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THE USE OF QUICKLIME AS AN ACTIVE FILLER ON COLD RECYCLED MIXTURES STABILIZED WITH BITUMEN

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Abstract

With the increasing usage of cold recycling techniques on maintenance of flexible pavements, also increases the need to better characterize the properties of cold recycled mixtures, usually composed of aggregates, reclaimed asphalt, active filler and bitumen, understanding the properties of cold recycling mixtures to set the design process on a performance-based approach. This research was designed to evaluate evolution on mechanical behaviour related with the use of quicklime (calcium oxide) as active filler on a BSM mixture with 100% RAP; the quicklime was added on different contents up to 5%, stabilised either with emulsion or foam bitumen, considering that the heat derived from its chemical reaction with water can be very convenient to deal with environmental limitations on the construction of a BSM layer. Alongside, this research also compares, in a qualitative and quantitative way, the changes in mechanical properties when cement is used as active filler. Indirect tension tests and simplified monotonic triaxial tests were run on emulsion and foam-based BSM mixtures produced with either quicklime or cement, added on different amounts. The mixtures were also subjected to temperature measurements on post-mixing phase. The results show that the use of quicklime may bring various advantages to cold recycling operations, with considerable increase and maintenance of temperature, up to around 20° C, with manageable performance variation, even when added on higher amounts. Results also indicate that mixtures designed with cement are more susceptible to mechanical behaviour changes when compared to the ones designed with lime, which suggests that mixtures designed with cement need a more precise mix design and specially a more accurate mixing control on field operations.

Keywords: Cold recycling mixtures; cold recycling mix design; bituminous stabilised materials; quicklime; RAP; reclaimed asphalt; active filler.

Sommario

Con il crescente utilizzo di tecniche di riciclaggio a freddo per la manutenzione di pavimentazioni flessibili, aumenta anche la necessità di caratterizzare meglio le proprietà delle miscele riciclate a freddo, solitamente composte da inerti, asfalto rigenerato, filler attivo e bitume, comprendendo le proprietà delle miscele da riciclo a freddo da fissare il processo di progettazione su un approccio basato sulle prestazioni. Questa ricerca è stata progettata per valutare l'evoluzione del comportamento meccanico correlato all'uso di calce viva (ossido di calcio) come filler attivo su una miscela BSM con RAP 100%; la calce viva è stata aggiunta su diversi contenuti fino al 5%, stabilizzata con emulsione o bitume schiumato, considerando che il calore derivante dalla sua reazione chimica con l'acqua può essere molto conveniente per far fronte alle limitazioni ambientali sulla costruzione di uno strato BSM. Parallelamente, questa ricerca confronta anche, in modo qualitativo e quantitativo, le variazioni delle proprietà meccaniche quando il cemento viene utilizzato come filler attivo. Prove di tensione indiretta e prove triassiali monotoniche semplificate sono state eseguite su miscele BSM a base di emulsione e schiuma, prodotte con calce viva o cemento, aggiunte in quantità diverse. Le miscele sono state inoltre sottoposte a misure di temperatura in fase di post-miscelazione. I risultati dimostrano che l'utilizzo della calce viva può apportare diversi vantaggi alle operazioni di riciclo a freddo, con notevole aumento e mantenimento della temperatura, fino a circa 20° C, con variazioni gestibili delle prestazioni, anche in presenza di quantità maggiori. I risultati indicano anche che le miscele progettate con cemento sono più suscettibili ai cambiamenti del comportamento meccanico rispetto a quelle progettate con la calce, il che suggerisce che le miscele progettate con cemento necessitano di un mix design più preciso e specialmente di un controllo della miscelazione più accurato nelle operazioni sul campo.

Resumo

Com o crescente uso de técnicas de reciclagem a frio na manutenção de pavimentos flexíveis, aumenta também a necessidade de melhor caracterizar as propriedades das misturas recicladas a frio, geralmente compostas por agregados, asfalto fresado, filler ativo e ligante betuminoso, entendendo as propriedades dessas misturas para solidificar o processo de design em uma abordagem baseada no desempenho. Esta pesquisa teve como objetivo avaliar a evolução do comportamento mecânico relacionado ao uso de cal virgem (óxido de cálcio) como filler ativo em uma mistura tipo BSM com 100% RAP; a cal virgem foi adicionada em diferentes teores de até 5%, estabilizada tanto com emulsão quanto com espuma de asfalto, visto que o calor derivado de sua reação química com a água pode ser muito conveniente para lidar com as limitações ambientais na construção de uma camada de BSM. Paralelamente, esta pesquisa também compara, de forma qualitativa e quantitativa, as mudanças nas propriedades mecânicas quando o cimento é utilizado como filler ativo. Testes de tensão indireta e testes triaxiais monotônicos simplificados foram executados em misturas de BSM à base de emulsão e espuma produzidas com cal viva ou cimento, adicionadas em diferentes quantidades. As misturas também foram submetidas a medições de temperatura na fase de pós-mistura. Os resultados mostram que o uso da cal virgem pode trazer diversas vantagens às operações de reciclagem a frio, com considerável aumento e manutenção da temperatura, até cerca de 20° C, com variação de desempenho administrável, mesmo quando adicionado em quantidades maiores. Os resultados também indicam que as misturas projetadas com cimento são mais suscetíveis a mudanças de comportamento mecânico quando comparadas às projetadas com cal, o que sugere que as misturas projetadas com cimento precisam de um projeto de mistura mais preciso e, principalmente, de um controle de mistura mais preciso nas operações de campo.

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Chapter 1 - Introduction

Cold recycling of pavements refers to the operations of the recovering and re-using material from an existing pavement, without heating aggregates. This technology can be currently employed to construct pavements for all types of roads, covering minor local roads to major multi-lane highways. Whenever a pavement is distressed, recycling the existing material becomes an option and provides benefits such as lower construction costs, improved service life and a major reduction in the negative environmental impact. The cold recycling technology includes a wide range of applications:

- the "in-place" techniques that use the materials that came directly from a damaged pavement to build either a layer of the new pavement or the whole new pavement directly in place.

- the "in-plant" techniques" that use the materials stocked and handled in a construction plant (stable or with mobile equipment).

The selection of mix type and production equipment depends on a list of aspects, such as availability of equipment, hauling distances, properties and composition required on the executive project, and costs of production, transportation, and laying.

Cold in-place recycling and in-plant recycling with mobile equipment are growing in importance since it provides environmental and economic benefits; among these techniques, the stabilizations with bitumen are now probably the most used. Several authors in recent years listed some main advantages of cold recycling techniques such as reduction of consumption of natural materials and reduction of amount of waste, as it allows to reuse high-cost material, reduction of energy consumption, as it avoids aggregate heating, fuel consumption and resulting CO_2 emissions, and reduces transportation and heavy vehicle traffic (Ebel and Jenkins 2007; Dave, 2011; Stroup-Gardiner, 2011; Betti et al., 2017; Tebaldi et al., 2018).

On the other hand, the authors also state some challenges to be faced, such as designing a proper mixture using the available materials, controlling the mixture's water content, and quick achievement of bearing capacity sufficient to allow completion of repaving work. Wirtgen´s cold recycling technology manual (2012) lists some of the benefits of the adoption of cold recycling for pavement rehabilitation projects. Those benefits include:

- Environmental benefits: the material in the existing pavement is fully used, causing the reduction of the amount of virgin material brought from quarries, the haulage of heavy vehicles, and consequent damage on existing roads in the influence area of the project. In addition, the overall energy consumed by cold recycling is significantly less when compared to all other rehabilitation options.

- Quality benefits: the use of modern recycling equipment brings consistent, high quality mixing of the in-situ materials with water and stabilising agents, promoting the achievement of homogeneous product.

- Construction time benefits: modern recycling equipment are capable of high production rates, causing the reduction of construction times, shorter project costs, and shorter time periods of disrupted traffic.

- Safety benefits: relatively high levels of traffic safety that can be achieved, as the recycling operation can be accommodated within the width of one traffic lane.

- Cost benefits: all above mentioned benefits contribute to make cold recycling a most attractive process for pavement rehabilitation in terms of cost effectiveness.

Where an existing pavement is recycled, old asphalt surfacing is usually mixed with the bottom layers and treated with some binder material to form a new base or subbase layer. This new layer may be constructed using Bitumen Stabilized Materials (BSM), which are composed of a granular material (such as virgin aggregates, recycled cement treated materials, and/or up to 100% reclaimed asphalt), treated with either bitumen emulsion or foamed bitumen (Asphalt Academy, 2009). BSM mixtures are specifically designed to make base and subbase layer of flexible pavements. BSM enhances the properties of recycled pavement materials, providing equal or better service lives compared to those achievable with virgin materials, at a lower cost. According to Ebel and Jenkins (2007), binder content in mixes with a high percentage of RAP may be reduced to achieve similar mix properties because no binder absorption takes place in case of the RAP particles, cohesion is enhanced, and durability and moisture susceptibility is improved by the old binder on the RAP particles.

Cold in place recycling using BSM technology is a popular technique, most probably, according to Betti et al. (2017), because it can be simply obtained mixing reclaimed asphalt (RA) aggregates from the bound layers with the aggregates from the unbounded layers of pavement. Together with several advantages, the authors state an important challenge faced by pavement engineers and researchers: how to manage the addition of active fillers. Small amounts of active filler can significantly increase retained strength without affecting the flexibility of the layer. The active fillers also facilitate the dispersion of bitumen in the mixture, help the control over the moisture content and treat fine plastic particles in the aggregates. Fillers also promote emulsion separation, and act as a dispersion catalyst with foamed bitumen. It is therefore common practice to use cement or hydrated lime in conjunction with bituminous stabilizing agents. When cement is used as active filler, Asphalt Academy (2009) suggests the application rate must be limited to a maximum of 1% by mass of dry aggregate. The application rate of hydrated lime may be increased up to 1.5% or more, whenever lime is required to modify plasticity. According to Asphalt Academy

(2009), above these application rates, an increase in mix stiffness may compromise the deformability of the material, and the layer may present brittle behaviour, which encourages shrinkage and traffic-associated cracking. One last recommendation regards the content of bitumen, which should not be exceeded by the content of active filler, to ensure the benefits of bitumen treatment are achieved. Lastly, a BSM solution can be quite customized for a specific purpose, depending on the project needs. Different mix proportions and particular properties of the selected aggregates, bitumen and active filler, may produce a compound with similar behaviour of either granular materials, cemented materials or hot-mix asphalt (Jenkins et al., 2012).

However, the intense use of BSMs leads constructors to face unfavourable weather conditions during construction phases: mainly temperatures too low to allow the proper dispersion of the bitumen and rain that makes too high the water content in the mixtures. Right now, the solution at these contingencies is to wait until the weather conditions become favourable: temperature stably up than 10°C and dry season. Some general recommendations on the execution of recycled layers (Stroup-Gardiner, 2011; Wirtgen, 2012) include lower limits for ambient (~5-10°C) and pavement temperature (~10-15°C). Low ambient temperatures are especially prejudicial for cold recycled mixtures stabilised with foamed bitumen, as the superficial tension of the bubbles changes, which may cause problems with the distribution of the asphalt droplets throughout the mixture. In addition, Raschia et al. (2020) also showed that ambient temperature during transportation of cold bitumen treated mixtures, produced either with emulsion or foamed bitumen, influences directly the effort required for the mixtures on-field compaction. Technical guidelines (Asphalt Academy, 2009; Stroup-Gardiner, 2011; Wirtgen, 2012) also discourage works under misty or rainy weather, anticipated overnight freeze, wet RAP stockpiles or roadway, and windy conditions when the solution includes the spreading of powdered chemical stabilising agents. It must be noticed that the contractors are normally using empirical approaches to avoid the stop of the work, but in many cases, there are no guarantees on the final quality of the materials laid down.

Thus, this research hypothesizes that the is possible use of Calcium Oxide (CaO) as active filler on BSM mixtures can help constructors to deal with on-field ambient conditions, such as cold weather and/or excessive moisture, Figure 1, taking advantages of the exothermic chemical reaction between CaO and water.

Figure 1 - Main hypothesis of the research

1.1. Objective and scope

The main objective of this thesis is to evaluate the use of calcium oxide (CaO) as an active filler to produce Bituminous Stabilised Mixtures on pavements cold recycling operations.

As specific objectives, it is possible to highlight:

- Evaluate mechanical behaviour of BSM mixtures produced with bitumen emulsion and different amounts of CaO.
- Evaluate mechanical behaviour of BSM mixtures produced with foam bitumen and different amounts of CaO.
- Compare obtained mechanical results from the CaO innovative mixtures with a reference BSM produced with foam bitumen and cement.
- Evaluate if the heat produced by the hydration reaction of CaO during mixing

phase is enough to have a significant increase of the overall mix's temperature.

- Evaluate if temperature behave along the time, after mixing phase, can be compatible for mix transportation, lay down and compaction phases.

To achieve these objectives a testing campaign to evaluate the mechanical behaviour of the mixtures in function of the amount of added CaO (Figure 2), as well as series of temperature measurements after mixing (Figure 3), were carried on.

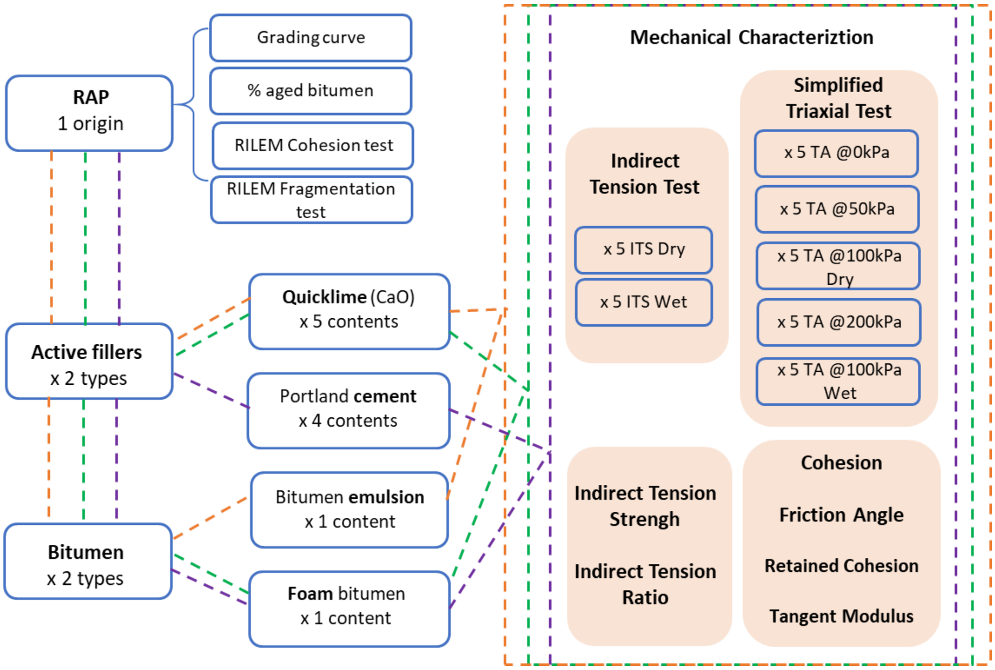

Figure 2 – Scheme of mechanical characterization campaign

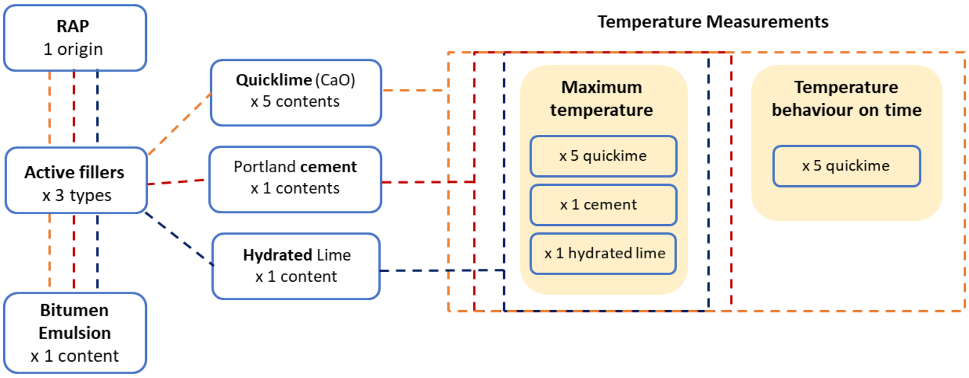

Figure 3 – Scheme of temperature measurements campaign

1.2. Organization of the thesis

This thesis shows the results of a comprehensive research work on the possibility to use calcium oxide as an active filler for BSM to take advantage of the heat generated during hydration reaction to allow preparation, laying down and compaction of mixtures when the ambient temperature is lower than recommended ones to operate properly.

- Chapter 1 presents a brief introduction on the theme, as well as the objectives and scope of the research.
- Chapter 2 brings a theoretical background and previous findings of scientific and technical literature on BSM.
- Chapter 3 discusses properties and uses of calcium oxide and its hydration process, necessary to better understand the processes involved on the designed mixture for the present research.
- Chapter 4 is all about materials and methods applied to obtain the results and discussions presented.

- Chapter 5 presents the results found after data analysis and the hypotheses proposer to explain these results.

- And finally, a summary and conclusions of the research are shown on Chapter 6.

Chapter 2 – Bituminous Stabilised Materials

The Asphalt Academy (2009), one of the most advanced technical guidelines regarding classification for design purposes, the mix and structural design and construction aspects of BSM, defines these mixtures as pavement materials, normally granular materials or reclaimed asphalt, treated with either bitumen emulsion or foamed bitumen. The addition of bitumen emulsion or foamed bitumen to produce a BSM results in an increase in material strength and a reduction in moisture susceptibility because of the way the bitumen is dispersed amongst the finer aggregate particles. The Norwegian Public Roads Administration guidelines for cold bitumen stabilized base courses (2014) reinforces that cold bituminous stabilised materials have a relatively low initial strength, however as the fine particles are bounded, these mixes are less moisture susceptible than corresponding materials without the stabilising agent. Additionally, as the stiffness increases quickly as the material gradually has its moisture content reduced, during curing period (Jenking et al., 2012; Bessa et al., 2016; Pasetto et al., 2020), the layer must be well drained.

Therefore, a highlight on BSM mixtures is the significant increase in cohesion when comparison to untreated granular material, even if they present similar friction angle, performing satisfactorily when cohesive strength is optimised, while retaining enough flexibility so that friction resistance is still activated under load. Improved durability and moisture sensitivity are also main features of BSM mixtures, and lower quality aggregates can often be successfully used. Thus, behaviour of BSMs is like unbound granular materials, but with improved cohesive strength and reduced moisture sensitivity. On the other hand, BSM mixtures are not like hot-mix asphalt, as they have lower bitumen content. Figure 4 presents a scheme on the components of granular unbounded materials, non-continuously bounded (such as BSM) and fully bound materials.

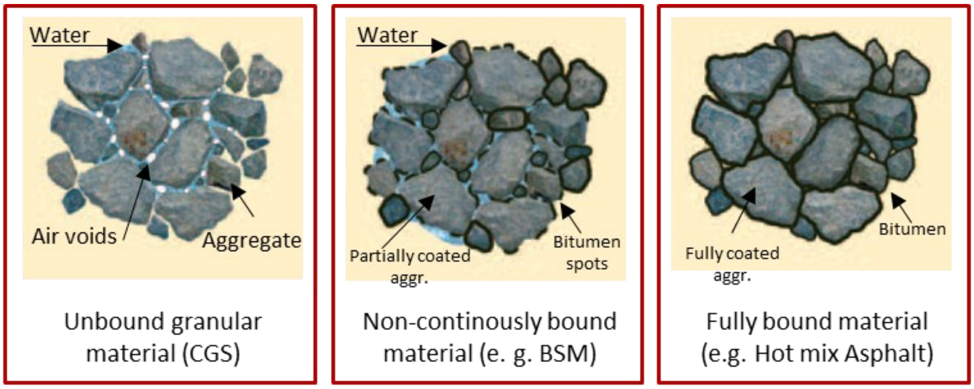

Figure 4 - Unbound, partially bound and fuly bound pavement material scheme, adapted from Wirtgen (2012)

Active fillers in the form of cement or hydrated lime are usually added to the mix, to improve retained strength under saturated conditions, and to assist the dispersion of the bitumen. The cement content should not exceed 1% and should also not exceed the percentage of the bitumen stabiliser. It is recommended that the bitumen content exceeds the active filler content, to ensure the benefits of bitumen treatment are achieved. Amount of cement above these limits may change the mechanical behaviour, from a predominantly frictional material to a predominantly cohesive one, see Figure 5 (Asphalt Academy, 2009). It results on an increase of brittleness of the layer, requiring an adequate structural design.

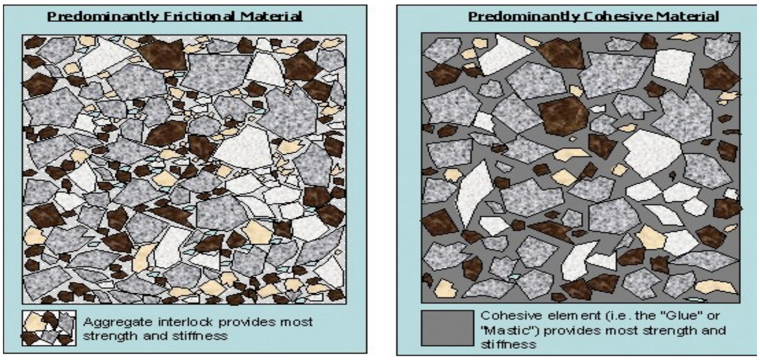

Figure 5 – Possible internal arrangement of the mixtures particles on cold recycled mixtures (Asphalt Academy, 2009)

According to Austroroads guide to pavement technology (Jameson, 2019) the bitumen emulsion acts on BSM agglomerating fine particles, causing the decrease of permeability, improving cohesive strength, and decreasing moisture sensitivity by coating fines. On the other hand, foamed bitumen acts on BSM developing inter-particle bonds causing significant increase of modulus and tensile strength. Both types of stabilising agents are applicable to granular materials with low cohesion and low plasticity. Figure 6 shows the expected behaviour of BSMs when compared to other pavement materials, as a function of both bitumen and active filler contents (Asphalt Academy, 2009). It is possible to understand that BSM is such a versatile material, as a mix can be designed to behave more granular-like, cemented-like, or hot-mix asphalt materials, by changing the mix proportions of aggregate, bitumen and/or active filler.

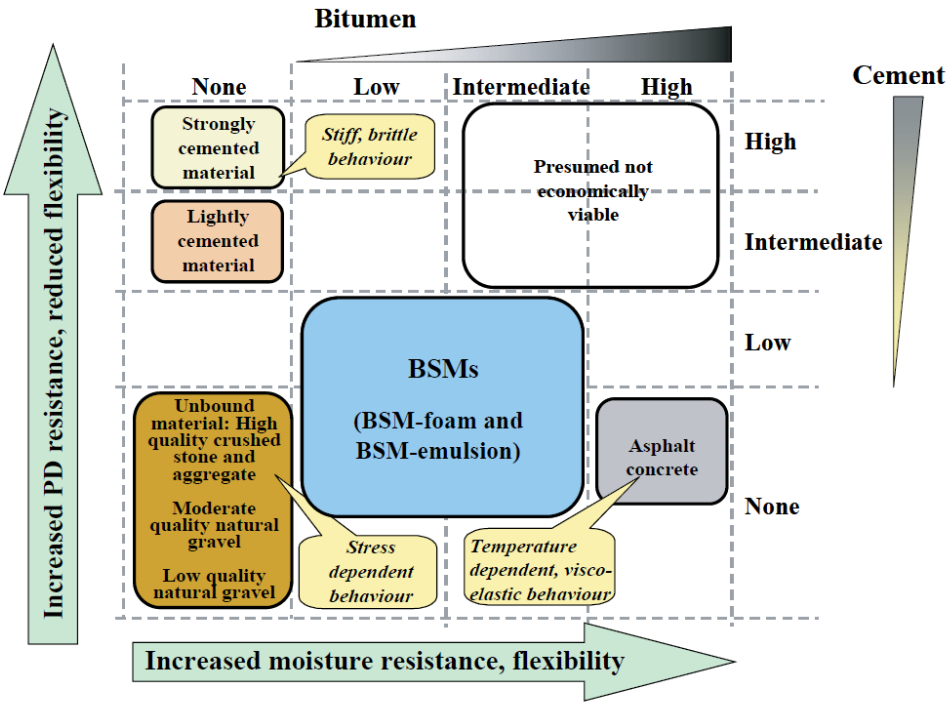

Figure 6 – Conceptual Behaviour of Pavement Materials, as presented on Asphalt Academy (2009)

BSM layers should be designed to resist mainly against two in the fundamental failure mechanisms permanent deformation (or rutting) and moisture susceptibility. Rutting refers to accumulated shear deformation due to repeated loading (traffic) and can be improved by appropriate material selection (e.g., aggregate angularity, shape, hardness and roughness), mix design (e.g., addition of limited amount of bitumen and active filler), and on-field execution (e.g., improved compaction and proper curing). Moisture susceptibility is the damage caused by exposure of the layer to high moisture contents (e.g., under misty and rainy weather), which under traffic loads causes high pore-pressure, culminating in loss of adhesion between bitumen and the aggregate. Moisture resistance can be strengthened by appropriate material selection (e.g., aggregates continuous grading), mix design (e.g., addition of proper amount of bitumen and active filler), and on-field execution (e.g., improved compaction).

In general, there are two common ways of adding fresh binder to cold recycling processes. Bitumen can be added in a temporary state of low viscosity, either as emulsion or foamed bitumen. Table 1 compares characteristics of both treatment process, emulsion-based BSM and foam-based BSM, as the items 2.1 and 2.2 discuss their uses with more details, always in the context of cold recycling mixtures.

The quantities of residual bitumen emulsion or foamed bitumen added do not typically exceed 3% by mass of dry aggregate. Austroroads (2019) indicates that foamed bitumen stabilised pavement materials commonly have from 2.5% to 3.5% binder content, as Asphalt Academy guidelines (2009) indicates typical foam bitumen content varying from 1.7% to 2.5% on BSMs. The bitumen disperses only amongst the finest particles, resulting in a bitumen-rich mortar between the coarse particles.

Table 1. Comparison between emulsion and foam bitumen application on BSM, adapted from Wirtgen (2012)

Factor	Emulsion-based BSM	Foam-based BSM
Aggregate types applicable	- Crushed rock - Natural gravel - RAP	- Crushed rock - Natural gravel - RAP - Marginal (sands)
Bitumen mixing temperature	20 – 70°C	160 – 180°C (foaming temperature)
Aggregate temperature during mixing	Ambient (>10°C)	Ambient (>15°C)
Moisture content	OMC + 1% - emulsion content	70% – 90% of OMC
Type of aggregate coating	Partial coating of coarse particles and cohesion of mix with bitumen / fines mortar	Coating of fine particles only with "spot welding" of mix from the bitumen / fines mortar
Construction and compaction temperature	Ambient	Ambient
Air Voids	10 – 15%	10 – 15%
Important parameters of binder	- Emulsion type - Residual bitumen - Breaking time - Curing	- Half-life - Expansion ratio - Curing

2.1. Emulsion-based BSM

Bitumen emulsion is composed by neat or modified bitumen held in suspension in water by an emulsifying agent, inside industrial plant (Figure 7). Commercial emulsions can be either anionic or cationic, depending if the emulsifying agent has a negative or a positive charge, respectively. Bitumen emulsions are manufactured in specific industrial plants and have shelf life of several months, as long as storage guidelines are precisely followed.

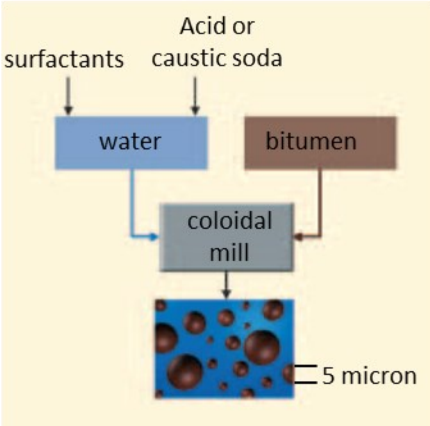

Figure 7 - Schematic manufacture process of bitumen emulsion, adapted from Wirtgen (2012)

The moisture and type of aggregate in the mix plays an important role in dispersing the bitumen emulsion and controlling the separation of the bitumen from the water (i. e., breaking process). Aggregates attract the individual bitumen droplets when mixed, mainly smaller fractions (filler) due to their higher surface area and charge concentration. After compaction should take place the breaking process, allowing the bitumen to act no longer as a lubricant, but as a binder. Extra care should be taken when constructing thicker layers (> 150 mm) of emulsion-based BSM to ensure that the bitumen emulsion breaks within a reasonable interval. Emulsion-based BSM presents a sprinkled visual aspect due to the concentration of bitumen on the finer particles.

As a general indication, aggregates with temperatures of 10°C or higher can be treated with bitumen emulsion without compromising the bitumen distribution and particle coating. On a study to investigate the effect of temperature on each step of emulsion-based cold recycled mixtures production process (i. e., mixing, transportation and compaction, and curing), Raschia and colleagues (2020) pointed out that there are no standardization establishing the minimum temperature required to produce a cold bitumen treated material, but only recommendations found on manuals. Those recommendations are based on their experience, without distinguish the three different processes: mixing, transportation and laydown, and compaction. It was possible to identify technical guidelines suggesting 5°C as the minimum temperature for laydown, whereas in other cases a temperature of at least 10°C is recommended to carry out a cold recycled project using emulsion. The same study concluded that low temperature (around 5°C) of transportation and compaction operations plays critical effect on cold recycled mixtures workability, as they required higher compaction energy to reach the target volumetric properties.

2.2. Foam-based BSM

Foam bitumen is produced on the construction site by injecting a small amount of pressured water and air directly into hot asphalt (Figure 8), while it is mixed with the recycled materials. As the hot bitumen and water mix together, the bitumen expands as the water turns to steam, creating bubbles with a thin film of asphalt with about 10 times more coating potential. Foaming facilitates better dispersion of the asphalt into the materials to be recycled.

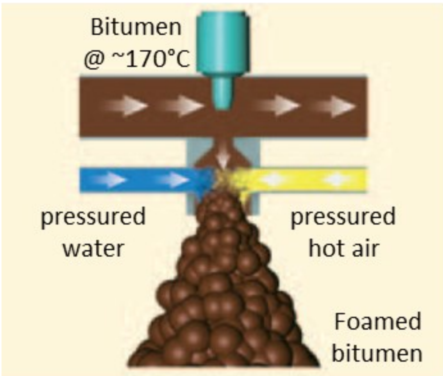

Figure 8 - Schematic production process of foam bitumen, adapted from Wirtgen (2012)

The two key parameters that control the quality of the foam are expansion ratio, defined as the ratio between the maximum achieved volumes of the foam to its original volume, and half-life, defined as the time elapsed from the time the foam was at the maximum volume to the time it reaches half of the maximum volume (Figure 9a). Maximized expansion ratio and half-life are desired for a better coating, dispersion of the bitumen and workability. According to Wirtgen (2017), at the same amount of foaming water addition, the hotter the bitumen, the greater the expansion; however, half-life will be correspondingly shorter (Figure 9b). The established optimum bitumen temperature and water addition represent important information for the machine operator and for the quality of the foam bitumen at the construction site.

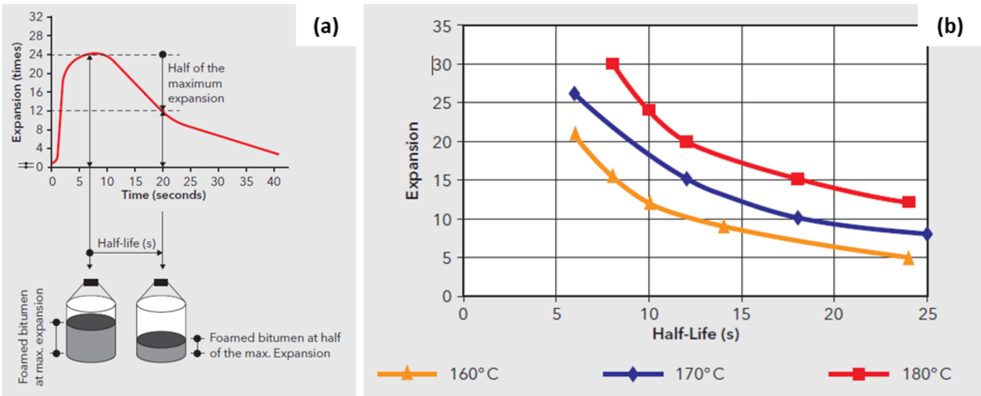

Figure 9 – Expansion and half-life of foam bitumen at different foaming temperatures (Wirtgen, 2017)

Like emulsion-based BSM, also foam-based BSM requires sufficient fine particles to facilitate the dispersion of the bitumen. Wirtgen (2009) suggests a minimum of 5% passing the 0.075 mm sieve.

The use of foam as stabilising agent on cold mixtures is influenced by the mixing temperatures, as shown by Jenking et al. (2000). According to the researchers, both tensile strength and stiffness have presented lower values with mixtures where prepared at 13°C with respect to those prepared with 21°C, as shown on Figure 10.

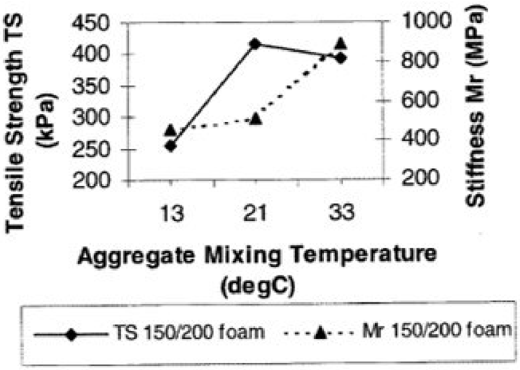

Figure 10 - Effect of lower mixing temperatures on BSM stiffness (Jenkings et al. 2000)

On the other hand, the same researchers showed significant benefits on particles coating when aggregates are moderately heated before the treatment with foam. As presented on Figure 11, it was possible to infer that when heated previously, the aggregates were better covered by the bitumen.

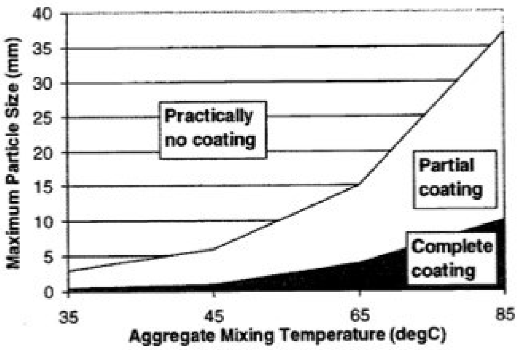

Figure 11 – Particle coating as function of size and temperature during mixing with foam bitumen (Jenkins et al., 1999)

2.3. Considerations on cold recycled mixtures mix design

The use of BSMs can be particularly challenging, as a wide number and types of ingredients can compose them. Those ingredients include aggregates, water, bitumen and active filler, with varies their own variability, availability and cost. The formulation of a BSM requires consideration not only of volumetric and compaction characteristics, but also the engineering properties and durability. Cold-in-place recycled mix design approaches and the applied test procedures still vary considerably, not only among European countries (Mollenhauer et al., 2011), but also around the globe (Jones et al., 2009; Jenkins et al. 2012; Tebaldi et al. 2014). Batista and colleagues (2014) pointed out some key points still needing further investigation with respect to cold recycled mixtures, such as the effect of different laboratory compaction methods, the influence of different accelerated laboratory curing procedures, suitable test procedure for water sensitivity assessment, and the evaluation of different performance test methods and mix design requirements.

After establishing the correct granular composition (RA + corrective materials if required) and selecting bituminous binder to be used (either foam or emulsion), mix design proceedings involves the determination of water content to optimize the mix workability and the layer compaction during construction; the requirements of bituminous emulsion/bitumen foam content to ensure the desired mix stability and strength during the pavement’s service life.

Previous researchers (Jenkings, 2000; Batista et al., 2012; Kuna et al. 2016) pointed out that the determination of optimal water content for cold recycled mixes can be assessed according to Proctor laboratory test results. On the other hand, Batista et al. (2014) highlighted that there is no consensual method for detecting the optimum bitumen content. According to the mentioned researchers, even though the selection of the bitumen content being usually based on the mechanical properties of the mixture (such as Indirect Tension Strength, Resilient Modulus, Uniaxial Compression Strength), the correspondent test procedures differ considerably worldwide, regarding either compaction methods, specimens' dimensions, curing procedures, testing conditions and/or required quality parameters. For the present research, the mix design was conducted using aa methodology proposed by the industry (Wirtgen, 2017), with some adaptations, considering the equipment available on the University of Parma´s laboratory. The used mix design methodology is presented and discussed on the item 4.5.

2.4. BSM testing and classification

The Indirect Tensile Strength (ITS) of a BSM can be determined through indirect tension test, which measures the resistance to failure of a cylindrical specimen 152 mm in diameter and 95 mm, high when a vertical compression load is applied to the curved sides of the specimen (Figure 12). This test provides a reference to the historic performance of mixes (ITSdry) and a measure of moisture resistance (ITSwet).

Figure 12 – Indirect tension test specimen and configuration

Besides indirect tension test, the monotonical confined compression test (simple triaxial test) was used to determine the shear properties of the BSM, i.e. cohesion and internal friction angle (Jenkins et al., 2012). This is simplified triaxial test developed by Jenkins and his colleagues (2012), as a part of a major project to develop adequate mix design procedures of BSM. They developed a simple triaxial cell apparatus that allows laboratories to access the mix properties, with the advantages of cost, simplicity and speed of testing, and with comparable results to the traditional triaxial test. According to Asphalt Academy (2009), the simple triaxial test apparatus (Figure 13) is only applicable to monotonic triaxial testing to obtain cohesion and friction angle values. In addition, it is also possible to calculate the monotonic stiffness of the material, i. e. tangent modulus, which provides an indication of resilient response of the material.

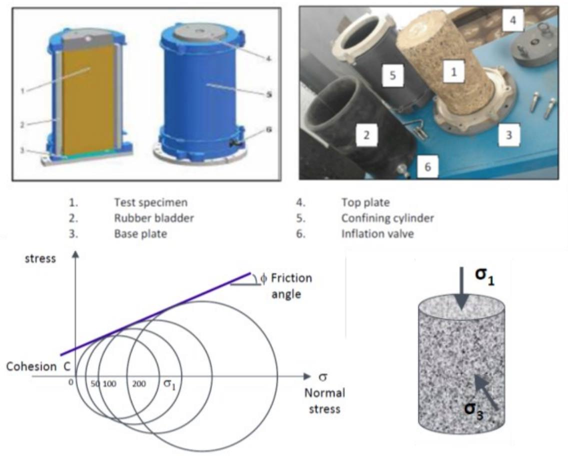

Figure 13 - Triaxial test specimens and configuration.

According to Tebaldi et al. (2018) the triaxial testing has also recommended by few cold recycling methods to determine the strength gain and extent of curing. The triaxial testing of cold mixes at early age can be considered adequate, as the material tends to present a more "granular-like" behaviour than a cohesive one, as in that of asphalt concrete. The triaxial testing is used to obtain shear properties of the cold recycled materials and their behaviour in confined conditions. The Asphalt Academy (2009) design manual for cold mixes recommend triaxial testing for roadways with traffic levels above $6x10^6$.

Asphalt Academy (2009) proposes a classification of BSMs, including three classes of material: BSM1 has a high shear strength and is typically used as a base layer for design traffic higher than $6x10^6$ equivalent standard axles, BSM2 has a moderately high shear strength and is typically used as a base layer for design traffic lower than

$6x10^6$ equivalent standard axles, BSM3 is only suitable for design traffic lower than 10^6 equivalent standard axles. Table 2 highlights the required indicators for each class.

Table 2. Classification criteria for BSM according to Asphalt Academy (2009)

Test or indicator	BSM 1	BSM 2	BSM 3
ITSdry (φ150mm)	> 175 kPa	135 - 175 kPa	95 - 135 kPa
ITSwet (φ150mm)	> 150 kPa	100 - 150 kPa	60 - 100 kPa
Cohesion	> 250 kPa	100 - 250 kPa	50 - 100 kPa
Friction angle	> 40°	30 - 40°	< 30°
Retained Cohesion	> 75%	60 - 75%	50 - 60%

Chapter 3 - Calcium oxide and the hydration of calcium oxide

Quicklime is the commercial name of a chemical compound, which consists mainly of calcium oxide (CaO), with some magnesium oxide (MgO) as a secondary constituent (higher is the amount of CaO higher is the pureness (title) of the material). It is produced by the thermal decomposition of limestone, inside specific kilns at temperatures around 1100°C, in a process known as calcination. Limestone is a mineral mainly constituted of calcium carbonate, and their deposits occurs naturally and are distributed widely throughout the world (Oates, 2010). The use of quicklime and hydrated lime as an important construction matter dates back to 1000 B.C. and is an important ingredient on several industries to the present-day, such as water treatment, agriculture, construction, mortars, food processing and chemical industries (Leontakianakos et al., 2015). The U.S. Geological Survey (2019) estimated the global production of lime products to be over 420.000 ton on the year of 2018.

The hydration process of calcium oxide (quicklime) is exothermic and discharges an important amount of heat (Equation 1) generating calcium hydroxide ($Ca(OH)_2$) commonly named hydrated lime or slaked lime. The heat generated on hydration reaction is 1135 kJ/kg, approximately half of the latent heat to boiling water, 2260 kJ/kg. The weight ratio of calcium hydroxide to calcium oxide is 1.32, based on the molecular weights: it means that for each kilogram of CaO, should be mixed with 320g of water, to produce 1.32 Kg of $Ca(OH)_2$ (Oates, 2010). So, each unit of $Ca(OH)_2$ must be prepared with 76% of its weight of CaO and a minimum of 24% of its weight as a necessary reaction water. This is an important consideration to be taken into account on the BSM mix design phase.

$$CaO + H_2O \leftrightarrow Ca(OH)_2 + 1135\ kJ/kg_{CaO} \quad (1)$$

According to Oates (2010), the reactivity of quicklime can be defined as the rate at which it reacts with water. Complete hydration can take place in a matter of a few minutes or continue over a period of months, and some conditions that influence the rate of reactivity of quicklime are the content of MgO, presence of impurities, porosity, grain size, temperature of hydration water, and mechanical agitation (Leontakianakos et al., 2015). Anyhow, quicklime has a high affinity for water and is a more efficient desiccant than silica gel. The hydration process of quicklime into hydrated lime is associated with an increase in volume by a factor of 2.5 times (Oates, 2010), so care should be taken to avoid expansion of products that contain lime not fully hydrated. Most commercial quicklime products have compacted bulk densities ranging from 900 to 1200 kg/m^3, while compacted bulk density of hydrated lime ranges between 450 and 640 kg/m^3. This characteristic is important regarding the materials logistics on construction sites: the use of quicklime lime instead of hydrated lime may offer the advantage of a more efficient transportation operation, either from supplier to the construction plant, or from the plant to the job site.

The industry of infrastructure has already a solid and consolidated use of quicklime to treat soils with high plasticity index (clay soils), bringing to the soil a new chemical and thermodynamical balance (Little, 1995). In addition, the immediate reaction of quicklime with water produces hydrated lime, a material already vastly used by asphalt producers as an active filler in hot mixtures and in cold recycled mixtures. In addition, hydrated lime is usually added on cold recycled mixtures with success for the following purposes (Ramanujam & Jones 2007):

- Flocculate and agglomerate the clay fines.
- Stiffen the bitumen binder.
- Act as an anti-stripping agent to assist the dispersion of the foamed bitumen throughout the host material.
- Increase the modulus and improve the early-life rut resistance of the stabilised material.

The potential direct gains in the BSMs productions would include drying over wet RAP and/or virgin aggregates, heating the mixture due to the exothermic reaction increasing its workability and bitumen dispersion on cold weather workdays, reduction of acquisition and transportation costs. Because quicklime becomes hydrated lime almost immediately after being mixed with water) and because the filler is mixed with aggregate and water before adding emulsion (or in case, before foaming), in fact the one that is really acting as active filler in the mixes it is the hydrated lime; for this reasons the quick lime can be defined as the material that becomes the active filler in the mixture, in other words, the quicklime can be defined as a "*pre-active filler*".

A comprehensive report on occupational exposure limits for CaO and $Ca(OH)_2$ (SCOEL, 2008) assumes as normal an occupational exposure level of 1 mg/m³. Thus, the inhalation of 10 m³ during an 8-hour workday would result in a daily inhaled dose of 7.1 and 5.4 mg of calcium, respectively. At these levels, the systemic effects due to occupational exposures can be considered negligible, as a daily intake level up to 2500 mg/day is considered tolerable.

As CaO reacts with water on the external surfaces of the body, converting to $Ca(OH)_2$, liberating OH^- ions, and skin and the mucous membranes can be affected. The effect from the high alkalinity can increase to skin burn, skin ulcer formation and eye injuries. According to Winder and Carmody (2002), with pH varying around 13, aqueous suspensions of CaO and $Ca(OH)_2$ may remove lipids from the skin and cause drying, cracking and irritant contact dermatitis.

Finally, SCOEL (2008) states that, all together, the main effect of CaO and $Ca(OH)_2$ is the alkali effect, with the difference that CaO develops heat by reaction with water and causes desiccation of tissue. Regardless, considering that CaO forms slightly more OH^- ions than liberated from $Ca(OH)_2$ par mass unit, this difference is considered without toxicological importance, and a common occupational exposure limit is proposed for the both substances, which should not bring major concerns for on-site works using CaO as a pre-active filler, instead of $Ca(OH)_2$ as active filler, on cold recycling operations.

Chapter 4 - Materials and Testing Methods

4.1. Bituminous materials

Before the beginning of this research, the emulsion supplier tested a cationic emulsion to evaluate its interaction with quicklime. A small amount of quicklime was directly mixed inside a container with emulsion. The result was unsatisfactory, as the immediate reaction with the emulsion’s water generated an enormous amount of heat, causing the immediate separation of the emulsion, with the bitumen coagulated on the filler. After the failure of the first attempt, the project´s emulsion supplier designed a neutral pH experimental emulsion specially to produce the BSM mixtures with quicklime. The emulsion has 60% of residual neat 50/70 penetration grade bitumen.

For the foam bitumen, the same neat 50/70 penetration grade was provided by the supplier, so the bitumen origin was kept constant for all the mixtures tested on the project. The foaming temperature used was 170°C, as recommended by the supplier. For the foaming phase, a 2.2% on weight of foaming water was established after the expansion and half-life test (Figure 14).

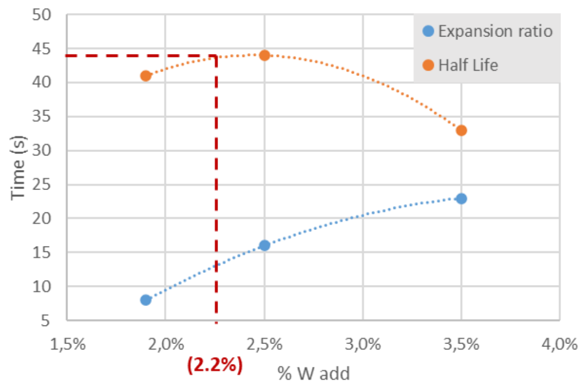

Figure 14 – Half-life and expansion ratio of the bitumen used on the foam

4.2. Dry Aggregates

As initial statement of this research, it was chosen to design a BSM using 100% of reclaimed asphalt as aggregate. The RA used has a 4.3% average amount of aged bitumen and comes from uncovered stockpiles from milling works on local roads. Figure 15 presents the size distribution of the RAP used throughout this research, added with 5% of mineral filler (calcium carbonate). Target gradings are the ones recommended on technical guidelines for cold recycling projects (Wirtgen, 2012).

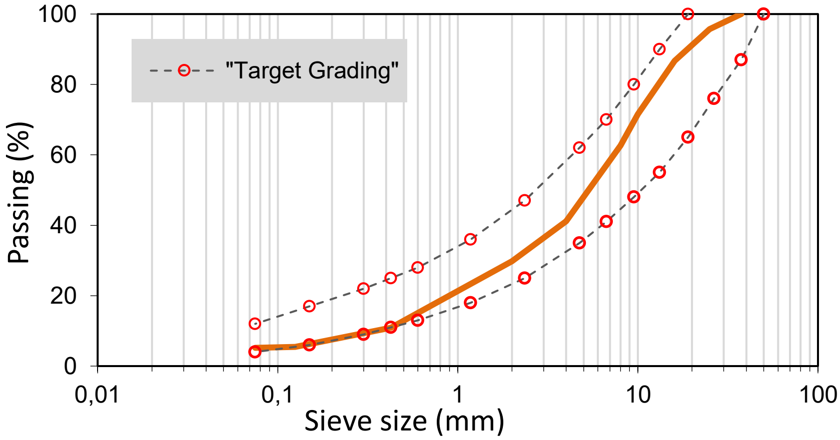

Figure 15 - Size distribution of the RAP

The RILEM classification protocols for RAP (Tebaldi et al., 2018), suggests the use of two parameters to evaluate the reclaimed asphalt used on cold recycling projects. With respect to the Fragmentation Test, which measures the particle resistance to fragmentation under a series of shocks induced by dropping of a rammer, on a confined sample placed in a cylindrical steel mould. The RAP can be classified as a class D, which correlates with a Los Angeles Abrasion ≤ 30 (Preti et al. 2019b). Regarding the Cohesion Test, RAP material can be classified as “active” or “inactive”, depending on the capacity of the residual binder to glue the particles together after compaction. The resulting cohesion is directly linked to the penetration of the aged binder and the compaction temperature, recycling. The old bitumen content of RAP may be considered potentially active as the ITS at 70°C > 100kPa (Preti et al. 2019a).

4.3. Active Fillers

The quicklime used on the project was provided by Carmeuse and is classified EN459-1 as CL90-Q, size gradation 0-90µm, which describes a highly pure (CaO + MgO content > 90%; MgO content < 5%) and fine powder quicklime.

The cement used for the reference BSM mixture was a common portland cement, classified EN/197-1 as CEM I.

4.4. Preliminary investigations on the temperature and workability

Before preparing the mix design to start the research, two preliminary investigations were run to clarify some premisses of the research plan. Firstly, a known volumetric mix design of a cold recycled mixture, developed inside a RILEM TC 264-RAP round robin, was reproduced and tested on the laboratory, to better understand the effects of increasing the amount of cement on the mixture. The goals were to get experienced with the laboratory equipment to foam, mix and compact the specimens, as well as to the MTS testing machine to perform ITS and triaxial tests. Besides, from the obtained results, it would be possible to confirm or refute a presumed higher brittleness with higher cement contents.

Thus, the following mixtures were prepared and tested on the laboratory (Table 3), following the recommendations of the equipment's supplier (Wirtgen, 2017). Specimens were free surface cured for 14 days before testing.

Table 3. Preliminary investigated foam-based BSM with cement

Mix Design	FB-C0	FB-C1	FB-C1.5	FB-C2
RAP	93%	93%	93%	93%
Total filler content	7%	7%	7%	7%
Mineral filler content	7%	6%	5.5%	5%
Active filler content (cement)	0%	1%	1.5%	2%
Water content	3%	3%	3%	3%
Foam bitumen content	3%	3%	3%	3%

Results showed basically two important points:

- The addition of cement on percentages higher than 1% did drastically change the mechanical behaviour of the mix (Figure 16), even if the amount of bitumen was high (i.e., ratio bitumen/cement > 1). Lower energy (external work, i.e., the area under stress-strain curve) was necessary to break the specimens with 2% of cement, indicating the mixture became more brittle.

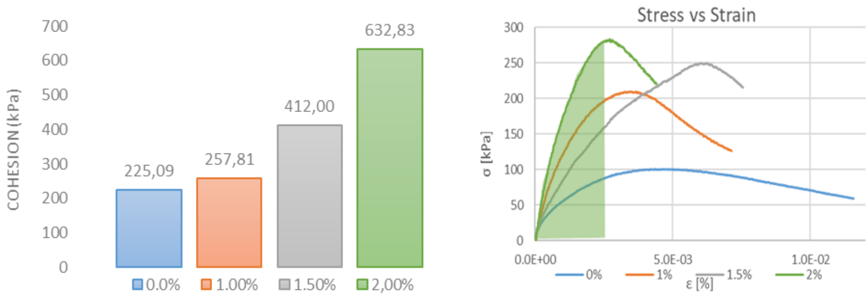

Figure 16 - Cohesion and Stress vs. Strain curve of preliminary investigations

- Water content was too low to allow the fully hydration of cement on FB-C2 mixture, as the indirect tension strength of the specimens subjected to 24-hour water bath increased when compared to the dry specimen (Figure 17).

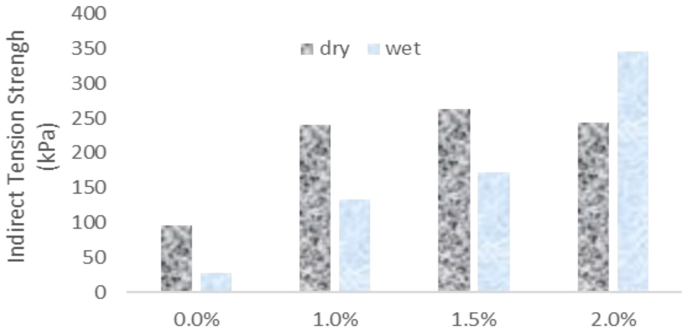

Figure 17 – ITS test results of preliminary investigations

The given results were an indication that a proper mix design should be carried out with a different approach. Instead of using a volumetric approach, which is similar to the mix design of HMA, a different approach would be followed, as better detailed on item 4.5.

The second preliminary investigation was carried out to investigate the interactions between the CaO and the bitumen. A small scale of four BSM mixtures (around 2 kg, each) were manually produced according to recipe indicated on

Table 4. Two different sequences of mixture were prepared.

Table 4. Preliminary investigated emulsion-based BSM with CaO

Mix Design	EM-L2	EM-L3	EM-L4	EM-L5
RAP	93%	93%	93%	93%
Total filler content	7%	7%	7%	7%
CaO content	1.52%	2.28%	3.04%	3.80%
Final active filler content ($CaOH_2$)	2%	3%	4%	5%
Reaction water	0.48%	0.72%	0.96%	1.20%
Total fluid content	3.48%	3.72%	3.96%	4.2%
Emulsion residual content	3%	3%	3%	3%

One of the sequences was the “traditional” one, i.e., dry aggregates including CaO, then water, then emulsion (Figure 18). The second (Figure 19) was he addition of

CaO was dislocated to the end of the mixing process. Thus, a total of eight samples were prepared and observed.

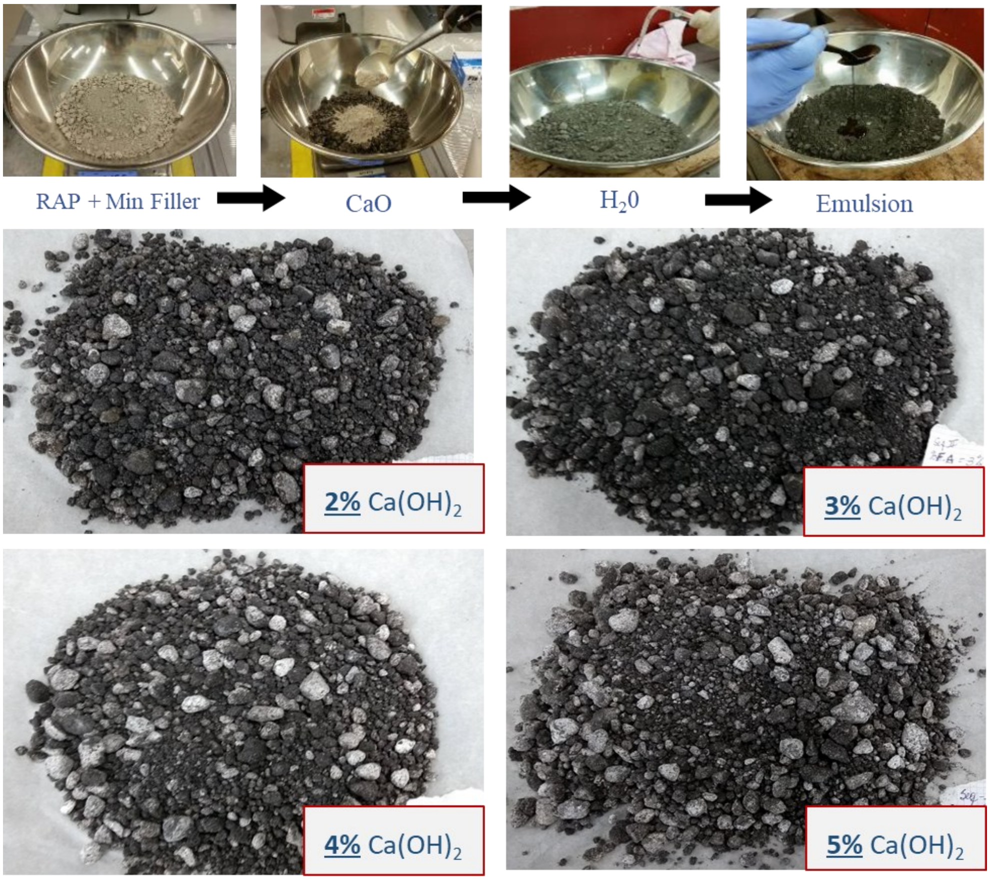

Figure 18 – Small scale preliminary test on traditional mixing sequence

Three different main aspects were observed: the hypothesis that the hydration of the CaO would be strong enough to heat the mixture; the behaviour of the emulsion with respect to its separation; and the coating of the aggregates by the bitumen.

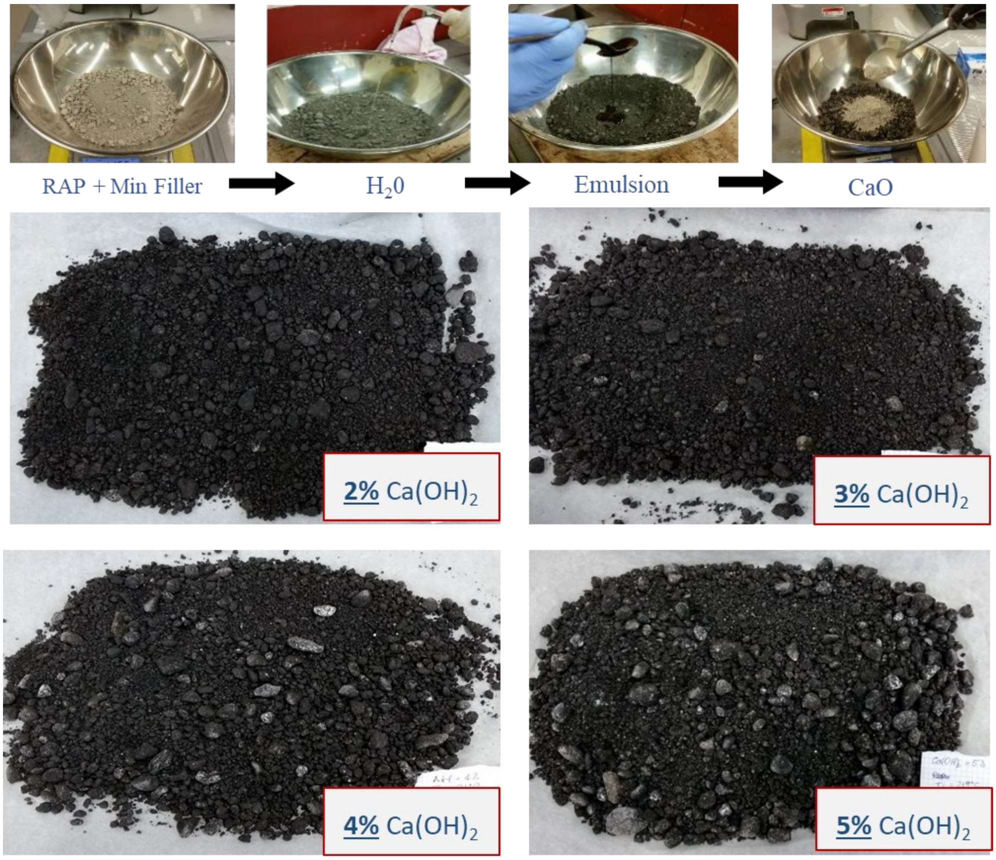

Figure 19 - Small scale preliminary test on a different mixing sequence

The temperature measurements were done using a digital infrared thermometer (Figure 20) and the other aspects were observed throughout visual inspection.

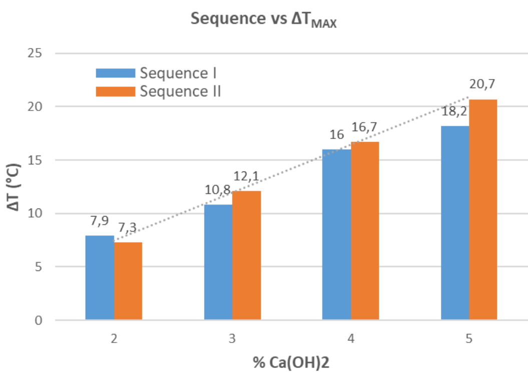

Figure 20 – Preliminary temperature measurements

Some important preliminary findings were observed and guided the next steps of the research:

- CaO hydration reaction was able to increase the temperature of the mixture.
- ΔT depends directly on the amount of added CaO.
- It takes between 4 to 5 minutes for the mixture to reach a maximum ΔT; After reaching ΔT_{MAX}, the temperature starts to drop down.
- No premature separation was observed on the traditional mixing sequence.
- Total fluids content needs to be adjusted, as the covering of the aggregates was not satisfactory on the traditional mixing sequence.

Thus, it was decided to carry on the research by making a new mix design (i.e., Proctor/Vibrating Hammer method by Wirtgen, 2017), to reproduce on the lab scale the traditional mixing sequence (i.e., stabilising agent at the end), and systemise the caption of temperature development on time, with t-type thermocouples, on 25 kg batches of each mixture.

4.5. BSM mix design method

For mix design purposes, an initial content of active filler was fixed on 1% on the total weight of dry aggregates. The type of active filler used on the mix design procedures was hydrated lime, and the bitumen was emulsion. The procedures followed the recommendations of the Laboratory Handbook for BSM Cold Recycling, by Wirtgen (2017), considering that the laboratory was equipped with their laboratory equipment comprising WLB 10 S laboratory foamed bitumen plant, WLM 30 twin-shaft pugmill mixer, and WLV-1 vibratory hammer compaction unit. Figure 21 presents a flow chart of the mix design procedure followed, to allow a better understanding for each stage.

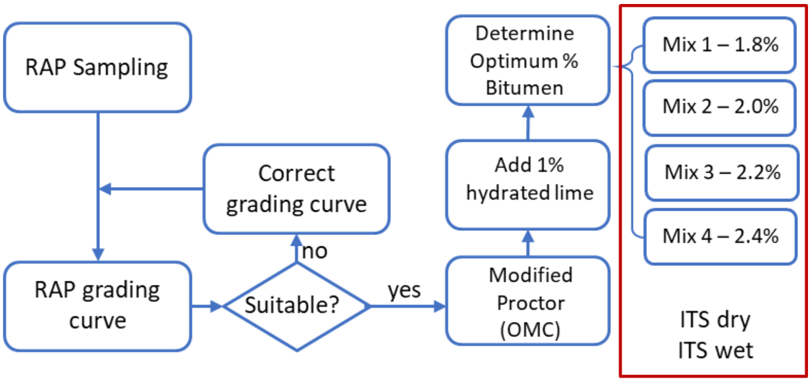

Figure 21 - BSM mix design flow chart (adapted from Wirtgen, 2017)

Thus, after the characterization of the RAP (see item 4.2), the next step was to determine the Optimum Moisture Content. The modified AASHTO T-180 (2004) test was run on the dry aggregates (RAP + mineral filler), resulting on a content of 5.2% of dry aggregates weight. The result is presented on Figure 22.

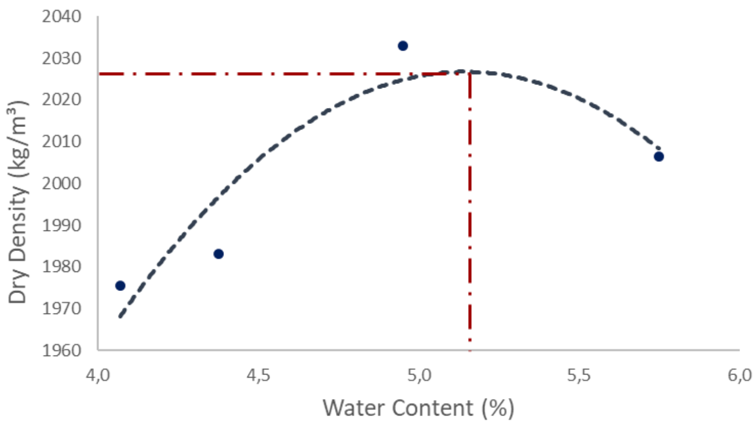

Figure 22 – Result of the Modified Proctor

After fixing the percentage of active filer (1%) and moisture content (5.2%), the next step was to determine the optimum bitumen content. Initial content was fixed following the guideline shown on Figure 23 (Wirtgen, 2017), i. e., 2.2% on total dry weight. Besides 2.2%, three other bitumen content were used to prepare ITS specimens, as recommended on the guidelines, i. e., 1.8%, 2.0%, and 2.4%.

Guidelines for estimating optimum foamed bitumen addition			
Fraction passing 0.075 mm sieve (%)	Foamed bitumen addition (% by mass of dry aggregate) Fraction passing 4.75 mm sieve		Typical type of material
	< 50%	> 50%	
< 4	2.0	2.0	Recycled asphalt (RAP)
4 - 7	2.2	2.4	RAP / Graded crushed stone / Natural gravel / blends
7 - 10	2.4	2.6	
> 10	2.6	3.2	Gravels / sands

Figure 23 – Initial estimation for bitumen addition, as in Wirtgen (2017)

The optimum bitumen content (BC) was then determined indirect tension test, at ambient temperature (around 25°C) and controlled displacement rate of 50.8 mm/min. Minimum ITS values for dry specimens is fixed at 225kPa, and 100ka for wet specimens. As shown on Figure 24, the mix design resulted on a 2% optimum residual bitumen content, by weight of total dry aggregate.

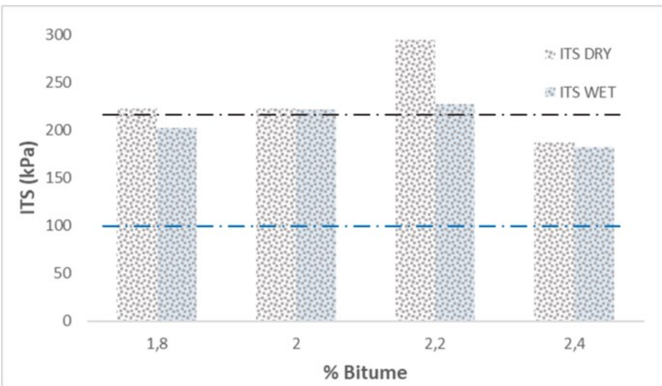

Figure 24 - ITS results to determine optimum bitumen content

4.5.1. Fluid Consideration

The moisture content of the mixed material is one of the most important variables directly influencing the end-product. The effectiveness of bitumen dispersion, the compaction effort required to achieve density, and the potential for surface cracking are all significantly influenced by not only the actual moisture content itself, but also by the uniformity of the moisture content throughout the recycled material.

However, some considerations must be considered to adjust the amount of mixing water on emulsion-based BSM. According to Wirtgen (2017), both the water and the bitumen inside the emulsion act as lubricants for BSM-emulsion mixes. In that sense, the optimum moisture content (OMC) obtained should be then considered the total mixing fluid content, as better is explained in equation 2, where FMC is the on-field moisture content (equivalent to the on-lab added mixing water content), EWC is the water content of the emulsion, and RBC is the residual bitumen content, as it also works as a lubricant on emulsion phase.

$$\mathrm{OMC}_{(AASHTO\ T180)} = \mathrm{OFC} = FMC + EWC + RBC \tag{2}$$

Another important point must be taken into consideration when balancing the amount of mixing water on a BSM mixture with quicklime, which is the water necessary for its hydration reaction. As shown above, one unit on weight of hydrated lime needs 0,76 units of CaO added to 0,24 units of water. Thus, to prepare the specimens with 1% of active filler, 0.24% of water was added the total fluid content of 5.2%, see Table 5. On an in-plant recycling operation, the hydration reaction water would be the amount of water dried out by this process on a wet RAP stockpile.

With respect to foam-based mixtures, as recommended by Asphalt Academy (2009), 90% of the OMC was selected as the water content. The same considerations to balance the amount of mixing water due to the use of quicklime was adopted, with the addition of 0.24% of water for every 1% of total active filler, see Table 6.

When it comes to foam-based BSM, final contents of hydrated lime were the same as the emulsion-based BSM, i.e., 1, 2, 3, 4 and 5%, hence, the amount of added quicklime was, respectively, 0.76, 1.52, 2.28, 3.04, and 3.8%. Foam bitumen content was kept at 2%. The mixing moisture content was 90% of the modified proctor OMC, i. e., 4.7%, added to the respective amount of reaction water, i.e., 0.24, 0.48, 0.72, 0.96, and 1.20%. The percentage of mineral filler was balanced to keep the total amount of filler constant at 5%. The final foam-based BSM mix design is detailed on Table 6, on percentages by weight on total dry aggregate.

Table 6As mentioned before quicklime works as a pre-active filler, so to have naming of the investigated mixture easily comparable with the mixtures with cement used for the performance comparison, the investigated percentages of active filler were named in function of the "final content of hydrated lime (fcHL)" to consider the real active filler generated by the CaO hydration and is really acting in the mixture.

4.5.2. BSM mix design results

As initial statement of this research, the total content of filler (mineral filler + active filler) was fixed at 5% of the weight of total dry aggregates, an adequate fine particle (<0,075mm) content for both emulsion-based (2-9%) and foam-based (4-10%) BSM, as recommended the by Wirtgen (2012). This total content of filler was kept constant in all the mixtures, making a reduction of the mineral filler when the content of active filler was increased. The investigated BSM mixes were made with 1, 2, 3, 4 and 5% of final hydrated lime, hence, the amount of added quicklime was, respectively, 0.76, 1.52, 2.28, 3.04, and 3.8%, and the amount of reaction water, added beyond the OFC, were respectively 0.24, 0.48, 0.72, 0.96, and 1.20%. The percentage of mineral filler was balanced to keep the total amount of filler constant at 5%. The final emulsion-based BSM mix design is detailed on Table 5, on percentages by weight on total dry aggregate.

Table 5. Mix design for investigated emulsion-based BSM with lime

Mix Design	EM-L1	EM-L2	EM-L3	EM-L4	EM-L5
RAP	95%	95%	95%	95%	95%
Total filler content	5%	5%	5%	5%	5%
Mineral filler content	4%	3%	2%	1%	0%
Final active filler content (hydrated lime)	1%	2%	3%	4%	5%
Quicklime content	0.76%	1.52%	2.28%	3.04%	3.80%
Reaction water content (RWC)	0.24%	0.48%	0.72%	0.96%	1.20%
Optimum fluid content	5.2%	5.2%	5.2%	5.2%	5.2%
Total emulsion content	3.3%	3.3%	3.3%	3.3%	3.3%
Residual bitumen (60%) content	2%	2%	2%	2%	2%
Mixing water content (OFC-EWC-RBC+RWC)	2.11%	2.35%	2.59%	2.83%	3.07%

When it comes to foam-based BSM, final contents of hydrated lime were the same as the emulsion-based BSM, i.e., 1, 2, 3, 4 and 5%, hence, the amount of added quicklime was, respectively, 0.76, 1.52, 2.28, 3.04, and 3.8%. Foam bitumen content was kept at 2%. The mixing moisture content was 90% of the modified proctor OMC, i. e., 4.7%, added to the respective amount of reaction water, i.e., 0.24, 0.48, 0.72, 0.96, and 1.20%. The percentage of mineral filler was balanced to keep the total amount of filler constant at 5%. The final foam-based BSM mix design is detailed on Table 6, on percentages by weight on total dry aggregate.

Table 6. Mix design for investigated foam-based BSM with lime

Mix Design	FB-L1	FB-L2	FB-L3	FB-L4	FB-L5
RAP	95%	95%	95%	95%	95%
Total filler content	5%	5%	5%	5%	5%
Mineral filler content	4%	3%	2%	1%	0%
Final active filler content (hydrated lime)	1%	2%	3%	4%	5%
Quicklime content	0.76%	1.52%	2.28%	3.04%	3.80%
Reaction water content (RWC)	0.24%	0.48%	0.72%	0.96%	1.20%
Moisture content (90% OMC)	4.7%	4.7%	4.7%	4.7%	4.7%
Mixing water content (WC+RWC)	4.94%	5.18%	5.42%	5.66%	5.90%
Foam bitumen content	2%	2%	2%	2%	2%

At last, the reference traditional cement-based mixture was prepared with different amounts of cement, i.e., 1, 1.5, 2 and 2.5%. The mixing moisture content was 90% of the modified proctor OMC, i.e., 4.7%. Foam bitumen was used as stabiliser, and its content was kept at 2%. The percentage of mineral filler was balanced to keep the total amount of filler constant at 5%. The final foam-based BSM mix design is detailed on Table 7, on percentages by weight on total dry aggregate.

Table 7. Mix design for investigated foam-based BSM with cement – reference mixture

Mix Design	FB-C1	FB-C1.5	FB-C2	FB-C2.5
RAP	95%	95%	95%	95%
Total filler content	5%	5%	5%	5%
Mineral filler content	4%	3.5%	3%	3.5%
Active filler content (cement)	1%	1.5%	2%	2.5%
Water content (90% OMC)	4.7%	4.7%	4.7%	4.7%
Foam bitumen content	2%	2%	2%	2%

4.6. Specimens Mixing and Compaction Method

The testing specimens were prepared on the laboratory, using Wirtgen's WLM 30 mixer and compacted on the WLV 1 vibratory hammer (Kelfkens, 2008). Each batch was prepared with around 24kg of dry aggregate. All dry aggregates (RAP, mineral filler and active filler) were put inside the mixing chamber and pre-mixed for 30 seconds. Then, the required amount of water was added, and mixed for another 60 seconds. Finally, was added required amount bitumen (foam or emulsion), Figure 25 (a) and the material was mixed for another 60 seconds. After mixing, the material was dumped into a container, ready to be compacted, Figure 25 (b). The specimens were compacted immediately after mixing, according to the procedures recommended by Asphalt Academy (2009) for the vibratory hammer, Figure 25 (c), following the requirements presented on Table 8.

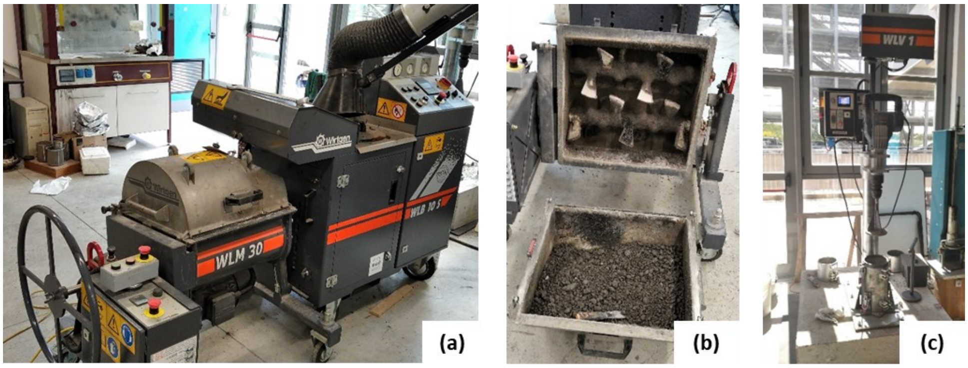

Figure 25 - Specimens mixing and compaction

Table 8. Requirements for the specimens' compaction using WLV 1

Requirements	ITS test	Triaxial test
Number of specimens	6	10
Specimen diameter (mm)	152	152
Specimen height (mm)	95	300
Number of layers	2	5
Thickness of each layer (mm)	47.5	60

4.7. Temperature Measurements

The temperature evolution after lime addition and during the mixing phase it is one of the fundamentals elements to understand if the use of quick lime and the above-mentioned concept of "pre-active filler" can make sense and if there are real advantages in the use of this technical solution.

For the temperature measurements, batches of 24kg of emulsion-based BSM were prepared exactly as reported above, one batch for each one of the 5 different contents of quicklime. After mixing, the material was dumped into a container, and five T-type thermocouples were immersed on different points inside the mixture. Each thermocouple realized one temperature measurement every 3 seconds, for a total of 15 minutes, as shown on Figure 26. Thus, it was possible to determine the maximal temperature reached, and its evolution to the top and decrease. It is important to underline one point: all the mixture preparation procedure was made with the same equipment for preparation of the specimens of cold recycled mixtures.

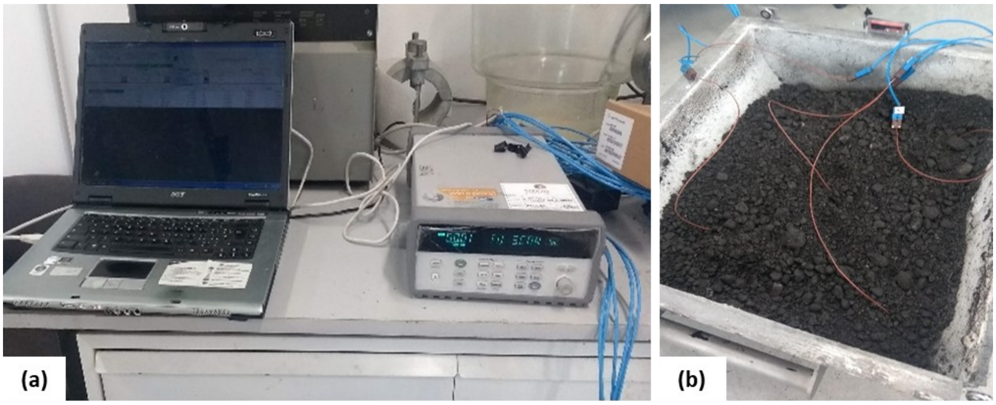

Figure 26 - Temperature measurements on emulsion-based BSMs

4.7.1. Thermodynamic model

The physical problem is represented by the heat conduction inside a block composed of recycled asphalt. Inside the asphalt it is inserted quicklime and water to use the heat released by the lime hydration reaction to increase the temperature of the recycled material to a value that permit the installation of the obtained new pavement. The amount of water and quicklime is limited if compared to the one of recycled material (around 3%) and does not significantly modify the thermal properties of the whole domain: therefore, the hydration reaction and the heat released by it can be modelled simply considering a heat source inside the domain composed by only asphalt. Under these assumptions the energy balance equation inside the studied domain can be expressed in the form of Equation 3, where *k, ρ* and c_p are the recycled asphalt thermal conductivity, density, and specific heat, respectively. In this expression, since the heat released by the hydration reaction of quicklime is supposed to vary with time, the volumetric heat generation q_g in the domain is considered time dependent.

$$k\nabla^2 T + q_g(t) = \rho c_p \frac{\partial T}{\partial t} \tag{3}$$

Two different boundary conditions applied on the outer surface of the recycled asphalt block were considered. Equation 4a represents a Dirichelet boundary condition where T_s is the imposed temperature at the external surfaces of the recycled asphalt block. Equation 4b, instead, represents a Robin boundary condition where T_{env} is the environmental temperature and R_{env} is the overall heat-transfer resistance between the asphalt block and the surrounding environment.

$$k\frac{\partial T}{\partial n} = T_s \tag{4a}$$

$$k\frac{\partial T}{\partial n} = \frac{(T_{env} - T)}{R_{env}} \tag{4b}$$

As first step it was verified that the heat released by the hydrating reaction of quicklime is completely transferred to the recycled asphalt domain thus resulting in an increase of the asphalt temperature. The heat quantity generated by the stoichiometric quicklime reaction could be reduced and not completely traduced in an asphalt domain temperature augmentation due to the not perfect mixing of the materials that could create zones where the quicklime has not enough water to complete the reaction and other zones with the opposite problem, where the quicklime quantity is lower than the stoichiometric value. To verify it a set of preliminary tests was performed: a cylindrical tank with an internal diameter of 30 cm was filled with recycled asphalt for a height of about 10 cm (Figure 27). Then a 3% in weight of quicklime was added with the stoichiometric quantity of water for the hydrating process and the whole mixture was stirred for approximately 60 seconds. The temperature was monitored with multiple T-type thermocouples placed inside the material.

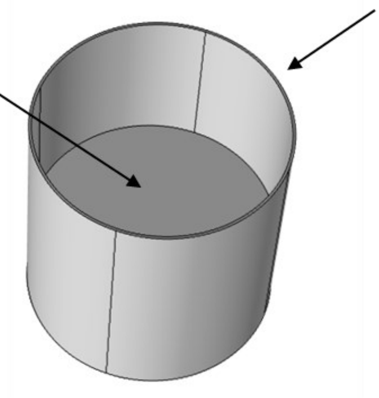

Figure 27 - Sketch of the numerical model

To estimate heat released by the hydrating reaction of the quicklime efficiently transferred to the recycled asphalt thus producing a domain temperature increase, an inverse problem approach was adopted. In particular, the temperature distribution experimentally measured by the thermocouples was employed as input data of the inverse heat conduction problem in the material to estimate the amount of the heat transferred to the recycled asphalt under an approach based on least squares minimization (Beck et al. 2016). A 3-D numerical finite element model of the whole test section (tank and volume of material) was implemented within the Comsol Multiphysics environment (see Figure 27). Calling Y (Y_i = measured temperature at time i, i = 1. . .n) the temperature data experimentally measured and T the corresponding simulated temperature obtained from the solution of the numerical problem by imposing a function of heat releasing, the estimation problem is solved by minimizing the function shown on Equation 5.

$$S = \sum_{i=1}^{n}(Y_i - T_i)^2 \quad (5)$$

Another important information that can be obtained by the inverse approach is the time evolution of the heat released by the hydrating reaction. This knowledge could be useful in the mixing phase of the material before stocking it for transport to the building site. Knowing the heat realising time and its progression can permit to choose the proper time of mixing and the insulation of the mixing set up to avoid heat loss with the ambient in the period during which the released heat is more important. Additional information could be given also about the conservation process that follows the mixing operations.

Following the inverse approach, the function of heat releasing is modified until reaching the values that permits to minimize the target function *S*: the obtained distribution represents the best approximation of the real value that characterize the studied sample. The minimization of *S* was performed by the Nelder-Mead algorithm (Nelder et al. 1965) that is a well-known algorithm for multidimensional unconstrained optimization.

Figure 28 reports the estimated function of heat releasing and the comparison between experimentally measured temperature and the restored temperature distribution, during time *t*.

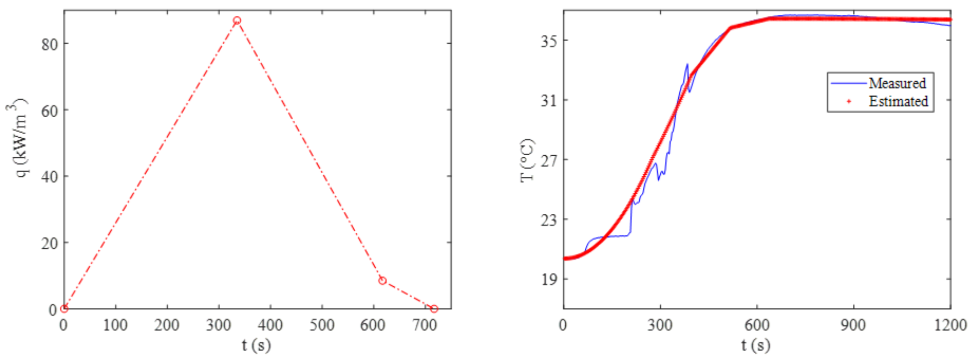

Figure 28 - Function of heat releasing (a) and comparison between estimated and measured temperature distribution(b)

It is possible to see from Figure 28b that the reconstruction of temperature is satisfactory .Thus, by integrating the area subtended by the curve reported in Figure 28a, the value of the heat released during the reaction can be found: it corresponds to that reported in Equation 5 with an uncertainty of about 15%. Since it was verified that the heat released by the hydrating reaction of quicklime is almost completely transferred to the recycled asphalt domain producing an increasing of its temperature, the heat generation through the hydration reaction of the quicklime was not modelled. It was considered the ideal case of complete hydration of the quicklime with all the heat released by the reaction converted in an augmentation of the reclaimed asphalt particles temperature.

4.7.2. Simulation Scenarios

Two hypotheticals yet possible scenarios were used to simulate the influence of the quicklime hydration reaction on a real scale in-plant mix, with the production of 20 tons of mix (capacity of one truck), every 6 minutes.

The first scenario refers to an operation with environment temperature at 5° C, and required compaction (i.e., hypothetically after 1 hour) temperature of 15° C. The model should try to answer the optimal amount of quicklime addition to increase the temperature and consider its decrease for one hour of resting inside the truck, as the final temperature should reach 15° C for laying and compacting the mix. This analysis allows to evaluate if this is a possible solution for a real scale to deal with low-temperature recycling operation.

The second scenario refers to an analogue recycling operation, but with environment temperature at 35° C, and the addition of 3.8% of CaO (i.e., a final hydrated lime content of 5%). The model should try to answer the maximum increase of temperature during mixing phase, and its decrease during one hour of resting period inside the truck. This analysis allows to evaluate if this is a possible solution to mobilize a certain amount of oxidized bitumen on the RAP particles, for a real scale cold recycling operation on hot weather regions.

4.8. Indirect Tension Strength (ITS) Test

The ITS test was used as an indirect measure of the tensile strength and deformability of the BSM, by measuring the resistance to failure of a cylindrical specimen 152 mm in diameter and 95 mm high when a constant displacement is applied to the edges of the specimen. For each one of the 5 different contents of lime, and 2 types of bitumen, a set of 6 specimens were prepared (Figure 29). All the specimens were free-surface cured for 28 days at room temperature.

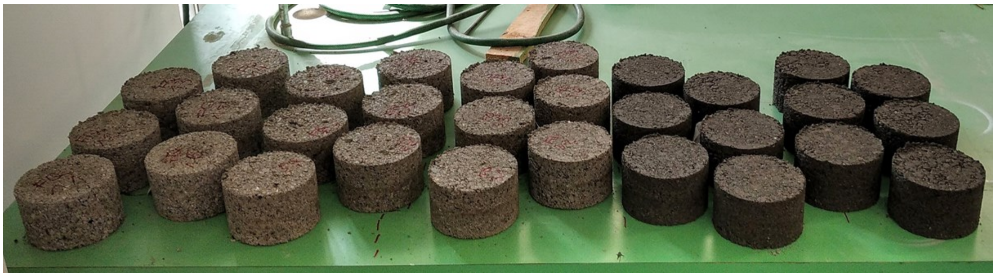

Figure 29 – Foam-based ITS specimens on curing phase

After the curing period, 3 replicates were conditioned into a water bath at room temperature for a 24-hour period, then surface dry, then tested (Figure 30). The other 3 replicates were tested dry after the curing period. The specimens were subjected to a constant controlled diametral displacement of 50.8 mm/minute, until break. All the tests were performed at ambient temperature but being sure to be always around 25°C (Asphalt Academy, 2009).

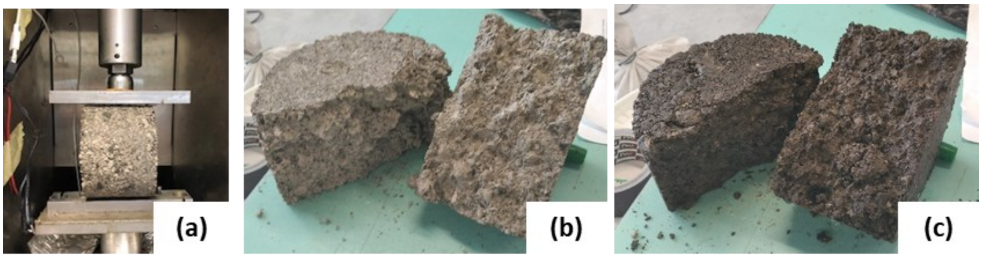

Figure 30 - ITS test configuration (a) and post-test dry (b) and wet (c) specimens

4.9. Simple Triaxial Test

For each one of the 5 different contents of active filler, a set of 10 specimens were prepared, with 152 mm diameter and 300 mm height. The specimens were free-surface cured for 28 days at room temperature. After the curing period, 2 replicates were conditioned into a water bath at room temperature for a 24-hour period, then surface dry, then tested at a confining pressure of 100kPa. The other 8 replicates were tested dry after the curing period, being 2 replicates at each fixed confining pressure (0, 50, 100 and 200 kPa). The applied controlled displacement was 3 mm/minute, at ambient temperature (Asphalt Academy, 2009). Figure 31 shows the specimen and testing configuration.

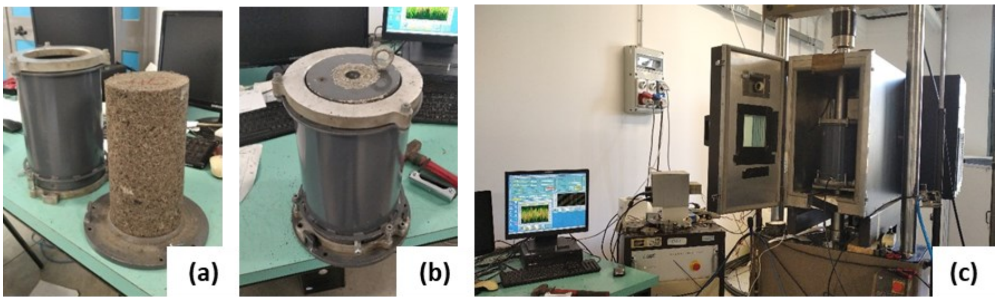

Figure 31 - Triaxial test specimen and configuration

Chapter 5 - Results and Discussions

5.1. Evolution of Temperature

The results regarding the temperature measurements are presented on Figure 32 and Figure 33. They show, as expected, a quite linear increase of the maximum temperature of the mixture with the increase of the final amount of hydrated lime. In all the investigated mixtures there was an almost immediate increase of the temperature due to the heat generated by the calcium oxide hydration reaction; after reaching the peak the temperature stays almost constant for all the monitored 15 minutes after the mixing for all the amounts of the final content of hydrated lime. The maximum increase of temperature of the mixture was above 20°C with the addition of 5% of final amount of hydrated lime (3.8% of quicklime).

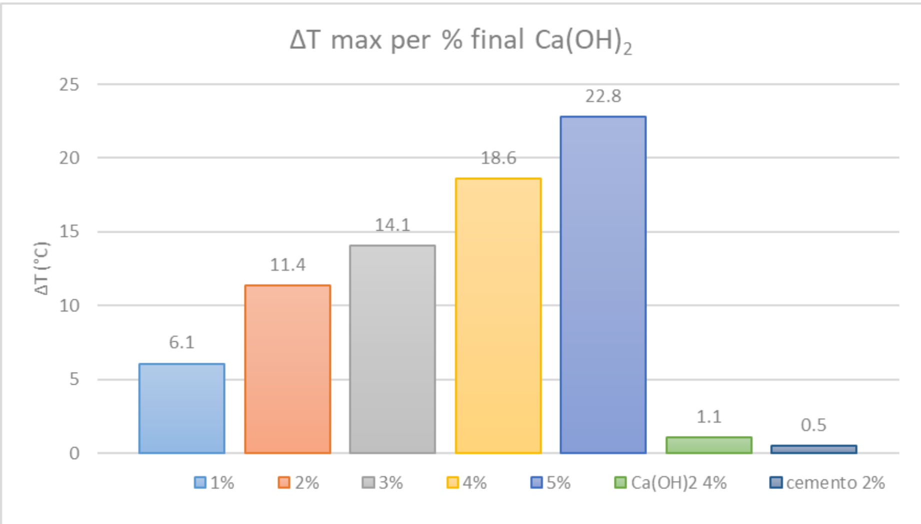

Figure 32- Maximal Temperature Variation of BSM

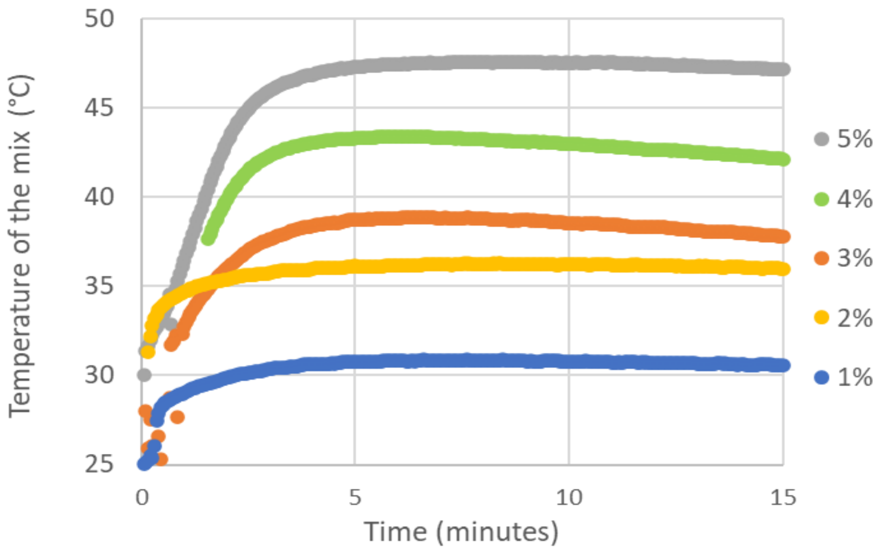

Figure 33- Temperature increasing over time of BSM produced with quicklime

Figure 34 shows a scheme of each production phase of a BSM layer (i.e, mixing of dry ingredients, bitumen addition and mixing, and transport, lay down and compaction), with respect to the achieved temperature of the mixture. From this result, some hypothesis can be pointed out:

- The hydration of the quicklime happens during the first 5 minutes of mixing and heats in an effective way the whole mix.
- Quicklime can be considered a pre active filler, as it is possible to infer that the reaction is fully completed when the mix stops heating, during the first minutes of the mixing phase.
- The mix keeps heated long enough for transportation, laying and compaction of the material on the job site.

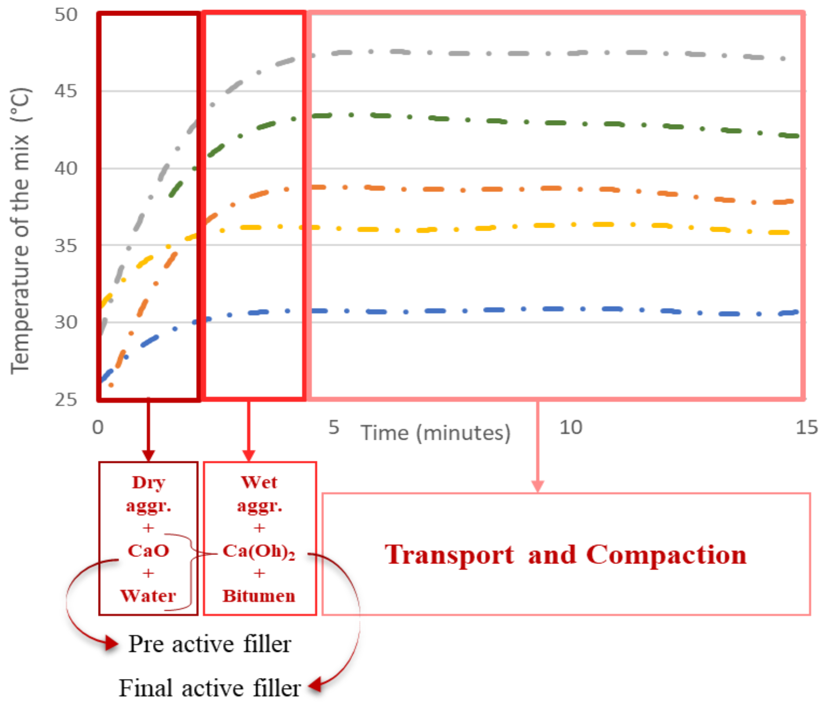

Figure 34 – BSM Production phases overlapped with CaO hydration process

The increase of the mix's temperature and the amount of time in which the temperature is stable are consistent with mixing and compaction time: it means that it is possible to obtain the benefit of the temperature increasing during mixing and compaction on field stabilization processes. Considering that the used equipment has not specific temperature insulation, it is reasonable to predict that the benefit related to the temperature increasing can be obtained also with in-plant stabilization processes. Figure 1 shows that, in climatic zones like northern Italy, the temperature increasing generated by quicklime hydration makes it possible to have all the year the proper materials' temperature for mixing and compaction. This result indicates the possibility to use quicklime as a pre-active filler.

5.1.1. Thermodynamical Simulation Results

As explained in the item 4.7.2, two hypotheticals scenarios were simulated the to evaluate the influence of the quicklime hydration reaction on a real scale in-plant mix.

Under the first scenario, the amount of quicklime that must be added to the recycled asphalt ($20 \cdot 10^3$ kg) to obtain the increase of temperature from 5° C (ambient temperature) to 15 ° C (laydown temperature) is around 300kg (i.e., 1.5%). If necessary, to consider the possible reductions in the heat provided to the asphalt due to the not perfect mixing process, a correction factor of about 1.2 could be taken. Then it is necessary to understand if the transport to the working site inside a truck for 1 hour could cause an excessive reduction of temperature that compromise its direct adoption. To find out the temperature reduction it was implemented a 3D model of the material fitted in a truck with 3.5 (x) x 2 (y) x 1.4 (z) m of dimensions, Figure 35.

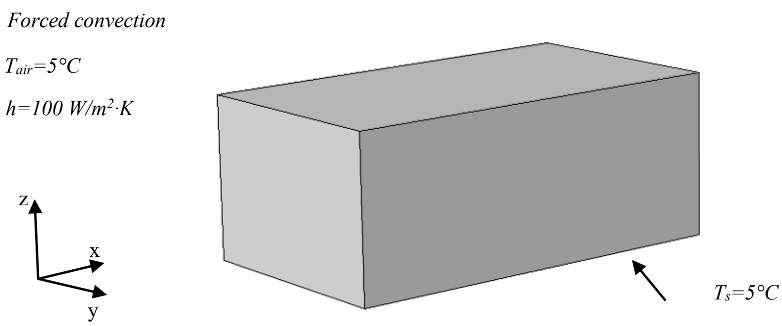

Figure 35 – Sketch of the 3D numerical model and boundary conditions

The domain was a parallelepiped with the dimensions above mentioned and composed by reclaimed asphalt (λ = 0.756 W/m·K, c_p =1674 J/kg·K, ρ = 2100 kg/m³). The initial temperature was set to 15 °C that is the temperature reached by the material thanks to heat released by the quicklime hydration reaction.

On the lower surface, the one that lays on the cargo bed it was considered a conservative condition of imposed temperature T_s = 5°C that is the ambient temperature. On the other 5 surfaces it was imposed a condition of forced convection: the convective heat transfer coefficient h was considered equal to 100 $W/m^2 \cdot K$, a typical value of forced convection with air at high velocity. Even this condition is quite conservative because it was considered the absence of the cargo covering that will significantly reduce the air cooling. Figure 36it is reported the temperature distribution on three different planes of the asphalt parallelepiped after 1 hour of transport on the truck under the boundary conditions above described. During the travel, the temperature of the external layers of the asphalt decreases but only less than 10 cm of material are interested by this reduction.

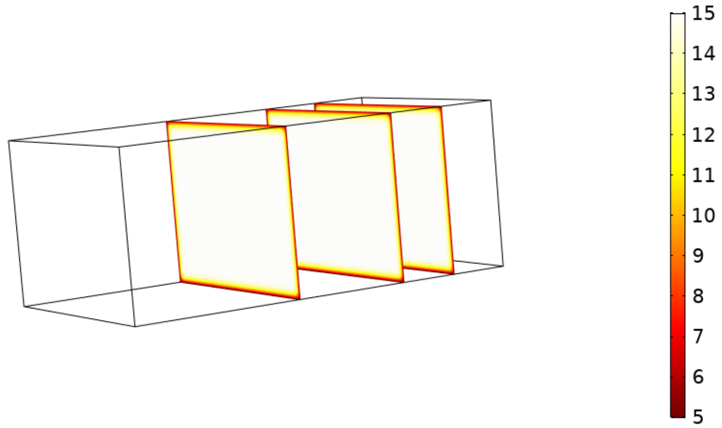

Figure 36 – Temperature distribution on 3 different planes after 1 hour

The average temperature of the whole volume diminishes of about 0.7° C going from 15°C to 14.3° C. It could be seen that only the first 9 cm are interested by a substantial decrease of temperature after 1 hour. The situation is the same in the perpendicular direction. This fact means that the external 9 cm of material could be eliminated, and the remaining part could be adopted in the construction site. The portion of discarded material, that of course can be reused, correspond to about 350 kg (1.75 % of the total amount). These results are very promising, furthermore considering that the boundary conditions adopted are very cautious and then the amount of discarded material will be lower. Moreover, adopting thin layers of insulating material to cover the asphalt, the portion of discarded material could be significantly reduced.

Under the second scenario, the domain is the same of the first scenario, but in this case the starting temperature is 35° C, i.e., the ambient temperature. Adding to the domain 5% in weight of $CaOH_2$ (3,8% of CaO), the temperature reached at the end of the mixing is 60.7° C. As in the first scenario the material after the quicklime hydration is transported with a truck to the construction site with an itinerary of 1 hour. On the lower surface it was considered a condition of imposed temperature T_s = 35°C that is the ambient temperature. On the other 5 surfaces it was imposed a condition of forced convection and the convective heat transfer coefficient *h* was considered equal to 100 $W/m^2 \cdot K$.

In this scenario the average temperature of the whole volume decreases of about 2° C going from around 60° C to 58° C at the end of 1 hour of transport in a truck under the boundary conditions above defined. Figure 37 shows the temperature evolution on three different points, 1 cm, 5 cm, and 20 cm from the upper border, respectively. Also, for this scenario, only the superficial layers (less than 10 cm) are interested by the temperature reduction and that the portion of discarded material will therefore be limited.

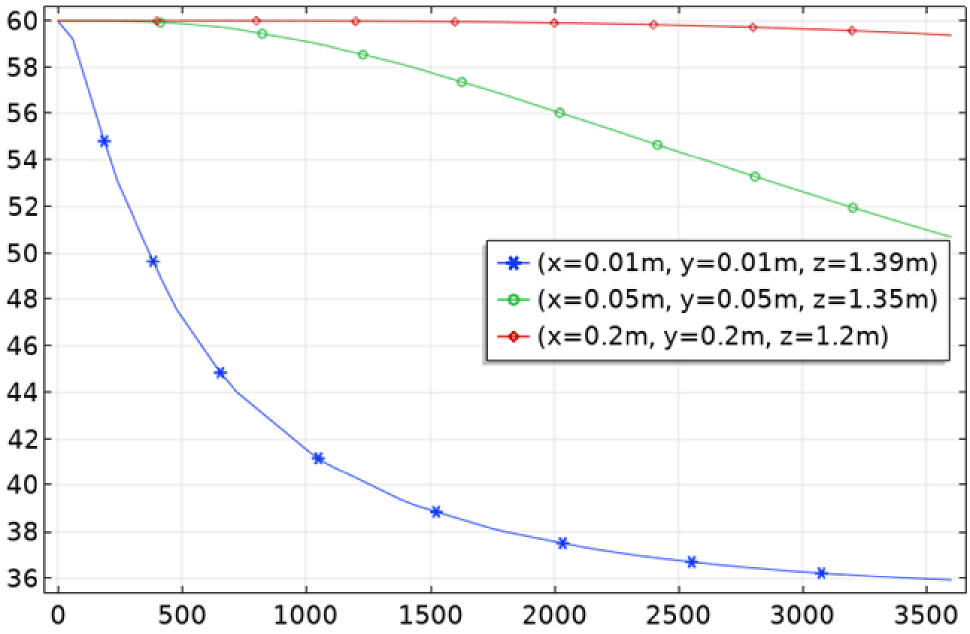

Figure 37 - Temperature evolution in 3 different points, on the second simulation scenario

5.2. Emulsion-based BSM with Quicklime

On this section the results of the indirect tension test and monotonical triaxial test for mixtures produced with emulsion and quicklime are presented. Based on the ITS test results (Figure 38), it is possible to observe that the indirect tension resistance of the mixtures (grey columns) varies within a small range, especially considering the mixtures with 2, 3 and 4% of final hydrated lime. The peak of resistance is reached when the amount of active filler is 3%. However, it is also possible to observe a decrease on the dry resistance to rupture of the mixtures with 4 and 5% of lime. For the indirect tension ratio specimens (blue columns), the added lime provides a retained indirect tension resistance always above 55%, reaching up to 80% when the amount of lime is 5%.

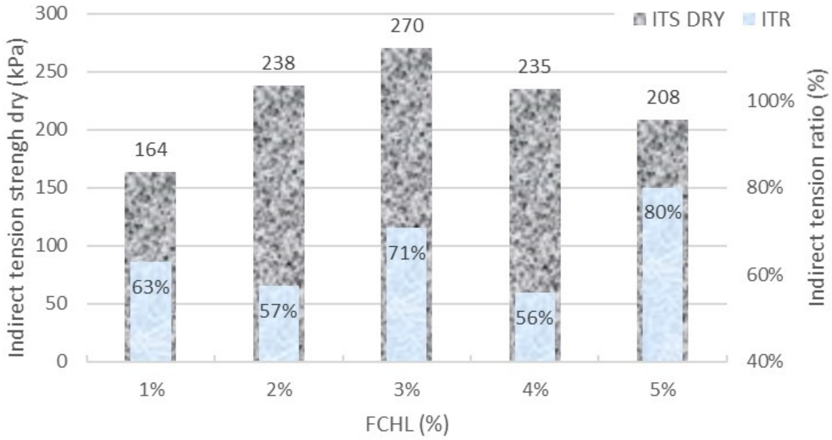

Figure 38 - ITS and ITR of emulsion-based BSM

The results of the monotonical triaxial test (Figure 39) seem to endorse the ITS test results, indicating the uniformity of behaviour between the mixtures with 2, 3 and 4% of final hydrated lime, regarding both the cohesion and the friction angle. For the mixture with 5% of lime an important increase on the friction angle is reported, although the respective cohesion remained constant.

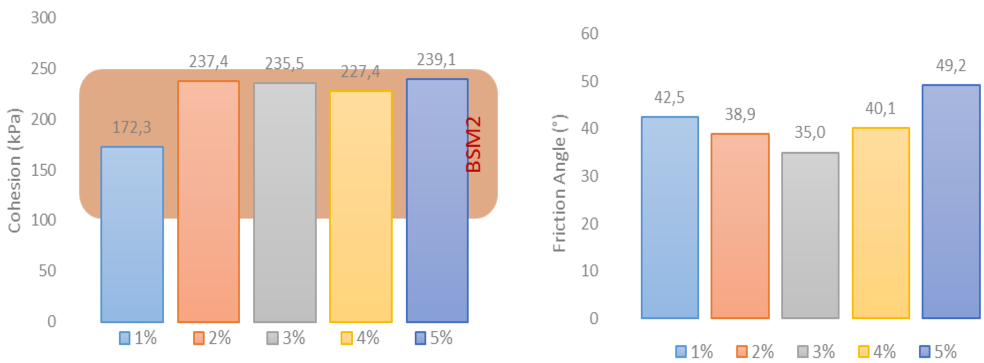

Figure 39 – Cohesion and internal fiction angle of emulsion-based BSM

The graphics presented on Figure 40 refer to the curves load vs. displacement of emulsion-based BSM with lime, taken from the of the monotonical triaxial test made at 100 kPa of confining pressure. This result shows that even though the mixture prepared with 5% of lime became stiffer, an increase of brittleness (equivalent to a reduction of the external work) was not observed. Thus, it is possible to assume that the material did not present a tendency to become fragile.

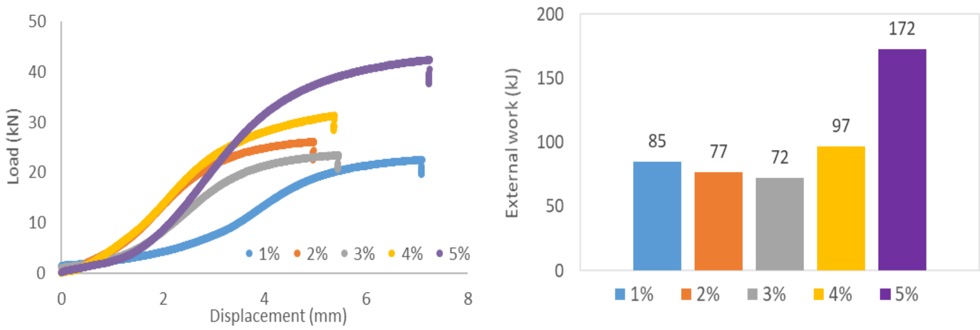

Figure 40 – Load vs. displacement curves and corresponding external work (kJ) for the emulsion-based BSM, at 100 kPa confining pressure

Overall, it is possible to observe that the increments of lime introduced on the mixtures did not carry a significant change on their mechanical behaviour, as all mixtures would be classified as BSM2 according to according to Asphalt Academy (2009) classification system, reposted on Table 2. This means quicklime may be used as a possible active filler designed for cold recycled mixtures. In addition, a constant mechanical behaviour with growing percentages of final hydrated lime, specially between 2 and 4%, may be a very interesting characteristic to the field management, especially when water content control is necessary.

5.3. Foam-based BSM with Quicklime

This section presents the results of the indirect tension test and monotonical triaxial test for mixtures produced with foam bitumen and quicklime. Based on the ITS test results (Figure 41), it is possible to observe that the indirect tension resistance of the mixtures (grey column) varies within a small range, considering the mixtures with 1 and 2% of final hydrated lime content (FHLC). However, an interesting leap (approx. 54%) of the indirect tension strength of the mixtures with 3, 4 and 5% of FHLC was observed. Interesting to highlight, though, that mixtures with 3, 4 and 5% of FHLC kept constant ITS values (356 kPa on average). For the indirect tension ratio (blue columns), the added lime provides a retained indirect tension resistance always above 55%. However, unexpected lower ITR (blue columns) were found with the increase of FHLC.

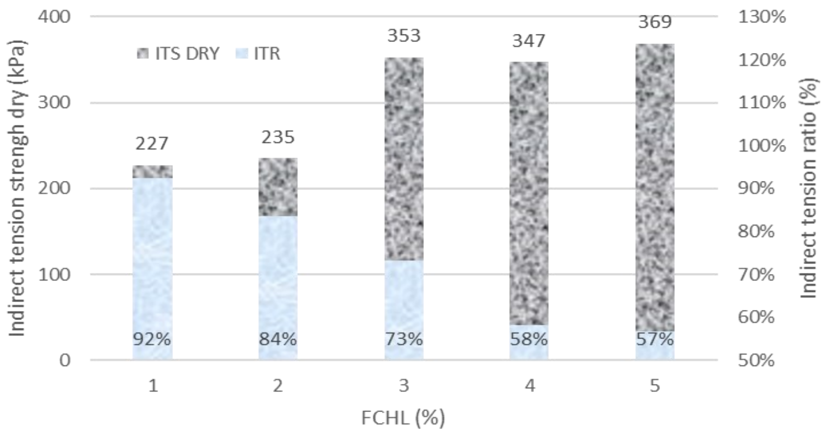

Figure 41 - ITS and ITR of foam-based BSM

The results of the monotonical triaxial test (Figure 42) seem to endorse the ITS test results, indicating the uniformity of behaviour between the mixtures with 1 and 2% of FHLC, regarding the cohesion. Also in this test, an interesting leap (approx. 66%) of the cohesion of the mixtures with 3, 4 and 5% of FHLC was observed. For the mixture with 5% of lime an important increase on the friction angle is reported, although the respective cohesion remained constant.

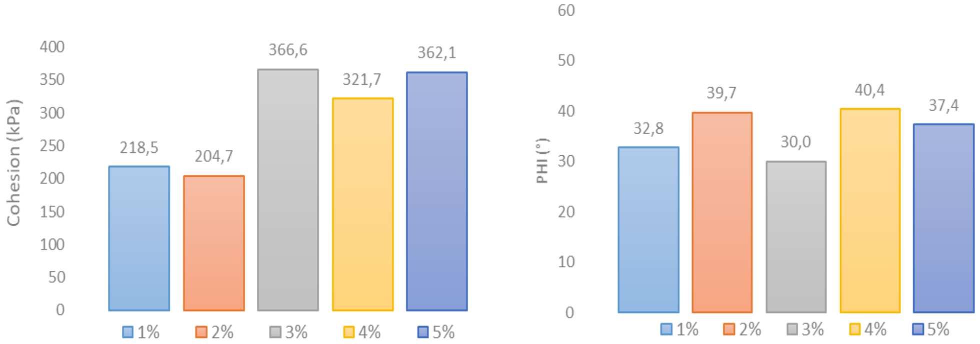

Figure 42 – Cohesion and internal fiction angle of foam-based BSM

The graphics presented on Figure 43 refer to the curves load vs. displacement of foam-based BSM with lime, taken from the of the monotonical triaxial test made at 100 kPa of confining pressure. This result shows that even though the mixture prepared with 3, 4 and 5% of lime became stiffer, an increase of brittleness (equivalent to a reduction of the external work) was not observed. Thus, it is possible to assume that the material did not present a tendency to become fragile.

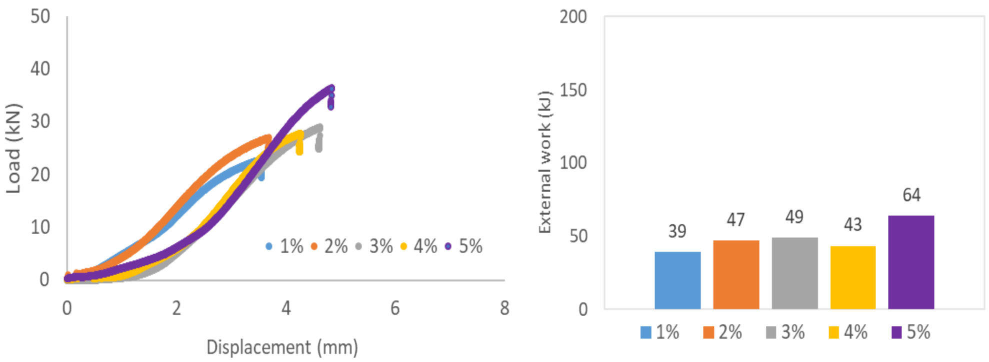

Figure 43 – Load vs. displacement curves and corresponding external work (kJ) for the foam-based BSM, at 100 kPa confining pressure

Overall, it is possible to observe that the increments of lime introduced on the emulsion-based BSM did not carry a significant change on their mechanical behaviour, as all mixtures would be classified as BSM2 according to Asphalt Academy (2009) classification system, reposted on Table 2. As for the foam-based BSM, the classification was kept constant for 1 and 2% FHLC (i.e., BSM 2), however an upgrade of performance (i.e., classification as BSM 1) was observed on the mixtures produced with 3, 4 and 5% (Figure 44).

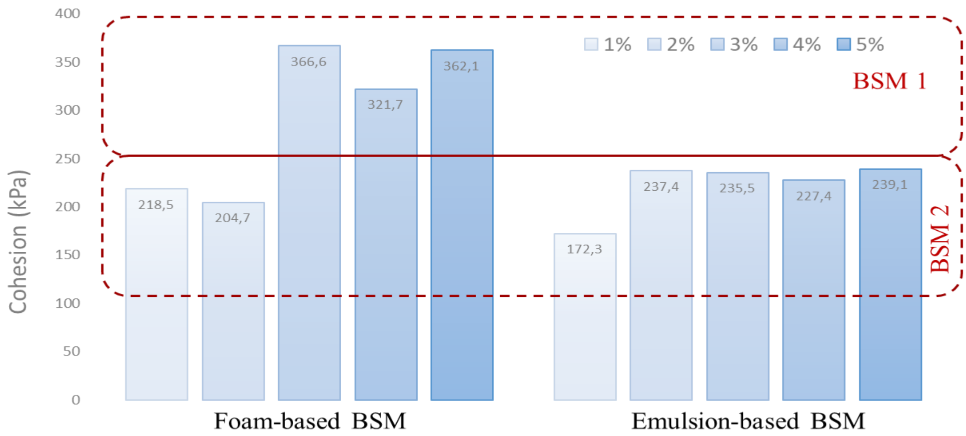

Figure 44 – Classification of emulsion and foam-based BSM, with respect to cohesion results

This reported upgrade on stiffness, however, was not followed by a more brittle behaviour. This means quicklime may be used as a possible pre active filler designed for cold recycled mixtures. In addition, on the intervals were mechanical behaviour is kept constant with growing percentages of FHLC, especially for the emulsion-based BSM. That behaviour can be considered quite an interesting characteristic to the field management, both for adverse climate conditions and water content control. In addition, the stability of the mechanical performances with the increasing content of lime allows to increase the amount of lime to increase the mix's temperature without any substantial change in the mix's mechanical behaviour. Again, these results confirm the possibility of use of lime as a pre-active filler.

5.4. Foam-based BSM with cement

Based on the ITS test results (Figure 45), it is possible to observe that the behaviour of the mixtures with 1, 1.5, 2 and 2.5% of cement, the indirect tension strength of dry specimens increases in a linear relationship with the cement content (grey columns), with 70% increase of strength when comparing 1 and 2% of cement addition. For the indirect tension ratio (blue columns), the added cement provides a retained indirect tension resistance always above 64%, a better performance than BSM produced with lime with respect to water resistance. Those results indicate, also, that the mix design based on the methodology proposed by Wirtgen (2017) was able to better address the optimum water content on cement based BSM, considering the phenomena observed on the preliminary investigations (Figure 17), where the mixture with 2% of cement appeared not fully hydrated.

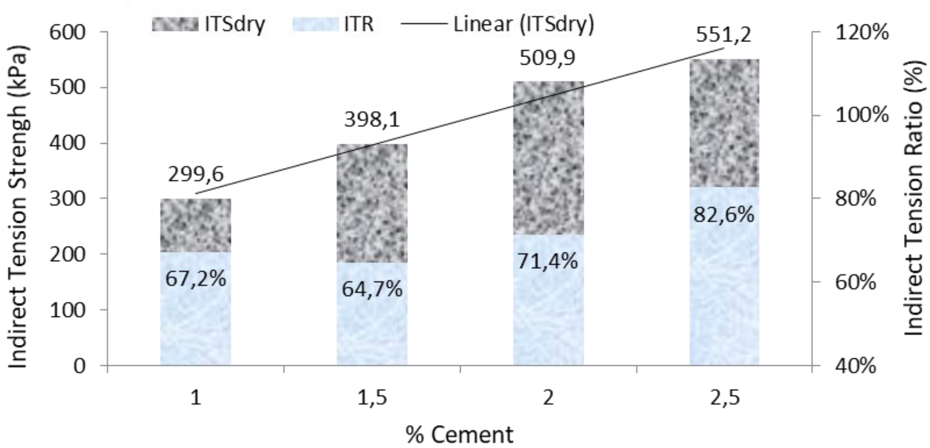

Figure 45 – ITS and ITR of foam-based BSM with cement

Based on the monotonical triaxial test results (Figure 46), it is possible to observe that the behaviour of the mixture with 2% of cement presented a leap on the mechanical shear properties, as both an important increment on cohesion (approx. 40%) and decrease of the friction angle are observed. This result allows to make the hypothesis that the cement has become the real binder of the mixture, instead of the bitumen, which might create an increase of fragility on those mixtures.

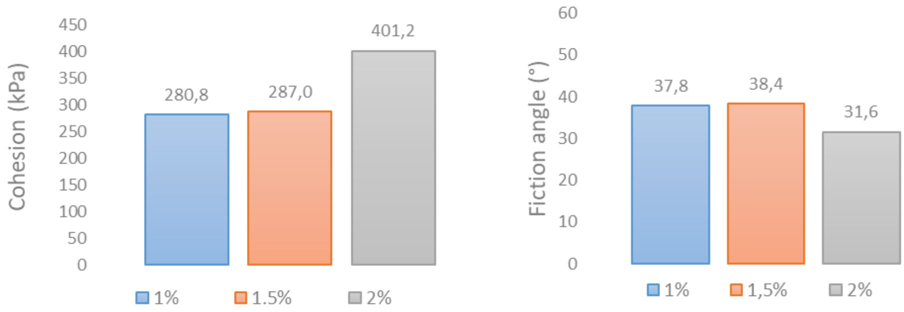

Figure 46 - Cohesion and internal fiction angle of foam-based BSM with cement

5.5. Foam-based BSM with lime vs. cement

As previously stated, the mechanical behaviour of foam-based BSM with cement will be analysed as a reference data, and compared to foam-based BSM with quicklime, especially with respect to how their performance change at each increment of active filler.

Evaluating overall results of mechanical behaviour of these partially bounded materials change according to the amount of added active filler, either cement or lime, it is possible to conclude that BSM designed with cement are more susceptible to mechanical behaviour changes when compared to BSM designed with lime, as cohesion and friction angle changed substantially after successive additions of 0.5p.p. of cement. This means that the structural design of the layers must be followed to a more precise mix design of the BSM itself, along with a more accurate mixing control on field operations. Comparing foam-based BSM the same amounts (2%) of FHLC and cement, indirect tension strength doubles (Figure 47).

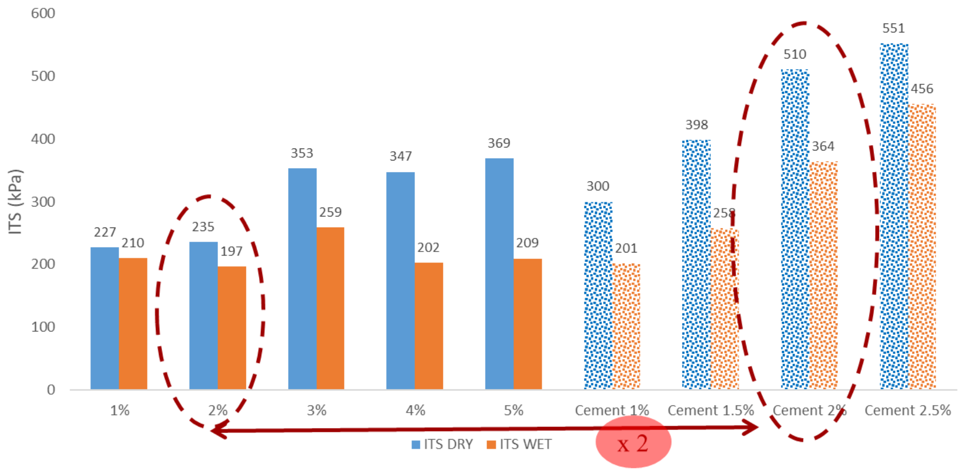

Figure 47 – Comparison of ITS results of foam-based BSM with quicklime and cement

The same variation, i.e., a double cohesion, was found comparing the results of triaxial test of foam-based BSM the same amounts (2%) of FHLC and cement (Figure 47).

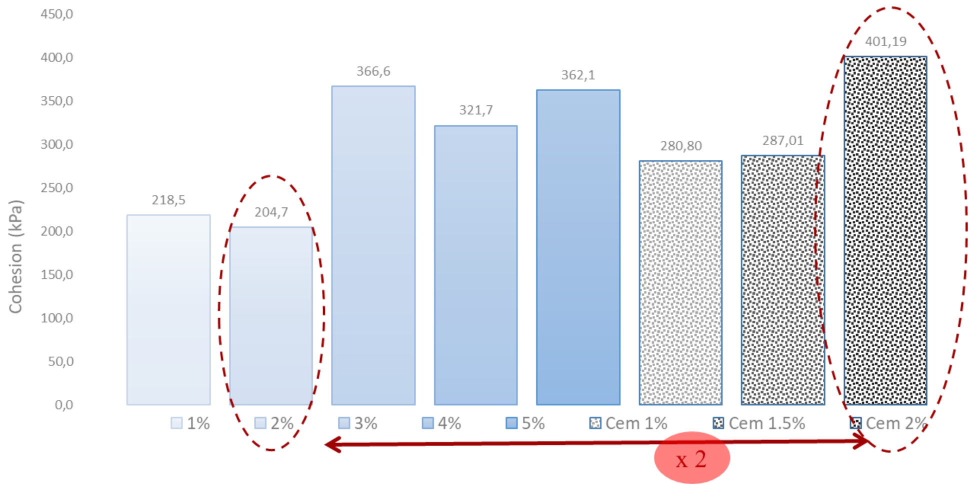

Figure 48 - Comparison of Cohesion results of foam-based BSM with quicklime and cement

The differences showed by BSM with lime and BSM with cement are in agreement with the definition made by Bocci et al. (2012). Considering the mechanical performances of a BSM with cement they defined this kind of mixture as a cement–bitumen treated materials. Considering these differences, it is possible to define two different kinds of BSM in function of the used active filler: cement–bitumen treated BSM and lime treated BSM. As showed by the results above, the main differences between the two treatments are the changes connected with the increasing of the amount of active filler. While with cement there is a linear change in the general mechanical behaviour, correspondent behaviour was not observed with the increasing of lime.

Chapter 6 – Conclusions and Future Works

This thesis shows the results of a research work aimed to understand the effects of the use of quicklime to make bitumen stabilised material on cold recycling operations of pavements. Main conclusions are pointed out bellow:

- Quicklime did work as a pre-active filler, as the reaction with water was fully completed during mixing phase of the mixture.
- CaO+Water reaction was capable to heat the whole mix, even with lower contentes of quicklime.
- Stabilising Agent (Foam Bitumen or Emulsion) must be added after the reation CaO+Water.
- The increment of temperature is important but does not seem to influence the workability and compactability of the specimens.
- The increment of up to 4% of quicklime on emulsion-based BSM seems possible during working site management with no need of structural re-design.
- The increment of up to 5% of quicklime on foam-based BSM seems to improve its strengh without becoming brittle.

Considering the timing of is hydration reaction, quicklime can be considered a "pre-active filler" because it becomes almost immediately hydrated lime and this one it's who is working as active filler in the mixture. The mechanical results show that the use of quicklime does not bring negative effect either in the mixing phase or in the compaction phases: the characteristics of a BSM made with quicklime are totally in agreement with the characteristics of a common BSM mixture.

On the other hand, even a small increase of cement (0.5% on the weight of the dry aggregates) makes a radical change in the mechanical behaviour. The above showed results lead to state that above that 1% the cement plays also the role of a binder and not only the role of an active filler. This is in agreement with the limit of 1% of cement in the BSMs stated in the Asphalt Academy (2009). Thus, special care should also be taken when designing the amount of cement, as percentages above 1.5% on dry aggregate weight as they may produce highly brittle BSM.

The temperature measurements confirmed the fundamental hypothesis that was the basis of this research work: it is possible to use the quicklime to increase the temperature of the BSM.

Water control must be accurate, for either quicklime or cement-based mixtures. With respect to BSM designed with quicklime, attention should be made to add a parcel of water content corresponding to the reaction water, necessary to hydrate the quicklime. With respect to BSM designed with cement, it is evident that the mix design phase must be performed with special attention to the water content, to provide full hydration of cement particles in the mix.

Considering the difference on the bulk densities and considering a smaller volume of quicklime is necessary to obtain the designed amount of final hydrated lime that will work as active filler, if a source of water is available close to the mixing plant or close to the job site, this simple and yet innovative process allows a considerable saving of environmental, energetic and financial resources.

At last, the use of quicklime as pre-active filler it is possible, and it brings important benefits form the operational and from the economical points of view.

Even though important results were achieved on this research, some further investigations are encouraged:

- Deeper investigations on the possibility of mobilization of aged bitumen in the RAP, due to the elevation of RAP temperature, especially when using quicklime on hot climate regions, as the mix temperature may reach the softening point of the aged bitumen.

- Deeper investigation of BSM produced with quicklime on experimental sections, with respect to workability, compactability, and long-term performance.

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