DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

INFLUENCE OF FOAMING WATER CONTENT AND MIXING TEMPERATURE ON FOAM ASPHALT MIXTURES

by

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INFLUENCE OF FOAMING WATER CONTENT AND MIXING TEMPERATURE ON FOAM ASPHALT MIXTURES

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"INFLUENCE OF FOAMING WATER CONTENT AND MIXING TEMPERATURE ON FOAM ASPHALT MIXTURES"** completed by **SOLOMON TOMBE MARX LADU** under supervision of **PROF. DR. ALİ TOPAL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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I dedicate this thesis to my beloved wife and children for their continuous support.

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INFLUENCE OF FOAMING WATER CONTENT AND MIXING TEMPERATURE ON FOAM ASPHALT MIXTURES

ABSTRACT

High air void content and inadequate coating of coarse aggregate particles are major challenges in the application of warm mix asphalt (WMA) using foam asphalt technology. Aggregate particle coating has significant influence on air voids content in foam asphalt mixture and is directly dependent on the volume of foam bitumen in the mixture and production temperature as well. This is especially significant to the foam asphalt mixture where the amount of foaming water content dictates the resulting volumes of foam bitumen produced. Therefore, foaming water content is an important mix design parameter in the production and performance of foam asphalt mixtures.

The objectives of this study are to investigate the influence of foaming water content on foam asphalt mixtures, and develop a fundamental understanding about the significance of foaming water content together with mixing temperature in the interaction of foam bitumen and mineral aggregates and performance of foam asphalt mixtures. For this purpose, Marshall Stability and Indirect Tensile Strength tests were applied to investigate the influence of foaming water content (2, 4, 6 and 8 percent) at varying level of mixing temperatures (120, 100 and 80 degrees Celsius).

The obtained results show that the increase in foaming water content resulted in reduction of Marshall Stabilities and densities while the air voids content increased. Fundamentally, the results have also revealed that the reduction in mixing temperature (80 degree Celsius) has adversely affected the air voids content, densities and stabilities of the foam asphalt mixtures. The mixing of foam asphalt at high temperatures (120 degree Celsius) reduces the content of air voids, while enhancing Marshall stability and density.

Keywords: Foaming water content, foam asphalt, mixing temperature, air voids content

KÖPÜK ASFALT KARIŞIMLARINDA SU İÇERİĞİNİN VE KARIŞTIRMA SICAKLIĞININ ÖNEMİ

ÖZ

Yüksek hava boşluğu içeriği ve kaba agrega parçacıklarının yetersiz kaplanması, köpük asfalt teknolojisi kullanılan ılık karışım asfalt uygulamalarında zorluklara neden olmaktadır. Agrega parçacıklarının bitümle yeteri kadar kaplanmaması, köpük asfalt karışımında hava boşlukları içeriği üzerinde önemli bir etkiye sahiptir ve karışımdaki köpük bitümünün hacmi ve üretim sıcaklığı ile doğrudan ilişkilidir. Bu, köpüren su içeriği miktarının üretilen köpük bitümü hacmini belirlediği köpük asfalt karışımları için özellikle önemlidir. Bu nedenle, köpüklü su içeriği, köpük asfalt karışımlarının üretimi ve performansında önemli bir karışım tasarım parametresidir.

Bu çalışmanın amacı, köpüklendirme su içeriğinin köpük asfalt karışımları üzerindeki etkisini araştırmak ve köpük bitüm ile mineral agrega etkileşiminde köpüklendirme su içeriğinin karıştırma sıcaklığı ve köpük asfalt karışım performansı ile ilgili temel bir anlayış geliştirmektir. Bu amaçla, farklı seviyelerde karıştırma sıcaklıklarında (120, 100 ve 80 santigrat derece) köpüklendirme su içeriğinin (2, 4, 6 ve 8 yüzde) etkisini araştırmak için Marshall Stabilitesi ve Dolaylı Çekme Mukavemeti testleri uygulanmıştır.

Elde edilen sonuçlar; köpüklendirme su içeriğindeki artışın, karışımın hava boşluğu içeriğini arttırırken, Marshall Stabilitesi ve yoğunluğunun azalmasına neden olduğunu göstermektedir. Sonuçlar aynı zamanda, karıştırma sıcaklığının düşmesi ile (80 santigrat derece) köpük asfalt karışımlarının hava boşluğu içeriğinin arttığını, yoğunluk ve stabilitesinin olumsuz etkilendiğini ortaya koymaktadır. Köpük asfaltın daha yüksek sıcaklıklarda (120 santigrat derece) karıştırılması ile karışımın hava boşluğu içeriği etkili bir şekilde azaltılarak yoğunluğu artar ve böylece daha yüksek Marshall stabilite değerleri elde edilebilmektedir.
Anahtar Kelimeler: Köpüklendirme su içeriği, köpük asfalt, karıştırma sıcaklığı, hava boşlukları içeriği

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INTRODUCTION

1.1 Background

The growing concerns on reduced availability of aggregates and environmental pollution resulting from industries related to transportation infrastructure activities (production of HMA), has led to the development of cleaner and economically sound production techniques. Warm mix asphalt (WMA) has emerged as the remedy to these concerns related with the production of hot mix asphalt (HMA). WMA is a technology for sustainable development, as it conserves natural resources by recycling existing materials, significantly reduces emission of hazardous gases to the environment and improves pavement-working conditions. WMA technologies generally rely on modification of bitumen properties to improve the interaction between bitumen and aggregates at lower production temperature as compared to HMA.

The advance of WMA technology using bitumen foaming technology has made foam asphalt a common rehabilitation technique in many parts of the world. Foam asphalt technology reduces production costs and produces a more environmentally friendly product than traditional HMA. These benefits encourage the use of foam asphalt as a better choice in pavement rehabilitation projects. Many parts of the world have used foam asphalt for years in their road rehabilitation projects. The application of foam bitumen in many countries and states is increasing; hence, clear understanding of the production techniques and properties of foam bitumen is necessary. The foam bitumen is produced by injecting cold water (normally 1 - 4% by weight of bitumen) into the hot liquid bitumen (170 – 190 ^{o}C) resulting in spontaneous foaming, which temporarily changed the properties of the bitumen physically.

Foam asphalt and HMA have some common elements of the mix design process that include selection of materials and some test methods, but some clear differences occur in the composition and mix design process. In comparison to HMA, foam asphalt is more complex to effectively perform the mix design and analyze. Apparently, the binder properties differ significantly between foam asphalt and HMA. Volumetric composition has become more complex by the presence of the water phase in foam asphalt mixes. These and other parameters require attention in the development of well-formulated mix design procedures of foam asphalt mixtures (FAM).

Muthen (1998) outlined that moisture content in foam asphalt during mixing and compaction has been recognized as a very important parameter in mix design by many researchers. Thus, in foam asphalt mix properties and pavement design the influence of water is an important issue.

At lower mixing temperatures, moisture condition of aggregates particles plays an important role in softening and breaking down agglomerations in the mix. This results in to an easy dispersion of bitumen during mixing and compaction of FAM. The optimization of the mechanical properties of FAM such as density, air voids content, strength and stability may depend on the optimum moisture conditions. Jenkins (2000) stated that aggregates particles in FAM are partially coated compared to HMA materials, this results into higher air voids content making foam asphalt mixtures highly moisture susceptible.

Aggregate particles coating has significant influence on air voids content in FAM and is directly dependent on the volumes of foam bitumen in the mix and production temperature as well. This is particularly significant to the foam asphalt mixtures where the amount of foaming water content dictates the resulting volumes of foam bitumen produced. As such, foaming water content is an important parameter in the production of foam asphalt mixtures.

Foaming water content may have an adverse influence on the properties of foam bitumen, which in turn affects coating of large aggregates in FAM. Consequently, strength, density and high voids content problems may arise due to poor binding of aggregates particles together or insufficient adhesion between binder and aggregates particles. This area is still unclearly understood and is therefore becoming an important subject area of study. Therefore, as water is very important for bitumen foaming, foam asphalt mixing and compaction, better understanding of the influence of foaming water on FAM is essential such that optimization of both the foam bitumen and the mix becomes possible in production of foam asphalt.

1.2 Scope and Aim of the Study

The aim of this study is highly motivated by the growing concerns on the high air void content, incomplete coating of large aggregates and the complexity in density-voids analysis resulting from the inclusion of water phase in foam asphalt mix. These problems still need more research efforts, because they remain to be major challenges in application of WMA technology using foam bitumen specially concerning the mechanical performance of foam asphalt mixtures. Hence, in this study the influence of foaming water content and mixing temperature on foam asphalt mixtures is questioned.

Therefore, the main objectives of this study are:

- To investigate the influence of foaming water content and mixing temperature on foam asphalt mixtures.
- To develop a fundamental understanding about foaming water content, together with mixing temperature significance in the interaction of foam bitumen and mineral aggregates and performance of foam asphalt mixtures.

1.3 Methodology

In this study, conventional asphalt test methods will be applied throughout the investigations at varying foaming water content and mixing temperature. Marshall Stability test will be performed to evaluate the foam asphalt mixture performance including density – voids analysis. Indirect tensile strength test will be applied to measure the strength and moisture susceptibility conditions of foam asphalt mixture at various foaming water contents.

1.4 Organization of the Study

The study composed of five chapters:

- Chapter One - introduces a general background to foam asphalt concept related to the objectives of the study, aim and scope of the study and the methodology involved.
- Chapter Two – emphasises on literature review about foam bitumen and foam asphalt production techniques.
- Chapter Three – focuses on the methodology involved in investigation of the water content influence and mixing temperature on foam asphalt mixtures.
- Chapter Four – contains the results and analysis of the investigations made during the study.
- Chapter Five – presents conclusions and recommendations of the study.

CHAPTER TWO
FOAM ASPHALT MIX TECHNOLOGY

2.1 Introduction

This chapter sets light on previous studies on foam asphalt technology and problems involving mix design procedures. Available studies and literatures about foam bitumen have shown that the bitumen foaming process was first proposed by Csanyi in the mid-1950s, and regard its application in the stabilization of soils or base materials, which began with Csanyi (1957). Originally, the concept was applied through the use of steam injection into hot bitumen by Csanyi, but later on Mobil Oil Australia modified the concept by introducing cold-water injection in to the stream of hot bitumen and then the foam bitumen was used to mix with cold, wet aggregate or soil (Muthen, 1998). The desired outcome for stabilization was the coating of the fine particles by binder and the spot welding of the coarse aggregate to achieve some measure of cohesion. This type of stabilization is usually done in place but can also be accomplished by a mixing plant (Muthen, 1998).

In comparison to HMA, FAM is produced at reduced temperature. The reduction in production and compaction temperatures results to decrease of fuel or energy consumption, cutting of CO_2 emissions and improvement of paving working conditions. However, experience shows that foam asphalt produced at lower temperature still requires improvements to meet the requirements for heavy-duty roads (Biruk et al., 2015). Higher void content as compared to HMA and incomplete coating of large aggregates are main issues requiring enhancement. As such, the influence of foaming water content on foam asphalt mix performance is questioned in this study.

According to (Biruk et al., 2015), foam bitumen mix contains hot bitumen, water and air. Foam Bitumen is produced through a process whereby small quantities of water, normally 1.0 – 4.0 % by weight of the bitumen, injected into hot bitumen at a temperature 170 – 180 ^{o}C. The bitumen expands to about 5 – 15 times its original volume forming foam, which is highly efficient in wetting and coating the surface of fine particles. The bitumen needs to be sufficiently foamed to have adequate potential for coating of the aggregates particles. Insufficient expansion of foam bitumen results into binder dispersion problems on aggregates during mixing. Most of the foaming water is evaporated as steam when the foam collapses; this leaves the residual bitumen with similar properties as the original bitumen.

Fortunately, the process of bitumen foaming regardless of the mechanical methods being applied all amounts to injecting a small quantity of cold water (1 – 4% by weight of bitumen) in to hot bitumen (170 – 190 ^{o}C), and allowing the generation of steam to expand the bitumen through the formation of voids results to bitumen foaming (Fort et al. 2011). Thus, lessons learned in base and soil stabilization apply to WMA production using foam bitumen. There are varieties of methods to disperse a foaming agent such as water into a medium such as hot liquid bitumen. Water in a liquid state is introduced to the hot binder stream, wherein it turns to steam (NCHRP, 2015).

The main purpose for modifying bitumen properties in foam asphalt technology is to reduce the viscosity and increase the volume of the binder in order to achieve better dispersion of binder and coating of aggregate particles at low production temperature. The best way to disperse asphalt on cold, wet aggregate was by using cutback solvents or emulsions before the development of the foaming process. Fortunately, foam asphalt does not require solvents or emulsions, so the environmental and financial drawbacks associated with cutback and emulsified asphalts are eliminated. As a result, interest in foam asphalt has grown recently (Wood, 1984).

2.2 Definition of Foam Asphalt

Muthen, Lewis and Vos (1999) have defined foam asphalt as, a mixture of pavement construction aggregates and foam bitumen. The production of foam bitumen is by injecting cold water (at ambient temperature) in to hot bitumen causing bitumen foaming in an expansion chamber. When cold water comes in to contact with hot bitumen the physical properties of the hot liquid bitumen are temporarily changed. During bitumen foaming process, the cold water turns into steam that is contained within the hot bitumen resulting in to formation of bubbles (Figure 2.1). However, the foam bitumen does not last longer before the foam dissipates and the bitumen retains its original properties. Foam bitumen is mixed with aggregates before the foam collapses.

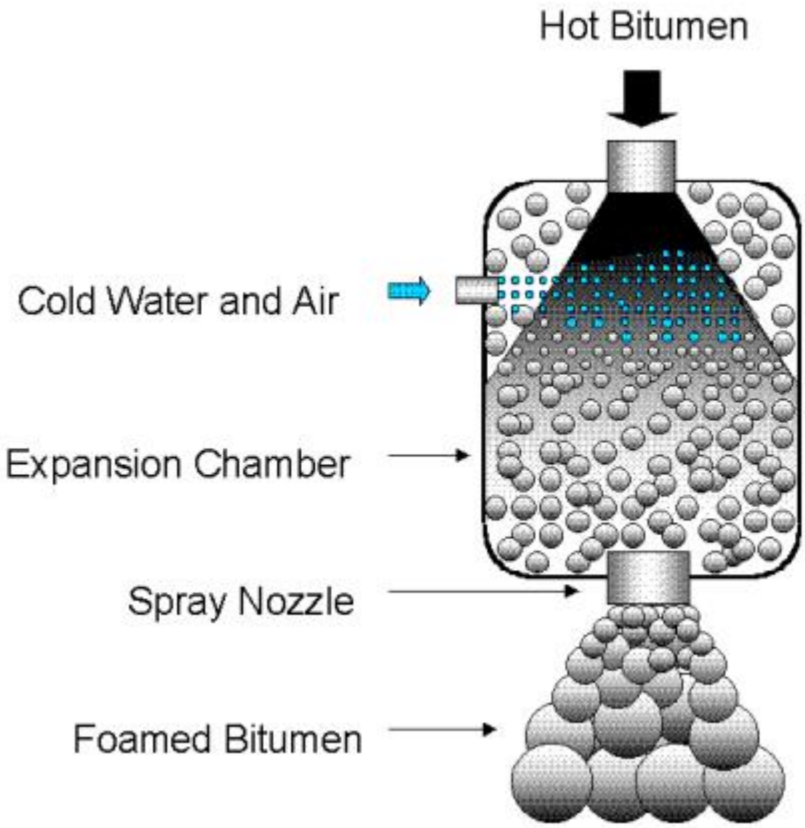

Figure 2.1 Foamed bitumen production (Jenkins, 2000)

Muthen (1998) had stated that, the physical properties of the bitumen such as the surface area is being temporarily increased and viscosity being reduced substantially to make mixing with moist aggregates possible. In addition, Jenkins et al. (2000) in a study on developments in the uses of foamed bitumen in road pavements mentioned that, foam bitumen can be applied as a treatment agent for varieties of materials including traditional high-quality crushed stones, reclaimed asphalt pavement (RAP) materials and low-quality materials such as those with a high plasticity index. Foam asphalt mixtures (FAM) can be produced in place (in situ recycling) or in an asphalt plant. To achieve optimum properties of FAM, foam bitumen contents are determined as percentage by weight of aggregates or mix materials (Muthen 1998).

2.3 Applications of Foam Asphalt Mix

Jenkins et al. (2000) studied developments in the uses of foamed bitumen in road pavements, stated that as the use of foam bitumen increased, varying areas of application have also increased. Earlier in 1957, Csanyi initially perceived foam bitumen as a means of improving the quality of marginal mineral aggregates such as loess, to enable them to be used in road pavements. Studies and development in this area subsequently found that, foam bitumen could be used to produce cold mixtures when added to mineral aggregates of varying qualities, where the mix can be placed and compacted at ambient temperatures. These qualities have encouraged the use of foam bitumen for rehabilitation of road pavements through the use of cold in place recycling, (Jenkins et al., 2000).

The main applications of foam bitumen include the following:

a) conventional cold mixes with good quality or marginal aggregates,
b) cold mixes with Reclaimed Asphalt Pavements (RAP) material,
c) half-warm and warm foam bitumen mixes and,
d) Specialized surface dressing.

Every area of foam bitumen application needs different properties of foam for optimal performance. Parameters such as bitumen type, foaming agent (if any), bitumen temperature during foaming and foaming water content etc.

2.3.1 Benefits of Foam Asphalt mix

Shatec (2013) reported that, the use of foam asphalt mix technology in pavement rehabilitation and reconstruction has been on the rise in the recent years because it offers many advantages that include:

2.3.1.1 Environmental Benefits

- Reuse of both the aggregates and bitumen in the existing aged pavements results in conservation of natural non-renewable resources.

- Reducing or eliminating disposal of old distressed pavement materials that are inherent in conventional rehabilitation methods,
- Foam asphalt technology recycles and reuses fully the materials in the existing distressed pavement. As such “zero waste” approach is established to pavement rehabilitation where the entire existing asphalt pavement layer is processed and reused in-place without the need for off-site transportation of waste materials. Therefore, there is no need to allocate land or sites for disposal of spoil or the wastes and the volume of new material that has to be imported from quarries is minimized. Noise and dust from blast activities at the quarry sites has also been mitigated. In addition, haulage is drastically reduced or totally eliminated, and as a result the overall energy consumption is significantly reduced, as are the greenhouse emissions and the damaging effect of haulage vehicles to roadways in the vicinity of the project site and traffic delays resulting from this increase in construction traffic.

2.3.1.2 Reducing Energy Consumption

In-place recycling and reuse of existing pavements drastically reduced or fully eliminated haulage resulting in to overall reduction in energy consumption. In addition, in foam asphalt mixtures aggregates can be mixed without heating or low temperature heating which results into energy conservation.

2.3.1.3 Economic Benefits

Economic benefits from the use of in-place/on-grade construction activities (no hauling of material to and from the plant). In foam asphalt mixes, no fuel is required for heating the asphalt layer, resulting in significantly reduced energy consumption compared to other rehabilitation treatments.

- Significant saving in material cost due to full utilization of existing asphalt concrete without the need of virgin materials or the disposal of the milled off asphalt concrete material. It is important to note that pavements can be recycled again and again.

- Because of the significant savings that can be achieved, available limited funding can be stretched to benefit other projects.

2.3.1.4 Structural Benefits

In base stabilizations, it is worth mentioning that foam bitumen treatment considerably results in high shear strength and significantly reduces the air voids and moisture susceptibility. The strength properties of foam asphalt mix can be compared to those of cemented materials, but FAM exhibits flexibility and fatigue resistance.

2.3.1.5 Construction Benefits

Foam asphalt offers advantage of constructing the pavement in somewhat unfavorable weather conditions without imparting negatively on the workability or the properties of the finished pavement. Additionally, it is easy to stockpile or store foam asphalt for extended durations mean while maintaining the workability of mix. Compaction, shaping and finishing foam asphalt layer is achievable at low temperature. As such, foam asphalt roads can be opened to carry traffic almost right after finishing pavement construction.

However, Jenkins (2000) outlined that; there are also some major challenges associated with the application of foam asphalt mixes (FAM) that should be taken into account:

- Producing a satisfactorily quality foam asphalt requires high level of skill and an advanced experience in dealing with FAM.
- Refining process of bitumen sometimes add anti-foamants substance such as silicones making difficult to produce foam bitumen with high quality, unless foaming agents are added during bitumen faoming. This comes with additional cost.
- Developments in foam asphalt pavement design methods and procedures are still very limited in that making accurate design of the entire pavement

structure difficult. This is partly because of the limited researches being carried out regarding foam asphalt.

- Durability is still a concern when dealing with foam asphalt mixtures. It is difficult to accurately prove cost-benefits of foam asphalt pavements, without reliable long term pavement performance predictions, the life-cycle cost benefit is difficult to ascertain. For this reason, many clients are not often prepared to take the risk of using a less well researched product.

2.4 Design Considerations of Foam Asphalt

2.4.1 Properties of Foam Bitumen

CSIR Transportek (1998) in a report on foamed asphalt mixes – mix design procedure stated that, foam bitumen is a hot liquid bitumen which has been physically and temporarily changed in to foam state by injecting a small amount of water (typically 2 % by weight of bitumen) into the hot bitumen. The report further stated that, there are two basic parameters used to characterize foam bitumen, these are expansion ratio and half-life. Expansion ratio of the foam bitumen is the ratio of the maximum volume of foam bitumen achieved to the final volume of the foam bitumen when the foam has dissipated. On the other hand, half-life is the time (in seconds) between the moment foam bitumen achieves its maximum volume and the time it dissipates to half of the maximum volume. During the mixing process of foam asphalt production, the foam bitumen properties play a very important role. It can be expected that maximized expansion ratio and half-life will promote foam bitumen dispersion and coating aggregates particles.

According to Cold recycling technology (2010), the two properties that formed the basis of a bitumen's suitability for use in foam asphalt mixtures are expansion ratio and half-life. Cold recycling technology (2010) considered expansion ratio as the measure of foam bitumen viscosity and that expansion ratio describes how well foam bitumen dispersion will be achieved in the mix, while half-life indicates the rate of collapse of the foam and measures the stability of bitumen's foam. The foam bitumen properties can be shown graphically as depicted in Figure 2.2.

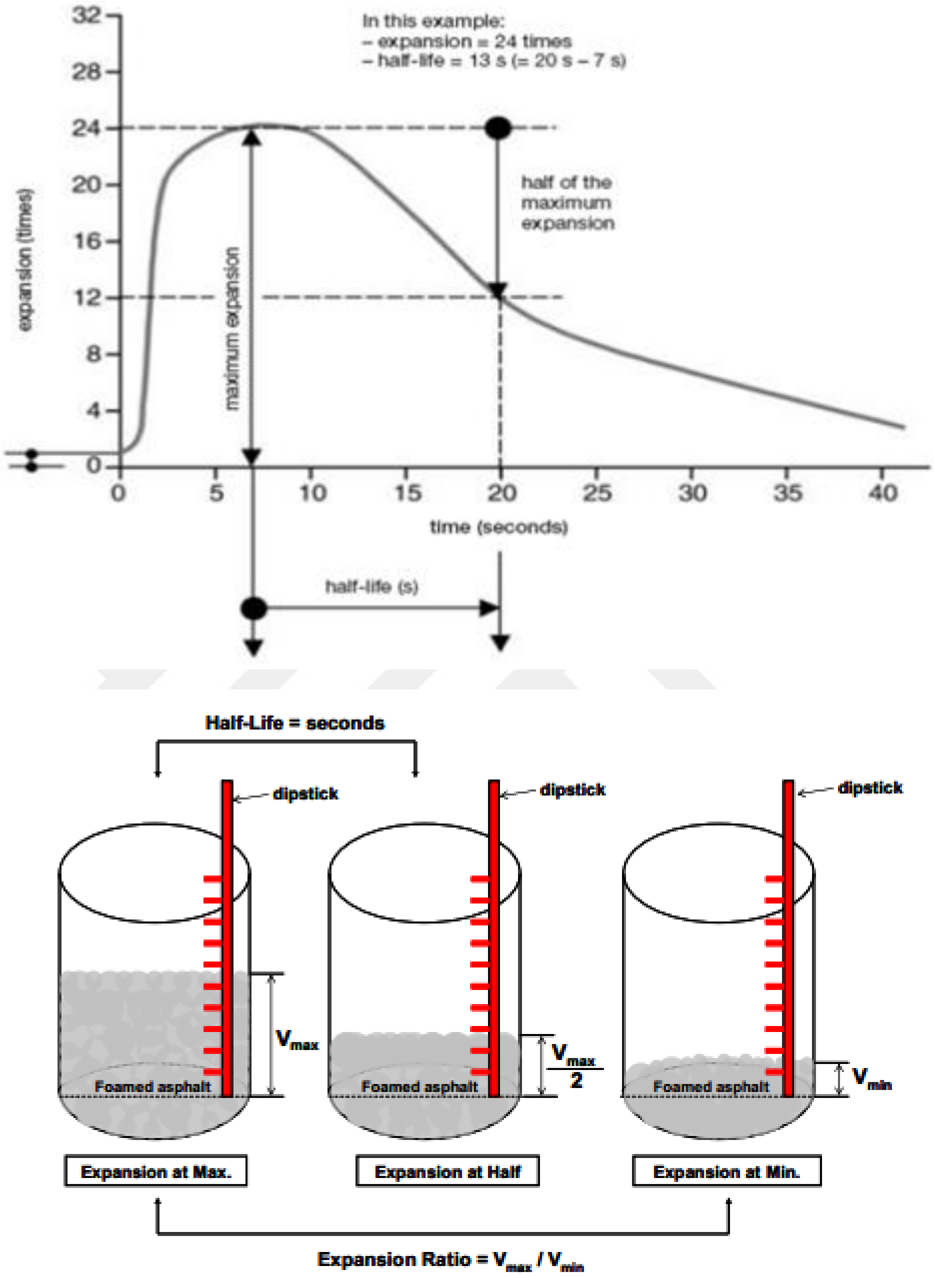

Figure 2.2 Illustration of expansion ratio and half-life (Wirtgen, 2004)

Biruk et al. (2015) conducted a study and found that foaming softer binder results in higher expansion ratio compared to harder binder. The half-life does not give a clear indication about the stability of the foam, for initial water contents in the foam higher than 1 %. In addition, the temperature distribution on the surface of the foam bitumen is non-uniform, and the minimum to maximum temperature range is significant when using high amount of water content (4% by wt.).

However, in earlier studies Brennen et al. (1983) found that foam bitumen volume produced, the foaming water content used and the temperature at which the foam bitumen was produced affected the expansion ratio and half-life of foam bitumen from any bitumen. Higher foaming temperatures and increased amounts of foaming water both resulted in increased expansion ratios, but decreased half-lives. In the laboratory, the size of the container was found to affect the foam parameters (Ruckel et al, 1982). Ruckel et al. (1982) recommended limits of 8-15 for the expansion ratio and at least 20 seconds for the half-life. Maccarrone et al. (1994) found that, using certain foaming agents (additives) highly improved foam bitumen properties resulting in high values of expansion ratios (greater than 15) and half-lives (greater than 60 seconds).

As explained in previous sections, higher foaming properties of bitumen play important role in coating aggregates particles during mixing of foam asphalt. CSIR Transportek (1998) stated that, using the appropriate amount of water, air pressure and type of nozzle might make bitumen from any source to be foamed; however, it is also important to note that:

- bitumen containing silicone substances might hinder the bitumen foaming potential;
- softer bitumen has superior foaming properties,
- foaming potential of bitumen is intensified by using anti-stripping agents,
- bitumen temperatures above 160 °C is considered acceptable for bitumen foaming process,
- producing foam bitumen at higher foaming water contents increased the expansion ratios but decreased half-life of foam bitumen,
- bitumen foaming agents can be used to increase the expansion ratios and half-life to values greater than 15 and 60 seconds respectively, and
- compressive strength and cohesion of foam asphalt mixtures are normally greater when expansion ratios are high (15:1).

2.4.1.1 Foamability

Jenkins (2000) described the bitumen foaming process physically due to the physical and temporal nature of the bitumen foam. The moment cold-water surface comes in to contact with the surface of hot bitumen, foaming process begins as a result conservation of energy. That moment when a cold-water droplet (at ambient temperature) touches the surface of hot bitumen at 170 to 180 °C, chain of events occur that can be described as follows, (Jenkins, 2000):

- Firstly, energy is being exchanged between the hot bitumen and the surface of the cold water droplet. In the process of heat exhanged, the surface temperature of the cold water droplet is increased while the bitumen temperature is being reduced to almost equal that of the water droplet.
- At 100 °C temperature, the latent heat of steam is reached causing vaporization at the surface of the water droplet. This process continues to reduce the temperature of the bitumen around the water droplet.
- The steam generated during the vaporization process of water droplet results into an explosive expansion within the bitumen. Steam is trapped in tiny bitumen films creating bubbles under pressure causing a continuous phase of bitumen foaming in the expansion chamber of the foaming system. It is in this way that bitumen bubbles are formed under heat and pressure. Heat exchange continues and more steam is generated causing more bubbles. The slightly cooler bitumen helps in keeping the bubbles intact by the action of surface tension.
- The bitumen bubbles expand continuously as the pressure of the steam is being counteracted by the surface tension of the bitumen film during the explosive expansion. This continues until a state of equilibrium is reached. This process can similarly be explained that, the bitumen bubbles burst when the given time of loading for elongation of the bitumen might be exceeded.
- Steam insulation layer is formed at the surrounding of the unvaporized water for larger water droplets within the bitumen foam limiting additional steam from being generated.

- Both bitumen and water have low properties of thermal conductivity as a result stability of the bubbles can last for some few seconds.

Brennen et al. (1983) analyzed and summarized the primary variables that influence foam bitumen properties as follows:

- The produced quantity of foam bitumen,
- The foaming water content in the foam bitumen,
- The bitumen temperature during foaming.

Maccarrone et al. (1994) in a study about additives or "foamants" in production of foam bitumen found that using 0.5% to 0.75% foamant resulted to expansion ratio of the foam bitumen between 8: 1 and 15: 1 respectively. While the half-life of foam bitumen increased to of 40 seconds, an indication of improved foam bitumen properties due to the use of additives. To achieve the desired foam bitumen properties, it is very useful to apply foaming agents especially where bitumen contains silicone or other defoamant substances.

2.4.1.2 Foam Bitumen Decay

Jenkins (2000) outlined breaking down of foam bitumen bubbles comes as a result of the following:

- Once the surface of the bitumen films come into contact with cold or ambient air the temperature of the steam is reduced. Foam bitumen bubbles at the surface or frontier of the colloid mass encountered the ambient air first. The pressure in the foam bitumen bubble disappears accordingly as the steam temperature drops to its minimum. When the bitumen film’s rate of recovery is exceeded as the pressure and temperature change reduces, surface tension becomes significant resulting into the collapse of the foam bitumen bubbles. Larger bubbles collapse first because of the rapid lost of temperature from their larger surface exposure to cold air.

- Elongation limit of the bubbles bitumen film being exceeded. For large water droplets, the steam pressure inside the foam bitumen bubbles forces the bitumen film to expand upto the limit. Therefore, beyound the ductility limit of the foam bitumen film failure becomes imminent. Here again, the larger foam bitumen bubbles will collapse first and steam will escape. In case of any presence of small water droplets within the bubbles, smaller foam bitumen bubbles will be generated due to the lesser engergy in the mix.
- Polydiverse colloidal mass. Adamson (1990) stated that the most mechanically stable configuration of a bubble pattern is met when septums of the bubbles meet at 1200. The inverse of this theory is also true i.e. metastability with foams of a polydiverse nature is achieved through over riding of bubbles with a variety of bubble sizes.

2.4.2 Foam Bitumen Content (FBC)

The determination of optimum foam bitumen content in foam asphalt mix is not clear as compared to HMA. The range of foam bitumen contents (FBC) that can be used as optimum foam bitumen content is limited by the indirect tensile strength (both dry and wet) and moisture susceptibility condition (Figure 2.3). Binder content to fines content is an important parameter in determination of foam bitumen content. I.e. foam asphalt mix is highly influenced by the binder-fines ratio required to form the mastic. According to Asphalt Academy TG2 (2009), flexibility and tensile strength of foam asphalt are measured by the Indirect tensile strength test (ITS) as a reflection of materials' flexural characteristics. The Academy also described ITS method as the most economical in determining the optimum foam bitumen content.

Asphalt Academy TG2 (2009) recommended that, Marshall specimens (100 mm diameter) should be used to determine the optimum foam bitumen content specimens in level 1 as depicted in Table 2.1 (level 1 is an indication of the highest quality mix). To give additional confidence and refine the optimum foam bitumen content, Asphalt Academy TG2 (2009) recommended the use of 150 mm specimens. Asphalt Academy TG2 (2009) and cold recycling technology (2010) both share similar recommendation for the determination of optimum foam bitumen content. Both guidelines recommended curing of foam asphalt specimens for 72 hours at 40 °C in a force draft oven. ITS_{dry} test is conducted at 25°C after curing the specimens while ITS_{wet} is determined after soaking these specimens for 24 hours at 25°C.

Table 2.1 Interpretation of ITS tests (Asphalt Academy TG2, 2009)

Test	Specimen diameter	BSM1	BSM2	BSM3	Purpose
ITS_{dry}	100 mm	> 225	175 to 225	125 to 175	Indicates optimum bitumen content.
ITS_{wet}	100 mm	> 100	75 to 100	50 to 75	Indicates need for active filler.
TSR	100 mm	N/A			Indicates problem material where TSR < 50 and ITS_{dry} > 400 kPa.
ITS_{equil}	150 mm	> 175	135 to 175	95 to 135	Optimise bitumen content.
ITS_{soaked}	150 mm	> 150	100 to 150	60 to 100	Check value on ITS_{wet}.

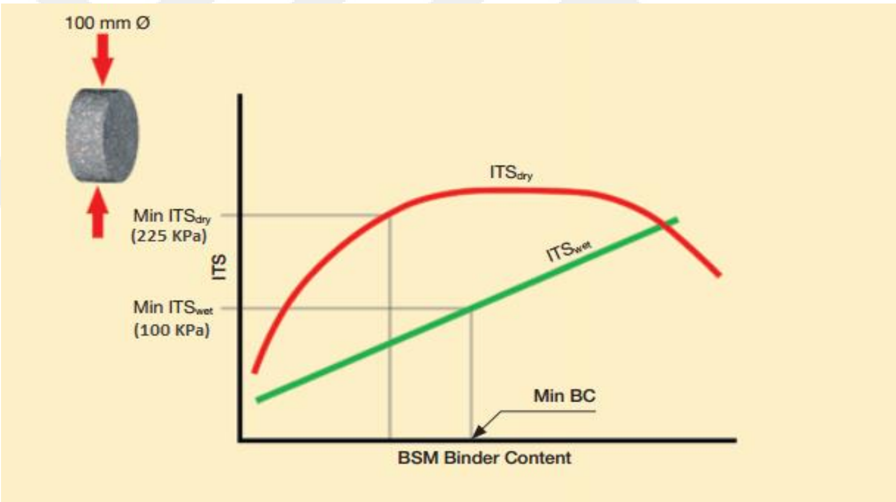

Figure 2.3 Interpretation of minimum binder content for level 1 mix (Cold recycling manual, 2010)

2.4.3 Comparing Foam Bitumen, Bitumen Emulsion and HMA

Foam bitumen and other bituminous binders differ significantly in properties and production process. The treatment process for foam asphalt, BSM-emulsion and hot mix asphalt can be compared according to Table 2.2.

Table 2.2 Summary of comparison of foam bitumen, bitumen emulsion and HMA

Factor	Bitumen Emulsion	Foam Bitumen	Hot Mix Asphalt
Aggregates type applicable	• Crushed rock • Natural gravel • RAP, cold-mix • RAP, stabilized	• Crushed rock • Natural gravel • RAP, stabilised • Marginal (Sands)	• Crushed rock • 0 – 50% RAP
Bitumen temperature during mixing	20 °C -70 °C	170 °C - 190 °C (before foaming)	140 °C - 180 °C
Aggregate temperature during mixing	• Ambient (>10 °C)	• Ambient (>15 °C)	• Hot only (140 °C-200 ° C)
Moisture content during mixing	OMC plus1% minus Emulsion Content	Fluff point i.e. 65% - 85% of OMC	Dry
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 bitumen/ fines mortar	Coating of all aggregate particles with controlled film thickness
Construction and compaction temperature	Ambient	• Ambient • Half-warm mix temperature • Warm mix temp.	140 °C – 160 °C
Air Voids	10 – 15%	7 – 15%	3 – 7 %
Rate of initial strength gain	Slow	Medium	Fast
Modification potential of binder	Yes	?	Yes
Important parameters of binder	• Emulsion type (anionic or cationic) • Residual bitumen • Breaking time • Curing	• Half-life • Expansion ratio • Curing	• Penetration • Softening point • Viscosity

2.4.4 Aggregate Properties

2.4.4.1 Particle Size Distribution

A wide range of aggregates materials is suitable for treatment using foam bitumen. Quality and marginal aggregates can be used to produce foam asphalt. Particle size distribution plays an influential role on stability and strength of foam asphalt mixes. Since foam bitumen is highly effective in binding the fine aggregates particles, many studies and guidelines recommended 5% passing the 0.075 mm (No. 200) sieve as the minimum requirements (Figure 2.4). Insufficient amount of fine aggregates in a mix results to improper dispersion of foam bitumen and bitumen rich agglomerations are formed.

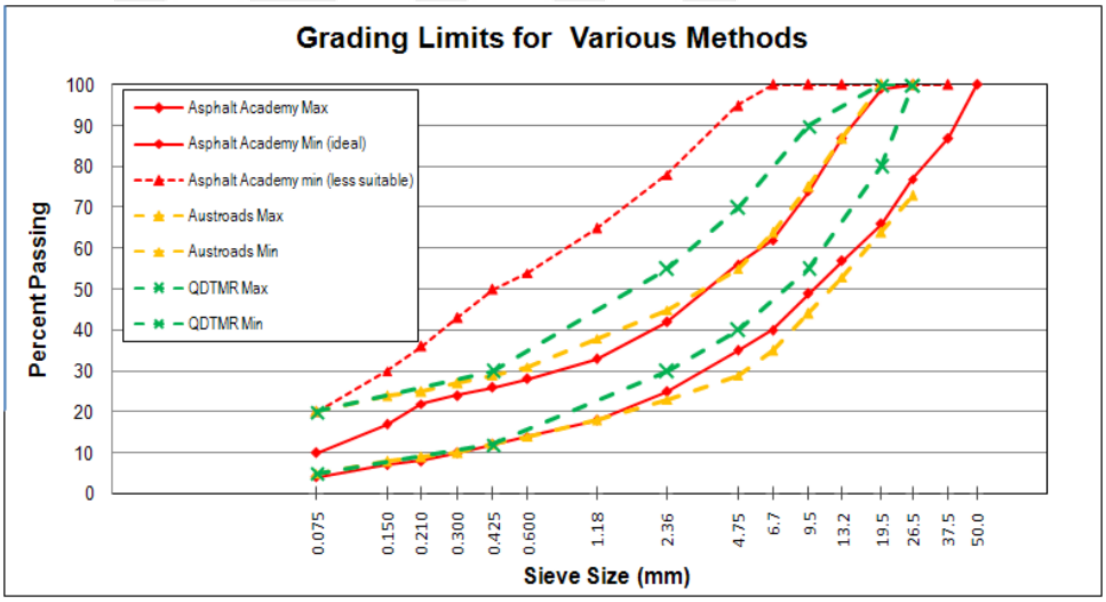

Figure 2.4 Grading limits for various methods (Austroads, 2011)

Sakr and Manke (1985) had concluded in a study that higher percentages of fine aggregates in foam asphalt mixtures increases stabilities, and Semmelink (1991) in a similar trend showed that the percentages of fine aggregates in foam-stabilized sands significantly influence workability, strength and stability.

However, various technical standards and guidelines such as TMR, Austroads, Asphalt Academy and cold recycle manual recommended addition of lime, cement and other similar material to improve the gradation of aggregates with fines deficiency.

CSIR Transportek (1998) recommended that, aggregate materials that had fallen outside the grading envelope might be stabilized but extreme care should be taken. It can be said that both Asphalt Academy TG2 and Austroads recommended slightly coarser grading envelope than the Transportation and Main Roads guideline (TMR). The critical role being played by fine aggregates in foam asphalt made many guidelines and methods to require a minimum 5% passing the 0.075 mm sieve (see Figure 2.4). The mixture of foam bitumen and fine aggregates forms a mastic with higher viscosity that binds together the coarser aggregates particles. According to Asphalt Academy TG2 (2009), the grading envelope shown in Figure 2.4 is a grading for very low trafficked roads because the grading limits are closer to that of coarser sand. However, Austroads (2011) recommended rectification by adding the deficient fractions of materials that felt outside the grading limits.

Cold recycling manual (2004) had shown a unique relationship for achieving the minimum voids and the best particle packing in equation (2.1). This relationship is useful as it provides flexibility with the filler content of a mixture. A value of n = 0.45 is utilized to achieve the minimum voids.

$$P = \frac{(100-F)(d^n - 0.075^n)}{(D^n - 0.075^n)} + F \tag{2.1}$$

Where: d = selected sieve size (mm)

P = percentage by mass passing a sieve of size d (mm)

D = maximum aggregate size (mm)

F = percentage filler content (inert and active)

n = variable dependent on aggregate packing characteristics (0.45)

The particle size distribution according to the various methods for heavily trafficked bases is summarized as shown in Table 2.3.

Table 2.3 Aggregates grading envelope according to various methods (Austroads, 2011)

Sieve size (mm)	Percentage passing			
	Austroads Part 4D	TMR	TG2	Proposed for base with > 1000 ESA/day
26.5	73–100	100	77–100	100
19.5	64–100	80–100	66–99	80–100
9.5	44–75	55–90	49–74	55–90
4.75	29–55	40–70	35–56	40–70
2.36	23–45	30–55	25–42	30–55
1.18	18–38		18–33	22–45
0.600	14–31		14–28	16–35
0.425		12–30	12–26	12–30
0.300	10–27		10–24	10–24
0.150	8–24		7–17	8–19
0.075	5–20	5–20	4–10	5–15

2.4.4.2 Aggregate Plasticity

According to Austroads (2011), plasticity limits is one of the criteria that assist in determination of aggregates suitability for stabilization, and determination of the type and application rate of additive (cement or lime). A Plasticity Index (PI) of 10 is recommended by TMR as the maximum. TMR outlined the importance of lime in foam asphalt as follows:

- Agglomeration and flocculation of clay fines in foam asphalt,
- Stiffening the foam bitumen,
- act as an anti-stripping agent,
- assisting in dispersion of bitumen throughout the mix, and
- improving initial stiffness and early rut resistance.

The use of 1.5 to 2.0% of hydrated lime in foam asphalt mixes is common in TMR (Ramanujam et al., 2009). Austroads (2006) stated that PI of 10 or less is an indication of materials suitability for stabilization; but above this level, pre-treated with lime is required.

In a similar way, Asphalt Academy (2009a) also recommended that, lime should be used for treatment of materials having plasticity index above 10 but the Academy limited percentage usage of hydrated lime to be 1.5%.

2.4.4.3 Angularity of Aggregates

Ali and Burak (2004), in a study on determination of fine aggregate angularity in relation with the resistance to rutting of hot-mix asphalt concluded that the more aggregate angularity the less susceptible to rutting of HMA. This is because angular aggregate particles compared to rounded aggregate particles create more particle to particle interlock.

Compared to HMA, aggregate angularity and interlock play a greater role than the viscosity of the binder in foam asphalt mixture. Since fine aggregates content is a critical criterion in foam asphalt, fine aggregates angularity becomes the appropriate indicator of suitability for foam bitumen treatment (Austroads, 2011).

Sakr and Manke (1985) in a study found that stability in foam asphalt mixtures are greatly affected by interlock of aggregates particles than by the binder viscosity, which differs from that of HMA. CSIR Transportek, (1998) recommended that 10 should the minimum value for particle index (ASTM D3398, 2006). Leek (2010) later in a study concluded that low angularity of aggregates caused shear failure in early-life shear of some pavements in Western Australia treated using foam bitumen.

2.4.4.4 Aggregate Durability

Durability can be defined as that the measure of resistance which aggregates particles show to maintain their mechanical properties, shape and size during service life. Alternatively, durability is the measure of weathering and abrasion resistance of a material against environmental factors during service life. Durability in the long term exhibits the deterioration in performance of materials.

Aggregates durability can be measured by physical and mechanical properties test procedures such as Los Angeles value, wet/dry strength variation and soundness tests etc. However, it is important to note the individual test limits to assure performance of the materials during construction and in-service life. The mechanical properties of aggregates including stiffness, shear strength and permanent deformation is affected by the construction factors and hence their long-term performance.

2.4.5 Secondary Binders

Austroads (2011) described the moisture dependency of the strength characteristics of foam asphalt mixtures as high. Lime treatment might be required for some materials types in the existing aged pavement to enable satisfactory performance. This may result from the used of low foam bitumen contents resulting in to high air void contents in the foam asphalt mixtures. To minimize moisture susceptibility of FAM, the use of additives such as lime is recommended.

CSIR Transportek (1998) found that cement can play similar role as lime, however, the used of hydrated lime is more common than cement in Australia because hydrated lime is cheaper. Jenkins (2008) outlined that secondary binder (additives) are used for the following purposes:

- stabilisation of foam bitumen in order to gain cementitious bonds and early strengths,
- modifier to reduce plasticity,
- dispersion of foam bitumen, and
- anti-stripping agent.

Austroads (2011) reviewed various foam bitumen mix design guidelines and method on the use of secondary binders and outlined that:

- Asphalt Academy TG2 – recommended zero to 1% cement and zero to 1.5% hydrated lime.

- TMR – recommended 1.5% hydrated lime where PI < 6% and 2% hydrated lime where PI > 6%.
- City of Canning – initially recommended 1.5% quicklime but significant transverse cracking was observed, as a result 0.8% quicklime being used causing no cracks.

2.4.6 Moisture Conditions

As explained in the previous sections, moisture conditions in foam asphalt mixing and compaction is very important criteria of the mix design. Thus, special attention needs to be given to foaming water contents and aggregates mixing moisture content. Ruckel et al. (1982) recommended that in preparation of trial mixes, moisture-density relationship should be well studied. At low temperature, workability of foam asphalt is highly affected by insufficient amount of water causing inadequate dispersion of foam bitumen. On the contrary, density and strength of foam asphalt mixtures might be reduced due to the use of too much water, and specimens curing time will be increased.

CSIR Transportek (1998) reported that foam asphalt mix properties such as air voids, density, strength, swelling and water absorption are being optimized at varying moisture conditions. Therefore, it is critical to consider the importance of moisture during mixing and compaction to achieve optimum properties of FAM. It is also important to note that foaming water content is different from moisture content required for mixing and compaction in FAM.

2.4.6.1 Optimum Moisture Content (OMC)

Asphalt Academy TG2 (2009) recommends that, the optimum moisture content of each different type of aggregate should be determined by Proctor test according to ASTM D-698 or ASTM D-15557. This quantity of moisture represents the desired amount of total fluid content required to achieve the optimum compaction of the mix. ("Total fluid content" is the mixing water plus the foam bitumen of the mix). Trial mixes should be made to evaluate the density and stability of specimens prepared at different levels of fluid content such as lower and greater amounts of the OMC from the aggregate being used.

2.4.6.2 Fluff Point Moisture Content

Asphalt Academy TG2 (2009) stated that maximum loose volume is occupied by material at a certain moisture content known as the "fluff point". Asphalt Academy TG2 (2009) further explained that for blending of aggregates with foam bitumen the ideal moisture content is the fluff point. The optimum mixing moisture content during foam asphalt mixing is taken as 65 to 85% of the optimum moisture content (OMC) using modified AASHTO compaction according to Asphalt Academy TG2 (2009) and Cold Recycling Technology (2010). Asphalt Academy TG2 (2009) is also considering the fluff point as the minimum aggregates mixing moisture content.

2.4.6.3 Foaming Water Content

To assess the foaming properties of the bitumen, expansion ratio and half-life of foam bitumen is measured after producing foam bitumen at varying foaming water contents (1 – 4% at 0.5% increments). Bitumen temperature is normally maintained between 170 ^oC and 190 ^oC before injecting cold water.

Asphalt Academy TG2 (2009) stated that, foaming water content is one of the dominant factors with great influence on the foam bitumen properties (see Figure 2.5). It can be clearly observed from Figure 2.5 that, increasing foaming water content generates more expansion of the foam bitumen, but resulting to a rapid decay, i.e. decreasing the half-life.

The two most important factors determining the quality of foam bitumen are bitumen temperature and foaming water content. At higher temperature of bitumen, the quality of bitumen foaming is improved. To determine the temperature of bitumen for foaming, Asphalt Academy TG2 (2009) recommended a sensitivity analysis in the laboratory. Note that attention should be given to bitumen temperature limits to avoid damaging the bitumen.

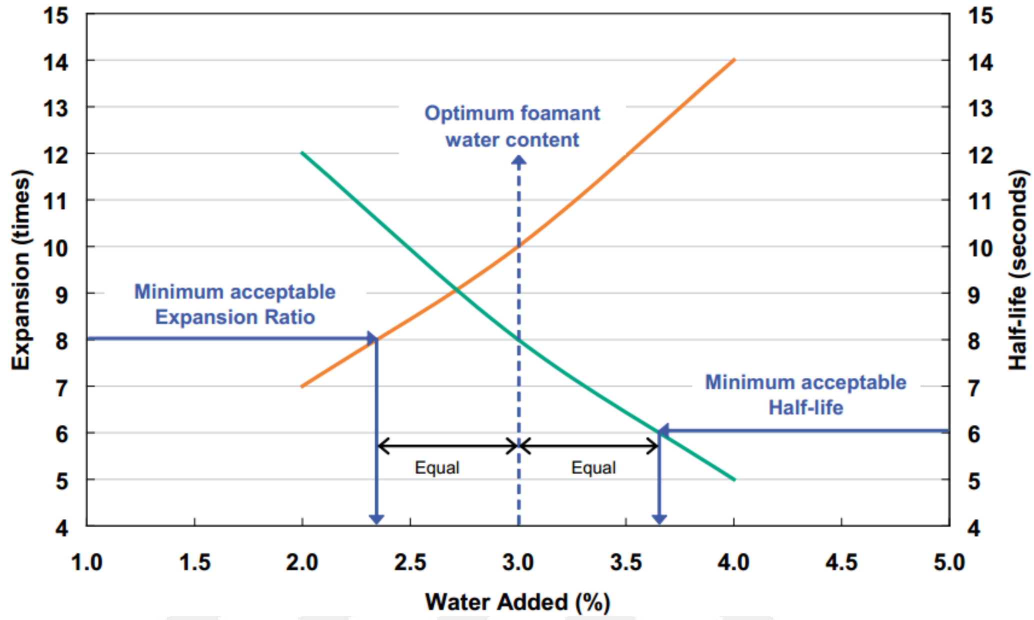

Figure 2.5 Determination of Optimum Foamant Water Content (Asphalt Academy TG2, 2009)

The optimum foaming water content is determined in a manner that both the minimum specified expansion ratio and half - life are met. Table 2.3 shows summary of minimum values of expansion ratio and half-life according to various guidelines and methods.

Table 2.4 Minimum expansion ratio and half-life (Austroads, 2011)

Source	Minimum expansion ratio	Minimum half-life
Austroads Guide to Pavement Technology Part 4D (2006)	15	30–45 seconds
TMR Ramanujam and Jones (2008), Ramanujam et al. (2009)	Recommended limit: 12 Absolute limit: 10	Recommended limit: 45 Absolute limit: 20
South African Asphalt Academy TG2 (2009)	Temp 10–25 °C: 10 Temp > 25 °C: 8	6

2.4.6.4 Water Quality

Austroads (2011) outlined the importance of the quality of the water being used in production of foam bitumen to ensure reliability of mix quality. Acceptable foam bitumen properties might be possible to achieve by the use of impure water but this practice may lead to dislodging and blocking the pipes through which water is being injected in to hot bitumen during foaming process.

2.4.7 Compaction

Compaction of specimens is an important parameter of the mix design as it reduces the air voids content in the mix and improves aggregates particle contact and interlocking. The performance of the pavement is significantly influenced by density achieved during compaction. Furthermore, compaction is critical in improving adhesion and cohesion between the foam bitumen mastic and the aggregates particles. Various methods and guidelines recommended different methods and equipment for compaction of foam asphalt mix. These can be summarized as follows:

Austroads Guide Part 4D recommended two methods of specimen compaction:

- Marshall hammer applying 50 blows to each face
- Gyratory compaction (80 cycles).

The Marshall method of Compaction has been widely used in compaction of foam asphalt mix as such it is being used in the TMR method.

Asphalt Academy TG2 (2009) recommend the use of vibratory hammer compaction because it simulates field compaction and achieves expected field density. Modified AASHTO compaction had been associated with problems like delamination within the specimen, not simulating field compaction. Thus, Vibratory hammer compaction is preferred. However, Asphalt Academy TG2 (2009) specified that Marshall Compactor can be used when vibratory hammer compactor is not available in compaction of Level 1 specimens (100 mm diameter).

2.4.8 Curing Conditions

Curing is the process by which compacted foam asphalt material or specimen discharges water through evaporation. The curing process results in reduction of moisture content that leads to early strength gain and increases rut resistance.
Laboratory curing conditions is an accelerated method aim to simulate the field curing conditions because it is impractical to cure for months as in the field. Many methods and studies have shown that laboratory curing of specimens at 40° C for 72 hours has produced optimum results (Figure 2.6).

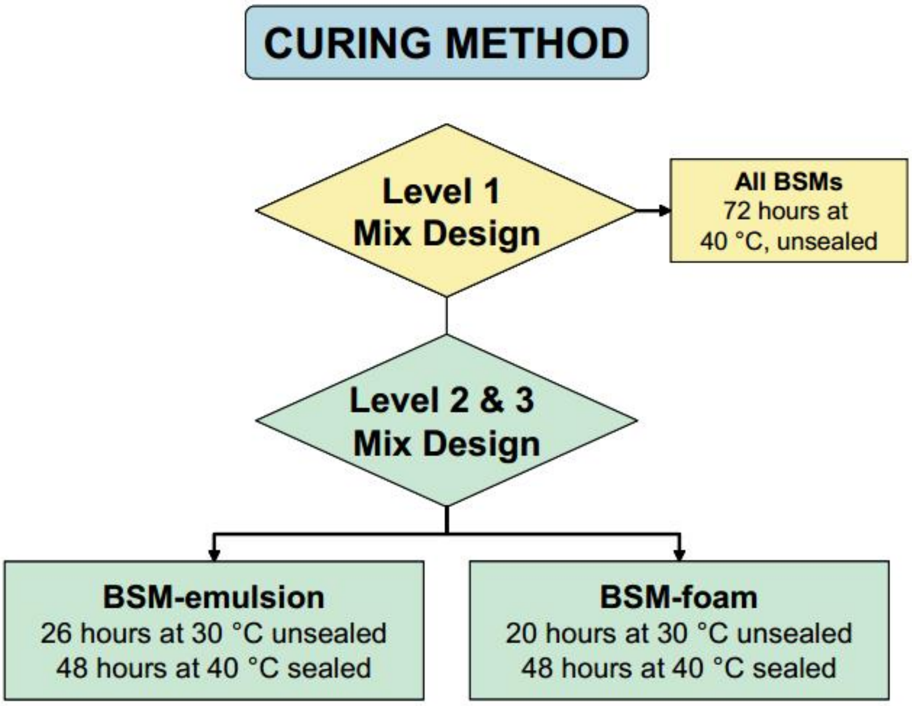

Figure 2.6 Curing methods in various levels of mix design (Asphalt Academy TG2, 2009)

The mix design procedure for the foam asphalt mix can be summarized as shown in Figure 2.7.

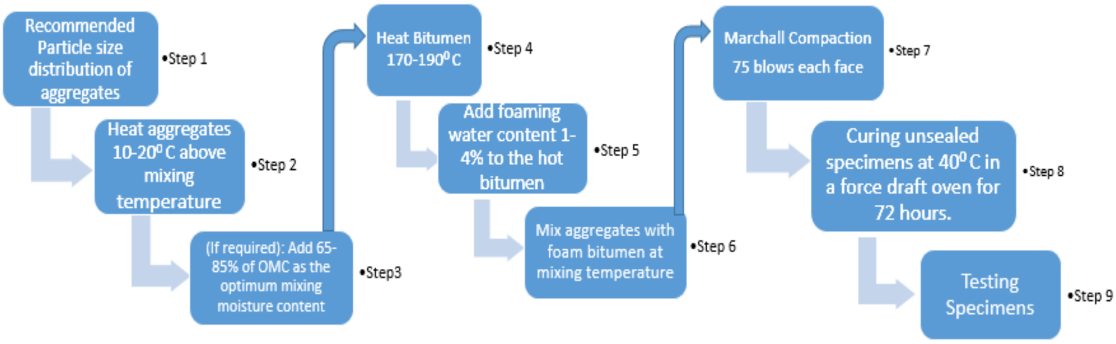

Figure 2.7 Laboratory mix design procedure of foam asphalt mix

2.5 Mechanical Test Methods

2.5.1 Indirect Tensile Strength Test

As described earlier, ITS provides a measure of foam asphalt tensile strength and flexibility in reflecting the flexural properties of the mix according to Asphalt Academy TG2 (2009). Indirect tensile strength test is also being used extensively in the pavement industry partly because it is an economical method for investigation.

Generally, the standard ITS test is used to test the briquettes under both dry and wet conditions. The ITS is determined by measuring the ultimate load to failure of a specimen which is subjected to a constant deformation rate of 50.8 mm/minute on its diametrical axis according to ASTM D6931. The ITS for each specimen to the nearest 1 kPa is determined using the following formula:

$$ITS = \frac{2000*P}{\pi*h_{ave}*d} \tag{2.2}$$

Where:

ITS = Indirect Tensile Strength in kPa

P = maximum applied load in N

h_{ave} = average height of the specimen in mm to one decimal place

d = diameter of the specimen in mm to one decimal place

The tensile strength ratio (TSR) for each set of specimens is determined using the following formula:

$$TSR = \frac{ITS_{wet}}{ITS_{dry}} * 100\% \tag{2.3}$$

Where ITS_{wet} = average ITS of all wet specimens in the set

ITS_{dry} = average ITS of all dry specimens in the set

2.5.2 Triaxial Test

Austroads (2011) stated that friction angle values and cohesion is being measured using a simple triaxial test (STT). An indication of material resilient response is provided by the monotonic stiffness of the material and tangent modulus (Etan). However, according to Asphalt Academy TG2 (2009), the resilient modulus is not directly measured by the tangent modulus. Advanced triaxial setups may also be used for testing. To classify bituminous stabilized materials (BSMs) according to Asphalt Academy TG2 (2009) and Cold Recycling Technology (2010), tangent modulus, cohesion, and friction angle are used. The specified limits used for classification of BSMs are shown in Table 2.5.

Table 2.5 Interpretation of triaxial tests (Asphalt Academy, 2009)

Test or Indicator	**BSM1**	**BSM2**	**BSM3**
Cohesion (kPa)	> 250	100 to 250	50 to 100
Friction Angle (^{o})	> 40	30 to 40	< 30
Retained Cohesion (MIST)	> 75	60 to 75	50 to 60

2.5.3 Moisture Induced Sensitivity Test

Austroads (2011) outlined that, the apparatus used for moisture induced sensitivity test (MIST) is used to conditioned triaxial specimens. At realistic pore pressures, MIST applies cyclic moisture ingress. Retained cohesion percentage for BSM is provided by comparing cohesion values of specimens with and without moisture exposure according to Asphalt Academy TG2 (2009). These values assist in the classification of the mix as shown in Table 2.5.

2.6 Engineering Properties of Foam Asphalt

CSIR Transportek (1998) reported that, optimization of foam asphalt mix strength properties including CBR, stability and resilient modulus occurred at a particular intermediate foam bitumen content according to previous studies. In addition, the treatment of materials using foam bitumen is expected to improve fatigue resistance and cohesion, and decrease moisture susceptibility of the untreated granular materials. The physical and mechanical properties of foam asphalt mixes are important parameters in determining the suitability of foam asphalt mixtures in service life. These properties include:

2.6.1 Moisture Susceptibility

According to Cold Recycling Technology (2010), moisture susceptibility is the damage to pavements resulting from environmental factors such as pore-water pressures and high moisture under traffic loads. Moisture susceptibility results in loss of adhesion between the binder and aggregate particles. The high air void content and partially coated nature of large aggregates make moisture susceptibility an important criterion in the performance evaluation of foam asphalt mixtures.

Muthen (1998) in a study on foam asphalt mix design procedure stated that, due to the relatively low foam bitumen contents and high air void contents in foam asphalt mixtures (FAM) the strength characteristics of FAM are highly moisture-dependent. While in earlier studies, Castedo Franco et al (1983) found that moisture susceptibility of FAM could be decreased considerably by the use of additives (lime) during mixing. Lewis (1998) also confirmed that cement could be use as additives due to its effectiveness as lime and economical. Higher foam bitumen contents can also be applied to decrease moisture susceptibility in foam asphalt mixtures. This is due to the higher densities achieved; lower air voids content and increased coating of the moisture-sensitive fines with binder.

Cold recycling manual (2010) recommended that moisture resistance be enhanced by:

- Increased bitumen content, bearing in mind the cost implications.
- Addition of active filler, usually limited to 1% by mass of dry aggregate.
- Improved compaction.
- Smooth continuous grading.

2.6.2 Temperature Susceptibility

Bissada (1987) in a study concluded that, foam asphalt mixes at temperatures above 30 °C had higher moduli than HMA mixes after 21 days'curing at ambient temperatures. The incomplete coating of large aggregate particles by foam bitumen maintains the friction between the aggregates particles at higher temperatures. However, Muthen (1998) stated that, the viscosity and stability of the bitumen-fines mastic would reduce at high temperatures, as such, strength is lost.

2.6.3 Tensile Strength and Unconfined Compressive Strength (UCS)

Marek and Anna (2013) conducted a laboratory study on mechanical parameters of foamed bitumen mixtures in the cold recycling technology, concluded that the increase in content of the binding agents (foamed bitumen, Portland cement) in recycled materials leads to obtaining tensile strength retained (TSR) at the higher level.

In an earlier study, Bowering and Martin (1976) suggested that in practice the UCS of foam asphalt mixtures (FAM) usually between 1.8 MPa to 5.4 MPa and tensile strengths of FAM is between 0.2 MPa to 0.55 MPa, depending on environmental conditions such as moisture. Furthermore, they also found that foam asphalt mixtures had strength properties that could be greater than those of materials treated using bitumen emulsion at higher foam bitumen contents.

Both Asphalt Academy TG2 (2009) and Cold Recycling Technology (2010) recommended that, for good performance foam asphalt after 72 hours of curing should have minimum ITS_{wet} and ITS_{dry} of 100 kPa and 225 kPa respectively. Van Wijk and Wood (1983) found that specimen curing significantly influences strength of FAM.

2.6.4 Stiffness and Resilient Modulus

Sunarjono (2007) studied tensile strength and stiffness modulus of foam asphalt material concluded that, the initial strength and stiffness modulus of foamed asphalt material are low; however, these properties improve significantly during curing period. The increasing strength and stiffness of specimens is mostly caused by loss of moisture.

Fu et al (2009) conducted a study on laboratory test methods for foamed asphalt mix resilient modulus and concluded that, foamed asphalt transformed the material behavior from that of typical unbound granular materials to that of partially asphalt-bound materials, without significantly increasing the resilient modulus values.

Marek and Anna (2013) in a laboratory study on mechanical parameters of foamed bitumen mixtures in the cold recycling technology concluded that, the foamed bitumen and Portland cement contents in the mixes have a significant influence on the changes of the resilient modulus at 25 °C; the values of MR increased when the bitumen binder and hydraulic binder content increased.

Ramanujam and Fernando (1997) in a study concluded that, the stiffness of foam asphalt mixtures can be compared to those of cement-treated materials, yet foam asphalt mixtures have the added advantages of flexibility and fatigue resistance.

2.6.5 Abrasion Resistance

Muthen (1998) in a study stated that, Foam asphalt mixes are not suitable for wearing/friction course applications due to the lack of resistance to abrasion and raveling.

2.6.6 Density and Volumetric

Generally, increase in foam bitumen content increases the density of a mix while air voids decrease to the minimum. The strength and density of foam asphalt mixtures are largely interdependent and directly proportional in relation to each other.

2.6.7 Fatigue Resistance

One of the important factor in determination of the structural capacity of foam asphalt pavement is the fatigue resistance. The mechanical properties of Foam asphalt mixtures are comparable to ones of cemented materials. Sunarjono (2012) investigated the fatigue performance of foam asphalt specimens and found that fatigue life of foam asphalt is shorter as compared to that of hot mix asphalt.

Moreover, in earlier studies Bissada (1987) considered that the fatigue properties of foam asphalt to be inferior to those of HMA. Little et al (1983) in a similar trend found that some foam asphalt mixtures showed fatigue resistance lower as compared to conventional hot mix asphalt.

2.7 Construction Process of Foam Asphalt

Raffaelli (2004) outlined that the foamed asphalt process rebuilds the pavement from the bottom up, and can eliminate symptomatic problems associated with the existing roadbed, such as reflective cracking and shallow base failure. Compared to cemented materials, foam asphalt is more fatigue resistant and flexible; aggregates of various qualities can be treated using foam bitumen compared to other treatment agents and it has strength characteristics approaching those of cemented materials. Foam bitumen decreases the moisture susceptibility and increases the shear strength of granular materials.

Production of foam asphalt at low temperature considerably improves the pavement-working conditions. Raffaelli (2004) further explained that with foam asphalt, paving and compaction is achievable at lower temperatures as compared to hot mix asphalt. Foam bitumen is produced in the field and then mix with the aggregates while still in a foam state to produce a FAM. Better dispersion of foam bitumen on aggregates is achievable at high volumes of foam bitumen. Foam bitumen bubbles burst during the mixing process with aggregates; this generates thousands of tiny bitumen sufficient to bind the fine aggregates particles. The binder-fines mastic then acts as mortar to weld the coarse aggregate particles together under compaction effort.

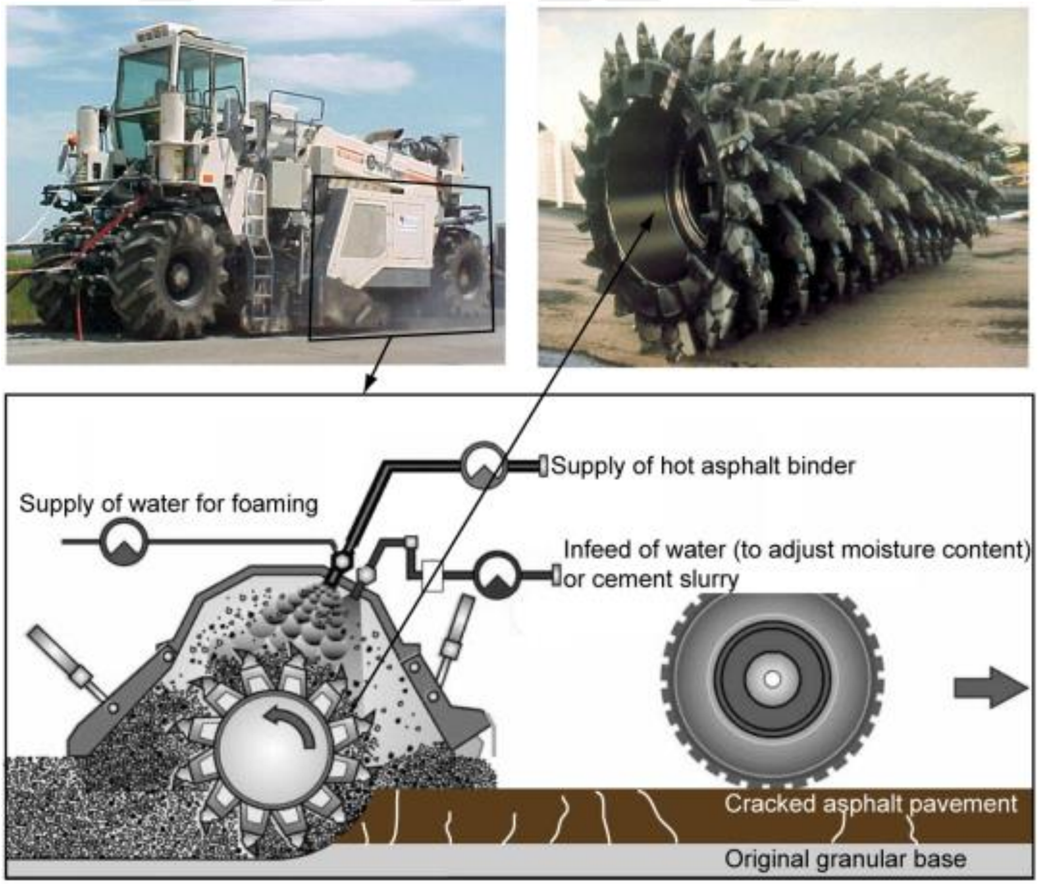

Figure 2.8 Production of foamed asphalt in the field (Fu, 2009)

Raffaelli (2004) stated that while the bitumen foaming action may take less than 15 seconds, after being mixed with aggregates foam asphalt remains workable for long enough to complete compacting, grading and finish-rolling. A wide range of aggregates may include pulverized material from the existing roadway, soils, additional processed or native aggregates, or additives such as cement or fly ash are workable in FAM. Foam asphalt recycling equipment is usually run in a “train” with one piece of equipment closely following the next (Figure 2.8). For example, the recycling or mixing machine can be coupled with an asphalt supply tanker and a water cart.

The recycler propels the tanker in front and pulls the water cart behind. Typically, the foam asphalt is compacted with a sheepsfoot roller, then rough graded, compacted with a smooth, steel-drum roller, then fine graded, and finally finished by pneumatic rubber tire roller. Often a roadway can be recycled and reconstructed at a rate of one to two lane miles per day, and the finished pavement can be opened to traffic within a few hours of production. A chip seal or hot mix overlay can be placed within two days (Raffaelli, 2004).

2.8 Action of Foam Bitumen

Materials treated with foam bitumen do not exhibit black color as with hot-mix asphalt (see Figure 2.9). This is due to the partial coating of large aggregate particles by foam bitumen. When foamed bitumen comes into contact with aggregate, the bitumen bubbles burst into millions of tiny bitumen droplets that seek out and adhere to the fine particles, specifically the fraction smaller than 0.075 mm.

The bitumen droplets can exchange heat only with the filler fraction and still have sufficiently low viscosity to coat the particles. The foam asphalt color results from action of bitumen bound filler that acts as a mortar between the coarse particles. There is therefore only a slight darkening in the color of the material after treatment. The addition of cement, lime or other such fine cementitious material (100 % passing the

0.075 mm sieve) assists the bitumen to disperse, in particular where the recycled material is deficient in fines.

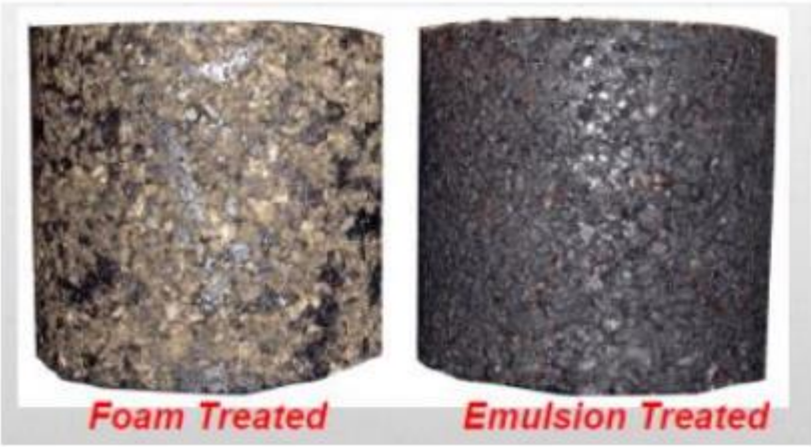

Figure 2.9 Foamed bitumen dispersion and binding in the treated mix

2.8.1 Particle Coating

Jenkins et al. (2000) stated that the mixing technique of conventional (cold) foamed asphalt mixes is very important as the thermal gradient between the aggregate at for example 20 ^{o}C and the foam bitumen at about 110 ^{o}C, is high. They further explained that the viscosity of the bitumen increases rapidly upon contact with the cold aggregate, as the thin films of bitumen make contact with the stone particles during mixing. This is particularly relevant as the mass of aggregate is usually some 20 times that of the binder. The equilibrium temperature of a cold mix immediately after mixing is commonly less than 10 ^{o}C higher than the original aggregate temperature.

Jenkins et al., (2000) outlined that the aggregate temperature thus has the dominant effect. The equilibrium temperature is, therefore, usually below the binder softening point. Therefore, only the time for thermal conductivity from bitumen to aggregate is available for mixing. Dispersion of the foam bitumen in the mix and suitable aggregate coating are appreciably dependent on the mixing energy and technique used. Two foam asphalt mixtures with the same aggregate- and binder-type and content can have appreciably different properties, depending on the manufacturing technique.

Aggregates particles in foam asphalt mix compared to hot mix asphalt are partially coated (see Figure 2.10).

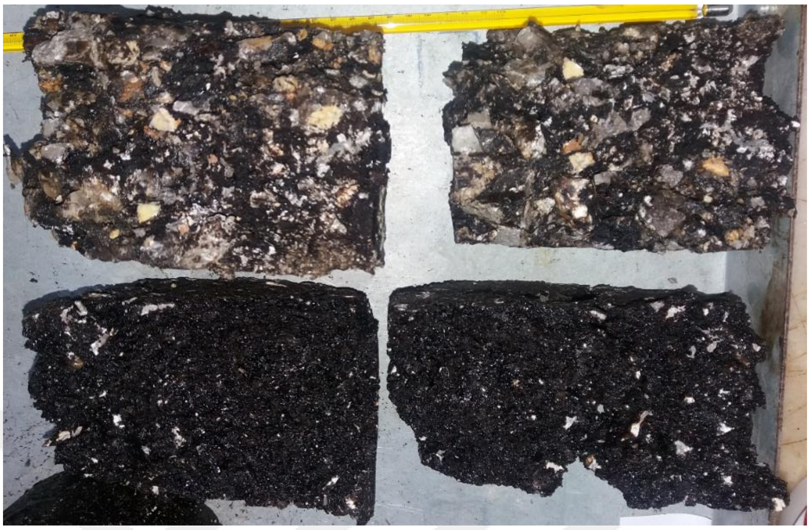

Figure 2.10 Aggregate particles coating in foam asphalt and hot mix asphalt Marshall Specimens

In the case of half-warm foam asphalt mixes, the equilibrium temperature is appreciably higher, i.e. more time is available for foam bitumen dispersion during mixing. Nevertheless, the effective mixing time remains measurable in seconds rather than minutes. As a result, the mixing-moisture content, -time and -method now become the important variables.

Jenkins et al. (2000) used magnification techniques to observe variations in foam bitumen dispersion with different temperatures of aggregate at mixing for a continuously and semi-gap graded material with a maximum particle size of 26.5 mm. Analytically, the observed improvements in foam bitumen dispersion were evaluated and quantified to classify aggregates coating. Thus, aggregates particles coating was categorized into three groups as follows (see Figure 2.11):

1. Practically uncoated particles, with less than 20% binder coverage.
2. Partially coated particles, with 21–99% coverage; and
3. Completely coated particles, with 100% coverage.

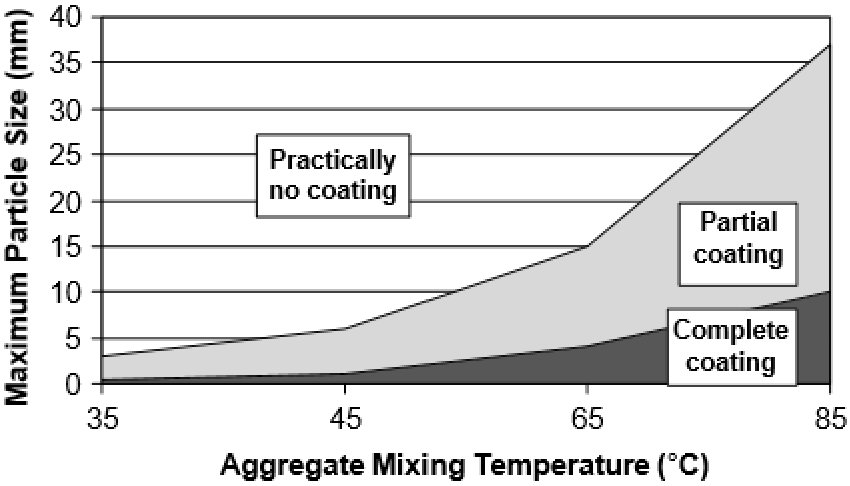

Figure 2.11 Effect of aggregate temperature on particle coating for a continuously graded material mixed with foamed bitumen (Jenkins et al. 1999)

Table 2.6 Summary of foam asphalt mix design procedure according to various methods

Standard / **Factor**	**South African Asphalt Academy Technical Guidelines 2 (2009a)**	**Austroads Guide to Pavement Technology Part 4D (2006)**	**Queensland Department of Transport and Main Roads (TMR), Ramanujam and Jones (2008)**
Treatment Agent	Foam Bitumen	Foam Bitumen	Foam Bitumen
Additives	* When cement is used as the active filler in BSMs, the cement content should be limited to 1% or less. * When using hydrated lime, the application rate may be increased to 1.5% or more where the lime is required to modify plasticity.	* Recommends 1% lime or 2% cement when supplementary binder is required.	* 2.0% lime for PI ≥ 6% up to the maximum PI of 10 * 1.5% lime for PI < 6%.

Table 2.6 Summary of foamed asphalt mix design procedure according to various methods (Continue)

Standard / Factor	South African Asphalt Academy Technical Guidelines 2 (2009a)	Austroads Guide to Pavement Technology Part 4D (2006)	Queensland Department of Transport and Main Roads (TMR), Ramanujam and Jones (2008)
Mixing Condition	* Minimum expansion ratios = 8 at aggregate temp. > 25 ºC * Minimum expansion ratios = 10 at aggregate temp. 10-25 ºC * Minimum half-life of 6 seconds irrespective of aggregate temp. * The mixing moisture content is 65% to 85% of OMC as determined by modified AASHTO	* Minimum expansion ratio = 15 * Minimum half-life = 30−45 seconds	* Minimum expansion ratio = 12 * Minimum half-life = 45 seconds * Bitumen temp. 170 - 190 °C * PI < 6% – prepare test samples at 70% Optimum Moisture Content (OMC) of the untreated material using Standard compaction * PI 6−10% – prepare test samples at 70% OMC of the untreated material using Standard compaction or higher
Mix Proportion	* The bitumen content is usually between 1.7% and 2.5%.	* Recommends testing at three bitumen contents, 2%, 3% and 4% bitumen by mass.	* The trial bitumen content is commonly 3%.

Table 2.6 Summary of foamed asphalt mix design procedure according to various methods (Continue)

Standard / Factor	South African Asphalt Academy Technical Guidelines 2 (2009a)	Austroads Guide to Pavement Technology Part 4D (2006)	Queensland Department of Transport and Main Roads (TMR), Ramanujam and Jones (2008)
Curing Method	* Oven curing temperature is 40 °C for 3 days and tested dry after either submerged under water for 24 hours or in a vacuum	* Oven cured at 60 °C for three days and tested dry after either submerged under water for 24 hours or in a vacuum chamber for 10 minutes.	* Oven curing temperature is 40 °C for 3 days and tested dry after either submerged under water for 24 hours or in a vacuum
Experimental Method	* The ITS test is used as an indirect measure of the tensile strength and flexibility of the BSM to reflect the flexural characteristics of the material. * A simple triaxial test (STT) is used to obtain cohesion and friction angle values. * Moisture induced sensitivity test	* Resilient modulus (indirect tensile modulus) of three samples both wet and dry is plotted to determine the binder content at the maximum resilient modulus.	* The design binder content is determined from the indirect tensile modulus results of the trial mixes in accordance with AS2891.13.1.

CHAPTER THREE
EXPERIMENTAL WORK

3.1 Introduction

This chapter presents the discussion about the selected materials (aggregates and asphalt binder), preparation and testing methods, and foam asphalt mix design procedures used in the experimental program of this study. The objectives of the experimental work are to evaluate the influence of foaming water content on foam asphalt specimens by applying Marshall Stability and Indirect Tensile Strength tests. According to the testing methods, the engineering properties of foam asphalt specimens that included; air voids content, density, Marshall Stability, ITS_{dry}, and ITS_{wet}, are measured at varying foaming water contents and levels of mixing temperature.

To meet the objectives of this study, materials including aggregates and asphalt cement were collected and prepared for a comprehensive laboratory investigation. Aggregate materials used in the foam asphalt mix design process during experimental work consisted of both moist and dry aggregates. An experimental approach program was developed for materials and specimen preparation techniques, testing equipment and procedures to achieve the aims of this study. According to the test methods involved, aggregates and bitumen suitability were tested to confirm meeting foam asphalt mix requirements according to Asphalt Academy Technical Guidelines TG2 (2009).

The experimental approach program for this study was divided in to two major parts namely:

- Constituent materials preparatory tests – this section mainly focused on materials preparations including testing suitability of materials to meet minimum acceptable requirements according to foam asphalt mix design procedures.

- Foam asphalt performance tests – this part investigated the influence of foaming water content on foam asphalt mixtures by applying the methodology outlined earlier in chapter one of this study.

Details of the experimental approach program is shown in Table 3.1.

Table 3.1 Experimental approach program

Description	**Material**	**Test**
Constituent Materials Preparatory Tests	Aggregates	Particles size distribution (Sieve Analysis)
		Specific gravity tests (Coarse and fine aggregates)
		Proctor Test (Maximum Dry Density & Optimum Moisture Content)
	Bitumen	Conventional Tests (Penetration Test, Softening Point, Viscosity & RTFOT)
		Bitumen Foamability Tests (Expansion Ratio & Half-life)
Foam Asphalt Performance Tests	Foam Asphalt	Marshall Stability & Density-Voids Analysis
		Indirect Tensile Strength (ITS) Test

After preparation of the materials involved in the experiment work, trial foam asphalt mixes were prepared to determine optimum working conditions for the experimental investigations. During the preparation of trial specimen for the laboratory study, several key issues were encountered regarding foam asphalt mix design. These include appropriate test methods for foamed asphalt, preparation of specimens (mixing moisture content and aggregate temperature), optimum binder content, aggregate gradations (specially amount of fines content), specimen curing, and the interpretation of results. The experimental investigations were carried out after the determination of optimum working conditions to produce foam asphalt specimens.

3.2 Constituents Materials Preparations

3.2.1 Aggregates

A large supply of representative aggregate materials was collected for undertaking the laboratory study. The representative sample of virgin aggregates (limestone) were collected from stockpiles around Izmir and transported to the laboratory to be prepared and used in this study's investigations. The aggregates stockpiles consisted of various aggregate sizes.

3.2.1.1 Particle Size Distribution

For the purpose of this study, the aggregates were then sieved through a set of sieves for gradation. Aggregate materials retained at each sieve size ranging from fillers to 12 mm were contained separately (Figure 3.1).

Figure 3.1 Aggregates particles sieved and separated according to size

The gradation of aggregate materials to be used in the foam asphalt mix was then determined according to Asphalt Academy guidelines (TG2). The details of prepared aggregate particles size distribution are presented in Tables 3.2.

Table 3.2 Particles size distribution according Asphalt Academy guidelines (TG2)

Sieve size	Upper limit	Mid-point	Lower limit
25	100	88.5	77
19.5	99	82.5	66
12	87	77	67
9.5	74	61.5	49
4.75 (No. 4)	56	45.5	35
2.36 (No. 10)	42	33.5	25
0.6 (No. 40)	28	21	14
0.3 (No. 80)	24	17	10
0.075 (No. 200)	10	7.5	5

Aggregate particles retained at 19.5 mm sieve size and above were not used as part of the gradation envelope. Foam bitumen coats and binds the fine particles to form mastic which spot-weld the large aggregate particles together. Thus, in this study, 12 mm sieve size was used as the nominal maximum aggregate particle size of aggregates gradation in preparation of the foam asphalt specimens.

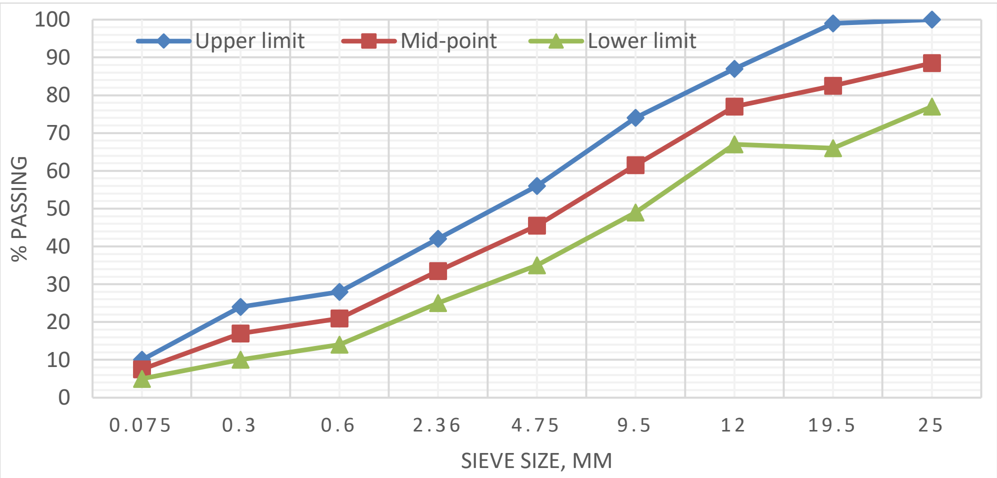

Figure 3.2 Particle size distribution curve

In this study, the mid-point of the gradation envelope as depicted in Figure 3.2 was used as the recommended gradation in the foam asphalt mix design.

3.2.1.2 Specific Gravity Test

Besides gradation, other mechanical properties tests such as specific gravity and Proctor tests were performed. The specific gravity of the coarse and fine aggregates, and fillers were determined using the procedures designated in ASTM C 127 and C 128. Results of specific gravity test are shown in Table 3.3.

Table 3.3 Specific gravity of coarse aggregates, fine aggregates and fillers

Description	**Coarse Aggregate**	**Fine Aggregates**	**Fillers**
Bulk Specific Gravity	2.65	2.652	2.655
Apparent Specific Gravity	2.70	2.688	2.69
Effective Specific Gravity	2.68	2.67	2.6725

3.2.1.3 Proctor Test

Proctor test was conducted to determine the optimum moisture content of the aggregates. The optimum water content and maximum dry density of the representative sample were determined according to AASHTO T180. Prior to mixing the aggregates with foam bitumen, the optimum moisture content (OMC) corresponding to maximum dry density of the representative aggregates (with the recommended gradation) was determined to be 7.2% using Proctor test (see Figure 3.3).

At low mixing temperatures, dry aggregates were to be mixed with optimum mixing moisture content (OMMC) before adding foam bitumen. Optimum mixing moisture content (OMMC) acts as a lubricant in the aggregates; it increases the workability of the mix and results in adequate dispersion of the foam bitumen. Therefore, 75% of the optimum moisture content (fluff point) was found and used as the optimum mixing moisture content (OMMC) in the preparation of foamed asphalt mix.

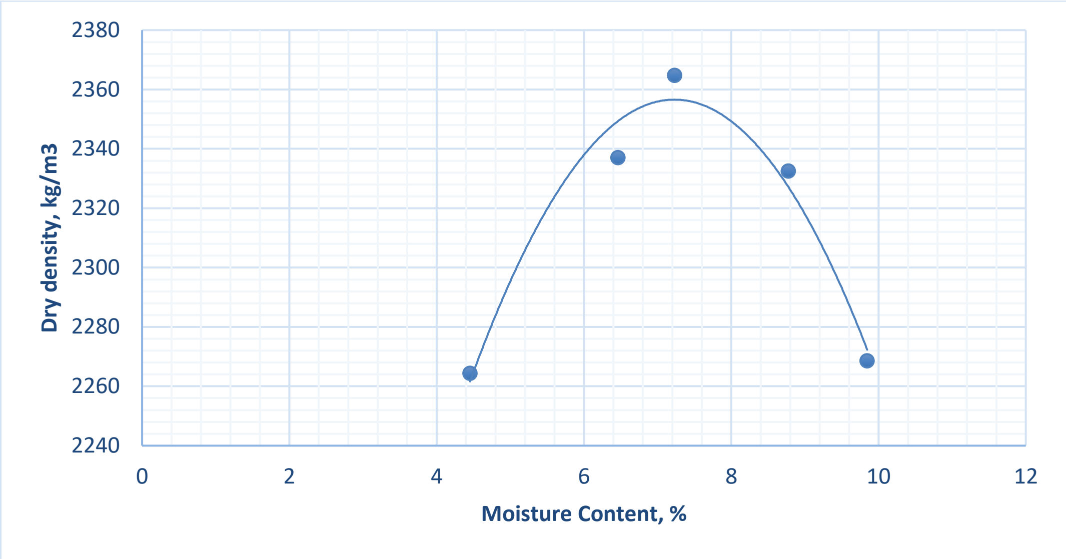

Figure 3.3 Determination of optimum moisture content

3.2.2 *Asphalt Binder*

In this study, asphalt binder (Bitumen) was sourced from a refinery in Izmir and transported to the laboratory to be foamed and used in the experimental investigations. Various conventional bitumen tests were conducted on the bitumen sample. Details of the test results on the binder's basic properties are shown in the Table 3.4. The test results confirmed the suitability of the bitumen's properties to be used in production of foam asphalt specimens for the experimental investigations. The reasons for selecting a particular binder for specific tests were discussed in the relevant sections in the preceding chapter.

Table 3.4 Conventional Bitumen tests results

Description	**Test**	**Result**
Bitumen Basic Properties	Penetration Test at 25 ^{o}C	66 (50/70)
	Viscosity Test at 135 ^{o}C	387.5 cP
	Softening Point Test	53 ^{o}C
	Rolling Thin Film Oven Test	Loss on mass = 0.53%

3.2.3 Foamability Characteristics

In this study, the first step in the experimental work before producing a foam asphalt was testing the suitability of the bitumen foaming potential. Normally, this is being done by quantifying the expansion ratio and half-life of the foamed bitumen in order to select and characterize the optimum foaming properties of the asphalt binder. Expansion ratio is an indicator of how well the foam bitumen will coat the paving materials, while half-life is an indicator of the foam's overall stability. The expansion ratio and half-life of an asphalt binder depends on the chemical constituents of the asphalt, its temperature, and the amount of water used for foaming.

The laboratory foaming process was validated by injecting varying amounts of foaming water content (2 – 4.5% of bitumen weight) in to hot bitumen (185 ^{o}C). The hot bitumen content was maintained same at 50 g at each round of foam bitumen production. Expansion ratio and half-life were measured at each foaming water content increment (0.5% increments) as shown in test results in Table 3.5.

Table 3.5 Expansion ration and half-life test results

Bitumen, (gm)	**Foaming water content (FWC), %**	**Expansion ratio**	**Half-life, (Seconds)**
50	2	3	14
50	2.5	5	13
50	3	6	11
50	3.5	8	9
50	4	9	7
50	4.5	10	6

Graph of measured values of expansion ratio and half-life versus foaming water content was plotted and used according to Asphalt Academy TG2 to determine the optimum foaming water content (OFWC).

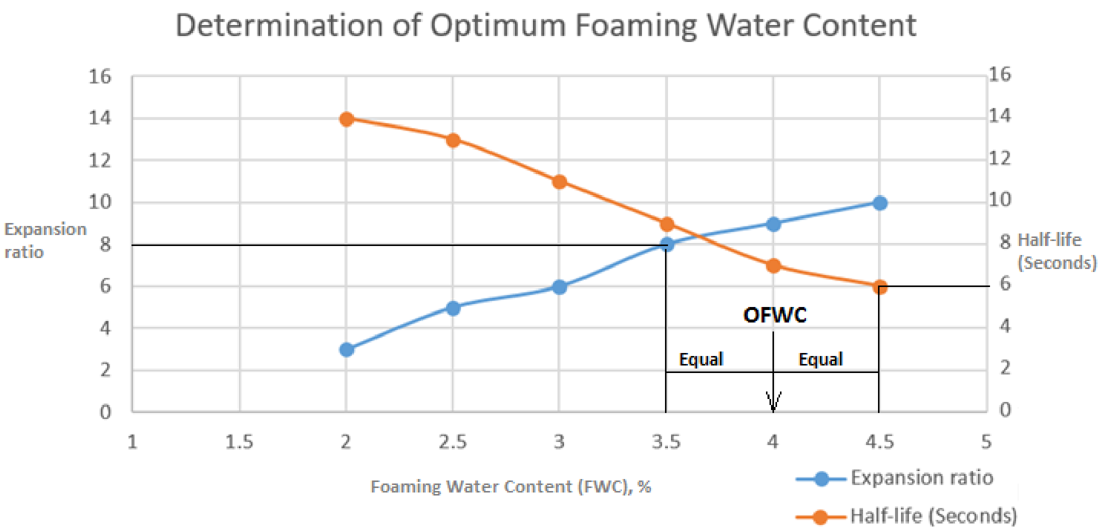

Figure 3.4 Determination of optimum foaming water content

From Figure 3.4, the foaming water content of 4% was found to be the optimum foaming water content (OFWC) in terms of an expansion ratio of 9 and a half-life of 7. It can be visually observed from Figure 3.4 that, the expansion ratio and half-life are inversely related in that, for a given temperature, the expansion ratio increases with increase in amounts of foaming water content, while the half-life decreases with increase in amounts of foaming water content.

3.3 Foam Asphalt Performance Tests

The initial phase of the mix design was carried out as a preliminary preparation to assess, specimen preparation procedures and test methods, foamability characteristics of Izmir asphalt binder, and temperature sensitivity of the foamed asphalt mix. Thereafter, followed some detail laboratory investigations to determine the influence of foaming water content on foam bitumen and foam asphalt mixture at various mixing and compaction temperatures. In this part of the experimental work, the investigation approach was to prepare Marshall Specimens at varying foaming water content using optimum foam bitumen content (OFBC) while maintaining all other parameters at constant conditions.

3.3.1 Optimum Foam Bitumen Content (OFBC)

Following the determination of optimum foaming water content, a laboratory mix design of foam asphalt Marshall Specimens was prepared to determine the optimum foam bitumen content for both dry and moist aggregates to be used in the investigations (Figure 3.5).

In the first round, moist aggregates were mixed with foam bitumen. The PG 50/70 bitumen was foamed and used as the stabilizing agent for the laboratory foam asphalt mix design. In preparation of the test specimens, varying foam bitumen content (4-5% at an increment of 0.5%) were used with the optimum foaming water content remaining at 4%. Marshall compacted foam asphalt specimens at 75 blows (each face) were prepared at mixing temperature of 80 ^oC for Indirect Tensile Strength test. The 101 mm diameter and 63.5 mm high specimens were cured in a force draft oven for 72 hours at 40 ^oC without sealing the specimens until they reach a constant (dry) mass.

Figure 3.5 Foam asphalt specimens after compaction

At room temperature (25 ^oC), Indirect Tensile Strength test (ITS_{dry}) was conducted on the specimens to determine ITS_{dry} values. Thereafter, duplicate of the specimens were then soaked in water for 24 hours at 25 ^oC before testing to determine the ITS_{wet} value. As a result, ITS_{dry}, ITS_{wet} and ITR were determined.

Table 3.6 ITS results to determine optimum foam bitumen content

Binder Content (%)	ITSdry, (kPa)	ITSwet, (kPa)	ITR, %
4	362.05	109.78	30.3
4.5	382.35	197.86	51.7
5	378.48	224.58	59.3

According to Asphalt Academy TG2, as ITS_{dry} and ITS_{wet} values are above minimum requirement 225 kPa and 100 kPa respectively, the ITR test results were plotted in graph as depicted in Figure 3.6 to determine the optimum foam binder content.

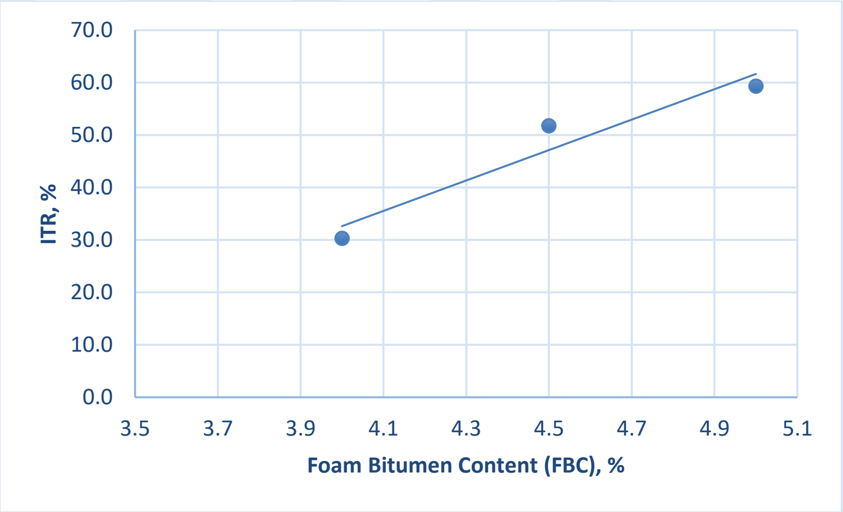

Figure 3.6 Determination of optimum bitumen content using ITS test results

From the graph, the lowest foam bitumen content with ITR > 50% was determined to be the optimum foam binder content. Hence, Foamed bitumen content of 4.5% was selected as the optimum foam binder content.

In the second round, dry aggregates were mixed with foam bitumen to determine the optimum binder content at 120 ^{o}C mixing temperature. Marshall Specimens were prepared following the same procedures used in the first round of the mix design. After

3 days at 40 °C of curing, the specimens were prepared and tested for Marshall Stability and density-voids analysis. Test results are shown in Table 3.7.

Table 3.7 Marshall Stability test results to determine optimum foam bitumen content

FBC, %	FWC, %	Unit Weight, gm/cm3	Air Voids Va, %	Stability, kgf	Flow, mm
3.5	4	2.38	6.90	883	2.82
4	4	2.42	4.65	960	3.30
4.5	4	2.42	3.68	1153	3.75

A relation between foam bitumen content and air voids was plotted in a graph to determine the optimum foam bitumen content at 4% air voids content. From the Figure 3.7, at 4% air voids content the optimum foam bitumen content was determined to be 4.3%.

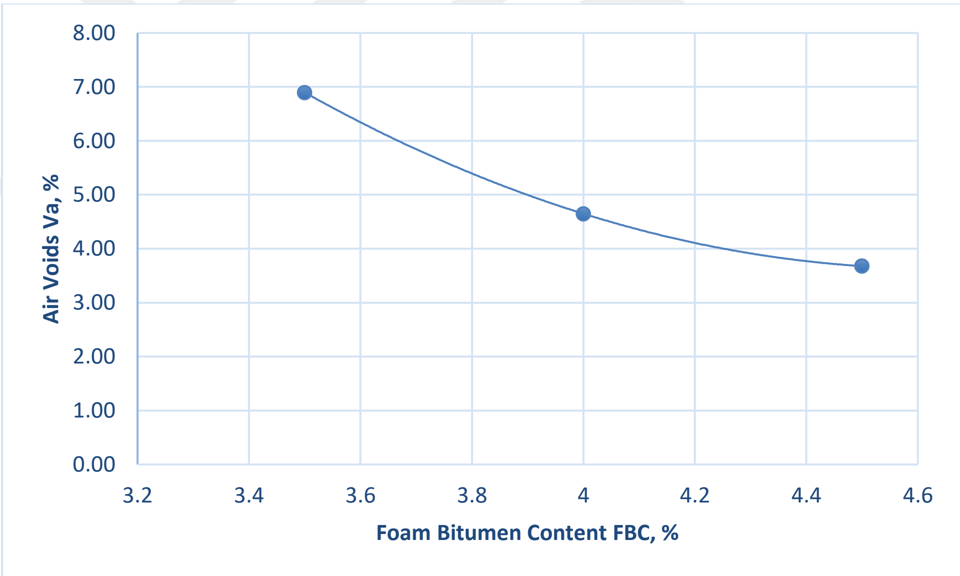

Figure 3.7 Determination of optimum foam bitumen content using Marshall Stability test results

3.3.2 Marshall Stability Test

In this part of the investigation, the focus was to prepare foam asphalt specimens to be used for density – voids analysis and Marshall Stability test in order to evaluate the influence of foaming water content. 1150 g of aggregates material (using the recommended gradation) were measured and used in preparation of 101 mm diameter and approximately 63.5 mm height cylindrical foam asphalt specimens at varying foaming water content. During preparation of the specimens, all other parameters and conditions including mixing and compaction temperatures, aggregate gradations, and other aspects of mix design remained the same. While on the other hand, foaming water content was the only variable in the mix. Thus, changes in the tests results obtained resulted from the variations in the foaming water content, and therefore considered as the influence of foaming water content on the foam asphalt specimens.

Conventional procedures for preparation of Marshall Specimens in hot mix asphalt were followed to prepare the foam asphalt specimens in the experimental work. The investigation was validated in three rounds of foam asphalt mix design. Three levels of mixing temperature composed the three rounds of mix design with each round consisted of varying foaming water content (2%, 4%, 6%, and 8%). Marshall Stability and ITS tests were conducted at each round of foam asphalt mix design. Details of the foam asphalt mix design parameters for each round can be summarized as shown in Table 3.8.

Table 3.8 Summery of foam asphalt mix design parameters

Property	**Mix Design Parameter**		
	Round 1	**Round 2**	**Round 3**
Mixing temperature	120 ^{o}C	100 ^{o}C	80 ^{o}C
Compaction Temperature	110 ^{o}C	90 ^{o}C	70 ^{o}C
Bitumen Temperature	185 ^{o}C	185 ^{o}C	185 ^{o}C
Foaming Water Content (FWC)	2%, 4%, 6%, & 8%	2%, 4%, 6%, & 8%	2%,3%, 4%, 5%, 6%, & 8%
Optimum Foaming Bitumen Content	4.3%	4.3%	4.5%
Aggregates Temperature	120 ^{o}C	100 ^{o}C	80 ^{o}C
Specimens Curing	40 ^{o}C for 3 days	40 ^{o}C for 3 days	40 ^{o}C for 3 days
Mixing time	60 seconds	60 seconds	60 seconds

101 mm diameter and 63.5 mm high Marshall Specimens were prepared at three rounds of mixing temperature and at various foaming water content (2%, 4%, 6% and 8%) using the optimum foam bitumen content for all specimens. The specimens were compacted at 75 blows (each face) and placed in a forced-draft oven for 72 hours curing at 40 ^{o}C. During preparation of the specimens, a substantial improvement in the workability of foam asphalt mix was observed due to the increase of mixing temperature from 80 ^{o}C to 120 ^{o}C. Consequently, the aggregate particles in the foam asphalt mix were better coated and the specimens become increasingly darker as the mixing temperature increased from 80 ^{o}C to 120 ^{o}C (see Figure 3.8).

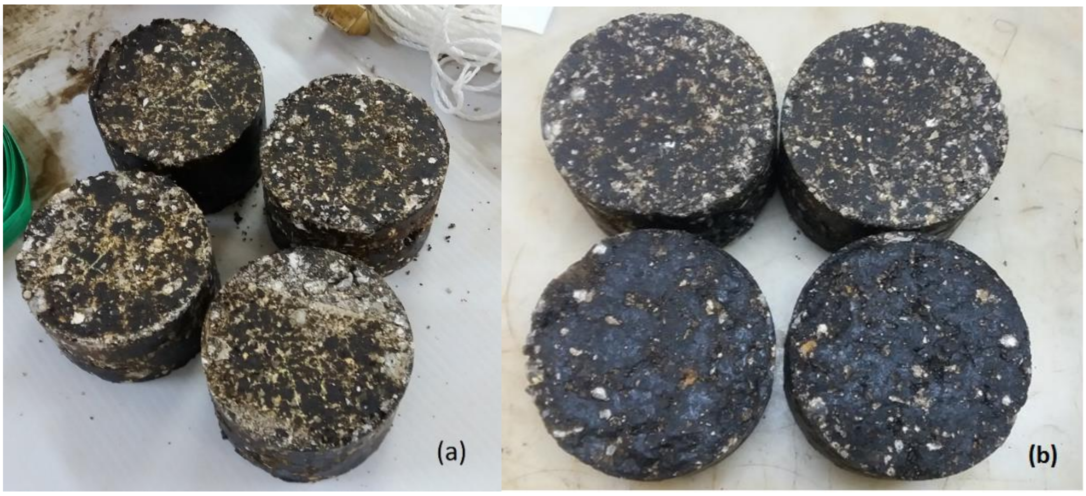

Figure 3.8 Foam asphalt specimens at, (a) 80^{o}C and (b) 100^{o}C and 120^{o}C mixing temperature

Marshall Stability test was conducted after the curing the specimens. The foam asphalt specimens were prepared for Marshall Stability test by placing in a water bath at 60 ^{o}C for 35 minutes after volumetric measurements were done. Marshall Stability test was applied at 60 ^{o}C soaked specimen's temperature. Density-voids analysis was done using the values from volumetric measurements.

3.3.3 Indirect Tensile Strength Test

101 mm diameter and 63.5 mm high Marshall Specimens were prepared following the same foam asphalt mix design parameters applied in Marshall Stability test (Table 3.8). Indirect tensile strength tests specimens were prepared for both dried and wet

specimens' tests. After 72 hours of force draft oven curing at 40 ^{o}C, the specimens were allowed to cool down to room temperature (25 ^{o}C) for about one hour before testing at 25 ^{o}C for dry indirect tensile strength (ITS_{dry}). While a duplicate of the dry specimens subject to water conditioning were then soaked in a water bath at 25 ^{o}C for 24 hours after which ITS_{wet} at 25 ^{o}C was measured (Figure 3.9).

Figure 3.9 Indirect Tensile Strength (ITS) test of foam asphalt specimen

CHAPTER FOUR
RESULTS AND ANALYSIS

4.1 Introduction

In this chapter, the results of the experimental investigation and analysis of the results are presented and discussed to evaluate the influence of foaming water content on foam asphalt. According to the investigation approach applied in the experimental work of this study, the results of both Marshall Stability and Indirect Tensile Strength tests have revealed the influence of the foaming water content on foam asphalt mixtures. Compared to foaming water content, foam asphalt mixing temperature has greater influence on the performance of foam asphalt mixtures.

4.2 Marshall Stability Test Results

Following 72 hours of curing foam asphalt specimens, Marshall Stability test was conducted to measure Marshall stability and Flow values. Density and voids properties of foam asphalt specimens including unit weight, specific gravity, and air voids content were determined from the volumetric measurements.

In this section, summary of Marshall stability table representing the selected engineering properties of foam asphalt specimens are presented. From the Marshall Stability test, engineering properties such as air voids content, unit weight (density), Marshall Stability and Flow are used to evaluate the influence of foaming water content on foam asphalt specimens.

Table 4.1 shows the Marshall Stability test and density-voids analysis results of foam asphalt specimens produced at varying foaming water content (2%, 4%, 6% and 8%) and three different levels of mixing and compaction temperatures. The test results revealed the influence of foaming water content in combination with mixing and compaction temperature on foam asphalt mixtures.

Table 4.1 Marshall Stability test and density-voids analysis results of foam asphalt specimens

Factor	**Mixing Temp.**	**Foaming Water Content**				**Standard Criteria (HMA)**
		2%	**4%**	**6%**	**8%**	
Air Voids, %	120 °C	3.43	3.45	3.62	3.87	3 – 5%
	100 °C	3.94	3.98	4.17	4.19	
	80 °C	6.48	7.26	7.18	7.04	
Marshall Stability, Kgf	120 °C	1156	1163.69	1131.8	1128.4	> 900 Kgf
	100 °C	955.4	960.43	902.74	883.39	
	80 °C	636.9	604.4	583.5	613.6	
Unit Weight, gm/cm^3	120 °C	2.436	2.436	2.432	2.425	2.4 – 3 gm/cm^3
	100 °C	2.440	2.430	2.415	2.415	
	80 °C	2.338	2.319	2.320	2.321	
Flow, mm	120 °C	3.01	3.33	3.72	3.45	2 - 4 mm
	100 °C	3.73	3.84	3.66	3.61	
	80 °C	2.2	2.2	2.8	2.9	

4.2.1 Influence of Foaming Water Content on Air Voids Content

The air voids content in the foam asphalt specimens were determined from the measured values of bulk specific gravities and theoretical maximum specific gravities. It can be observed from the Marshall Stability test results that; foaming water content insignificantly influenced the air voids content in foam asphalt mix at varying mixing temperature.

From Figure 4.1, it can be explained that at various levels of mixing temperature, increasing the foaming water content from 2% up to 8% slightly increased the air voids content of the foam asphalt mixture. At 80 °C and 100 °C mixing temperature, a clear observation can be made on the trend line that shows a slight increment in air voids content as the foaming water content increases. Similar trend is also observed at 120 °C temperature at which air voids content increased slightly as the foaming water content increased from 2% to 8%.

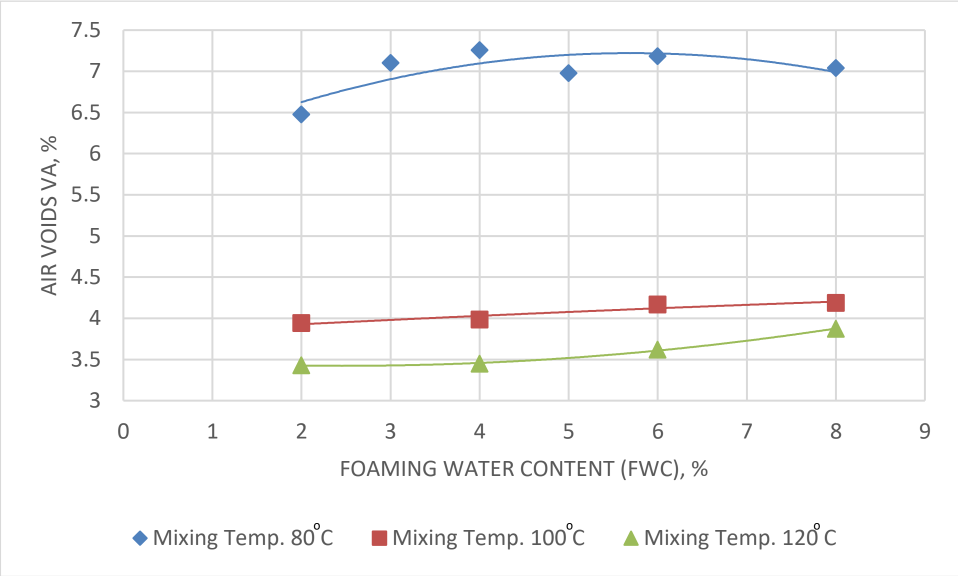

Figure 4.1 Influence of foaming water content on air voids content

4.2.2 Influence of Mixing temperature on Air Voids Content

In comparison to foaming water content, mixing temperature has proven greater influence on air voids content. Thus, mixing foam asphalt at high temperature effectively reduces the air voids content that enhances the performance of foam asphalt mixture.

At 80 ^{o}C mixing temperature, higher air voids contents were observed at various foaming water contents, however, the air voids contents were reduced by almost half when foam asphalt specimens were produced at 120 ^{o}C mixing temperature (Figure 4.2). Meanwhile, the air voids content of foam asphalt specimens produced at 100 ^{o}C and 120 ^{o}C mixing temperature are relatively the same. This observation can also be explained that mixing foam asphalt at or above 100 ^{o}C may considerably reduce the air voids content to about 4%.

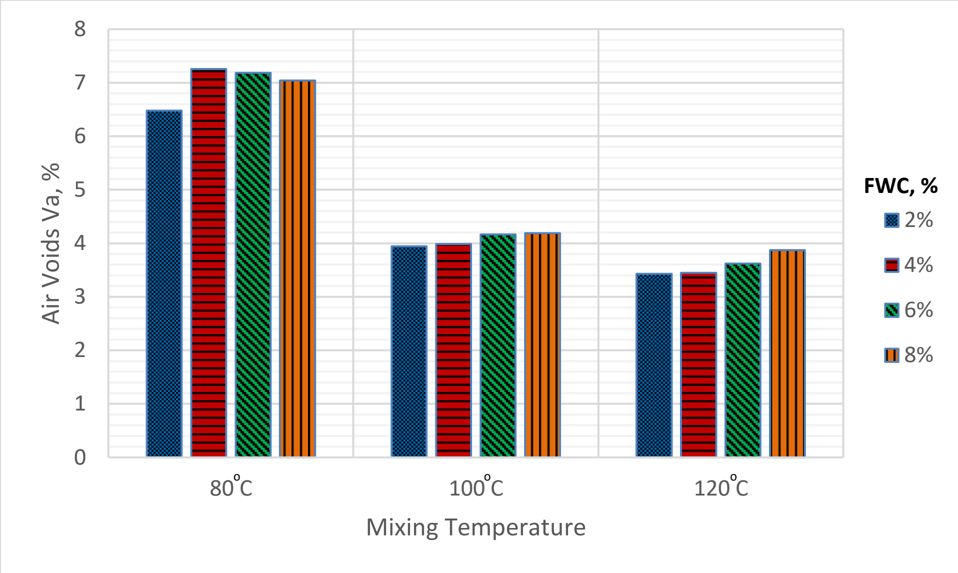

Figure 4.2 Influence of mixing temperature on air voids content

4.2.3 Influence of Foaming Water Content on Marshall Stability

Foaming water content is an important parameter in the production of foam bitumen. Increase in foaming water content increases the volume of foam bitumen, which results into better coating of aggregate particles in a foam asphalt mix. However, the results from Marshall Stability test indicated that mixing foam asphalt using higher foaming water contents resulted into slight reduction of Marshall Stabilities that negatively affects performance of the foam asphalt mixtures.

Figure 4.3 shows slight reduction in Marshall Stability as the foaming water content increases from 2% to 8%. This similar trend can be observed throughout the three levels of mixing temperature. At 100 ^{o}C mixing temperature, the gradually reduction in Marshall Stability can be clearly observed as the foaming water content being increased from 2% to 8%.

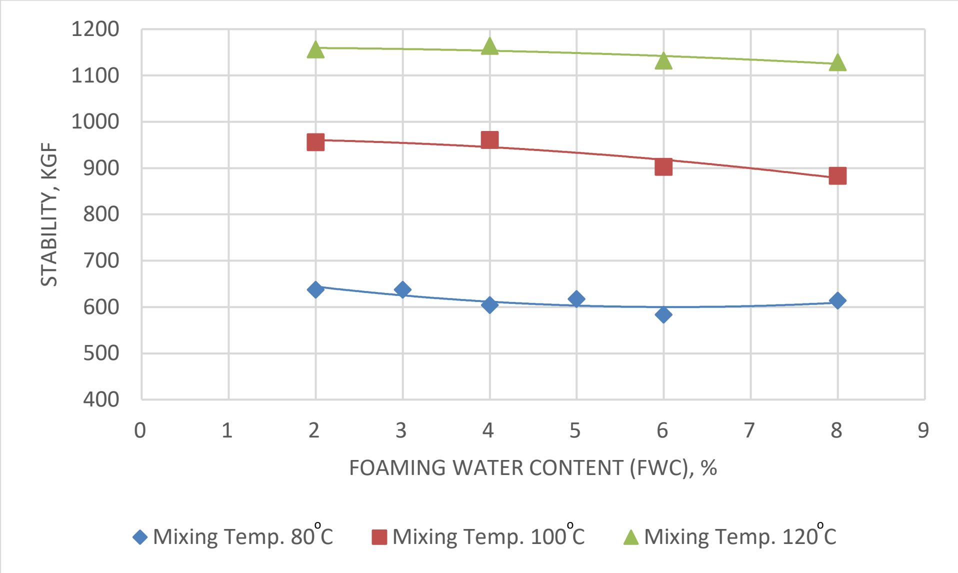

Figure 4.3 Influence of foaming water content on Marshall Stability

4.2.4 Influence of Mixing Temperature on Marshall Stability

Unlike foaming water content, Marshall Stability test results (in Figure 4.4) indicated that mixing foam asphalt at higher temperatures adversely increased the Marshall Stabilities, which improves the mix performance. There is a considerable increment in Marshall Stability of specimens prepared at 100 °C and 120 °C mixing temperature as compared to specimens produced at 80 °C mixing temperature.

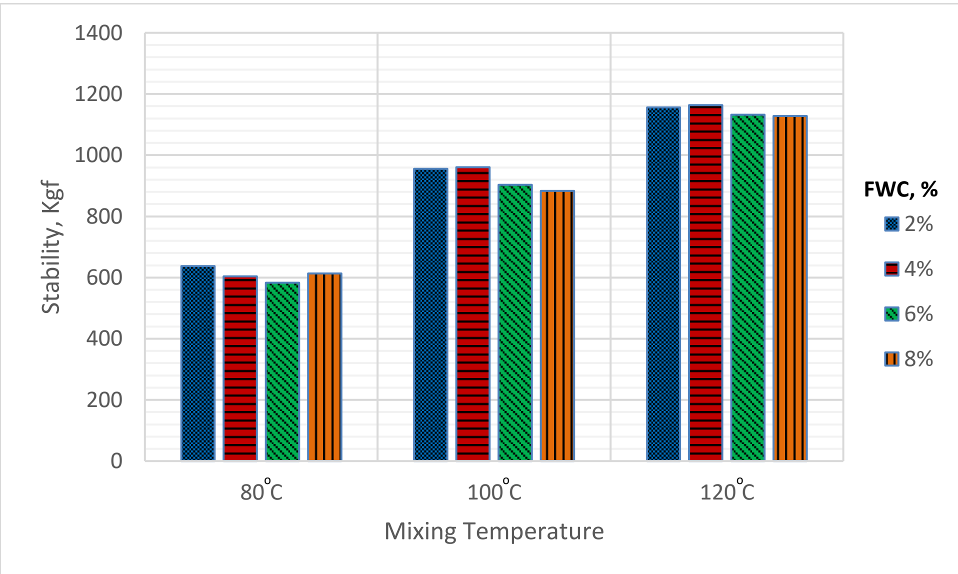

Figure 4.4 Influence of mixing temperature on Marshall Stability of foam asphalt

4.2.5 Influence of Foaming Water Content on Density of Foam Asphalt

Results from Marshall Stability test showed that, densities of foam asphalt mix are insignificantly influenced as the foaming water content increases from 2% to 8% specially at mixing temperatures 80 ºC and 120 ºC (Figure 4.5). But a slight reduction can be observed clearly at 100 ºC foam asphalt mixing temperature. The slight variations in the rate of density change can be attributed to the small amount of foaming water content in foam asphalt mix, which has almost negligible effect on compactability of foam asphalt mixtures.

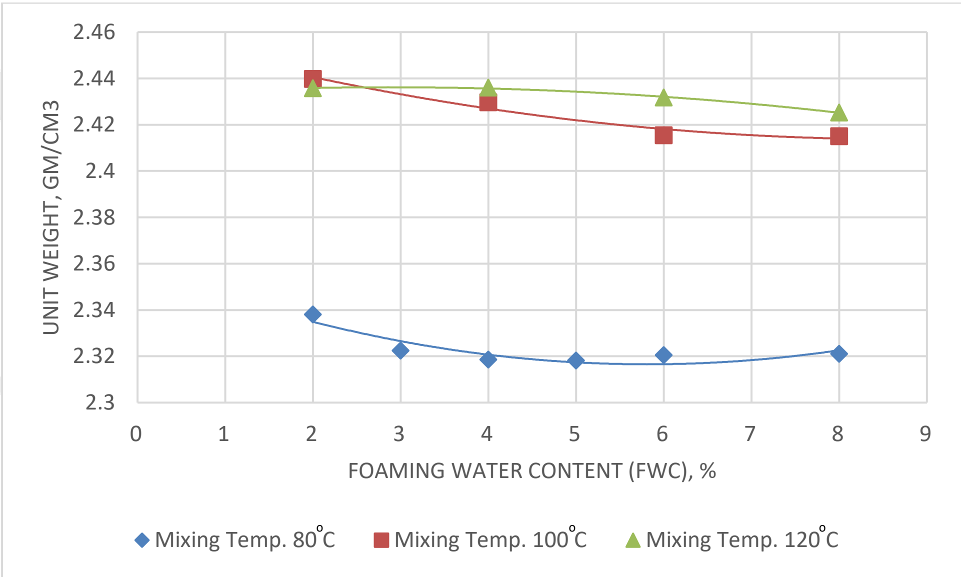

Figure 4.5 Influence of foaming water content on density of foam asphalt mixture

4.2.6 Influence of Mixing Temperature on Density of Foam Asphalt

Mixing temperature is very important in improving workability and easing compaction of foam asphalt mixtures. In comparison to foaming water content, mixing temperature plays a significantly greater role in preparation of foam asphalt mixtures. This influential role can be apparently observed from the variation in the densities of foam asphalt specimens relative to the variation of mixing temperature as depicted in Figure 4.6. Foam asphalt specimens acquired higher densities as the mixing temperature increased. It can be observed from Figure 4.6 that, mixing foam asphalt at higher temperatures as 100 °C and 120 °C compared to 80 °C has considerably improved the mix performance by increasing the specimens' densities.

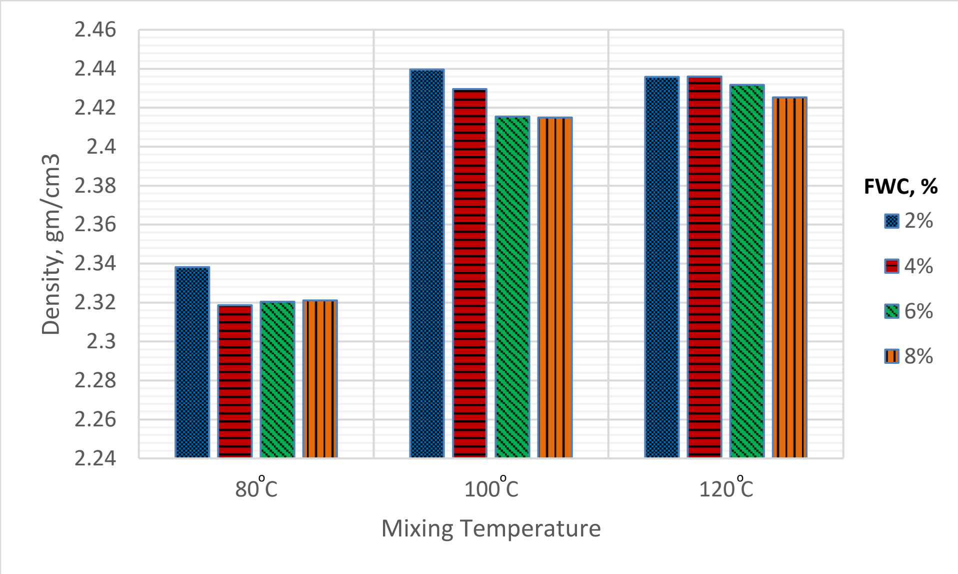

Figure 4.6 Influence of mixing temperature on density of foam asphalt

4.2.7 Influence of Foaming Water Content & Mixing Temperature on Flow

The results obtained on flow values of foam asphalt mixtures exhibit insignificant influence of both mixing temperature and foaming water content. From Figure 4.7, slight increment can be observed in Flow values of foam asphalt specimens as the mixing temperature increased from 80 °C to 120 °C. This slight increment in Flow values is insignificant when compared to the influence observed on other mechanical properties such air voids, Marshall Stability, and density of foam asphalt specimens. Similarly, increasing foaming water content has revealed insignificant influence on Flow values of foam asphalt specimens.

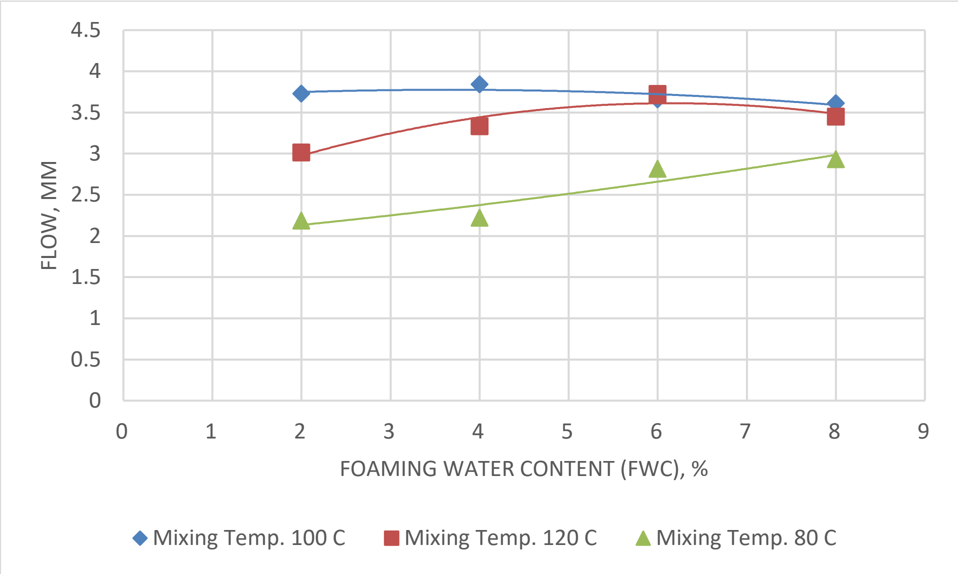

Figure 4.7 Influence of foaming water content and mixing temperature on flow of foam asphalt

4.3 Indirect Tensile Strength Test Results

Indirect tensile strength (ITS) test was applied in three rounds of foam asphalt mix design for both dry and wet foam asphalt specimens. Indirect Tensile Strength test results of both dry and water conditioned specimens are shown in Table 4.2. The test results showed the influence of foaming water content and mixing temperature on foam asphalt specimens.

Table 4.2 Indirect Tensile Strength test results

Factor	Mixing Temp.	Foaming Water Content				Standard Criteria (Asphalt Academy TG2, 2009)
		2%	4%	6%	8%	
ITS_{dry}, KPa	120 ºC	648.5	659.0	727.7	662.7	> 225 KPa
	100 ºC	715.2	723.0	711.5	705.6	
	80 ºC	336.1	427.9	504.0	403.1	
ITS_{wet}, KPa	120 ºC	742.7	690.2	695.8	710.9	> 100 KPa
	100 ºC	634.0	698.6	693.4	708.1	
	80 ºC	270.3	346.9	373.4	295.5	
ITR, %	120 ºC	114.5	104.7	95.6	107.3	> 50 %
	100 ºC	88.6	96.6	97.5	100.4	
	80 ºC	80.4	81.1	74.1	73.3	

4.3.1 *Influence of Foaming Water Content & Mixing Temperature on Dry ITS*

The indirect tensile strength of specimens produced at 80 ^{o}C mixing temperature are much lower than that of specimens produced at 100 ^{o}C and 120 ^{o}C mixing temperatures (Figure 4.8). It is a clear indication of increased performance when production temperature of foam asphalt mix is increased.

On the other hand, foaming water content at high mixing temperature slightly influence the indirect tensile strength of foam asphalt mix. At 100 ^{o}C and 120 ^{o}C mixing temperatures, insignificant variations in values of indirect tensile strength can be observed as the foaming water content increases. While at 80 ^{o}C mixing temperature, indirect tensile strength increased around the optimum foaming water content (4%) and decreased as the foaming water content increased to 8%.

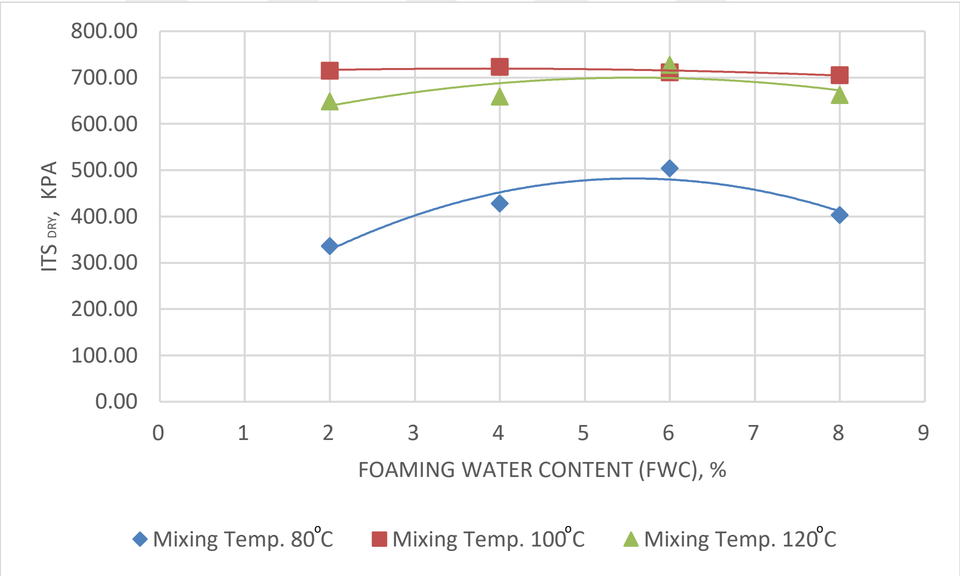

Figure 4.8 Influence of foaming water content on ITS_{dry} of foam asphalt mixture

4.3.2 *Influence of Foaming Water Content & Mixing Temperature on Wet ITS*

The indirect tensile strength test results (Figure 4.9) showed that, water conditioned specimens prepared at 100 ^{o}C and 120 ^{o}C mixing temperature produced higher indirect tensile strength (ITS_{wet}) as compared to specimens prepared at 80 °C mixing temperature.

From Figure 4.9, a clear trend could not be observed in the indirect tensile strength variations of specimens prepared at 100 °C and 120 °C mixing temperature as the foaming water content increases. This can be deduced that, at higher mixing temperature the influence of foaming water content becomes relatively insignificant on indirect tensile strength when compared to mixing temperature.

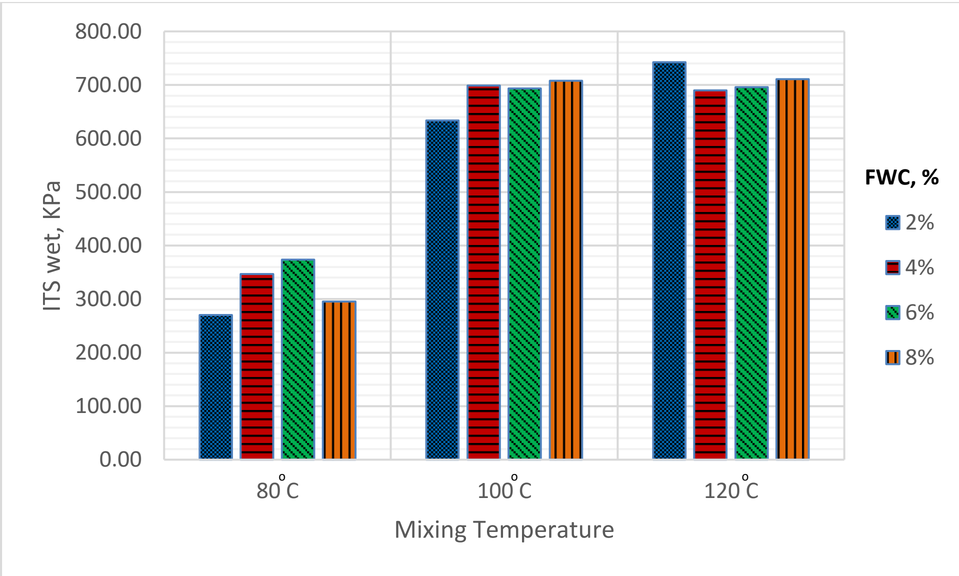

Figure 4.9 Influence of mixing temperature on ITS_{wet} of foam asphalt specimens

4.3.3 Influence of Foaming Water Content & Mixing Temperature on ITR

From Figure 4.10, the influence of mixing temperature on foam asphalt mixtures can be observed that ITR increased when mixing temperature was increased. Foam asphalt specimens exhibit more resistance to moisture susceptibility when produced at higher mixing temperature. It can also be deduced that the performance of foam asphalt specimens improved when the mixing temperature increased.

On the other hand, foaming water content insignificantly influenced the ITR of the foam asphalt specimens. A clear trend cannot be observed on the ITR behavior of foam asphalt specimens as the foaming water content increases (Figure 4.10). At 80 °C mixing temperature, slight reduction in the ITR of foam asphalt specimens as the foaming water content increases from 2% to 8%. However, at 100 °C mixing temperature a slight increment can be observed from the trendline as the foam water content increased from 2% to 8%. While at 120 °C mixing temperature the trendline does not clearly exhibit the influence of foaming water content on the foam asphalt specimens.

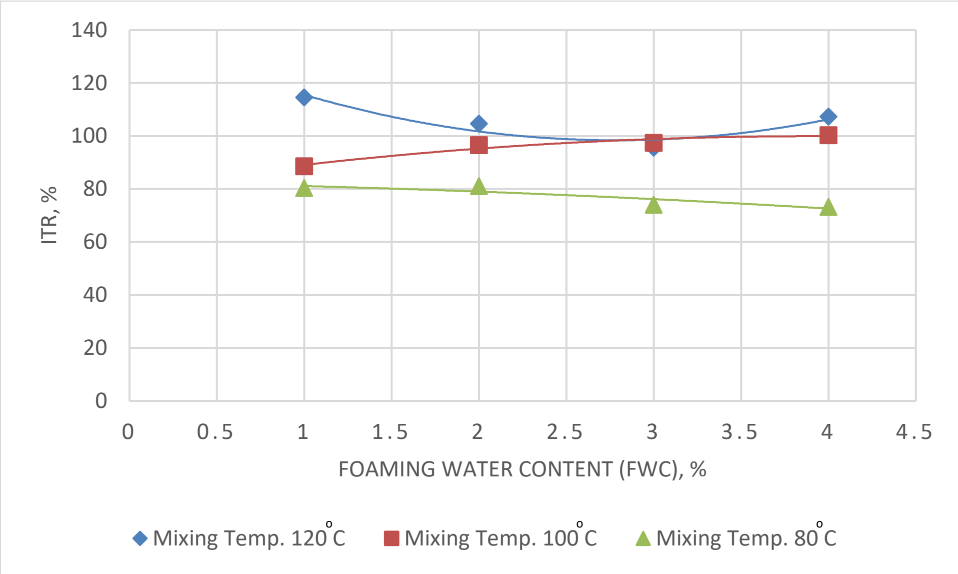

Figure 4.10 Influence of foaming water content on ITR of foam asphalt specimens

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

In this study, the influence of foaming water content together with mixing temperature on foam asphalt mixtures was investigated by experimental methods. Marshall Specimens were produced at varying foaming water content (2%, 4%, 6% and 8%) and three levels (80 ^{o}C, 100 ^{o}C, and 120 ^{o}C) of mixing temperature in the foam asphalt mix design. The investigation was validated in three rounds of foam asphalt mix design with each round represented a level of mixing temperature. Marshall Stability and Indirect Tensile Strength tests were applied to determine the foam asphalt performance under the influence of varying foaming water content at different levels of mixing temperature.

The investigations and results obtained in this study have set light on the influence of foaming water content and mixing temperature on foam asphalt mixtures. Evaluation of the mechanical properties such as air voids, Marshall Stability and Flow, density, ITS_{dry}, ITS_{wet} and ITR of foam asphalt specimens revealed some fundamental concepts about foaming water content and mixing temperature influence on foam asphalt mixtures.

Conclusions

Following the experimental investigations applied in this study, the influence of foaming water content and mixing temperature on foam asphalt mixtures can be deduced as follows:

- Increase in foaming water content as compared to mixing temperature insignificantly influenced the air voids content in foam asphalt mixtures at 80 ^{o}C, 100 ^{o}C, and 120 ^{o}C mixing temperature. While increasing the mixing temperature reduces the air voids in foam asphalt mixtures and improves coating of large aggregates particles.
- Marshall Stability of foam asphalt mix slightly reduces as the foaming water content increases. i.e. use of high foaming water content in foam asphalt

mixtures might result to unacceptable influence on Marshall Stability of foam asphalt. Unlike foaming water content, increasing mixing temperature (80 ^{o}C, 100 ^{o}C, and 120 ^{o}C) of foam asphalt improves the workability of the mix that results into higher Marshall Stability and enhanced performance.

- Increasing foaming water content (2%, 4%, 6% and 8%) in foam asphalt mix slightly reduces the density of foam asphalt mixtures. However, the density of foam asphalt is significantly increased by mixing at higher temperatures. Production of foam asphalt at high mixing temperature (below HMA production temperature) improves compaction and hence higher densities are achieveable.
- Increase in foaming water content has relatively insignificant influence on the Flow values of foam asphalt specimens, while increase in mixing temperature from 80 ^{o}C to 120 ^{o}C slightly increased the Flow values of foam asphalt specimens.
- At high mixing temperature (100 ^{o}C, and 120 ^{o}C), foaming water content slightly influenced the indirect tensile strength of foam asphalt mix. While at 80 ^{o}C mixing temperature, indirect tensile strength increased around the optimum foaming water content (4%) and decreased as the foaming water content increased to 8%. Indirect Tensile strength increased when production temperature of foam asphalt mix is increased.
- Mixing temperature as compared to foaming water content has more adverse influence on air voids, coating of large aggregate particles and the performance of foam asphalt mixtures.

Recommendations

After extensive laboratory investigations, the following recommendations are made for future studies on related areas of foam asphalt studies:

- The scope of this study has limited the experimental investigations on the influence of foaming water content and mixing temperature on foam asphalt mixtures to use virgin aggregates (limestone). Thus, future studies should consider application of wider range of materials including RAP materials, in order to test the validity of conclusions made in this study.

- The focus of this study was investigation of the influence of foaming water content and mixing temperature on foam asphalt mixtures using the methods applied earlier. However, the effect of using various active fillers and additives to reduce the high air voids content and improve coating of large aggregates particles in foam asphalt mixtures are major areas of consideration. Future studies should give attention to the use of various active fillers and additives to improve the properties of foam asphalt at lower production temperature.

Therefore, in light of the experimental methods applied and conclusions made in this study, future studies should consider performance evaluation of foam asphalt mixtures by applying test methods such as resilient modulus, Unconfined compressive strength (UCS), Triaxial test, fatigue and rutting resistance.

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APPENDICES

A.1 Round One (Mixing Temp. = 120^0 C): Marshall Stability Test Results Table

Sample ID	FBC ,%	FW C,%	Weight of Specimen (gm)			Vol. of Spec., cm³	Specific Gravity		Air Void Va, %	Thickn ess,m m	Stability			Flow , mm
			in air	in water	SSD		Bulk, Gmb	Max. Gmm			Meas., Kg	Corelat. Ratio	Correct. , Kg	
A1	4.3	2	1191	705.4	1195	489.9	2.431	2.523	3.642	61.7	1143	1.046	1195.58	3.85
A2	4.3	2	1197.5	707.5	1200	492.6	2.431	2.523	3.647	61.8	1089	1.043	1135.83	2.35
A3	4.3	2	1200.8	712	1203	490.7	2.447	2.523	3.008	63.3	1095	1.038	1136.61	2.84
Average							**2.436**		**3.432**				**1165.70**	**3.1**
B1	4.3	4	1200.8	711.5	1204	492.5	2.438	2.523	3.362	61.5	1127	1.053	1186.73	3.68
B2	4.3	4	1198.4	709.4	1201	491.5	2.438	2.523	3.359	61.63	1037	1.049	1087.81	3.22
B3	4.3	4	1189.5	702.7	1192	489.2	2.431	2.523	3.629	63.59	1152	1.056	1216.51	3.09
Average							**2.436**		**3.450**				**1163.69**	**3.33**
C1	4.3	6	1193.6	706.8	1195	488.5	2.443	2.523	3.155	61.13	1087	1.065	1157.66	3.6
C2	4.3	6	1202.1	710	1206	496	2.424	2.523	3.940	62.23	1004	1.033	1037.13	3.8
C3	4.3	6	1195.1	705.8	1198	492.2	2.428	2.523	3.753	63.46	1160	1.035	1200.60	3.43
Average							**2.432**		**3.616**				**1131.80**	**3.61**
D1	4.3	8	1192.1	704	1195	490.6	2.430	2.523	3.691	61.5	1090	1.053	1147.77	3.23
D2	4.3	8	1192.5	704.6	1195	490.3	2.432	2.523	3.600	61.97	1085	1.04	1128.40	3.39
D3	4.3	8	1194.7	703.6	1198	494.9	2.414	2.523	4.316	63.24	1053	1.053	1108.81	3.72
Average							**2.425**		**3.869**				**1128.33**	**3.45**

A.2 Round Two (Mixing Temp. = 100^0 C): Marshall Stability Test Results Table

Sample ID	FB C,%	FWC, %	Weight of Specimen, (gm)			Vol. of Spec. (cm^3)	Specific Gravity		Air Void Va, %	Thickness,mm	Stability			Flow, mm
			in air	in water	SSD		Bulk, Gmb	Max. Gmm			Meas., Kg	Corelat. Ratio	Correct., Kg	
A1	4.3	2	1198.4	710	1203.5	493.5	2.428	2.526	3.87	62.93	877	1.015	890.1	4.12
A2	4.3	2	1192.9	705	1196.1	491.1	2.429	2.526	3.84	62.13	993	1.035	1027.7	3.45
A3	4.3	2	1199.0	708	1203	495	2.422	2.526	4.11	63.54	932	1.0175	948.31	3.61
Average							**2.427**		**3.94**				**955.41**	**3.73**
B1	4.3	4	1196.2	709.8	1199.8	490	2.441	2.526	3.36	62.5	939	1.025	962.5	3.51
B2	4.3	4	1200.1	709.2	1205.4	496.2	2.419	2.526	4.25	63.07	961	1.0125	973	4.69
B3	4.3	4	1199.4	707.8	1204	496.3	2.417	2.526	4.32	63.98	925	1.0225	945.8	3.32
Average							**2.426**		**3.98**				**960.43**	**3.84**
C1	4.3	6	1195.1	710.1	1201.5	491.4	2.432	2.526	3.72	63.63	810	0.992	803.52	2.82
C2	4.3	6	1198.2	708	1203.8	495.8	2.417	2.526	4.33	62.9	1010	1.015	1025.15	3.78
C3	4.3	6	1198.1	707	1203.5	496.5	2.413	2.526	4.47	63.82	873	1.0075	879.5	4.37
Average							**2.421**		**4.17**				**902.74**	**3.66**
D1	4.3	8	1199.5	711.3	1206.6	495.3	2.422	2.526	4.13	63.43	825	1.0025	827.06	4.41
D2	4.3	8	1197.7	708.5	1204.9	496.4	2.413	2.526	4.48	63.47	933	1.0024	935.2	3.59
D3	4.3	8	1193.3	706.6	1198.4	491.86	2.426	2.526	3.96	63.52	862	1.03	887.86	2.84
Average							**2.420**		**4.19**				**883.39**	**3.61**

A.3 Round Three (Mixing Temperature = 80^0 C): Marshall Stability Test Results Table

Sample ID	FBC ,%	FW C,%	Weight of Specimen (gm)			Vol. of Spec. (cm³)	Specific Gravity		Air Void Va, %	Thick., mm	Stability			Flow, mm
			in air	in water	SSD		Bulk, Gmb	Max. Gmm			Meas., Kg	Corelat. Ratio	Correct. , Kg	
A1	4.5	2	1181.9	685.5	1188.0	502.6	2.352	2.5	5.93	63.18	701.3	1.008	706.94	2.2
A2	4.5	2	1194.5	689.7	1201.9	512.2	2.332	2.5	6.72	64.67	623	0.97	604.31	2.1
A3	4.5	2	1194.3	688.2	1200.7	512.5	2.330	2.5	6.78	64.45	639.2	0.976	624.31	2.21
Average							**2.338**		**6.48**				**645.19**	**2.17**
B1	4.5	4	1173.5	670.6	1181.1	510.5	2.299	2.5	8.05	64.43	668	0.978	653.30	2.11
B2	4.5	4	1197.8	691.7	1204.1	512.4	2.338	2.5	6.49	63.83	576	0.993	571.97	2.4
B3	4.5	4	1190	683.6	1196.7	513.1	2.319	2.5	7.23	64.5	613.9	0.975	598.87	2.21
Average							**2.319**		**7.26**				**608.05**	**2.24**
C1	4.5	6	1193.9	687.5	1202.5	515	2.318	2.5	7.27	64.43	663	0.978	648.41	2.23
C2	4.5	6	1207.8	693.3	1213.3	520	2.323	2.5	7.09	63.83	538	0.993	534.23	3
C3	4.5	6	1200.9	690.4	1207.9	517.5	2.320	2.5	7.18	64.13	589	0.965	568.39	3.2
Average							**2.320**		**7.18**				**583.68**	**2.81**
D1	4.5	8	1187.9	681.3	1193.7	512.4	2.318	2.5	7.27	64.53	644	0.975	627.90	2.9
D2	4.5	8	1193.1	684.9	1197	512.1	2.330	2.5	6.81	64.37	623	0.978	609.29	2.62
D3	4.5	8	1190.5	683.1	1195.4	512.3	2.324	2.5	7.04	64.45	619	0.976	603.66	3.27
Average							**2.324**		**7.04**				**613.62**	**2.93**

A.4.1 Round One (Mixing Temp. = 120^0 C): Dry Indirect Tensile Strength Test Results Table

Sample ID	FWC,%	Binder Content (%)	Thickness, (mm)	Diameter, (mm)	Load, (Kgf)	Accel. Gravity,(g)	Force, (N)	ITS, (KPa)
A1	2	4.3	62.1	101.6	700	9.81	6867	693.24
A2	2	4.3	62.13	101.6	610	9.81	5984.1	603.82
Average ITS								**648.53**
B1	4	4.3	61.3	101.6	661	9.81	6484.41	663.16
B2	4	4.3	61.33	101.6	653	9.81	6405.93	654.81
Average ITS								**658.98**
C1	6	4.3	61.27	101.6	709	9.81	6955.29	711.66
C2	6	4.3	61.77	101.6	747	9.81	7328.07	743.74
Average ITS								**727.70**
D1	8	4.3	61.87	101.6	682	9.81	6690.42	677.92
D2	8	4.3	61.27	101.6	645	9.81	6327.45	647.42
Average ITS								**662.67**

A.4.2 Round One (Mixing Temp. = 120^0 C): Wet Indirect Tensile Strength Test Results Table

Sample ID	FWC,%	Binder Content (%)	Thickness, (mm)	Diameter, (mm)	Load, (Kgf)	Accel. Gravity, (g)	Force, (N)	ITS, (KPa)
A3	4	4.3	62.93	101.6	557	9.81	5464.17	544.3436
A4	4	4.3	62.3	101.6	733	9.81	7190.73	723.5884
Average ITS								**633.966**
B3	4	4.3	62.37	101.6	759	9.81	7445.79	748.4136
B4	4	4.3	63.23	101.6	667	9.81	6543.27	648.7514
Average ITS								**698.5825**
C3	4	4.3	62.87	101.6	686	9.81	6729.66	671.0522
C4	4	4.3	62.73	101.6	730	9.81	7161.3	715.6871
Average ITS								**693.3697**
D3	4	4.3	63.77	101.6	707	9.81	6935.67	681.834
D4	4	4.3	61.97	101.6	740	9.81	7259.4	734.3885
Average ITS								**708.1112**

A.5.1 Round Two (Mixing Temp. = 100^0 C): Dry Indirect Tensile Strength Test Results Table

Sample ID	FWC,%	Binder Content (%)	Thickness, (mm)	Diameter, (mm)	Load, (Kgf)	Accel. Gravity, (g)	Force, (N)	ITS, (KPa)
A1	2	4.3	61.73	101.6	677	9.81	6641.37	674.48
A2	2	4.3	62.07	101.6	763	9.81	7485.03	755.99
Average ITS								**715.24**
B1	4	4.3	62.13	101.6	717	9.81	7033.77	709.73
B2	4	4.3	62.4	101.6	747	9.81	7328.07	736.23
Average ITS								**722.98**
C1	6	4.3	62.93	101.6	686	9.81	6729.66	670.41
C2	6	4.3	63.33	101.6	775	9.81	7602.75	752.61
Average ITS								**711.51**
D1	8	4.3	62.48	101.6	786	9.81	7710.66	773.67
D2	8	4.3	62.23	101.6	645	9.81	6327.45	637.43
Average ITS								**705.55**

A.5.2 Round Two (Mixing Temp. = 100^0 C): Wet Indirect Tensile Strength Test Results Table

Sample ID	FWC,%	Binder Content (%)	Thickness, (mm)	Diameter, (mm)	Load, (Kgf)	Accel. Gravity, (g)	Force, (N)	ITS, (KPa)
A3	4	4.3	62.93	101.6	557	9.81	5464.17	544.3436
A4	4	4.3	62.3	101.6	733	9.81	7190.73	723.5884
Average ITS								**633.966**
B3	4	4.3	62.37	101.6	759	9.81	7445.79	748.4136
B4	4	4.3	63.23	101.6	667	9.81	6543.27	648.7514
Average ITS								**698.5825**
C3	4	4.3	62.87	101.6	686	9.81	6729.66	671.0522
C4	4	4.3	62.73	101.6	730	9.81	7161.3	715.6871
Average ITS								**693.3697**
D3	4	4.3	63.77	101.6	707	9.81	6935.67	681.834
D4	4	4.3	61.97	101.6	740	9.81	7259.4	734.3885
Average ITS								**708.1112**

A.6.1 Round Three (Mixing Temp. = 80^0 C): Dry Indirect Tensile Strength Test Results Table

Sample ID	FWC,%	Binder Content (%)	Thickness, (mm)	Diameter, (mm)	Load, (Kgf)	Accel. Gravity, (g)	Force, (N)	ITS, (KPa)
A1	2	4.5	64.53	101.6	330	9.81	3237.3	314.5053
A2	2	4.5	64.47	101.6	375	9.81	3678.75	357.725
Average ITS								**336.1151**
B1	4	4.5	64.6	101.6	373	9.81	3659.13	355.1011
B2	4	4.5	63.5	101.6	517	9.81	5071.77	500.7171
Average ITS								**427.9091**
C1	6	4.5	64.43	101.6	549	9.81	5385.69	524.0345
C2	6	4.5	64.43	101.6	507	9.81	4973.67	483.9444
Average ITS								**503.9894**
D1	8	4.5	64.9	101.6	421	9.81	4130.01	398.945
D2	8	4.5	63.87	101.6	423	9.81	4149.63	407.3044
Average ITS								**403.1247**

A.6.2 Round Three (Mixing Temp. = 80^0 C): Wet Indirect Tensile Strength Test Results Table

Sample ID	FWC,%	Binder Content (%)	Thickness, (mm)	Diameter, (mm)	Load, (Kgf)	Acceleration Gravity, g)	Force, (N)	ITS, (KPa)
A3	2	4.5	64.2	101.6	380	9.81	3727.8	364.0191
A4	2	4.5	64.77	101.6	186	9.81	1824.66	176.6098
Average ITS								**270.3144**
B3	4	4.5	62.57	101.6	404	9.81	3963.24	397.0917
B4	4	4.5	65.9	101.6	318	9.81	3119.58	296.7682
Average ITS								**346.93**
C3	6	4.5	64.4	101.6	298	9.81	2923.38	284.5811
C4	6	4.5	64.93	101.6	488	9.81	4787.28	462.2214
Average ITS								**373.4013**
D3	8	4.5	64.2	101.6	285	9.81	2795.85	273.0144
D4	8	4.5	64.23	101.6	332	9.81	3256.92	317.8892
Average ITS								**295.4518**