designed for assessing and evaluating the mix properties according to field conditions. Additionally, field construction procedures must be correctly addressed to improve the curing process.

The use of active fillers could make the mix design analysis more complicated as bitumen and active fillers have different interactions with moisture. While active fillers need water for the hydration process, bitumen is hydrophobic and repeals the water. This will affect interaction between bitumen and granular particles.

Moisture susceptibility has been extensively studied (Asphalt Academy, 1992; Bowering, 1976; Fu et al, 2008). The discussion in this chapter focuses on establishing how it can be developed, what are the variables that influence the process as well as how it can loss moisture and increase strength.

Studies carried out in this chapter discuss extensively the strengthening/curing mechanism with the objective to recommend the most appropriate laboratory procedures for evaluating the impact of active fillers and others variables on mechanical properties of FB mixes.

4.2 Background Regarding the Curing Process of Foamed Bitumen Mixes

4.2.1 Discussion of Variables Affecting Curing Process

As it was defined, curing is the process in which foamed bitumen materials acquire strength with time. The strengthening mechanism of FB mixes is associated with the moisture loss process, i.e. strength increases as the moisture content of the material decreases. Therefore, moisture content (and strengthening) of the mix will be significantly affected by environmental conditions prevailing at the place where the project is located. Air temperature and relative humidity as well as the moisture content and permeability of the other materials of the pavement and subgrade will affect this process. Also, it is necessary to consider that the length of the construction projects is usually extensive and therefore environmental conditions vary during the period, thus affecting the moisture loss process.

Hence, given the wide variety of environmental conditions in which these projects can be located, to simulate the field curing conditions in a laboratory may become very difficult. Attempting to simulate all possible conditions is counterproductive, reason why it is very important to design a laboratory procedure to assess the impact of each variable on the properties of the FB mix.

Most of the accelerated curing procedures adopted have focuses on defining the temperature and moisture parameters during a specific period of time. Curing procedures of specimens in an oven at 60ºC during 72 hours have been used extensively (Bowering, 1970; Lancaster et al., 1994; Muthen, 1999, Hodgkinson and Visser, 2004; between others). Other researchers proposed to use longer curing periods: 7 to 28 days (Nataatamadja, 2001; Long and Ventura, 2004). Ruckel et al (1983) recommended using a standard procedure based on 3 levels of curing, representing the short, medium and long term. Ruckel et al. suggested a curing of specimens in the compaction molds at ambient temperature for one day to simulate one day of field curing (short-term); a curing of 40ºC during 24 hours to simulate field conditions in the first 7 to 14 days after construction (medium term); and a curing of 40°C during 72 hours to simulate field conditions in the long term. Curing procedure using 40ºC during 72 hrs was adopted by the South African guidelines (Asphalt Academy, 2002; Asphalt Academy, 2009).

On the other hand, cement or the other active fillers such as lime used in FB mixes needs water for the hydration process. Due to it is necessary to add water during mixing process of FB mixes to get density, the free moisture in the mix is enough for guarantee the hydration process of the active filler. Thus, prevailing moisture conditions in the projects will not affect the cement curing process.

Although there are many options available to represent laboratory curing for FB mixes, the most important one is to design a laboratory procedure capable to identify the impact or the influence of any specific variable on the properties of the mix. For example, the use of longer period of curing, for example 40 °C during 7 days or more, will not represent the FB mix properties of a project located in an environment with very high relative humidity and/or low temperatures. In this case, laboratory specimens will get strength quickly, overestimating the mechanical properties of the real project.

One of the specific objectives of this study is to understand the strengthening process or stiffness evolution of the FB mixes, in order to select the most appropriate laboratory procedure to evaluate and determine the contribution of the cement as active filler in the curing process of these types of mixes.

4.2.2 Background of the In-Situ Stiffness Evolution in Existing Projects

Limited information was found regarding the evolution of the strength and/or stiffness on time for FB projects. Between 2004 and 2006, a field experiment on a heavily trafficked Greek highway was undertaken by the NTUA (National Technical University of Athens) Laboratory of Highway Engineering with the aim to explore in situ foamed bitumen recycled layer material properties (Loizos, 2007). The objective of this study was to characterize the properties of the mixes during the early life of the recycled pavement. A comprehensive research study was performed involving a two-year monitoring of the pavement stiffness using Falling Weight Deflectometer (FWD) analysis as well as others non-destructive and laboratory tests.

Pavement structure was: 9 cm of asphalt concrete base and wearing course; 25 cm of foamed bitumen recycled layer; around 15-20 cm of CBM layer (Cement-Bound Material); 15 cm of granular subbase; all over a limestone subgrade. Foamed Bitumen mix was prepared using 3.2% of bitumen (800/100 pen grade) and 1.0% of Portland cement as active filler. Results of the FWD backcalculated stiffness of the FB recycled layer on four stations (S1 to S4) are shown in Figure 4-1, using 50 KN of load. The graph shows the minimum, average and maximum modulus of the FB mix (named Foamix in that study), in the Inner Wheel Path (IWP). Although there is a large variability in results, there is a clear trend regarding the stiffness evolution during the analysis period. This trend indicated that stiffness increase substantially during first 12 months and then almost keeps constant during the rest of the period, with a slightly increase on time.

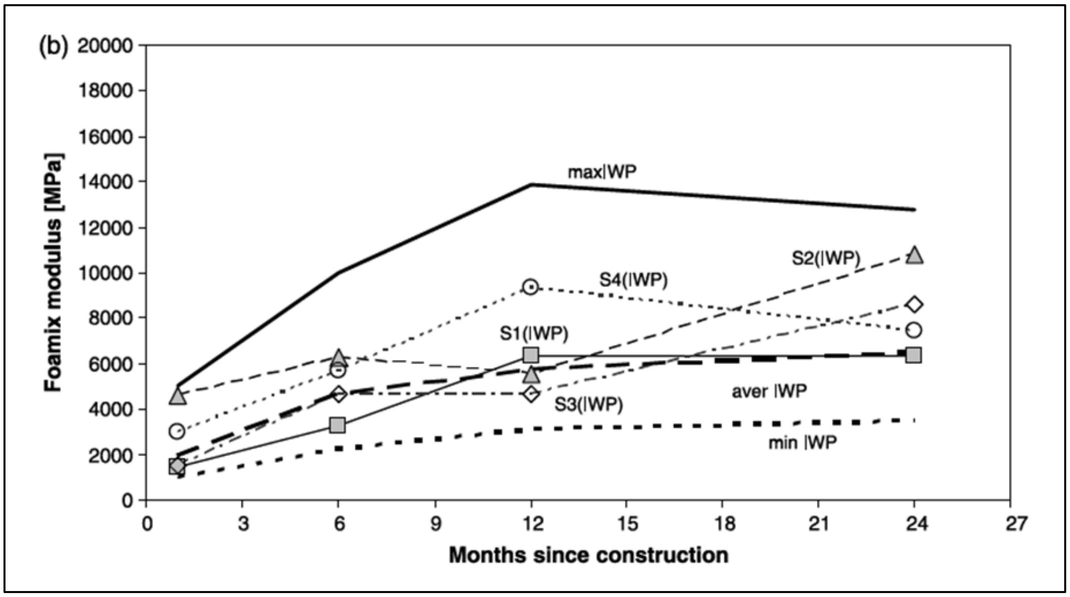


Figure 4-1: Stiffness evolution monitored in Greek FB recycling project (Loizos, 2007)

The author of this study did not report the moisture content of the mix during FWD tests, nevertheless based on the average of the backcalculated stiffness values it is possible to validate what was proposed by Bowering (1970), who stated that FB mixes do not develop full strength until most of the mixing moisture has evaporated.

4.3 Study of the Stiffness Evolution of FB Mixes During Early Stage

4.3.1 In-Situ Monitoring of the FB Stiffness

In this research project, an in-situ monitoring of the FB mix stiffness evolution was carried out using the FWD on the “La Madera” Project located in Chile. The project was built between October 2005 and May 2006, i.e. starting during the first weeks of spring and finishing in the middle of Fall.

The existing pavement was made of 10 cm of a traditional asphalt concrete layer, 40 cm of granular bases, all over a sand type soil subgrade. Twenty cm of the pavement structure were recycled using a FDR process and the new pavement structure is compound by a FB layer in a thickness of 15 cm in average with 5 cm of asphalt concrete as a surface layer. The FB layer was constructed using 2.8% of bitumen and 1.0% of cement.

“La Madera” recycled project is located between 12 to 45 km in-land from the coast near Concepción city (South Latitude 36º 46'). The layout of the project runs along Bio-Bio river for almost its entire length. The climate in Concepcion is considered oceanic and the cool waters of the Pacific Ocean help to maintain mild temperatures throughout the year. Mean temperature is 17 °C during summer and 8 °C during winter. The annual precipitation is 1,100 mm (43.3 in), which concentrates during the months of May to October (winter).

Results of the backcalculated FB layer and subgrade stiffness, for 50 KN loads, are shown in Figure 4-2. FWD data were collected between 24 and 25 November 2006 across the entire 33 km long project, 6 months after completion of the construction project. FWD values depicted in the Figure 4-2 are the ones obtained in the outer wheel path and were normalized at 25 °C. Backcalculated values were obtained using CalBack, new backcalculation software developed by UCPRC and Dynatest Group for Caltrans (Lu et al, 2009). This tool was selected since it allows selecting the most appropriate analysis algorithm from multiple available options. Because FB mixes have different stress-dependent behavior according to the mix constituents, specifically bitumen and cement content, the model used for backcalculation analysis could affect significantly the results obtained. Statistical parameters of the whole process for the FB mix where:

RMS (Rooth Mean Square) of 2.8% with a standard deviation of 1.8%, which is considered as a very good fit.

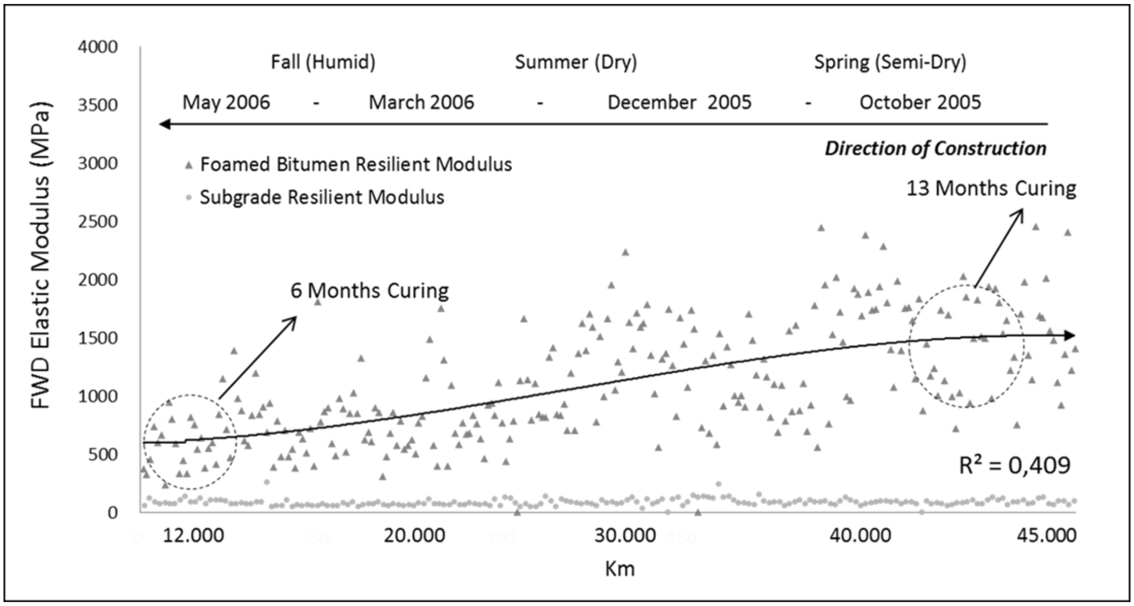


Figure 4-2: FWD back calculation values of "La Madera" recycled project

Results from FWD backcalculation analysis revealed a clear trend between stiffness and curing period. Sections located in km 12 – 15, with an average curing period of 6 months, showed an elastic modulus as low as 35% of the ones with a curing period of 13 months located near km 45. It is necessary to consider that a large part of the project was done within a warm period between October and March, therefore mixes were able to lose its moisture and to cure. In contrast, mixes built during April and May probably were not able to cure, keeping its moisture constant during all the cold period. This situation is reflected in the values obtained, where the elastic modulus in the last sections (near km 12) is as low as those normally obtained for granular bases.

The situation described for “La Madera” project is consistent with results presented by Loizos (2007) in Greece, where the monitoring carried out to the FB layer, resulted in an increased of the elastic modulus during the first twelve months of operations.

Based on this type of analysis, it is possible to state that there will be significant differences in the estimated mechanical properties of the foamed bitumen mixes if inappropriate laboratory procedures are used. As it was discussed in Section 2.7, the mix design procedure evaluates FB mixes in accelerated cured conditions, i.e. representing the properties of the mix once it loses its moisture and develops strength. The curing procedure usually exposes the mix to 40 °C temperature during 72 hrs, which guaranties that the mix will lose most of its moisture. The information provided in this stage of the research, indicates that FB mix conditions simulated in laboratory do not represent what actually happens on the field during the early stage, i.e first weeks after construction. This necessarily may impact the performance of all the pavement structure, especially considering that this type of projects use to be opened to traffic after a couple of hours since construction.

Otherwise, one of the questions arising during this study was related to the impact of the active filler in the strengthening process, specifically cement which is the most used. As was discussed in Section 2.7 and Section 4.1, active fillers used in foamed bitumen mixes interact in a very different way with moisture in comparison with bitumen which is hydrophobic. While foamed bitumen needs to lose its moisture to get strength, cement needs water to react and produce cementitious bonds between particles of the aggregates. Therefore, the use of cement would improve the curing process in two different ways: a) reacting with water and producing additional bonds between particles, and b) using part of the mixing moisture incorporated in the mix during construction process thus helping the strengthening of the mix by reducing the relation water/bitumen.

Cementitious reaction of the cement starts immediately after mixing process and get an important percentage of the 28 days strength during the first 24 hours. Thereby, if foamed bitumen needs to lose the moisture to get strength, then probably the major part of the strength during early stage of the FB mix comes only from the cohesion provided by the cement as well as by the contact between aggregate particles.

Based on the above, it is possible to state that it is necessary to include in the curing procedures one additional step to evaluate the early strength of the mix - for example using a 24 hr curing period at ambient temperatures – to evaluate the role of the cement content not only for the early strength of the FB mix but also the role in the curing process.

4.3.2 Laboratory Experiment for Evaluating the Stiffness Evolution During Early Stage and the Impact of Cement on Strengthening Process

A laboratory experiment was carried out with the aim of evaluating and interpreting the strengthening process of the foamed bitumen mixes and its relationship to the presence of moisture. Additionally, the laboratory test program was designed to study the impact of cement during this process.

This study was carried out for different curing conditions, in order to assess the stiffness evolution in normal and extreme moisture conditions. For normal curing conditions, samples were taken out from the mold immediately after preparation and left “open to air” in various conditions: In an open room in laboratory and in the open field outside the laboratory. While some samples were left with the perimeter sealed with plastic others were left without any seal. Normal temperatures during the period of analysis range from 10 °C to 25 °C and relative humidity between 40 - 80%. This setup was selected in order to simulate normal environmental conditions that might be found in the field. For extreme (or worst) curing conditions, samples were taken out from the mold immediately after preparation and left in a conditioned room with 100% relative humidity.

Resilient Modulus Triaxial tests (TxRM) were conducted in 150 mm diameter and 300 mm height samples for 1, 15, 28, 45 and 67 days after samples preparation. Mixes were prepared and cured using “open to air” procedure, i.e. specimens were left at ambient temperature (refer to Table 3-4). Results for 180 days samples were obtained from cured specimens at 40 °C during 72 hrs and soaked at 25 °C during 24 hrs. Every single step was monitored and the moisture content of specimens registered.

One RAG material was used at this stage, according to the information provided in section 3.2.1. The experiment design for this study is summarized in Table 4-1.

Table 4-1: Experiment design for the stiffness evolution during early stage (strengthening process)

Variable	**# of levels**	**Values**
RAG source	1	UCPRC RAG. (Refer to Section 3.2.1)
Bitumen grade	1	Shell PG 64-16.
Foaming properties	1	150°C, 3% foaming water
Foamed bitumen content	1	3%
Active filler type	1	Portland cement
Active filler content	3	0% - 1% - 2%
Test methods	1	Resilient Modulus Cyclic Triaxial Test (TxRM)
Compaction Effort	1	56 blows per layer – 12 layers Triaxial
Curing Process and Period	5	Open to Air. 1, 14, 30, 45, 65 days.
TxRM replicates	2	2 specimens (in average) per mix plus 2 for 100% RH

Figure 4-3 shows results of TxRM tests. Each value plotted represents the TxRM of the mix for 0.1 seconds of loading pulse duration, 67 kPa of confining pressure and the average of four deviation stresses (67, 135, 167, 200 kPa). All the TxRM test results used in this stage are presented in Annex 1.

In order to statistically support the results obtained in these experiments, a Two-Sample T test and an ANOVA were carried out. Table 4-2 shows results of these tests.

In addition, Table 4-3 shows values of moisture content for every sample during the first 45 days of testing as well as moisture loss and the rate of moisture loss in percentage per day for every type of mix.

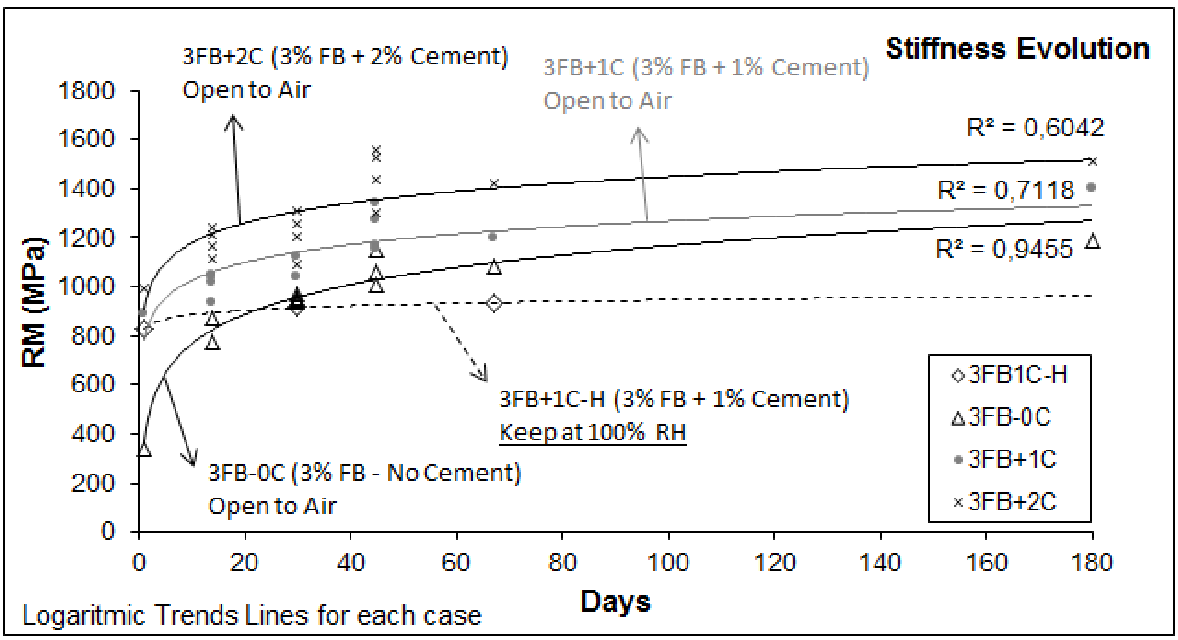


Figure 4-3: Stiffness evolution for FB mixes using normal and extreme curing conditions

Based on the TxRM results of Figure 4-3, the following observations are made:

- Results confirm trends observed in La Madera Projects. TxRM of the FB mix with 3% bitumen and 1% cement (3FB+1C) - similar doses of the ones used in La Madera project - increases steadily. This increase is directly related to the loss of moisture showed by the specimen, evaluated at the time the test was conducted (see Table 4-3). In this specific case, TxRM values of the mix after one day and after two weeks were 63% and 71% of the six month TxRM value. Average moisture content of mixes with one day and two weeks were 5,7% and 3,8% respectively.
- Stiffness of mixes with 3% of foamed bitumen and 1% cement, kept at 100% relative humidity (3FB+1C-H), remained relatively constant during the period of evaluation. This data support what was stated by Bowering (1970); FB mix does not develop strength until moisture content decreases. This tells that in a project without the minimum conditions of drainage, the mix will not be able to develop the required strength, affecting the structural capacity of the whole pavement.
- Results from mixes with and without cement, all of them with 3% of foamed bitumen, show a significant difference in the stiffness in the first weeks. This trend was maintained during the period of analysis. Based on all the results, differences may be explained only by the presence of cement.
- In addition, the same strengthening rate could be observed during the period of analysis for mixes with one and two percentage of cement (3FB+1C and 3FB+2C). It is a fact that most of the cement reacts during the first hours after mix preparation; this could mean that the stiffness evolution after the first weeks is only originated from the interaction between foamed bitumen and granular material (see statistical analysis in Table 4-2). This statement is also supported by comparing mixes with same bitumen and cement content, but kept

at different curing conditions (3FB+1C-H and 3FB+1C). Both have relative similar stiffness after 24 hrs, but evolution during time was different.

Table 4-2: Results of statistical analysis for stiffness evolution experiments

ANOVA. Variable: Tx Resilient Modulus

Parameters	Levels	p
C1: Curing Time (days)	14, 30, 45	0
C2: Cement Content (%)	0, 1, 2	0
C1 x C2	---	0,593

TEST T (2 Samples)

Differences	FB3C0 – FB3C1	FB3C1 - FB3C2	FB3C0 - FB3C2
IC (95%)	-259,1 y -33,8	47,7 y 297,3	195,1 y 443,1
p	0,014	0,009	0

Results from Test T showed in Table 4-2 indicated that means of the values for the stiffness evolution of each mix are different. Results obtained from ANOVA test indicate that variables “Curing Time” and “Cement Content” have a significant impact of the Resilient Modulus of the FB Bitumen mix. In addition, indicates that there is not interaction between the variables “Curing Time” and “Cement Content”. Thus, the increasing rate of the stiffness during time will be explained mainly by the impact of the variable “Bitumen Content”.

Table 4-3: Moisture evolution of TxRM specimens of curing study

Moisture Content (%)				
Days	**1**	**14**	**30**	**45**
Specimens	---			
3FB-**0C** (a)	5.3%	2.1%	1.8%	
3FB-**0C** (b)	5.6%	4.9%	1.8%	1.6%
3FB-**0C** (c)	5.6%	1.8%	1.5%	1.6%
3FB-**0C** (d)	5.6%	4.6%	1.8%	1.8%
Average (%)	5.5%	3.4%	1.7%	1.7%
Moisture Loss (%)	---	2.2%	3.8%	3.9%
3FB+**1C** (a)	5.3%	2.6%	2.0%	1.7%
3FB+**1C** (b)	5.7%	4.5%	4.0%	3.6%
3FB+**1C** (c)	6.2%	3.4%	2.5%	2.6%
3FB+**1C** (d)	5.7%	4.6%	3.4%	3.3%
Average (%)	5.7%	3.8%	3.0%	2.8%
Moisture Loss (%)	---	2.0%	2.8%	2.9%
3FB+**2C** (a)	6.5%	3.9%	3.4%	2.9%
3FB+**2C** (b)	5.8%	5.1%	4.5%	4.2%
3FB+**2C** (c)	6.1%	3.8%	3.1%	2.7%
3FB+**2C** (d)	6.1%	5.4%	4.4%	4.2%
Average (%)	6.1%	4.6%	3.9%	3.5%
Moisture Loss (%)	---	1.6%	2.3%	2.6%

Data provided in Table 4-3 shows the moisture content evolution of each specimen during the period of analysis. Moisture content of mixes evaluated decreases during the period of analysis, as expected. By linking the average moisture data of FB mixes with stiffness, it can be clearly seen that both variables are strongly correlated. Results of the co-relation between RM and moisture content are showed in Figure 4-4. Results support the fact that that once cement reacts, then increased stiffness is due primarily to an increase in strength between the particles of aggregate and bitumen droplets.

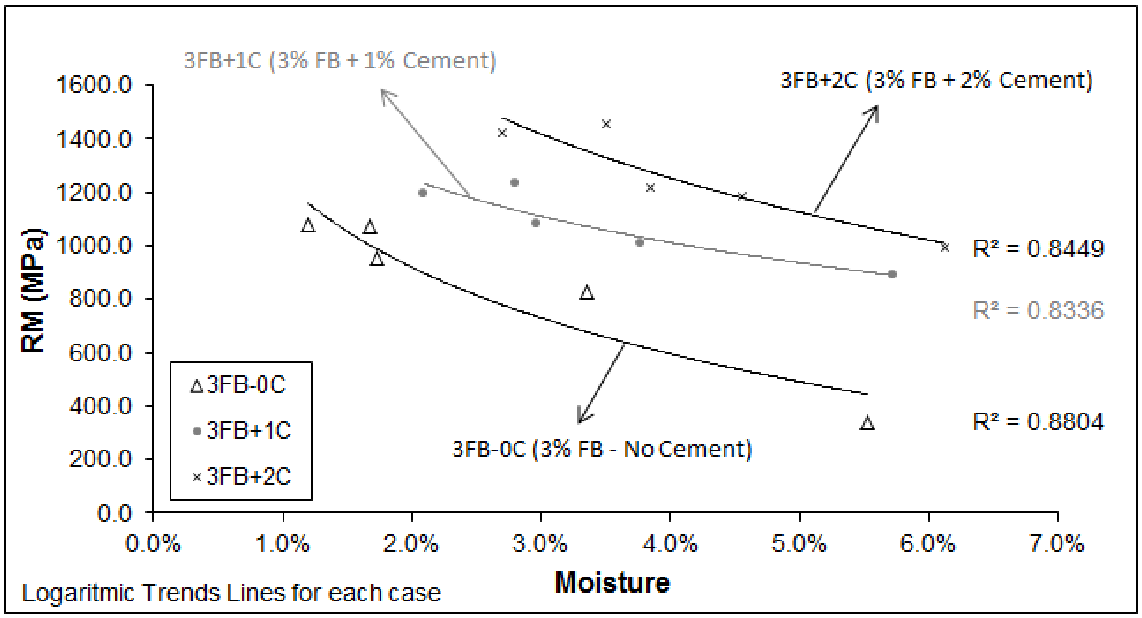


Figure 4-4: Stiffness evolution and its moisture dependency

Based in the information provided, it is possible to assess the evolution of the FB mix stiffness using the moisture and cement contents as variables. This relation may be represented by the following equation:

$$TxRM(MPa) = 1239 - 301 \times CemCont - 139 \times MoistCo \qquad R^2 = 92.0\% \qquad (eq.\ 4.1)$$

where:

CemCont: Cement Content in absolute values, i.e. 1% = 1.0

MoistCont: Moisture Content in absolute values, i.e. 4.3% = 4.3

Based on the results shown in Figures 4-3 and 4-4, when comparing results of stiffness between mixes with and without cement, significant differences were observed. These differences are larger as the moisture of the mix increases and as the cement content increases. As it was discussed in Section 2.7, although it has been demonstrated that cement is very important to improve the properties of the FB mixes, still this variable is not part of the mix design procedure. It is recommended that this specific topic should be reviewed.

4.4 Foamed Bitumen Mix Composition and Curing Process Description

Analysis presented in this section are mainly qualitative and based on experience of the author as well as the experience laboratory testing performed during this stage of the research program.

Foamed Bitumen mix is a composite material formed by three phases. a) the “aggregate skeleton” formed by large aggregate particles; b) the “mastic” or bonded fines particles with bitumen and/or active filler; and c) the “un-bonded fines particles” that partially filling the voids in the skeleton. The structure described for FB mixes is shown in Figure 4-5 (Adapted of Fu et al, 2010). The handling of the curing process requires understanding the strength and stiffness development mechanism of each phase, as well as the composite element.

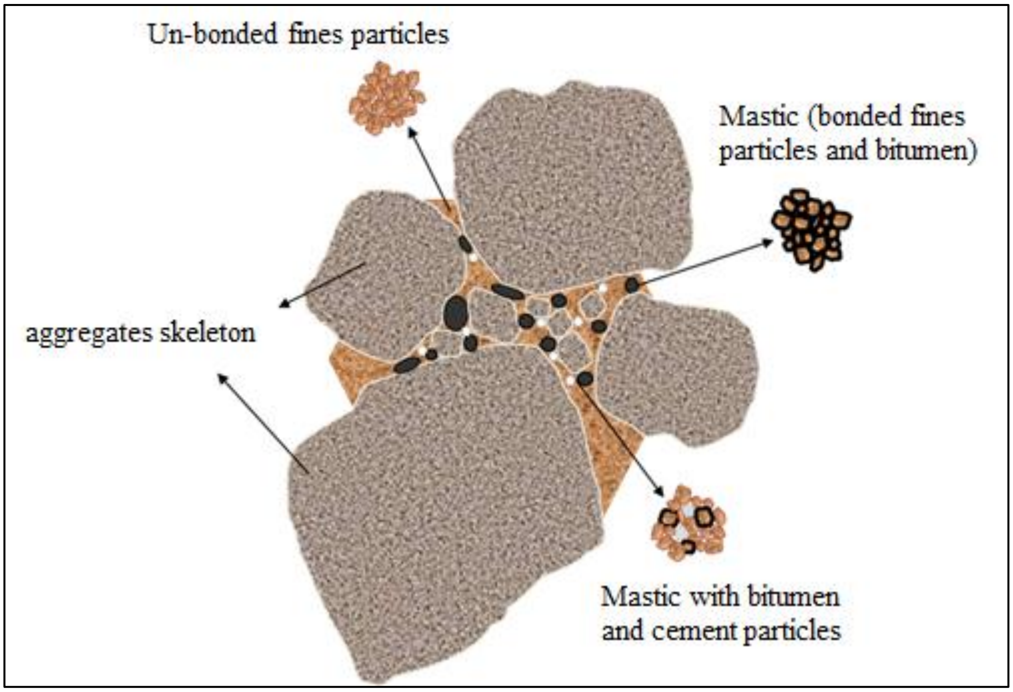


Figure 4-5: Conceptual scheme of foamed bitumen mix structure (Adapted from Fu et al, 2010)

As described in Section 2.2.2, during mixing process, the bitumen bubbles burst producing tiny bitumen particles that disperse throughout the aggregate. These particles adhere to finer particles of the aggregates (fines sand and smaller) forming a fairly stiff and stable mastic (Bowering and Martin, 1976).

During compaction, the bitumen particles in the mastic are physically pressed against the larger aggregates of the granular material resulting in localized non-continuous bonds named “spot welding”. Fine aggregate particles can only be partially coated by bitumen during foaming process to form the mastic, while a considerable portion of the voids in the aggregate skeleton are filled by fine mineral particles (Jenkins, 2000).

The active filler is incorporated in the same process and at the same time when the FB is injected and it is distributed uniformly throughout the mix. When it gets in contact with water, it reacts forming individuals bonds with the fine particles and coarse aggregates.

It is a fact that FB mixes do not develop full strength until most of the mixing moisture has evaporated, the curing process (or strength/stiffness development) will be affected by the specific relations between moisture and the materials of each phase.

The aggregate skeleton is formed by large aggregate particles, which can resist the applied stresses by contacts between particles. Strength of the mix from this mechanism is available immediately after compaction and is not affected by moisture content.

The "un-bonded fines particles" phase consists of fine aggregate particles not bonded by bitumen or active filler during mixing, and that fills the voids in the aggregate skeleton. It has low strength immediately after compaction when it is still wet, but can develop strength when dry (Fu, 2009). Once dry, the available moisture will be quickly absorbed by this phase, losing its adhesion.

The "mastic" is formed by fines particles, bitumen droplets and active filler particles. The active fillers of the mastic phase will capture and consume the water required for hydration process, transforming it into no-susceptible moisture particles. Then, assuming that most part of the fines particles, which are susceptible to moisture, are embedded by the bitumen, this phase should not be substantially affected by moisture presence.

Now analyzing the material as a whole, and due to the hydrophobic nature of bitumen, "aggregate skeleton" and "un-bonded fines particles" phases could have contact problems with the mastic phase in the case of moisture presence. After mixing, aggregates are enclosed by a membrane of water, which will prevent the bitumen droplets and aggregate sticking together. Based in the fact that FB mixes needs to lose moisture to obtain strength, the physical bond between the mastic phase and the aggregates will not develop until the water membrane covering the aggregates disappears.

Figure 4-6 shows the curing process associated with foamed bitumen based on the mechanism proposed by Fu et al (2010). In this process when FB is injected onto moist aggregate (RAG), it partially bonds the fines particles to form the mastic, visible in the loose mix as small droplets (Figure 4-2[a]). Aggregate particles in the loose mix are mostly coated with a water membrane. After compaction, the asphalt mastic droplets are pressed against the aggregate particles (Figure 4-2[b]), but due to the presence of the water membrane, they do not physically bond to the aggregates until most of the molding moisture has evaporated (Figure 4-2[c] and Figure 4-2[d]). During the curing process the water membrane evaporates, allowing the bitumen mastic droplets and aggregate particles stick together. However, once the physical bonds between them have formed, only partial damage to these bonds will occur if water is re-introduced into the mix (Figure 4[e]).

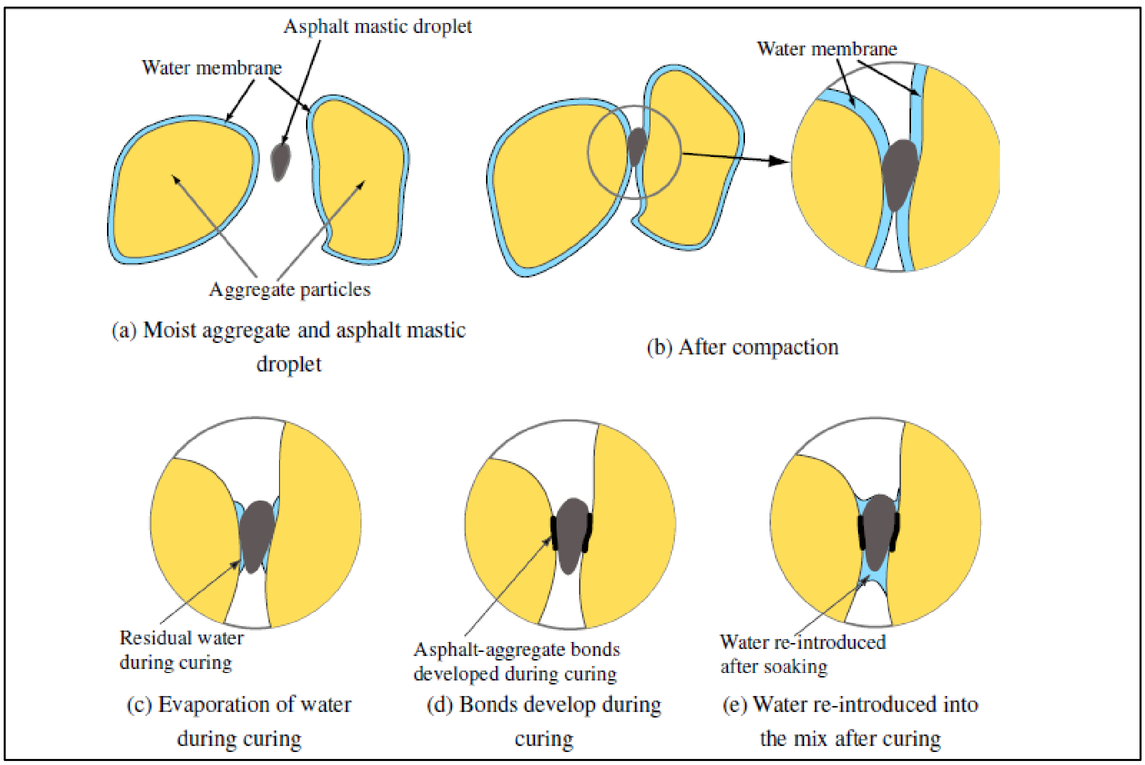


Figure 4-6: Conceptual illustration of the curing process for FB mixes (Fu et al, 2010)

Fu et al (2010) conducted long term curing experiments to support this proposal. Figure 4-7 illustrates results of Triaxial Resilient Modulus (Tx RM) tests performed on samples with different moisture conditioning. Mixes were produced using 4.5% of bitumen without cement or other active filler. Test results are plotted against the confining stress and for a loading duration of 0.1 sec. After compaction, the triaxial specimens were left in the molds with the bottom tightly sealed and placed on shelves in a room with no climate control for a period of six months. Local weather conditions were mild with little diurnal temperature variation and moderate to high humidity. Ambient temperatures varied between 10 and 25°C during the curing period. Limited evaporation occurred after the six month period had elapsed. Each specimen was subjected to multiple Tx RM tests with different moisture pre-conditioning. Table 4-4 shows the preconditions that the specimen was consecutively subjected before each test and the moisture content at which each test was performed.

Table 4-4: Preconditioning before each TxRM Test (Fu et al, 2010)

Sequence index	**Conditions experienced before testing**	**Moisture Content**
Test 0	Immediately after compaction (no test performed)	5.2%
Test 1	6 month cured in mold at ambient temperature and moisture	1.9%
Test 2	soaked in water for 72 hrs	4.6%
Test 3	Dried in a forced draft oven at 40 °C for 120 hrs	0.7%
Test 4	soaked in water for 7 days	3.6%

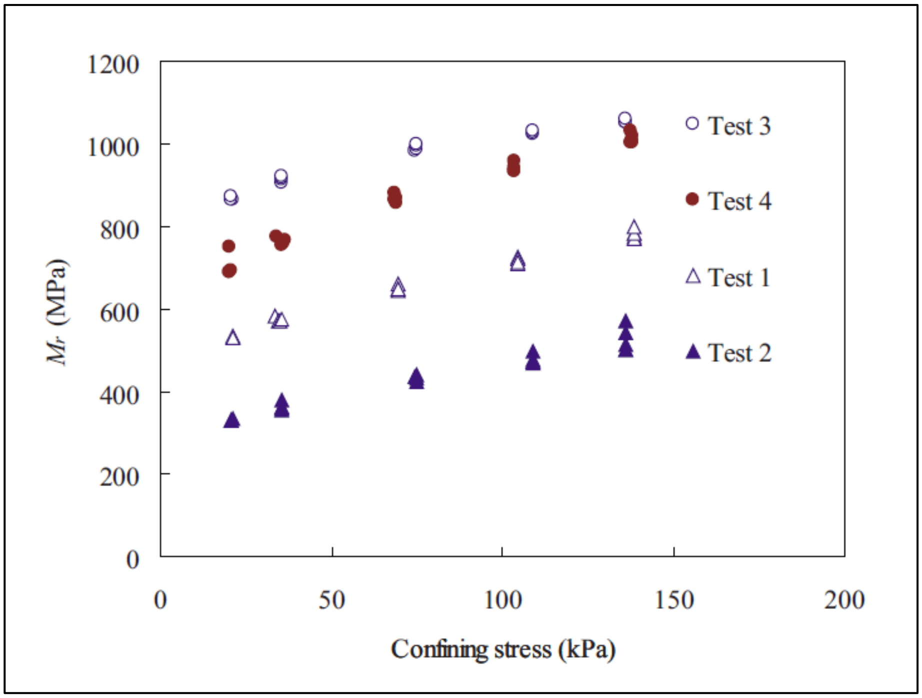


Figure 4-7: TxRM test results for the long term curing experiments. Fu et al (2010)

When the specimen was extruded from the mold, 1.9% molding water remained and stiffness was 650 MPa approximately for 60 kPa of confining stress, corresponding to the state shown in Figure 4-6b. When specimen was soaked (test 2), resilient modulus measured in this state was only slightly higher than would be measured in the uncured state. When the specimen was subjected to further oven drying (Test 3), significant stiffness improvement was observed, corresponding to the state shown in Figure 4-6d. When the specimen was re-soaked, only minimal stiffness reduction occurred (10 – 20% depending on the stress state). When comparing the results of Tests 2 and 4, it was evident that bonds between the mastic and aggregate particles developed during the drying process and not during the six months of initial curing when limited evaporation occurred.

Mix used for this experiment did not use cement as active filler, which will modify the differences obtained between each of the tests carried out. Similar experiments were conducted during this research work using mixes with 3% of bitumen and 1% of cement. Results of the TxRM tests are shown in Figure 4-8.

Similar trends were obtained but with smaller differences between the results of each test, as expected. While mixes with bitumen only showed differences of almost 200%, mixes with bitumen and cement showed differences of 50% between maximum and minimum values for specific conditions of the triaxial test.

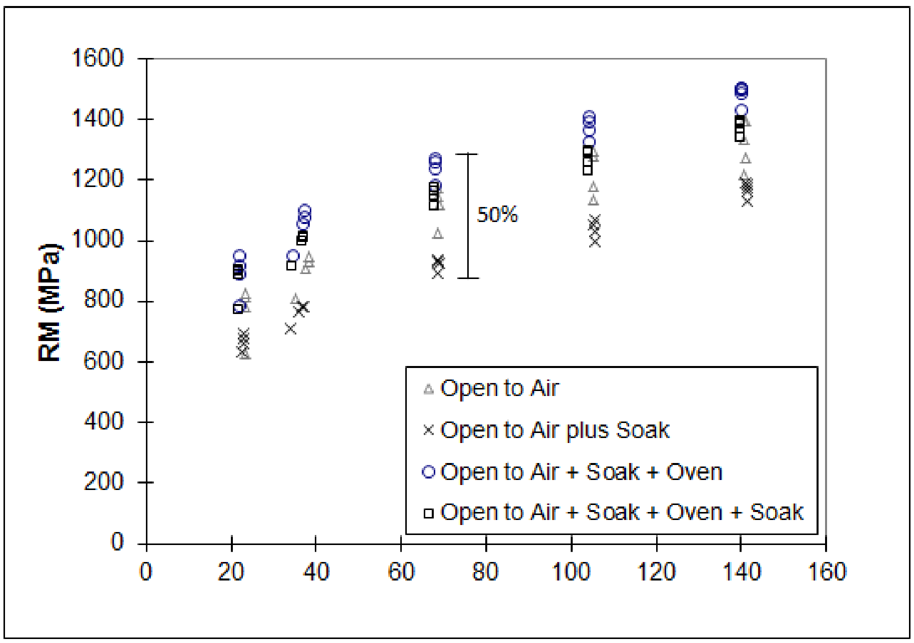


Figure 4-8 TxRM test results for curing experiment using bitumen and cement

4.5 Summary and Conclusions of Curing Process of Foamed Bitumen Mixes

Although it has been argued that foamed bitumen mixes need to lose their moisture for developing strength (Bowering, 1970; Jenkins, 2000), studies to validate this in the field are limited (Loizos, 2007). Also, studies carried out have not included any particular analysis with cement or any other active filler. This specific issue is considered to be very important since cement needs water for the hydration process, which would help with the curing process of the whole mix. Additionally, it is expected that moisture and temperature conditions in the project affect the curing process in terms of the moisture loss. If weather conditions or drainage conditions are not appropriate, the drying process is not carried out and mix will not get strength.

During the present research work, an in-situ monitoring of the FB mix stiffness was carried out in a 33 km long project built in different weather conditions, in order to collect data regarding the effect of relative humidity and temperature in the strength development of the FB mix. Sections were evaluated at different curing periods, i.e. while some sections were evaluated after 6 months of construction, others were evaluated after 13 months. While some of the sections were built in summer, others were built in spring and fall. Results showed a clear trend regarding the time of construction and the stiffness of the mix, supported what was observed by Loizos in Greece (2007). Additionally, results showed that mixes constructed during fall, after 6 months of operations, still have a very low stiffness values, equivalent to 1/3 part of the stiffness obtained on mixes constructed in spring. Based on this information it is possible to conclude that sections constructed in spring or summer all had the summer period for losing their moisture and gaining strength. In contrast, sections constructed during fall were not able to lose moisture and thus develop strength.

Based on information provided by experiments carried out in this stage of the study, a laboratory research work was conducted to investigate this evidence. Around forty five Triaxial Resilient Modulus (TxRM) laboratory tests were performed for estimating the stiffness evolution of these mixes. Specimens were evaluated during 180 days using normal and extreme curing conditions. Specimens subjected to normal curing showed similar trends to these observed in field. Specimens subjected to extreme curing conditions were left in a room with 100% relative humidity after mix preparation. These specimens did not lose moisture and did not develop strength, supporting what was stated by previous researchers (Bowering, 1970).

TxRM tests were conducted for mixes with 3% of bitumen without and with 1% and 2% of cement. FB mixes with cement showed a stiffness equivalent to twice these values obtained in FB without cement during first days, but the same trend in terms of increased stiffness during the evaluation period. This means that once the cement reacts, the increased strength is primarily regulated by increased cohesion between the particles of granular material and bitumen droplets, what occurs as the FB mix loses its moisture.

Some specimens with 3% bitumen and 1% cement were left in a room with 100% of relative humidity, they showed the same stiffness values for the first days of the specimens cured in normal conditions, but after a few days the stiffness remained constant during the rest of the period of analysis. This fact confirms that projects must always include an adequate drainage design to guarantee that FB layer loses its moisture and thus increases its stiffness. In addition, construction plans of FB recycling/stabilizing projects should restrict the construction if it is carried out in wet and/or cold periods. If some projects will be constructed without an adequate drainage system, some specific considerations must be considered when evaluating the FB mix stiffness for structural design purposes.

Regarding the importance of the cement in the curing process, results indicate that cement absorbs part of the available water in the mix, thus accelerating the strengthening process of the bitumen. Additionally, as it was discussed previously, cement is the main agent responsible for the resistance of the FB mix during the first days after construction, reaffirming the importance that has for the proper behavior of these mixes.

At this stage, every single step was monitored and the moisture content of specimens registered. While comparing stiffness of each mix with its moisture content, similar trends were observed between mixes with and without cement, but significant differences in terms of stiffness. Results showed that mixes with 2% of cement can double the stiffness of mixes without cement and same bitumen content. Based on these results, it is possible to state that it is very important to quantify the real contribution of the cement on the mechanical properties of FB mixes in the medium and long term. The contribution of cement content will be analyzed in detail in the next chapter in conjunction with other active fillers.

Based on findings at this stage of the study, it is possible to conclude that it is very important to review mix design procedures currently used. Current procedure evaluates mix strength in cured samples, whereas findings of this study showed that FB mixes will develop its strength based on several other factors related to the curing procedure used. As an overall recommendation, a 24 hr – unsealed samples - in open laboratory room, at normal temperature and humidity conditions, is recommended as laboratory curing procedures for representing the short-term mechanical properties of the FB mix. This procedure will help to evaluate the contribution of the cement or other active filler, especially for the first days after construction.

5. ROLE OF ACTIVE FILLERS ON MECHANICAL PROPERTIES OF FOAMED BITUMEN MIXES

5.1 Introduction

Although these mixes were originally prepared only with foamed bitumen, traditionally some type of active filler is added to the mix to improve certain mechanical properties of the final mix. Based mostly on the experience and studies made public, nowadays, it is well accepted that active fillers are used in conjunction with foamed bitumen to: a) modify the fine fraction of the aggregate gradation (Saleh, 2004); b) reduce moisture sensitivity of the mix (Asphalt Academy, 2002), and/or c) improve early strength of the mix (Khweir, 2007).

The first identification of this particular issue was presented by Lancaster et al (1994), who reported that if the granular material is lacking in fines, then an additive such as CWFD (Cement works flue dust) could be used, which should also provide some cementitious bonding within the mix.

In the literature, limited information can be found regarding specific studies for evaluating the benefits of the active fillers on the properties of FB mixes. Most of the conclusions regarding the contribution of active fillers have been made indirectly from studies that have analyzed the influence of the bitumen and in which different types of active fillers were used in the mixes. While some researchers have reported the study of foamed bitumen mixes without any active filler (Sunarjono, 2007; Fu, 2009), others have reported the use of Cement (Thenoux et al., 2003; Loizos et al., 2007; Twagira et al. 2006; Jenkins et al., 2007; Long and Theyse, 2004), Lime (Nataatmadja, 2001; Leek, 2001; Ramanujam and Jones, 2007), Fly-Ash (Saleh, 2007) and other active fillers (Lancaster et al., 1994; Hodkinson and Visser, 2004). In this context, conclusions regarding the influence of the active fillers have not been well supported.

Regarding specific studies focused on evaluating the influence of active fillers, most of them have been focused on evaluating the mechanical properties of cured FB mixes, i.e.

investigating mixes that have acquired strength and stiffness. At the laboratory level, Hodgkinson and Visser (2004) reported the effect of different cementitious active fillers on Indirect Tensile Strength of the mixes and Khweir (2007) reported the effect of various levels of cement on the stiffness of the mix. Twagira et al. (2006) reported fatigue performance of selected cold bituminous mixes with 1% cement. Long and Theyse (2004) presented a permanent deformation transfer function for foamed bitumen mixes including the ratio of cement to bitumen. It was not possible to find information regarding the influence of other active fillers besides cement or lime.

5.2 Experiment Design

This stage of the research program was conducted with the aim of defining the impact of active fillers in the mechanical properties of foamed bitumen mixes. Four active fillers were used at this stage of the study: portland cement, lime, cement kiln dust (CKD) and fly-ash Class C. Figure 5-1 shows each of the active fillers used.

Figure 5-1: Pictures of the active fillers used

The laboratory test program was designed for evaluating mechanical properties of the FB mixes in the short and medium. The short term represents the mix properties during the first days after construction while medium term represents the mix properties when have lost most of its moisture and have got most of its strength.

The mechanical properties in the short and medium term were simulated through the use of different curing conditions, which were defined based on information obtained from the previous research stage. Based on these results, is possible to state that the curing procedures actually used in laboratory do not necessarily represent what really happens to the mix in field conditions in the early stage nor does it permit the evaluation of the effect of the active fillers, which acquire strength relatively quickly in comparison with the curing process of the bitumen. Based on this, two curing methods were selected for the short and medium term.

a) Fresh Conditions (for the short term). This curing procedure was selected to represent the curing conditions of the mix during the first days after construction in order to evaluate the properties of the mix on those highway projects where it is necessary to allow trafficking immediately after construction. Once mixed and compacted, specimens were left at ambient temperature for 24 hours. Laboratory program was adjusted for testing the specimens after exactly 24 hours.

b) Normal Conditions (for the medium term). This curing procedure was selected in order to evaluate the mix properties during the mean period of service life, matching the general practice of other studies. In this case, specimens were dried in a forced draft oven at 40 °C for 72 hours.

It is well known that foamed bitumen mixes are susceptible to moisture conditioning. Therefore, specimens cured at normal conditions were then soaked in water for 24 hours at 25 °C before being tested. The ratio of the results of specimens tested in dry conditions and those tested in soak conditions was used to define the moisture susceptibility of the mix. During this study, detailed laboratory procedures were followed in order to guarantee the same water conditioning period for every type of mix and specimen tested.

Indirect Tensile Strength tests in 100 mm diameter specimens and Resilient Modulus Cyclic Triaxial Tests (TxRM) in 152 mm diameter specimens were used for evaluating mixes for the short and medium term. One RAG material was used in this stage, according to information provided in section 3.2.1. The experiment design for this stage is summarized in Table 5-1.

Table 5-1: Experiment design for evaluating mechanical properties of the FB mixes in the short and medium.

Variable	# of levels	Values
RAP source	1	UCPRC RAG. See Section 3.2.1
Bitumen grade	1	Shell PG 64-16.
Foaming properties	1	150°C, 3% foaming water
Foamed bitumen content	2	0% and 3%
Active filler type	4	Portland cement; Cement Kiln Dust (CKD): Lime (Hydrated); Fly Ash Type C.
Active filler content	4	0, 1, 2 and 3%
Curing Process	3	Fresh and Normal
Test methods	2	ITS (Indirect Tensile Strength) Resilient Modulus Triaxial Test (TxRM) Permanent Deformation Triaxial Test (TxPD)
Compaction effort	1	Defined in section 3.4.2
ITS replicates	9	3 for fresh; 2 for cured-dry; 4 for cured-soak
TxRM replicates	2	1 for cured-dry; 1 for cured-soak
TxPD replicates	1	Only for cured-soak

Additionally, dry-wet cycles using TxRM test in cured specimens were conducted in order to evaluate the durability of mixes with different cement contents. This procedure is used to evaluate the permanence over time of cementation capabilities provided by stabilizing agents (Khoury and Zaman, 2007). The experiment design for the durability testing is summarized in Table 5-2.

Table 5-2: Experiment design for dry-wet cycles evaluation (Durability)

Variable	**# of levels**	**Values**
RAP source	1	UCPRC RAG. See Section 3.2.1
Bitumen grade	1	Shell PG 64-16.
Foaming properties	1	150°C, 3% foaming water
Foamed bitumen content	2	0% and 3%
Active filler type	1	Portland cement
Active filler content	3	0%, 1% and 2%
Curing Process	1	Cured. Defined in Table 3-4
Test methods	1	Resilient Modulus Cyclic Triaxial Test (TxRM)
Compaction effort	1	Defined in section 3.4.2
TxRM replicates	1	
TxRM specimens	5	2x1x3x1 (0% cement – 0% bitumen not tested)
Dry-Wet Cycle	1	24 hrs at 40 °C in Oven and 48 hrs at 25 °C in water (soak conditions)
Wet-Dry Cycles Evaluations	4	0, 5, 14 and 20 cycles

5.3 Analysis of Results

Results obtained were analyzed according to service life period of the mixes, i.e. for the short and medium term. Short and medium terms were analyzed together with the aim of comparing the influence of the different active fillers used and their interaction with bitumen.

5.3.1 Indirect Tensile Strength (ITS) Test for the Short and Medium Term

Figure 5-2, shows ITS results for specimens in fresh conditions with and without foamed bitumen, representing the properties of the mix in the short term. Table 5-3, shows the summary for the ITS results for the short and medium term. In addition, Table 5-3 shows results of the Tensile Strength Retained (TSR) of each mix, which results are discussed further in this Section.

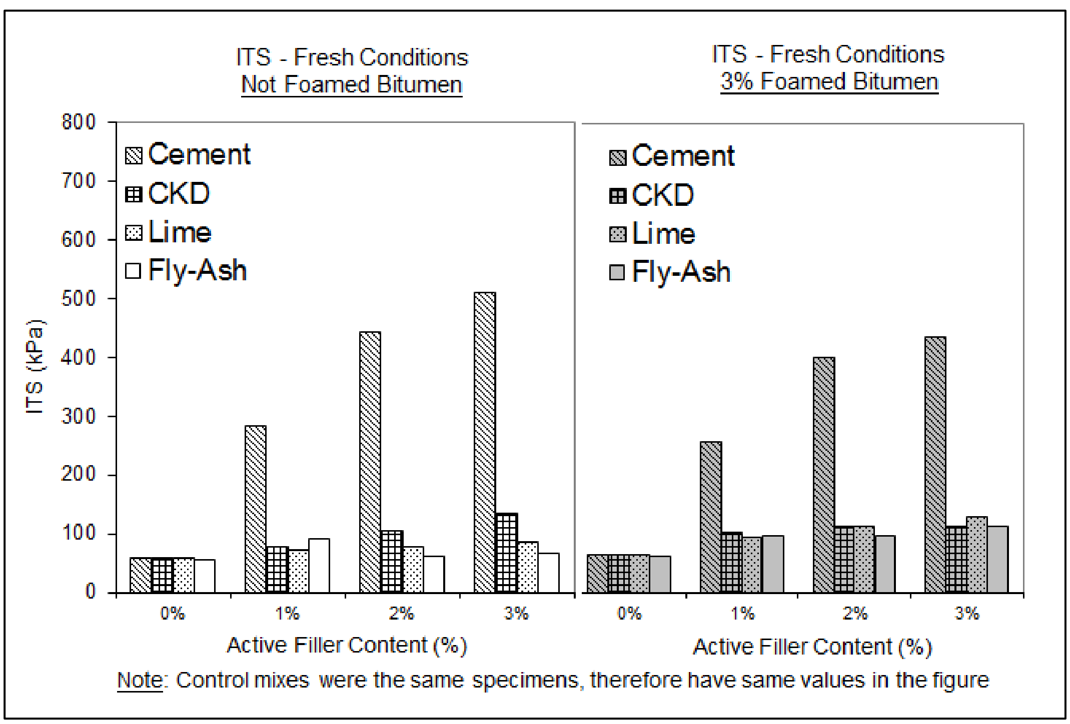


Figure 5-2: ITS values for fresh specimens with and without foamed bitumen

Table 5-3: Indirect tensile strength results (ITS)

Active Filler Type	Curing and Water Conditioning	Foamed Bitumen Content							
		0% (Control)				3%			
		Active Filler Content							
		0%	1%	2%	3%	0%	1%	2%	3%
		Indirect Tensile Strength (kPa)							
Cement	Fresh	57	279	438	506	62	256	398	433
	Cured-Soaked	34	379	594	725	211	418	721	748
	Cured-Unsoaked	319	384	705	853	535	602	838	819
	TSR	11%	99%	84%	85%	40%	70%	86%	91%
CKD	Fresh	57	76	103	133	62	101	113	111
	Cured-Soaked	34	138	400	412	211	286	526	611
	Cured-Unsoaked	319	226	556	860	535	401	766	947
	TSR	11%	61%	72%	48%	40%	71%	69%	65%
Lime	Fresh	57	71	76	84	62	92	111	128
	Cured-Soaked	34	106	186	182	211	272	413	393
	Cured-Unsoaked	319	175	199	301	535	413	519	596
	TSR	11%	60%	94%	61%	40%	66%	80%	66%
Fly Ash	Fresh	57	90	62	68	62	97	96	112
	Cured-Soaked	34	89	94	91	211	190	221	275
	Cured-Unsoaked	319	357	249	226	535	506	480	497
	TSR	11%	25%	38%	40%	40%	37%	46%	55%

Based on the results shown in Figure 5-2, which show ITS results for specimens tested in fresh conditions, the following observations were made:

- By comparing mixes without active fillers, the addition of 3.0% of FB to the control mix did not show benefits based on ITS for specimens tested in fresh conditions. While the untreated mix has 57 kPa of ITS, the mix with FB and without the active filler has 62 kPa of ITS. The tensile strength obtained under these conditions was mostly attributed to suction forces in the mineral filler phase.

- The addition of cement to FB mix significantly increased the ITS of the fresh specimens, with strength increasing with higher cement content, as expected.

The other three active fillers tested, showed very little ITS increase for fresh specimens compared to mixes without active fillers.

- By comparing ITS of the mixes with and without FB, it is interesting to note that mixes with cement and FB have smaller ITS than mixes with cement and without FB. Mixes with CKD, lime and fly-ash did not show any trend.

- Looking at specimens that were only cured in fresh conditions, it is possible to conclude that ITS obtained in mixes with FB and cement is only due to presence of the cement. These findings support the need to use cement to ensure minimum strength of an FB mix during its early stage. FB mixes that used active fillers other than cement did not show a significant increase in strength during the early stage.

On the other hand, to analyze the interaction between FB and each type of active filler for the medium term, cured-soaked ITS values for mixes with and without FB where plotted in Figure 5-3.

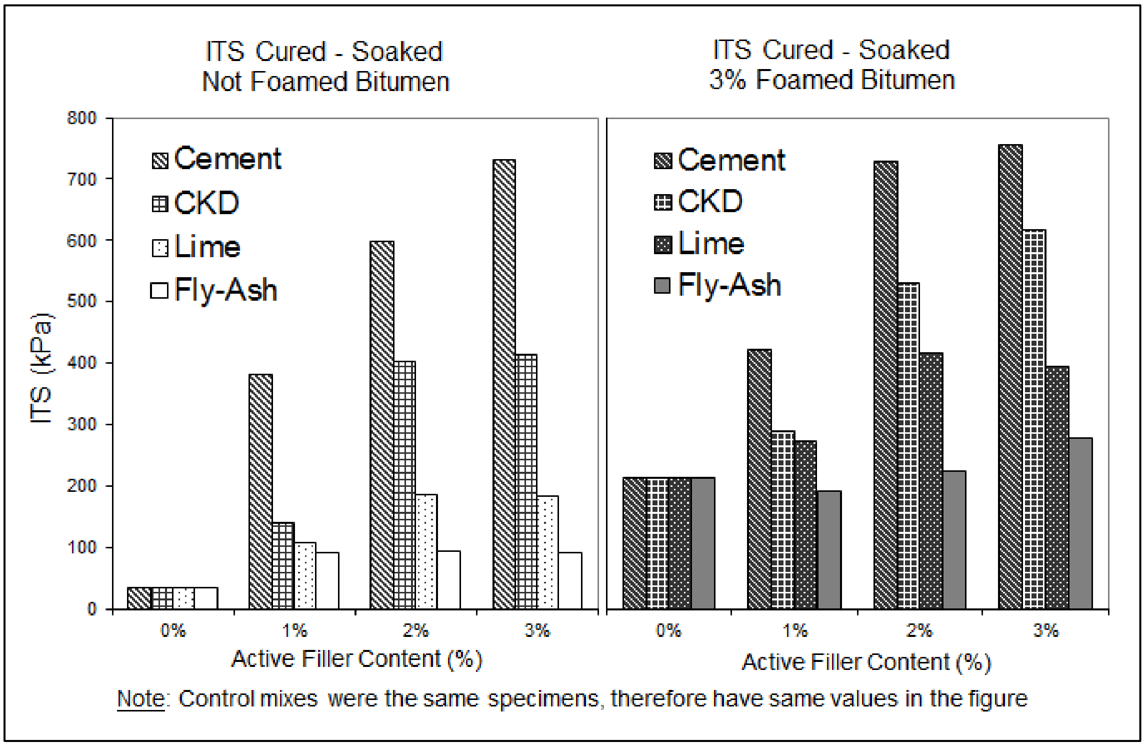


Figure 5-3: ITS values for cured and soaked specimens with and without FB

Based on Figure 5-3, the following observations were made:

- Opposite to that observed in the case of the FB mixes in fresh condition, the addition of 3.0% of FB to the control mix did show significant benefits on strength. While the untreated mix had 34 kPa of ITS, the mix with FB and without the active filler had 211 kPa of ITS.

- Cement had the most significant effect on the soaked ITS of the four active fillers tested, followed by cement kiln dust, lime and fly-ash. Strengths increased with higher cement content, but were not influenced by the presence of FB, i.e. ITS of the mix with FB and cement is due mostly to cement.

- The addition of CKD increased the soaked strengths of the specimens considerably, with strengths increasing with a higher application rate, specifically above two percent. Specimens treated with both CKD and FB had higher strengths than specimens treated with CKD alone.

- The addition of lime provided only a marginal increase in strength on the specimens without FB, with strengths increasing slightly with a higher application rate. When combined with FB, higher strengths were recorded.
- Fly-Ash had little influence on the strength, with only slight increases recorded at an application rate of three percent. Slightly higher strengths were recorded when the fly-ash (three percent) and FB were combined.

5.3.2 Triaxial Resilient Modulus (Tx RM) Test Results

Mechanical properties of the FB mixes were also evaluated using Triaxial Resilient Modulus (TxRM) tests in cured specimens. Figure 5-4, shows TxRM results for specimens cured within 72 hours at 40 °C and soaked for 24 hours at 25 °C. Each mix was prepared using 3.0% of FB and 2.0% of one of the active fillers. Resilient modulus values are shown for 0.1 second loading pulse duration and with four deviator stresses for each confining pressure. All the TxRM test results used in this stage are presented in Annex 2.

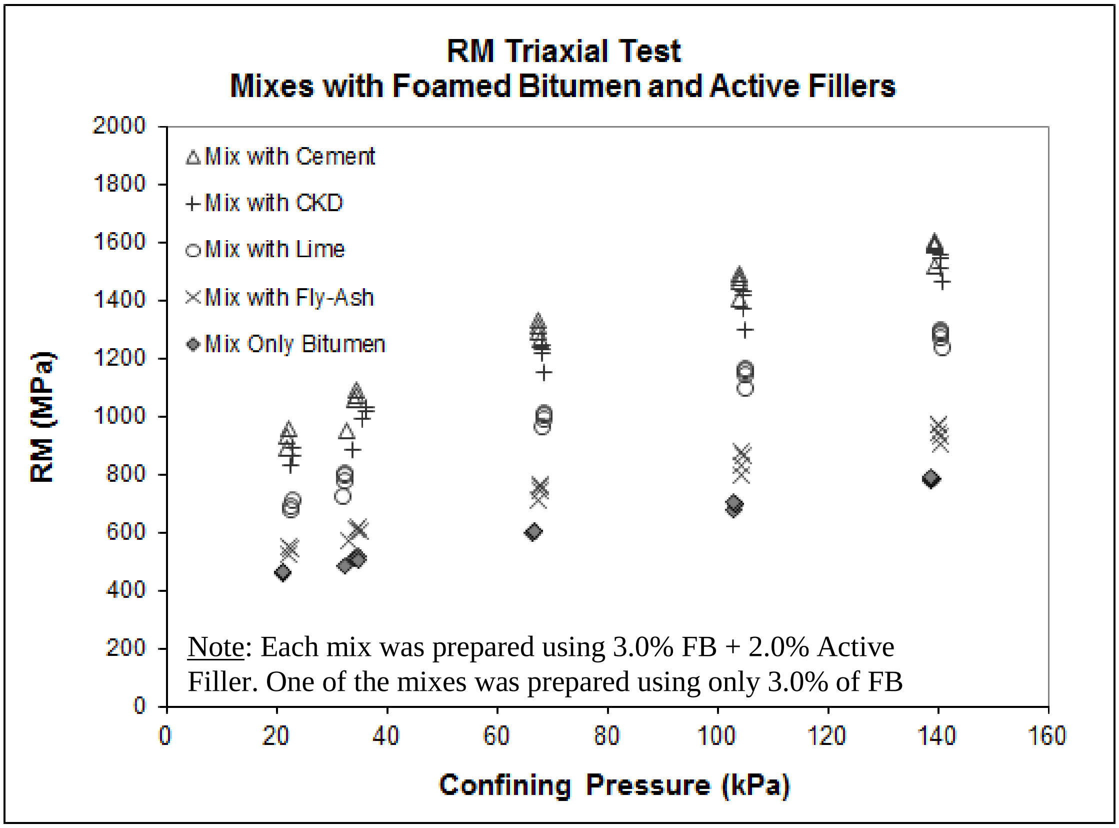


Figure 5-4: Triaxial resilient modulus test results for cured and soak specimens.

Based on results presented in Figure 5-4, it may be concluded that active fillers play a fundamental role in the stiffness of foamed bitumen mixes. For example, Resilient Modulus values for 67 kPa of confining pressure vary from 700 MPa for mixes with foamed bitumen and Fly-Ash to 1300 MPa for mixes with foamed bitumen and cement.

By comparing mixes prepared with foamed bitumen and active fillers with mixes prepared with foamed bitumen and without active filler, it is found that the mix with fly-ash has 1.15 times larger resilient modulus. It is also found that mixes with lime, CKD and cement have 1.6, 1.9 and 2.0 times larger resilient modulus, respectively.

5.3.3 Moisture Susceptibility of FB Mixes with Different Active Fillers

Tensile Strength Retained (TSR) is defined as the ratio between cured ITS values in soaked and dry conditions, and represents mechanical susceptibility of the mix against the presence of moisture (moisture susceptibility). According to international literature, this value should be higher than 60-70% when mixes are to be affected by seasonal changes and moisture conditions (Asphalt Academy, 2002).

As shown in Table 5-3, the addition of 3.0% of FB to the RAG (for samples without active filler) reduced the moisture susceptibility of the RAG from 11% to 40%. Based on the low value of this parameter, it is possible to confirm the importance of the use of active fillers in foamed bitumen mixes to reduce this sensitivity. Results showed that the addition of cement improves TSR by 80% on average, while the addition of CKD and lime improves the TSR value by 70% on average. Fly-ash improved TSR only by 46%.

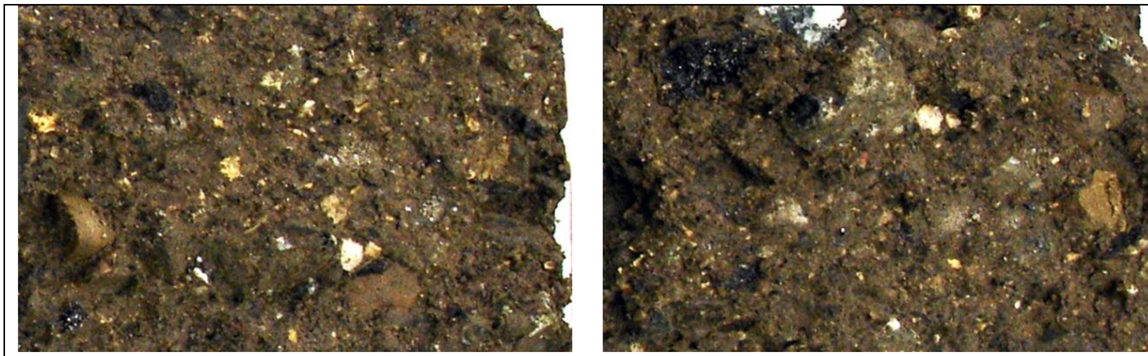
Similar results were obtained when TxRM results are used. Table 5-4 shows TxRM values in dry and soaked conditions, at three reference stress states defined by RM_i = RM (σ_0 , σ_d , T) with σ_0 as confining stress, σ_d as deviator stress and T as duration of the haversine load pulse. TxRM values at dry and soaked conditions were used to calculate Resilient Modulus Retained (RMR), which use the same concept as the Tensile Strength Retained (TSR) values. In this case, the RMR value presented in Table 5-4 was obtained as the average of the RMR for each of the three reference stress states used.

Comparing RMR results from Table 5-4 with TSR results from Table 5-3, FB mixes with cement, CKD and lime showed approximately same trend in terms of moisture sensitivity, i.e. FB mixes using these active fillers improve significantly the moisture sensitivity in compare of the FB mix with fly-ash. However in this last case when using RMR as parameter, the difference of moisture sensitivity between the FB mix with fly-ash and the others is smaller than using TSR. This may be explained due to the influence of the mineral skeleton of RAG used, which plays an important role in the TxRM test in comparison with the ITS test.

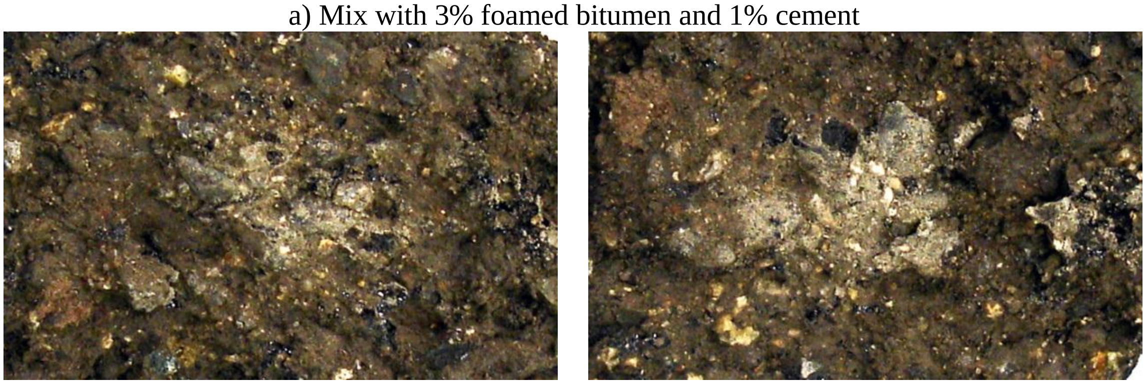
Table 5-4: Triaxial Resilient Modulus Retained values for foamed bitumen mixes and different active fillers

Active Filler	Water Conditioning	$Mr_i = Mr(\sigma_0, \sigma_d, T)$ = (kPa, kPa, sec)			Tx RMR (%)
		(20.7, 41.4, 0.1)	(68.9, 137.9, 0.1)	(103.4, 206.8, 0.1)	
Cement	dry	1185	1503	1684	83%
	soak	894	1293	1488	
CKD	dry	1169	1512	1698	79%
	soak	832	1216	1429	
Lime	dry	1083	1359	1531	70%
	soak	679	988	1160	
Fly-Ash	dry	985	1205	1328	61%
	soak	527	746	879	

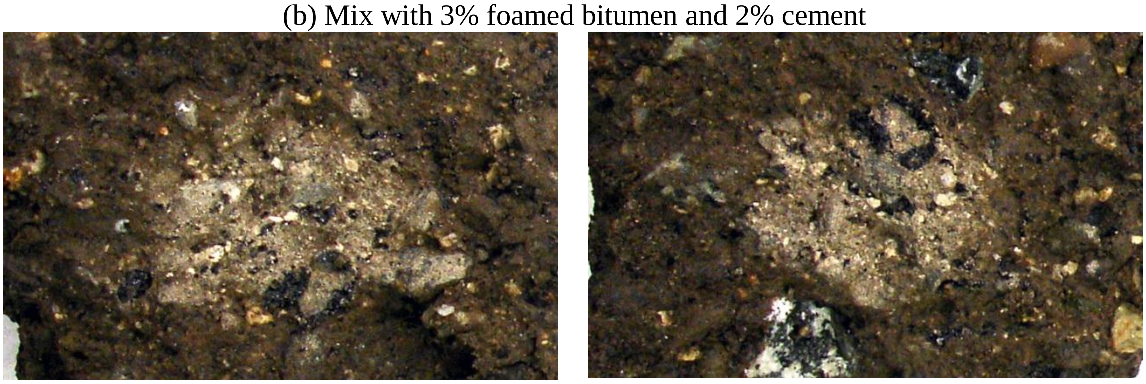
Reduction of the moisture susceptibility could be seen across the fracture faces of the specimens tested for ITS after soaked. Figure 5-5, shows the specimen fracture faces from three ITS tests with bitumen content of 3.0% and cement contents of 1.0%, 2.0% and 3.0%, respectively. No dry areas were observed on the specimens with one percent of cement. However, an increasing dry "core" may be seen in the middle of the fracture faces of the specimens with 2% and 3% cement content. Soaking time and conditions for all specimens were the same.



a) Mix with 3% foamed bitumen and 1% cement



(b) Mix with 3% foamed bitumen and 2% cement



(c) Mix with 3% foamed bitumen and 3% cement

Figure 5-5: Photography of the ITS fracture face of mixes with foamed bitumen and cement

5.3.4 Fracture Energy Index and Ductility Index of FB Mixes with Different Active Fillers

Based on the results using ITS and Triaxial Resilient Modulus tests, it is possible to conclude that active fillers play a main role in terms of the strength/stiffnesses properties of FB mixes. However, the results of the performance of these mixes in the field have demonstrated the benefits that the use of bitumen has in stabilizing granular materials. The question that arises is: ITS test adequate in evaluating the strength for these types of mixes?

Fracture energy and ductility are parameters used for quantifying the capacity to release energy, which is related to the capacity of the material for resisting cyclic loads. Thus, both parameters may be used for evaluating the benefits of different types of stabilizing agents in granular materials.

Definitions of the Fracture Energy and Ductility Indexes are presented in Section 2.5.2 of this document using the Figure 2-10. Table 5-5 and Figure 5-6 show the results for the Fracture Energy Index and Ductility Index for each mix based on ITS test.

Table 5-5: Fracture Energy Index and Ductility Index values

Active Filler Type	Curing and Water Conditioning	Foamed Bitumen Content							
		0% (Control)				3%			
		Active Filler Content							
		0%	1%	2%	3%	0%	1%	2%	3%
		Fracture Energy Index (J)							
Cement	Fresh	0.6	3.4	5.1	5.7	1.4	3.7	6.8	7.3
	Cured-Soaked	0.3	4.3	5.4	6.0	4.3	6.9	9.4	13.1
	Cured-Unsoaked	3.2	5.6	8.6	7.4	12.0	12.0	10.0	11.4
CKD	Fresh	0.6	1.1	1.3	1.6	1.4	1.5	2.1	2.0
	Cured-Soaked	0.3	1.7	4.5	3.5	4.3	5.7	8.4	11.5
	Cured-Unsoaked	3.2	2.8	5.6	7.5	12.0	8.3	13.2	14.8
Lime	Fresh	0.6	1.0	1.2	1.4	1.4	1.6	1.9	2.3
	Cured-Soaked	0.3	1.3	2.3	2.1	4.3	5.8	8.7	7.2
	Cured-Unsoaked	3.2	2.0	2.6	3.2	12.0	8.1	10.1	9.4
Fly Ash	Fresh	0.6	1.2	0.9	1.0	1.4	1.7	1.4	1.8
	Cured-Soaked	0.3	1.0	1.1	1.1	4.3	3.1	4.8	5.0
	Cured-Unsoaked	3.2	3.9	2.5	2.2	12.0	10.7	9.7	10.6
		Ductility Index (mm)							
Cement	Fresh	1.37	1.21	1.15	1.11	2.20	1.44	1.67	1.67
	Cured-Soaked	1.21	1.10	0.90	0.82	2.00	1.63	1.29	1.74
	Cured-Unsoaked	1.07	1.43	1.23	0.86	2.20	1.97	1.18	1.37
CKD	Fresh	1.37	1.44	1.28	1.20	2.20	1.49	1.82	1.75
	Cured-Soaked	1.21	1.25	1.11	0.85	2.00	1.95	1.57	1.90
	Cured-Unsoaked	1.07	1.23	1.00	0.87	2.20	2.07	1.67	1.53
Lime	Fresh	1.37	1.45	1.58	1.59	2.20	1.67	1.70	1.73
	Cured-Soaked	1.21	1.16	1.22	1.17	2.00	2.09	2.07	1.81
	Cured-Unsoaked	1.07	1.10	1.28	1.06	2.20	1.95	1.91	1.54
Fly Ash	Fresh	1.37	1.29	1.39	1.48	2.20	1.68	1.50	1.62
	Cured-Soaked	1.21	1.13	1.18	1.20	2.00	1.63	2.16	1.78
	Cured-Unsoaked	1.07	1.06	1.00	0.98	2.20	2.10	1.98	2.09

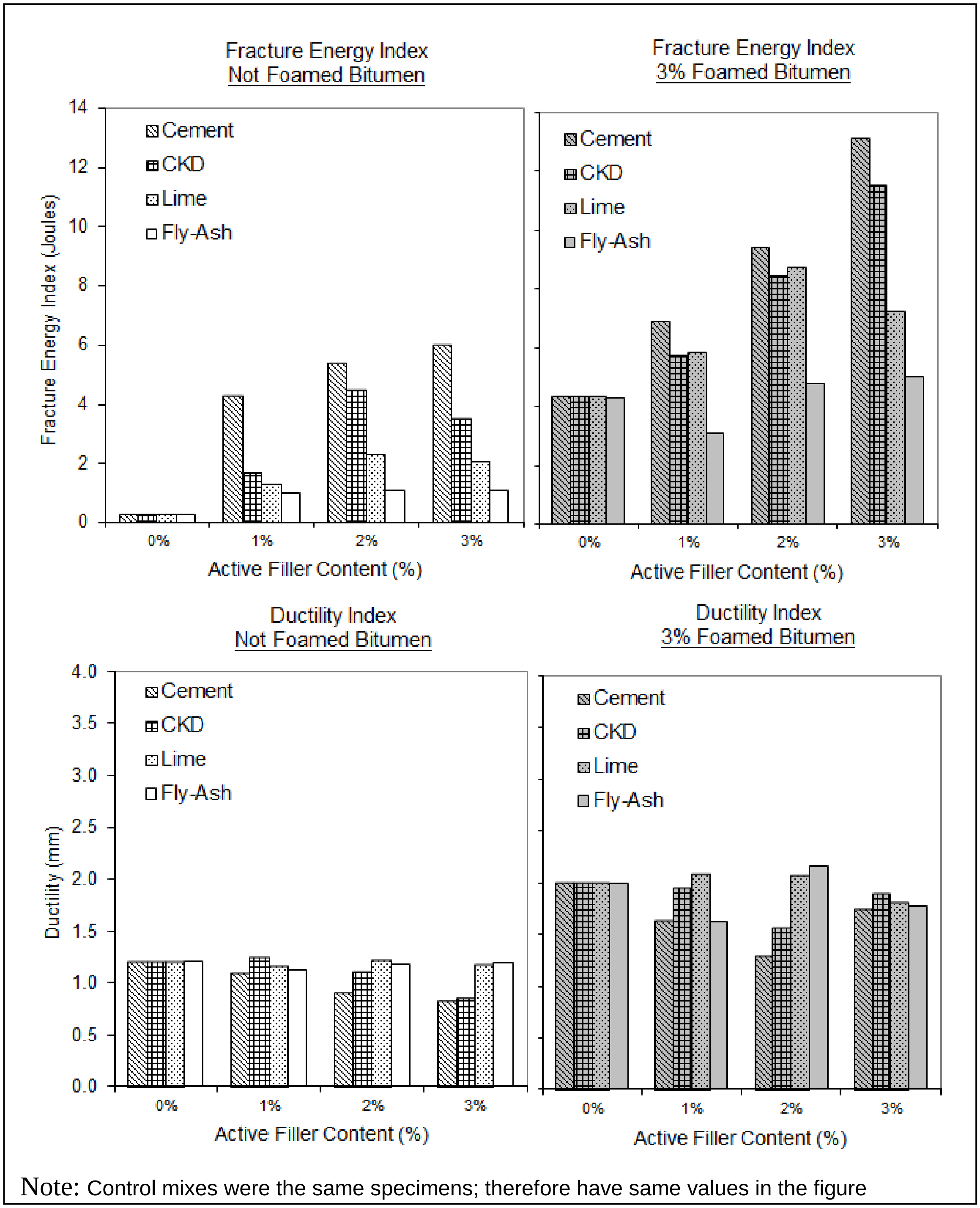


Figure 5-6: Fracture Energy and Ductility Index values for cured-soaked ITS

Based on results presented in Table 5-5 and Figure 5-6, the following observations were made:

- The addition of cement to the mix increased the Fracture Energy Index. Also, the addition of cement reduced the Ductility Index of the mix, as was expected.
- Fracture Energy Index for each of the active fillers showed similar trends to those observed from the ITS results. The only significant exception was the mix treated with cement, where the addition of foamed bitumen showed no significant benefits in strength gain, but showed significant improvement in Fracture Energy. This indicate that cement and foamed bitumen in combination will provide a less brittle but equally strong specimen than if cement alone was used.
- The Ductility Indexes of the cement and CKD specimens without foamed bitumen were lower than the untreated control specimens at application rates of 2% and higher, but were not affected by the addition of lime and fly-ash. When combined with foamed bitumen, the ductility indexes of the specimens with active filler were generally lower than the control specimens with cement and CKD.

5.3.5 Triaxial Permanent Deformation (TxPD) Test Results

Figure 5-7 shows the results for the Permanent Deformation (TxPD) test. Each mix was prepared using 3.0% of foamed bitumen and 2.0% of one of the active fillers. Specimens were soaked at 25 °C – after the curing process - for 7 days before being tested. TxPD test was carried out using 68.9 kPa as confining stress and with three different test patterns:

a) One cycle of 20,000 repetitions at 300 kPa deviator stress
b) One cycle of 20,000 repetitions at 500 kPa and
c) Five cycles of 30,000 repetitions at 700 kPa, for a total of 190,000 repetitions.

The loading pulse (haversine) duration was 0.1 sec with a relaxation period of 0.2 sec. Each test was carried out over 22 hours.

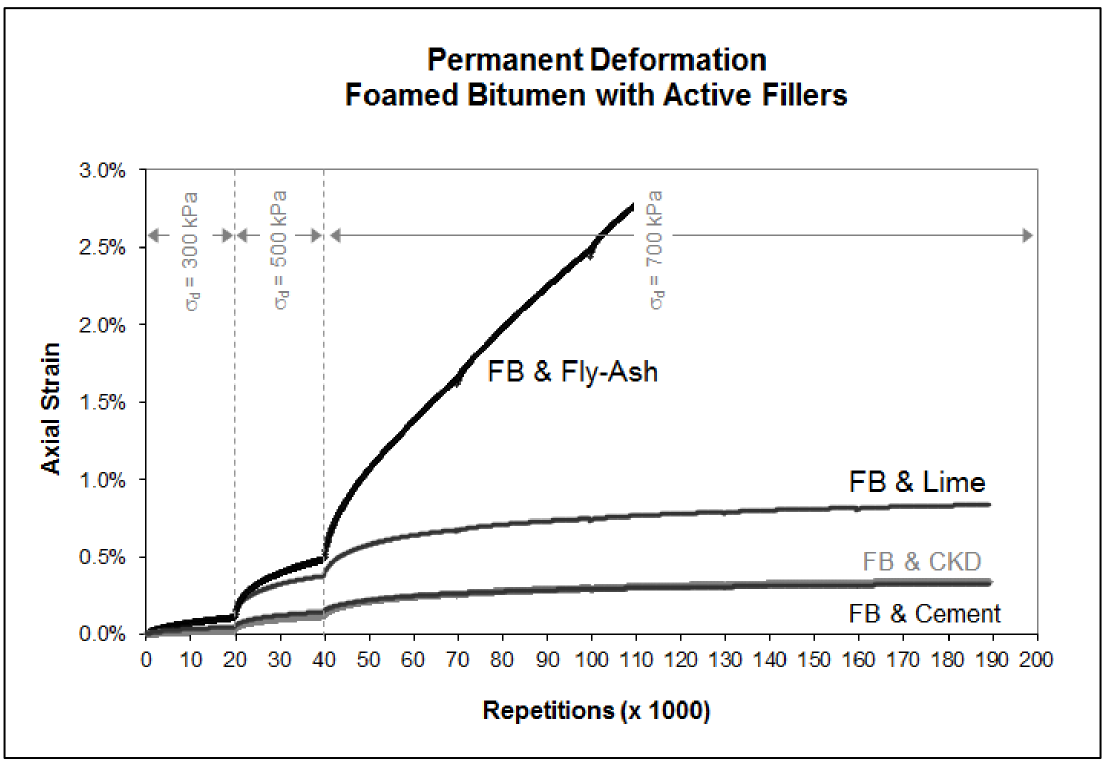


Figure 5-7: Triaxial Permanent Deformation test results.

Based on the results from permanent deformation tests, the following observations were made:

- Similar trends to those observed during ITS and TxRM tests were recorded for the TxPD tests, i.e. performance of each FB mix is significantly affected by the active filler type used.
- FB mixes with cement and CKD showed similar trends in terms of permanent deformation. FB mix with lime showed a slightly lower performance in comparison to FB mixes with cement and CKD, but significantly more than the one with FB and fly-ash. All mixes developed plastic deformation but the deformation rate was stabilized after a certain number of cycles, except for the FB mix with fly-Ash.
- FB mix with fly-ash performed poorly for this particular test. The mix showed an increasing rate of permanent deformation and collapsed before the test finished.

Based on these results, it is possible to conclude that active fillers play a fundamental role with respect to permanent deformation on FB mixes. As it was observed in results from ITS and TxRM tests, fly-ash is not able to provide additional cohesion to the FB mix, instead acting as an inert fines particles. Thus, with the exception of the fly-ash type used, the addition of any active filler like the ones tested is strictly necessary in every case to guarantee a good long-term performance of the FB mixes.

5.3.6 Durability of FB Mixes with Cement as Active Filler

The amount of stabilizing agents used in FB mixes is relatively low compared to traditional asphalt or concrete mix. Based on the international experiences reported, FB contents range from 1.5 to 3.0% while cement contents range from 1.0 to 2.5%.

The low content of stabilizing agents used is able to treat only a portion of the fine particles of granular materials, therefore bonds provided are limited and non-continuous inside the mix, making these types of mixes moisture susceptible. In this case, moisture variations in real projects over years, could significantly affect the durability of the bonds provided by the bitumen and/or cement.

The use of the Triaxial Resilient Modulus test after dry-wet cycles is a procedure that has been used to evaluate the permanence over time of cementation provided by stabilizing agents (Khoury and Zaman, 2007). In this research work this procedure was used for evaluating mixes with different contents of bitumen and cement. Details of the experiment design are presented in Table 3-7 in the Section 3.5.2.

Figure 5-8 presents results of this experiment for four mixes designed with different bitumen and cement content, according to definitions presented in Table 5-6. Resilient modulus values are shown for 0.1 second of loading pulse duration, 67 kPa of confining pressure and the average value of the four deviator stresses used. All the TxRM test results used in this stage are presented in Annex 3.

Table 5-6: Mix definitions for durability experiments

Mix	Bitumen Content (%)	Cement Content (%)
No FB + 1% Cem	0	1
3% FB – No Cem	3	0
3% FB + 1% Cem	3	1
3% FB + 2% Cem	3	2

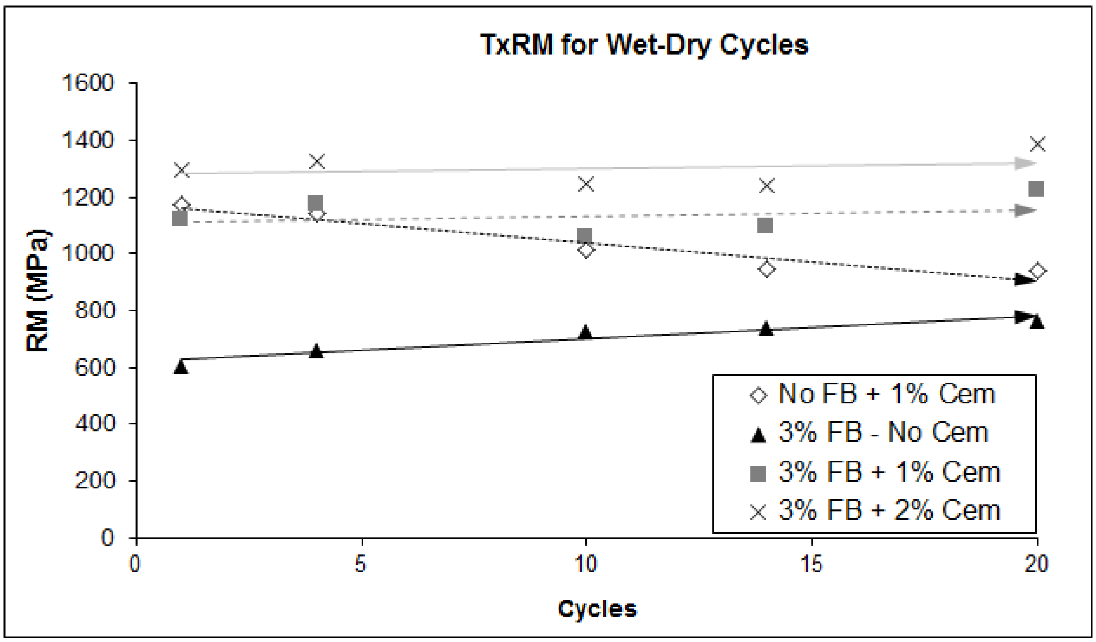


Figure 5-8: Durability test results.

Based on results presented in Figure 5-8, the following observations were made:

- Mix without FB and with 1% cement (NoFB+1%Cem) showed a reduction of the TxRM as the Dry-Wet cycles increased with a constant rate. This means that bonds provided by cement - at the content used - lose their effectiveness in the long term as the material is affected by the presence of dry-wet periods.

- The opposite, a mix with 3% of FB and without cement (3%FB-NoCem), showed an increasing TxRM as the dry-wet cycles increased. This means that bonds provided by bitumen keep their effectiveness in the long term.
- When both stabilizing agents are joined together (Mixes 3%FB+1%Cem and 3%FB+2%Cem), the stabilized mix showed a good performance in terms of durability. TxRM values increase as the dry-wet cycles increase, but at a lower rate than the ones obtained for the mix with bitumen and without cement.

As a general conclusion, it is possible to conclude that bitumen plays an important role in the long term performance of the mix, since it is able to keep the bonding properties over a longer period of time.

5.4 Summary and Conclusions

Although it is currently accepted that FB mixes must use some type of active filler to improve their mechanical properties, no systematic studies have been performed to define the role that the active filler meets throughout the life of the FB mix or its recommended content.

In this research program, a wide range of tests were conducted in FB mixes with the aim of establishing the role of the active filler in the mechanical properties of FB mixes. Indirect Tensile Strength, Triaxial Resilient Modulus, Triaxial Permanent Deformation and Durability tests were carried out in mixes using different bitumen and cement content. FB specimens were mixed and conditioned using different procedures for evaluating the properties in the short, medium and long term.

Only one type of granular material with inert fine particles passing the 0.075 mm sieve was used and four types of active fillers were test: Portland cement type II, cement kiln dust, lime type S (Hydrated) and fly-ash class C. Based on the results of the research program, the main conclusions may be summarized as the following.

Portland cement, CKD and lime were very effective for improving strength, stiffness and permanent deformation resistance of the FB mixes tested in the medium and long term performance, i.e. in cured specimens. In all cases, portland cement had better performance compared to lime and CKD. The use of fly-ash in conjunction with FB did not show the same improvements as the other active fillers. Based on results, it is possible to conclude that fly-ash acted as inert filler. These trends could be different if other types of fine particles are used. In this research work, fine particles of the RAG were inert or non-plastic.

When comparing the influence of the cement and bitumen to the strength of the cured FB mix, the increase due to bitumen is marginal in comparison to the increase due to cement. The cement masks the effect of the bitumen in terms of strength. When lime, CKD, or fly ash was used, the effect of the bitumen proved to be significantly important.

In the short term, since FB mix takes a long time to dry, Portland cement plays an important role in helping to improve the early strength of FB mixes. The use of lime, CKD and fly-ash did not improve early strength of FB mixes. This fact is very important as most of FB recycling/stabilizing projects require the treated section of road to be opened to traffic after a few hours. Early strength provided by the cement is therefore a key issue in the construction process and must be correctly evaluated at the mix design stage.

On the other hand, mechanical properties of FB mixes are very susceptible to moisture conditions in the medium and long term. Cement, CKD, and lime help to reduce this restriction since they provide cementitious properties to the fine particles of the aggregates.

Since it is well accepted that bonds provided by cement are strong but fragile in comparison with the ones provided by bitumen, which are weak but ductile, fracture energy test was conducted to evaluate benefits provided by bitumen. Fracture Energy and Ductility are parameters used to quantify the capacity to release energy, which at the same time is related to the capacity of the material for resisting cyclic loads. Fracture Energy Index for each of the active fillers showed similar trends to that observed from the ITS results. The only significant exception was the mix treated with cement only, where the addition of foamed bitumen did not show significant benefits in strength gain. But it showed instead significant improvement in the Fracture Energy index. This means that cement and foamed bitumen combined will provide a less brittle but equally strong layer compared to that of cement alone, improving the performance of FB mixes in the long term.

Regarding durability of the bonds provided by both stabilizing agents, samples with cement and without bitumen did not show good results. On the contrary, samples with bitumen, with and without cement, performed well in the test performed.

In summary, based on strength and stiffness properties, Portland cement appears to offer the most advantages compared to the other active fillers tested. Portland cement reduces water susceptibility and increases early, medium, and long-term strength. Foamed bitumen improves ductility and durability, and therefore the long term performance of the FB mixes.

Finally, it is necessary to mention that results obtained here are dependent on RAG used, mainly due to the type of fine particles passing the 0.075 mm sieve. In Chile, normally Full Depth Recycling projects using FB are carried out on existing pavement with a granular base compounds by good quality materials with inert fine particles. Further research is recommended in order to evaluate the interaction between active fillers and other types of fine particles.

6. LONG TERM STIFFNESS EVOLUTION OF FOAMED BITUMEN MIXES

6.1 General Discussion

As discussed in Chapter 4, the stiffness of foamed bitumen (FB) mixes increases gradually from the day of construction until reaching a constant value after a period of approximately 12 months. This information was made known by Loizos (2007) from field studies conducted in Greece (see Figure 6-1). This proposal was also confirmed in this research work by field studies conducted in Chile. The reasons for this behavior are related to loss of moisture during the curing period, a fact that has also been stated by Bowering (1970), Jones et al (2008) and Fu et al (2010), based on observations from laboratory tests.

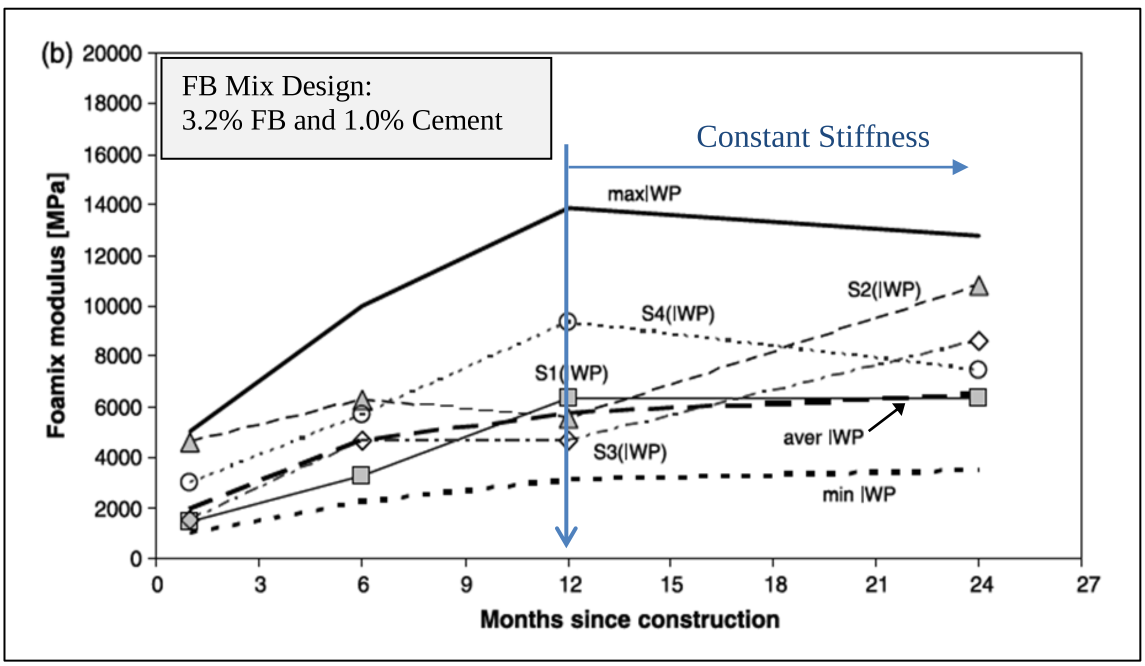


Figure 6-1: Increase of elastic modulus retro-calculated by Loizos (2007) for the FB layer

Studies carried out in Greece were conducted over 24 months. The stiffness of the FB mix was remained constant throughout the period of analysis once it reached its maximum value in the twelfth month.

Conversely, research studies carried out in South Africa (Long, 2001) indicated that FB layers show a gradual decrease in stiffness due to traffic loads. Figure 6-2 shows results of the accelerated pavement testing performed on recycled pavements using FB and cement as the stabilizing agents in the study. Bitumen and cement contents were 1.8% and 2.0% of the FB layer, respectively. After construction of the pavement, a 40 KN traffic load was applied using the HVS: Heavy Vehicle Simulator or Accelerated Pavement Testing (Verhaeghe et al, 2006; Du Plessis et al, 2008). Multi depth deflectometer (MDD) was used for measuring deformations at different depths of the pavement structure. The modulus of each pavement layer was obtained through back calculation. For this study it was not possible to obtain data regarding the curing period and conditions during construction of the test section.

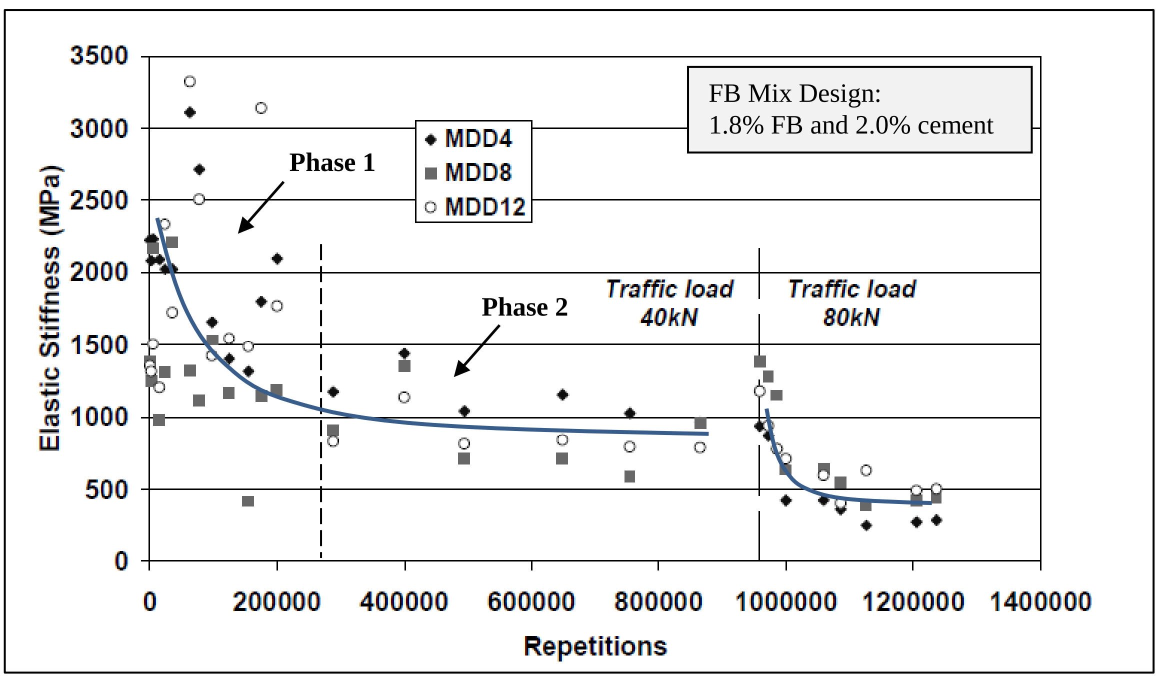


Figure 6-2: Decrease of stiffness in the FB Layer due to load cycles (Long, 2001)

Based on the HVS test, Long (2001) states that FB degradation has two phases. The first phase corresponds to a decrease in stiffness until a constant stiffness state, without having a physical manifestation on the pavement layer. The second phase is represented by a constant stiffness of the FB layer, as shown in Figure 6-2. During the test, at approximately 1.000.000 load cycles, the traffic load was increased to 80 KN. With the increased load, the stiffness of the FB layer showed a similar trend to that observed during the first 300,000 load cycles with 40 KN, with a stiffness decreasing gradually until a constant stiffness state is reached. Results provided by the accelerated pavement test in the long term also indicated that during the second phase, the material behaves as a granular material, accumulating permanent deformation due to repetitive load cycling. The TG2 2002 guide (Asphalt Academy, 2002) proposed that the "constant stiffness state" can be comparable to a granular material only in the effective elastic modulus and behavior, but not in the physical composition of the materials.

Based on analysis of the results of the research study presented above, it is possible to conclude that the reasons for the difference observed in terms of the stiffness evolution between the Greek and South African studies could be related with the stress-state of the FB layer at the time of the analysis. For supporting this assumption, a simple multi-layered linear elastic model was used for quantifying stresses and strains in the FB layer for each pavement structure. In the model, the dual truck tires were modeled with two 20 KN loads with a separation of 350 mm and contact pressure of 700 kPa. For both cases, results of stresses and strains were evaluated at one quarter of the thickness of the FB layer, measured from the bottom of the FB layer.

Table 6-1 shows the details of the material elastic properties and thickness of each pavement structure evaluated during these studies, as well as stresses and strains calculated at the bottom quarter of the FB layer thickness.

Table 6-1: Pavement structure characteristics in Greece and South Africa projects

Layer	**Modulus (MPa)**	**Greece**				**South Africa**			
		T (cm)	σ (kPa)	ε (μm)	SR	T (cm)	σ (kPa)	ε (μm)	SR
Surface Layer	4000	9	---	---	---	3	---	---	3
FB Layer	1200	25	60	45	0.2	25	165	100	0.55
Other Layer	1000 (*)	10	---	---	---	---	---	---	---
Subbase	250	15	---	---	---	25	---	---	25
Subgrade	90 (**)	---	---	---	---	---	---	---	---

(*) Cemented treated layer, (**) Estimated by the author, SR = Stress divided by the Indirect Tensile Strength (ITS = 300 kPa), T = Thickness of the layer, σ = stress, ε = strain

Based on the results obtained by the structural analysis, it may be concluded that the FB layer of the pavement structure of Greece was subjected to a stress ratio (SR) of 20% while that of South Africa was subjected to a stress ratio (SR) of 55%. This information indicates that if the SR of the FB layer is lower than a certain value, the mix does not deteriorate due to cyclic loads. This behavior is similar to that of asphalt concrete mixes, which do not develop fatigue when deformations are smaller than a certain value, known as "Fatigue Endurance Limit", represented by "ε_y" in Figure 6-3 (NCHRP 646, 2010).

As discussed in Section 2.6, stiffness evolution observed in pavement structures with FB layers may also be explained by studying the microstructure of the FB material. The tiny bitumen and cement particles disperse throughout the aggregates adhering to the finer particles (fine sand and smaller) creating the mastic that coats the large aggregates. Bonds formed by stabilizing agents (bitumen and active filler) are not continuous in the microstructure (the aggregates are "spot welded"). When traffic loads are applied to the pavement structure, the FB layer is deformed producing strains and stresses in the microstructure. These stresses could break some of the bonds if they are larger than the allowable strength, producing a decrease in cohesion in the long term, and therefore a decrease in FB stiffness. If the stresses or strains are smaller than the admissible values determined by the mastic, then the FB mix will keep its original cohesion and stiffness.

Nonetheless, it is well known that FB mixes may bear tensile stresses. They are also unable to develop fatigue cracks, i.e. when the maximum stresses are produced in the bottom of the layer, the bonds in that area will break and the mix will behave as an untreated material in that particular section. Based on the above discussion, it is expected that after a period of time, the FB stiffness will reach a limiting value. This depends on the stress/strain level which depends on prevailing loads in the road, similar to the behavior observed in the analyzed pavements. In the case of the pavement structure of Greece, it is probable that a stress ratio of 20% was lower than the minimum required for generating some damage to the bonds produced by the bitumen and cement particles.

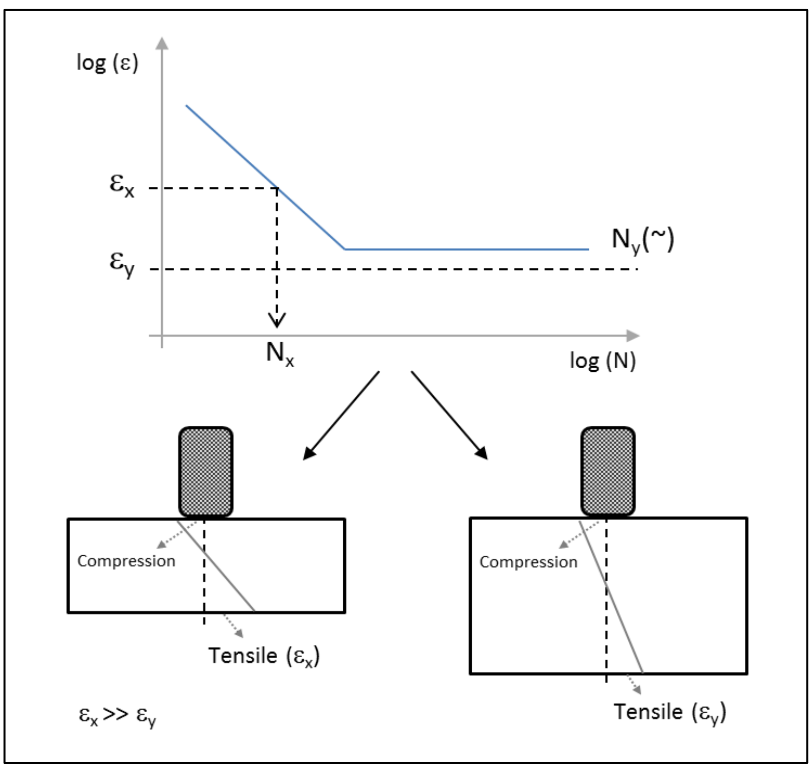


Figure 6-3: Graphic description of the “Endurance Limit” (NCHRP 646, 2010)

This stage of the research study was focused on quantifying the stiffness evolution of FB mixes subjected to different levels of stress ratio. This information is used for two purposes:

a. For establishing the impact of the different content of bitumen and cement on the long term performance of the FB mixes.
b. For defining the maximum stress level that is to be accepted in the FB layer, which can be used in the structural design process for a recycled pavement.

6.2 Experiment Design for Evaluating the Long Term Stiffness Evolution

This stage was focused on evaluating the stiffness evolution of the mix and its stress-state dependency. The laboratory test program was designed to study the impact of the bitumen and the cement during this process. One RAG material was used at this stage, according to the information provided in section 3.2.1.

The stiffness evolution was evaluated using the Indirect Tensile Fatigue Test (ITFT) in 150 mm diameter and 60 mm in height specimen. The test was stress controlled and strains were measured using two LVDTs. The tensile stress (σ_x) at the center of the specimen was calculated using Equation 6.1, while the elastic modulus (S) of the mix was calculated using Equation 6.2. The Stress-Ratio concept (SR; see Equation 6.3) was used in defining the load pattern for each test and was calculated as the quotient between the estimated tensile stress (σ_x) and the ITS (ITS: Indirect tensile strength or maximum strength of the specimen).

$$\sigma_x = \frac{2P}{\pi t d} \qquad \text{(eq. 6.1)}$$

where *P* as the vertical load (kN), *t* as the thickness of the specimen (m) and *d* as the diameter (m).

$$S = \frac{\sigma_x}{\varepsilon} \qquad \text{(eq. 6.2)}$$

where σ_x (kPa) as the estimated tensile stress and ε as the measured tensile strain (mm/mm).

$$SR = \frac{\sigma_x}{ITS} \qquad \text{(eq. 6.3)}$$

where σ_x (kPa) as the estimated tensile stress and *ITS* (kPa) as the maximum tensile stress.

Stress Ratios (SR) of 20%, 30%, 40% and 50% were used for each specimen during the ITFT. There were 5,000 load cycles applied for each SR. Details and an example of the ITFT used are described in section 3.3.4.

Mixes with different bitumen and cement content were produced in order to evaluate the contribution of each stabilizing agent to the stiffness evolution. Of the nine mixes of the factorial presented in Table 6-2, only five were used: Mixes B, D, E, F and H. One RAG material was used in this part of the research, according to the information provided in section 3.2.1. Details of the experimental design of this research work are summarized in Table 6-3.

Table 6-2: Mixes used in this experiment

	Bitumen Content (%)		
Cement (%)	**1.0**	**2.0**	**3.0**
0.0	A	**B (FB2C0)**	C
1.0	**D (FB1C1)**	**E (FB2C1)**	**F (FB3C1)**
2.0	G	**H (FB2C2)**	I

Table 6-3: Experiment design for evaluating the long term stiffness evolution

Variable	# of levels	Values
RAG source	1	PUC RAG. See Section 3.2.1
Bitumen grade	1	Mobil AC-24. Section 3.2.2
Foaming properties	1	165°C, 2.5% foaming water
Foamed bitumen content	4	0%, 1%, 2% and 3%
Active filler type	1	Portland cement
Active filler content	3	0% - 1% - 2%
Test methods	1	Indirect Tensile Fatigue test (ITFT)
Compaction Effort	1	Gyratory compaction
Curing Process	1	Cured (72 hrs at 40 °C)
Water Conditioning	1	Dry
ITFT replicates	3	
Stress-State Levels	4	Stress Ratio equal to (Effective Stress / ITS)

6.3 Discussion of the Validity of the ITFT

The Indirect Tensile Fatigue Test (ITFT) and the Indirect Tensile Resilient Modulus Test (ITM) were adopted using the same setup as the ITS test (see section 3.3.4 for more details) and originally for testing asphalt concrete mixes (AASHTO TP31 [deleted in 2002]; ASTM D4123 [withdrawn without replacement in 2003] and LTPP P07).

The validity of the ITFT and the ITM have been widely discussed because results obtained for the stiffness of FB mixes are normally greater than those obtained by other tests, such as the Resilient Modulus Triaxial Test (TxRM) and the Flexural Beam Test for Dynamic Modulus and Fatigue (AASHTO T321). The stiffness of FB mixes reported in literature using the ITM test (Nataatmadja, 2001; Marquis et al., 2003; Ramanujam & Jones, 2007) have indicated values within a range of 4,000 and 5,000 MPa, which are similar to those normally used for hot mix asphalt concrete. Resilient Modulus of FB mixes reported in literature using the TxRM test (Jenkins et al., 2002; Halles & Thenoux, 2009) and the Cyclic Flexural Beam test (Long & Ventura, 2004, Twagira et al., 2006; Ramanujam & Jones, 2007) have indicated values within a range of 700 MPa and 3,000 MPa. This is consistent with results from field deflection measurements, including Falling Weight Deflectometer (FWD) tests (Lane & Kazmierowski 2003, Gonzalez et al, 2009) and multi-depth deflectometer (MDD) tests (Long & Theyse, 2004).

Although these differences are evident, it cannot be concluded that one of these tests is more appropriate to quantify the elastic modulus of the FB mixes. The boundary conditions by which these tests are performed in the laboratory in any of the cases represent exactly what happens in the field. To some degree, the flexural beam test simulates the stress state of the FB layer subjected to loading of a wheel, with tensile stress at the bottom and compressive stress at the top of a beam specimen (See Figure 6-3). However, it does not include the horizontal confinement stresses in the pavement structure. Conversely, the TxRM test applies a compressive confining stress and a deviator stress, but no tensile stress can be induced within the specimen in a typical test setup.

In the case of the ITM test, horizontal tensile strains and stresses are induced within the cylindrical specimen subjected to a vertical strip load, under very complex boundary conditions based on the elastic theory of a homogeneous continuum mix. As discussed in Section 6.1, bonds formed by stabilizing agents (bitumen and active filler) are not continuous in the microstructure. In some cases when relative low content of stabilizing agents are used, the FB mix may not behave as a bond-mix. Therefore, it is impossible to ensure that the material is behaving as a homogeneous continuum mix.

In this research work, Indirect Tensile setup was used in monitoring the evolution of the elastic/resilient response of the mix under cyclic loads (Indirect Tensile Fatigue test – ITFT) and for different stress ratios as discussed in section 6.2. The stiffness values obtained with this test are not used for structural design purposes. They are only used for quantifying the change between the initial and resulting stiffness (of equilibrium) after a certain number of cycle loads, and in defining the trend for each stress-ratio applied.

Later, the ratio (in percentage) between the initial stiffness (S.Ini) and the stiffness of equilibrium (SEq) using the ITFT is used as a shift factor for defining the Triaxial Resilient Modulus (TxRM) of the FB mix for an specific pavement structure. Further discussion on this procedure is carried out in Section 6.5.

6.4 Analysis of ITFT Results

6.4.1 Statistical Analyses of ITFT Results

Different statistical analyses were carried out to ITFT results for resolving if there are significant differences between means of the mixes tested and if the factors analyzed have a significant influence on the stiffness evolution. Details and results of these analyses are showed in Annex 4.

As a result of these analyses, is possible to state that:

- A General Lineal Model was applied using the parameters bitumen content, cement content and stress-ratio. 3 levels were used for each parameter. Based on the general lineal model applied, p-values of the parameters bitumen content, cement content and stress-ratio are 0,000. Thus, it is possible to conclude that the contribution of these parameters on the stiffness evolution is significant.

- Impact of the bitumen content on the stiffness evolution. The p-value for the stiffness evolution ANOVA is 0.000. Thus, it is possible to conclude that there are significant differences in stiffness evolution for mixes with different bitumen content. However, the confidence intervals for the means of mixes FB1C1 and FB3C1 do overlap. This suggests that the population means for these mixes are similar. In the opposite, the confidence intervals for the means of the mix FB2C1 does not overlap with the ones of mixes FB1C1 and FB3C1. Thus, the population means of the mix FB2C1 is different than population means of the other two mixes.

- Impact of the cement content on the stiffness evolution. The p-value for the stiffness evolution ANOVA is 0.000. Thus, it is possible to conclude that there are significant differences in stiffness evolution for mixes with different cement content. Looking at stiffness evolution results of mixes FB2C0, FB2C1 and FB2C2, the intervals for the means of the three mixes do not overlap. This suggests that the population means for these mixes are different.

Based on the statistical results obtained, it is possible to state that the stiffness evolution trends observed can be analyzed independently according the bitumen or cement content used. In the next sections, the effect of the bitumen and cement content on the stiffness evolution of the FB mixes is analyzed.

6.4.2 Effect of the Foamed Bitumen Content on the Stiffness Evolution

Figure 6-4 shows results of the ITFT carried out in mixes FB1C1, FB2C1 and FB3C1 in order to evaluate the *effect of the bitumen content on the stiffness evolution*. Results correspond to the average of the two specimens evaluated. Trend lines were fitted and extrapolated to each mix for each SR with the objective of estimating the stiffness for additional load cycles. Examples of the trend lines for FB2C1 are shown in Figure 6-4.

Table 6-4 shows details of the trend lines of each mix as well as the stiffness expected at 100,000 and 1,000,000 load cycles. It must be noted that a couple of tests were carried out using more than 100,000 cycles in order to verify the extrapolation created. Results of these tests are showed in Annex 5.

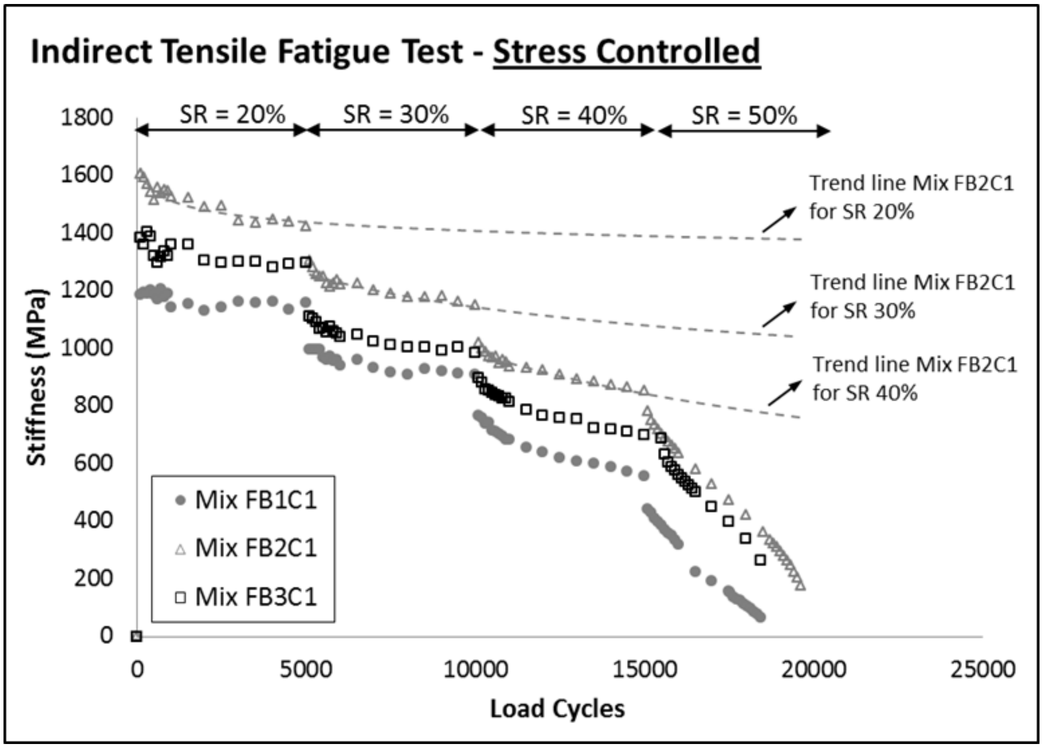


Figure 6-4: ITFT stiffness evolution of mixes with different bitumen content

Table 6-4: Details of trend lines adjusted to each mix and estimated stiffness

	Stress Ratio	$y = a*x^b$ a	b	R^2 (%)	Long Term Stiffness for i load cycles i = 100,000	i = 1,000,000
Mix FB1C1 (1% FB+1%Cem)	20	C	-0.013	50.7	1,098	1,066
	30	C	-0.136	83.4	654	478
	40	C	-0.755	96.6	131	23
Mix FB2C1 (2% FB+1%Cem)	20	C	-0.031	88.5	1,310	1,220
	30	C	-0.140	85.3	828	600
	40	C	-0.384	94.5	407	168
Mix FB3C1 (3% FB+1%Cem)	20	C	-0.019	61.2	1,220	1,168
	30	C	-0.157	90.1	682	475
	40	C	-0.581	96.3	228	60

y: Stiffness of the Indirect Tensile Test
x: Load cycles.
a,b: Regression coefficients
C: Constant value

Based on results of Figure 6-4 and Table 6-4, the following observations were made:

- Similar to results of the ITS test, there is an optimum bitumen content. In this case, Mix FB2C1 with 2.0% FB and 1.0% cement gave the best results for the stiffness evolution for the RAG used in this research.
- In general, all mixes show similar trends in terms of stiffness evolution at different stress ratios. According to results presented in Table 6-4, curves were fitted to measured values. The curves are described by a power relationship with a-b regression coefficients. Table 6-4 shows that "b" coefficients for each mix are very similar when the SR value is the same. For example, when a SR of 30% was applied, "b" coefficient for mixes FB1C1, FB2C1 and FB3C1 were -0.136, -0.140 and -0.157 respectively.
- The stiffness of the FB mixes plateaus after a certain number of load cycles when the stress ratio is in the order of 20%. For example, Mix FB2C1 showed a relative constant stiffness of 1200 – 1300 MPa for the long term, which represents almost 80% of the initial Stiffness (1600 MPa). In the case of SR being equal to 30%, the mix showed a good evolution of stiffness, with a constant decreasing line with a low slope. In this case, the stiffness of the mix was 600 MPa after 1 million load cycles, which represents the 37.5% of the initial stiffness (1600 MPa). This demonstrated that after all the load cycles were applied, the mix is still able to keep cohesion due to the effect of the stabilizing agents. Similar results are observed in mixes FB1C1 and FB3C1. In the case of SR being equal to 40%, mixes showed a clear reduction in stiffness with load cycles. All of them showed almost null stiffness after 1 million cycle loads.
- When mixes were subjected to a stress ratio of 50%, specimens failed in a relative short period of time. This indicates that stresses and strains applied are

much larger than the tensile strength provided by the FB and cement on the mix.

- Table 6-5 shows the slope of the trend line for each mix when SR is 50%. When mixes were subjected to a SR of 50%, the stiffness rates of change were very similar for each mix. This means that the FB content did not significantly affect the behavior of the mix under these stress conditions.

Table 6-5: Slope of the trend line for mixes FB1C1, FB2C1 and FB3C1 when failed.

Mix	Stress Ratio (%)	Slope (m) (y = m*x + b)
FB1C1	50	-0.1116
FB2C1	50	-0.1207
FB3C1	50	-0.1189

6.4.3 Effect of the Cement Content on the Stiffness Evolution

Figure 6-5 shows results of the ITFT carried out to mixes FB2C0, FB2C1 and FB2C2 in order to evaluate the *effect of the cement content on the stiffness evolution*. Results correspond to the average of the results of two specimens.

Trend lines were fitted and extrapolated to the modulus measured for each SR with the aim of estimating the stiffness if additional load cycles were applied. Examples of the trend lines for mix FB2C2 loaded at different SRs are depicted in Figure 6-5. Table 6-6 shows regression coefficients of trend lines used for each mix as well as the amount of stiffness expected for 100,000 and 1,000,000 load cycles.

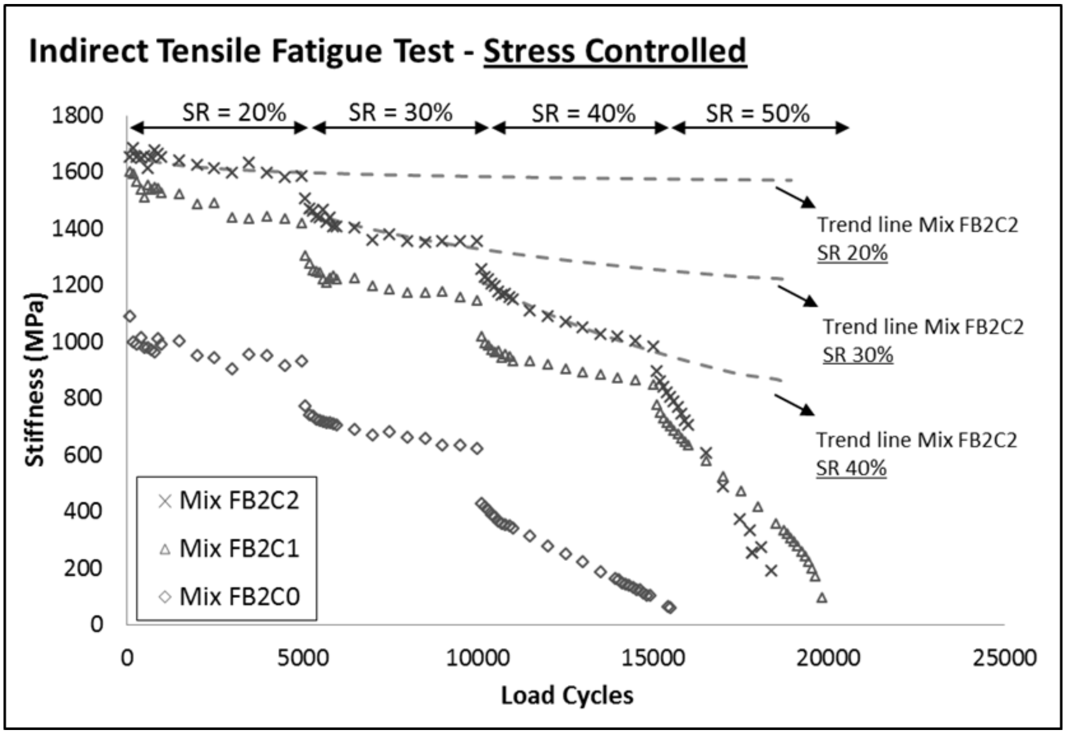


Figure 6-5: ITFT stiffness evolution of mixes with different cement content

Table 6-6: Details of trend lines adjusted to each mix and estimated stiffness

	Stress Ratio	$y = a*x^b$ a	b	R^2 (%)	Long Term Stiffness (MPa) for i load cycles i = 100,000	i = 1,000,000
Mix FB2C0 (2% FB+0%Cem)	20	C	-0.031	70.2	849	791
	30	C	-0.261	95.1	341	187
	40				Failed	
Mix FB2C1 (2% FB+1%Cem)	20	C	-0.031	88.5	1,310	1,220
	30	C	-0.140	85.3	828	600
	40	C	-0.384	94.5	407	168
Mix FB2C2 (2% FB+2%Cem)	20	C	-0.013	61.2	1,538	1,493
	30	C	-0.139	90.1	844	613
	40	C	-0.576	96.3	324	86

y: Stiffness of the Indirect Tensile Test
x: Load cycles.
a,b: Regression coefficients
C: Constant value

Based on results of Figure 6-5 and Table 6-6, the following observations were made:

- As it was supported with the statistical analysis carried out, there are significant differences between mixes without cement (mix FB2C0) and with cement (mixes FB2C1 and FB2C2) for the same bitumen content. Mixes with cement (FB2C1 and FB2C2) have larger stiffness compared to mix FB2C0 (with FB only). While stiffness of mixes FB2C1 and FB2C2 are 1310 MPa and 1538 MPa respectively for 100,000 cycles and SR of 20%, stiffness for mix FB2C0 is 849 MPa. These results indicate that a pavement structure with FB2C1 and FB2C2 layers will have a better structural capacity than with mix FB2C0 after the load cycles applied.
- Additionally, mixes FB2C1 and FB2C2 were able to withstand more cycles than mix FB2C0 for the same test loading sequence. While mix FB2C0 collapsed for a SR equal to 40%, mixes FB2C1 and FB2C2 collapsed for a SR equal to 50%.
- The stiffness of the FB mixes plateaus after a certain number of load cycles when the stress ratio is in the order of 20%, guaranteeing that the mix will keep its cohesion in the long-term.
- For the case of a SR equal to 30%, mixes with cement (FB2C1 and FB2C2) showed an acceptable stiffness evolution. It is interesting to note that although mix FB2C2 initially has a greater stiffness than mix FB2C1, when extrapolated to 100,000 cycles, the stiffness of both tends to be the same. Stiffness of mix FB2C1 is equal to 828 MPa for 100,000 extrapolated cycles while stiffness of mix FB2C2 under the same conditions is 844 MPa.
- In the case of an SR equal to 40%, mix FB2C1 showed a better stiffness evolution than mix FB2C2. The stiffness rate of change for mix FB2C2 was significantly higher than mix FB2C1. When comparing trend lines fitted to the data, it can be seen that values of the variable "b" are -0.384 for mix FB2C1 and -0.576 for mix FB2C2. If the fitted equations are used to extrapolate the

stiffness, at 1 million load cycles the stiffness of mix FB2C1 is 168 MPa while stiffness of mix FB2C2 is 86 MPa. In contrast, mix FB2C0 (only with FB) collapsed for a SR equal to 40%.

- In the case of an SR equal to 50% in mixes FB2C1 and FB2C2 or an SR equal to 40% in mix FB2C0, trend lines were fitted to the data (see Table 6-7). The slopes for each equation (m) indicate that as the cement content increases, the rate of change of the stiffness also increases. This means that when increasing the cement content, mixes with the worst behavior are obtained for a SR of 50%.
- Overall, the use of 2.0% cement in a FB layer will be beneficial only if the FB layer is loaded to a SR equal or lower than 30%. If the FB layer is loaded to a SR equal or higher than 40%, it is recommended only to use 1.0% cement together with FB.

Table 6-7: Slope of trend lines for mixes FB2C0, FB2C1 and FB2C2 when failed.

Mix	Stress Ratio (%)	Slope (m) (y = m*x + b)
FB2C0	40	-0.0643
FB2C1	50	-0.1207
FB2C2	50	-0.2183

6.5 Proposal for Analysis of Pavement Structures with Recycled Layers

The methodology presented in the above section for estimating the stiffness evolution of the FB mix could be used as a guide for recommending a minimum thickness of the FB layer.

As was discussed in previous sections, the stiffness of the FB mix will trend to a specific constant value according the load cycles applied and depending on the stress state of the FB mix. The stiffness value reached - using the Indirect Tensile Fatigue Test (ITFT) - is called *Stiffness of Equilibrium* (S.Eq) in this research work. Thus, Stress Ratio (SR) concept was used for representing the stress state of the mix for different cases and a mathematical relationship between SR and S.Eq was found. Thus, the S.Eq value can ranged from the initial stiffness (S.Ini) to any specific stiffness value, depending on the mix type, number of load cycles and the SR value.

Then, a mathematical relationship between SR and S.Eq was built using the *Long Term Stiffness values* presented in Tables 6-3 and 6-5 for 1,000,000 load cycles and for each SR value.

In addition, in this research work, the parameter *RSIE* was defined as the ratio between the S.Eq and the *Initial Stiffness (S.Ini)* obtained using the ITFT (See equation 6.4). Then, values of the RSIE can range from 0% to 100% depending on the SR of the mix and the load cycles applied. Table 6-8 shows RSIE values for mixes FB2C1 and FB2C2 based on the mathematical relationship between SR and S.Eq discussed in the above paragraph.

$$RSIE\ (\%) = \frac{S.Eq}{S.Ini} * 100 \quad \text{(eq. 6.4)}$$

where

S.Eq as the Stiffness of Equilibrium evaluated with the ITFT

S.Ini as the Initial Stiffness evaluated with the ITFT

Table 6-8: Mathematic relationship between SR and RSIE

Mix Type	Stress Ratio (%)	S.Eq. (MPa) for 1,000,000 load cycles	RSIE (%) for 1,000,000 load cycles
	10	1520	95
Mix FB2C1	20	1216	76
(2% FB + 1% Cem)	25	880	55
	30	576	36
Initial ITT	35	352	22
Stiffness	40	160	10
1600 (Mpa)	45	48	3
	50	0	0
	10	1700	100
Mix FB2C2	20	1513	89
(2% FB + 2% Cem)	25	1037	61
	30	646	38
Initial ITT	35	374	22
Stiffness	40	187	11
1700 (Mpa)	45	102	6
	50	0	0

In this study, RSIE is used as a “shift factor” for defining the most representative elastic modulus of the FB layer in the pavement structure in the long term (Effective Elastic Modulus), which in this case is based on the Resilient Modulus measured using the Triaxial Test (TxRM). The TxRM is used since, as previously discussed in section 6.3, it is similar to those moduli found in the field.

According to equation 6.5, this procedure proposes that the Effective Elastic Modulus (EEM) must be defined using the RSIE as a shift factor.

$$EEM(MPa) = RSIE(\%) \times [\Delta TxRM](MPa) + \alpha\ (MPa) \qquad \text{(eq. 6.5)}$$

where,

RSIE: Ratio between the stiffness of equilibrium (S.Eq) and initial stiffness (S.Ini) using the ITFT for a specific Stress-Ratio of the FB layer (see Table 6-8)

α: TxRM value of the untreated granular material for a specific stress state (see note below).

ΔTxRM: The difference between the initial TxRM value and α (untreated granular material) of the FB mix

Note: α and ΔTxRM values used must be selected for the same stress state condition. 68,9 kPa as confining stress and 137,9 kPa as deviator stress are recommended.

Hence, when the RSIE is zero - as was the case when mixes were evaluated with SR equal to 50% - the material still had an Elastic Modulus equivalent to the TxRM of the original (or remaining) granular material (represented by the parameter "α" in Equation 6.5).

In contrast, when the RSIE is 100%, the mix then has a Stiffness equal to 100% of the TxRM of the mix. Intermediate values are defined based on the mathematic relation between SR and S.Eq found in the previous section and showed in Table 6-8.

Procedure applied is based on two main backgrounds.

a. As discussed in section 6.3, the Stiffness obtained using the Indirect Tensile Fatigue Test setup (ITFT) does not appropriately represent what happens in a real pavement structure. Therefore, the stiffness using the ITFT cannot be used as a parameter for defining the Effective Elastic Modulus (EEM) of the FB layer in the pavement structure. However, from a conservative point of view it may be assumed that the ITFT is useful for evaluating the cohesion provided by the stabilizing agents and does not serve to evaluate the contribution of the friction between aggregates. In contrast, the resilient modulus obtained using the Triaxial test (TxRM) is able to represent the contribution of the aggregates friction as well as the cohesion provided by the stabilizing agents. In addition, values obtained using the Triaxial test are more consistent with results from field deflection measurements, including Falling Weight Deflectometer and multi-depth Deflectometer.

b. Results provided by Long (2001) using accelerated pavement tests (see Figure 6-2) showed that the stiffness of the FB layer decreases from its initial value to a constant state of stiffness. The initial stiffness value represents the effect of the cohesion provided by the stabilizing agents as well as the effect of the friction aggregates. The "constant stiffness state" represents the second phase of the FB layer stiffness which is comparable to the stiffness of the granular material that compound the FB mix. In this case, the stiffness of the granular material is provided only by the aggregate friction.

In summary, the ITFT setup is used for evaluating the stiffness due to the cohesion provided by the stabilizing agents. Once this cohesion is lost due to cyclic loads applied, the remaining elastic modulus is provided mainly by the friction of the aggregates represented by the TxRM value of the untreated granular material. Figure 6-6 shows the conceptual approach discussed in previous paragraphs.

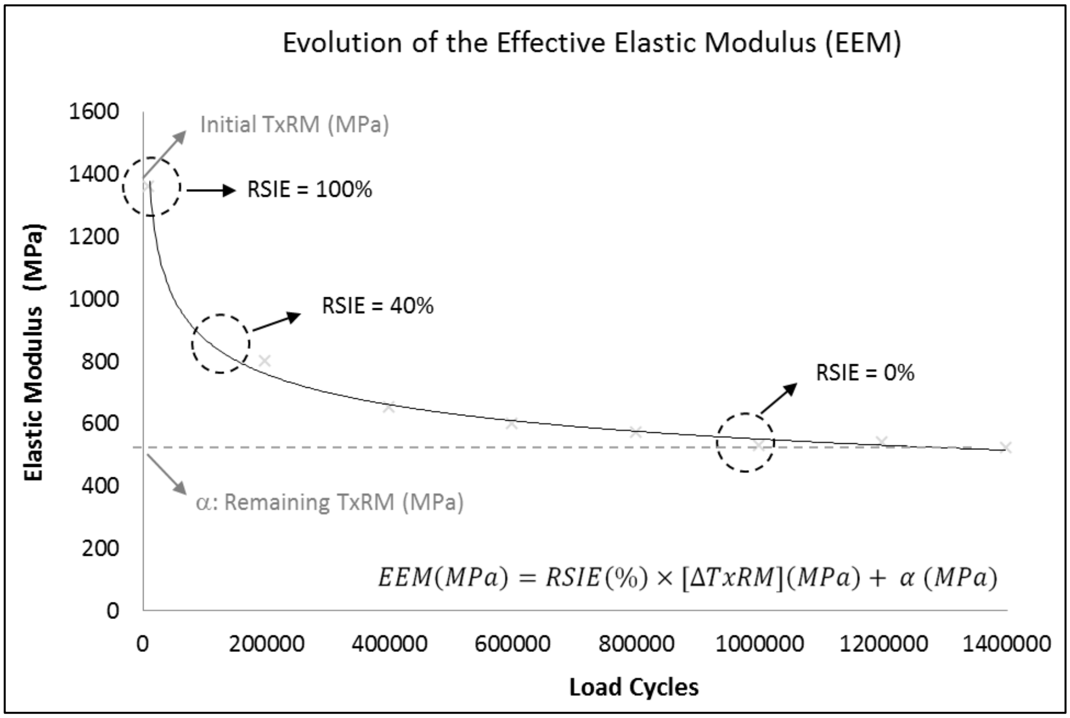


Figure 6-6: Conceptual approach for defining the Effective Elastic Modulus of FB mixes

Finally, based on the relationship between SR and RSIE presented in Table 6-8 and equation 6.5, two equations were fitted to the data for estimating the Effective Elastic Modulus (EEM) of mixes FB2C1 and FB2C2 directly from the Stress Ratio at which the mix is affected. Figure 6-7 shows results of these curves.

The Resilient Modulus estimated from curves shown in Figure 6-7 represents the EEM of the FB mix after one million cycle loads under a stress state represented by the Stress Ratio. Thus, as the SR increases, stresses in a specific point of the FB layer will increase, affecting the long term performance of the mix, which will be reflected in the EEM of the mix.

Curves shown in Figure 6-7 may be used in any pavement structure using an FB layer. However, they were developed only for one RAG material type (reclaimed asphalt pavement and granular materials) and two mix types in terms of the foamed bitumen and cement content.

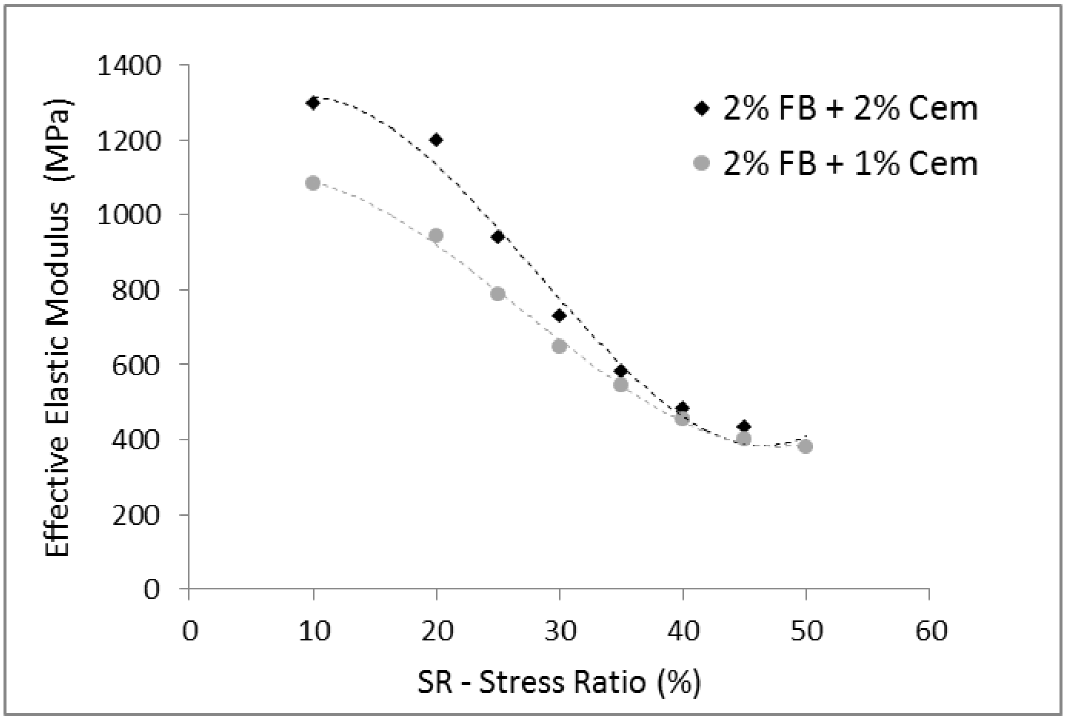


Figure 6-7: Mathematic relation between SR and the EEM of the FB mix

Based on curves proposed in Figure 6-7, a pavement analysis exercise using three different pavement structures was conducted. Table 6-9 shows details of the pavement structures used for the analysis.

Table 6-9: Details of pavement structures analyzed

Layer	Elastic Modulus (MPa)	Thickness (cm)	Foamed Bitumen Content	Cement Content
Asphalt Concrete	4000	5	---	---
Recycled Layer	800	**10 - 15 - 20**	**2.0%**	**1.0%**
Granular Sub-base	150	15	---	---
Subgrade	76	---	---	---

Figure 6-8 shows stresses calculated for each pavement structure using simple multi-layered linear elastic models. The FB layer was divided into six sub-layers, each with a thickness equal to 1/6 thickness of the FB layer (t). Stresses were calculated in the middle of each sub-layer and values were used for calculating the stress ratio (SR) of each sub-layer. The Effective Elastic Modulus (EMM) for each sub-layer was then calculated using curves proposed in Figure 6-7 as well as the average EMM for each FB layer. Results of these calculations are presented in Table 6-10.

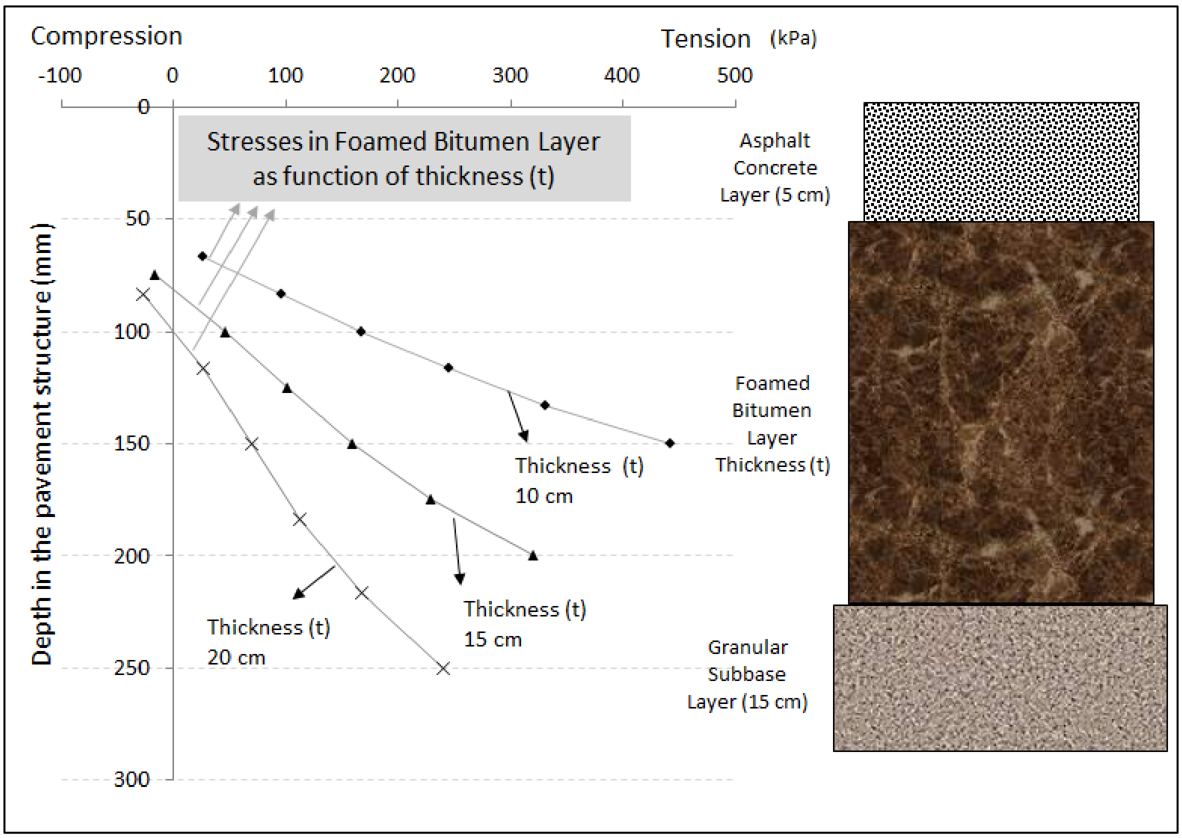


Figure 6-8: Stresses calculated for each pavement structure

Table 6-10: EMM for each structure

FB Layer Thickness (t)	Fiber of the FB Layer	Stress Ratio (%)	EMM (MPa) 2% FB + 1% Cem	Average EMM (MPa)
10 cm	(1/6) t	<10	1083	614
	(2/6) t	18	964	
	(3/6) t	38	481	
	(4/6) t	> 50	386	
	(5/6) t	> 50	386	
	(6/6) t	> 50	386	
15 cm	(1/6) t	< 10	1083	722
	(2/6) t	< 10	1083	
	(3/6) t	21	896	
	(4/6) t	37	500	
	(5/6) t	> 50	386	
	(6/6) t	> 50	386	
20 cm	(1/6) t	< 10	1083	801
	(2/6) t	< 10	1083	
	(3/6) t	14	1039	
	(4/6) t	26	769	
	(5/6) t	40	446	
	(6/6) t	> 50	386	

With information provided in Table 6-10 and properties of each layer of the pavement structures analyzed, fatigue life of the asphalt concrete and subgrade layers may be estimated using one of the fatigue models available. As example, Table 6-11 shows the fatigue life for the asphalt concrete layer of the pavement structures analyzed using traditional fatigue cracking models.

Table 6-11: Fatigue life of the Asphalt Concrete layer for pavement structures analyzed

Layer	**Thickness of each layer (cm)**		
	Pavement Structure A	Pavement Structure B	Pavement Structure C
Asphalt Concrete	5	5	5
Recycled Layer	**10**	**15**	**20**
Granular Sub-base	15	15	15
Sub-grade	---	---	---
Fatigue Life of the Asphalt Concrete (*)	1.42E+06	5.38E+06	11.6E+06

Notes:

- (*) Fatigue life for 50% of the surface cracked
- Properties of each layer are showed in Table 6-9

6.6 Summary and Conclusions

It is well accepted that the stiffness of foamed bitumen mixes change over time. At the first stage of its structural life, the stiffness increases due to the curing process. During the second stage, some researchers have proposed that stiffness decreases due to traffic loads. However, there are also others studies that have not shown that behavior and FB mixes have maintained stiffness close to the initial value. Additionally, it is necessary to mention that studies reported in the literature have been carried out over a limited period of time. Hence, these other conclusions may not be valid.

On the other hand, there is no information regarding the degree of influence that stabilizing agents used - bitumen and active fillers – have on the stiffness evolution of the FB mixes. The limited studies carried out have been focused on establishing the contribution of these additives to the short-term mechanical properties.

This stage of the research work was focused on studying the impact of different bitumen and cement contents on the stiffness that FB mixes acquire over time. The ITFT

(Indirect Tensile Fatigue test) was used as a tool for evaluating the stiffness evolution of the FB mix. Tests were carried out for different stress ratios based on the assumption proposed in this research work that rate of change of the stiffness depends on the stress level which the FB layer will be affected within the pavement structure.

As a result of these tests it was found that if the FB layer is affected to a stress ratio near 20%, the stiffness of the FB mix will remain relatively constant over time with a stiffness value close to the initial. As the stress ratio increases, the rate of change of the stiffness also increases. If the stress-ratio is near 50%, the mix will fail and the cohesion provided by stabilizing agents will reduce to zero in a relative short period of time. In this case the stiffness will be equivalent to the elastic/resilient modulus of the reclaimed material without stabilizing agents.

Analysis of the bitumen content effect showed very little influence on the rate of change of the stiffness, but it was possible to find an optimum content that maximizes the initial stiffness. Conversely, the effect of cement content was significant on the stiffness evolution as well as on the absolute value of stiffness. However, results showed that the use of 2% of cement in the FB layer will be beneficial only if the FB layer is loaded with a SR less than or equal to 30%. If the FB layer is loaded to a SR equal to or greater than 40%, it is recommended to use only 1% cement with FB.

Finally, as a result of the methodology adopted during this stage of the research, a pavement analysis procedure was proposed for estimating the long term stiffness of FB mixes. This procedure may be used for pavement design when an FB layer is used in the pavement structure.

It must be noted that the research work and procedure proposed was carried out using only one aggregate source, one bitumen source, a single active filler and a single temperature. All these factors contribute significantly to the FB mix performance and therefore results obtained are limited. Conclusions must be validated using a larger experimental design.

7. CONCLUSIONS

7.1 General Thoughts

At the beginning of this research work many questions were posted regarding properties and performance of Foamed Bitumen (FB) mixes. A major question was related to the strength and stiffness that FB mixes develop during time (strengthening or curing process) from the construction phase and subsequently in the long term. The mix design methodology currently used evaluates the properties of cured FB mixes and uses the maximum stress as parameter, which only represents the mechanical properties of the FB mix once has lost most of its moisture and hence has acquired its maximum strength.

In the short term, it was necessary to know in detail how FB strength evolves during the first days after construction because normally these types of projects must be opened to traffic a few hours after construction. Therefore, the pavement structure must acquire a minimum strength that meets the structural design criteria for each of the underlying layers. Although it is widely accepted that the strengthening of the FB mix is directly related to the loss of moisture over time - defined as the curing process - there was not enough information regarding variables influencing this process the most and restrictions to be taken into account to avoid potential problems over time.

In the long term, it was important to understand the process of the stiffness evolution of FB mixes for purposes of determining the lifetime of the FB layer and the other underlying layers of the pavement structure. While there was information about field mechanical properties in the long term, these were limited and conflicting according to each of the different cases analyzed. Also, there was no conclusive information at the laboratory level by means of which to assess this situation.

Closely related to the issue of strength evolution over time, was another question regarding the procedure used to define the optimum content of the stabilizing agents (bitumen and cement, or some other active filler) and the contribution of these to the mechanical properties of the FB mixes during each life stage. The mix design procedure typically used worldwide (Asphalt Institute, 2002; Asphalt Institute, 2009), only incorporates a criterion to select the bitumen content, while cement is not subject to any selection criteria. The mix design procedure only indicates what the maximum acceptable cement content is, due to potential shrinkage problems.

According to the information gathered and discussed in Chapter 2 of this document, it may be stated that both questions - the strength or stiffness evolution over time and the real contribution of the stabilizing agents - are strongly linked and therefore a detailed study of each of these questions is required.

This chapter presents the most important conclusions and recommendations that arise from this research.

7.2 Main Conclusions

In this section, the main conclusions discussed in Chapters 4, 5 and 6 are presented.

7.2.1 Strengthening (or Curing) Process of Foamed Bitumen Mixes

In-Situ monitoring of the stiffness of a foamed bitumen mix and triaxial resilient modulus laboratory tests were carried out to study the strength development of the mix in the short term, i.e. during the curing process. Laboratory analyses were carried out including the cement content as a variable. Main conclusions of this stage of the research work may be summarized as follows:

- Foamed bitumen mixes acquire strength due to bitumen and cement addition in separate ways. Strength obtained from cement is fast because cement reacts with the water available from the construction process of the mix. On the other hand, foamed bitumen mixes need to lose the moisture to develop strength from bonds provided by bitumen. If for some reason, the foamed bitumen mix remains in moist condition during its service life, then it will never gain strength provided by the bitumen. Results from this research work showed that mixes with six months in service did not develop strength when they were exposed to moist conditions during the period, and stiffness values after that period were very similar to the reclaimed granular materials without any stabilizing agent.

- In the short term, since FB mix takes a long time to dry, portland cement plays an important role in helping to improve early strength of FB mixes. This fact is very important as most of FB recycling/stabilizing projects require that the treated section of road be opened to traffic after a few hours. Early strength provided by the cement is therefore a key issue in the construction process.

7.2.2 Role of Active Fillers on Mechanical Properties of Foamed Bitumen Mixes

An extensive and systematic laboratory study was carried out to study the role of active fillers in the mechanical properties of foamed bitumen mixes for the short, medium and long term. Cement, lime, CKD and fly-ash were tested in conjunction with bitumen using Indirect Tensile Strength, Triaxial Resilient Modulus, Triaxial Permanent Deformation and Durability tests. Main conclusions of this stage of the research work may be summarized as follow:

- The selection of the appropriate active filler is very important since each of them contributes in a distinct way to the mechanical properties of the foamed bitumen mixes.
- When comparing the influence of the cement and bitumen on the strength of the cured FB mix, the increased strength due to bitumen is marginal in comparison to the increase due to cement. In others words, it is possible to conclude that cement masks the effect of the bitumen in terms of strength. When lime, CKD or fly ash was used, the effect of the bitumen was shown to be more important.

- Based on strength and stiffness properties, portland cement appears to offer the most advantages compared to the other active fillers tested. Portland cement reduces water susceptibility and increases early as well as medium and long-term strength.
- Results obtained from Fracture Energy analysis indicated that cement and foamed bitumen combined will provide a less brittle yet equally strong layer as when cement alone is used, improving long term performance of FB mixes.
- Results from durability tests indicated that bitumen plays a very important role in improving the long term behavior compared to that of cement.
- Fly-ash behaved as inert filler, due to the properties of the fine fraction of the RAG used.

7.2.3 Long Term Stiffness Evolution of Foamed Bitumen Mixes

A systematic laboratory program was carried out using the ITFT (Indirect Tensile Fatigue Test) as a tool for evaluating the stiffness evolution of the FB mix in the long term. ITFT was carried out for different stress ratios based on the assumption proposed in this research work that the rate of change of stiffness will depend on the stress level at which the FB layer will be affected within the pavement structure. Main conclusions of this stage of the research work may be summarized as follow:

- Stiffness of FB mixes will evolve in the long term according to the stress state developed in the FB layer of the pavement structure. The higher the stress state in the FB layer is, the higher the rate of change will be due to cyclic loads, and the lower the long term stiffness will be.
- If the FB layer is affected by a stress ratio close to or lower than 20%, then the stiffness of the FB mix will stay relatively constant over time with a stiffness value close to the initial. Results also showed that mixes with a stress ratio close to 50% failed in a relative short period of time.

- Analysis of the bitumen content effect showed very little influence on the rate of change of stiffness, but it was possible to find an optimum content that maximizes stiffness in the long term. Conversely, the effect of cement content was significant on the stiffness evolution as well as in the absolute value of stiffness. However, results also showed that the use of 2% of cement in the FB layer will be beneficial only if the FB layer is loaded with a SR equal to or lower than 30%. If the FB layer is loaded to a SR equal to or higher than 40%, it is recommended to only use 1% cement with FB. This last result sounds logical considering that as the cement increases, ductility decreases or the mix becomes more fragile.

7.3 Recommendations Based on Acquired Knowledge

As discussed and supported by results of this research work, strength/stiffness evolution of FB mixes is complex and depends on a couple of factors that have not been addressed correctly. Based on analyses carried out, main recommendations of this research work may be summarized as follow:

- Short-term strength/stiffness of FB mixes must be evaluated at the mix design stage with the objective of defining the minimum strength required for supporting traffic loads without producing damage to the underlying layers. Therefore, it is recommended that the curing method of 24 hours in fresh condition, unsealed sample, be included in the mix design procedure, along with the traditional process of curing 72 hours at 40 °C. This procedure will help to quantify the strength and stiffness in the early stage as well as to select the most appropriate active filler type and content to include in the FB mix.
- Active fillers should be considered in all foamed bitumen FDR projects, as they complement the bitumen contribution by improving the mechanical properties and reducing the moisture susceptibility of the mechanical properties.

- When comparing the influence of the cement and bitumen in the cured FB mix strength, the contribution due to bitumen is marginal in comparison to the contribution due to cement. In others words, cement masks the contribution of the bitumen in terms of strength. Therefore, during the mix design stage, the procedure for selecting the optimum bitumen content must be done using only bitumen. After selecting the bitumen content, cement content should be evaluated independently following the same procedure and using fixed bitumen content.
- Regarding the quantity of cement, it is recommended to always use the minimum required. Cement improves strength properties of foamed bitumen mixes but also could lead to shrinkage cracking. Further research is needed to evaluate this specific issue.
- FB mixes need to lose the moisture added during construction process to acquire strength. Therefore, projects must always include an adequate drainage design to guarantee that the FB layer loses its moisture and thus develops strength. Construction programs of FB recycling/stabilizing projects should restrict the construction if it is carried out in wet and/or cold periods. If some project is to be constructed without an adequate drainage system, some specific considerations must be defined when evaluating the FB mix stiffness for structural design purposes.

In Annex 6 an Adapted Mix Design Procedure for FB mixes is proposed. This preliminary procedure takes into account all the recommendations given in this research work. This proposal was not validated formally, but it includes the key individual steps validated during this research work.

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9. ANNEXES

ANNEX 1. Triaxial Resilient Modulus Tests. Study of the Stiffness Evolution During Early Stage

In this annex the triaxial resilient modulus tests carried out for this specific stage are showed. These test are part of the results provided in Section 4.3.2 of this document.

TxRM test results for sample FB3-C1 (H)

Mix 3FB-1C(H)	Confining Pressure (kPa)	Deviator Stress (kPa)	Trixial Resilient Modulus (MPa)				
Curing Period (Days)			1	14	30	45	67
3% Bitumen	20.7	20.7	607	630			624
	20.7	41.4	628	659			659
1% Cement	20.7	51.8	634	678			678
	20.7	62.1	642	693			700
100% RH	34.5	34.5	658	710			713
	34.5	68.9	700	764			764
	34.5	86.2	710	780			788
	34.5	103.4	707	781			786
	68.9	68.9	810	891			901
	68.9	137.9	823	923			933
	68.9	165.8	831	930			940
	68.9	206.8	831	937			946
	103.4	68.9	941	997			1008
	103.4	103.4	961	1033			1044
	103.4	156.7	962	1052			1062
	103.4	206.8	963	1068			1079
	137.9	68.9	1068	1129			1153
	137.9	103.4	1088	1163			1199
	137.9	137.9	1090	1175			1211
	137.9	209.7	1080	1187			1211
	137.9	275.8	1055	1189			1225

TxRM test results for samples FB3-C0

Mix 3FB-0C	Confining Pressure (kPa)	Deviator Stress (kPa)	**Triaxial Resilient Modulus (MPa)**					
Curing Period			1 Day		14 Days			
Sample			K0-C		K0-A	K0-B	K0-C	K0-D
3.0% Bitumen	20.7	20.7	317		604		508	
	20.7	41.4	257		633		570	
0.0% Cement	20.7	51.8	257		659		575	
	20.7	62.1	253		670		589	
	34.5	34.5	300		686		609	
	34.5	68.9	281		734		645	
	34.5	86.2	272		748		655	
	34.5	103.4	268		759		659	
	68.9	68.9	323		847		731	
	68.9	137.9	327		878		776	
	68.9	165.8	341		884		798	
	68.9	206.8	365		892		800	
	103.4	68.9	441		926		824	
	103.4	103.4	443		976		858	
	103.4	156.7	445		1002		891	
	103.4	206.8	449		1010		919	
	137.9	68.9	517		1049		938	
	137.9	103.4	510		1081		966	
	137.9	137.9	508		1094		985	
	137.9	209.7	508		1092		1020	
	137.9	275.8	504		1069		1015	

Mix 3FB-0C	Confining Pressure (kPa)	Deviator Stress (kPa)	**Triaxial Resilient Modulus (MPa)**			
Curing Period			30 Days			
Sample	Sample		K0-A	K0-B	K0-C	K0-D
3.0% Bitumen	20.7	20.7	659	680	630	711
	20.7	41.4	689	702	683	771
0.0% Cement	20.7	51.8	710	724	697	784
	20.7	62.1	716	737	709	791
	34.5	34.5	747	762	726	822
	34.5	68.9	808	814	798	865
	34.5	86.2	819	827	830	880
	34.5	103.4	831	836	841	878
	68.9	68.9	909	918	911	966
	68.9	137.9	945	954	972	975
	68.9	165.8	950	958	976	978
	68.9	206.8	950	962	971	973
	103.4	68.9	1013	1028	973	1043
	103.4	103.4	1052	1061	1057	1066
	103.4	156.7	1080	1081	1084	1078
	103.4	206.8	1090	1085	1101	1078
	137.9	68.9	1159	1149	1091	1140
	137.9	103.4	1196	1184	1152	1157
	137.9	137.9	1213	1197	1184	1169
	137.9	209.7	1211	1191	1205	1165
	137.9	275.8	1196	1174	1200	1150

Mix 3FB-0C	Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)					
Curing Period			45 Days					67 Days
Sample	Sample		K0-A	K0-B	K0-C	K0-D		K0-C
3.0% Bitumen	20.7	20.7		839	782	838		786
	20.7	41.4		967	836	950		876
0.0% Cement	20.7	51.8		979	867	965		913
	20.7	62.1		1000	872	979		921
	34.5	34.5		1013	877	971		898
	34.5	68.9		1066	922	1007		947
	34.5	86.2		1079	929	995		958
	34.5	103.4		1080	939	1002		954
	68.9	68.9		1148	1005	1068		1065
	68.9	137.9		1158	1010	1068		1072
	68.9	165.8		1157	1007	1059		1073
	68.9	206.8		1141	1013	1063		1112
	103.4	68.9		1250	1100	1127		1158
	103.4	103.4		1261	1087	1130		1099
	103.4	156.7		1229	1092	1124		1175
	103.4	206.8		1217	1086	1127		1200
	137.9	68.9		1323	1151	1179		1232
	137.9	103.4		1326	1154	1178		1230
	137.9	137.9		1319	1159	1180		1223
	137.9	209.7		1267	1142	1167		1271
	137.9	275.8		1256	1128	1161		1292

TxRM test results for samples FB3-C1

Mix 3FB-1C	Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)					
Curing Period			1 Day		14 Days			
Sample			K1-C		K1-A	K1-B	K1-C	K1-D
3.0% Bitumen	20.7	20.7	694		684	655	647	566
	20.7	41.4	740		735	752	731	624
1.0% Cement	20.7	51.8	746		771	770	759	660
	20.7	62.1	759		783	786	768	672
	34.5	34.5	763		789	807	742	683
	34.5	68.9	798		860	873	832	748
	34.5	86.2	806		871	878	849	757
	34.5	103.4	801		881	897	849	763
	68.9	68.9	891		995	1018	970	899
	68.9	137.9	888		1049	1029	1013	938
	68.9	165.8	887		1068	1048	1028	949
	68.9	206.8	885		1082	1054	1038	952
	103.4	68.9	983		1161	1143	1101	1017
	103.4	103.4	991		1197	1171	1146	1082
	103.4	156.7	978		1229	1186	1188	1102
	103.4	206.8	968		1239	1185	1197	1118
	137.9	68.9	1055		1302	1264	1250	1191
	137.9	103.4	1065		1337	1294	1305	1224
	137.9	137.9	1057		1355	1299	1332	1233
	137.9	209.7	1029		1354	1283	1325	1218
	137.9	275.8	994		1332	1261	1314	1182

Mix 3FB-1C	Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)			
Curing Period			30 Days			
Sample			K1-A	K1-B	K1-C	K1-D
3.0% Bitumen	20.7	20.7		680	625	652
	20.7	41.4		757	692	736
1.0% Cement	20.7	51.8		779	707	774
	20.7	62.1		794	738	802
	34.5	34.5		802	755	824
	34.5	68.9		877	831	933
	34.5	86.2		895	840	954
	34.5	103.4		909	859	964
	68.9	68.9		1000	932	1063
	68.9	137.9		1040	998	1135
	68.9	165.8		1055	1023	1138
	68.9	206.8		1064	1038	1148
	103.4	68.9		1110	1048	1190
	103.4	103.4		1153	1103	1246
	103.4	156.7		1179	1156	1285
	103.4	206.8		1198	1192	1295
	137.9	68.9		1238	1168	1325
	137.9	103.4		1276	1218	1373
	137.9	137.9		1293	1265	1402
	137.9	209.7		1307	1298	1416
	137.9	275.8		1310	1299	1401

Mix 3FB-1C	Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)					
Curing Period			45 Days					67 Days
Sample			K1-A	K1-B	K1-C	K1-D		K1-C
3.0% Bitumen	20.7	20.7	806	896	811	921		669
	20.7	41.4	949	1002	898	1071		838
1.0% Cement	20.7	51.8	979	1027	919	1097		869
	20.7	62.1	986	1051	927	1119		884
	34.5	34.5	984	1038	934	1123		865
	34.5	68.9	1066	1124	1012	1217		970
	34.5	86.2	1077	1142	1025	1225		996
	34.5	103.4	1079	1154	1044	1237		1015
	68.9	68.9	1152	1235	1114	1315		1095
	68.9	137.9	1168	1261	1149	1339		1195
	68.9	165.8	1177	1274	1167	1350		1223
	68.9	206.8	1180	1302	1187	1364		1257
	103.4	68.9	1253	1323	1222	1383		1215
	103.4	103.4	1267	1356	1251	1421		1262
	103.4	156.7	1264	1377	1291	1435		1365
	103.4	206.8	1267	1391	1309	1457		1386
	137.9	68.9	1321	1423	1310	1468		1304
	137.9	103.4	1328	1433	1334	1493		1360
	137.9	137.9	1336	1441	1343	1485		1424
	137.9	209.7	1331	1452	1384	1509		1489
	137.9	275.8	1320	1442	1353	1500		1489

TxRM test results for samples FB3-C2

Mix 3FB-2C	Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)				
Curing Period			1 Day	14 Days			
Sample			K2-B	K2-A	K2-B	K2-C	K2-D
3.0% Bitumen	20.7	20.7	714	649	735	748	719
	20.7	41.4	728	731	767	819	809
2.0% Cement	20.7	51.8	717	767	802	868	853
	20.7	62.1	701	786	826	890	880
	34.5	34.5	831	799	870	880	857
	34.5	68.9	842	879	908	986	980
	34.5	86.2	855	895	935	1016	1030
	34.5	103.4	865	892	956	1038	1046
	68.9	68.9	993	1069	1097	1179	1173
	68.9	137.9	986	1118	1155	1244	1212
	68.9	165.8	993	1123	1187	1266	1230
	68.9	206.8	1001	1140	1214	1288	1242
	103.4	68.9	1065	1226	1280	1350	1312
	103.4	103.4	1057	1279	1333	1401	1359
	103.4	156.7	1065	1324	1383	1458	1391
	103.4	206.8	1062	1348	1394	1464	1411
	137.9	68.9	1138	1401	1468	1523	1462
	137.9	103.4	1124	1455	1530	1583	1532
	137.9	137.9	1125	1489	1562	1613	1561
	137.9	209.7	1118	1495	1564	1619	1556
	137.9	275.8	1112	1484	1564	1579	1540

Mix 3FB-2C	Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)			
Curing Period			30 Days			
Sample			K2-A	K2-B	K2-C	K2-D
3.0% Bitumen	20.7	20.7	679	710	834	698
	20.7	41.4	749	767	916	776
2.0% Cement	20.7	51.8	785	790	954	810
	20.7	62.1	804	817	969	831
	34.5	34.5	823	858	993	871
	34.5	68.9	905	943	1080	984
	34.5	86.2	935	961	1105	1021
	34.5	103.4	950	993	1126	1031
	68.9	68.9	1047	1120	1248	1166
	68.9	137.9	1106	1206	1317	1265
	68.9	165.8	1100	1232	1336	1296
	68.9	206.8	1115	1259	1343	1307
	103.4	68.9	1169	1305	1393	1303
	103.4	103.4	1226	1367	1447	1401
	103.4	156.7	1278	1427	1508	1479
	103.4	206.8	1296	1456	1531	1517
	137.9	68.9	1323	1467	1555	1507
	137.9	103.4	1394	1531	1601	1565
	137.9	137.9	1433	1585	1639	1638
	137.9	209.7	1446	1605	1663	1661
	137.9	275.8	1431	1585	1658	1665

Mix 3FB-2C	Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)					
Curing Period			45 Days					67 Days
Sample			K2-A	K2-B	K2-C	K2-D		K2-C
3.0% Bitumen	20.7	20.7	754	919	1046	1028		796
	20.7	41.4	917	1036	1185	1163		1032
2.0% Cement	20.7	51.8	962	1082	1226	1213		1079
	20.7	62.1	975	1105	1252	1238		1095
	34.5	34.5	990	1057	1230	1227		1052
	34.5	68.9	1117	1202	1343	1358		1189
	34.5	86.2	1144	1243	1340	1386		1210
	34.5	103.4	1159	1281	1354	1406		1262
	68.9	68.9	1252	1329	1469	1499		1324
	68.9	137.9	1311	1443	1503	1553		1413
	68.9	165.8	1324	1469	1569	1578		1463
	68.9	206.8	1321	1505	1561	1594		1499
	103.4	68.9	1380	1465	1576	1622		1417
	103.4	103.4	1410	1531	1571	1650		1466
	103.4	156.7	1438	1591	1656	1700		1568
	103.4	206.8	1441	1616	1684	1709		1620
	137.9	68.9	1466	1605	1670	1699		1494
	137.9	103.4	1508	1647	1684	1727		1559
	137.9	137.9	1509	1673	1731	1753		1620
	137.9	209.7	1494	1705	1750	1766		1694
	137.9	275.8	1492	1697	1709	1738		1717

ANNEX 2. Triaxial Resilient Modulus Tests. Role of Active Filler in Mechanical Properties of Foamed Bitumen Mixes.

Results showed in the next table are part of the information provided in Figure 5-4 of the Section 5.3.2 in this document.

Bitumen Content		3.0%				
Active Filler Type		Cement	CKD	Lime	Fly-Ash	- Without -
Active Filler Content		2.0%				0.0%
Water Conditioning		Cured & Soaked				
Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)				
20.7	20.7	816	747	617	481	446
20.7	41.4	894	832	679	527	455
20.7	51.8	930	863	694	544	465
20.7	62.1	958	894	712	548	467
34.5	34.5	952	885	725	570	482
34.5	68.9	1057	992	776	607	512
34.5	86.2	1074	1017	799	615	517
34.5	103.4	1091	1031	806	613	506
68.9	68.9	1262	1151	964	713	598
68.9	137.9	1294	1216	988	746	605
68.9	165.8	1308	1233	1006	758	605
68.9	206.8	1331	1247	1008	762	605
103.4	68.9	1402	1297	1100	797	680
103.4	103.4	1464	1373	1146	831	695
103.4	156.7	1475	1418	1161	866	697
103.4	206.8	1488	1429	1160	879	704
137.9	68.9	1521	1466	1235	907	777
137.9	103.4	1594	1514	1282	931	782
137.9	137.9	1603	1548	1298	947	786
137.9	209.7	1595	1560	1288	969	788
137.9	275.8	1596	1548	1270	974	790

ANNEX 3. Triaxial Resilient Modulus Tests. Durability of FB mixes with Cement as Active Filler

Results showed in the next tables are part of the information provided in Figure 5-8 of the Section 5.3.6 in this document.

Mix without FB and 1.0% of Cement (NoFB+1%Cem)

Bitumen Content		0.0%				
Active Filler Content		1.0%				
Cycles		1	5	10	14	20
Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)				
20.7	20.7	799	724	628	602	638
20.7	41.4	873	812	661	650	670
20.7	51.8	897	829	683	668	679
20.7	62.1	907	846	696	683	691
34.5	34.5	910	848	706	708	649
34.5	68.9	981	929	803	771	762
34.5	86.2	1006	946	819	798	780
34.5	103.4	1005	954	831	799	794
68.9	68.9	1144	1094	917	907	886
68.9	137.9	1170	1149	1000	946	935
68.9	165.8	1186	1160	1046	967	967
68.9	206.8	1197	1166	1085	980	989
103.4	68.9	1266	1240	1018	1018	1019
103.4	103.4	1317	1281	1114	1059	1058
103.4	156.7	1353	1324	1173	1099	1095
103.4	206.8	1362	1339	1203	1113	1108
137.9	68.9	1435	1407	1159	1141	1107
137.9	103.4	1474	1442	1225	1166	1157
137.9	137.9	1488	1477	1267	1189	1186
137.9	209.7	1490	1494	1278	1202	1196
137.9	275.8	1462	1478	1290	1200	1187

Mix with 3.0% of FB and without Cement (3%FB-NoCem)

Bitumen Content		3.0%				
Active Filler Content		0.0%				
Cycles		1	5	10	14	20
Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)				
20.7	20.7	424	475	511	519	469
20.7	41.4	455	478	560	538	603
20.7	51.8	465	490	564	556	608
20.7	62.1	467	501	575	566	607
34.5	34.5	482	511	593	594	607
34.5	68.9	512	556	632	630	662
34.5	86.2	517	560	636	637	671
34.5	103.4	506	564	642	639	666
68.9	68.9	598	650	719	728	746
68.9	137.9	605	664	727	742	761
68.9	165.8	605	663	735	748	768
68.9	206.8	605	665	732	750	771
103.4	68.9	680	730	795	802	816
103.4	103.4	695	744	812	821	837
103.4	156.7	697	756	821	841	844
103.4	206.8	704	762	820	837	849
137.9	68.9	777	815	875	885	881
137.9	103.4	782	830	883	899	899
137.9	137.9	786	836	892	905	899
137.9	209.7	788	839	891	907	907
137.9	275.8	790	836	883	896	909

Mix with 3.0% of FB and 1.0% of Cement (3%FB+1%Cem)

Bitumen Content		3.0%				
Active Filler Content		1.0%				
Cycles		1	5	10	14	20
Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)				
20.7	20.7	792	809	692	738	768
20.7	41.4	890	890	766	807	951
20.7	51.8	913	912	791	834	989
20.7	62.1	920	924	808	857	994
34.5	34.5	920	930	812	870	1000
34.5	68.9	997	999	888	933	1077
34.5	86.2	1004	1020	918	954	1097
34.5	103.4	1000	1021	941	957	1099
68.9	68.9	1105	1148	982	1057	1178
68.9	137.9	1129	1170	1066	1099	1222
68.9	165.8	1124	1185	1077	1107	1238
68.9	206.8	1128	1184	1098	1122	1242
103.4	68.9	1194	1252	1073	1156	1260
103.4	103.4	1231	1282	1125	1198	1304
103.4	156.7	1256	1315	1176	1232	1333
103.4	206.8	1259	1328	1215	1238	1343
137.9	68.9	1322	1382	1194	1289	1346
137.9	103.4	1349	1414	1220	1312	1391
137.9	137.9	1367	1434	1257	1354	1410
137.9	209.7	1364	1441	1302	1355	1405
137.9	275.8	1347	1448	1307	1352	1397

Mix with 3.0% of FB and 2.0% of Cement (3%FB+2%Cem)

Bitumen Content		3.0%				
Active Filler Content		2.0%				
Cycles		1	5	10	14	20
Confining Pressure (kPa)	Deviator Stress (kPa)	Triaxial Resilient Modulus (MPa)				
20.7	20.7	816	807	682	739	785
20.7	41.4	894	924	839	793	1008
20.7	51.8	930	971	877	822	1048
20.7	62.1	958	996	906	837	1070
34.5	34.5	952	1009	908	871	1033
34.5	68.9	1057	1108	1022	928	1204
34.5	86.2	1074	1133	1057	941	1200
34.5	103.4	1091	1128	1080	939	1222
68.9	68.9	1262	1275	1193	1061	1333
68.9	137.9	1294	1337	1247	1122	1381
68.9	165.8	1308	1354	1270	1167	1405
68.9	206.8	1331	1350	1279	1215	1428
103.4	68.9	1402	1364	1318	1208	1452
103.4	103.4	1464	1463	1368	1250	1512
103.4	156.7	1475	1536	1414	1345	1544
103.4	206.8	1488	1567	1434	1402	1557
137.9	68.9	1521	1578	1436	1356	1587
137.9	103.4	1594	1646	1494	1437	1613
137.9	137.9	1603	1699	1528	1486	1638
137.9	209.7	1595	1744	1543	1562	1640
137.9	275.8	1596	1752	1531	1561	1631

ANNEX 4. Statistical Analyses for ITFT Results

Results showed in the next tables are part of the information provided in section 6.4 of this document.

General Lineal Model (GLM)

ANOVA (GLM). Variable: ITFT Modulus (Stiffness)		
Parameters	Levels (Values)	P
Bitumen Content	3 (1, 2, 3)	0.000
Cement Content	3 (0, 1, 2)	0.000
Stress Ratio	3 (20, 30, 40)	0.000

ANOVA. Tukey Method for 95% confidence. Variable: ITFT Modulus (Stiffness)

Bitumen Content	**N**	**Mean**	**Group**
2.0	317	1,089	A
3.0	90	863	B
1.0	108	800	C
Cement Content	**N**	**Mean**	**Group**
2.0	108	1,217	A
1.0	306	1,047	B
0.0	101	489	C
Stress Ratio	**N**	**Mean**	**Group**
20	162	1,198	A
30	194	891	B
40	159	662	C

Definitions:

- P: P-Value
- N: The number of observations included for each level of the factor.
- Mean: The mean of the observations for each level. These sample means provide an estimate of the population means for each level.

ANOVA Unidirectional (Bitumen as variable)

```
                                 Individual 95% Confident Intervals for Mean
Mix        N   Mean   Est.Dev.  --------+---------+---------+---------+-
FB2C1 158   984,1     430,5                         (-----*-----)
FB3C1 141   789,2     369,5      (-----*-----)
FB1C1 120   790,9     332,5     (------*------)
p = 0,000 < 0,05                --------+---------+---------+---------+-
                                       800       900      1000      1100
```

ANOVA Unidirectional (Cement as variable)

```
                                 Individual 95% Confident Intervals for Mean
Mix        N   Means   Est.Dev.  -----+---------+---------+---------+----
FB2C0 128   572,8      333,7     (---*--)
FB2C1 159   978,5      434,9                         (--*--)
FB2C2 142  1204,2      402,4                                    (--*--)
p = 0,000 < 0,05                 -----+---------+---------+---------+----
                                     600       800      1000      1200
```

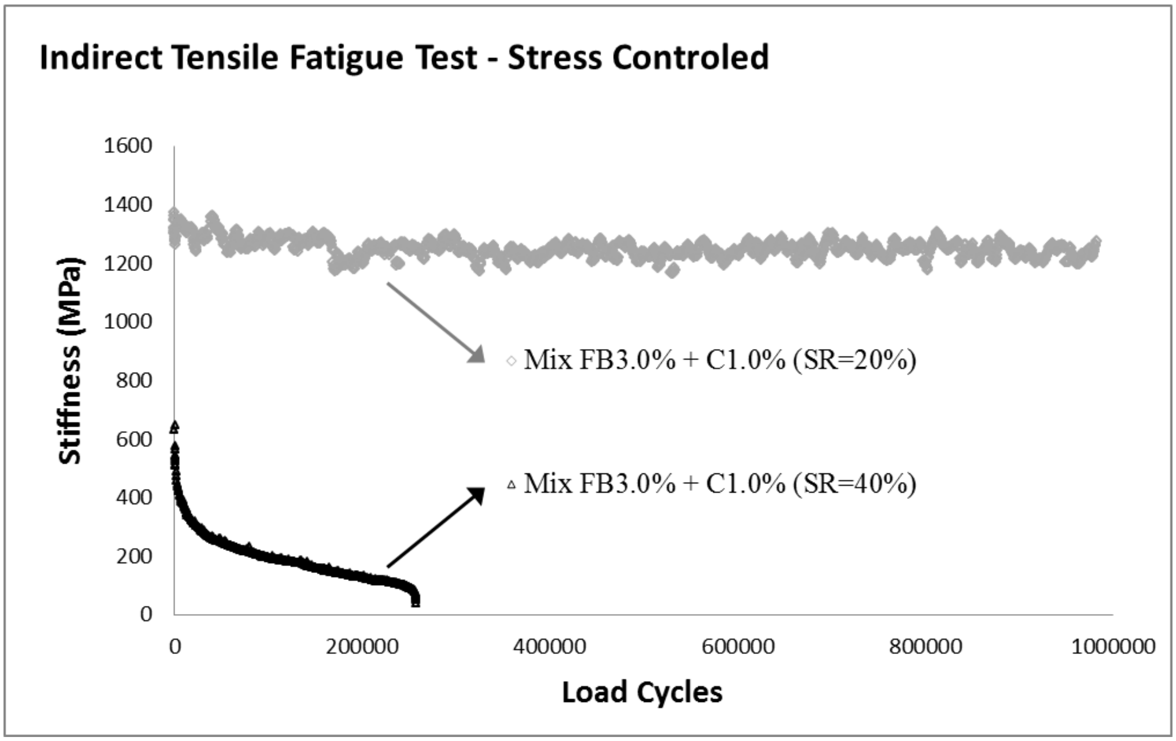
Definitions:

- N: The number of observations included for each level of the factor.
- Mean: The mean of the observations for each level. These sample means provide an estimate of the population means for each level.
- Est.Dev: The sample standard deviations for each level. Analysis of variance assumes that the population standard deviations for all levels are equal.

ANNEX 5. Indirect Tensile Fatigue Tests (ITFT)

Results showed in the next figure are part of the information provided in Figure 6-4 of the Section 6.4.2 in this document.

ITFT results for longer load cycles



ANNEX 6. Adapted Mix Design Procedure (Preliminary Proposal)

This mix design procedure was adapted from guides proposed by Asphalt Academy of South Africa (2002). It includes all the recommendations given by this research work. Main differences are:

- Optimum bitumen content is selected using mixes without cement (or any other active filler)
- Selection of the optimum cement content is carried out considering properties of the FB mix in fresh conditions, representing properties of the mix during the first days after construction, as well as in accelerated cured condition, representing mixes with maximum achievable strength. In addition, selection of the cement content must consider the structural analysis of the pavement designed.

The mix design procedure is summarized in the next Figure.