FOAM

Duurzame funderingen door in situ recycling met schuimbitumentechnologie

PART III:

Mix design of BSM

EMIB
Energy & Materials in Infrastructure & Buildings
University of Antwerp

Odisee
DE CO-HOGESCHOOL

Opzoekingscentrum voor de Wegenbouw
Samen voor duurzame wegen

AGENTSCHAP INNOVEREN & ONDERNEMEN
Vlaanderen is ondernemen

Project "Duurzame funderingen door in-situ recycling met schuimbitumentechnologie"
"FOAM-project"

Title report: Part III Mix Design of BSM

Version and date: 03-02-2023 v.1
Status report: Final

Project Coördinator : Wim Van den bergh; wim.vandenbergh@uantwerpen.be ; +32 486 79 86 86

Reporting : Ecem Nur Barisoglu; ecemnur.barisoglu@uantwerpen.be
Karolien Couscheir; karolien.couscheir@uantwerpen.be

Acknowledgements:
We are grateful for the help provided by Wynand van Niekerk from BSM Laboratories (Pty) Ltd in South Africa to finalize the mix design. We would also like to extend our deepest gratitude to Loudon International, who supported us in completing our project.

Project funded by VLAIO – Flemish Government (Grant HBC.2020.2094) and in collaboration with industry

Project Team Partners: UAntwerpen, BRRC and Odisee

Project Sector Partners: Agentschap Wegen en Verkeer, stad Antwerpen, North Sea Port, Lareco, COPRO, Topcon, VlaWeBo, Cementbouw, Ingevity, BESIX, Viabuild, Colas, Willemen Infra, DIBEC, Wirtgen Group, De Bruycker-kemp, Bomag

1 Introduction

1.1 Project Description

The Tetra project HBC.2020.2094 "Sustainable base layers through in-situ recycling with foamed bitumen technology" - referred to as the "FOAM project"- has the overall objective of technically, economically, and ecologically testing and evaluating foamed bitumen technology for base layers, leading to a more sustainable base. The results are disseminated for further implementation. The project started on November 1st, 2020 and was finalised on 31 October 2022. The project was carried out by the University of Antwerp, the Belgian Road and Research Centre, and Odisee University College. The project was funded by VLAIO.

To obtain sustainable road structures, attention should not only be paid to the asphalt pavement, but the base layer also plays a decisive role. Bitumen Stabilised Material "BSM" is a material in which the granulates - in this project 100 % reclaimed asphalt - are held together by maximum 3 % foamed bitumen or bitumen emulsion. The FOAM project tested the use of BSM as a base material, investigating its structural, environmental and economic impact. The project resulted in a method for mixture design and structural road design with BSM and was demonstrated through the construction of pilot sections. These trial sections are further followed up by a monitoring campaign.

The report of the FOAM project consists of 6 reports.

- PART I: Management report FOAM project
- PART II: Market Potential for BSM in Flanders
- PART III: Mix design of BSM
- PART IV: Structural design of pavements with BSM
- PART V: Sustainability Assessment of pavements with BSM
- PART VI: Synthesis report of test sections

This report " PART III: Mix design of BSM" describes the suitable materials for foamed bitumen stabilisation and explains the mix design procedure to evaluate the BSM constituents such as aggregate or RAP, foamed bitumen, active filler, and their different combinations to achieve the best performance of BSM.

1.2 Bitumen Stabilised Materials (BSM)

Bitumen stabilisation is a pavement rehabilitation technique that uses the existing and/or imported granular material and binds it together with bitumen to produce a flexible pavement material for use in base and subbase pavement layers. Bitumen stabilised granular materials (BSMs) are produced using either foamed bitumen or bitumen emulsion. In recent years, significant progress has been made in the design methods for foamed bitumen stabilised materials (BSM-Foam) that allow using high percentages of reclaimed asphalt pavement material (RAP).

Foamed bitumen is a mixture of water, air, and hot bitumen. In small quantities of cold water (2-3 % by weight of bitumen) and air under pressure is injecting into hot bitumen (between temperatures of 150 and 180°C), as a result, an instant expansion of the bitumen to about 15 times its original volume occurs. And spraying the foamed bitumen into the mixing drum coats some fine particles (typically < 0.063 mm in diameter), creating a mortar rich in bitumen between the coarse particles. As a result, the performance of the material is enhanced by combining the coated fines and active filler (i.e. cement, lime, fly ash). BSM-Foam is generally regarded as cold-mixes, as they are placed and compacted at

ambient temperature. This indicates that the bonding mechanism of BSM-Foam mixtures differs from hot mix asphalt. Therefore, an appropriate mixture design is essential to increase the use of this technology in the rehabilitation of pavements in Flanders.

This report aims to investigate the international methods used to determine the key design parameters that need to be considered in the foamed bitumen mix design procedure to provide a complete BSM-Foam mix design procedure for Flanders. The following documents were reviewed:

- Technical guideline: Bitumen Stabilised Materials: A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials, TG2 (Sabita, 2020)
- Guide to Pavement Technology Part 4D: Stabilised Materials, AGPT04D -19 (Austroads, 2019)

Based on this review and the findings in the literature, a mix design procedure is proposed for Flanders.

1.3 South African Method - TG2

In South Africa, there has been significant research and development into procedures and specifications for foamed bitumen stabilisation. TG2 guideline covers the key performance considerations for BSMs, followed by a detailed analysis of the tests to evaluate the characteristics of the components. Permanent deformation and moisture susceptibility are the two primary distress mechanisms that need to be considered in the mix design of BSMs. Because adding more than 1% of cement results in the material acting like cement-treated material, which diminishes the flexibility benefit. Therefore, the TG2 guideline is applicable for BSM mixtures containing a maximum of 1% cement.

The mix design of BSM characterises BSM-Foam mixes by indirect tensile strength (ITS) test in dry and soaked conditions to select the active filler type and bitumen content. Subsequently, the ITS testing is supplemented by monotonic triaxial testing to enable accurate and reliable refinement of the amount of bitumen required.

1.4 Austroads Method

Austroads has a developed mix design method for foamed bitumen mixes. This method is commonly recommended for projects using bitumen contents of 2.5% to 3.5% and hydrated lime/cement contents of 1–2% for host materials with up to 20% RAP Therefore, the Austroads mix design procedure recommends employing indirect tensile modulus (ITSM) and indirect tensile strength (ITS) tests to evaluate the performance of the BSM-Foam mixtures. Moreover, the latest report published in Austroads developed a fatigue relationship to predict the performance of foamed bitumen stabilised materials to improve the mix design procedure. According to this report, it was found that combining the materials' flexural strength with the flexural modulus can provide a means of predicting the fatigue behaviour of BSM-Foam materials.

2 Materials Suitable for Foamed Bitumen Stabilisation

2.1 Aggregate

Various materials are suitable for stabilising with foamed bitumen and highly depend on the quality of the aggregate. Virgin or recycled aggregates have been successfully used in the foamed bitumen stabilisation. It is important to note that due to cost-benefit considerations, RAP is commonly used material in the process. Additionally, when in-situ recycling is applied, the selection of the aggregate is limited to the materials present in the existing pavement.

2.1.1 Aggregate plasticity

Plasticity limits assist in determining the suitability of an aggregate for stabilisation and may be used to determine the application rate and type of secondary binder (cement and/or lime, fly ash). When working with virgin aggregate, the plasticity of the fine fraction of the aggregate is critical. According to TG2 guideline, materials with a plasticity index (PI) higher than 6 are not applicable to stabilise with foamed bitumen, while Austroads recommends a maximum PI of 10. If plasticity is the concern in the materials, both guidelines recommend to treat the material with lime to reduce the PI. **The critical value of 6 is also recommended for Flanders.**

2.1.2 Reclaimed Asphalt Pavement (RAP) material activity

The RAP is likely to be "active," that is, sufficiently soft to interact with other binders, if the penetration of the recovered binder from RAP exceeds 10 dmm and the binder appears shiny black and feels sticky. Further examination is thus necessary. If the RA is active, more fractions must be blended in before bitumen can be stabilised, such as 15% to 25% crusher dust. This will provide an angular sand skeleton that will improve the shear resistance of the mix. Before starting the mixture design procedure, a simple procedure should be followed to determine the activity level of the RAP material used.

1. Heating the representative amount of RAP to 70 °C.
2. Compact four specimens (D:100 mm) with the Superpave gyratory compactor (N=30).
3. Water bath of the specimens for 24 hours at 25 °C.
4. Carry out the ITS_{wet} test following the European Standard (EN 12697-23).

The binder is inactive when ITS values are less than 100 kPa, and active when ITS values are greater than 100 kPa.

2.1.3 Strength

The tendency for breaking down under compaction depends on how strong the aggregate is. Since foamed bitumen stabilisation concentrates the bitumen on the finer fractions, any extra fines produced during the material's subsequent compaction have a detrimental impact on its shear characteristics and its sensitivity to moisture. The "breakdown coefficient" is calculated for the percentages passing the 5 mm, 2 mm, 0.425 mm and 0.063 mm sieves, as given in Table 1, and is then summed up. The material should be subjected to a durability test in cases where the Breakdown Coefficient is higher than 20 or the percentage of materials passing through a sieve with a 0.063 mm opening difference is 5% or more.

Table 1: Breakdown Coefficient

Sieve Size (mm)	Passing Sieve Size (%)		Difference (%)
	Before Compaction	After compaction	
5	42	51	9
2	31	35	4
0.425	14	19	5
0.063	8	12	4
Breakdown Coefficient			22

2.1.4 *Durability*

The durability as explained in TG2, does not apply solely to the moisture resistancse of a BSM or the resistance to ageing of the bitumen in the mix. It also applies to the durability of the untreated aggregate before stabilisation. The Durability Mill Index (DMI) is the preferred test parameter for such an evaluation. This test identifies the potential durability of aggregates in terms of breakdown and generation of excessive plastic and non-plastic fines. The test has the most potential to simulate the likely breakdown of the materials in service, and is applicable to all material types. Although acceptable limits for these tests were initially applicable to granular materials only, these limits have been adapted for pretreated (parent) materials for use in the selection of component aggregates for bitumen stabilisation. Where materials are blended, the DMI value must satisfy the worst-case requirement of the individual constituents. The DMI requirements are only applicable to poor material classes. RAP is excluded from DMI requirements. The DMI limits recommended by TG2 is shown in Table 2.

Table 2. Durability Mill Index, Limit for Rocks and Soils

Aggregate Type	Rock and Soil Group	DMI Limit	$P_{0.425}$ (%) after DMI
Granites, gneiss, granite	Acid Crystalline	< 420	< 35
Hornfels, quartzite	High silica		
Dolomite, limestone	Carbonate		
Ironstone, magnesite, magnetite	Metalliferous		
Calcrete, ferricrete, silcrete	Pedogenic materials	< 480	< 40
Sandstone, siltstone, conglomerate	Arenaceous	< 125	< 35
Greywacke, tillite	Hornfels, Diamictite		
Mudrock, phillites, shale	Mudrock		
Basalt, Dolerite, Gabbro	Basic crystalline	< 80	< 35
	Argillaceous	Not Suitable	

2.1.5 *Aggregate temperature*

According to both Austroads and TG2 guidelines, the degree of dispersion and the characteristics of the mix are significantly influenced by the aggregate temperature before the production of BSM-Foam. The aggregate particle size that can be coated increases with higher aggregate temperatures. Therefore, temperature measurements of the aggregate are crucial before beginning laboratory or field production. It is not recommended to attempt field mixing with aggregate temperatures below 15 °C. When the aggregate temperature is between 12 °Cand 15 °C, mixes should only be made with bitumen

with remarkable foaming properties (expansion ratio and the half life), and under the guidance of a professional with extensive BSM expertise.

2.1.6 Grading

An important factor to take into consideration is the fine content of the aggregate, which should ideally be over 5%, because the foamed bitumen coats the fine particles (< 0.063 mm). Therefore, the mastic (mix of bitumen and fines) has a significantly higher viscosity than the raw bitumen and acts as a mortar between coarse aggregates, increasing the material's durability and strength. However, the relationship between the bitumen and fines content in the mortar must be considered since excessive bitumen tends to function as a lubricant and weaken the mortar's strength and stability. The behaviour of foamed asphalt mixes differs from hot-mix asphalt in that the aggregate interlock has a higher impact on stability than the viscosity of the binder. This indicates that foamed asphalt mixes are less sensitive to temperature than hot-mix asphalt, and it also supports the conclusion that the grade of bitumen employed does not have a critical influence on foamed asphalt mixes. The grading envelope recommended by TG2 is also adopted in this report.

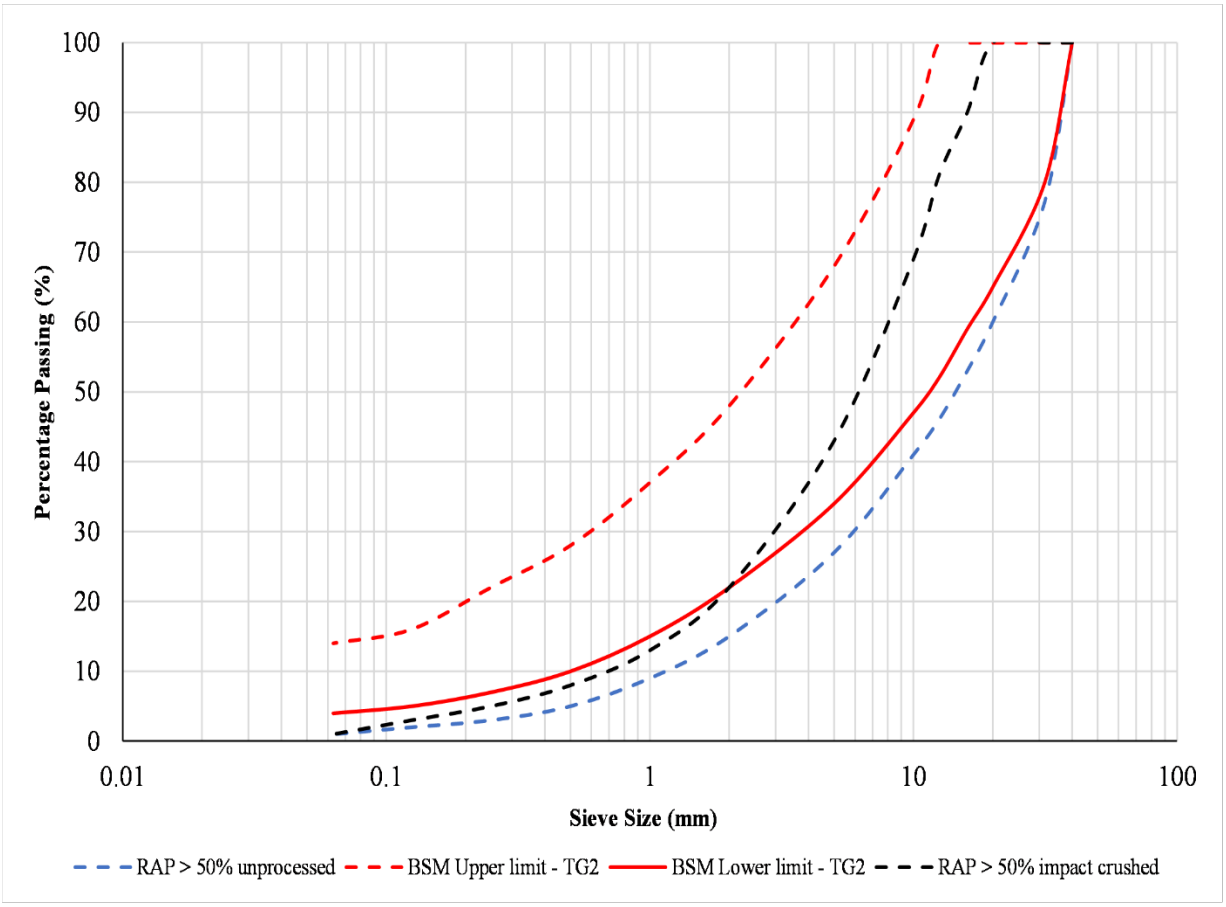

Figure 1. Grading envelope for BSM-Foam and RAP (TG2)

Table 3. Recommended grading for BSM-Foam (TG2)

Sieve size (mm)	Percentage passing each sieve size (%)			
	BSM lower limit	BSM upper limit	RAP > 50% unprocessed	RAP > 50% impact crushed
40	100	100	100	100
31.5	80	100	77	100
20	65	100	60	100
16	59	100	53	90
12.5	52	100	46	81
10	47	89	41	69
5	34	68	27	43
2	22	48	15	22
1	15	37	9	13
0.5	10	28	5	8
0.25	7	22	3	5
0.125	5	16	2	3
0.063	4	14	1	1

2.2 Bitumen

Although softer and harder bitumen has been used effectively in the past and may be used when available, bitumen types with penetration grade 70/100 are typically chosen for BSM-foam. Harder bitumen is often avoided for practical reasons since it won't disperse as well in the mix due to the poor quality of foam. Alongside the bitumen's penetration grade, the foaming properties of each bitumen type need to be tested, namely Expansion ratio (ER) and Half-life (HL).

Expansion Ratio (ER) is defined as the ratio between the maximum volume of bitumen achieved in the foamed state to the volume of the original bitumen. It is a measure of the viscosity of the foam and determines how well bitumen will be dispersed in the mix. During foam formation at a given bitumen temperature and foaming water content, the expansion ratio rises to a maximum value and then reduces with time.

The half-life (HL) is the time it takes a given foamed bitumen to settle to half its maximum volume or expansion ratio. It measures the stability of any given foam and provides an indication of its rate of collapse. It also determines the length of the mixing period of foamed bitumen with the moist aggregates.

Table 4. The minimum limits for ER and HL

Aggregate Temperature	15 °C to 25 °C	> 25 °C
Expansion Ratio, ER (times)	≥ 10	> 8
Half-life, HL (secs)	≥ 8	≥ 6

Appendix I explains how to determine the bitumen temperature and the percentage of water addition needed for a particular bitumen source to achieve the optimal foaming qualities with maximum

expansion ratio and half-life. To find the best quality of the bitumen ER and HL are measured at three different temperatures ranging from 160 °C to 190 °C.

The application rate (%) of water injected into the expansion chamber to produce the foamed bitumen is one of the main parameters affecting the foaming qualities. A higher injection rate of water into the hot bitumen results in more expansion (higher ER), but it also has a quicker half-life (1/2). Figure 2 illustrates the determination of the optimum water addition to producing foamed bitumen. The two main variables affecting foam quality are bitumen temperature and water application rate. Usually, higher bitumen temperatures result in better foam quality.

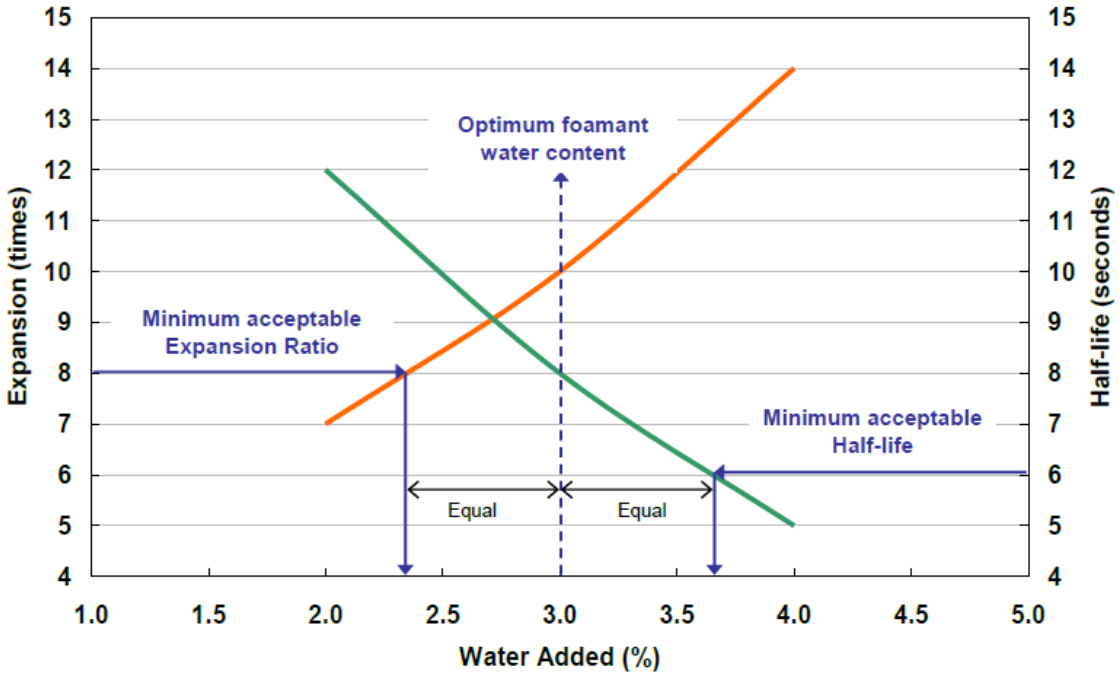

Figure 2. Determination of Foam Characteristics: Optimum Water Addition to Hot Bitumen (TG2)

2.3 Active Filler

Fillers that chemically alter the qualities of the mix are referred to as active fillers in this report. The purpose of incorporating active filler in BSM-Foam is expressed in the guidelines (TG2, Austroads)

- Improve the adhesion of the bitumen to the aggregate.
- Improve dispersion of the bitumen in the mix.
- Modify the plasticity of the natural materials (reduce PI).
- Increase the stiffness of the mix and rate of strength gain.
- Accelerate curing of the compacted mix.

Commonly ordinary early-strength cement and hydrated lime are used in BSM-Foam mixtures. Depending on the project requirements, fly ash, quick lime and various types of cement can also be utilised. Availability, price and the performance of the active filler in BSM-Foam mixtures determine which active filler type is suitable for the project. In the mix design, ITS_{wet} values are used as critical values to determine the type of active filler.

The active filler addition is limited to a maximum of 1% by mass of the dry aggregate in the TG2 guideline, while Austroads recommends between 1% to 3%. Both approaches recommend using lime when the parent material's plasticity is a concern (above 6%). Treating material with hydrated lime

will modify the mixture and reduce plasticity. If this scenario occurs, the application rate of hydrated lime can increase. When adding lime to materials containing amorphous silica, caution must be used since the pretreatment can increase the strength and stiffness of the composite (e.g. ITS_{DRY} well in excess of 300 kPa). Since the active filler dominates the bitumen's contribution to durability, this causes the material to lose some of its flexibility. When pretreating with lime, sufficient time must be allowed for modification to take place before bitumen treatment. Depending on the material type, 4 hours or more may be necessary for effective lime modification.

When using cement as an active filler, the amount of time between mixing the cement with the material and applying the foamed bitumen should be minimised as much as possible both in the lab and on the job site. After cement comes into touch with a moist material, the hydration process starts instantly and assists the fine particles in adhering together. The quantity of filler available for bitumen dispersion in the BSM mix decreases with the duration of time between premixing with cement and bitumen application. Stockpiling BSM is governed by this idea. It is advised to be careful with the time delay when cement is used as an active filler.

It is also recommended in this report that the application rate of active filler must be a maximum of 1% by mass of dry aggregate. The application rate might increase if only the performance of the mixture doesn't meet the requirements. However, it is advised to first check the suitability of different types of active filler at a 1% application rate before increasing the application rate.

3 Mix Design Procedure for BSM-Foam

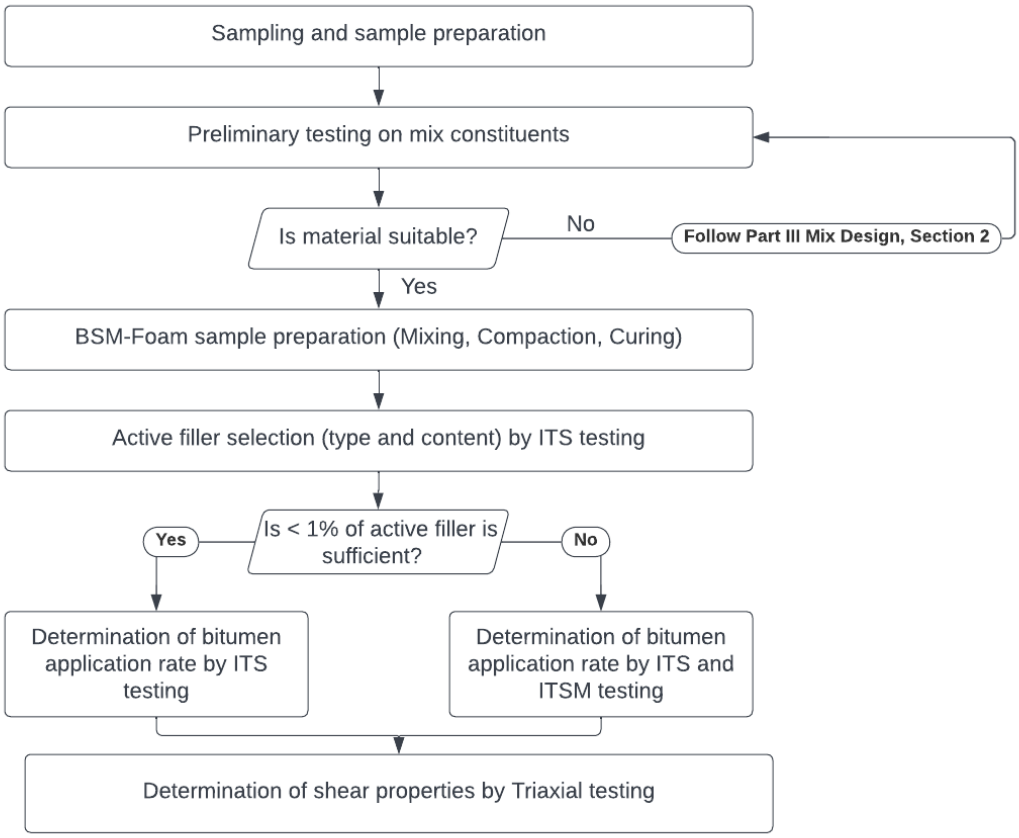

Figure 3. Mix Design Procedure for BSM-Foam

The constituents are used in conjunction with each other to help build a structurally robust paving material. The currently used approaches for foam bitumen mix designs are based on various mix formulations and interpretations. The procedures and factors that must be taken into account in order to create an effective mix design are shown in Figure 3.

3.1 Sampling and Sample Preparation

When undertaking a mix design for in situ stabilisation, the samples of pavement material selected for testing must represent the material to be stabilised. Therefore, the selection of representative samples for testing requires bulk samples to be classified according to a visual description and the results of standard laboratory classification tests (EN 932-1). The material must be sampled from test pits excavated in the existing pavement or extracted from stockpiles of material that will be used for construction. Test pits are commonly used for exposing and sampling foundation and construction materials. The test pit must be large enough to permit detailed examinations of the material in situ to be conducted or to obtain large, undisturbed samples as required by the investigation. Test pits are usually located in the outer wheel path of trafficked lanes. A sample of sufficient size from each pavement layer should be placed in a separate container or thick plastic bag and sealed to avoid loss of moisture content. Every container/bag must be clearly labelled, showing the appropriate information, e.g. test pit ID, the layer (e.g. upper subbase) and the thickness of the layer.

Sampling from the stockpile should be taken carefully. Segregation often occurs when materials are stockpiled; therefore, ensuring representative samples from stockpiles is difficult. Consequently, taking the samples from different locations around the stockpile is crucial. Extracting samples must be placed into a sealed container or plastic bag. Samples should be stored in an area where contamination cannot occur. Additionally, it is advised to cover the stockpile to protect it from environmental effects (e.g. UV light, rain), because external factors could negatively affect the BSM-Foam mixture performance.

3.2 Preliminary Testing

After selecting the most suitable parent material (aggregate), considering the criteria mentioned in section 2.1, aggregate, critical in the mix design, should be subjected to preliminary testing.

3.2.1 Moisture content and hygroscopic moisture content

Particular attention should be given to the mineral aggregate's moisture content when mixing with the foamed bitumen. Moisture is necessary for field compaction, bitumen dispersion during mixing, and softening and breakdown of aggregate agglomerations. Excessive water in the mixture reduces strength, accelerates curing, and affects aggregate coating, while inadequate water reduces workability, bitumen dispersion, and compaction. Bearing in mind that the moisture required for foaming the bitumen differs from the moisture needed for mixing and compaction. However, since moisture is critical for mixing and compaction, these operations should be considered when optimising the moisture content.

Hygroscopic moisture content is a term that stands for the moisture content of air-dried material. It is an important step to determine the moisture content of the end material. Two air-dried samples, each approximately 1 kg, are used to determine the material's hygroscopic (air-dried) moisture content following the standard test procedure EN 1097-5 for moisture determination.

3.2.2 Modified Proctor

The Modified proctor test establishes a relationship between moisture content and dry density. The results define the correct moisture content for optimum mixing and compaction, meaning the optimum water content and maximum achievable dry density. In addition, the maximum dry density is used as a reference when determining the degree of compaction of a constructed layer. Maximum dry density (MDD) and Optimum moisture content (OMC) are defined by following EN 13286-2 Modified proctor test procedure. The moisture content of the material needs to be between 60 and 75% of the optimum moisture content (OMC) (from MDD compactive energy) during mixing and applying the foamed bitumen. And the required moisture content for laboratory compaction is 100% OMC "Fluff Point" is defined as the ideal moisture content at the time of mixing, the moisture content at which the material achieves maximum volume.

Figure 4. Modified Proctor Test

3.2.3 Grading

The recommended optimum particle size distributions of TG2, adopted in this report, are shown in Figure 1. Materials that fall outside the recommended grading envelopes, whether coarse or fine, can be rectified by adding the deficient fractions. The grading should be consistent inside the envelope. A poorly graded material is difficult to compact, and the consequent low density achieved will significantly affect the strength, especially under saturated conditions. The washed fine procedure must be followed on virgin aggregate materials used as the base course. However, the dry sieve analysis procedure can be followed when working with RAP Dry or washed sieve analysis should follow EN 933-2.

Figure 5. Sieve analysis

3.2.4 *Atterberg limits and RAP activity*

The Atterberg limit test, according to NBN CEN ISO/TS 17892-12, is used to determine the plasticity of the parent material to be stabilised. However, plasticity is not a concern when the RAP is the main component. Therefore, performing this test when working with RAP is not recommended. As explained in section 2.1.1., if the plasticity is >6, the material should be treated with lime. On the other hand, the main concern is the activity level of the binder when working with RAP Therefore, It is advised to follow the activity level test described in Section 2.1.2.

3.2.5 *Quartering method for material preparation*

The material must be prepared according to the quartering method before mixing to have the same gradation as in bulk samples. EN 932-2 procedure is followed for the quartering method.

3.2.6 *Foaming characteristics*

Foamed bitumen is characterised according to its expansion ratio and half-life duration (See section 2.2). Foaming characteristics of a specific bitumen are influenced by numerous factors, of which the most important are:

- Temperature of the bitumen. Foaming characteristics of most bitumen will improve at higher temperatures.
- Added water volume. In general, the bitumen expansion ratio will increase with the increase of added water, whereby the half-life duration will decrease.
- Pressure under which the bitumen is injected into the expansion chamber. Low pressures (under 3 bar) will negatively influence the expansion ratio and half-life duration.

The procedure explained in Appendix I should be followed to determine the bitumen's foaming characteristics and select the best quality.

Figure 6. Quartering method

3.3 Mixing

The technique the binders and aggregate are mixed is crucial because there is only a limited amount of mixing time before the foam collapses and returns back into a highly viscous state that has no affinity to coat particles. Therefore, the mixing process of BSM-Foam should be dynamic, and the mixer type is essential. The moisture content of the loose mixture can significantly affect the density to which the

test cylinders can be compacted. A twin-shaft pug-mill type mixer is recommended to use in the laboratory. The moisture content during laboratory mixing needs to be considered in 3 phases:

Phase 1: Add 60% of OMC (i.e. fluff point moisture) to the material plus active filler and mix for 30 seconds, before adding foamed bitumen.

Phase 2: Add foamed bitumen and mix for 30 seconds.

Phase 3: Add remaining 40% of OMC and mix for a further 30 seconds.

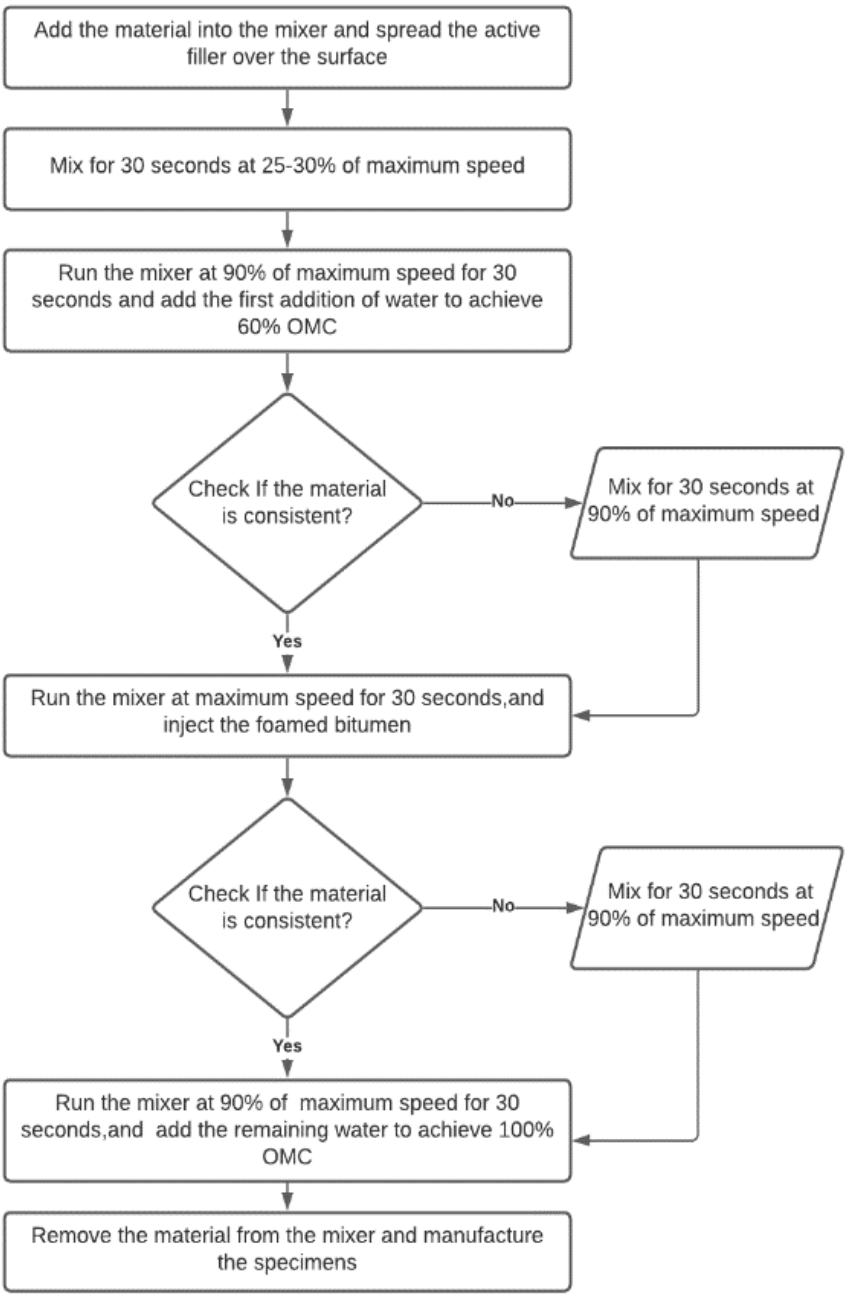

Figure 7. Mixing process of BSM-Foam mixtures

Figure 8. Mixing BSM

3.4 Compaction

An appropriate laboratory compaction technique should simulte the field compaction as closely as possible, more importantly, should achieve the expected void contents in the field. Several compaction technologies are available today, such as Marshall and gyratory compaction for asphalt, Modified Proctor, and vibratory hammers for granular layers. Impact compaction has some drawbacks while being the most widely used laboratory compaction method for granular materials. The specimens compacted in several layers might result in higher air voids at the interface between layers and do not provide the desirable repeatability and reproducibility. Therefore, gyratory and vibratory compactions are now commonly employed methods for BSM-Foam mixtures to simulate field compaction as closely as possible since impact compaction employs impact loads, whereas modern field compaction uses a combination of vibration, kneading, and increased pressures. Therefore, it is recommended to use either a Superpave Gyratory Compactor (SGC) or Vibrating Hammer to manufacture BSM-Foam mixtures, depending on the availability of the equipment. The procedure to compact with a Gyratory or vibrating hammer is explained in Appendix I. The compaction method differs for Indirect Tensile Strength (ITS) and Triaxial specimens.

Moisture content is critical in BSM-Foam mix design. Therefore the compaction of the BSM-Foam mixtures must be done within 30 minutes after the mixing is completed. Otherwise, the mixture loses moisture, and the desired compaction level is not achieved.

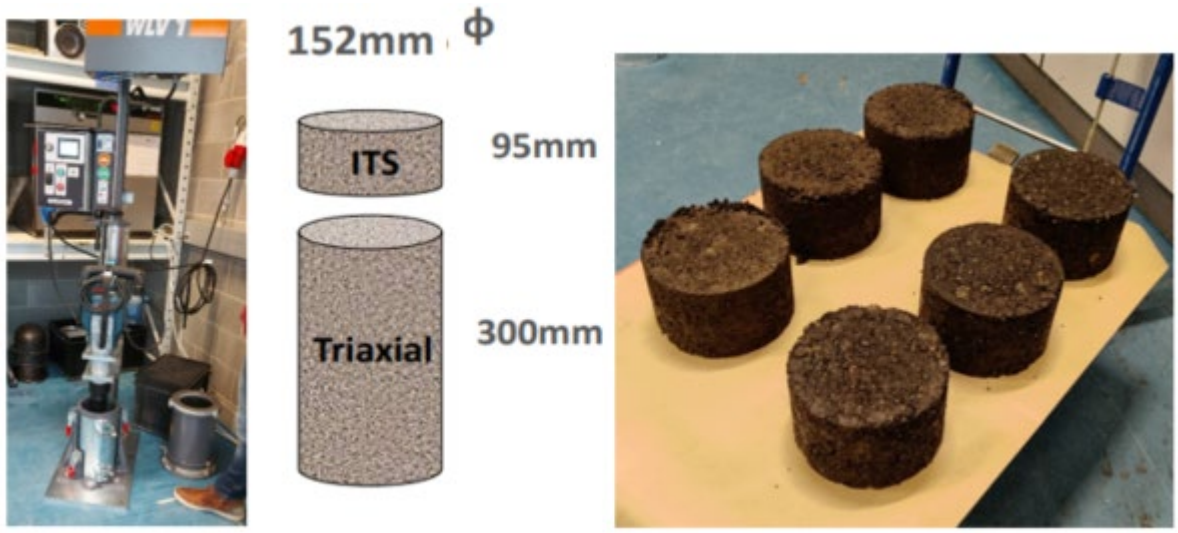

Figure 9. Compaction with vibrating hammer

3.5 Curing

Studies have shown that foamed asphalt mixes do not develop their full strength after compaction until a large percentage of the mixing moisture is lost. This process is termed curing. Curing is the process whereby the foamed asphalt gradually gains strength over time, accompanied by a reduction in moisture content. The moisture content present during the curing significantly impacted the mixture's ultimate strength. A laboratory mix design approach would need to simulate the field curing process to evaluate the properties of field mixes to laboratory-prepared mixes. It is almost impossible to simulate real field curing conditions in the laboratory since curing foamed asphalt mixtures in the field takes many months. Therefore, an accelerated laboratory curing procedure is required, in which the strength gain characteristics can be correlated with field behaviour, especially with the early, intermediate and ultimate strengths attained. This characterisation is especially important when structural capacity analysis, based on laboratory-measured strength values, is required. The curing procedure differs between ITS and Triaxial specimens, owing to the geometric differences, i.e. both specimens are 150 mm in diameter, but the ITS is 95 mm height versus the 300 mm height triaxial specimens.

Figure 10. Cured and tested specimens

ITS specimen curing

Six specimens of 150 ± 2 mm in diameter and 95 mm high are manufactured for each mix composition in the mix design. The procedure adopted from TG2 guideline follows:

1. Once the specimens have been extracted from their respective moulds and marked, they are placed in a forced draft oven at a temperature of 40 °C (±1 °C) and a minimum period of 72 hours (3 days). Until the moisture loss of the specimens is less than 10 gr within 4 hours, therefore it is important to control the moisture loss during curing in the oven until the specimens achieve constant mass. The curing of ITS specimens yields the "Dry" condition for testing.
2. The specimens are then taken out of the oven and placed into a cooling chamber at a constant temperature of 25 °C (±2 °C). After cooling for a minimum time of 20 hours, determine the bulk density of each specimen.
3. Exclude from testing any specimen with a bulk density that differs from the mean bulk density of all six specimens by more than 2.5%.
4. Place half of the specimens (3) under water in the soaking bath for 24 hours at 25 °C (± 2 °C). After soaking, remove the specimens from the water, surface dry with a piece of cloth and test immediately.

Triaxial specimen curing

Ten specimens, 150 mm in diameter and 300 mm height are manufactured for each test. The procedure adopted from TG2 guideline follows:

1. Leave all ten specimens overnight (at least 12h) in their respective moulds covered with a moist hessian cloth.
2. The following day, remove the specimens from their respective moulds, mark each one with an appropriate identification number and determine the bulk density of each specimen.
3. Calculate the mean and standard deviation of the bulk density for all ten specimens and determine if any of the specimens are outliers that must be excluded from further testing. If more than two specimens are excluded then the test must be abandoned, as detailed in the test method.
4. Place the specimens in a forced draft oven at a temperature of 40 °C (± 1 °C) for a period of 8 hours. After 8 hours, remove all specimens from the oven, place each in a loose-fitting plastic bag, seal the bags and return the specimens to the oven at 40 °C (± 1 °C) for a further 48 hours. This curing of the triaxial specimens yields an "Equilibrium" condition for testing.
5. Take the specimens out of the oven after 48 hours. Remove two of the specimens from their plastic bags and place under water in a soaking bath for 24 hours. Ensure that the specimens are submerged with at least 25 mm of water covering the top faces.
6. Place the remaining specimens in fresh (dry) plastic bags, seal and leave to cool to 25 °C (± 2 °C) for a minimum cooling period of 12 hours. The specimens are only removed from their plastic bags and weighed immediately before testing.
7. Remove the soaked specimen(s) from the water after soaking for 24 hours, surface dry and weigh before testing.

3.6 Indirect Tensile Strength (ITS) Testing

ITS testing is used to evaluate the mixtures' mechanical performance, select the active filler type and content, and the bitumen application rate. The recommended limits for its test results are provided in Table 5.

Table 5. Indirect Tensile Strength Limits for Classification (TG2)

Class	ITS Limits	
	ITS_{DRY} (kPa)	**ITS_{WET} (kPa)**
BSM1	> 225	> 125
BSM2	> 175	> 100

For ITS testing,cylindrical specimens with 95 mm height are prepared at room temperature (25 ± 2 °C) using the Vibrating hammer and Superpave Gyratory compaction methods, having 152 ± 2 and 150 ± 2 mm diameter, respectively. ITS test is followed according to EN 12697-23:2017. The reason to manufacture 95 mm height specimens is; that in the past, both indirect tensile strength (ITS) and unconfined compressive strength (UCS) has been used in the BSM-Foam mix design to evaluate engineering properties, mechanical properties and the failure mechanism. It has been found that ITS and UCS tests have a correlation (linear relationship), and ITS can be used to assess the flexibility of foamed bitumen stabilised mixtures. However, ITS and UCS (both) have limitations when it is followed by European or AASHTO standards, e.g. the recommended height range for ITS testing is 35 to 75 mm, and the plane stress is considered achieved while interpreting the results. Unlike hot mix asphalt mixtures, there is no direct relationship between the applied force and the stress at the centre of the specimen for BSM-Foam. Therefore, the height recommendation is 95 mm, i.e. ratio of diameter to height is 1.6. With this, a plane stress state will not be achieved, and ITS test is a more compressive test than a tension test, and it will give an indication of the flexibility of the specimens without performing the UCS test.

Figure 11. Indirect Tensile Strength (ITS) testing

3.6.1 Active filler selection

The ITS$_{WET}$ value is often taken into account when choosing the active filler type and content, but all test findings should be taken into account. ITS testing of different mixes made from the same sample determines whether an active filler is necessary and which active filler (e.g. cement, fly ash…) is appropriate for the material. The amount of bitumen is added to select the active filler type, and content is determined by the fractions passing the 4.75 mm and 0.063 mm sieves. As explained in Table 6 in TG2:

Table 6. Guidelines for estimating nominal bitumen addition (TG2)

Fraction passing 0.063 mm Sieve (%)	**Bitumen Addition (% by mass of dry aggregate)**		**Typical Material Types**
	Fraction Passing 4.75 mm Sieve		
	< 50%	**> 50%**	
< 4	2.0	2.0	RAP
4 - 7	2.2	2.4	Graded crushed stone, Natural gravel, Blends
7 – 10	2.4	2.8	
> 10	2.6	3.0	Gravels, Sands

Six specimens with 150 ± 2 mm diameter and 95 mm height are manufactured for each batch using gyratory or vibrating hammer compaction methods (See Section 3.4, and Appendix I). And the specimens are cured in line with the curing method explained in Section 3.5. ITS$_{DRY}$ and ITS$_{WET}$ (primary indication) are obtained for each mixture, and this indicates whether an active filler is required for the BSM or not. The bitumen application rate for the active filler selection is decided according to Table 6. In the first stage the addition of active filler restricted to 1% by dry mass of aggregate, then several active fillers, e.g. cement, fly ash, lime, are tested to determine the active filler type. The active filler that produces the highest ITS$_{WET}$ value, indicates greater compatibility to the mix components and is used in the subsequent mixes that follow. If the ITS$_{WET}$ values for both active fillers are of the same order (difference < 5%), then either type of active filler may be selected.

If the ITS$_{WET}$ values are below the limitation that is shown in Table 5, the active filler amount should be increased to 1.5%, 2% and should be tested again. The example is shown in Figure 12.

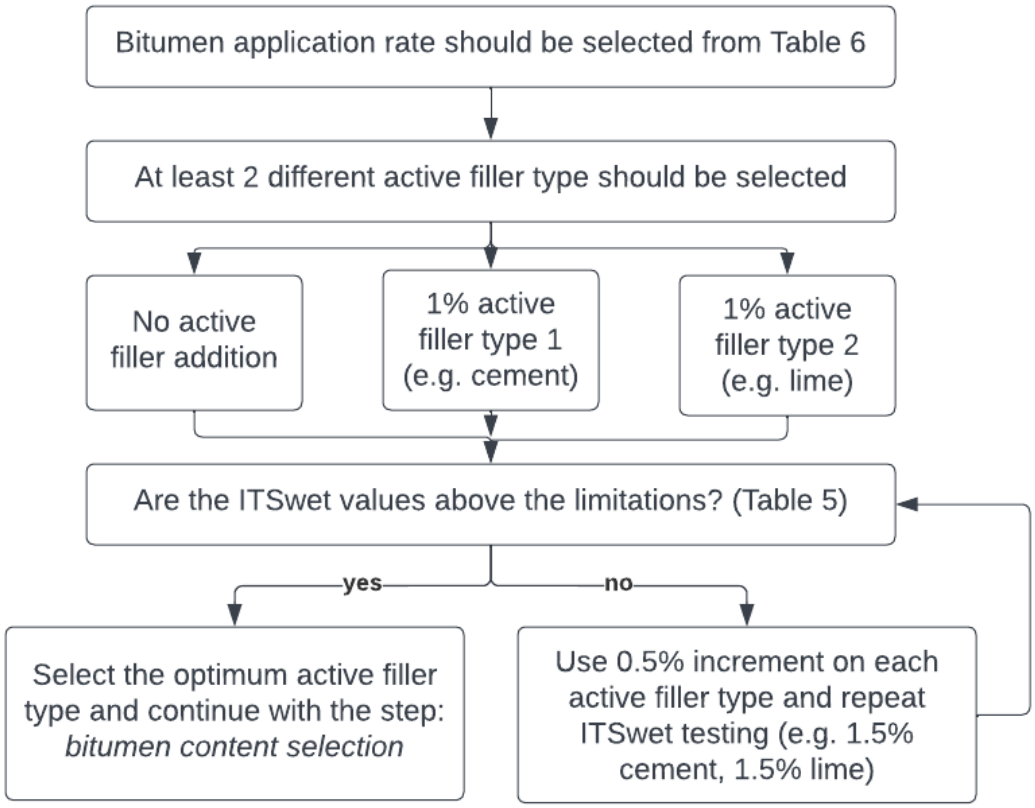

Figure 12. Active filler selection

3.6.2 *Bitumen content selection*

Once an active filler has been chosen, the amount of bitumen needed to meet the classification requirement is determined. Three samples at different bitumen application rates are prepared, each with the selected type and amount of active filler (preferable at 1% cement or hydrated lime). A different application rate has been selected according to Table 6. And the bitumen application rate increased and/or decreased at 0.2%, for each mixture. The same procedure as active filler selection, six specimens (D: 150 ± 2 mm , H: 95 mm) is prepared and subjected to ITS_{DRY} and ITS_{WET} testing. The amount of added bitumen that meets both the ITS_{DRY} and ITS_{WET} classification requirement is selected as the optimum bitumen application rate. Bitumen content provides both adequate strength and the maximum reduction in moisture susceptibility

3.7 Indirect Tensile Strength Modulus (ITSM)

For lightly-bound materials and bound materials, the indirect tensile modulus may be used to determine the resilient modulus of cylinders, similarly as used for asphalt. Indirect tensile strength modulus rest is recommended w**hen the application rate of active filler exceeds 1% and the bitumen application rate is higher than 3%, however it is important to note that these application rates are not recommended for BSM-Foam.** If only the project requires a high amount of bitumen and active filler ITSM can be used as proposed in the Austroads guideline. In this case, material behaves as a flexible bound material with a propensity for fatigue cracking. Given that modulus rather than strength is used for asphalt, another flexible bound material, they consider modulus more appropriate

than strength for BSM-Foam. ITSM can provide additional information on selecting active filler amounts and bitumen application rates. ITSM samples are prepared with gyratory or vibratory hammer compaction having 150 ± 2 mm diameter and 60 ± 2 mm height. This test is performed by following EN 12697-26 (both soaked and unsoaked conditions).

ITSM is determined with the following parameters:

Test pulse period: 3000 ms

Pulse rise Time: 124 ms

Poisson ratio: 0.35

Target resilient strain: 50 microstrain

Test temperature: 25 °C

From the test results of the four specimens, three of the four indirect tensile modulus values which are closest in value are selected. Where the individual result of any of the three results is outside the range of ±30% of the mean, the tests should be repeated. The 90th percentile value of the selected three results shall be the characteristic modulus value at the particular bitumen and secondary binder content combination. The minimum requirements for ITSM values are given in Table 7:

Table 7. Indirect Tensile Strength Modulus (ITSM) limits for classification (interpreted from Austroads)

	ITSM$_{DRY}$ (Mpa)	**ITSM$_{WET}$**	**Ratio**
BSM1	> 3000	> 1800	0.45
BSM2	> 2500	> 1500	0.40

3.8 Monotonic Triaxial Testing

In order to create a reliable mix design, the shear characteristics of the BSM-Foam, cohesion and internal friction angle, must be evaluated. Two batches of each ten specimens are prepared following the compaction and curing method (see Appendix I) at the optimum bitumen application rate and active filler type and content. The eight unsoaked specimens are then removed from their bags and subjected to triaxial testing, two specimens at each of four confining pressures: σ3 = 0 kPa, 50 kPa, 100 kPa and 200 kPa. The maximum applied stress is determined for each confining pressure and used to plot the Mohr-Coulomb circles from which the shear properties of Cohesion (C) and the Internal Angle of Friction (φ) are determined, as shown in Figure 13.

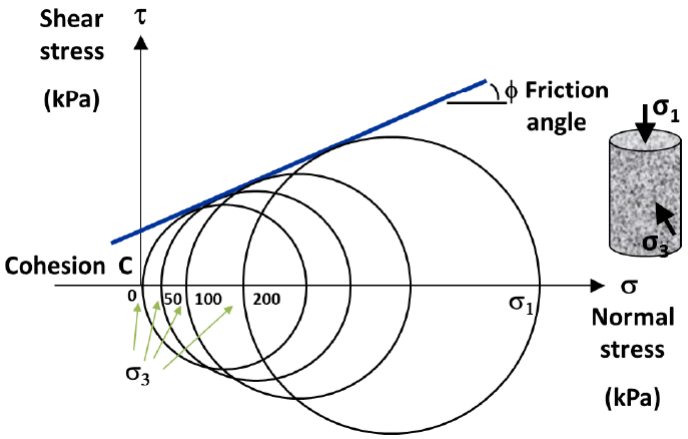

Figure 13. Mohr-Coulomb Plot of Monotonic Triaxial Results (TG2)

Figure 14. Triaxial testing

The two soaked (or wet) specimens are then tested at a confining pressure of 100 kPa. The resulting applied stress ($\sigma_{1,f\ S}$) was compared with that for the unsoaked specimen (at equilibrium moisture content) at the same confining pressure $\sigma_{1,f\ U/S}$ to determine the Retained Cohesion (RetC). This process is used to determine the moisture resistance of the BSM. The Retained Cohesion is defined by the percentage of residual cohesion of the BSM after moisture exposure, as defined by the equation below.

$$\text{Retained Cohesion (RetC)} = \frac{\text{CohesionWET}}{\text{CohesionEQUIL}} = \frac{\sigma_{1,f,\ 100WET} - 100}{\sigma_{1,f,\ 100EQUIL} - 100} .100$$

Where:

$\sigma_{1,f,\ 100WET} = \sigma_{1,f}$ for soaked specimen, submerged under water for 24 hour at 25 °C and tested with σ_3 = 100 kPa confinement (kPa)

$\sigma_{1,f,\ 100EQUIL} = \sigma_{1,f}$ for unsoaked specimen and tested with σ_3 = 100 kPa confinement (kPa)

In summary, the interpretation of the mix design results with specification requirements are provided in Table 8.

Table 8. BSM-Foam classification

Class	RAP (%)	ITS (kPa)		Triaxial		
		ITS_{DRY}	ITS_{WET}	Cohesion (kPa)	Friction Angle (°)	Retained Cohesion (%)
BSM1	< 50%	225	125	250	40	75
	50-100%	225	125	265	38	75
BSM2	< 50%	175	100	265	38	65
	50-100%	175	100	225	35	75

4 APPENDICES

4.1 Appendix I: Lab method principles.

The most applicable binder, filler, parent material (aggregate), and quantity required to meet the bitumen stabilised material should be determined through laboratory tests.

Details of the sampling and laboratory testing associated with the stabilisation mix design are described below.

1. **Field Sampling and Sample Preparation**

When undertaking a mix design for in situ stabilisation, the samples of pavement material selected for testing must represent the material to be stabilised. Therefore, the selection of representative samples for testing requires bulk samples to be classified according to a visual description and the results of standard laboratory classification tests. (EN 932-1)

This section is divided into two parts. The first part explains obtaining samples and the second part explains preparing samples for testing in the laboratory.

- Sampling from test pits

Test pits are commonly used for exposing and sampling foundation and construction materials. The test pit must be large enough to permit detailed examinations of the material in situ to be conducted or to obtain large, undisturbed samples as required by the investigation. Test pits are usually located in the outer wheel path of trafficked lanes.

A sample of sufficient size from each pavement layer should be placed in a separate container or thick plastic bags and sealed to avoid loss of moisture content. Every container / bag must be clearly labelled showing the appropriate information, e.g. test pit ID, the layer (e.g. upper subbase) and the thickness of the layer.

- Sampling from stockpile

Segregation often occurs when materials are stockpiled; therefore, it is difficult to ensure representative samples from stockpiles. Therefore, it is crucial to take the samples from different locations around the stockpile. Extracting samples must be placed into a sealed container or plastic bag. Samples should be stored in an area where contamination cannot occur.

2. **Preliminary Testing**

This section explains the procedure of preliminary tests on bitumen stabilised materials.

- Air Dry

The first step before starting the mixture design is air drying the samples obtained from test pits or stockpiles. The material (RAP) must be spread onto a clean dry surface protected from rain or wind. The thickness of the material spread for the air-dry procedure should be a maximum ± 3 cm. After drying to constant mass, material must be collected according to the quartering method to have the same gradation as in bulk samples. EN 932-2 procedure is followed for the quartering method.

- Moisture content and Hygroscopic Moisture Content (EN 1097-5)

Hygroscopic moisture content is a term that stands for the moisture content of air-dried material. It is an important step to determine the moisture content of the end material. Two air-dried samples, each approximately 1 kg, are used to determine the material's hygroscopic (air-dried) moisture content following the standard test procedure EN 1097-5 for moisture determination.

- Sieve Analysis to determine grading (EN 933-2)

Washed fine procedure must be followed on granular materials used as base course however, it is recommended to follow dry sieve analysis procedure when working with RAP.

- Atterberg Limits

The Atterberg limit test, according to NBN CEN ISO/TS 17892-12, is used to determine the plasticity of the parent material to be stabilised. RAP does not have plasticity, It is therefore Atterberg Limit tests on RAP material is not required.

- Modified Proctor Test (EN 13286-2)

The Proctor test is used to establish a relationship between moisture content and dry density. The results define the correct moisture content for optimum compaction; meaning the optimum water content and maximum achievable dry density. In addition the maximum dry density is used as a reference when determining the degree of compaction of a constructed layer. Maximum dry density (MDD) and Optimum moisture content (OMC) is defined by following EN 13286-2 Modified proctor test procedure.

3. The Foaming Unit (Wirtgen WLB 10 S)

This section explains how to produce foamed bitumen using WLB 10 S. Filling the water tank must be done when there is no air pressure in the system, in other words, before starting the internal compressor and connecting the external compressed air supply. The water tank of the WLB 10 S must be filled with adequate water (at least half of the water tank). This is carried out by opening the water valve at the back of the unit and pouring water into the funnel. The water level indicator on the right side of the unit shows when the water tank is full. Water valve must be closed after filling with water.

The points should be taken into account when working with the foaming unit:

- Regular draining of the entire water system is recommended to avoid corrosion in the water tank.
- Only clean potable water is to be used and the temperature of the water is recommended to be higher than 20 °C.
- The water filter should be checked and cleaned regularly.

The correct bitumen nozzle must be screwed in before start working. It is easier to screw the nozzles in and out once the heating circuit for the bitumen nozzle has been heated up. The bitumen to be foamed must be preheated in a suitable oven to a temperature of at least 120 °C before adding into the bitumen tank. The required amount of bitumen is approximately 3-5 liters. The required air and water pressures can now be read off at the corresponding pressure gauge (factory setting: air pressure 5 bar / 73 psi and water pressure 6 bar / 87 psi) and adjusted if necessary using the adjuster screws. Starting with the foaming unit steps as follows:

1. Once the power supply is connected, the foaming unit can be switched on by using the red main circuit. The heater and the pump should still be switched off at this time.

2. Each heating circuit can be set at the desired temperature using the multi-function display. The value of each heating circuit should not exceed 100 °C, while the pump is turned off, meaning before the bitumen circulation starts.
3. The heating circuit can now be switched on at the set temperature. And, the illuminated LEDs indicate that the heating circuit in question is heating up to the set temperature. The LED fades out when the set temperature has been reached. The unit is ready to start working on.
4. When the temperatures reaches 100 °C then the preheated bitumen (3-5 liters) can be added into the bitumen tank of WLB 10 S. And the lid is closed. It is important to take precaution while working with hot bitumen such as facial protection, heat resistant gloves, and laboratory clothes.
5. The temperature can be set at 130 °C to start the bitumen circulation. When the heating circuit of the pump reaches a temperature higher than 130 °C, and the bitumen circulation can start switching on the pump button. The pump should only be started once the added bitumen is in liquid faze.
6. It is recommended to check always pressure gauge to make sure the circulation is not prevented by cold bitumen (blockage) within the system. In this case, it is necessary to heat up the system for a longer period before starting the circulation. Free circulated bitumen does not produce backpressures, therefore, If the bitumen pressure gauge shows pressure during circulation which means there is a blockage inside the system and the pump immediately must be switched off.
7. The temperature of each heating circuit now can be set at a working temperature (160 °C - 180 ±5 °C). The duration to reach the set temperature depends on the initial bitumen temperature and the quantity of the added bitumen. To check whether the set temperature has been reached or not can be checked on display or by the LED lights. If the LED lights go out, it means that the set temperature has been reached. Once the working temperature reaches, the foaming unit is ready to produce foamed bitumen.

Calibrating Flow Rates

The flow rates of bitumen and water should be checked every time the unit is turned on.

Bitumen flow rate

For the calibration and checking bitumen flow rate, it is important to make sure the correct nozzle is screwed and the water valve is closed before start working. After closing the water valve, pressing the water and air buttons simultaneously will ensure that no water is left in the system. The empty bucket should be placed under the bitumen nozzle, and the bucket tare must be set to zero. The required amount of bitumen is set on the display . Principally, 500 g of bitumen should be selected for calibration. Pressing the bitumen flow button results in the required amount of bitumen to be pumped through the nozzle into the bucket. Then, the bitumen in the bucket can be weighted (before weighing the bucket tare must be set to zero). The flow rate can be adjusted using the rotary knob if required.

Water flow rate

The empty bucket should be placed under the bitumen nozzle and the water valve should be open. The scaled lines on the flow-through meter show the flow rate in liters per hour. Table I.1 shows the water flow rates (liters per hour) for different foaming water content (%) and bitumen flow rate (50 g/sec. and 100 g/sec.).

Table I.1. Conversion of water flow rate from % to l/h

Bitumen flow rate (g/sec.)	**Amount of water added [%]**								
	1	1.5	2	2.5	3	3.5	4	4.5	5
	Water flow rate [l/h]								
100	3.6	5.4	7.2	9.0	10.8	12.6	14.4	16.2	18
50	1.8	2.7	3.6	4.5	5.4	6.3	7.2	8.1	9

Water and air buttons must be pressed simultaneously to make settings and, the adjuster screw for the flow-through meter can be operated by free hand until it the float remains steadily in the required position

4. Determining the Foaming Properties (Expansion Ratio and Half-life)

The Expansion Ratio (ER) and Half-life (HL) are two characteristics that determine bitumen's suitability to be used. The Expansion Ratio (ER) is the maximum volume of foam relative to the original volume. And, The Half-Life (HL): is the time the foam takes to collapse to half of its maximum volume. These characteristics depend on:

- Bitumen type
- Bitumen temperature
- Bitumen water quantity
- Air and water pressure

The following procedure aims to determine the bitumen temperature and percentage of water addition required to produce the best foam bitumen with the largest expansion ratio and with the longest possible half-life for a particular source of bitumen. The test has been repeated at three (3) different bitumen temperatures (ranging between 160 °C and 180 °C) to determine the percentage of water added to achieve the optimum foaming characteristics. The procedure to determine the expansion ratio and half-life is followed by:

1. The foaming unit WLB 10 S should be prepared by following sections 3.
2. Set the bitumen temperature at 160 °C.
3. Prepare a stopwatch to measure the HL, the bitumen bucket (20 liters) and the measuring rod (dipstick) that are matched can be used to measure ER and HL. The measuring rod supplied by the Wirtgen WLB 10 S which is calibrated for a steel drum of 257 mm in diameter and 500 g of bitumen.
4. Prepare a stopwatch (to measure the half life) and a dipstick (to measure the expansion ratio).
5. Set the water flow rate of 100 g/sec. (This means spraying time of 5 seconds). The water flow meter is normally set to inject 2% of water by mass of bitumen for the first testing cycle.
6. Then, the foamed bitumen can be discharged into a preheated (±75 °C) steel drum for a calculated spray time for 500 g of bitumen. Immediately after the foam discharge stops, start a stopwatch. Note the spraying time, and immediately continue measuring the time.
7. Use the dipstick to estimate (to the nearest whole number) the maximum height that the foamed bitumen reaches in the container and record it as the maximum Expansion Ratio (ER = h1).

8. Measure the time that the foam takes to dissipate to half of its maximum volume in the container. When this point is reached, stop the stopwatch. Record the elapsed time to the nearest second as the foamed bitumen's half-life (t1).
9. Empty the container and repeat the steps above 3 times. And record each readings (h1, h2, h3, t1, t2, t3). Then calculate the average values.
10. Repeat the steps above (Step 1 to Step 8) for a range of at least three water injection rates, typically 1%, 2%, 3% and, 4% by mass of bitumen.
11. Repeat the steps above (Step 1 to Step 8) for the bitumen at two higher temperatures, typically 170 °C and 180 °C. It is important to note that the bitumen should NOT be heated above 190 °C.
12. Select the optimum water injec
13. Select the optimum water injection rate and bitumen temperature that matching with the requierements given in Table I.2.

Table I.2. ER and HL requierements

Aggregate Temperature	**15 °C to 25 °C**	**> 25 °C**
Expansion Ratio, ER (times)	≥ 10	> 8
Half-life, HL (secs)	≥ 8	≥ 6

- Calculation of the bitumen discharged in 5 seconds.

$M_b=(M_{bc}-M_c)$ where:

M_b : Mass of bitumen discharged in 5 seconds (g)

M_c : Mass of empty container (g)

M_{bc} : Mass of container and bitumen (g)

- Preparation of a chart to plot expansion ratio and half life at three different water injection percentages acoording to Table I.3.

Table I.3. Guideline to prepare a chart to plot ER and HL (TG2)

	Horizontal Axis	**Vertical Axis**	
	Water injection rate	**Left Ordinate: ER**	**Right Ordinate: HL**
Unit	Percentage (%)	Times expansion	seconds
Scale	20 mm = 0.5%	5 mm = 1 time	5 mm = 2 seconds

Example of the chart shown in Figure I.1.:

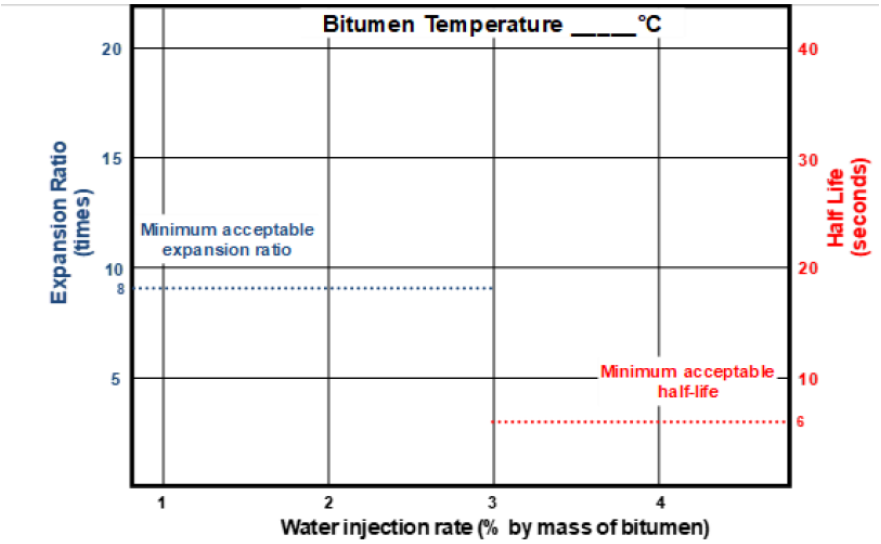

Figure I.1. Chart to plot ER and HL as a template (TG2)

Once the optimum water addition has been defined in relation to the type of bitumen used and the bitumen temperature, it is now possible to start mixing materials.

5. Mixing

The amount of bitumen, active filler, and water to be added to air-dried material (RAP) is calculated based on dry mass of the material. The Wirtgen pug mill mixer (WLM 30) is recommended to achieve a homogenous mixture. When working with WLM30, using at least 20 kg of material for one mix is recommended.

The oven-dried mass of the material used in the mix (aggregate) is calculated as follows:

$$M_{OD} = \frac{M_{AD}}{1 + (W_{AD}/100)}$$

M_{OD} : oven-dried mass of material to be mixed (g)

M_{AD} : air-dried mass of material to be mixed (g)

W_{AD} : Water content of the air-dried material (% of the oven-dried mass)

The required amount of active filler or foamed bitumen to be added to the mixture is calculated as follows:

$$M_{AF} = P_{AF} . \frac{M_{OD}}{100}$$

$$M_{FB} = P_{FB} . \frac{M_{OD}}{100}$$

M_{OD} : oven-dried mass of material to be mixed (g)

P_{AF} : percentage of active filler to be added (%)

M_{AF} : mass of active filler to be added (g)

M_{FB} : mass of foamed bitumen to be added (g)

P_{FB} : percentage of foamed bitumen to be added (%)

The required amount of water to achieve OMC in the BSM-Foam mix is calculated as follows:

$$M_W = \frac{OMC \times (M_{OD} + M_{AF} + M_{FB})}{100} - (M_{AD} - M_{OD})$$

OMC : optimum moisture content of the parent material (%)

Mw : amount of water required to achieve OMC

The sample to be mixed shall be prepared as described:

1. Add the air-dried material (temperature is between ±15°C and ±25 °C) along the length of the mixer and distribute the active filler (e.g. cement) over the surface of the added material at ambient temperature.
2. Start the mixer (WLM 30) at 25-30 % of the maximum speed for 30 seconds.
3. The mass of the first addition of water is calculated to achieve 60% of OMC. In this stage, slowly pour the first addition of water while the mixer is running at 90% of maximum speed. Mix for 30 seconds. After mixing is completed, check if the moisture content of the material is consistent. If variable colour is observed, mix for a further 30 seconds to achieve consistency.
4. Move the mixer under WLB10S foaming plant, cover must be correctly placed under the foaming nozzle. Start the mixer at maximum speed. Once the mixer is running at full speed, inject the foamed bitumen (the injection temperature ± 100 °C after foaming completed). Let the mixer run for 30 seconds. Foamed bitumen in the material ranges between 1.8 % - 3% in total mass. Therefore, the material temperature is slightly increasing (± 25 °C).
5. Reduce the mixing speed to 90% of the maximum and slowly pour the remaining water to achieve 100% of OMC. Let the mixer run for 30 seconds. Check the material consistency; if the appearance is not uniform, run the mixer for a further 30 seconds.
6. Remove the material from the mixer by rotating the mixer to let the material fall into the cover. The material taken from the mixer is immediately transferred to a sealed container and used to manufacture the test specimens within 30 minutes. In exceptional circumstances, the maximum time delay between mixing and manufacturing test specimens is four (4) hours, and the material must be protected in a sealed bag.

The mixing process for foamed bitumen stabilised materials are shown in Figure I.2..

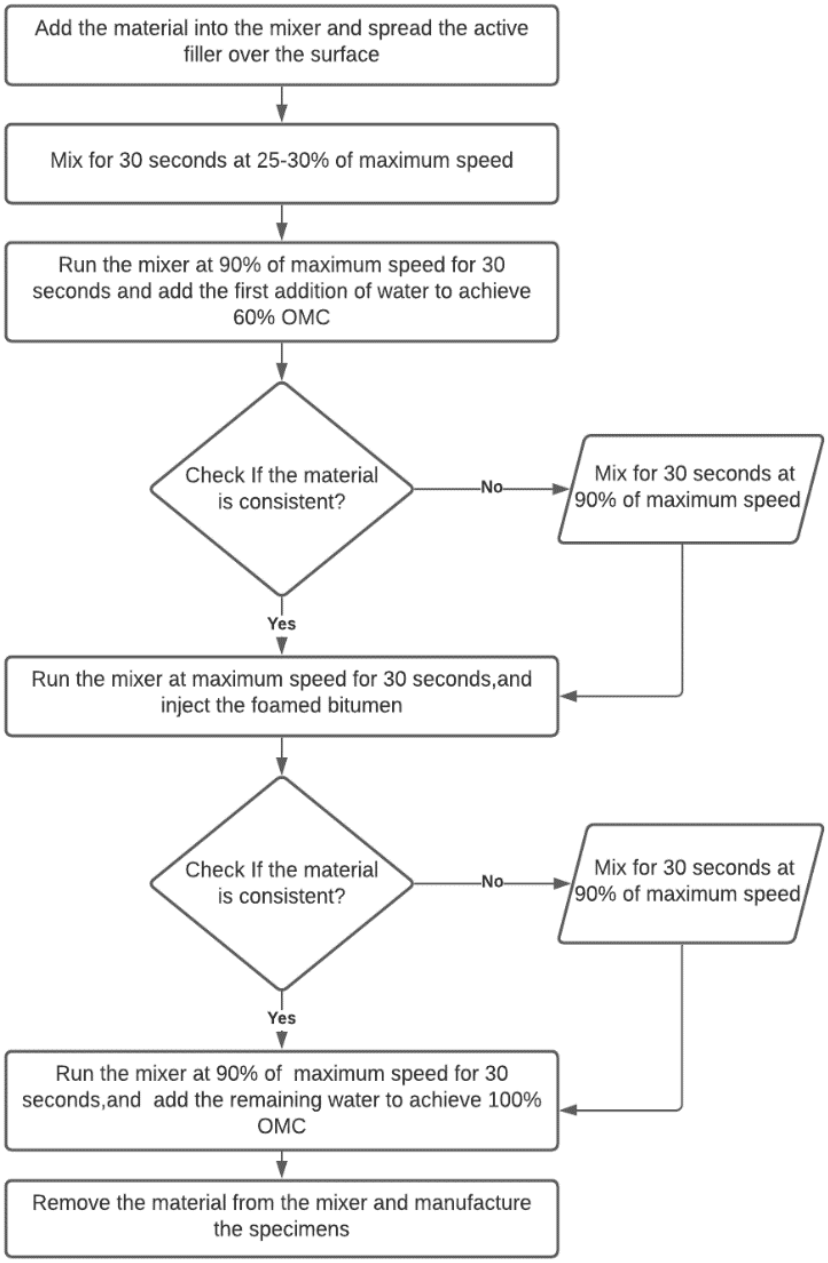

Figure I.2. Mixing procedure for BSM-Foam.

6. Compaction

A gyratory or vibrating hammer compaction method is recommended BSM-Foam mixes, depending on the availability of the equipment. Since both compaction methods have a different working mechanisms, the compaction procedure also differs.). Test specimens for mix design are manufactured at 100% of optimum moisture content (determined from the modified proctor test). It should be noted that the maximum allowed time delay between mixing the material with foamed bitumen and manufacturing test specimens is 4 hours (in a sealed bag).

The mass of each BSM-Foam specimen to be compacted is calculated as follows:

$$M_{BSM} = \frac{(\prod x D^2)}{4 \times 10^6} \times H \times (MDD \times (1 + \frac{OMC}{100}))$$

M_{BSM} : Mass of each BSM-Foam specimen at OMC (g)

MDD : Maximum dry density of parent material (kg / m^3)

OMC : Optimum moisture content of parent material (%)

D : Diameter of the mould/specimen to be compacted (mm)

H : Height of the specimen to be achieved after compaction (mm)

The required mass for each layer is calculated as follows:

$$M_L = \frac{M_{BSM}}{n}$$

M_L : mass of the BSM-Foam specimen for each layer (g)

n : number of layers to be compacted

Gyratory

The gyratory specimen requirements for ITS test and Triaxial test are shown in Table I.4.

Table I.4. Requirements for gyratory compaction

	ITS test	**Triaxial test**
Number of specimens per batch	6	10
Specimen diameter [mm]	150 ±2	150 ±2
Specimen height [mm]	95±1	2 * (150 ± 1)
Number of layers	1	1
Layer thickness [mm]	-	150

The recommended gyratory compaction settings are 0.82^0 angle of gyration, speed of 30 rpm and 600 kPa compaction pressure according to EN12697-31. The height limit is set at 95 mm for ITS specimens and 150mm for Triaxial specimens. Triaxial specimens are prepared as two separate specimens and tested as placed one on top of another to reach 300 mm height. The use of perforated moulds assists in completing the first curing stage of BSM-Foam mixtures.

The procedure to manufacture the test specimens is as follows:

1. Place the determined amount of material in the mould. Compaction with gyratory is made at one layer.
2. Set the gyratory settings on the software and start the compaction; compaction should end before reaching max. 200 gyrations.
3. If the compaction takes longer than 200 cycles, stop the compaction procedure and take the material out. Then, place half of the material in a mould and run the compaction at a height limit of 48 mm for ITS and 75 mm for Triaxial specimens. When the height is reached, remove the mould, add the second half of the material, and rerun the compaction for a height limit of 95 mm for ITS and 150 mm for Triaxial specimens. Ensure that the compaction for each layer takes less than 200 gyrations. If this happens, terminate the manufacturing procedure and ensure the Maximum Dry Density (MDD) used in the calculation is correct. It is also important to note that, If water leakage from the mould is observed during compaction, stop

the compaction procedure and repeat the Modified Proctor test to determine the correct MDD and OMC values. Then revised the mixing and compaction procedure using the correct values.

4. Once the compaction is completed, carefully place the mould and specimen on the ambient temperature room and record the mass and follow the curing instruction in Section 7.

Vibrating Hammer

The steps required to manufacture test specimens with WLV1 vibrating hammer are covered in this section. The vibrating hammer specimen requirements for ITS test and Triaxial test are shown in Table I.5.

Table I.5. Requirements for vibrating hammer compaction

	ITS test	Triaxial test
Number of specimens per batch	6	10
Specimen diameter [mm]	150 ±2	150 ±2
Specimen height [mm]	95±1	300±1
Number of layers	2	5
Layer thickness [mm]	47.5	60

If the required height cannot be achieved in 120 seconds with the vibrating hammer, compaction should stop and the layers may be increased to 3 layers for ITS test specimens and to 6 layers for triaxial test specimens. The vibrating hammer works in two different functions named distance measurement and time measurement. Distance measurement allows the vibrating hammer to run until a specific height is achieved. On the other hand, time measurement allows the vibrating hammer to run for a set time in seconds. For the compaction of BSM-Foam mixtures, distance measurement is selected in vibrating hammer. The procedure for compaction is as follows:

1. Ensure that the calibration is made for WLV 1. Clean the mould and base plate. Lubricate the inside of the mould with a light application of lubricating grease or non-stick spray. Fix the mould and base plate to the concrete block. Check the alignment of the mould and vibratory hammer by lowering the tamping foot into the mould. Check that the lifting system provides sufficient slack for the tamping foot to rest on the base plate.
2. Place the determined amount of material for the first layer in the mould. Then, Use the spatula to spread the material evenly in the mould avoiding segregation. Then use the Interlayer Roughening Device (IRD) to level the material inside the mould.
3. Lower the vibratory hammer until the tamping foot rests on the material. Ensure the lifting system is slack, allowing the hammer to slide downwards as the material compacts. Turn on the vibratory hammer and start the timer. When the height is reached for the first layer, the vibrating hammer will lift automatically. Record the time taken to compact the layer. When the compaction time for any layer exceeds 120 seconds, terminate the manufacturing procedure, increase the number of layers and start the procedure again. In the unlikely event of the problem persisting with an increased number of layers, terminate the manufacturing procedure and seal all the material in airtight containers. Repeat the Modified proctor test on a new sample of the untreated material to determine the correct values for the MDD and OMC. Then start the procedure again using the revised MDD as the target density.

4. Use the interlayer roughening device (IRD) to prepare the surface of the compacted layer inside the mould by applying sufficient pressure and rotating the IRD several times until the top of the compacted material is loosened. When the surface has been sufficiently roughened, proceed immediately with the next layer.
5. Place the material for the second layer and compact it as described in Steps 2 and 3. For Triaxial specimens, this step is repeated for 5 layers.
6. Once the compaction is completed, carefully place the mould and specimen on the ambient temperature room and record the mass and follow the curing instruction in Section 7.
7. **Curing**

The curing process allows BSM-Foam mixtures to acquire their strength by losing a significant amount of moisture in the mix. The curing process is essential in the short and long-term material characteristics. The curing of the specimens for ITS and Triaxial testing is different.

Curing of ITS specimens:

1. Once the compaction is completed, leave the specimens a minimum of 4 hours before removing them from their respective moulds and carefully placing each on a carrying plate.
2. And record the mass of specimens before placing them into an oven.
3. Place the six specimens on their carrying plates in the oven at a temperature of 40 ± 1 °C for a period of at least 72 hours. Ensure that there is a minimum air space of 25 mm between specimens.
4. After 72 hours, remove one specimen per batch from the oven and record the mass, then repeat this after 4 hours. The curing is completed when there is less than 10 g of loss. Take the specimens from the oven and record the weight of each specimen. And continue with measuring the height at three evenly spaced points around the circumference (h1, h2 and h3), calculate the average and record to the nearest 0.5 mm. And, measure the diameter at mid-height, at three evenly spaced points (d1, d2 and d3), calculate the average and record to the nearest 0.1 mm.
5. Then, place three of the specimen of each batch into a cooling chamber at 25 °C. And place the other three from each batch in the water bath and soak for 24 hours at 25 °C. Ensure that the specimens are covered by at least 25 mm of water.

Curing of Triaxial specimens

1. Leave all ten specimens overnight in their respective moulds covered with a moist hessian cloth.
2. Remove the specimens from their respective moulds the following morning.
3. Place the specimens in the oven at a temperature of 40 ± 1 °C for 8 hours. Ensure that there is a minimum air space of 25 mm between specimens. To avoid damage to the large specimens, exercise care when moving them. Specimens are always moved on their respective carrier plates.
4. Record the mass of each specimen before placing them into an oven.
5. After 8 hours curing at 40 ± 1 °C, remove all the specimens from the oven. Place each specimen in a loose-fitting plastic bag and seal the bag. Then, Place the specimens (in plastic bags) into the oven at a temperature of 40 ± 1 °C for 48 hours.
6. Remove the specimens from the oven after 48 hours and take them out of their respective plastic bags. Record the weight of each specimen. And continue with measuring the height at

three evenly spaced points around the circumference (h1, h2 and h3), calculate the average and record to the nearest 0.5 mm. And, measure the diameter at mid-height, at three evenly spaced points (d1, d2 and d3), calculate the average and record to the nearest 0.1 mm.

7. Place the eight of the specimens in a dry loose fitting plastic bags and leave in the cooling chamber at 25 °C for a minimum 12 hours. Then, place two of the specimens under water for 24 hours in a soaking bath at a temperature of 25 °C.

8. Indirect Tensile Strength Testing

The ITS value for each specimen is first determined. The ITS_{DRY} and ITS_{WET} values are then calculated by averaging the results for the respective unsoaked and soaked specimens. It is important to maintain the temperature at 25 °C throughout the testing.

According to EN 12697-23, ITS is measured by applying a compression load along the diameter of a cylindrical specimen at a 50 ± 2 mm/minute constant rate using two steel strips on the specimen top and bottom to procreate tension zone passing through the centre of its loaded. The test is conducted at 25 °C temperature. The ITS of the specimen is calculated from:

$$ITS = \frac{2.P}{\pi \cdot D \cdot H}$$

Where ITS is the indirect tensile strength of the specimen (kPa); P is the peak load (kN); D is the specimen diameter (m); H is the specimen height (m).

Moisture sensitivity of the specimens is quantified by indirect tensile strength ratio (ITSR), defined as the percentage of the ITS of samples subjected to the submerged conditioning and those dry conditioned, based on the formula:

$$ITSR = \frac{ITS_{WET}}{ITS_{DRY}} .100$$

Where ITSR is the ratio of the indirect tensile strength calculated for the specimens under wet and dry conditions (%); ITS_{WET} is the average indirect tensile strength for wet specimens (kPa); ITS_{DRY} is average indirect tensile strength for dry specimens (kPa).

Once the test is completed, record the specimen identity, the maximum load applied (kN) and the displacement at break (mm). Immediately after the specimen has broken, remove it from the assembly and inspect the broken parts. Measure the temperature at the centre of the broken parts. For soaked specimens, estimate the extent of water penetration and record it as a percentage (e.g. ± 15% for the penetration. Break up one of the broken halves from each unsoaked specimen and combine them into a single sample. Separately, break one of the broken halves from each soaked specimen and combine them into a second sample. Extract a ±1kg representative sample from each (unsoaked and soaked) and determine the moisture content following the standard laboratory test procedure (i.e. overnight drying in an oven at 105°C).

9. Triaxial Testing

The purpose of performing triaxial testing is to determine the shear properties of BSM-Foam mixtures, cohesion (c) and friction angle (ϕ). The triaxial test is carried out on large specimens, each 150mm in diameter and 300mm high. Gyratory compacted specimens are tested placing two 150mm diameter specimens on top of each other, so 300mm height can be reached. Vibrating hammer allows to

compact the specimens at 300 mm height, therefore the specimens are manufactured as 1 specimen. The test method calls for 2 soaked and 8 unsoaked specimens to be tested. The test involves subjecting a series of specimens to different levels of confinement and determining the magnitude of the applied load required to break the specimen under each different confining pressure. Confinement is achieved by placing the specimen in an inflatable rubber membrane that is placed inside a steel cylinder. The bladder is then inflated to the required at four confining pressure (0 kPa, 50 kPa, 100 kPa, 200 kPa). The steel cylinder prevents the bladder from expanding, thereby ensuring that the pressure is uniformly transferred to the circumferential face of the specimen. Based on the results (confining pressure and applied load), simplified Mohr-Coulomb theory is used to calculate the shear properties of the material (Cohesion and Angle of Internal Friction) which feed directly into the mechanistic / empirical method for designing pavement structures. It is important to keep the temperature at 25 °C throughout the testing. Triaxial testing is performed as follows:

1. Set the compression testing machine in displacement control mode at a rate of 3 mm/min. Ensure that the load and displacement readings are measured and recorded every second.
2. Apply the vertical load up to a displacement of 18 mm (6% strain), or sooner if the load starts to reduce from the maximum.
3. Unload the specimen by returning the actuator to its start position and release the confining pressure. Move the actuator clear of the top plate and remove the confining cylinder assembly from the loading frame. Dismantle the confining cylinder and carefully remove the specimen from the bladder. Immediately break the specimen and record the temperature in the centre and middle to the nearest 0.1 °C.
4. Take a sample of approximately 1 kg of material from the middle portion of the specimen and place in a sealed container. Determine the moisture content.
5. Repeat the procedure until all the specimens (unsoaked and soaked) have been tested at the confining pressures (0 kPa, 50 kPa, 100 kPa, 200 kPa).

10. Indirect Tensile Strength Modulus

Indirect tensile modulus (ITSM) is only used when the BSM material requires more than 1% active filler and/or > 3% bitumen addition. ITSM should be determined as the average of each four specimens for soaked and unsoaked conditions. This test is performed by following EN 12697-26 (both soaked and unsoaked conditions). ITSM samples are prepared with gyratory or vibratory hammer compaction having 150 ± 2 mm diameter and 60 ± 2 mm height. And ITSM is determined with the following parameters:

Test pulse period: 3000 ms

Pulse rise Time: 124 ms

Poisson ratio: 0.35

Target resilient strain: 50 microstrain

Test temperature: 25 °C

4.2 Appendix II: Test results

1. Introduction

The FOAM project, a collaboration between the University of Antwerp (UA), the Belgian Road Research Centre (BRRC), Odisee University College of Applied Sciences, and the Belgian road industry and agencies, aims to demonstrate the feasibility of using the foamed bitumen for the base layer of pavement. The presented test results focus on incorporating RAP in the base layer of flexible pavements by in-situ cold recycling with foamed bitumen technology combined with active fillers. With this regard;

- the effect of different types of active fillers,
- changes in foamed bitumen content,
- two different compaction methods,
- incorporation geopolymer
- shear properties

are evaluated in terms of their mechanical properties in the mix design of FBMs.

2. Preliminary Test Results

Laboratory tests were conducted utilising 100% RAP material incorporating foamed bitumen to serve the purpose of the project.

2.1. Reclaimed Asphalt Pavement Material

When preparing mixtures with a high percentage of RAP, fewer variations are encountered if the RAP material is carefully stockpiled and stored. The RAP material used in this study was supplied by Viabuild, Belgium and sampled from a well-managed stockpile, which was previously subjected to a crushing process to achieve a 20 mm maximum aggregate size (0/20). The residual bitumen content in the RAP material was determined 6.0% according to EN 12697-1:2020 solvent extraction test. The sampled RAP was provided in big bags (500 kg) and stored under shelter in open space conditions. The quartering method following EN 932-2:2020 was used to ensure that the grading of the RAP used in the mix design was reflected as accurately as possible, and the RAP was stored in small sealed bags (25 kg). Before using the RAP for testing, the RAP material was subjected to an air-dry procedure in the laboratory at 20 ± 2 °C for 48 h.

Gradation of RAP material, particularly the fine aggregate content, plays a significant role in foamed bitumen mix design procedures. The RAP material gradation shown in Figure II.1 was determined by performing a dry sieve analysis test following EN 933-1:2012. It is worth noting that the upper and lower limits stands for the target gradation for the BSM-Foam studied in the present work, and the target grading shown as > 50% RAP Target is used for the target gradation for RAP.

i. Sieve analysis results

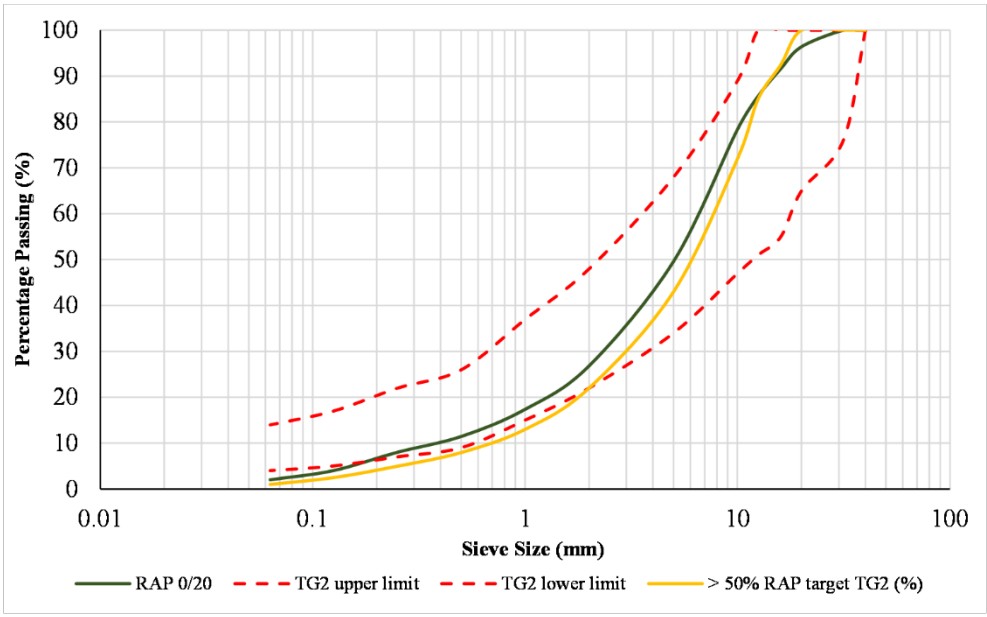

Figure II.1. Gradation of RAP and the recommended limits for BSM-Foam by TG2

Table II.1. shows the grading of RAP (0/20) material used in this project.

Table II.1. Grading of RAP (0/20)

Sieve size (mm)	Percentage passing each sieve size (%)			
	BSM lower limit	BSM upper limit	RAP (0/20)	Target RAP > 50% impact crushed
40	100	100	100	100
31.5	80	100	100	100
20	65	100	96	100
16	59	100	92	90
12.5	52	100	86	81
10	47	89	78	69
5	34	68	49	43
2	22	48	27	22
1	15	37	17	13
0.5	10	28	11	8
0.25	7	22	8	5
0.125	5	16	4	3
0.063	4	14	2	1

ii. RAP Activity

Each designer treats RAP differently in the mix design procedure of FBMs, with some taking into account the contribution of aged bitumen in RAP and others neglecting it; thus, assessing the activity level of the RAP material is recommended by TG2. The binder in the RAP used in this study is categorised as active. That means residual bitumen in the RAP is sticky and will interact with foamed

bitumen, giving additional tensile strength to the material. In such cases, TG2 recommends blending 15-20% crusher dust into the mix to kill the activity; thereby, having different fractions before bitumen stabilisation will provide shear resistance to the mixture. The RAP activity test is performed according to "Part III: Mix Design of BSM, section 2.1.2." And, the test results are presented in Table II.2.

Table II.2. RAP activity test results

RAP source	ITS$_{WET}$ (kPa)
Bag 1	564
Bag 2	247
Bag 3	110
Bag 4	105

The RAP activity test has been repeated for each big bag (500kg). It has been observed inconsistency with the results. The first provided bag has a high activity level (564 kPa that exceeds the 100kPa limitation) in the RAP. It has also been observed that the RAP was black and sticky visually. However, the RAP activity level for the remaining bags is considered to be within the limitations but slightly excessing the recommended value. This test has also been repeated for samples from the same stockpile, and the RAP activity level showed similar results as Bag 3 and Bag 4. Therefore, this study has decided to keep the RAP composition at 100%.

iii. Modified Proctor Test results

Moisture is a requirement for aggregates to facilitate bitumen dispersing during mixing and field compaction. In this project, the moisture content of the RAP in the small sealed bags was determined 2.7%, while the hygroscopic moisture content of RAP after air drying was found to be 0.7%. Modified Proctor test on the RAP material was carried out according to EN 13286-2:2010. The optimum moisture content (OMC) of the RAP material used in the present work was 5.7 %, and the maximum dry density (MDD) is calculated as 2030 kg/m3. The test results are presented in Figure II.2.

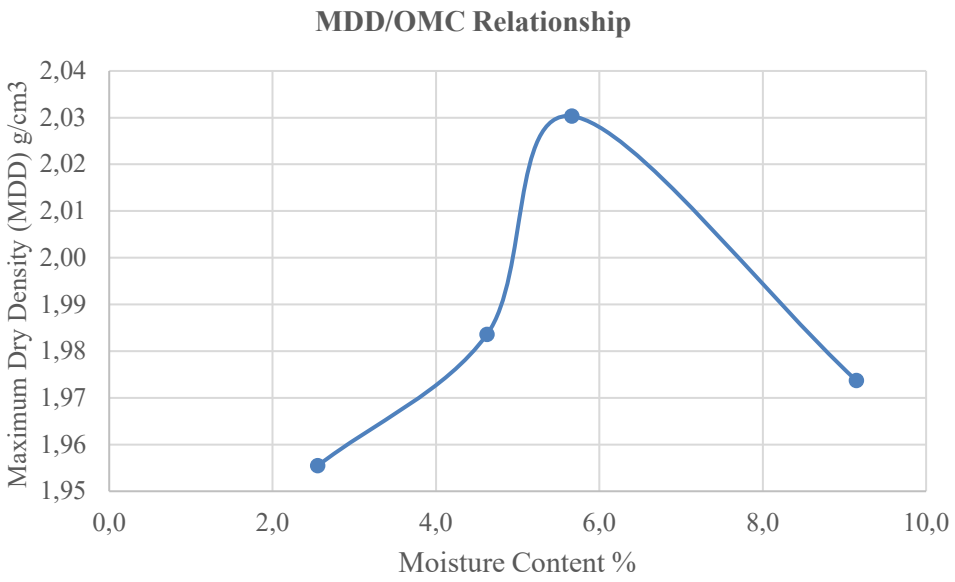

Figure II.2. Modified Proctor test results on RAP (0/20)

2.2. Bitumen

A virgin bitumen with 70/100 penetration grade has been selected in the present study.

Appropriate equipment is required to assess the properties of foamed bitumen; accordingly, a laboratory foaming plant (WLB 10 S) developed by Wirtgen was used in this study. Foamed bitumen was produced with an air pressure of 500 kPa, the water pressure of 600 kPa and bitumen temperature of 170 °C. The ER and HL of the foamed bitumen were obtained by applying several foaming water contents (FWC) ranging between 2.0% and 4.0% of the amount of bitumen by weight. The optimum FWC was determined to be 3.0% used in the present study. The ER and HL of the bitumen used in this study were determined by using the abovementioned settings 24 times and 10 s, respectively. Table II.3 presents the results of ER and HL.

Table II.3. Characteristics of bitumen

Characteristic	Unit	Value
Penetration grade	0.1 mm	70-100
ER	-	24
HL	s	10
FWC	%	3
Foaming temperature	°C	170
Foaming air pressure	kPa	500
Foaming water pressure	kPa	600

2.3. The Effect of Active Filler

Various active fillers such as cement, lime, fly ash or their combinations in different percentages can be added to mixes depending on the type of recycled material. In the first phase of the mix design, Portland cement CEM I 52.5 R HES (Cem I), blast furnace slag cement CEM III/A 42.5 N LA (Cem III), and hydrated lime at 1.0% by RAP mass were used in this project to assess the effect of different types of active filler. The bitumen application rate is selected at 2.0%, from Table 6 in "Part III. Mix design of BSM", and kept constant to evaluate the effect of active fillers. Volumetric properties of the mixtures were analysed by determining air void content (V_a) and bulk density (ρ_b). V_a is defined as the ratio of the volume of air voids in a bituminous specimen to the overall volume. EN 12697-8:2019. Where V_a is the air void content in the sample (% by volume); ϱ_m is the maximum density of the bituminous mixture (kg/m³); ϱ_b is the bulk density of the bituminous mixture (kg/m³). Figure II. 3. Shows the ITS results of different types of active filler.

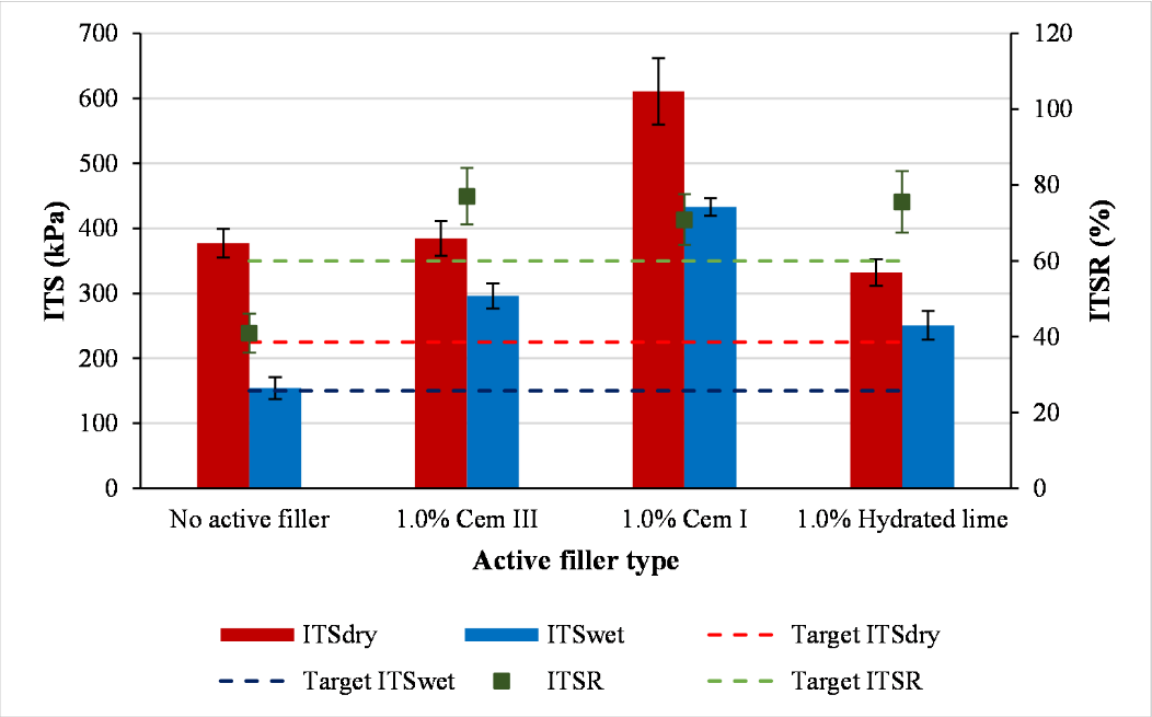

Figure II.3. ITS results of different active filler types

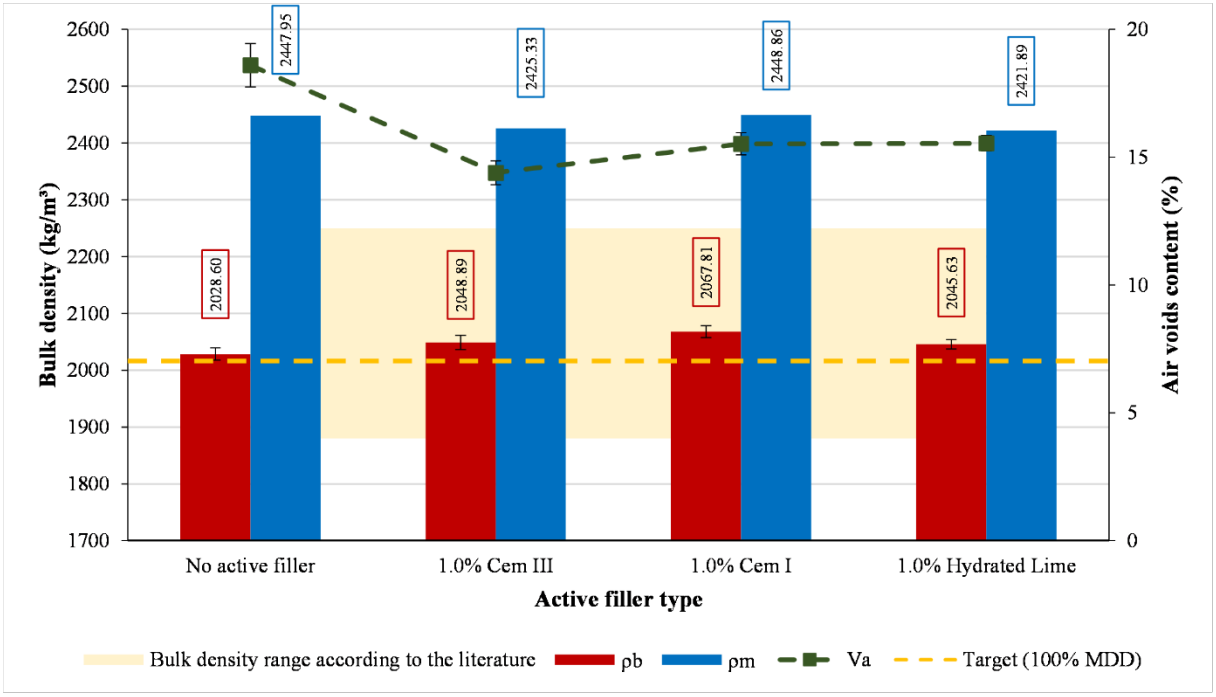

Figure II.4. Average bulk density and air void content of the mixtures with different types of active filler

An adequate level of air voids in BSM-Foam ensures resistance to the impact of environmental and traffic-related factors. The presence of an excessive amount of air voids in the mixture may decrease water and frost resistance. Hence, air void content is a crucial aspect to consider while selecting an active filler. The measured mean values of Va ranged from 14.4% to 17.8%, with a clear dependency on the active filler type used. The lowest Va mean value and the highest average bulk density were achieved with 1.0% Cem III.

In addition to the test results presented above, the effect of several active filler types has also been tested, such as:

- 1% Duras II filler
- 1% Cement 52.5 N
- 0.5% Duras II blended with 0.5% Cement III 42.5 N
- 1% Calstarite 30

The test results are presented in Figure II.5.

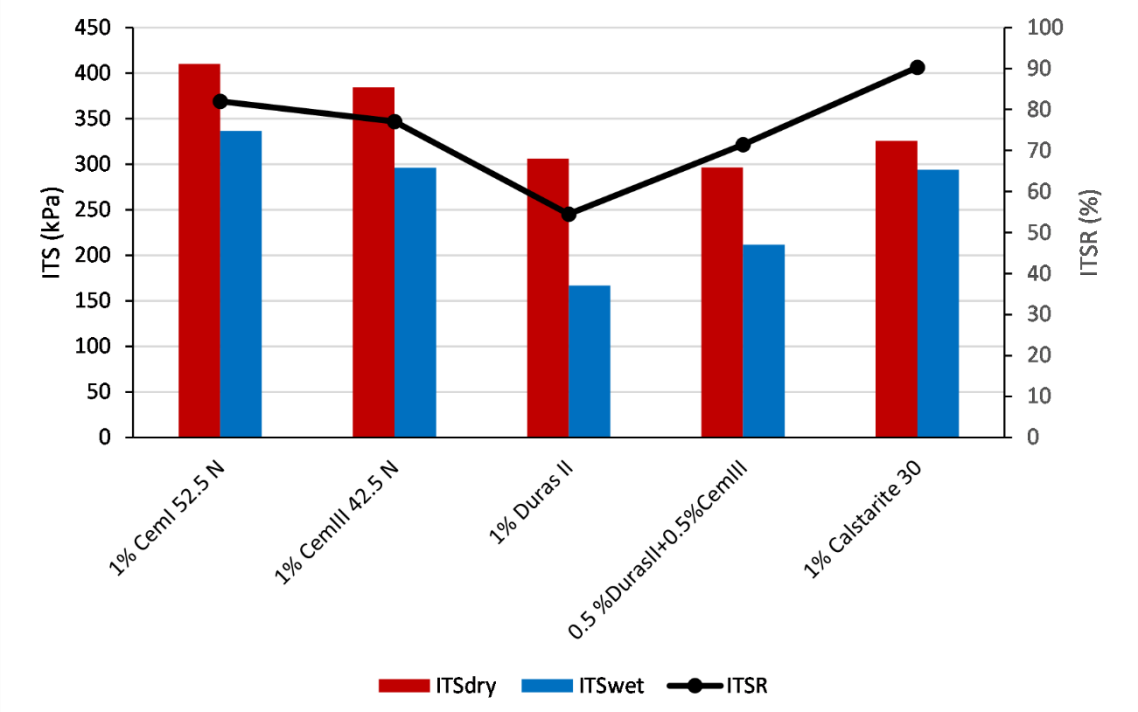

Figure II.5. ITS results of filler types and contents

This project evaluated the use of geopolymers in BSM-Foam mixtures. The slag used in this study is a commercial ground granulated blast furnace slag supplied by Ecocem (Netherlands). The chemical composition of the slag is given in Table 1. The basicity coefficient indicates that the slag in basic (CaO+MgO/SiO2+Al2O3) is 1.03. The slag has a medium particle size of 13.7 ⌀m indicating that it is finely ground and therefore suitable for alkaline activation. The activation of the slag is performed with a solution of sodium hydroxide (NaOH) supplied by VWR (98% pure) and water. The activator solution has 4.0% Na2O (by weight of slag). The water added in the first mixing process is 60% of the OMC of the mixture and is used for the activator solution. Table II. 4. Presents the chemical composition of ground granulated blast furnace slag (XRF).

Table II.4. Chemical composition of ground granulated blast furnace slag (XRF)

Main Oxides (%)							
CaO	SiO_2	Al_2O_3	MgO	SO_3	TiO_2	Fe_2O_3	Mn_2O_3
42.68	37.31	10.38	6.55	1.49	0.7	0.36	0.33

The effect of slag geopolymer on foamed bitumen mixes is shown in Figure II.6.

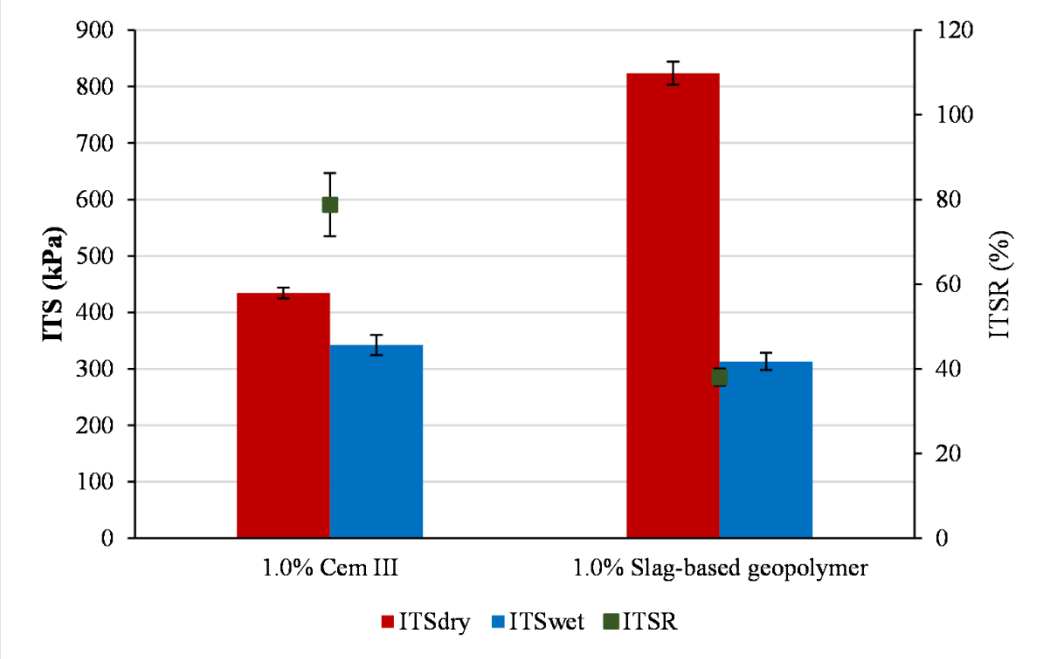

Figure II.6. The effect of geopolymer on BSM-Foam mixes

It was found that the addition of slag-based geopolymer sharply increases the ITS_{dry} values (824 kPa) while not affecting the ITS_{wet} values (314 kPa). One explanation could be the formation of soluble salts (sodium carbonate). The excess sodium in geopolymers in the presence of CO2 will lead to the formation of sodium carbonate (CaCO3). Soluble salts are water-sensitive components which, underwater exposure, could weaken or solubilise. A better curing procedure (i.e. under higher relative humidity) would likely improve the reactivity of the geopolymer, reducing the amount of free sodium and, therefore the formation of CaCO3. As a result, the incorporation of slag-based geopolymers in foamed bitumen mixes negatively affected the moisture sensitivity.

In conclusion, the addition of 1% CEM III/A 42.5 N LA (Cem III) as an active filler is selected as the best performance of the mixture, and the test results are in line with the ITS limitations. Therefore, there is no need to increase the active filler content or to perform indirect tensile modulus testing for this material.

2.4. The Effect of Bitumen Content

ITS test is also used to assess the bitumen content of the mixtures, and the results are illustrated in Figure II.6. The optimum bitumen content is determined by the bitumen content that provides sufficient strength and the highest reduction in moisture susceptibility. This research determines the optimum bitumen content at 2.2%, considering the results presented in Figure II.7 that align with BSM mixtures' limitations.

Table II.5. Indirect Tensile Strength Limits for Classification (TG2)

Class	ITS Limits	
	ITS_{DRY} (kPa)	ITS_{WET} (kPa)
BSM1	> 225	> 125
BSM2	> 175	> 100

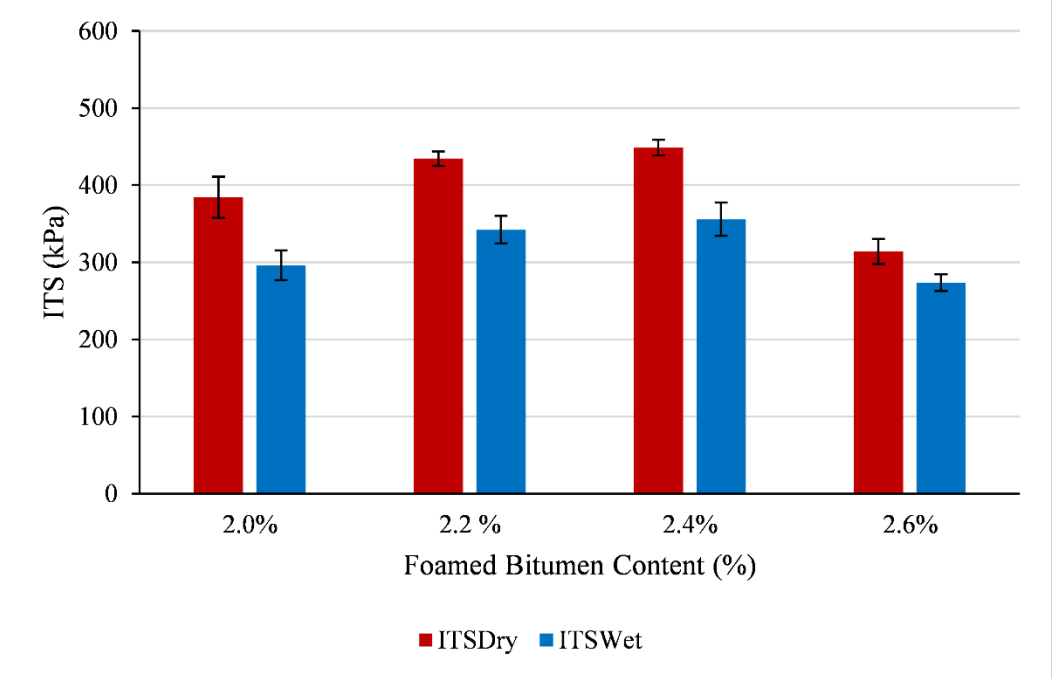

Figure II.7. The effect of bitumen content

2.5. The Effect of Compaction Methods (Gyratory Vs Vibrating Hammer)

This research is to benchmark gyratory, and vibratory compaction methods for BSM-Foam materials. ITS test is also used to assess the compaction method. The results are shown in Figure II.8 and Figure II.9.

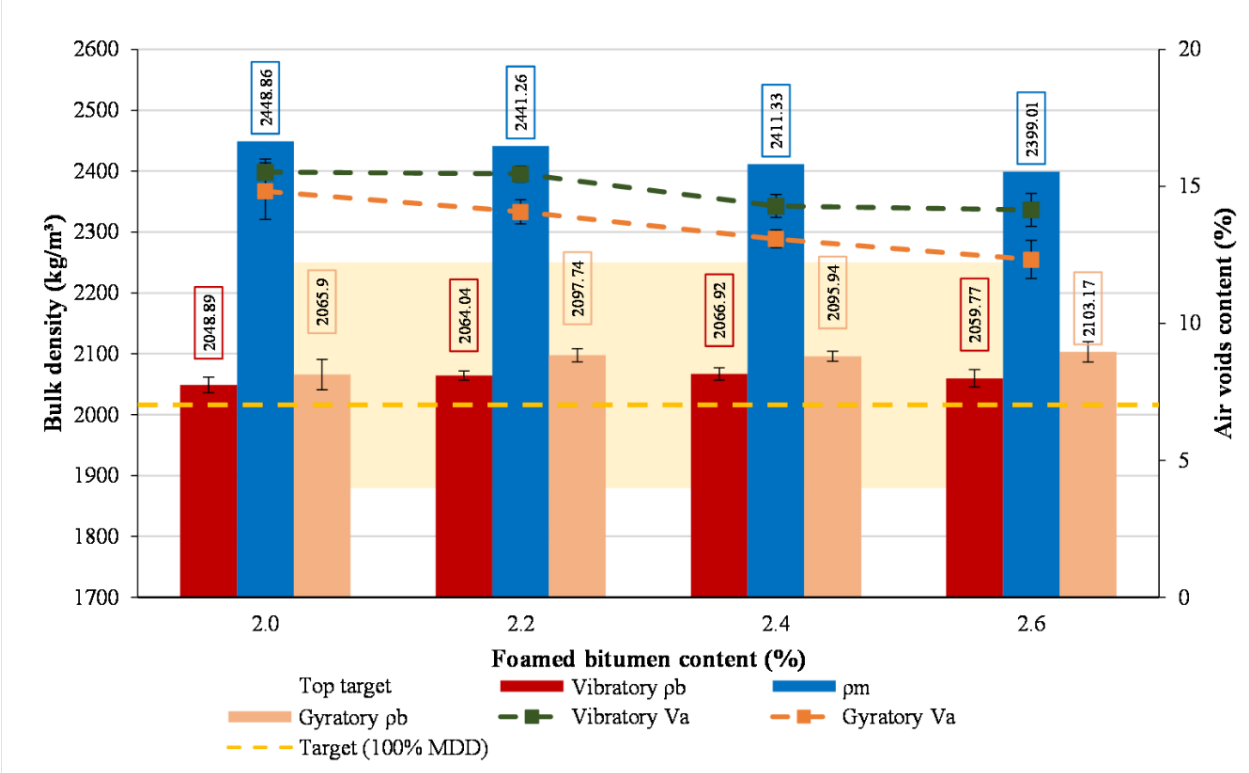

Figure II.8. Average bulk density and air void content of the FBMs gyratory and vibratory compacted using a different bitumen content

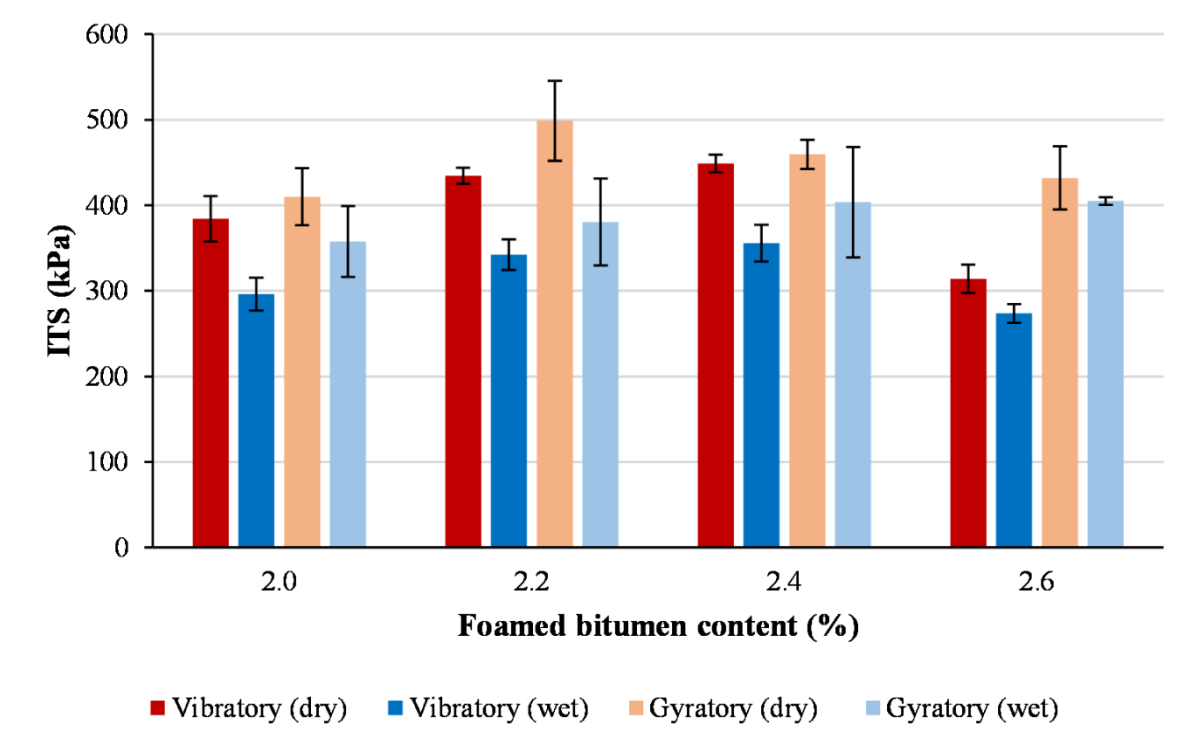

Figure II.9. Indirect tensile strength (ITS_{dry}, ITS_{wet}) of the mixtures compacted with gyratory and vibratory at different bitumen content

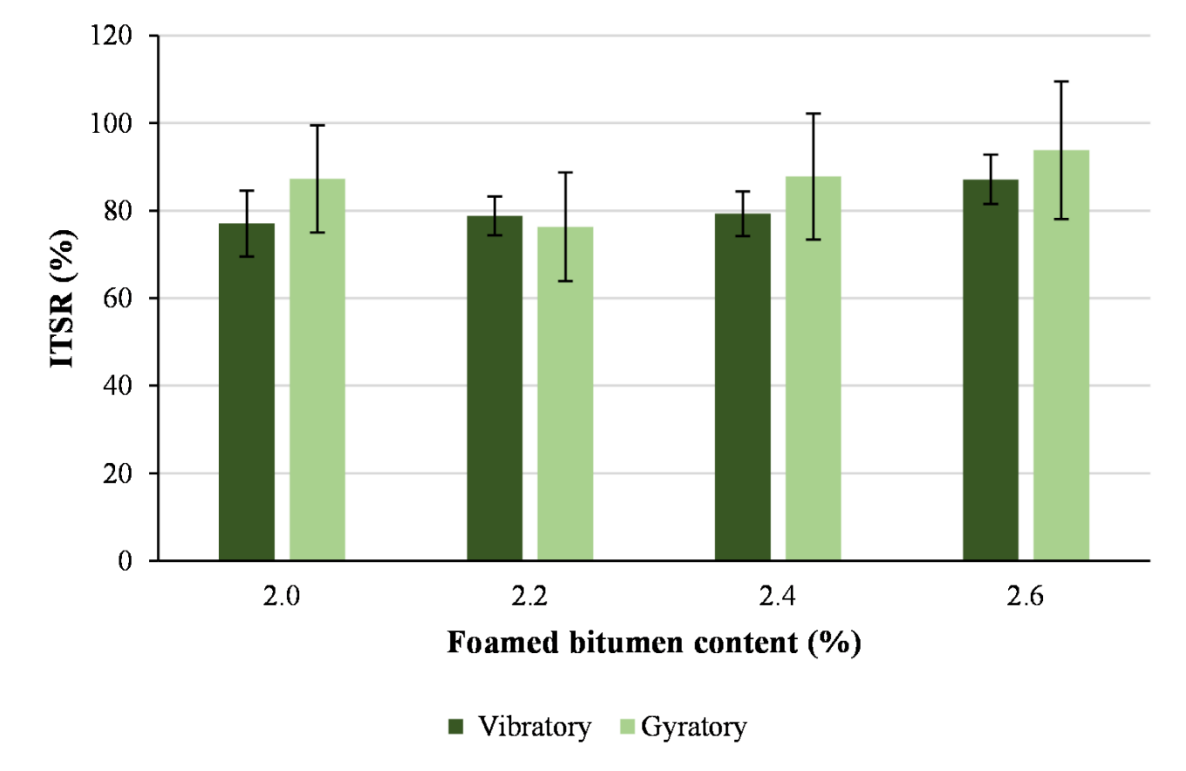

Figure II.10. Indirect tensile strength ratio (ITSR) of the mixtures compacted with gyratory and vibratory at different bitumen content

The results indicated a significant effect of the compaction method and bitumen application rate on the behaviour of the BSM-Foam. Analyses of the results illustrated that gyratory compacted samples had relatively high tensile strength in both conditions (dry and wet) than vibratory samples. The

possible explanation of this finding, the coarse aggregates crushes when subjected to cyclic loads, thus increasing the fine content and changing the gradation of the mixes. It should be noted that the compaction mechanisms of the vibratory and gyratory methods are different. The principle of the vibratory compaction method is to apply a significant impact of force while vibrating the material in the mould. On the other hand, the gyratory compaction method is based on a principle of simultaneous action of vertical static compaction and the shearing action resulting from the rotation of the mould on its inclined axis. These results showed that the tensile strength of the mixtures is affected by the compaction method.

2.6. Evaluation of shear properties

Monotonic triaxial test has been conducted on the optimum mixture that is 100% RAP stabilised with 2.2% foamed bitumen and 1% Cem III. Triaxial test is performed at 0 kPa, 50 kPa, 100 kPa and 200 kPa confining pressures. And two specimen are tested with soaked conditions. Cohesion (C) is determined 279 kPa while the friction angle (ϕ) is determined 35.3 º. Figure II.11. shows the triaxial test results. Due to laboratory set-up issues, soaked conditioned specimens are tested at 19-20 °C; this results in >100 kPa retained cohesion. However, ideally, it should be tested at 25 °C.

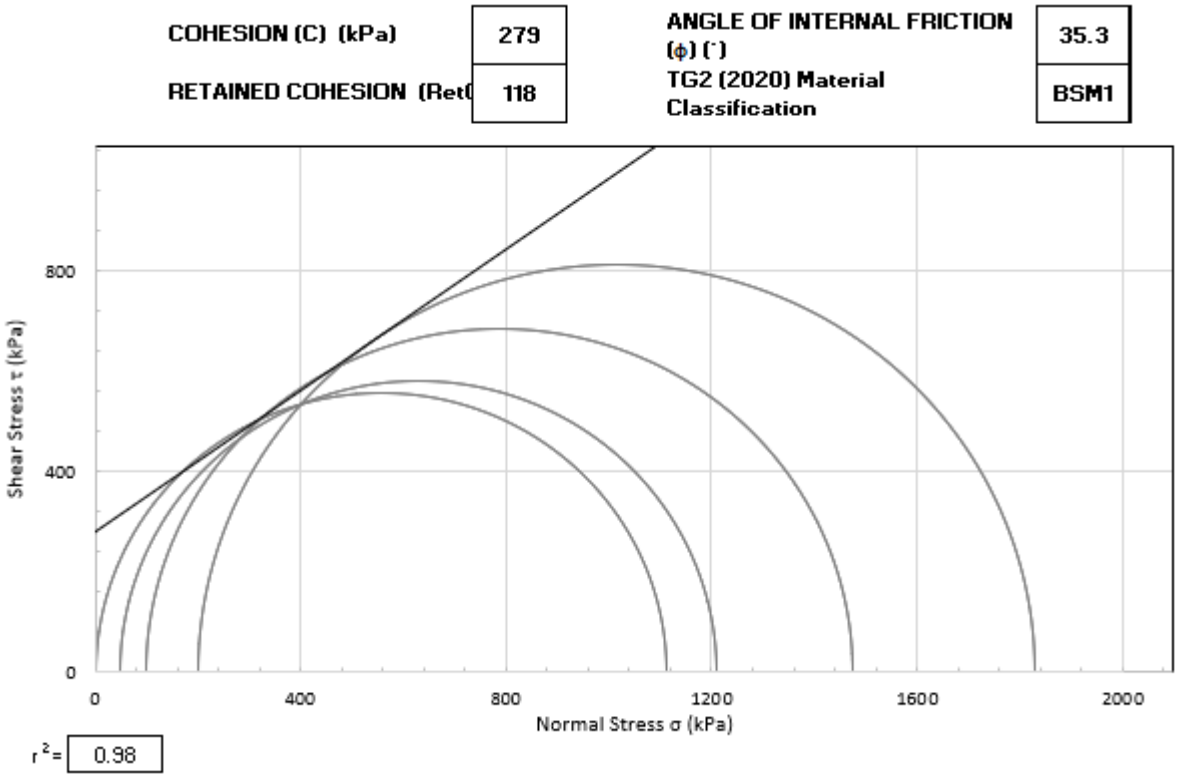

Figure II.11. Triaxial test results

According to the results obtained in the laboratory, cohesion value 279 kPa is hugher than the limitation of 265 kPa for BSM1 classification, however the friction angle is obtained 35.3 º that is slightly below the limitation of 38 º. Table II.6. shows the classification of BSM and boundaries for cohesion and friction angle.

Table II.6. BSM-Foam classification

Class	RAP (%)	ITS (kPa)		Triaxial		
		ITS_{DRY}	ITS_{WET}	Cohesion (kPa)	Friction Angle (°)	Retained Cohesion (%)
BSM1	< 50%	225	125	250	40	75
	50-100%	225	125	265	38	75
BSM2	< 50%	175	100	265	38	65
	50-100%	175	100	225	35	75

2.7. Indirect Tensile Strength Modulus (ITSM) results

ITSM test has been performed on the optimum mixture, 100% RAP stabilised with 2.2% foamed bitumen and 1% cement III. ITSM testing is performed on the optimum mixture at 25 °C to evaluate the resilient modulus. Poisson ratio 0.35 and target deformation 5 μm has been used to determine ITSM values. Specimens are compacted with vibrating hammer at 60 ± 2 mm height and 150 ± 2 mm diameter.

Table II.7. $ITSM_{DRY}$ test results of optimum mixture for 50, 124, 200 and 500 ms pulse rise times

Temperature (°C)	Pulse rise time (ms)	$ITSM_{DRY}$ (Mpa)	Average $ITSM_{DRY}$ (Mpa)
25	50	3820	3904
		3756	
		4071	
		3969	
	124	3679	3761
		3587	
		3906	
		3874	
	200	3275	3372
		3262	
		3508	
		3444	
	500	2832	2929
		2828	
		3031	
		3027	

The effect compaction method has also been evaluated with resilient modulus. Two batch of specimens compacted with gyratory and vibrating hammer is compared for optimum mixture. Results are presented in Table II.8.

Table II.8. The ITSM test results for gyratory and vibrating hammer specimens

Temperature (°C)	Pulse rise time (ms)	Compaction method	Average $ITSM_{DRY}$ (Mpa)
25	50	Vibrating hammer	3904
		Gyratory	3972
	124	Vibrating hammer	3761
		Gyratory	3840
	200	Vibrating hammer	3372
		Gyratory	3389
	500	Vibrating hammer	2929
		Gyratory	2912

Table II.9. ITSM test results at 25 °C , 15 °C and 0 °C

Compaction method	Temperature (°C)	Pulse rise time (ms)	Average $ITSM_{DRY}$ (Mpa)
Gyratory	25	50	3972
		124	3840
		200	3389
		500	2912
	15	50	5051
		124	4916
		200	4420
		500	3932
	0	50	7938
		124	7559
		200	6948
		500	6502

2.8. Comparison of Material Sampled From Test tracks vs Laboratory Produced

This project has constructed two test tracks using 100% RAP, 2.2 % foamed bitumen and 1% Cement III 42.5. The material from test tracks was collected from KMA. Right after KMA produces BSM material, it is collected and stored in plastic bags and sealed. The sealed bags were transferred to UA laboratories to be tested for ITS and Triaxial. However, it is important to note that due to the time delay between transportation and compaction, moisture loss has been observed. Figure II.12. The ITS results of test track 1 (Neder-Over-Heembeek) comparison of sampled and laboratory-produced material.

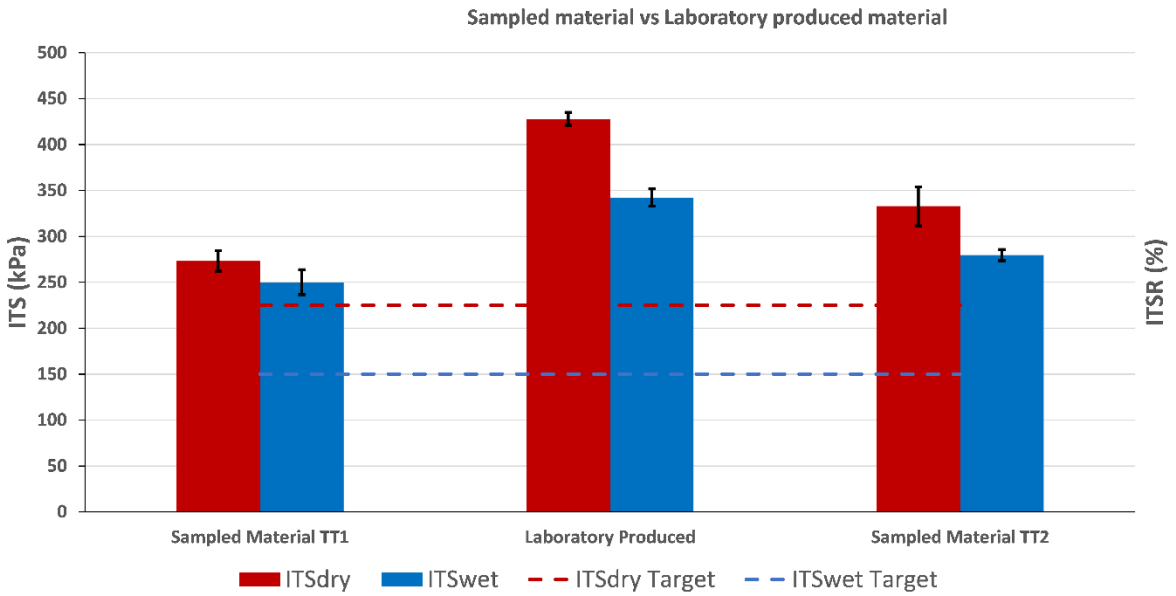

Figure II.12. ITS results of TT1 (Neder-Over-Heembeek) and TT2 (Puursesteenweg) sampled vs laboratory-produced material

Triaxial test results are presented in Table II.10.

Table II.10. Comparison of shear properties TT1 (Neder-Over-Heembeek) sampled vs laboratory-produced material

Mixture	Cohesion (C) (kPa)	Friction Angle (ϕ) (º)	Retained cohesion (RetC) (%)	Notes
Laboratory-produced material	279	35.3	118	Soaked specimens tested at 19-20 °C
TT1 (Neder-Over-Heembeek)	224	34.2	98	
TT2 (Puursesteenweg)	238	43.4	81	

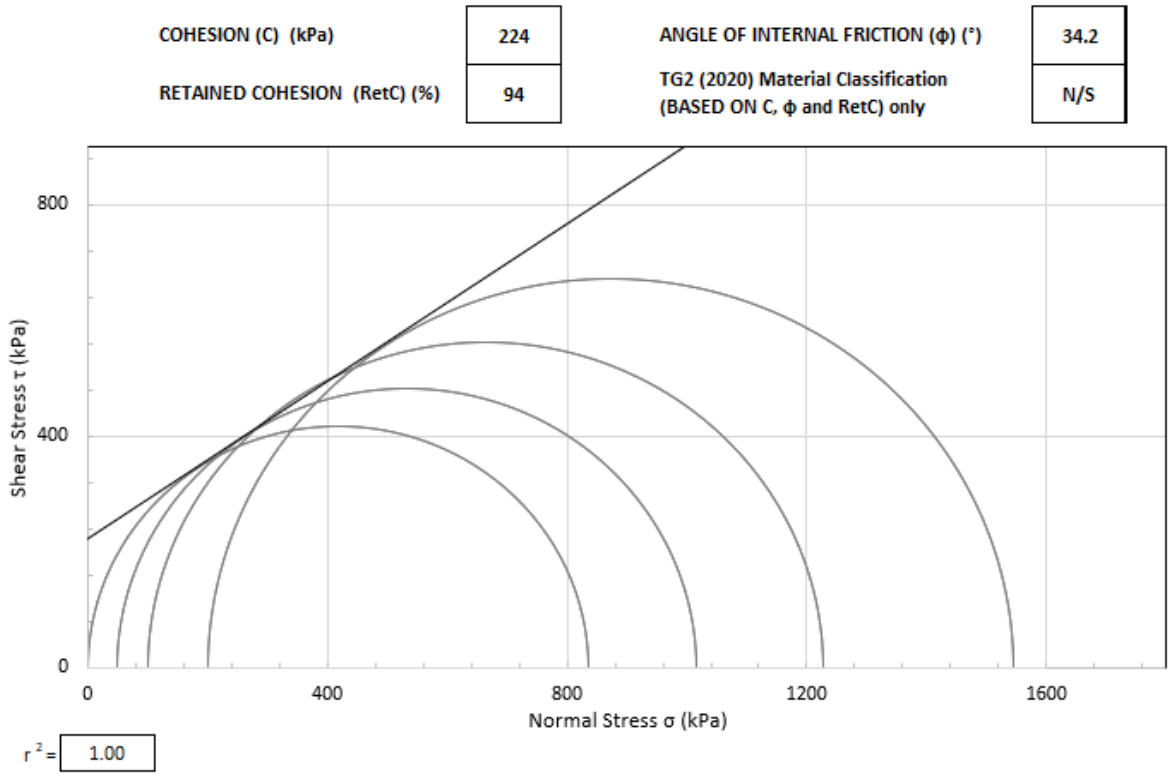

Figure II.13. Triaxial test results TT1 (Neder-Over-Heembeek)

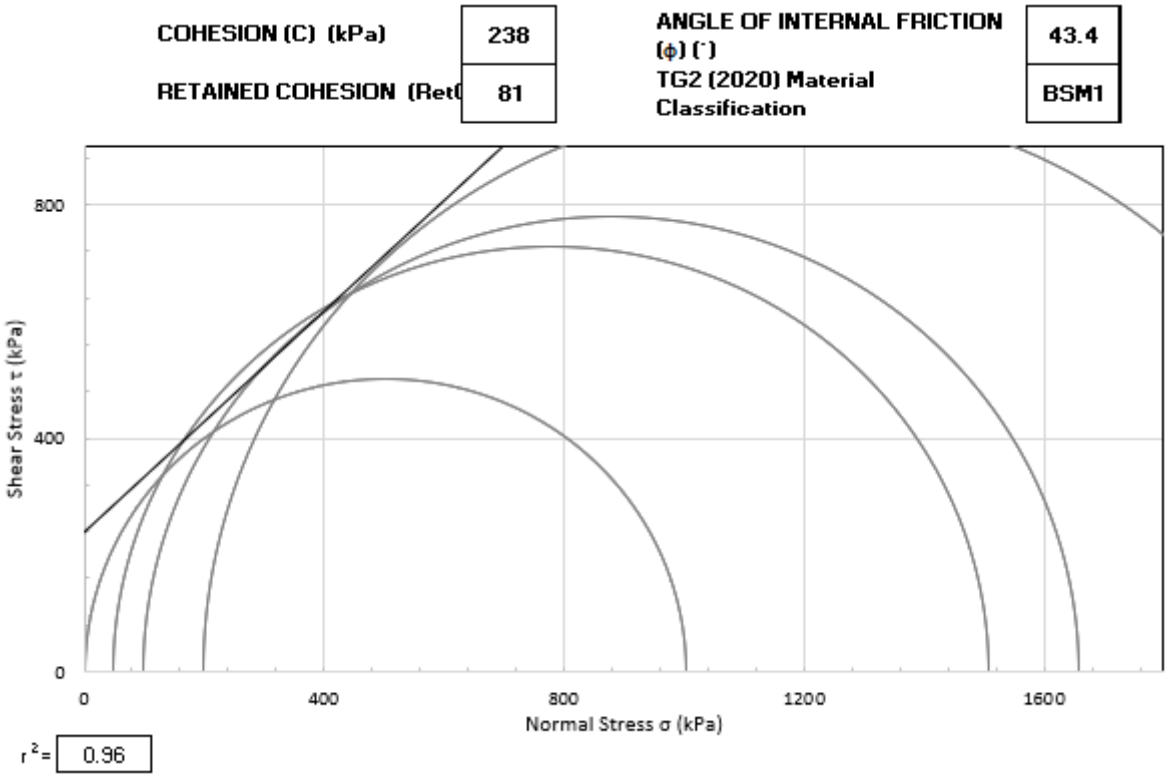

Figure II.14. Triaxial test results TT2 (Puursesteenweg)