

**WASTE PLASTIC BOTTLES AS ADDITIVE FOR STONE
MASTIC ASPHALT**

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ABSTRACT

These days, the increase in the number of road users has led to a dramatic increase in road traffic volume, traffic loads, and consequently, tyre pressure. These factors are important in contributing to pavement deformation and permanent structural or functional failure of the asphalt mixture. The high frequency of traffic loads can result in structural damage to asphalt pavements in the form of cracking of the asphalt layer, rutting along the wheel tracks, loss of adherence between aggregate particles and asphalt cement, which, in turn cause, stripping and other kinds of road surface deterioration.

Conventional bituminous material does not have the performance requirements for road construction, which are increasingly subjected to heavy loads, frequent stresses and various climatic and environmental conditions. When the produced bituminous mixture does not meet the climate, traffic, and pavement structure requirements, to qualify as an optimal mixture, this kind of bituminous mixture needs to be modified by an attractive alternative to gain the required properties to be able to overcome the stresses and distresses that the pavement undergoes resulting from bitumen deficiencies in the mixture. Modification of bituminous mixtures offers one answer to overcome this problem and thereby improve the performance and durability of the pavement.

Modification of the bituminous mix with polymer seems to have great potential for the successful application in the design of flexible pavements to enhance their effective service life. Adding polymer to the bituminous mixture increases its stiffness and improves its susceptibility to temperature variations in different regions and climates. The main advantage of polymer-modified bituminous mixture is its significant effect on

the pavement performance, which enhances its resistance against fatigue cracking, permanent deformation, and moisture susceptibility.

Nevertheless, polymer modified asphalt mixes are comparatively more expensive for road pavement. One way to reduce the expense of such construction and to make it more convenient is the application of inexpensive polymers, such as waste polymers. Recycling waste materials has a significant positive impact on the environment, as well as the potential to be cost-effective and improve the performance of flexible pavements.

The main purpose of this research is to determine the effect of incorporating waste plastic bottles (PET) on the engineering properties of stone mastic asphalt (SMA) mixture. The engineering properties of asphalt mixes that include various percentages of PET (0%, 2%, 4%, 6%, 8% and 10%) were calculated and assessed with laboratory tests. The appropriate range for the amount of waste PET was determined to be 4%~6% by weight of the bitumen content. The outcomes were statistically analysed and the determination of the significance at certain confidence limits was performed with the two factor variance analysis (ANOVA). The results show that the addition of PET has a significant positive effect on the properties of SMA and it can promote the re-use of waste material in industry in an environmentally friendly and economical way.

ABSTRAK

Dewasa ini, penambahan bilangan pengguna jalan raya telah membawa kepada peningkatan khususnya isipadu trafik, beban lalu lintas, dan seterusnya, tekanan tayar. Faktor-faktor ini adalah penting dalam menyumbang kepada ubah bentuk turapan dan struktur kekal atau kegagalan fungsian dalam campuran asphalt. Kekerapan beban trafik yang tinggi boleh menyebabkan kerosakan struktur turapan asphalt seperti keretakan lapisan asphalt, palohan/aluran berpunca daripada bekas roda, kehilangan rekatan antara bahan pengikat iaitu zarah agregat dan simen asphalt, yang mengakibatkan pelucutan dan lain-lain kerosakan pada permukaan jalan.

Bahan berbitumen konvensional biasanya tidak memenuhi keperluan bagi pembinaan jalan raya memandangkan jalan raya semakin terdedah kepada beban berat, tegasan kerap dan pelbagai keadaan cuaca dan alam sekitar. Apabila campuran berbitumen yang dihasilkan tidak sesuai dengan cuaca, trafik, dan keperluan struktur turapan, campuran berbitumen perlu diubah suai dengan menggunakan bahan alternatif dengan mencapai campuran yang optimum untuk mendapatkan sifat-sifat yang diperlukan untuk mengatasi tegasan dan kerosakan pada turapan akibat daripada kekurangan bitumen di dalam campuran. Oleh sebab itu, pengubahsuaian campuran berbitumen menawarkan satu jawapan untuk mengatasi masalah ini dan seterusnya meningkatkan prestasi dan ketahanan turapan.

Pengubahsuaian campuran berbitumen dengan polimer mempunyai potensi besar untuk digunakan dengan jayanya dalam reka bentuk turapan boleh lentur untuk meningkatkan jangka hayat perkhidmatan yang berkesan. Pertambahan polimer dalam campuran berbitumen boleh meningkatkan kekakuan dan meningkatkan kecenderungan kepada pelbagai suhu di kawasan-kawasan dan iklim yang berbeza. Kelebihan utama polimer-

diubahsuai dalam campuran berbitumen adalah kesan yang ketara ke atas prestasi turapan, yang mana boleh meningkatkan rintangan terhadap retak akibat kesan dari keupayaan beban gelas struktur, ubah bentuk kekal, dan kecenderungan terhadap kelembapan.

Walau bagaimanapun, campuran asfalt polimer-diubahsuai adalah mahal untuk turapan jalan. Salah satu cara untuk mengurangkan perbelanjaan pembinaan dan membuatkan ia lebih mudah adalah dengan menggunakan polimer yang murah, seperti polimer terpakai. Kitar semula bahan-bahan buangan mempunyai kesan positif terhadap alam sekitar, serta berpotensi untuk menjadi kos-berkesan di samping meningkatkan prestasi turapan lentur.

Tujuan utama kajian ini adalah untuk menentukan dan mengenalpasti kesan pencampuran botol plastik terpakai (PET) ke atas ciri-ciri kejuruteraan/fizikal campuran *Stone Mastic Asphalt* (SMA). Ciri-ciri kejuruteraan/fizikal campuran asfalt yang mengandungi pelbagai peratusan botol plastik terpakai iaitu 0%, 2%, 4%, 6%, 8% dan 10% telah dikira dan dinilai dengan ujian-ujian makmal. Julat yang sesuai bagi jumlah botol plastik terpakai adalah antara 4-6% berdasarkan berat kandungan bitumen. Keputusan ujian makmal telah dianalisis secara statistik dan penentuan yang penting pada had keyakinan tertentu dilakukan dengan analisis varians secara dua faktor (ANOVA). Hasil keputusan menunjukkan bahawa penambahan botol plastik terpakai mempunyai kesan positif yang ketara ke atas ciri-ciri SMA dan ini boleh menggalakkan penggunaan semula bahan buangan di dalam industri secara mesra alam dan ekonomi.

Dedicated to my beloved family:

Parents

Sisters & brother

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1. INTRODUCTION

1.1 Introduction

The past two decades have witnessed considerable productivity and competitiveness as a major challenge in most economic arenas in most of the developing and developed societies around the globe. This competitiveness and productivity require both an increase of production and an improvement in the efficiency and safety of their delivery and transportation facilities. As a result, heavily loaded and large-sized vehicles and containers, with greater axle loads and higher tyre pressure, have been designed and manufactured to uphold and survive the rampant economic competition in the global market. Consequently, the production of these heavy vehicles has substantially increased, which, in turn, has had a drastic effect on the existing road pavements. Therefore, the bituminous pavements are subjected to new modes of distress (Zahw, 1996).

The performance of bituminous pavements can be improved through the addition of polymers into the mixture which usually enhances the bitumen stiffness as well as its temperature susceptibility. When the stiffness of the bitumen increases, the resistance of the pavement against rutting, specifically in hot and tropical climates, improves accordingly, allowing the application of the base bitumen with relatively softer nature and, ultimately, rendering better low temperature performance (Chen et al., 2009, Shbeeb, 2007).

Many researches have been conducted to study the possibilities and features of alternative materials that can be used as an additive or modifier in bituminous mixture. Of course, the concept of applying additives to modify mixtures is not a new trend, as

there have been numerous attempts to modify bituminous mixtures to achieve a better performance and quality of hot mix asphalts (HMA) dating back many years (Yetkin, 2007, Tapkın et al., 2009). Nowadays, the application of polymers and fibers for this purpose has started to gain more attention among road paving agencies around the globe (Al-Hadidy and Tan, 2009, Al-Hadidy and Yi-qiu, 2009b). Nevertheless, in the case of Malaysia, the use of polymer in asphalt pavement is not sufficiently significant, which is believed to be due to the insufficient number of studies on the evaluation of the potential of polymer as an alternative material that is applicable to improvement of the performance of asphalt mixtures according to the climate conditions in Malaysia. Therefore, conducting a detailed research on the improvement of the performance of hot mix asphalt in Malaysia through the application of polymers as a modifier or additive material is an essential requirement in this field.

Today, polymer modified asphalt mixes are comparatively more expensive for road pavement. One way to reduce the expense of such construction and to make it more convenient is the application of inexpensive polymers, such as waste polymers (Ahmadinia et al., 2011). Recycling waste materials has a significant positive impact on the environment, as well as the potential to be cost-effective and improve the performance of flexible pavements. Furthermore, if the enhanced characteristics of asphalt mixture modified with waste polymer are significant, it can be potentially used as an additive or modifier in SMA as well.

However, the huge volume of the annually generated waste materials in industrialised and developed societies has turned into a serious problem threatening the purity of our environment. Polyethylene Terephthalate (PET) is currently utilised for packing various products in a wide range of industries including the carbonated beverage containers.

Although PET has been very useful for us in packaging services and beverage bottles, disposal of this material has created environmental problems, which have resulted in more serious concerns in the said societies. Waste re-use is especially essential in dealing with certain discarded materials such as plastic containers, which, due to their longer biodegradation period, are considered as very harmful factors contributing to the contamination of the environment and ecosystem (Ahmadinia et al., 2011).

The aggregate gradation employed in this study was gap graded gradation, which is stone mastic asphalt. Stone mastic asphalt (SMA) is a mixture with stable, tough, and rut resistant features based on stone-to-stone contact, which results in a strong mixture with high durability and quality (H. Behbahani, 2009, Ibrahim M, 2006). SMA is regarded as an optimum mixture that can be used for road pavement construction in areas with a substantial volume of heavy traffic and frequency of costly maintenance services .

1.2 Problem Statement

These days, the increase in the number of road users has led to a dramatic increase in road traffic volume, traffic loads, and consequently, tyre pressure. These factors are important in contributing to pavement deformation and permanent structural or functional failure of the asphalt mixture. The high frequency of traffic loads can result in structural damage to asphalt pavements in the form of cracking of the asphalt layer, rutting along the wheel tracks, loss of adherence between aggregate particles and asphalt cement, which, in turn cause, stripping and other kinds of road surface deterioration. These sorts of damage, especially in hot and tropical climates have obliged these countries to spend millions of dollars on repairing and maintaining their roads (Kamaluddin, 2008). The development of modified asphalt mixes has been the focal point of recent explorations over the past few decades to enhance the overall

performance of road pavement mixtures. Thus, a new research to evaluate the SMA performance with different kinds of additive or modification appears to be necessary.

Although the employment of plastic bottles, which are usually used as containers for soft drinks and mineral water is a common trend worldwide, disposal of the waste plastic bottles in large volumes has created a major problem, especially in large cities (Kamaluddin, 2008). To overcome the problem and identify an appropriate solution, an analysis was carried out on the feasibility of the utilisation of waste plastic bottles as a modifier for use in SMA. This is expected to reduce the construction cost, as well as identify an effective way for waste disposal in industrialised societies. Therefore, the current research focuses on the evaluation and assessment of the feasibility of applying waste plastic bottles as additives for the modification of SMA into a higher performance mixture

1.3 Objectives of the Study

The main purpose of the current study is to determine the effects of incorporating waste plastic bottles (PET) on the physical characteristics of SMA. The volumetric and engineering properties of SMA mixes with various percentages of PET were evaluated under laboratory conditions through laboratory experiments. The results of the tests were statistically analysed and determination of the significance was performed with two-factor variance analysis (ANOVA) at certain confidence limits. Furthermore, some studies on polyethylene modified asphalt mixes have also been taken into consideration in this dissertation.

The main objectives of this research are as follow:

1. To investigate how incorporating waste plastic bottle (PET) affects the engineering properties of SMA.
2. To study and compare some fundamental mix property such as resilient modulus, rutting performance and moisture susceptibility of SMA mixture as result of incorporation of waste PET.
3. To determine the extent to which pavement distresses could be controlled or prevented by using PET.
4. To propose a means of re-using waste materials to decrease the contamination and pollution of the environment as a result of industrial products using synthesised and artificial materials.

Therefore, in this study, the researcher has tried to use waste plastic bottles in SMA to enhance its performance, and to re-use a waste material in industry in an environmentally friendly and economical way.

1.4 Advantages

The major advantages of this study can be classified as below:

- a) Employment of recycled materials to improve the properties of SMA.
- b) Reduction of SMA costs compared with other SMA-modifications.
- c) Increasing and improving environmental protection.

The current study may result in the discovery of a new pavement material whose properties will, hopefully, be applicable to solving certain problems concerning road pavement and construction or, at least, will provide an answer to some particular questions relating to road pavement mixtures.

1.5 The Scope of the Study

This study focuses on the impact of the employment of waste PET as an additive in SMA. The mixture with a Nominal Maximum Aggregate Size (NMAS) of 19mm (designated as SMA20) was utilised for sample preparation. In this study the dry mix process was utilized with a kind of novelty, i.e., instead of mixing the additive with the aggregate prior to adding the bitumen, as is usually practiced in conventional methods, in this project the PET was added to the aggregate after the bitumen was added and blended with the aggregate in the mixture (Ahmadinia et al., 2011). The fundamental quality tests for aggregate and bitumen, Marshal stability and flow, volumetric properties, drain down test, indirect tension test for resilient modulus, wheel trucking and moisture susceptibility tests were carried out on the prepared samples. It should be noted here that none of the known studies have ever focused on the application of PET as an additive for SMA modification. The experiments were conducted at the centre for transportation research laboratory at the University of Malaya (UM).

1.6 Organisation of the Dissertation

The discussed and analysed points in this dissertation have been grouped into five chapters as briefly explained below:

- Chapter One: This chapter intends to introduce the reader to the topic and title of the research, as well as to the problem statement and the motives behind the study. The main objectives of the study are also presented in this chapter.
- Chapter Two: In this chapter, the researcher has reviewed the literature relating to the previous studies on the same topics in relation to the current study and forming the background of this research. Therefore, this chapter has attempted to provide a brief background on Stone Mastic Asphalt (SMA), polymers, and the advantages of using waste materials in construction projects.
- Chapter Three: The third chapter of this dissertation reviews the detailed laboratory testing methods introducing the experimental setup employed in this research.
- Chapter Four: This chapter presents the outcomes and engineering properties of the PET-mixes achieved in the current study. Discussion and analysis of the obtained outcomes and findings and their correlation with the collected data forms the major portion of Chapter Four.
- Chapter Five: This is the final chapter, which concludes the discussion by presenting a summary of the main points discussed in the previous chapters and provides the major results from the study, which are supported by the relevant literature employed for substantiation of the claims along with the results of the experiments and tests.

2. LITERATURE REVIEW

2.1 Introduction

Bituminous mixture is a composite material made up of other distinct materials, employed in a variety of civil engineering projects such as the construction of roads. It consists of mineral aggregate, bitumen and air voids, which are the main components of bituminous mixture, blended and then laid and compacted to form the surface of roads (Wikipedia, 2011). Mixing of the aggregate and bitumen is done using one of the following methods:

- **Hot mix asphalt (HMA)** is a mixture of aggregate and bitumen blended through heating. For paving and compaction, the mixture has to be hot enough to form the HMA. In the cold countries, paving is limited to warm seasons due to the cold weather during winter or autumn, which causes the compacted base to cool down the asphalt mixture too much before it is packed to the desired air void content. Hot mix asphalt is the most common bituminous mix around the world for road pavements with heavy traffic, such as trunk roads and expressways or airport lanes.
- **Warm mix asphalt concrete (WMA)** is a mixture created by adding waxes, zeolites, or asphalt emulsions, which are added to the mixture in different stages. This allows a significant reduction in temperature for mixing and laying which, in turn, leads to more savings in fossil fuels and a reduction in the air pollution and environmental contamination resulting from the emission of CO₂, vapours, and aerosols. The lower laying temperature not only helps in better working conditions, but also makes the surface availability faster for utilisation, especially, in

construction projects with critical tasks and time schedules. Furthermore, the application of such additives in HMA can yield more easily compacted mixes, specifically in cold climates for which the length of the hauls is limited by the temperature.

- **Cold mix asphalt concrete** is created by emulsifying the bitumen in water with soap before being mixed with aggregate, since the viscosity of bitumen emulsion is lower, which renders the mixture easy to work and compact. After the evaporation of a sufficient amount of water, the emulsion breaks allowing the cold mix to take on the cold HMA properties. Cold mix asphalt concrete is usually used to patch cracked or dug up asphalt parts on roads with lighter traffic services.
- **Cut-back asphalt concrete (CBMA)** is created by the dissolution of the binder within kerosene or any other lighter petroleum products before being blended with aggregate. Since the dissolved binder is less viscous, the mixture can be handled and compacted more easily. After the mixture laid the lighter petroleum fraction evaporates.
- **Mastic asphalt concrete** sometimes called sheet asphalt, is a mixture of hard grade blown bitumen (oxidised), which is blended in a green cooker while heating to make a liquid of high viscosity, and then the aggregate is added in the mixture. The resulting bitumen aggregate mix is matured through cooking (heating) for approximately 7 hours. The thickness of mastic asphalt concrete usually needs to be about 20-30 mm for road, sidewalks, walker's lanes and about 10 mm for roof and flooring applications (Wikipedia, 2011).

The design of bituminous mixes involves the precise selection and proportioning of the component materials in a way that the final product will have the optimal properties. However, the main objective for the design of bituminous paving mixes is obtaining an economical mixture of bitumen and gradation yielding a mixture with the following properties and features (Abdelaziz, 2008):

1. Sufficient amount of bitumen in the mixture, which ensures a stronger and durable pavement.
2. Sufficient air voids throughout the whole compacted mixture, which allows for a slight amount of extra compaction beneath heavy traffic loads without vulnerability against shortcomings, such as bleeding, flushing, instability. However, the voids should be sufficiently low to prevent the harmful moisture and air from affecting the coat.
3. Sufficient stability to save the mixture against displacement and distortion in the case of heavy traffic.
4. Sufficient workability to allow efficient mixture placement without separation.

Road pavements start experiencing functional deterioration once they are open to heavy traffic, or freezing of groundwater during the cold season. Deterioration can include fatigue or alligator cracks, edge cracking, grade depressions, slippage and block cracking, potholing, ravelling, shoving, stripping, and rutting. In cold regions, groundwater freezing beneath the surface layer can result in serious cracks in the asphalt mixture even during a single cool season (Wikipedia, 2011). One way to increase the service life of road surfaces is using certain additives such as polymers or fibers to modify and improve the properties of the mix.

Modification of the bituminous mixture using polymers or fibers appear to have the greatest potential for successful application in the design of flexible pavements to increase the service life of the pavement or to reduce the pavement layer or its base thickness (Ahmadinia et al., 2011, Al-Hadidy and Tan, 2009, Özen et al., 2008).

Polymer or fiber modified asphalt mixture is a mixture with a wide variety of different uses in civil engineering and construction projects (Casey et al., 2008). The addition of polymers to mixtures increases the stiffness of the bitumen and significantly improves its susceptibility against temperature fluctuations. This, in turn, enhances the mixture resistance to rutting which is one of the commonest problems dealt with in pavement project agents and engineers in hot or tropical regions. In these cases, adding polymers to the mixture allows the use of softer base bitumen, which can provide superior low temperature performance. The addition of polymer to binders results in a significant increase of its cohesiveness and adhesiveness to effectively and strongly bind the mixture of components together. However, polymer plays another important role in the generation of an aggregate coating substance to improve the roughness of the aggregate surfaces and produces as superior asphalt mixtures (Shbeeb, 2007).

Up to the current study, there has not been sufficient information about the application of polyethylene terephthalate (PET) in HMA, and it should be noted that there is not any known study that has ever concentrated on the application of PET to SMA. Therefore, the main purpose of the current study is to identify the impact of incorporating waste plastic bottles (PET) on the SMA properties.

2.2 Typical types of road surface deterioration

Bituminous mixtures experience damage because of heavy traffic loads under different climatic and environmental conditions. Failure in HMA is a very common occurrence in both cold and hot climates, however, some kinds of failures such as permanent deformation (rutting) are more serious and acute in hot climates, because severe increases in asphalt pavement temperature can reduce the stiffness of HMA causing deformation, especially under heavy traffic loadings. Common HMA pavement deterioration is caused by heavy traffic loading, cold or hot environment or climate, use of unsuitable materials, construction deficiencies, or other external causes such as utility cuts. However, in recent years, engineers and researchers have hypothesised that the surface cracking phenomenon may have a close relationship with the non-uniform distribution of 3D contact pressure gauged between the structure of the pavement and the tyres of vehicle (Jacobs MMJ, 1992b, Jacobs MMJ, 1992a).

The outcome resulting from the measurement of free-rolling car and truck tyres confirm that there is considerable pressure from longitudinal and transverse contact, in addition to the usual contact pressure that affects the contact area (Tielking JT, 1987). Moreover, the occurrence of longitudinal surface cracks is mostly expected in hot climates in which they usually appear as the result of large transverse tensile stress concentrations close to the tyre edges (Collop, 1993). Surface cracking is also an outcome of horizontal tensile stresses that are exerted on the layers of asphalt by repetitive cycles of daily fluctuations in temperature in regions with more unstable climatic conditions.

2.2.1 Cracking

2.2.1.1 Alligator or fatigue cracking

Alligator or fatigue cracking occurs on the surface of HMA pavements and appears as a series of interconnected cracks like the ones on an alligator skin. Fatigue cracks are often the result of heavy and continuous traffic loadings on the tyre pressure area. These cracks are mostly related to weakness in the base course or sub-grade, excessive loading, insufficient pavement thickness or a combination of all or some of these factors. Fatigue cracks initiate from the bottom side of the asphalt layer, where the tensile stress and strain under a wheel load is at its highest level. Figure 2.1 illustrates an example of fatigue cracking.

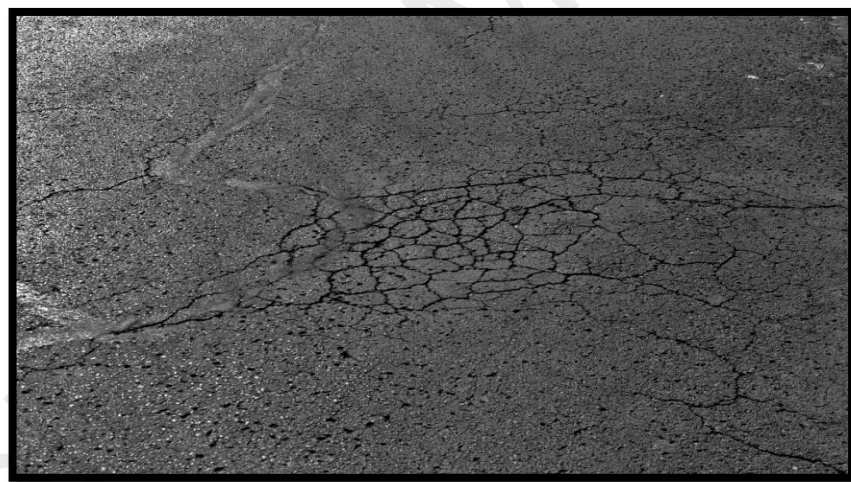


Figure 2.1: Alligator (Fatigue) Cracking (source: Asphalt Institute, 2009)

2.2.1.2 Edge cracking

Edge cracking is a longitudinal crack within one or two feet of the outer edge of the HMA pavement. With the passage of time and more traffic loadings further break-up of longitudinal cracks may take place beneath the pressure exerted by tyres as a result of heavy traffic causing crescent shaped cracks that branch to the edge of the HMA.

Because of this, edge cracks accrue at the edges of the roads due to inadequate support from a shoulder resulting from the weak base or sub-grade layer, frost heave or poor drainage. Figure 2.2 shows samples of edge cracks.



Figure 2.2: Edge Cracking (source: Asphalt Institute, 2009)

2.2.1.3 Block cracking

Block cracking is closely interconnected cracks in a large and rectangular series of pieces on the pavement surface. The size of these cracks is normally more than one foot (30cm) in each direction. These cracks usually occur in HMA with a hardened surface and cycles of daily temperature that cause shrinkage in the HMA layer. Nevertheless, it may also be triggered by volume changes in the fine aggregate in the HMA mixture containing low penetration binder and adsorptive aggregates. The difference between alligator (fatigue) cracking and block cracking is determined by the size of the blocks and presence of block cracking in non trafficked areas that can be helpful to differentiate them from each other. Figure 2.3 illustrates block cracking.



Figure 2.3: Block Cracking (source: Asphalt Institute, 2009)

2.2.1.4 Longitudinal (linear) and Transverse cracking

Longitudinal cracks are a kind of linear crack parallel or perpendicular to the HMA pavement axis, centre line, probably caused by one of the following:

- Asphalt layer shrinkage
- Fluctuations in temperature in harsh climates
- Poor construction for different sides of the HMA pavement, which can cause the axis or linear cracks to occur at the joints between two pavement sides
- Cracks occurring in underlying layers

The longitudinal cracking is illustrated in Figure 2.4 below.



Figure 2.4: Longitudinal cracking (source: Asphalt Institute, 2009)

2.2.1.5 Slippage cracking

Slippage cracking is easily identifiable from their appearance and shape. This sort of crack is shaped like half a moon and mostly appears at those parts of the HMA pavements that tolerate more vehicle turning or stopping. Pavements constructed with poor quality materials with inadequate bonding between their different layers can result in this problem in the weaker parts of the HMA surface, as illustrated in Figure 2.5 below.



Figure 2.5: Slippage cracking (source: Asphalt Institute, 2009)

2.2.2 Rutting

Within recent decades many pavements constructed with HMA have suffered from various kinds of problem including permanent deformation or rutting. Rutting is one of the permanent deformations of pavements, which mostly accrues under the wheel path resulting from heavy traffic loads on the roads (Jun Y, 2005). Rutting was believed to be a result of the increased number of trucks on the roads that exerted heavy tyre pressure on the pavements as a result of exceeding axle loads and traffic volume. This deformation is the earliest accruing distress, which sometimes only starts after a short

time, i.e., a few months, probably due to some failure in the layers of the asphalt or its underlying layers when the sub-grade soil is overstressed or the required density is not achieved because of inadequate compaction.

The particle shape of the aggregate is essential for the performance and workability of asphalt mixtures. When particles are angular rather than thin and flat, they show better performance against stresses and distresses; hence, the engineers recommend the application of angular particles to HMA. Particles with angular shapes which is a typical property of crushed stones, have stronger interlocking and better performance than round ones, and, consequently, better resistance against rutting brought about by heavy and repetitive traffic loads (Ahmadinia E, 2011).

Rutting can be a result of inappropriate mixture design such as high content of bitumen, high amount of rounded aggregate in the applied mixture and excessive filler or inadequate thickness of asphalt layer. The application of excessive bitumen in the mixture can result in a reduction of friction among the aggregate particles, which, in turn, can contribute to the loads tolerated by the cement of the bitumen rather than the structure of the aggregate. This problem can be created by insufficient thickness of the HMA pavement, poor compaction, or weakness in pavement layers which result from moisture infiltration or the use of materials of low quality in the asphalt mixture. Figure 2.6 presents rutting in HMA paved road (Gaiger, 2005).



Figure 2.6: Rutting (source: Pavement Interactive, 2008)

2.2.3 Ravelling

Ravelling and weathering occurs when the HMA pavement surface wears away because of the separation between the bitumen and the aggregate. Ravelling is usually discernible in the wheel path along the road where the highest pressure of vehicle tyre is exerted repetitively. Asphalt mixture of poor quality causes the pavement to become rougher. This leads to further and faster deterioration until displacement of the large pieces, which significantly reduces the life of the pavement, thereby requiring deep renovation. This problem ensues from the presence of both moisture and traffic. Figure 2.7 presents ravelling in HMA pavements.



Figure 2.7: Ravelling (source: Neal, 2007)

2.2.4 Potholes

Potholes are mostly caused by other types of pavement failure and deterioration continued over a long period of time. The source problems include alligator cracking, ravelling, poor drainage or the failure in patching of HMA pavements. This sort of distress creates bowl shaped holes in the pavement as displayed in Figure 2.8.



Figure 2.8: Potholes (source: Asphalt Institute, 2009)

2.2.5 Bleeding or Flushing

There is a direct relationship between the percentage of bitumen in the mixture and the bleeding problem that occurs on the asphalt pavement surfaces. The presence of excessive bitumen in the mixture can result in a thin asphalt film that covers the surface of the pavement. This phenomenon is known as bleeding or flushing. Bleeding or flushing can also be a result of an improperly made seal coat, too much bitumen in the mixture, excessive sealant in the joints and cracks beneath an overlay under heavy traffic, particularly in hot climates. The typical type of bleeding on the HMA pavement surface is presented in Figure 2.9.



Figure 2.9: Bleeding (source: Asphalt Institute, 2009)

2.3 Types of Hot Mix Asphalt (HMA)

Asphalt pavement or flexible pavement is widely employed throughout the globe. Asphalt pavement has good riding quality and it is much cheaper to construct in comparison to concrete or rigid pavements. HMA mixtures for asphalt pavement are divided into three main categories: dense graded mixture, open graded mixture, and gap graded mixture.

Dense graded mixture is a well-graded mix, which consists of bitumen and aggregate. The distribution of the size of aggregate particles is even and smooth from coarse to fine. Dense graded HMA is conventionally employed in road construction. One of the disadvantages of the dense grade mixture is that it does not have high resistance against rutting.

Open graded mixture is intended to let in water through its permeability, which makes it considerably different from other kinds of mixture such as dense graded or SMA, which are both relatively impermeable by comparison. Crushed gravel or stone with a very small percentage of sand, modified bitumen, and possibly fibers can sometimes be

incorporated into the surface mixture of open graded mixtures. One of the typical disadvantages of this category is its insignificant structural strength unlike dense graded mixture or SMA.

SMA is a gap-graded mixture, which maximises the durability and rutting resistance by the application of a stone skeleton bound together with a mixture comprising a binder, stabiliser, and mineral filler. SMA is considered to be a premium mixture despite its higher initial cost due to the enhanced binder content and application of durable aggregate. Nevertheless, the improved performance makes it suitable for high traffic loadings.

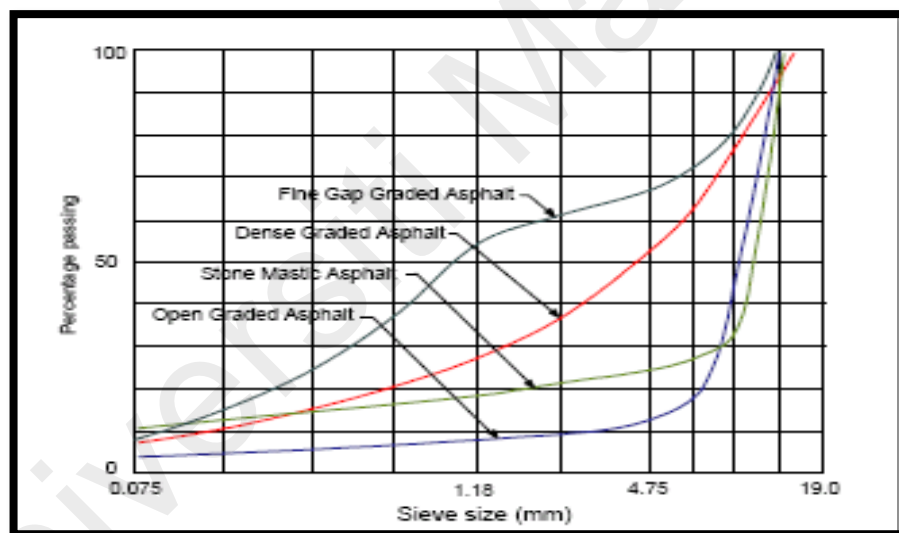


Figure 2.10: Various grading curves (source: Mangan and Butcher, 2004)

2.4 Stone Mastic Asphalt (SMA)

2.4.1 Introduction

SMA is a bituminous mixture made up of a skeleton of coarse aggregate and a binder rich mortar with as much as 6% to 8% liquid bitumen. SMA consists of crushed coarse

mixture, crushed fine aggregate, asphalt binder, mineral filler, and a stabiliser such as cellulose, mineral fibers, or a polymer for the binder (Chiu and Lu, 2007).

Figure 2.11 displays a view of a typical SMA mixture and conventional dense graded mixture. The image on the left shows a higher percentage of bitumen and fractured aggregate in comparison with the conventional hot mix asphalt shown in the right hand image. As the image illustrates, conventional dense graded mixture contains less bitumen content with a more uniform gradation of the aggregate particles.

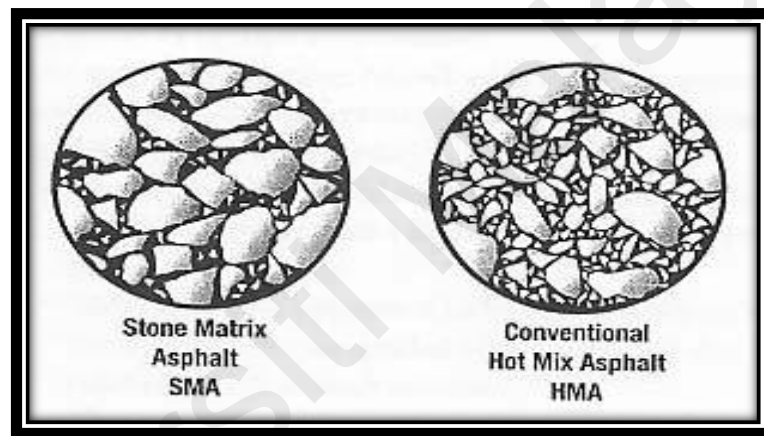


Figure 2.11: Comparison between SMA and conventional HMA (source: NAPA, 1999)

As confirmed and revealed by various case studies, the application of SMA to road surfacing considerably enhances the durability of the mixture, as well as the resistance against rutting. The resistance of SMA against rutting is higher in comparison to that of dense graded mixtures due to the coarse aggregate skeleton of SMA. This feature provides the contact of stone-on-stone among the component particles of the coarse aggregate (Moghaddam TB, 2011). The major reason for utilising fully crushed aggregate gap gradation (100%) is the enhancement of the degree of pavement stableness through the interlocking resulting from stone-to-stone contact (Ibrahim M, 2006). This interlock provides the mix with a stronger stone-on-stone skeleton that is

stuck more stably together as a result of a strong composition of asphalt cement, filler, and other additives in the mixture to improve its stability (H. Behbahani, 2009, Moghaddam TB, 2011).

SMA is characterised by a mixture of gap-graded aggregate, which minimises the fine and medium sized aggregate (as displayed in Figure 2.12) resulting in a stable and structurally tough mixture. The strength and stability of the SMA is because of the stone portion of the coarse aggregate skeleton, which results in an increase in the internal friction rate and the resistance of the mixture to shear thereby enabling it to resist rutting and wearing out as a result of repetitive studded tyre contact.

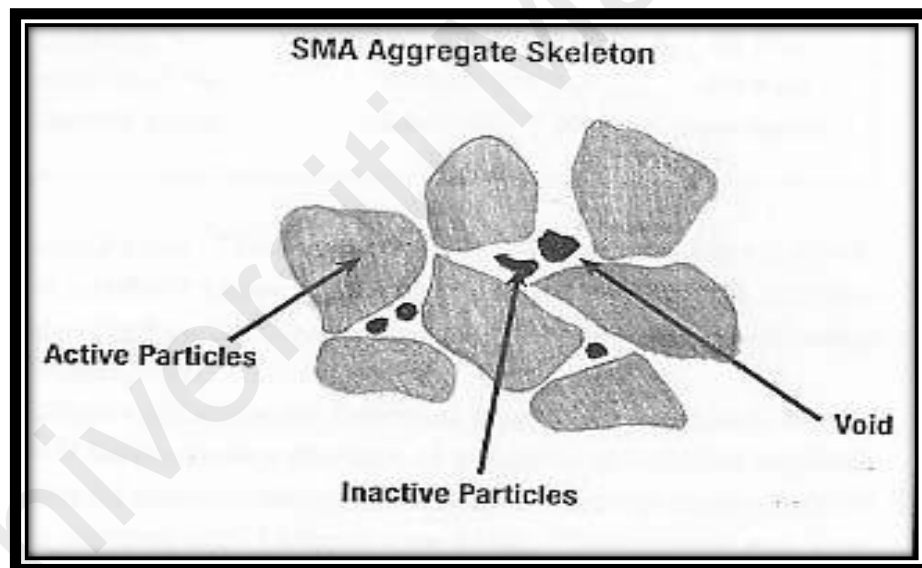


Figure 2.12: SMA aggregate skeleton (source:NAPA, 1999)

However, some weaknesses are distinguishable in the SMA structure, such as drain down, which ensues from the absence of mid-sized aggregate in the gap-graded mixture, which has a high asphalt binder content instead. Since the SMA is assembled in the silos and then transported by trucks to the construction site, after it is placed, the asphalt binder tends to drain down, which is called mixture draindown. Mix draindown is

usually avoided by adding cellulose fibres, mineral fibres or other modifiers to hold the binder in place thereby providing the mix with durability.

2.4.2 History of SMA

SMA was first developed and used in Germany in the mid-1960s to surface pavements to enhance their resistance against rutting as well as enhance their the durability (Ibrahim M, 2006). It was then introduced to the rest of Europe because of its better resistance to damage from studded tyres than other types of HMA (Roberts, 1996). The acronym of SMA is derived from the German term for split stone mastic asphalt (Keunnen, 2003). Based on its performance history, it began to be used as a pavement layer for highways carrying heavy traffic loads throughout Europe.

Because of the indispensable and significant achievements brought about by the utilisation of SMA in Europe, together with the collaboration of the Federal Highway Administration, it found its way to the US in 1991 and has since been used in the construction of road surfacing in some selected states across the country (H. Behbahani, 2009, Ibrahim M, 2006). Nowadays, over 28 states across the US utilise SMA in the construction of asphalt roads. According to reliable sources, the application of SMA has led to a considerable enhancement in pavement durability of up to 20–30 per cent in comparison to the conventional mixes used for such construction before (Al-Hadidy and Tan, 2009). These significant results have contributed to the increase of SMA application to various road constructions in the US. Following the US, Japan was the next country to use SMA for road pavement mixtures, which has also been backed by the strong success and achievements in that country (Ibrahim M, 2006).

Subsequently, Canada also employed SMA in the construction of road pavements across its states with significant success. Nowadays, the UK uses SMA to resurface most of the roads that encounter heavy traffic to render surface treatment economical and cost-effective. Today, SMA is considered as the top choice in pavement surfacing and resurfacing where high performance and long durability is an essential requirement in pavement construction throughout the globe. SMA application has recently extended its domain to most of the developing countries, especially in Asia and Latin America.

2.4.3 Advantages of SMA

The unique characteristics of SMA have proven it to be the optimal asphalt pavement, which enables the roads to withstand the heavy vehicle loadings and wear resulting from super wide, studded and single truck tires (Schimiedlin, 2002). Another property of SMA is its ability to provide optimum service concerning the decks of bridge as a wearing surface layer to protect the deck membranes. The two most important advantages of SMA are its resistance to rutting and its long term durability, which enhances the performance and effective life period of the pavements by 30-40 per cent in comparison to pavements constructed with conventional dense-graded HMA.

Moreover, SMA can also increase skid resistance as a result of the considerable percentage of fractured aggregates used in it, especially, in wet environments (NAPA, 1999). Despite the fact that SMA does not let water drain through it, the texture of its surface is like that of open-graded aggregate that absorbs the noise produced by the contact of the tyre with the asphalt surface. The noise killing ability of SMA is more than that of dense graded aggregate but it is equal to or insignificantly less than open

graded aggregate (Mangan and Butcher, 2004). Surfaces with coarser texture are able to absorb not only tyre noise but also glare and water spray on the pavement.

The noise absorbing characteristics of SMA make it a the preferred choice for drivers, passengers, and the people who are living in close proximity to roads with heavy traffic. The tranquillity and quietness that results from such pavement surfaces play a significant role in long distance travelling by creating a smooth and quiet voyage for the driver and passengers. This kind of texture also gives anti-splash characteristics to the pavements, especially in wet climates or seasons.

The SMA manufacturing plant for producing and compacting the SMA mixture, are the same tools and machinery used for HMA. The SMA is usable at intersections and similar points where the traffic stress is considerably high for which dense grade and open graded aggregate are not a suitable choice. In the case of pavements suffering from cracking problems, SMA is an optimal choice to be utilised as an overlay to reduce serious reflection cracking, which may result from the underlying cracked pavements due to the flexible mastic. The SMA durability needs to be greater than or, at least, equal to dense graded aggregate. However, it needs to be considerably greater than the open graded aggregate in any case (Mangan and Butcher, 2004).

SMA was initially used in asphalt mixes to enhance their level of resistance against studded tyre wear. Another advantage of SMA is that it can increase the resistance of the mixture against plastic deformation, which is one of the common problems that result from heavy traffic loading, which exerts severe stress on the pavement. Moreover, its rough surface provides adequate friction, especially, when the asphalt loses its surfacing cement film, which wears out through heavy and frequent vehicle traffic.

However, other advantages of SMA make it the most preferred mixture for pavement construction projects around the globe in comparison with other conventional HMA types. Some of these properties are its enhanced durability, high resistance to reflective cracking and improvement against ageing (Ibrahim M, 2006, Shbeeb, 2007) .

2.4.4 Disadvantages of SMA

There are also some disadvantages that might affect the conventionality of SMA as the preferred choice in comparison to other types. One of these disadvantages is related to the 20-25% extra cost that the project managers and investors are obliged to tolerate compared to other conventional mixture types such as dense-graded ones. The stronger crushed aggregate, higher bitumen content, and other fibers or additives are the main reasons for the higher cost of SMA (NAPA, 1999).

However, the most important disadvantage of SMA is its higher initial expense and its binder drainage. As SMA is gap-graded with high bitumen content, it needs to be stabilised by additives, such as polymers or fibers, to inhibit binder drainage over time (Ibrahim M, 2006, Shbeeb, 2007, Muniandy R, 2001) .

2.4.5 Composition of SMA

SMA is composed of crushed fine (sand) and coarse aggregate, bitumen, stabilising agents, and mineral fillers as displayed in Figure 2.13 below. The mixture of the stone skeleton provides gap-graded stone-on-stone texture to tolerate heavy loading exerted by frequent vehicle traffic on the road. This kind of structure strengthens the resistance

of the pavement against rutting and enhances its durability in continuous and long-term stress.

The fine aggregate, mineral filler, and bitumen make the binder adhere to the stone skeleton and provide the mixture with high cohesion. Other additives like polymers or fibres are added into the mixture to increase its stability and secure the mastic in the structure of the asphalt to reduce or block the bitumen drain down. Mineral fillers and additives are employed to reduce the binder drain down during pavement construction and raise the bitumen content in the mixture and enhance durability of the mixture.

SMA contains a high percentage of coarse aggregate (70-80%), a high percentage of bitumen (+6%), and a high percentage of mineral filler (about 10%) (Roberts, 1996).

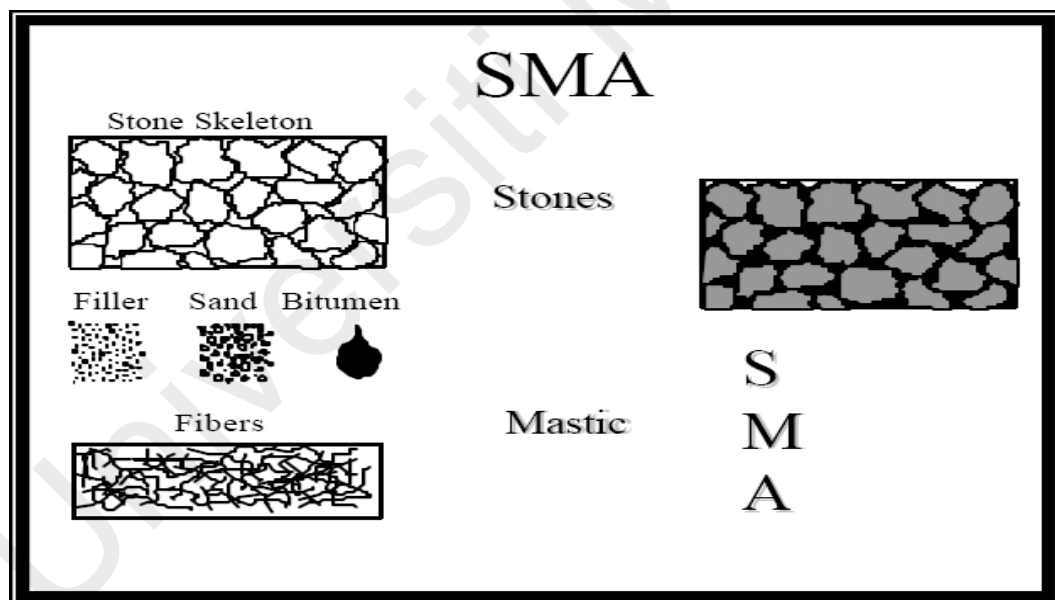


Figure 2.13: Major components of SMA mixture

2.4.5.1 Characteristics of Aggregates

The quality of aggregates employed in SMA needs to be high with a highly rough texture and cubic shape to be able to resist any displacement or rutting. The hardness of

the aggregate content helps the pavement to resist against breaking under heavy loadings of frequent tyre traffic. The aggregate should also have high resistance to polishing and abrasion (Pierce, 2000).

However, the first measure taken in designing the intended mixture is the careful selection of aggregates to meet the requirements of the mixture specification. The requirements of quality of coarse aggregate are presented in Table 2.1. Since the contact of stone-on-stone is the essential backbone of SMA, the aforementioned characteristics, specifically the shape and hardness of the aggregate, are more important in SMA rather than conventional dense graded mixes.

Table 2.1 : Coarse aggregate quality requirements (Jabatan Kerja Raya, 2005)

Test	Method	Specification
LA Abrasion, (% Loss)	ASTM C 131	$\leq 30 \%$
Aggregate Crushing Value	MS 30	$\leq 30 \%$
Flakiness Index	MS 30	$\leq 25 \%$
Polished Stone Value	MS 30	$\geq 50 \%$
Soundness (5 Cycles)	AASHTO T 104	$\leq 18 \%$
Magnesium Sulfate Water	MS 30	$\leq 2 \%$

2.4.5.2 Bitumen

The grade of bitumen content employed in SMA usually equals the same grade or slightly stiffer grade than used in dense-grade mixtures. When bitumen is stiffer, it

minimises any potential drain down and helps to reduce rutting, which is usually expected in higher temperatures. Nevertheless, stiffer bitumen might result in thermal cracking. Using high optimum bitumen content and increased film thickness in the SMA, minimises the possibility of thermal cracking, especially in comparison with dense-graded mixture (Roberts, 1996).

According to NAPA (1999), the utilisation of binders modified by polymer(s) along with fibre would enhance the resistance of the pavement against problems such as rutting or fatigue cracking. The modified bitumen can be achieved through incorporating a quantity of stabilising additives (such as polymers) to conventional bitumen.

2.4.5.3 Mineral Filler

The function of filler in the SMA is essentially to stiffen the bitumen rich SMA. The application of higher amounts of too fine a filler can lead to excessive stiffness of the mixture rendering it difficult to work, which might result in the mixture being susceptible to cracking. A mineral filler is usually added into the mixture as part of the gradation of the aggregate. The content of the filler (passing the 75 μ m sieve) in the SMA mixture can range from 8-10% of the total amount of aggregate

This high content of mineral filler in the mixture plays a significant role in the properties of SMA, especially relating to the air voids (VIM), optimum bitumen content (OBC), and mineral aggregate voids (VMA). Due to the relatively large amount of the filler, the performance of SMA becomes very different from the other types of HMAs (Ibrahim, 2005).

2.4.5.4 Stabilising Additives

During the last decade, a variety of additives have been introduced and developed to help improve the physical properties of the bituminous mixtures. Some additives, e.g., rubbers, fibers, artificial silica, polymers, carbon black, or a combination thereof, have been utilised in the mixtures. The role of these materials is to increase the stiffness and durability of the mastic during production and placement in hot conditions, especially in hot or tropical climates (Pierce, 2000).

Additives such as fiber and polymer are used in most of the current SMA projects. The addition of fibers into the SMA is normally to reduce or remove the drain down, which is usually experienced during mixing, transporting or compaction. Loose organic fibres (such as mineral and cellulose fiber), are commonly employed in mixtures by 0.3- 0.4% of the mixture weight (Brown and Manglorkar, 1993). Other fiber types, such as glass, polyester, rock wool, and natural wool fibers are appropriate for use in the mixture. However, cellulose fiber is acknowledged as being the most economical compared to other types (Mangan and Butcher, 2004).

When polymer is used, it is usually mixed with bitumen before being delivered to the plant, however, in some cases it has been added at the plant (Roberts, 1996). Adding polymer can further stiffen the bitumen and enhance its resistance to drain down. Furthermore, polymer can enhance the adhesion property of the bitumen to the aggregate, especially in wet conditions (Robinson, 2004). The polymers are added to the mixture usually in the range of 3.0–8.0% by weight of the bitumen (Ibrahim, 2005).

2.5 Mixture Design Overview

The methods used for SMA designing, production, and placement are similar to those applied to the design and production of dense graded mixtures, normally carried out by Superpave or Marshall procedures. SMA primarily uses gap-graded aggregate, while the standard mixture utilises an aggregate gradation that is more smooth and evenly distributed throughout the gradation resulting in the production of a denser mixture (Schimiedlin, 2002).

The design of an SMA plays a key role in the provision of an aggregate grading that will accept a high amount of bitumen, which provides a durable mixture, without binder drainage. However, an unsuitable or incorrect SMA design can result in such drainage in the truck bodies and fatted areas of the surfacing, particularly in thick surfacing areas. Conversely, the design of an aggregate that requires a low binder content in order to prevent binder drainage may result in a mixture with weak and short durability and have a reduced life.

Unlike an open-grade asphalt mixture, most of the voids among coarse aggregates within an SMA are usually filled with binder and mineral filler. Normally, 3-5% air void content is typically provided in the designed SMA. Excessive bitumen will push the coarse aggregate particles apart with a sudden reduction in the resistance of the pavement against shear deformation. The application of too little matrix may, however, lead to higher air voids in the mixture resulting in a reduction of the durability of the pavement, its fast ageing, and susceptibility to damage caused by moisture (Pierce, 2000).

2.6 Mix Design Methods

2.6.1 Marshall Method

The Marshall Method is the most conventional and common method employed for making and evaluating trial mixtures in obtaining the optimum bitumen content. This method was originally introduced by Bruce Marshall, a civil engineer collaborating with the Mississippi State Highway Department (Ghassan, 1992). However, the initial features of this method have been improved through time by the US Army Corps of Engineers, and standardised and elaborated in ASTM D1559 (Garber, 2002).

Usually, the Marshall Method is used in the design of SMA to provide verification of the acceptable amount of voids in SMA mixes. Specimens were prepared in the lab using 50 or 75 blows per side produced by a Marshall Hammer. It is easier to achieve the compaction of the SMA on the road and the desired density level in comparison to that required by conventional HMA (Ibrahim, 2005).

The procedures for heating, mixing, and compacting the mixture of aggregates and bitumen are specified by the Marshall Method, which is then subjected to a test of stability-flow test and an analysis of density-voids (Garber, 2002).

2.6.2 Superpave Mix Design

One of the products of the Strategic Highway Research Program (SHRP) is Superpave, which stands for superior performing asphalt pavements, and explains the material characteristics in respect of the traffic and climatic considerations (Huang, 2004). Most of the state highway agencies have been able to fully implement Superpave.

A bitumen specification based on climate and traffic loadings, a volumetric mixture design and analysis system, mixture analysis tests as well as a system of performance prediction including specific software, climatic database, and models of the environment and performance are the three main elements used in the Superpave. Nevertheless, the most important component of Superpave may be its new bitumen grading system, which is designed to link with pavement performance (Huang, 2004). Therefore, Superpave can be considered as a system based on performance. It is a system of specifications applicable to asphalt pavement design that is strong enough to successfully tolerate traffic loadings and climatic stresses.

The volumetric properties of Superpave include the percentage of air voids (VIM), voids in the mineral aggregate (VMA), and voids filled with bitumen (VFB). Superpave enables highway engineers to fine-tune the asphalt mixtures to adjust them to various climates and traffic loads. Therefore, pavements produced this way have been proved to be of higher durability and less likely to rut in hot weather or to crack in cold weather.

2.7 Additives

Conventional bituminous material does not have the performance requirements for road construction, which are increasingly subjected to heavy loads, heavy traffic, frequent stresses and various climatic and environmental conditions. When the produced bituminous mixture does not meet the climate, traffic, and pavement structure requirements, to qualify as an optimal mixture, this kind of bituminous mixture needs to be modified by an attractive alternative to gain the required properties to be able to overcome the stresses and distresses that the pavement undergoes resulting from bitumen deficiencies in the mixture. Modification of bituminous mixtures offers one answer to overcome this problem and thereby improve the performance and durability

of the pavement. Isacsson U (Isacsson and Lu, 1995) suggested the application of polymers to bituminous mixtures to modify it in a way to significantly enhance its performance. The main objective of the bitumen improvements is production of high quality bitumen materials that can effectively resist permanent deformation and fatigue cracking.

2.7.1 The need of additives

Much research has been conducted to determine the reasons and methods to modify bituminous materials. Lewandowski (Lewandowski, 1994) has done research on one such topic and summarised the main reasons for modification of bituminous materials with different types of additive as follows:

- To obtain softer blends at low service temperatures and reduce cracking
- To improve the fatigue resistance of blends
- To increase the stability and the strength of mixtures
- To reach stiffer blends at high temperatures and reduce rutting
- To reduce the structural thickness of pavements

According to the definition of King et al. (King, 1986), an asphalt modifier can be added to the binder or the mixture to improve its properties. The choice of the modifier for a specific project depends on various factors, such as construction ability, availability, cost, and expected performance. Roberts et al. (1996) stated that the technical reasons for applying modifiers in bituminous mixtures are to make stiffer mixtures at high service temperatures to resist rutting as well as to obtain softer mixtures at low service temperatures to minimise thermal cracking and improve the fatigue resistance of the asphalt pavement. Improvement in the performance of the bituminous mixture is affected by the polymer, which is largely due to the improvement

achieved in its rheological properties, which allow flexibility of the mixture under heavy loads. The modified mixture is less brittle at lower temperatures while it is stiffer at higher temperatures in contrast with normal mixtures. This makes polymer modification highly attractive for construction companies and pavement designers and agencies (Shbeeb, 2007).

According to Epps,(Epps, 1994), normal bitumen does not display good engineering properties in heavy loads and high or low temperature conditions. It becomes softer in high temperatures and more brittle in cold regions. In order to solve this problem, polymer is usually added to bitumen to improve its engineering properties. The main advantage of polymer-modified bitumen is its significant effect on the pavement performance, which enhances its resistance against fatigue cracking, permanent deformation, and moisture susceptibility. The stiffer the bituminous mixture, the more resistant it is to permanent deformation. Brule (1996) mentioned that polymer added to the mixture increases its elasticity and stiffness in hot climate temperatures (Hamed, 2010).

2.7.2 Classification of Additives

Studies that have been conducted to classify bitumen modifiers according to their composition, categorised it into several main groups, such as polymers (elastomeric and plastomeric), fillers, fibers, hydrocarbons, anti-stripping agents, and crumb rubber. These additives vary significantly in their physical and chemical properties, which have a wide variety of effects on asphalt concrete pavement performance accordingly. Asphalt additives render the mixture stiffer, especially, in hot conditions and less stiff at colder temperatures. They control the elasticity of the mixture in normal temperature conditions (Hamed, 2010).

Table 2.2: Types of asphalt additives (Roque, 2004)

Type of Modifier	Purpose	Example
Filler	<ul style="list-style-type: none"> -Fill voids - Increase stability -Improve bond between aggregate and binder 	<ul style="list-style-type: none"> -Portland cement -Fly ash -Lime
Elastomers	<ul style="list-style-type: none"> - Increase stiffness at higher temperatures. -Increase elasticity at medium range temperatures to resist fatigue cracking. - Decrease stiffness at lower temperatures to resist thermal cracking. 	<ul style="list-style-type: none"> -Natural rubber -Styrene-butadiene-styrene (SBS) -Styrene-butadiene rubber (SBR).
Fiber	<ul style="list-style-type: none"> -Improves tensile strength -Improve cohesion -Allow for higher asphalt content without drain down 	<ul style="list-style-type: none"> - Asbestos - Polyester -Fiber glass
Plastomers (Thermoplast)	<ul style="list-style-type: none"> -Increase high temperature performance -Increase structural strength -Increase resistance to rutting 	<ul style="list-style-type: none"> -Polyvinyl chloride (PVC) -Ethyl-vinyl-acetate(EVA) -Ethylene propylene (EPDM)
Oxidant	Increased stiffness after placement	- Manganese salts
Hydrocarbons (Natural Asphalts)	<ul style="list-style-type: none"> - Restore aged asphalts - Increase stiffness 	<ul style="list-style-type: none"> - Oils - Natural asphalts (Lake Asphalt) - Gilsonite
Anti-strippers	- Minimize binder stripping	<ul style="list-style-type: none"> - Lime - Amines
Antioxidant	- Increase durability by retarding oxidation	<ul style="list-style-type: none"> - Leads - Carbons - Calcium salts
Extender	- Decreases the amount of asphalt cement needed (typically 20 - 35% of total asphalt binder)	<ul style="list-style-type: none"> - Sulfur - Lignin

2.7.3 Benefits of Using Additives

Modified bituminous mixtures have higher stiffness and resistance against permanent and serious deformations and fatigue cracking (Hamed, 2010, Whiteoak.C.D, 1990). The area of bitumen additives is rather complex, in that the improvement in the pavement performance is related to the binder rheology and depends on the modifier type with respect to the polymer content. According to Bahia's (Bahia, 1995) study, the effect of polymer modification from the scanning electron microscope images, is that the modified bituminous mixtures have better binder-aggregate adhesion, which increases its toughness level. Polymer modification affects the binder's flexibility. This leads to fatigue resistance and increases the viscosity of the binder, which improves the tensile and compressive strengths of the mixtures. The role of the modified bitumen is to increase the resistance of bitumen to permanent deformation in hot climates (Brule.B, 1996).

One of the main advantages of applying polymer technology to bituminous mixtures is to improve the adhesion between the aggregates and binders. A study conducted by Khattak and Baladi (Khattak, 2001) on the influence of polymer as a modifier revealed that the modification can increase the resistance of bitumen to loading, while making it less susceptible to temperature fluctuations. Furthermore, some polymers increase the bitumen adhesion to the stones and its resistance to cracking. An ideal binder needs to have optimal cohesion and adhesion properties. The engineering properties of modified bitumen depend on the type of the applied modifier with respect to its content and also depend on the type of bitumen employed. However, the main advantage of elastomers such as (SBR) and (SBS) is their capability to increase the strength of the modified bitumen mixtures (King, 1999).

Numerous studies confirm that the application of crumb rubber modified binders to pavement mixtures can improve its resistance against fatigue cracking. According to Bahia and Davies (Bahia, 1994), the impact of crumb- rubber on engineering properties of bituminous mixtures is significant in a way that rubberised mixtures display higher resistance to rutting in comparison to the unmodified bituminous mixtures. Two kinds of blending process for bituminous mixtures are the wet and dry processes. In the wet process, the modifier is mixed with the bitumen prior to adding the aggregate, while in the dry process the modifier is first added to the aggregate and before the addition of the bitumen (Ahmadinia et al., 2011, Hamed, 2010).

Initial research on the case reveals that bitumen unmodified with polymer is very susceptible to fatigue, which can be significantly prevented by the application of additives to the mixture. Green and Tolonen (Green, 1977) reported that applying crumb-rubber to flexible mixtures should also take into consideration its impact on the chemical, physical, and rheological features of the bitumen binders modified by the crumb-rubber. The improvement achieved in the properties of the binders modified by the crumb-rubber depends on the interactive relationship between the bitumen and the crumb-rubber. In this respect, Hanson, et al. (Hanson, 1995) mentioned that crumb-rubber can be employed as a modifier for bitumen to reduce waste tyre pollution and enhance the engineering properties of bitumen mixes. The rutting test and indirect tensile test results confirm that the addition of rubber obtained from recycled tyres into bituminous mixture can significantly help improve its engineering properties (Hamed, 2010).

2.8 Polymer

2.8.1 Introduction

Polymer can be described as a synthetic or natural compound of normally high molecular strength made up of repeated, linked molecules (Tapkın et al., 2009). The polymers employed for modification purposes in bituminous mixtures are divided into three main categories: plastomers, thermoplastic elastomers, and reactive polymers. The addition of thermoplastic elastomers into binders gives them higher elasticity. However, the application of plastomers and reactive polymers make the binder stronger and more rigid against heavy traffic loadings that usually bring about serious deformations in the surfacing of the pavement (Al-Hadidy and Yi-qiu, 2009b, Al-Hadidy and Yi-qiu, 2009a). Furthermore, plastomers increase the stiffness and viscosity of the bitumen in moderate temperatures. Nevertheless, the achieved performance through these modifiers concerning the enhancement of bitumen elasticity in sudden and frequent temperature fluctuations is not considered as satisfactory as expected (Shbeeb, 2007). However, some plastomeric polymers commonly employed for modification purposes are ethylene-butyl acrylate (EBA), and polyethylene (PE) (Al-Hadidy and Yi-qiu, 2009b, Al-Hadidy and Yi-qiu, 2009a).

Modification of the bituminous mix with polymer seems to have great potential for the successful application in the design of flexible pavements to enhance their effective service life, or minimise the thickness of its layer or base thickness (Al-Hadidy and Tan, 2009, Özen et al., 2008). The application of polymer modified bitumen enhances the service life length of the pavement, especially in severe conditions such as parking areas tolerating heavy traffic loads, deformed road base, and stress-relieving interlayer. However, a modified binder is by no means a new phenomenon, it has been proven to meet the requirements for optimal performance in modern pavement construction and

coatings; in addition, it appears to be a practical, logical, and economical approach compared to other approaches.

Polymer modified bituminous mixture has a wide range of applications nowadays in most of the developed and developing countries (Casey et al., 2008). Adding polymer to the bituminous mixture increases its stiffness and improves its non-susceptibility to temperature variations in different regions and climates. This feature, in turn, raises the level of resistance of the mixture to rutting. In such cases, the applied polymers allow the application of softer base bitumen that can provide superior low temperature performance (Ahmadinia et al., 2011). Furthermore, polymer modified binders have a high degree of adhesion and cohesion. Polymer is also used to create aggregate coating material, believed to raise the roughness level of the aggregate surface and generate a superior asphalt mix (Shbeeb, 2007).

Today, asphalt mixtures modified by polymer are relatively more costly for road pavements (Chiu and Lu, 2007, Ahmed.LA, 2007). Therefore, it is important to analyse cost-effective methods to make the construction projects more economical and feasible before discussing its commercial use. For instance, block styrene-butadiene elastomer (also known as block SBS/SB rubber), is widely employed by many countries to modify the engineering properties of the asphalt mixture. Nevertheless, despite its excellent properties, the polymer modified mixture has one main disadvantage, that is, the high price of the block styrene-butadiene elastomer, which restricts its wide application to most construction and pavement projects, especially, in developing countries. One solution for this problem is the application of cheap polymers obtained from waste and disposed materials (Ahmed.LA, 2007).

2.8.2 History

The first patent for bitumen modification processes with synthetic or natural polymers dates back to 1843, while the initial test projects in this field were launched in Europe as early as the 1930s, and employment of neoprene latex was first enacted in North America in the 1950s (Yetkin, 2007). However, twenty years later (1970s), Europe had already overtaken the US in the application of polymer modified bituminous mixture for road pavement, since in Europe the warranties provided by contractors encouraged unprecedented interest in the reduced costs of the lifecycle despite the higher costs in the initial phases of the projects. These initial costs restricted the use of polymer modified bitumen in the United States. However, the mid-1980s witnessed the introduction and use of new types of polymers in Europe and then the US, where a poor economic outlook increasingly prevailed throughout the whole country. The Australian National Asphalt Specification has provided specifications and guides for polymer modified binders (Yetkin, 2007).

An approach to life cycle cost analysis has been developed by the US Federal Highway Administration (FHWA) to assess and measure the life cycle costs applicable to pavement construction that use asphalt rubber binders as well as other treatments. The results of relevant studies reveal the cost effective feature of asphalt rubber.

A survey by the US State Department of Transportation carried out in 1997 discovered that 47 of the 50 states in the country were interested in the application of modified binders in their future projects, while 35 of the respondents said that they would employ the binders even in greater amounts in future construction projects (Yetkin, 2007).

Many studies have been conducted on the evaluation of the performance of polymer-modified pavement mixtures around the world. Furthermore, experiments on binders have been undertaken in various labs in different regions the results of which are steadily being revealed. Based on a study known as Nevada, in 2003, the viscosity of binders modified by polymer at 60°C is usually greater in comparison to the viscosity of unmodified binders despite the slight modifications of the penetration rate at all temperatures .

2.9 Polyethylene Terephthalate (PET)

Plastics have become an inseparable aspect of modern life in developed and developing societies. Plastic materials have touched nearly all aspects of our life from very personal paraphernalia to the industrial pieces and machinery, which are used in clothing, computers, cars, telephones, packaging, etc. Packaging is one of the modern industries that consume plastic for packaging purposes and is the biggest consumer of plastics. Polyethylene terephthalate (PET), which is thermoplastic polyester, is commonly utilised in the packaging industry(Wikipedia, 2011) . Plastic bottles used for soft drinks, mineral water, tea boxes, biscuits boxes, and the like are also made of PET.

PET was first registered as a patented product by the Calico Printers' association of Manchester in 1941 and by Nathaniel Wyeth in 1973 who patented plastic bottles specifically. The versatility of plastic packaging has made it one of the most applied modern materials in nearly all fields and aspects of modern industry and life. However, there are numerous new applications of this material that are being developed yearly in various industrial and consumer societies.

The major portion of PET in the world (60%) is produced from synthetic fibers to be used to make plastic bottles; approximately 30% of the total demand for plastic products around the world. In the discussion of textile usage, PET is commonly known as "polyester" despite its widespread application in packaging services.

2.9.1 Structure

Polyethylene terephthalate (PET, also known as PETE, PETP or PET-P) belongs to the polyester family and is made of a thermoplastic resin (Ahmadinia et al., 2011). PET is one of the most essential raw materials used in making synthesised fibres. The structure of PET is formed of linear saturated thermoplastic polyesters, which have been in use since 1966. The procedure for making these kinds of polymers consists of two phases:

- a) Esterification of dimethyl Terephthalate with ethylene glycol
- b) Polycondensation

2.9.2 Properties of PET

Common features of polyethylene Terephthalate (PET) can be summarised as follows:

- ✓ Strong, hard, and stiff
- ✓ Properly and sufficiently tough, even at lower temperatures
- ✓ Adequate creep resistance
- ✓ High abrasion resistance and low friction
- ✓ High degree of dimensional stability
- ✓ Wide range of service temperature, i.e., 40°C to 100°C
- ✓ White colour in semi crystalline state
- ✓ Transparent in amorphous state (glass clear)

- ✓ High insulator to electrical currents or shocks
- ✓ High resistance against tracking
- ✓ Lower water absorption capability
- ✓ Physiologically acceptable
- ✓ High resistance against stress cracking
- ✓ High resistance against weathering and high temperatures
- ✓ Slightly lower stiffness, hardness, heat resistance in contrast to crystalline PET
- ✓ Higher toughness in contrast with crystalline PET.

The large and uncontrolled amount of PET bottles produced in recent decades has contributed to the creation of serious environmental problems, mostly because of the hygienic consideration, in that they are not reusable for refilling. Hence, nearly all the produced bottles are disposed of as waste plastic materials whose decomposition and return to nature is outside of the lifetime of the current generations (Mahdi et al., 2007). Recycling these PET bottles can be an effective and immediate solution to this problem in the industrial and consumer societies.

2.10 Waste Materials

2.10.1 Waste Materials and Environment

The construction of hundreds of kilometres of roads around the world every year results in the consumption of tonnes of raw materials and the impoverishment of natural resources in different parts of the globe. In addition, as an outcome of a consuming society, developed countries are currently facing a major problem from the huge waste materials produced daily by their citizens. The disposal of these waste materials has turned into one of the critical issues of municipalities in modern cities. However,

disposed waste material is not only limited to civil life, as they also come from some other sources, such as commercial, industrial, and the like. The worst part of the problem is that the major portion of the produced waste materials remain intact in nature for a long time or is expected to decompose at some time in the distant future, which, in turn, results in long-term environmental contamination obliging the authorities to find solutions, most of which are temporary, such as dumping the waste in landfills around large cities (Wen, 2007).

However, the currently available middens are running out of their capacity while the establishment of new sites for this purpose have encountered regulation stalemate, which restrict the conventional way of waste disposal through its burial around the living areas. This doubles the problem of waste disposal and finding new solutions and middens adds to the disposal costs that are imposed on the municipal authorities, and, ultimately, the taxpayers (Kassim et al., 2005). Solid and synthetic waste materials consume natural resources for their production, as well as cause serious environmental pollution of the water, land, and air. It is noteworthy to mention that pollution in any form is a kind of waste itself. Therefore, waste middens and landfill can contribute to serious environmental problems both in the long-term and short-term. Some of the risks and negative effects of waste dumping in middens and landfills around the domestic area can be summarised as follows:

- ✓ Fire or explosion, which is a threat to the living areas adjacent to middens and landfills, especially with organic (biodegradable) waste materials since they can easily generate a highly flammable combination of various gases such as methane, which is known as landfill gas.

- ✓ Contamination of the ground and surface water neighbouring the landfills and middens as a result of decomposition of waste materials in the landfills, which leads to landfill leachates that are highly risky and dangerous for hygienic purposes.
- ✓ Pollution of the local amenities available in those areas.
- ✓ Other environmental pollution brought about by odour, dust, noise, aesthetics and the like, which result from dumping and landfilling operations (Kassim et al., 2005).

However, the impact of landfill on the environment is not all negative. If landfill is rationally and logically engineered and controlled, it can yield some benefits as well, such as for the retrieval of derelict land in the necessary area. However, a serious problem for such projects is finding suitable sites and transportation costs, which finally lead to the high expense of landfills and disposal operations. New municipal regulations exacerbate the previous problems making waste disposal even more difficult. Some of these recent regulations:

- a) require high standards of landfill control and management, seeking simultaneously to discourage landfill of certain problematic waste materials
- b) attempt to progressively reduce landfilling operations of biodegradable materials, which form the major portion of the waste materials delivered to the disposal sites.

Since Landfill Tax is imposed on all types of waste materials delivered to middens and landfills, the total amount of waste materials heading to these sites has been significantly reduced resulting in the reduction of waste disposal, and the increase in the re-use and recycling of reusable products. There is also evidence that industrial waste is

being distributed on agricultural land as fertiliser, which is a good omen for the future of consumer societies.

2.10.2 Recycle of Waste Materials

Finding reasonable and cost-effective solutions for waste material disposal, such as recycling, is one of the important responsibilities of scientists, engineers, researchers, and governments. These solutions should not only consider the environmental advantages but also reuse the solid waste materials in projects, such as road construction (Xue et al., 2009). Therefore, effective recycling of waste is one of the solutions sought by many researchers. Well-managed recycling of waste has several advantages as mentioned below:

- It contributes to the reduction or prevention of exhaustion of natural resources
- It contributes to a reduction of environmental contamination due to the uncontrolled disposal of waste materials produced by industrial and domestic consumption
- It significantly saves money and energy

Recycling of waste materials can include some solid and non-decomposable materials such as plastic bottles, containers, or covers, which, due to their longer biodegradation period, cause serious harm to the environment disturbing the balance of the ecosystem. Therefore, to minimise the negative effects of such materials on the environment, it is totally reasonable and logical to recycle such materials through civil construction and industrial production (Fontes et al., 2010, Ismail and Al-Hashmi, 2008).

Recycling waste materials produced by industrial plants and workshops, especially, relating to civil engineering has seen significant developments in recent decades. Some of the successful examples of these developments include coal fly ash, silica fumes, and blast furnace slag. The reuse of risky waste has also been the subject of much research throughout years. Such research mainly focused on the impact of the residue on the properties of the construction materials as well as on its effects on the environment . The most recent studies have concentrated on the possibilities of reusing solid waste materials in road construction, which has recently turned into a hot issue. Apparently, this has two main causes, namely, the lack or reduction of natural resources usable for road construction and the existence of solid waste materials that can be reused in many construction projects in civil engineering (Aubert et al., 2007).

2.10.3 Typical Kinds of Waste Materials

During recent decades, there have been a limited number of researches focusing specifically on the incorporation of selected waste materials into asphalt pavement mixtures. Ground rubber tyres, ground glass, asphalt shingles, contaminated sand/soil, incinerator ash, and various kinds of waste polymers have been among those employed and utilised for such purposes. Certainly there are some other materials disposed of, which can be utilised in similar ways to be incorporated into HMA as modifiers in future construction projects. The availability of a sufficient quantity of the target material and continuity of its supply can be among the selection criteria. The cost of incorporation of the selected waste material can also be another factor, which enlists it as a candidate for such purposes.

In general, there are different types of waste. These include:

- ✓ Solid waste materials: any kind of disposed of household or office furniture, kitchen utensils, harmless industrial waste materials, construction and renovation debris, municipality and agricultural trash and discarded materials; many other non-toxic/non-hazardous solid waste materials are grouped into this category.
- ✓ Special waste materials: hazardous household or office waste such as chemicals, paints, and paint thinners, rechargeable batteries used in different devices at home or office, lead-acid batteries used in vehicles, oil, worn out tyres, etc.
- ✓ Hazardous waste materials: any liquid, solid, gaseous or hybrid material disposed of by hospitals, clinics, and health centres. These materials if left uncontrolled can threaten the health of the residents of that area in which they are discarded.

Collection, transportation, and disposal of solid waste materials have turned into a serious concern around the world in recent years (Kassim.TA, 1998, Kassim TA, 2000). In most countries, conventional technologies and systems can only remove 30–50 per cent of the produced solid waste materials and these wastes are disposed of in ways detrimental to the environment. Therefore, in order to solve or minimise this problem, the disposed materials can be exposed to recycling, reuse, and accelerated decomposition through economical and environmentally friendly practices (Kassim et al., 2005).

2.10.4 Waste Plastic

The growing quantity of plastic products, such as containers and bottles consumed yearly all over the globe from the most developed to the least developed countries has turned the disposal of this material into a serious problem, especially in developing and

developed societies. Plastic containers enjoy certain features that make them attractive and the preferred products of consumers. Plastic offers a strong material with low density that is ergonomic, durable, light, and cheap that is usable in packaging and other industrial, medical, food services and appliances, artificial implants, land/soil conservation, water desalination, flood prevention, housing, communication, and security applications, and so on. The annual consumption of plastic has globally jumped from about 5 million to 100 million tons within the second half of the last century. Hence, plastic has become one of the most important solid waste materials in recent decades (Siddique, 2008).

However, some plastic items, which are used to preserve food are disposable which have to be discarded after one-time-use and only a short time after purchase. Reusable plastic items are preferred since they can help save the resources and money of the consumers. Therefore, multi-trip plastic containers have gained more appeal among manufacturers and consumers. This, in turn, contributes to a reduction of plastic waste materials in the environment. Along with these solutions, recycling the disposable plastic items, or those that need to be discarded after a lifetime, can yield several advantages as follows:

- Preservation of limited fossil resources such as oil of which at least 8% is consumed for the production of plastic items in the world, 4% for petrochemical feedstock and 4% during manufacture, respectively,
- Reduction of energy consumption
- Reduction of disposed and discarded solid materials
- Reduction of Carbon-dioxide (CO₂), Sulphur-dioxide (SO₂), Nitrogen-oxide (NO) emissions (Ghalwash, 2006, Siddique, 2008).

Considering the points discussed above, recycling plastic waste materials contributes to a significant reduction in disposed plastic materials in the environment, as well as helping to preserve the natural fossil resources that form the main source of plastic production and manufacturing around the world.

2.11 General Studies on Using Additives in Road Construction

Normal bituminous mixtures conventionally used in pavement constructions are susceptible to extreme temperature variations and climactic conditions, which usually lead to problems such as cracking that may end up in fractures. Moreover, at higher temperatures during the hot seasons in tropical and hot regions bitumen mixture suffers from creep or flow. A stable pavement surface should not creep or flow under heavy traffic loadings. With this in mind, many researchers are involved in studies investigating the way they can modify bituminous mixtures by adding various additives to enhance its performance against the aforementioned problems.

During a shared study, Wu et al. (Wu et al., 2008) conducted an investigation concerning the impact of polyester fibers on fatigue and the rheological properties of bitumen and bituminous mixtures. Their studies reveal that the binder viscosity increases with the addition of more polyester fiber contents into the mixture, particularly, at lower temperatures. The results of their research confirm the possibility of an improvement of the mixture fatigue property through adding fiber, specifically, where the stress level is low.

Huang and White (Huang H, 1996) also carried out a research on asphalt overlays modified with polypropylene fiber. The modified and normal asphalt mixture samples

of cores were transferred to the laboratory to be investigated and analysed under controlled conditions. It was revealed that the modified asphalt mixtures were stiffer and displayed improvements in durability and fatigue resistance. However, the main problem with polypropylene fiber was that due to its low melting point, the fiber was inherently incompatible with hot bitumen. According to Huang and White, further studies were required to rightly perceive the visco-elastic properties of the fiber-modified bituminous mixtures.

In this regard, A. I. Al-Hadidy and Yi-qiu Tan (Al-Hadidy and Tan, 2009) employed starch (ST) and styrene-butadiene-styrene (SBS) to add to SMA mixes. Then physiochemical tests were carried out on modified and unmodified bitumen mixtures including performance tests such as Marshall stability, tensile strength, tensile strength ratio and resilient modulus. The test results reveal that damage caused by moisture and susceptibility of the mixture against temperature fluctuations and variations can be reduced through the addition of ST and SBS into the bituminous mix. According to the same results, ST can also play the role of an anti-stripping agent in the mixture, reduce the plant emissions, save energy by about 30%, and increase its resistance to chemicals and solvents. As per the multi-layer elastic analysis results, pavement mixtures modified by ST and SBS consume less construction materials for the pavement

Donnchadh Casey et al. also studied the potential of recycled polymer to modify binder. Some basic tests were prepared and conducted on bitumen to evaluate the impact of the recycled polymer on the properties of the bitumen. The results of the experiments showed that 4% of recycled HDPE in a pen grade binder can result in the most promising outcome and improve the properties of the binder.

Another research was conducted by Bradley Putman et al. in which they analysed the possibility of applying waste carpet and tyre fibers in the SMA mixture. The added fibers play the role of a stabiliser in the SMA to prevent drain down, which is a result of high asphalt binder contents. In this study, the researchers compared the performance of SMA mixtures modified by tyre fibers and carpet with mixtures made with normally used cellulose fiber and other polyester fibers produced specifically for use in HMA. Concerning the permanent deformation and susceptibility to moisture, there was no significant difference between the two fibers in their results. However, carpet and tyre fibers significantly contributed to an improvement of the mixture toughness in contrast to the cellulose ones (Putman and Amirkhanian, 2004).

2.12 Application of Polyethylene to Asphalt Concrete Mixes

In this study, a kind of polyethylene was used as an additive in SMA. The studies specifically concentrating on the modification of asphalt mixtures through the application of polyethylene are inadequate (Al-Hadidy and Yi-qiu, 2009a). The studies covering polyethylene reinforced asphalt mixture and binders form only a small portion of the current publications and there is still a necessity for further studies focusing specifically on this topic.

A joint research by Mohammad T. Awwad and Lina Shbeeb investigated the results of the employment of polyethylene polymers to improve the engineering properties of asphalt mixtures. Their study was conducted to determine the best and the most proper polyethylene type and proportion to be used in the asphalt mixture to obtain the optimal result. Hence, they applied two types of polyethylene to the aggregate coating, namely, Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE),

respectively. The addition of the polymers to the mixture was carried out in two forms, ground and unground. The produced mixture samples displayed that the ground HDPE imparts better engineering properties to the resulting mixture. The most appropriate percentage of the modifier suggested by researchers to be added to the mixture is 12% by the bitumen weight. The results of this experiment further confirm that the introduced HDPE can contribute to the enhancement of mixture stability, slight increase of air voids (VIM) and voids of the mineral aggregate (VMA) in it, as well as the reduction of the asphalt mixture density (Shbeeb, 2007).

Another study concentrating on the potentiality of LDPE prospects was jointly done by A. I. Al-Hadidy and Tan Yi-qiu to study the engineering properties of this polymer as a modifier that can be applied to asphalt mix modifications and improvements. The obtained outcomes confirm that the softening point of the binders modified by LDPE is comparatively higher, while its ductility values were fixed at the minimum specification range (100+ cm), which, in turn, resulted in a reduction in the percentage loss of weight due to heat and air, which means a significant improvement in the overall durability of the original SMA. Furthermore, the results reveal that LDPE modified SMA mixture can provide the optimal mixture for pavement construction and coating in regions with extreme temperature fluctuations and excessive moisture (Al-Hadidy and Yi-qiu, 2009a).

Sinan Hınıslıoglu and Emine Agar used other kinds of waste plastic materials with HDPE to modify bituminous mixtures to identify the impact of the HDPE modified binders with various blending temperatures, times lengths, and HDPE percentage. For this experiment, they used Marshall stability, Marshall quotient, and Marshall flow. They concluded that 4% of HDPE at 165°C mixing temperature blended continuously

for 30 minutes is the best condition for Marshall stability, Marshall flow, and Marshall quotient (MQ). As a result of new conditions applied to this experiment, the percentage of the Marshall quotient was raised by 50% in comparison to the control mixture. Furthermore, the researchers noted that resistance of the HDPE modified bituminous mix against serious deteriorations and deformation was significantly increased (Hınıslioğlu and Ağar, 2004).

A study by Zoorob and Suparma revealed that using recycled waste plastic materials mainly composed of LDPE in bituminous mixtures resulted in a significant enhancement of its stability, i.e., approximately 2.5 times greater than the stability of the control mixtures, and durability, while decreasing its density. In addition, the outcomes of the study showed that the plastiphalt fatigue life of the modified mixtures was longer than the control ones (Zoorob and Suparma, 2000).

Another relevant research by Osamu. K. and Masaru. Y. also investigated the possibilities of the application of disposed waste plastic, i.e., polypropylene and polyethylene, as part of the aggregate in the asphalt mixture. In their research, they found that the application of polyethylene or polypropylene contributes to a considerable improvement in the resistance to fluidity of dense-grade asphalt mixes. Moreover, it was also revealed that the addition of polyethylene would also contribute to significant enhancement in the bending fatigue destruction-resistance and anti-stripping properties of the dense-grade asphalt mixtures. Furthermore, the adding of polyethylene into the porous asphalt mixture can also result in significant improvements in its oil-resistance properties.

There have also been other studies on the topic among which was that of Yüksel Taşdemir who tried in his research to investigate the effects of polyethylene wax on bituminous mixtures. During his experiments, he noticed that adding the polymer significantly enhanced the rutting-resistance of the modified mixture (Yüksel, 2009).

Lamia A. Ahmed also applied Maleic Anhydride grafted Polyethylene as a polymer to bituminous mixture. The results of her experiments confirmed that by addition of the polymer the workability and efficiency of the mixture was significantly increased (Ahmed.LA, 2007).

2.13 Summary

This chapter focused on certain essential factors of bituminous mixtures as well as polymer modified asphalt mixtures and of waste materials. The application of polymer to asphalt mixture has been promoted as a means to improve the performance of asphalt mixtures. Adding polymer usually contributes to increase the stiffness of the bituminous mixture and improvement of its susceptibility to temperature variations and fluctuations. This, in turn, improves the resistance of the mixture to rutting. However, these days, asphalt mixtures modified by polymer are more expensive for road pavement purposes. Using waste polymers, as modifiers is one of the several ways to cut the expenses and reduce the overall cost of road pavement projects.

Recycling and reusing plastic waste can significantly contribute to saving the environment from further pollution and the economy from extra expenses. It is also helpful in controlling discarded waste such as plastic beverage and food containers. These containers have long biodegradation periods compared to the other materials, which adds to the importance of the problem with their long-term negative effects on

the ecosystem and environment balance. A reduction of the negative effects of these materials requires their recycling and reuse in construction and industrial projects. In addition to the above-mentioned points, this chapter further introduced Stone Mastic Asphalt (SMA), giving an elaborate background of its history, advantages, disadvantages, composition, and properties for better information of the readers.

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3. RESEARCH METHODOLOGY

3.1 Introduction

Chapter three of this thesis contains discussions on several experiments and the testing methods followed to evaluate the objectives of the current study. This chapter consists of three main sections, namely: the first section, which discusses the physical properties of materials used in the sample mixtures and related tests; the second section elaborates and deals with the Marshall mix design; and the third section explains the methods of performance tests on the SMA specimens. The Figure 3.1 (Flow chart) displays a summary of the methodology used in this research.

Laboratory experimental methods used in this research were all based on international standards, such as British Standard (BS), American Society for Testing and Materials (ASTM), Malaysian Standard Specification for Road Works (JKR (Jabatan Kerja Raya)), and the American Association of State Highway and Transportation Officials (AASHTO), to check material and mixture parameters and ensure achievement of optimal and satisfactory long-term mixture performance. During the current study, all samples and experiments were conducted at the highway and transportation laboratory of the University of Malaya (UM).

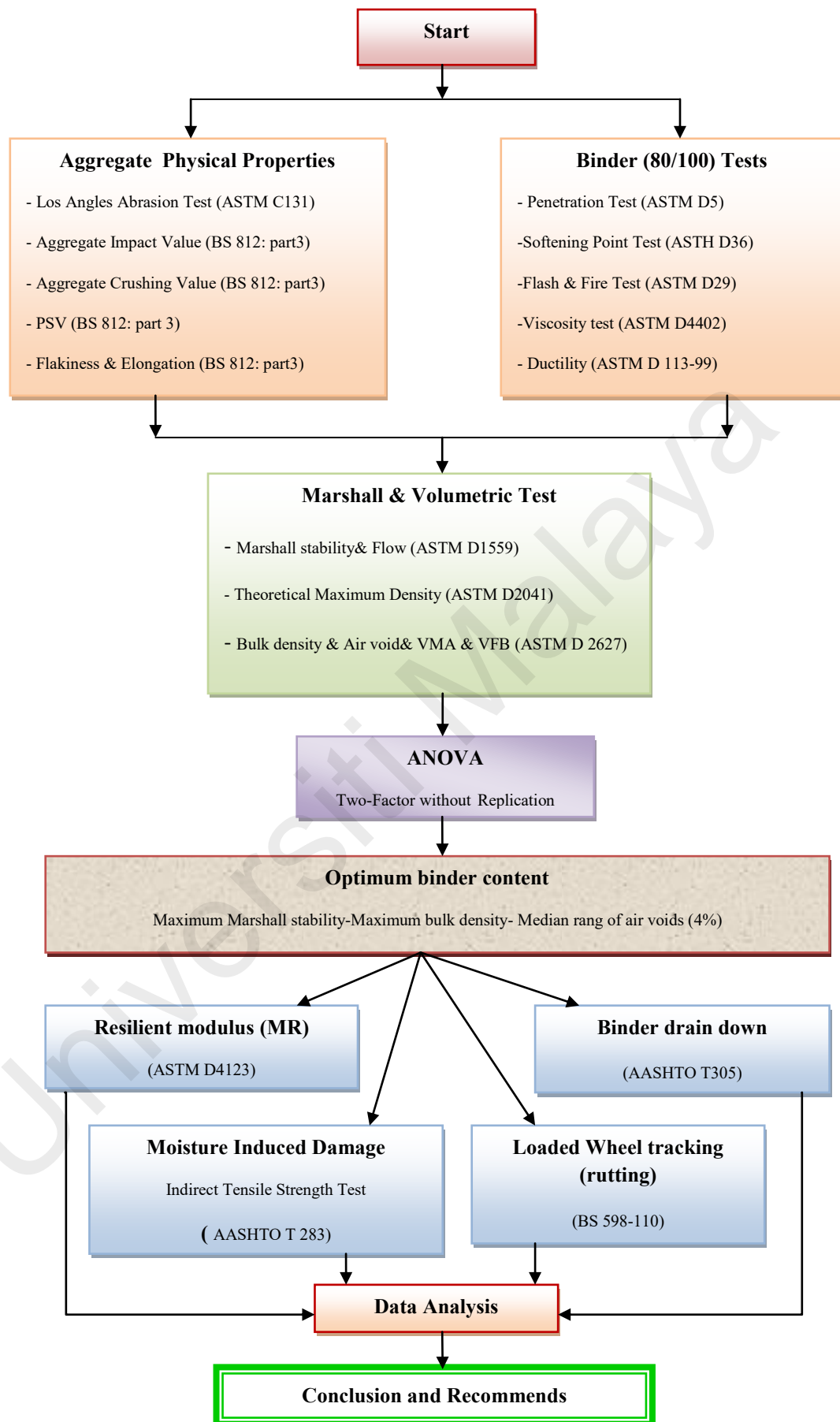


Figure 3.1: Chart flow for the research methodology

3.2 Materials selection

All the materials used in the experiments carried out in the current study were carefully selected and came from the same source to ensure their consistency characteristics. The crushed granite aggregate used in the specimens were all obtained from a quarry in Kajang, a suburb near Kuala Lumpur, the capital city of Malaysia. As shown in table 3.1, aggregates with SMA 20 gradation (according to Malaysian standard specification for road works (JKR)) were selected and used in the samples of SMA. The bitumen with 80/100 penetration grade, which has been commonly used in Malaysian road constructions for the past two decades, was employed for making specimens. This study used 9% filler, 2% of which was Portland cement and 7% consisted of stone powder. In addition, waste plastic bottles collected from domestic use and restaurants were used to make the samples. After collection, the plastic bottles were cleaned and washed carefully, dried and cut into small pieces and then crushed with special apparatus, as shown in figure 3.2. In the final stage, the crushed plastic bottles were sieved to obtain a smooth and fine powder.

Table3.1: Aggregates with SMA 20 Gradations

Sieve size (mm)	Gradation limits	Used gradation
19.0	100	100
12.5	85-95	90
9.5	65-75	90
4.75	20-28	24
2.36	16-24	20
0.6 00	12-16	14
0.300	12-15	13
0.075	8-10	9



Figure 3.2: Crushing machine (up), Crushed PET particles (down).

3.3 Physical properties of materials

Stone Mastic Aggregate (SMA) is a stable and tough mixture that is heavily dependent on stone-on-stone contact (NAPA, 1999). The philosophy revolving around the design of SMA is the development of a strong stone skeleton that has high bitumen and high mortar content.

Typically, SMA is formed of 8–12% of filler, 70–80% of coarse aggregate, 5–7% of binder, and 0.3% of fiber or polymer. Its toughness, strength, and resistance to rutting depends mostly on the type of aggregate used in the mixture, which needs to consist of 100% crushed aggregate of appropriate shape (cubicle) and other physical properties. In addition, the role the mortar binder plays is very significant in building strong binding between the various materials used in the asphalt mixture. Therefore, the quality and acceptability of their physical properties should be taken into consideration in SMA pavements.

3.3.1 Los Angeles Abrasion Test

The aggregate used to build the lower pavement layers may be used with a high level of abrasion loss because the high load and stress imposed by the wheels and heavy traffic have less impact on them than the aggregate in the top layers, mostly near the pavement surface, which are more subject to abrasion and require more hardness and toughness. Relatively high resistance to wear, as indicated by a low percentage of abrasion loss, is a desirable characteristic of aggregate used in the surface layers of asphalt pavements. A common test used to evaluate these properties of aggregates is the Los Angeles Abrasion Value (LAHV). A typical Los Angeles Abrasion apparatus has been displayed in Figure 3.3.

The aggregates need to be prepared and deposited in the drum of the apparatus along with steel balls. The drum will rotate with a specific number and defined time and then the abrasion loss of the aggregate will be calculated. ASTM C131 and AASHTO T96 standards show the procedures of the Los Angeles Abrasion Test. According to ASTM, the aggregate abrasion should be less than 30% (ASTM-C131, 1981).



Figure 3.3: Los Angeles Abrasion Value apparatus

3.3.2 Aggregate Impact Value Test

The strength value of aggregate is an essential property of aggregate that provides the required relative aggregate strength level making it capable of resisting the impact of traffic loadings. The laboratory strength value of aggregates was determined through the Aggregate Impact Test. This test with all details has been elaborated in British standard (BS 812: Part 3, 1975). According to this standard, the aggregate is put into the mould and compacted with the heavy impact of a metal hammer that weighs 14kg falling from a height of 38cm. For compact aggregates, 15 blows of the hammer are required. Figure 3.4 shows a sample of the standard Aggregate Impact Test Apparatus.



Figure 3.4: Aggregate Impact Test Apparatus

3.3.3 Flakiness and Elongation Index Test

The shape of the aggregate particles flat or elongated contents, which is one of the most vital factors in the degradation of the aggregates, especially in SMA mixtures. The flat or elongated aggregate particles refer, in fact, to those particles of which the ratio of their width to their thickness or length to width is bigger than the specified value. However, in the SMA mixtures, both ratios have been taken into consideration since they have a tendency to break down during the construction process as a result of the pressure exerted by heavy and frequent traffic loadings.

The flakiness test for aggregate concerns the thin and flat property of the aggregate in respect of their length or width. In highway engineers' terminology, flaky aggregate is an aggregate in which the thickness is less than 0.6 of its mean size. The Flaky Index of aggregate is found by weight of flaky aggregate that passes a special sieve as a

percentage of the aggregate tested. Figure 3.5 displays a special sieve (test plate) used in this test.

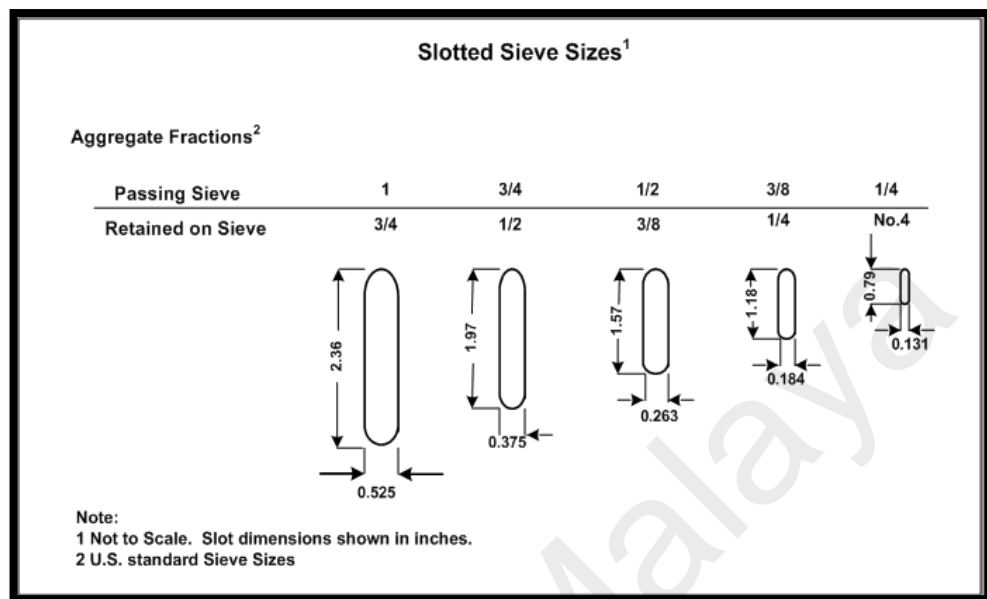


Figure 3.5: Slotted Sieve Openings

Flaky aggregates do not have sufficient strength and their strength is less than cubical aggregate. Therefore, flaky aggregate does not make as good a mixture as cubical aggregate. British standard (BS 812, Part 3) explains this test with all the necessary details, and, according to this standard, the flakiness index of the aggregate should be less than 20 per cent for use in asphalt pavements.

The elongation of aggregate concerns the length of the aggregate. The aggregate becomes elongated when the longest dimension (length) of the aggregates is 1.8 times greater than the mean dimension. The elongation test follows the same procedure as the flakiness test with the only exception being that the elongation test employs an elongation gauge, as shown in figure 3.6.



Figure 3.6: Elongation gauge

3.3.4 Aggregate Crushing Value (ACV)

The value of aggregate crushing indicates the aggregate capability and ability to resist crushing. A lower aggregate crushing value indicates the greater resistance ability of the particular aggregate against crushing. The ACV in the current study was determined according to the British Standard (BS 812: Part 3).

A sample of 14mm size chippings of the aggregate to be tested is placed in a steel mould and a steel plunger inserted into the mould on top of the chippings. The chippings were then subjected to a pressure for a period of 10 minutes and the force was gradually increased up to 400KN during the test time. This crushed the aggregate specimen down to a degree, which is dependent on the crushing resistance level of the material. Aggregates with a crushing value of 10 or less are considered as strong aggregates while those with an ACV higher than 25 are regarded as weak aggregates. According to the British Standard, aggregates with more than 30 per cent of ACV are not recommended for use in road pavement asphalt.

3.3.5 Polished Stone Value (PSV)

The polished stone value (PSV) gives a measure of the aggregate resistance against polishing resulting from friction of vehicle tyres in conditions that are very similar to those on the road surface. Where the road surface consists largely of aggregates, the polish status of the specimen aggregate is one of the main factors affecting the resistance of the surface to skidding. The actual relationship between skidding resistance and PSV varies with the type of surface, traffic conditions, and various other factors.

The PSV is conducted in two parts as follows:

- a) In the first phase samples of stone are subjected to polishing action through an accelerated polishing machine.
- b) In the second phase the polishing status achieved with each sample is gauged through a friction test, which is then expressed as a laboratory-determined PSV.

PSV is established through subjecting the sample aggregate to a process of standard polishing action as well as testing it with the Portable Skid Resistance Tester. The details of the complete procedure of the PSV test are available in the British Standard (BS 812: Part 3). The PSV of a variety of types of aggregate can be measured by application of the aggregate skid resistance value through the following equation:

$$PSV = S + 52.5 - C \quad \text{Equation (3.1)}$$

Where:

S= Mean sample skid value

C= Mean control sample skid value

3.3.6 Penetration

This test is one of the oldest empirical tests, which was used for measuring the consistency of asphalt cement. The main aim of this test was to classify bitumen specimens into different grades by determining the bitumen consistency. The penetration test procedure is explained in detail in the ASTM D5. The test is conductible at the standard test temperature (25°C), or at any other temperature (ASTM D5, 1986).

A typical penetration test consists of three measurements made on the samples of the asphalt binder, the average of which is used to provide the value of the single test. The unit penetration measurement is 0.1mm, therefore, 80/100 bitumen is placed between 8mm and 10mm. Figure 3.7 shows the process for measuring the penetration value.

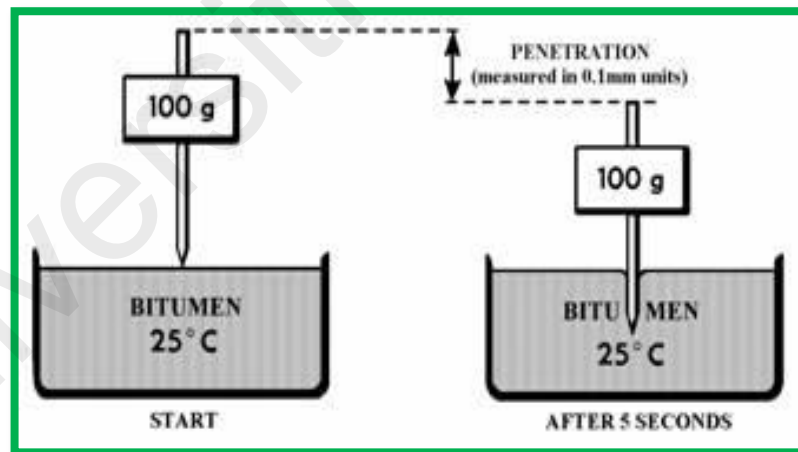


Figure 3.7 Penetration Process

3.3.7 Softening Point Test

The test of softening point is one of the main experiments used to test the used bitumen. The ring and ball (R&B) is the usual method employed for the measurement of the bitumen softening point. The softening point for bitumen is the specific temperature at

which bitumen starts to become soft and cannot resist the weight of the 3.5 gram steel ball any longer. For this test, two horizontal disks of bitumen, cast in shouldered brass rings (as illustrated in Figure 3.8), are heated at a controlled rate in a liquid bath while each supports a steel ball. The softening point is reported as the mean of the temperatures at which the two disks soften enough to allow each ball, enveloped in bitumen, to fall a distance of 25 mm (1.0 inch). The penetration test procedure has been elaborated in ASTM D36.

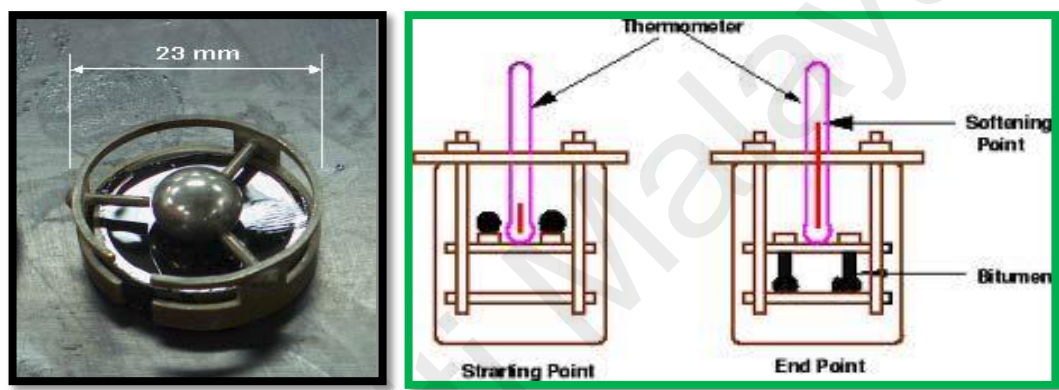


Figure 3.8: Softening Point Sample

3.3.8 Flash and Fire Point

Bitumen is a flammable liquid which can catch fire at high temperatures and, hence, it is a high risk material if adequate care is not exercised during different stages of the construction procedure. Therefore, it is important to note that the flash and fire point of a particular bitumen specimen is required to be able to control the temperature of the materials during the mixing and construction procedures.

The most common method used to test and determine the fire and flash point of an asphalt binder is the Cleveland Open Cup (COC), as described in ASTM D92. For this test, a full small cup of bitumen is subjected to a temperature increase up to specified

level to start melting, and a small flame with 0.16mm in diameter is applied to the surface of the molten bitumen at particular intervals as long as the first flash appears at any point on the bitumen surface. This particular temperature is registered as the Flash Point of the bitumen (ASTM D92, 1986).

3.3.9 Viscosity

The viscosity of a binder indicates its flow characteristics, which significantly affect the performance of a bituminous mixture. The viscosity test in the current study was conducted in complete accordance with ASTM D4402, and the Brookfield Rotational Viscometer (BRV) was employed to measure the viscosity level of the binder (ASTM D4402, 1987). The asphalt cement viscosity grading is based on the measurement of viscosity at 135°C. This temperature is selected because it is approximately the asphalt compaction temperature.

The measurement of asphalt binder viscosity can also be carried out at a temperature of 60°C, being the highest temperature the pavement is expected to be exposed to during the summer in hot regions. A temperature of 170°C is the approximate temperature used for the mixing and mixture laying down temperature. The results of the test are sometimes plotted on a viscosity-temperature graph with a line connecting the two points. The slope of this line indicates the temperature susceptibility of the asphalt binder, that is, the greater the slope of the line, the greater the temperature susceptibility of the asphalt binder.

The high susceptibility of the asphalt binder makes the binder become softer during the hot seasons and harder in cold seasons. This fluctuation makes a poor combination in

asphalt mixtures, which may affect the performance of the pavement. The relationship between the temperature and viscosity of the binder is also used to determine the appropriate temperature ranges applicable to laboratory conditions in which asphalt mixtures are mixed and compacted.

3.3.10 Ductility Test

The ductility of bituminous material is gauged by the distance to which it will elongate before breaking, when two ends of briquette bitumen sample are pulled at a specific speed and temperature. The testing temperature is $25 \pm 0.5^{\circ}\text{C}$ and a speed of 5 cm/min is specified.

This method allows measurement of the tensile properties of bituminous materials and it can also be utilised to ensure the materials ductility in accordance with specification requirements. Engineers and researchers consider ductility as an important feature of the asphalt mixture, which indicates its adhesiveness, that is, its ability to adhere to a stone without breaking away. The procedure for the ductility test is explained in detail in ASTM D113-99.

3.4 Marshall Mix Design

The Marshall mix design was employed to obtain the Optimum Binder Content (OBC) in accordance with ASTM D 1559. Bruce Marshall, a former Bituminous Engineer in the Mississippi State Highway Department in the US was the first person who formulated and introduced the initial pavement mixture design concept for this method. The procedure of design suggested by the Marshall Method was standardised by the American Society for Testing Materials (Robert et al., 1996). The Marshall method used

a standard test sample of 102mm in diameter (4- inch) and 64mm in height (2.5-inch). The main objective of this design was to obtain the best bitumen content for the mixture. The Marshall Design can be divided into two stages of lab experiment, namely: sample preparation and testing. In recent years, researchers and engineers have contributed to the improvement of the Marshall testing procedure by adding certain characteristics and features to it leading to a developed standard of mixing design.

The Marshall design method has been commonly employed for dense-graded HMA containing maximum aggregate size of one inch or less. This method has also been successfully utilised for SMA designs yielding acceptable performance results. Therefore, due to its simplicity, this method is still considered as the most common method employed for designing asphalt mixes (Tia.M, 2005).

3.4.1 Marshall Sample Preparation

The two methods that are usually used to add the selected additive to the asphalt mixture are the wet and dry processes. In the first method, the wet process, before the addition of the binder to the asphalt mixture, the binder is first mixed with the additive. While in the dry process method, the additive is blended with the aggregate prior to adding bitumen (Abtahi et al., 2010). In the current study the dry process was used with a novelty, which instead of blending the additive (PET) with the aggregate prior to adding the binder, the PET was added after adding the binder and blended with the aggregate into the mixture.

The control and PET mixtures were prepared for different binder contents. Five different binder percentages, that is, 5%, 5.5%, 6%, 6.5%, and 7% were determined by

the aggregate weight. Furthermore, the PET percentage added into the mixture varied between 0% and 10% (0%, 2%, 4%, 6%, 8%, 10%) based on the bitumen weight to see the effects of it on the asphalt mixture. Table 4 presents the PET gradation.

Table 3.2: The gradation of PET

Sieve size	Percent passing
1.18 mm	100
425 μ m	0

For each binder and PET content combination, 12 cylindrical specimens and 3 slab specimens were prepared. Three specimens out of the 12 specimens were used for the flow and Marshal stability tests, 6 specimens were utilised for the moisture susceptibility test, and 3 specimens were used for the resilient modules test. The 3 slab specimens were also exposed to the wheel tracking test.

The Marshall samples were prepared in accordance with ASTM D1559. The process employed in the preparation of the samples follows the steps provided below:

- Sieving the aggregates and classifying them into groups of different sizes according to the SMA 20 gradation. Each aggregate size is separately deposited in a different tray. Before proportioning, however, all the aggregates were first desiccated in an oven at 110°C.
- Weighing each aggregate size based on its proportion according to the SMA 20 gradation and keeping them in a plastic bag.

- Chopping the PET, weighing and classifying them into different contents and keeping them in different plastic bags.
- The containers of aggregates were kept in the oven at 180°C for 2 hours prior to making the samples.
- Placing the bitumen cans inside the oven at 160°C for 1 hour prior to proceeding to the sample making stage.
- Placing the specimen moulds inside the oven at 160°C for 1 hour before making the samples.
- The mixing process started along with depositing the aggregate in a bowl/pan and blending with filler at 160°C.
- Introducing the required amount of bitumen into the mixture inside the blender while the mixing process continued until coating all the aggregate with bitumen. This stage was fulfilled in about 5min.
- Introducing the crushed PET into the mixture and blending it with a combination for about 2 min.
- Putting a piece of filter paper on the fundamental plate and adjusting the mould.
- Transferring the mixture by a heated scoop from the mixing bowl/pan to the heated mould and compacting it fifteen times on the edges with a heated standard compaction rod and ten times on the central part.
- Slightly smoothening the mixture surface with spatula and putting a piece of filter paper on top of the mixture. It is essential that the temperature of mixture is carefully controlled in this stage.
- Depositing the mould assembly under the Marshall hammer for compaction and applying 50 blows to each sample surface at 145°C.
- Removing the base plate and filter papers from the sample when compaction is complete.

- Placing the moulds in the lab at room temperature for 24 hours.
- And, finally, the sample is ready for the testing procedure.

In the Marshall method each compacted sample is analysed through the following processes:

- Bulk specific gravity of sample
- Voids in the mineral aggregate (VMA)
- Voids filled with binder (VFB)
- Void in total mix (VTM)
- Marshall stability and flow

3.4.2 Theoretical Maximum Density

Two methods are usually used to determine the theoretical maximum density (TMD), namely: 1) calculation or 2) theoretical maximum density test. In this study, TMD was used to determine the volumetric properties of the samples. The asphalt mix TMD was measured through the Rice method in accordance with ASTM D2041. The asphalt mixture sample, prepared for the TMD test, was spread and separated into a loose form in the tray, weighed and vacuumed in a submerged condition for 25 minutes. Then, measurement of the loose specimen weight, submerged in water, was carried out (ASTM -D2041, 1986). The TMD value was achieved through the following equations:

$$TMD = Gmm \times \rho_w \quad \text{Equation (3.2)}$$

$$Gmm = \frac{A}{A - C} \quad \text{Equation (3.3)}$$

Where,

TMD = Theoretical Maximum Density (g/cm^3)

Gmm = Maximum Theoretical Specific Gravity

PW = Density of Water (1 g/cm^3)

A= Dry Specimen Mass (g)

C= Specimen Mass in Water (g)

3.4.3 Bulk Specific Gravity

The bulk specific gravity for each sample mixture was calculated according to ASTM-D2726 through the following equation:

$$G_{mb} = A/(B-C) \quad \text{Equation (3.4)}$$

Where,

Gmb = Bulk Specific Gravity

A = Dry Specimen Mass in the Air (g)

B = Saturated Surface-dry Specimen Mass in the Air (g)

C = Specimen Mass in the Water (g)

3.4.4 Voids In Mixture (VIM), Voids in Mineral Aggregates (VMA), Voids Filled with Bitumen (VFB)

Voids in mixture (VIM) for HMA is defined as the volume of the voids among the aggregates coated with bitumen. The void analysis was carried out in accordance with ASTM D3202. The measurement of the specimen voids was carried out using the following equation:

$$VIM = [1 - (Gmb / Gmm)] \times 100$$

Equation (3.5)

Where,

VIM= Air void

Gmb = Bulk Specific Gravity

Gmm = Theoretical Maximum Density

Other essential factors affecting the asphalt mixture design are VMA and VFB. The VMA refers to the inter-granular void space volume among the particles of aggregate of compacted pavement asphalt mix. It contains the air voids and the volume of the asphalt unabsorbed into the aggregate (Roberts, 1996). In other words, the VMA shows the portion of space in a compacted asphalt pavement or an asphalt sample without aggregate. VFB, on the other hand, is voids in the mineral aggregate that are filled with binder (excluding absorbed binder). Both VMA and VFB were determined through following equations:

$$VMA = 100 \times (1 - \frac{Gmb \times Ps}{Gsb})$$

Equation (3.6)

$$VFB = 100 \times (\frac{VMA - VIM}{VMA})$$

Equation (3.7)

Where,

VMA = Mineral Aggregate Voids

VFB = Bitumen Filled Voids

VIM = Air Voids

Gmb = Bulk Specific Gravity

PS = Percentage of the Aggregate in Total Mixture

GSB = Aggregates Bulk Specific Gravity

3.4.5 Marshall Stability and Flow

The Marshall stability and flow test measures the resistance to plastic flow of bituminous mixture cylindrical samples loaded on the lateral surface by means of the Marshall apparatus (Sabri, 2010). The maximum load carried by a compacted Marshall specimen at 60°C, with a loading rate of two inches per minute (50.8 mm/min) is defined as the Marshall stability, which significantly depends on the aggregate quality (angularity) and asphalt binder viscosity. The vertical deformation of the asphalt sample concurrent with running the Marshall stability (measured from the beginning of loading until when the stability starts to decrease) is defined as the flow (Pourtahmasb, 2009).

The high flow value displays high mixture plasticity, which can lead to pavement rutting failure in the future. In addition, the low flow value might be a result of the high volume of voids and insufficient asphalt may result in premature cracking in asphalt pavement (Pourtahmasb, 2009).

As defined by ASTM D1559, the standard Marshall specimen dimension is 101.6mm in diameter with a thickness of 63.5mm. The stability of a specimen with varying thickness was corrected according to the ASTM correlation ratio table. Measurement of the specimen stability and flow was carried out by immersing each sample in a water bath for half an hour at 60°C. Next, the specimen was removed from the water bath and placed within the grips of the Marshall apparatus. The loading was carried out at the standard rate of 50.8mm/min and the resulting stability and flow value was registered.

3.4.6 Optimum Binder Content

There are many factors that affect the bituminous mixture behaviour and performance. The design of the mixture is to determine its composition to ensure its strength and stability to be sufficient to meet the demands of heavy traffic as well as its workability to allow efficient application of the mixture to pavement without segregation. Furthermore, the mixture needs to contain sufficient bitumen and voids to enhance pavement durability in the long-term. For this purpose, optimum binder content is a necessity (Abdelaziz, 2008).

The optimum binder content (OBC) of a mixture is usually determined by the Marshall and volumetric property curves (bulk density, stability, VIM). OBC is the numerical average of the binder content percentage determined in accordance with the highest Marshall stability, maximum bulk density, and medium range of voids in total mixture.

For the current study, the optimum asphalt content was selected to provide 4% of air voids in the mixture and satisfy the maximum Marshall stability and maximum bulk density. The performance evaluations of SMA pavements issued by the National Centre for Asphalt Technology (NCAT) suggest that an asphalt content that is expected to produce an air void content of about 4% can provide sufficient protection against fat spots after laydown and rutting, especially in hot climates. However, according to the same source, in cold climates an air void content of about 3.5% is preferable.

After selecting the optimum binder content, the SMA properties should meet the standards displayed in Table 3.3 below:

Table 3.3: SMA Mixture Specification for Marshall Compacted Design

Property	Requirement
Binder content (%)	6 minimum
Air Voids (%)	4
VMA (%)	17 minimum
Stability (N)	6200 minimum
Drain down	Less than 3%

3.5 Resilient Modulus Test

This test method covers the procedure for testing the laboratory or field recovered cores of asphalt mixtures to determine the resilient modulus value using repeated load indirect tensile tests, under specified temperature, load and loading frequency. The test is carried out by applying compressive loadings with a sine wave or any other appropriate waveform. The loading is vertically applied to the vertical diametral plane of a cylindrical sample of asphalt mixture. The horizontal specimen deformation resulting from this application is gauged and then with an assumed Poisson's ratio is used to calculate a resilient modulus.

The resilient modulus value is applicable for evaluation of the relative material qualities, as well as to generate input for pavement design, or evaluation and analysis of the pavement. This test can also be utilised for the study of the impact of the temperature loading rate, rest periods, etc. Due to the non-destructive testing procedure,

tests can be repeated on a specimen to evaluate the stiffness properties of the mix sample (Abdelaziz, 2008).

The Universal Material Testing Apparatus (UMATTA) was employed to carry out the resilient modulus of SMA specimens according to ASTM D4123, which is a standard test method for the indirect tension for the resilient modulus of asphalt mixtures.

Each sample was preserved in a UMATTA machine for 24 hours at 25°C prior to initiation of the actual experiment. In order to measure the resulting deformation, two linear variable differential transducers (LVDTs) were attached to the specimen (See Figure 3.9). A pulsed diametral (compressive) loading force was used on the specimen and the total recoverable diametral strain resulting from this force application was measured using the two LDVT transducers from an axis of 90 degrees from the applied force. However, the strain resulting in the same axis as the applied force of the specimen was not measured. Therefore, the Poisson's ratio is required to be constantly entered to override the system default value of 0.35 to arrive at a resilient modulus value.

All the parameters required for the employed computer software, such as Poisson's ratio, pulse period, load, conditioning pulse count, and rise time were adjusted to comply with the standard. Each specimen was subjected to testing three times; each time, after 120° rotation, and the average of the three readings was considered as the ultimate value achieved.



Figure 3.9: Resilient Modulus Test Apparatus

3.6 Wheel-Tracking Test

The wheel-tracking test is employed for determination of the bituminous mixture susceptibility against plastic deformation, especially at higher temperatures under conditions similar to those experienced on actual roads with heavy traffic loadings. This value is assessable through a wheel-tracking test at the laboratory under controlled conditions of temperature and load.

The testing procedures can be carried out on sample mixtures either manufactured in a laboratory or cut and brought in from an asphalt pavement. The bituminous materials susceptibility to deformation was evaluated according to the degree of the resulted rut formed by repeated passes of wheel loads at a stable temperature. The wheel-tracking test simulates the passage of the traffic loads on the pavement surface to determine the rate of the permanent deformation features of bituminous mixture as well as its resistance to rutting under repeated loading at high temperatures, which are expected in hot and tropical regions such as Malaysia. This test measures the tracking and wheel-

tracking rate of the bituminous mixtures. Some terms need to be defined according to their applications in this study as follows:

- **Rutting:** rutting is defined as the relative reduction in thickness of the test sample caused by repeated passing (back and forth) of a loaded wheel.
- **Load cycle:** the load cycle consists of two passes (outward and reverse) of the loaded wheel.
- **Tracking rate:** the tracking rate refers to the depth of the sample mixture, which increases in millimetres per hour.
- **Wheel-tracking rate:** wheel tracking is defined as the rate of the gradual increase in the rutting depth over time as a result of the repeated back and forth passes of the loaded wheel (mm/h) (Abdelaziz, 2008).

The wheel-tracking test machine was initially developed and suggested by the Transport and Road Research Laboratory for examining the bituminous mixture rutting rate under various temperature and speed conditions. This test simulates the impacts of the loadings and traffic movements on moulded samples of road materials. Figure 3.10 shows a wheel-tracking test machine.

The load-tracking test was conducted according to the British Standard (BS 598-110, 1998). The testing of each specimen was conducted at 45°C with 21 cycles per min. In accordance with the standard, the test lasted for 45 min or as long as it took for the occurrence of 15 mm of deformation in the tested specimen, whichever occurred first, was the criterion in this case. A 520 kn loading was imposed on the specimen asphalt

surface by a wheel with 50mm width, and every 5 min (every 105 cycle) the rut depth was read from the gauge and recorded accordingly.



Figure 3.10: Wheel-Tracking test Machine

3.6.1 Specimen Preparation

For specimen preparation in this study, the test slabs were prepared with an equivalent density to the corresponding Marshall specimens. The required procedure for specimen preparation is as follows:

- Weighing each aggregate size according to the SMA 20 gradation and kept in a bag. For making slabs, the aggregate containers were kept in an oven at 180°C for about 2 hours prior to making the samples.
- The bitumen cans were placed within the oven and kept at 160°C for 1 hour prior to sample making.
- The aggregate was placed within a mixer to be blended with filler at 160°C. A mechanical mixer having a capacity of 12 kg and a mixing bowl, as shown in

figure 3.11, was used for mixing the materials speedily and thoroughly without the loss of fine aggregate.

- The required amount of bitumen was introduced into the mixer while the mixing continued until all the aggregate was covered with a bitumen coat, which took about 5min.
- Then the crushed PET was introduced into the mixer to be mixed with the other components of the combination; this stage took about 2 min.
- A steel mould that typically has a length of 300 mm long, 300 mm wide, and 50 mm thick was prepared.
- The slab thickness was specified to be twice the minimum size of the nominal maximum aggregate.
- The mould was then heated up to 160°C within one hour prior to placing the mixture in it.
- The area of the inner mould surface was covered with a grease coat to prevent the material from sticking to the surface.
- The batch mixture compaction was immediately initiated after the mixing task of the mixer was accomplished. Then the mixture was poured into the mould to be subjected to compaction by the roller compactor machine (Figure 3.11).
- During the final stage, moulds were placed at room temperature in the lab for 24 hours to cool down.
- After cooling down, the specimens were ready to be used in testing.



Figure 3.11: Mechanical Mixer (up), Roller Compactor Machine (down)

3.7 Moisture Induced Damage Test

Moisture susceptibility is a primary cause of distress in hot mix asphalt pavements. Moisture susceptibility is an assessment of how susceptible a HMA mixture's internal asphalt binder-to-aggregate bond is to weakening in the presence of water. This weakening, if severe enough, can result in stripping.

The outcomes achieved from the tests on moisture susceptibility of mixtures are applicable to the prediction of HMA susceptibility to stripping in the long-term as well as the evaluation of the anti-stripping additives, which can be added into the aggregate, binder, or HMA mix to increase its resistance to stripping.

The Indirect Tensile Strength Test (IDT) was employed in full compliance with AASHTO T283 standards to determine the susceptibility level of the SMA samples against moisture in wet environments. This method covers the specimen preparation and measurement of any changes detectable in the diametral tensile strength from the effects of saturation and accelerated water conditioning of compacted bituminous mixtures in the laboratory (AASHTO T283, 1995).

For this test, samples were divided into two groups. Through this method, six samples were made for each PET percentage of which half were to be tested dry (unconditioned) and the other half (conditioned) were to be tested with partial saturation and moisture conditioning.

The IDT test was also conducted on the first specimens group under a condition near room temperature, while the second group of specimens was subjected to vacuum saturation for approximately 5 min before being placed within a 60°C water bath for 24 hours. Prior to testing all the specimens of both groups were submerged in a 25°C water bath for two hours. Finally, the tensile strength ratio (TSR) was measured through testing the conditioned and dry specimen.

3.8 Binder Drain Down Test

The binder drain down test is more essential for SMA than conventional dense-graded mixtures. This test was developed and introduced by AASHTO T305 (2000); it is usually expected to simulate the likely conditions that the mixture will encounter during its production, storage, transportation, and placement stages. Binder drain down

concerns that part of the mix (fines and bitumen) that detaches from the specimen and starts flowing downward through the mixture to the bottom.

In this research, this test was carried out on three loose mixtures representing each selected mixture type to ensure that the engineering properties of the binder drain down of the SMA fell within the acceptable range of the preferred levels recommended by the mentioned standards. However, the more important aspects of the experiment were placement of the SMA loose mixture specimens in a wire basket manufactured especially for this purpose and using a standard sieve cloth of 6.3mm (Figure 3.12).

The wire basket was put in an oven on a pre-weighted pan or plate for one hour at an anticipated mix production temperature. After one hour, the plate or pan along with the basket of the specimens were removed from the oven and weighed. The mass of any binder that drained down from the bitumen to the pan was measured. The mass was then expressed as a percentage of the total mixture (Kamaluddin, 2008).

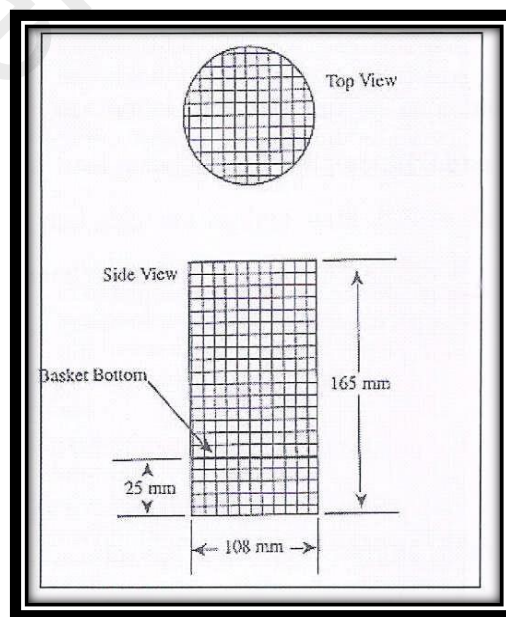


Figure 3.12: Dimension of Wire Basket

The percentage of the drained binder was calculated by subtracting the initial pan mass (before being placed into the oven) from the final pan mass (after being removed from the oven). The obtained results were divided into the initial total sample mass and then multiplied by 100 to get the percentage of the drain down. The calculation was based on the following formula:

$$\text{Binder Drainage (\%)} = [(C-B)/A] \times 100 \quad \text{Equation (3.8)}$$

Where:

A = Mass of initial total sample (gram)

B = Mass of the initial pan (gram) before being placed in the oven

C = Mass of the final pan (gram) after being removed from the oven

3.9 Analysis of Variance (ANOVA)

This study aimed to compare and contrast the SMA engineering properties with and without the chopped waste PET. For this purpose and to provide a better understanding, using the analysis of variance (ANOVA) technique, the various asphalt mixtures were statistically compared and a two-factor analysis of variance without replication was also utilised to evaluate the significance of the role and effect of each individual factor involved in determining the properties of the mixtures (Ahmadinia et al., 2011).

Analysis of Variance (ANOVA) is a statistical method employed for the evaluation of the relationships and differences that exist among the means of two or more data sets. This analysis is also considered as a guide for helping researchers to determine whether differences in a set of measurements or counts are the most likely ones expected from

the variations of random chance, or, conversely, we can say with a specific level of confidence that certain factors were the more likely reason for the event. ANOVA is a useful and powerful tool for determining if differences are statistically significant or not (Abdelaziz, 2008).

ANOVA was performed through Microsoft Excel, which actually has three different ANOVA function types available through the Analysis ToolPak that are usable for basic variance analyses, as explained below:

- Single Factor performs a simple variance analysis between two sets of data.
- Two Factors without Replication perform a variance analysis that exists between two or more sets of data. When there is just one specimen from each set of data, the two factors without replication is recommended.
- Two Factor with Replication is used for analysis of variances shared by two or more data sets, especially, when the number of the specimens is more than one from each set.

However, the main problem with the one factor masking the influence of the second factor can be overcome through a single two-way ANOVA, which simultaneously tests the possible impact of the two factors.

The F-ratio is the probability information generated by ANOVA which shows the variation proportion existing between the groups compared and contrasted with the variation within the same groups. Generally, the greater this value, the more likely the variation between the groups is significant.

The significance level of the data sets is determined by evaluating the F-ratio and comparing it to the F-critical value for the samples. If the F-ratio (F-statistic) is larger than F-critical, then the variation between the groups is statistically significant. If it is smaller than the F-critical value, the score differences are best explained by chance.

The observed P-value is the probability of observing the F-ratio or larger when the mean test results are equal. If the P-value is less than the desired level of significance (α), then the corresponding variant becomes significant. The level of significance (α) used in this research was 0.05, which represents the probability of 5% of the hypothesis represented by the model not being true (Abdelaziz, 2008).

4. RESULT AND DISCUSSION

4.1 Introduction

The current chapter focuses on the results of the experiments and tests elaborated upon in the previous chapter. High quality materials are essential for obtaining high quality SMA mixes. Acceptability of aggregate durability range and other tests required for the aggregates are among the factors that contribute to the desired quality of SMA. Furthermore, the significant role that bitumen plays in bituminous mixes is not ignorable or deniable. Therefore, the process began with tests of the materials. The achieved results were compared with the minimum standard requirements to determine the validity of the selected materials. The determination of optimum bitumen content was carried out based on the Marshall mixture design procedure. The following parameters were considered – Marshall stability, Marshall quotient, Marshall flow, bulk density, void filled with bitumen (VFB), voids in mineral aggregate (VMA) and air void (VIM).

This chapter also presents the SMA performance test, which included various percentages of waste PET. The performance tests including, wheel tracking test, moisture susceptibility test, resilient modulus test and drain down test were carried out on the mixtures that included 0%, 2%, 4%, 6%, 8% and 10% of waste PET (by weight of bitumen content). In addition, this chapter deals with the results of the two-way ANOVA employed for evaluation and assessment of the significance of each factor engaged in the determination of the properties of the mixes.

4.2 Materials test results

4.2.1 Aggregate Test Results

The quality of aggregate has a central role in the quality of asphalt mixture and the performance of the mixture is significantly affected by the aggregate blend properties (Pourtahmasb, 2009). The properties of the aggregate that significantly affect the asphalt mixture performance include shape, size, gradation and strength, which need to be strictly controlled and monitored.

Crushed granite with SMA20 gradation that was obtained from Kajang quarry (a suburb near Kuala Lumpur, Malaysian Capital) was used as the aggregate material. The result of aggregate tests is tabulated in table 4.1.

Table 4.1: Physical properties of the crushed aggregate.

Test	Standard used	Test result	Standard requirements	conformity
L.A. abrasion (%)	ASTM C-131	21%	Below 30%	OK
Soundness (%)	BS812: Part3	4.1%	Below 12%	OK
Flakiness Index (%)	BS 182: Part3	4%	Below 20%	OK
Elongation Index (%)	BS 182: Part3	14.3%	Below 20%	OK
Impact Value (%)	BS812: Part3	12.4%	Below 15%	OK
Polished Stone Value(%)	BS812: Part3	48.5%	Above 40%	OK
Aggregate Crushing Value (%)	BS812: Part3	20%	Below 30%	OK

Based on the achieved test results, this aggregate could satisfy the standard requirements, which makes it suitable for use in the asphalt mixture construction.

4.2.2 Bitumen Test Results

The bitumen used for this study was 80/100 penetration grade and the quality control of the bitumen was gauged through bitumen tests of penetration, softening point, viscosity, ductility, flash point and fire point. The results of these tests are presented in Table 4.2.

Table 4.2: The results of tests performed on bitumen.

Test	Standard used	Test results	Unit	Standard requirement	Conformity
Penetration (at 25°C, 100 g, 5 s)	ASTM D 597	87.7	1/10 mm	84-95	OK
Flash point	ASTM D-92	300	° C	275-302	OK
Fire point	ASTM D-92	317	° C	> 302	OK
Ductility (25°C)	ASTM D-113	100+	cm	-	OK
Softening point	ASTM D-36	48.2	°C	47-49	OK
Viscosity at 135°C	ASTM D4402	0.252	Pa.s	-	OK
Viscosity at 165°C	ASTM D4402	0.098	Pa.s	-	OK

The obtained values displayed in this table confirm that this type of bitumen meet the standard requirements and is a suitable choice for use in asphalt mixture construction.

4.3 Marshall test results and discussion

The Marshall test is probably the most common test used for determination of the OBC and properties of bituminous mixtures. The Marshall test was carried out on mixture samples with different percentages of waste PET content; the details of the testing procedure were described in the previous chapter. The bitumen content used in the mixtures ranged between 5% and 7% (5%, 5.5%, 6%, 6.5% and 7%) by the weight of aggregate and the percentage of the added PET ranged between 0% and 10% (0%, 2%, 4%, 6%, 8%, 10%) by weight of bitumen content.

The properties of the PET incorporated SMA bituminous mixtures were determined by a comparison with the control mixture (mixture with 0% PET). Parameters such as Marshall stability, voids in the mix (VIM), Marshall flow, bulk density, voids in mineral aggregate (VMA), and voids filled with bitumen (VFB) were also taken into consideration.

4.3.1 Marshall Stability

The Marshall stability is defined as the maximum load resistance developed during the test (at 60°C at a loading rate of 50.8 mm/min), prior to failure of the compacted specimen. The Marshall stability is also a measure of the bituminous mixture's susceptibility to deformation resulting from imposed loads. The stability of asphalt mixture depends upon both the internal friction and cohesion within the material (Abdelaziz, 2008).

The obtained results are presented in Table 4.3. Figure 4.1.1 shows the plot of the Marshall stability versus binder contents for each PET content. Overall, all the samples showed a similar trend, an increase in stability as the bitumen content increased up to an

optimum value. However, further addition of bitumen resulted in a decrease of the stability values.

Also figure 4.1.2 illustrates the Marshall Stability value versus PET content for each bitumen content. The diagram shows that the stability values of the different bitumen content depend on their relation with the PET content, which follow the same trend. After adding PET, the stability value increased until it reached the maximum level, which was approximately 6% of the used PET, after which it started to decrease. The values of Marshall Stability were generally higher in comparison to the control mix (mix with 0% PET). The only mixture that gave a lower stability value was the mixture with 10% PET (Ahmadinia et al., 2011).

The increase in stability by adding polymers to the hot mix asphalt is attributed to better adhesion developing between the materials in the mix (Sabina, 2009, Chen et al., 2009). However, PET has a high melting point (the melting point of PET is approximately 250°C) (Stephan.ZD, 2007) whereas the maximum temperature for the blend materials in the hot mix asphalt is less than 180 °C. Because of this high melting point researchers avoid using PET in the hot mix asphalt. In a joint experiment, Casey et al. applied different kinds of polymer as a modifier for the binder (PVC mulch, Isotactic PP mulch, LDPE mulch, HDPE mulch, ABS chips, Isotactic PP powder, MDPE mulch and PET chips) and in the case of PET, they concluded, that its high melting point hindered the mixing, making it impractical to make any further attempts to incorporate it into the bitumen (Casey et al., 2008).

The main idea for applying waste PET in this study was based on a different property. PET, in its natural state, is a semi-crystalline resin (Raabe D, 2004, Seyler.RJ, 1997,

Gueguen O, 2010), and the glass transition temperature (T_g) of PET is about 70 °C (Stephan.ZD, 2007, Keating MY, 2002, Li JM, 2008). After heating its properties start to change altering it into a material with less or more crystal properties and as illustrated in Fig. 4.1.2, its introduction into the mixture rendered the mixture stiffer with higher stability. Therefore, the main reason for this result is attributed to PET staying as a semi crystal in the mix and making a stiffer mixture.

As mentioned previously, this research used the dry process with the PET added in the last part of the mixing process. The main reason for this was to try to keep PET in the mixture in its natural state (semi-crystalline resin) with minimal change in its shape and properties.

It was confirmed by the ANOVA results that PET significantly affects the stability value at the 95% confidence level. Results show the value of F-ratio is greater in comparison to the value of F-critical and also, the P-value is smaller than α . Therefore, considering the two above premises, it can be concluded that the effects of PET on Marshall Stability is significant (Weidong, 2007).

A summary of the ANOVA results is given in the Appendix C.

Table 4.3: Stability values (KN) for different PET contents.

		PET content					
		0%	2%	4%	6%	8%	10%
Binder (%)	5%	9.31	9.76	10.29	10.47	10.22	10.07
	5.5%	9.72	10.45	10.93	10.91	10.67	10.12
	6%	9.3	10.43	10.67	10.71	10.03	8.99
	6.5%	8.81	9.95	10.34	10.64	9.89	9.36
	7%	8.57	9.25	9.39	9.51	8.94	7.95

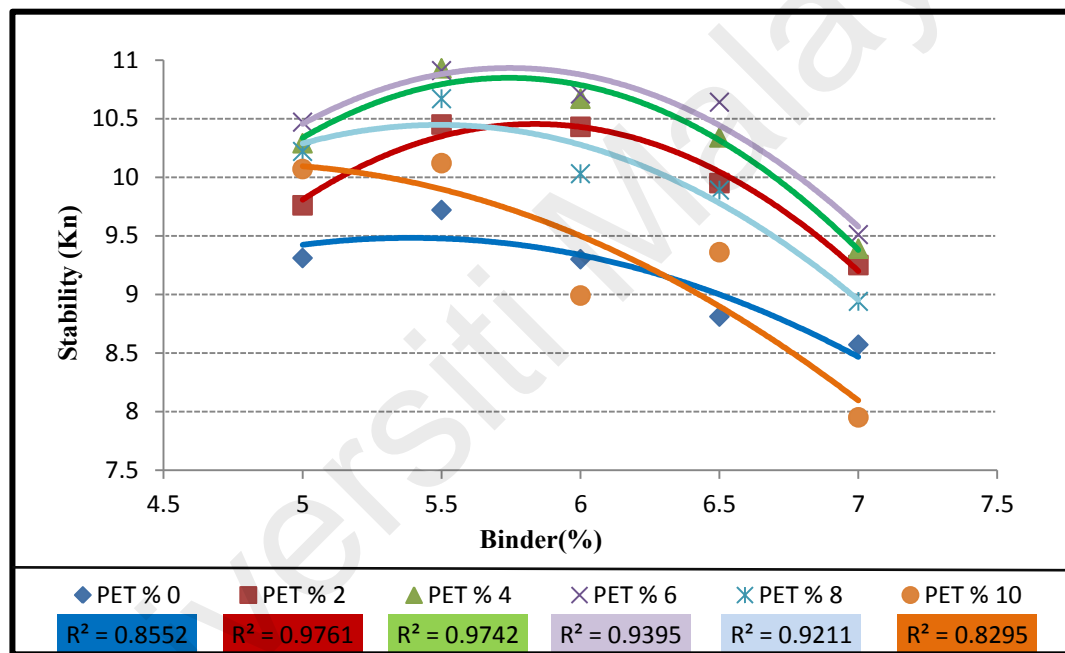


Figure 4.1.1: Marshall Stability value versus binder content for each PET content

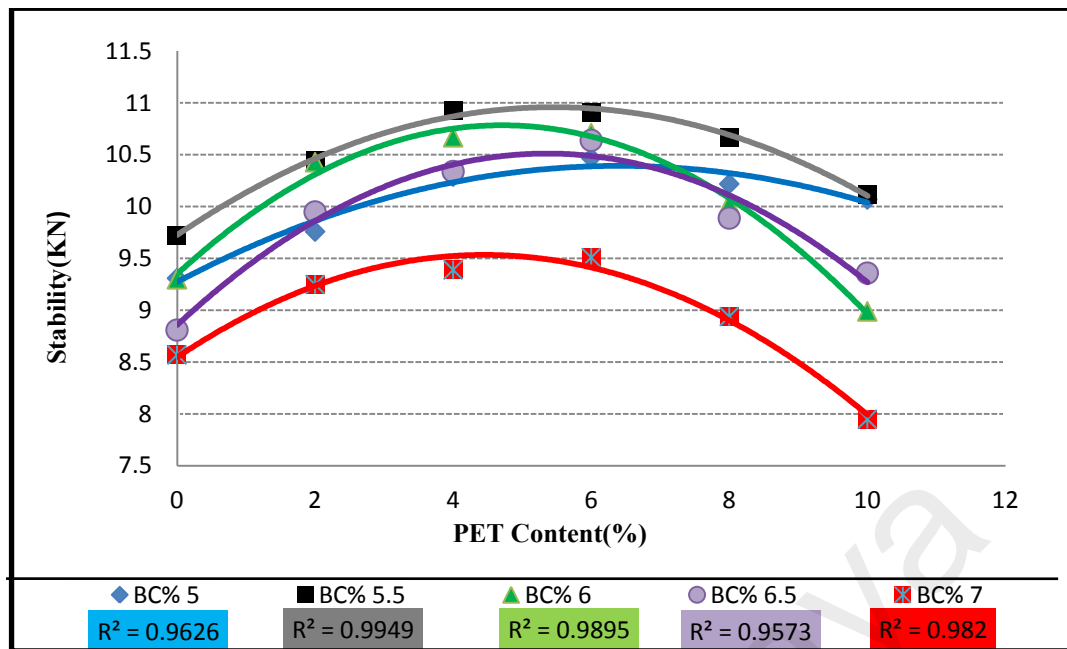


Figure 4.1.2: Marshall Stability value versus PET content for each binder content (BC).

4.3.2 Marshall Flow

The Marshall flow is the deformation of the specimen in mm at the point when the maximum load has occurred. Flow is understood to mean a measurement of the permanent strain that takes place in a Marshall test at failure (Abdelaziz, 2008). The obtained Marshall flow results are displayed in Table 4.4.

Figure 4.2.1 shows the flow value versus the binder content for each PET content. The figure illustrates that the Marshall flow increases following any increase in the bitumen content. Nevertheless, the increase in flow value with the addition of more binder is due to excessive binder in the mixture, which causes the aggregate to “float” within the mixture, which results in high flow value (Abdelaziz, 2008).

In the case of the relationship between the Marshall flow and PET content, as Figure 4.2.2 displays, any increase in the percentage of the PET leads to a slight decrease in the flow value accordingly. However, this decrease is only apparent until 4% of PET content in the mixture after which the rate starts to increase. This result can contribute to the formation of a stiffer mixture with adding PET into the mixture. However, a high percentage of PET causes the flow to increase while the stability decreases (Ahmadinia et al., 2011).

The results of ANOVA confirm the significance of the impact of PET on the value of the Marshall flow at the 95% confidence level. The results also support that the value of the F-ratio is bigger than the F-critical value and the value of P is smaller than α . Hence, we can conclude from the above premises that the influence of PET on the Flow level is significant (Weidong, 2007). The results of ANOVA for the Marshall flow are presented in Appendix C.

Table 4.4: Flow values [mm] for different PET contents.

		PET Content (%)					
		0	2	4	6	8	10
Binder (%)	5	2.37	2.31	2.35	2.53	3.14	3.45
	5.5	2.68	2.62	2.53	2.62	3.25	3.52
	6	3.41	3.02	2.87	2.58	3.42	4.08
	6.5	3.19	3.43	3.12	3.34	4.22	5.17
	7	3.93	3.89	3.66	3.70	4.36	5.06

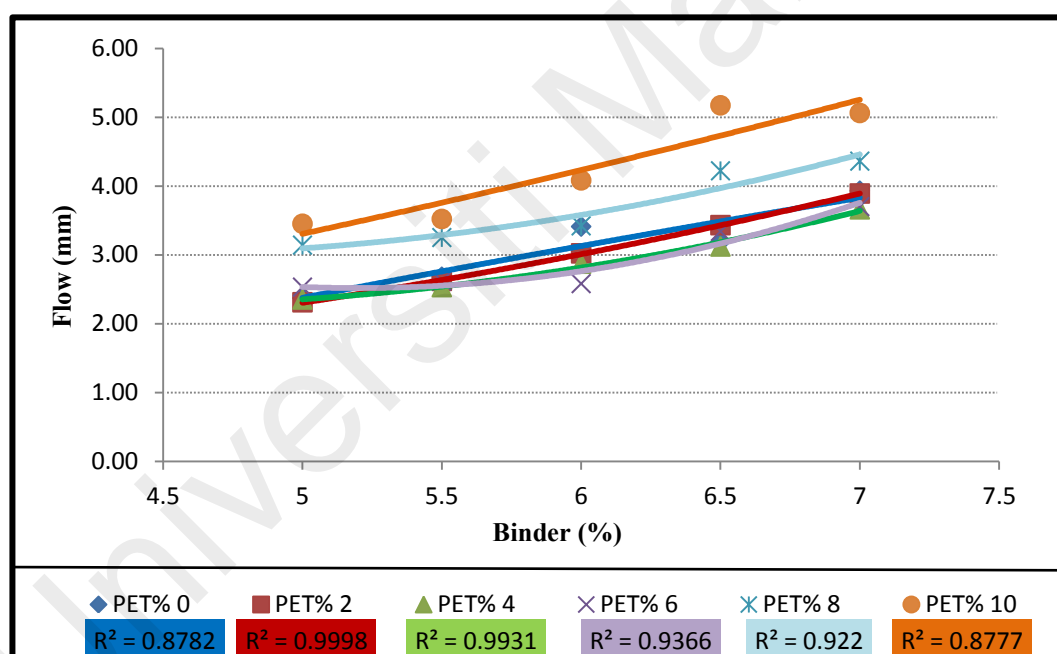


Figure 4.2.1: Marshall flow value versus binder content for each PET content

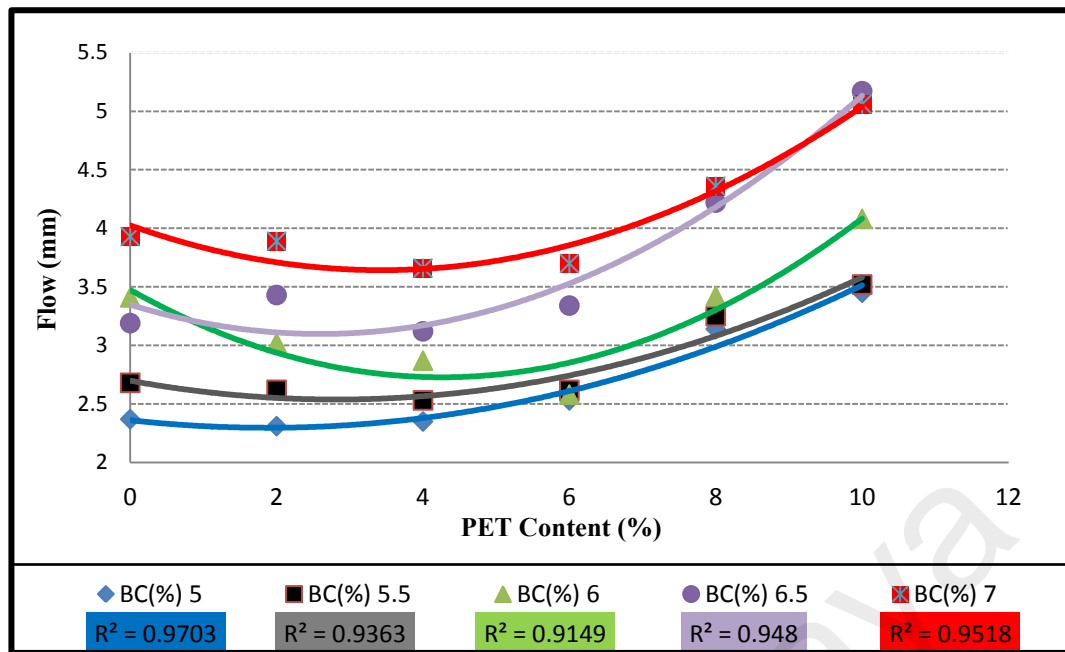


Figure 4.2.2: Marshall flow value versus PET content for each binder content(BC).

4.3.3 Marshall Quotient

Since the Marshall Quotient (MQ) is an indicator of the resistance against the deformation of the bituminous mixture (Hınıslıoğlu and Ağar, 2004, Ahmedzade and Yilmaz, 2008, Tayfur et al., 2007) MQ values are calculated to evaluate the resistance of the deformation of the specimens. The results obtained for MQ are tabulated in table 4.5.

Figure 4.3.1 shows the MQ value versus the binder content for each PET content. As Figure shows, the MQ value has a negative relationship with the binder content, i.e., the MQ value decreases with any increase in the bitumen content in the mixture specimen. Increasing the bitumen content in the mixture resulted in a sharp increase in the flow value, which could, in turn, lead to a decrease in the MQ.

As displayed in Figure 4.3.2, in the relationship between the MQ and PET content, the MQ values of the cases that contained 2%, 4% and 6% of PET were higher in comparison to those in the control mixture. Therefore, it can be concluded that due to its high MQ, the bituminous mixture with PET has higher stiffness and better resistance against serious deformation as a result of heavy loading (Ahmadinia et al., 2011).

The results of ANOVA confirm the significance of the effect of PET on the value of the MQ at the 95% confidence level. The results confirm that the value of the F-ratio is bigger than the F-critical value and the value of P is smaller than α . Therefore, the significance of the impact of PET on MQ can be concluded from the above premise (Weidong, 2007). The results of ANOVA for MQ are presented in Appendix C.

Table 4.5: Marshall quotient values for different PET contents.

		PET Content (%)					
		0	2	4	6	8	10
Binder (%)	5	3.93	4.23	4.38	4.14	3.25	2.92
	5.5	3.63	3.99	4.32	4.16	3.28	2.88
	6	2.73	3.45	3.72	4.15	2.93	2.20
	6.5	2.76	2.90	3.31	3.19	2.34	1.81
	7	2.18	2.38	2.57	2.57	2.05	1.57

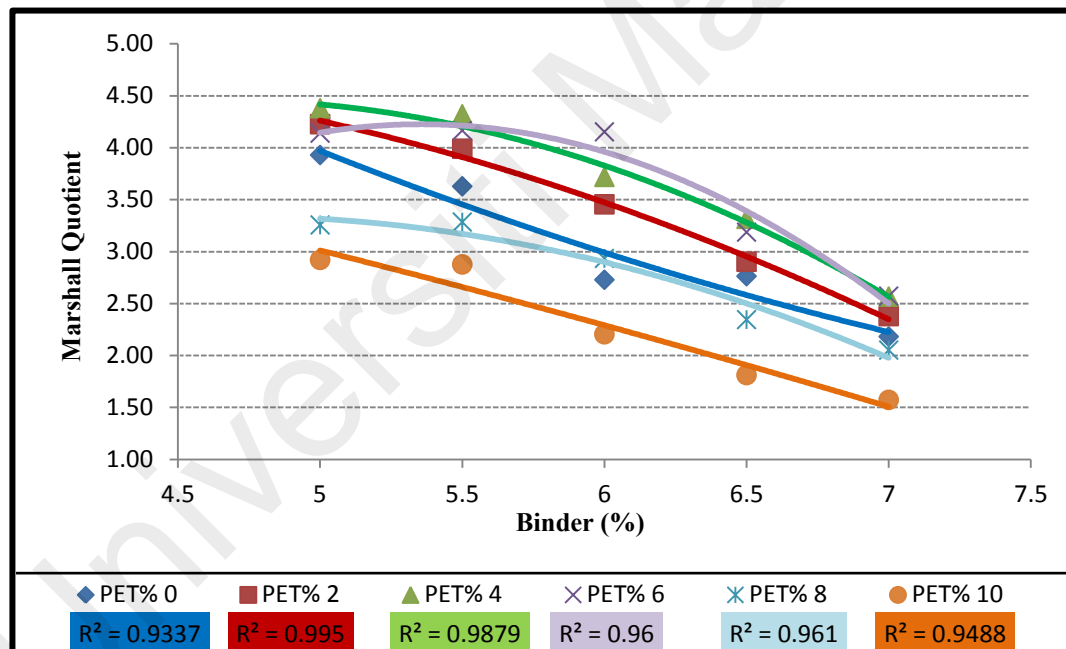


Figure 4.3.1: Marshall quotient value versus binder content for each PET content

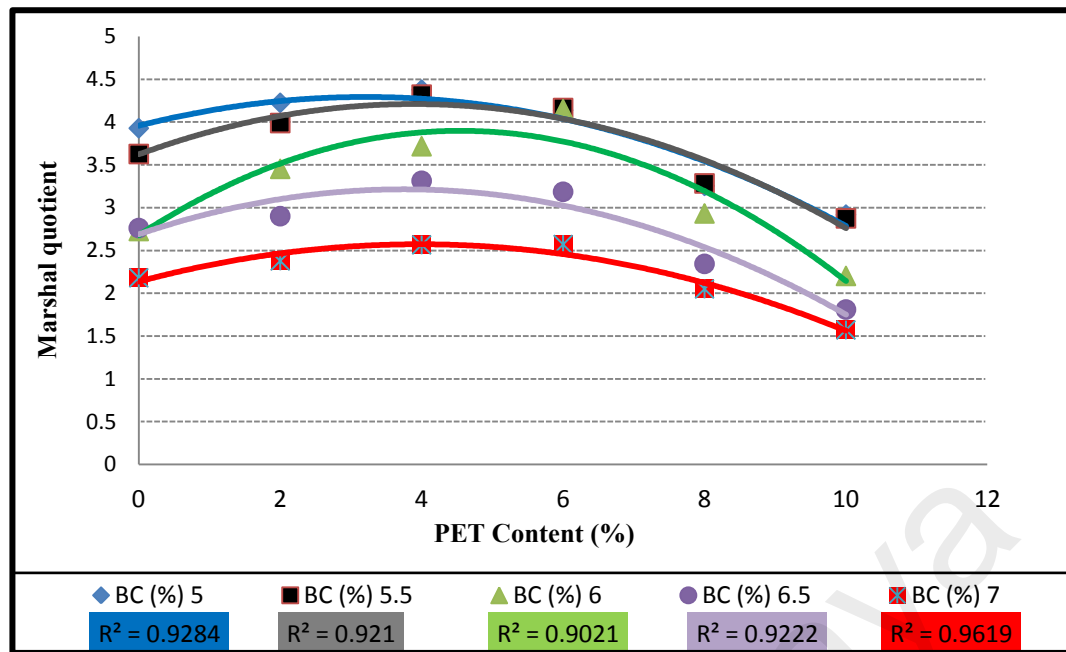


Figure 4.3.2: Marshall quotient value versus PET content for each binder content(BC).

4.4 Volumetric Test Results and Discussion

4.4.1 Bulk density of the compacted mix

The results obtained show that both PET and bitumen content influence the compaction features of the mixture. Therefore, they have a significant impact on the bulk density. Table 4.6 and Figure 4.4.1 show that the bulk density of the mixture increases with the increase in the bitumen content in the mixture. The main reason for this is because of the filling of the void space of the aggregate particles with bitumen. However, after filling the void space, the excessive percentage of the bitumen could lead to a significant decrease in the bulk density of the mixture.

As Figure 4.4.2 illustrates, for each of the binder contents, any increase in PET content reduces the bulk density of the mix and regardless of the PET content, the bulk density of the mixture was lower than that of the control mixture. The resulting decrease in the bulk density value is due to the lower specific gravity of the PET in comparison with the mineral aggregates (Ahmadinia et al., 2011).

The results of ANOVA support that the impact of PET on the value of the bulk density is significant (with a 95% confidence level). The ANOVA results show that the F-ratio value is greater than the F-critical value while the P-value is smaller than α . Therefore, we can conclude that the influence of PET on bulk density is significant (Abdelaziz, 2008). The results of ANOVA for bulk density are presented in Appendix C.

Table 4.6: Bulk density of the compacted mix values for different PET contents.

		PET Content (%)					
		0	2	4	6	8	10
Binder (%)	5	2.312	2.312	2.305	2.301	2.300	2.289
	5.5	2.324	2.322	2.311	2.311	2.303	2.292
	6	2.333	2.330	2.318	2.318	2.316	2.303
	6.5	2.335	2.329	2.323	2.317	2.308	2.305
	7	2.328	2.322	2.315	2.307	2.295	2.284

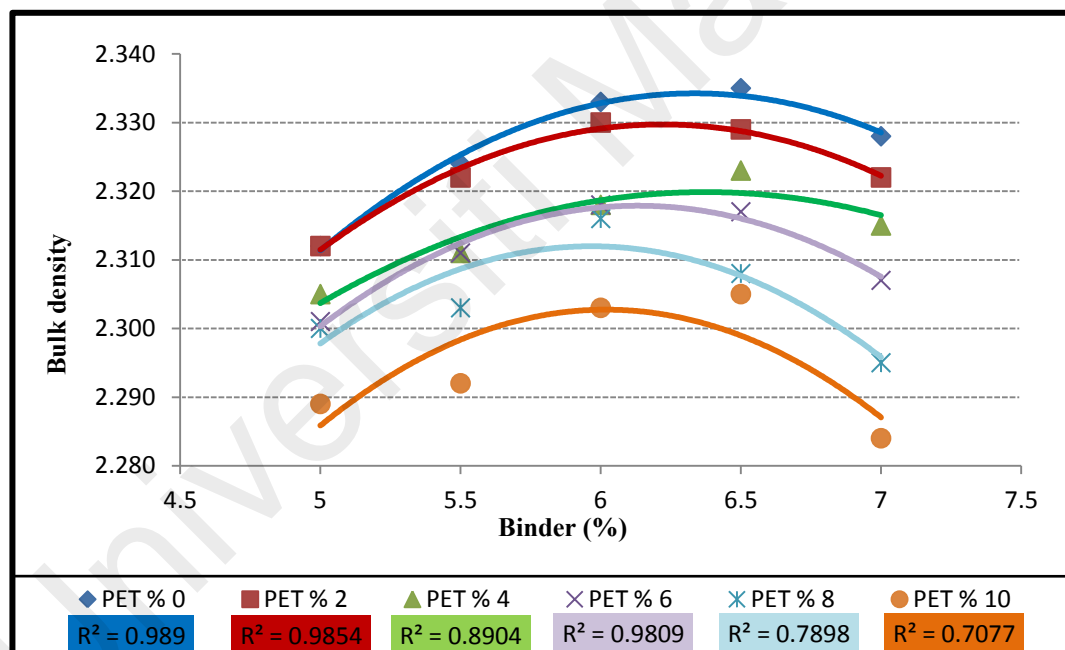


Figure 4.4.1: Bulk density value versus binder content for each PET content

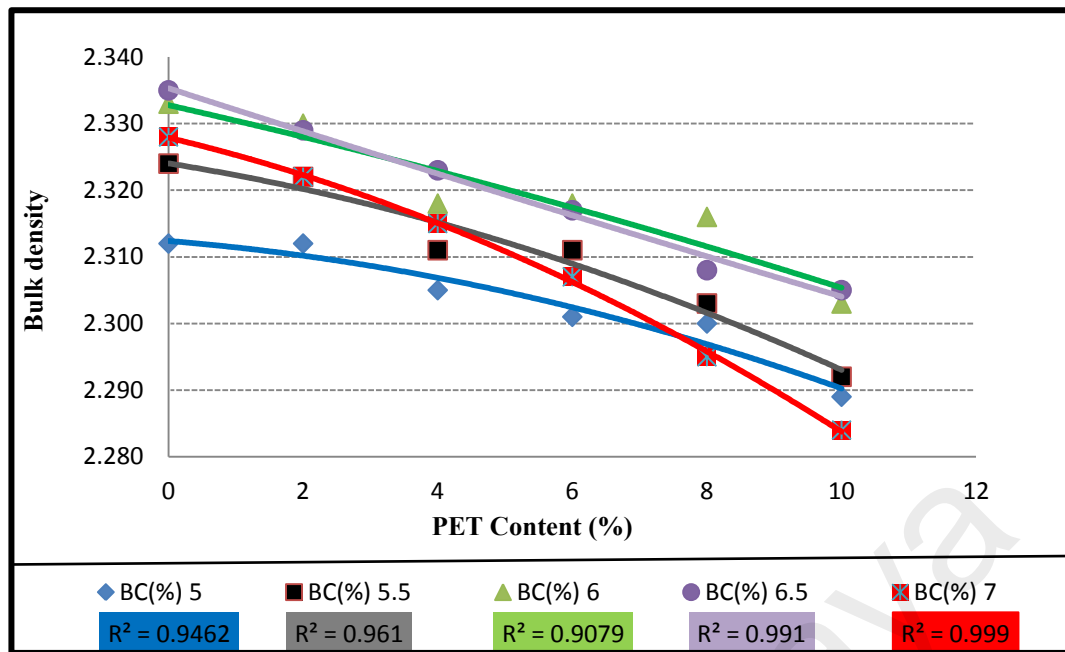


Figure 4.4.2: Bulk density value versus PET content for each binder content (BC).

4.4.2 Voids in the Mix (VIM)

The air voids is a vital parameter of bituminous mixtures used for pavement design and the achievement of optimum asphalt content (Ahmedzade and Yilmaz, 2008, NAPA, 1999, Sengoz and Topal, 2007). Excessive air voids can result in cracking, which is due to the insufficient amount of binder coating the aggregate while low air voids can result in more plastic flow (rutting) as well as asphalt bleeding (Chen et al., 2009). Therefore, it is essential to produce a mixture with sufficient air voids to have an impermeable and durable mixture as sufficient air voids help prevent the mixture from becoming a “hydraulic” material where surplus binder could be pumped to the surface beneath heavy traffic loadings and higher temperatures.

The VIM results are displayed in table 4.7. Figure 4.5.1 illustrates the relationship between the binder and the VIM for each PET content. Generally, with any increase in binder content, the VIM decreases for any PET content. This is due to the large amount of bitumen present in the mixture, which fills all the voids in the aggregates.

In the relationship between the air voids and PET content, as Figure 4.5.2 shows, increasing the PET content in the mixture results in more air voids in the mixture as a result of the chopped PET used in the mixture, which remains in the form of crystals, thereby increasing the surface area. The increased surface area, however, needs to be wetted with binder, which would finally lead to an increase in voids in the mixture. Furthermore, when PET was used in the mixture, it seemed to reduce its compact ability, therefore, a higher air void value might be obtained (Chen et al., 2009, Mahrez A, 2010).

The ANOVA results confirm the significance of the PET impact on the value of the VIM. The results support that the F-ratio value is bigger than the F-critical value and the P-value is smaller than α . Therefore, we can conclude from the above premise that the influence of PET on the air void is significant (Abdelaziz, 2008). The results of ANOVA for the air void are available in Appendix C.

Table 4.7: VIM values for different PET contents.

		PET Content (%)					
		0	2	4	6	8	10
Binder (%)	5.0	6.35	6.28	6.49	6.59	6.56	6.94
	5.5	5.24	5.25	5.63	5.57	5.82	6.21
	6.0	4.25	4.31	4.73	4.67	4.68	5.15
	6.5	3.56	3.74	3.92	4.10	3.95	4.24
	7.0	3.24	3.42	3.65	3.92	3.89	3.91

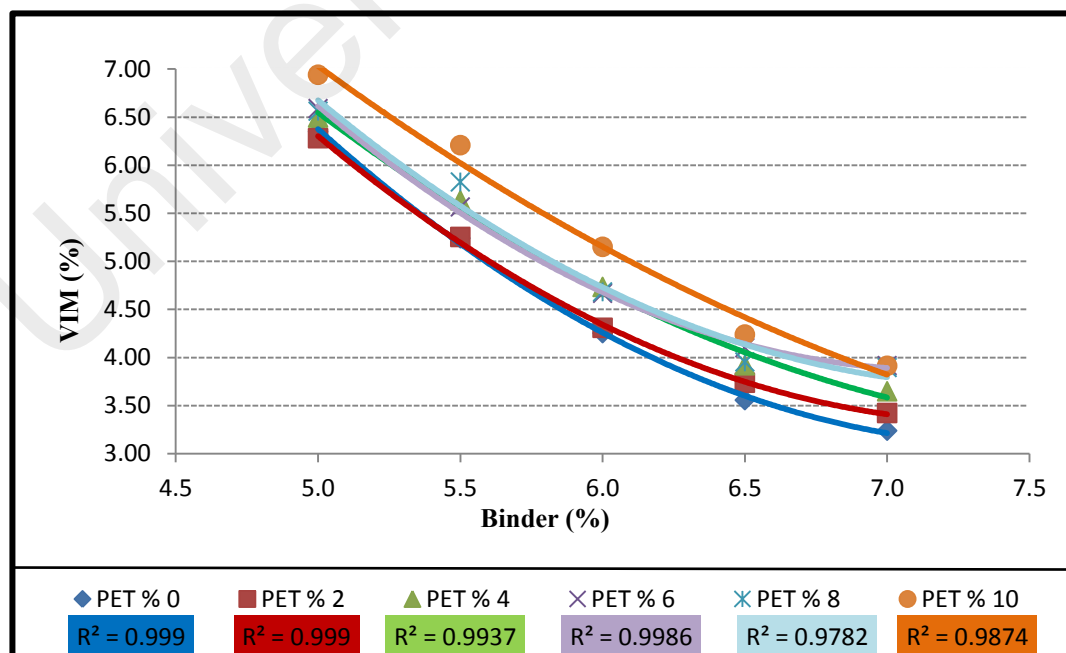


Figure 4.5.1: VIM value versus binder content for each PET content

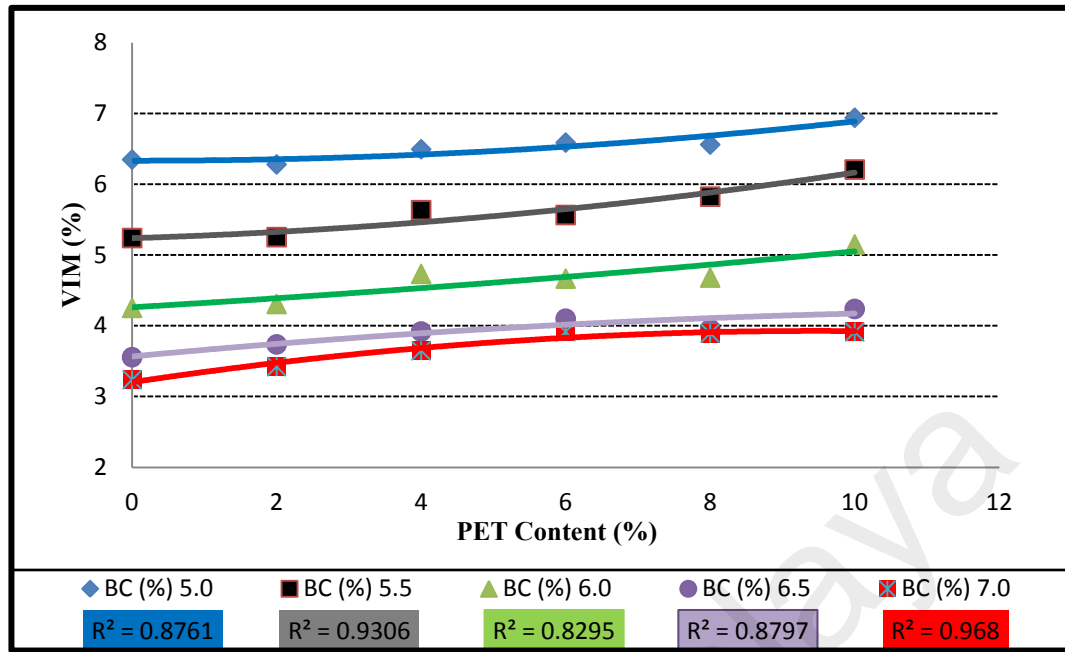


Figure 4.5.2: VIM value versus PET content for each binder content (BC)

4.4.3 Mineral Aggregate Voids (VMA)

Voids in mineral aggregate (VMA) provide space for binder films on the aggregate particles. The durability of the mix increases with the film thickness on the aggregate particles. In order to have the required durability of the mixture, minimum VMA requirements are recommended (Asphalt-Institute, 2007).

The obtained VMA results are presented in table 4.8 and the VMA value versus binder content for a PET percentage range is displayed in Figure 4.6.1. As the figure illustrates, in any PET content, the VMA decreases when the binder content increases. As Figure 4.6.2 displays, in the relationship between VMA and PET content, using the same binder, VMA increases when the PET content increases. The values of VMA were also higher than those of the control mixture.

In this case, the ANOVA results also confirm the significant impact of PET on the VMA value. The obtained results show that the F-ratio value is bigger than the F-critical value. In addition, the P-value is smaller than α . Therefore, based on this premise, we can conclude that PET has a significant impact on VMA (Abdelaziz, 2008). The ANOVA results for the VMA are available in Appendix C.

Table 4.8: VMA values for different PET contents.

		PET Content (%)					
		0	2	4	6	8	10
Binder (%)	5	17.04	17.12	17.45	17.67	17.78	18.25
	5.5	17.00	17.15	17.62	17.70	18.06	18.53
	6	17.07	17.26	17.76	17.84	17.99	18.52
	6.5	17.39	17.68	17.97	18.26	18.65	18.83
	7	18.02	18.31	18.63	18.99	19.49	19.95

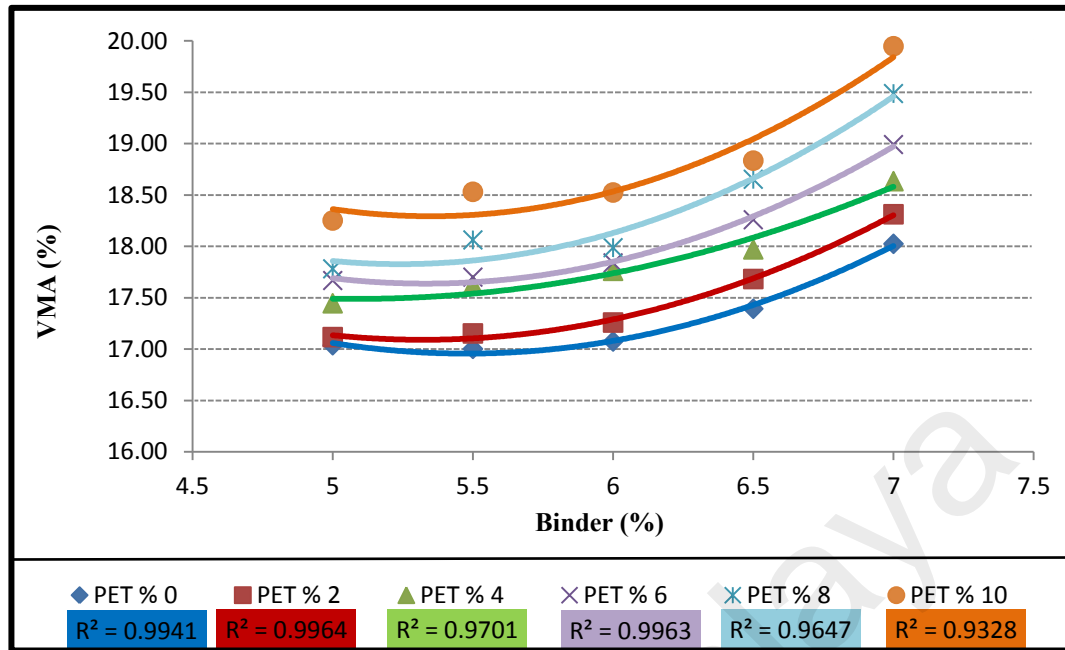


Figure 4.6.1: VMA value versus binder content for each PET content

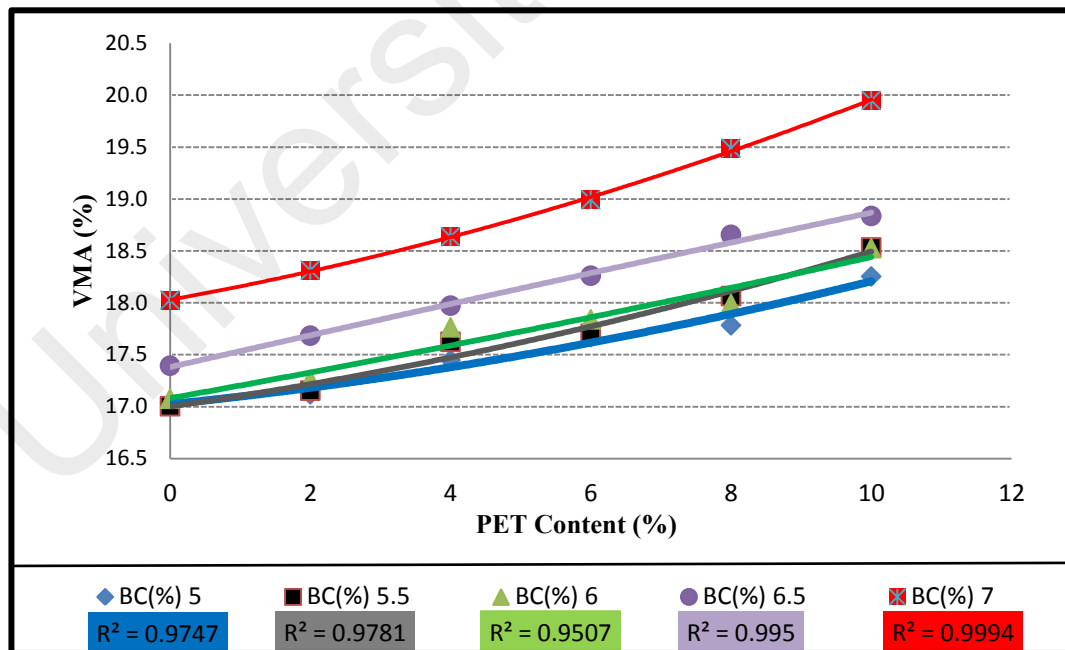


Figure 4.6.2: VMA value versus PET content for each binder content (BC)

4.4.4 Voids Filled with Bitumen (VFB)

The bitumen filled voids (VFB) are determined through the amount of VMA and air voids. This amount (VFB) shows the percentage of the VMA that is filled with binder. The results obtained for VFB are displayed in Table 4.9. Figure 4.7.1 also illustrates the VFB value versus the binder content for the PET percentage range. As shown in the figure, generally, for any PET content, there is an increase in VFB with any increase in binder content. Furthermore, concerning the relationship between VFB and PET content, as Figure 4.7.2 displays, using the same binder content, any increase in the PET content results in a slight decrease in VFB accordingly.

ANOVA results confirm that PET has the significant effects of the VMA value at 95% confidence level. Results show the value of F-ratio is greater in comparison to the value of F-critical and also, the P-value is smaller than α . Therefore, considering the two above premises, it can be concluded that the effects of PET on VMA is significant (Abdelaziz, 2008). ANOVA result for the VMA is given in the Appendix C.

Table 4.9: VFB values for different PET contents.

		PET Content (%)					
		0	2	4	6	8	10
Binder (%)	5	62.74	63.31	62.77	62.71	63.11	61.98
	5.5	69.18	69.38	68.03	68.56	67.75	66.50
	6	75.09	75.04	73.35	73.84	73.97	72.20
	6.5	79.55	78.87	78.20	77.54	78.81	77.50
	7	82.03	81.31	80.43	79.38	80.02	80.39

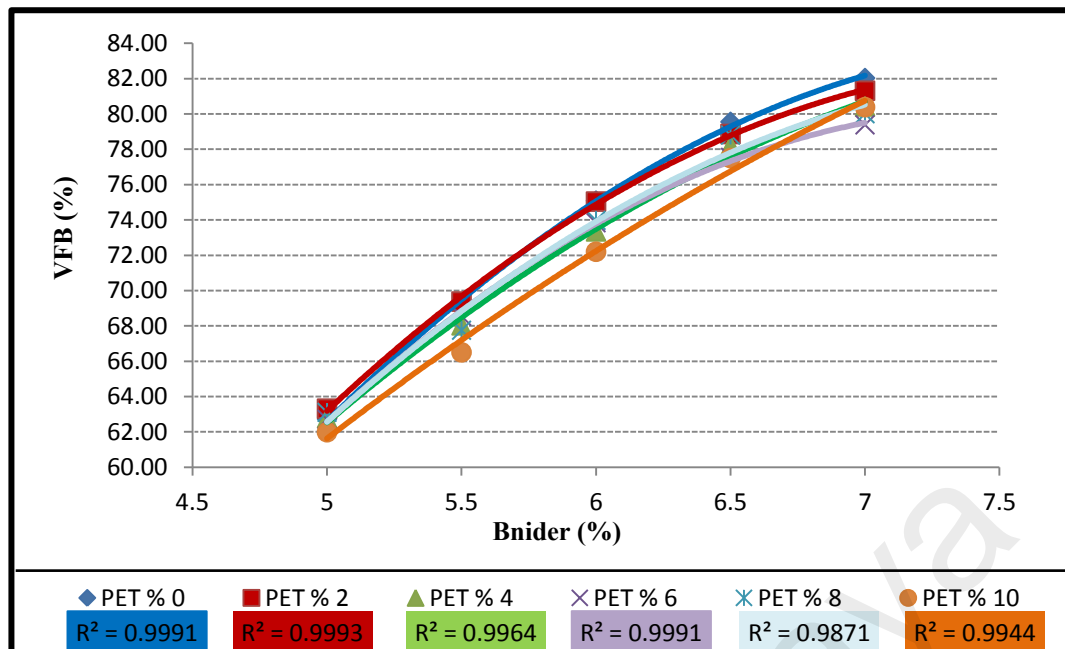


Figure 4.7.1: VFB value versus binder content for each PET content

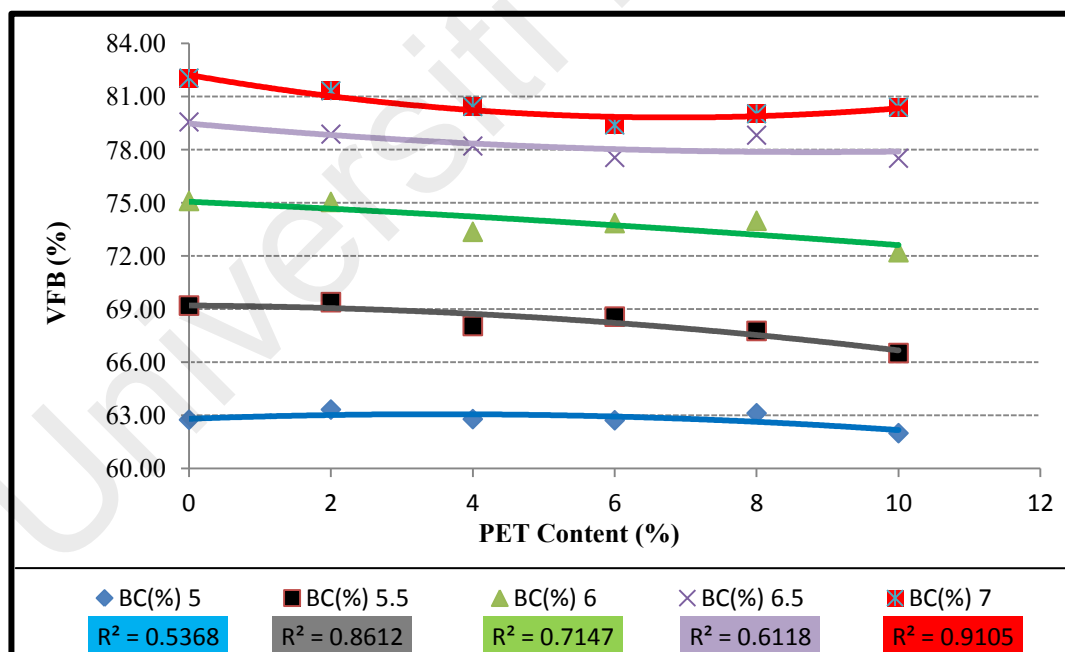


Figure 4.7.2: VFB value versus PET content for each binder content (BC)

4.5 Optimum Binder Content (OBC) Determination

The method of the Marshall mix design was employed to determine the OBC for different PET contents ranging between 0% - 10%, i.e., 0%, 2%, 4%, 6%, 8%, 10%. For the determination of OBC, three graphs, namely, stability, bulk density, and air void were plotted versus the percentage of binder for each PET content. Based on the plots, OBCs were calculated and registered. According to the Asphalt Institute (AI), the OBCs were selected in a way to satisfy the following requirements:

- Maximum Marshall Stability
- Maximum Bulk Density
- Median Range of Air Voids (between 3-5% for SMA) (Ibrahim M, 2006)

The OBCs obtained from the test parameters for the mixes with various PET content are tabulated in Table 4.11. As an example of the process of OBC determination, the OBC of a mixture containing 4% PET was calculated and displayed. The steps followed for such calculations for all the case are as below:

- 1) The peak point of the Marshall stability curve (Figure 4.8.1) showed 5.74 binder content, and was calculated with the given equation:

$$Y = -0.9286x^2 + 10.665x - 19.77$$

$$\frac{dy}{dx} = 0 \implies -1.8572x + 10.665 = 0$$

So,

$$X = 5.74$$

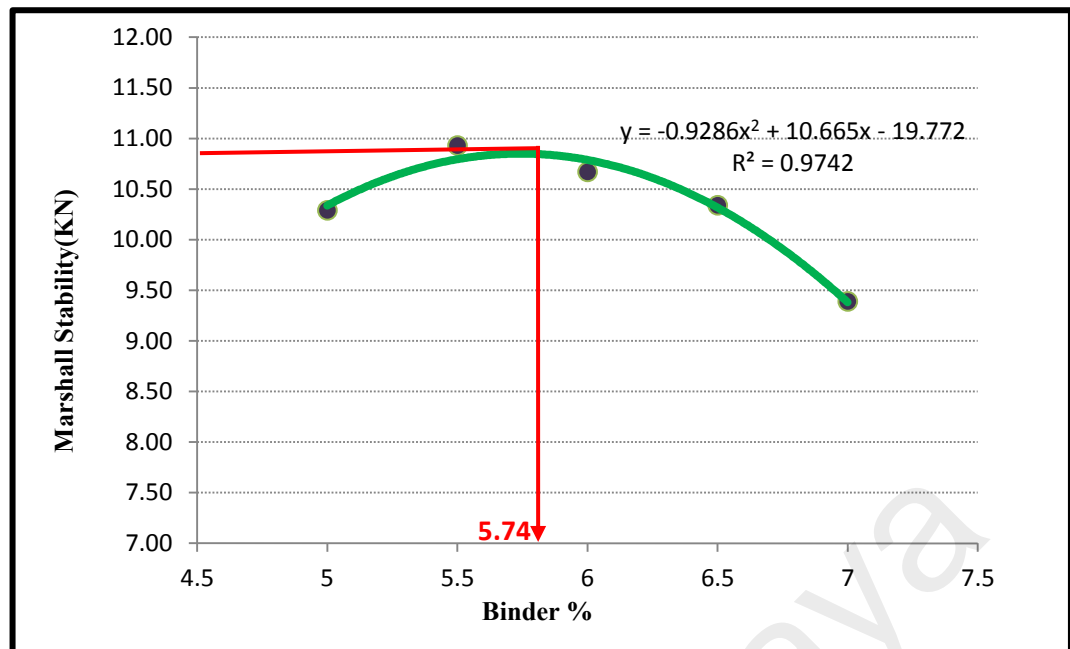


Figure 4.8.1: The peak point of the Marshall stability (mixture containing 4% PET)

- 2) The bulk density curve peak (Figure 4.8.2) showed 6.35 binder content, and was calculated with the following equation:

$$Y = -0.0086x^2 + 0.1093x + 1.9717$$

$$\frac{dy}{dx} = 0 \implies -0.0172x + 0.1093 = 0$$

So,

$$X = 6.35$$

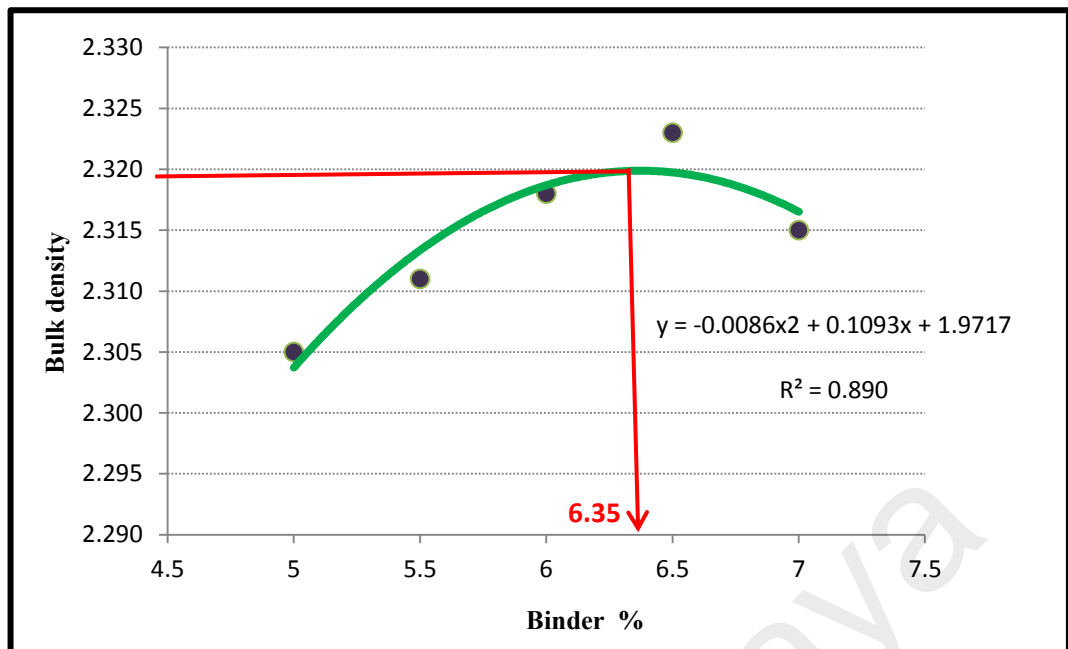


Figure 4.8.2: The peak point of the bulk density (mixture containing 4% PET)

3) Also another parameter required for OBC determination was the VIM curve (Figure 4.8.3), which showed 6.58 of binder content with optimum 4% air voids, and it was calculated with the mentioned equation, the result of which is presented in Figure 4.9.

$$y = 0.3616x^2 - 5.8212x + 26.613$$

$$y = 4 \text{ (4\% air void)} \implies 4 = 0.3616x^2 - 5.8212x + 26.613$$

So,

$$X = 6.58$$

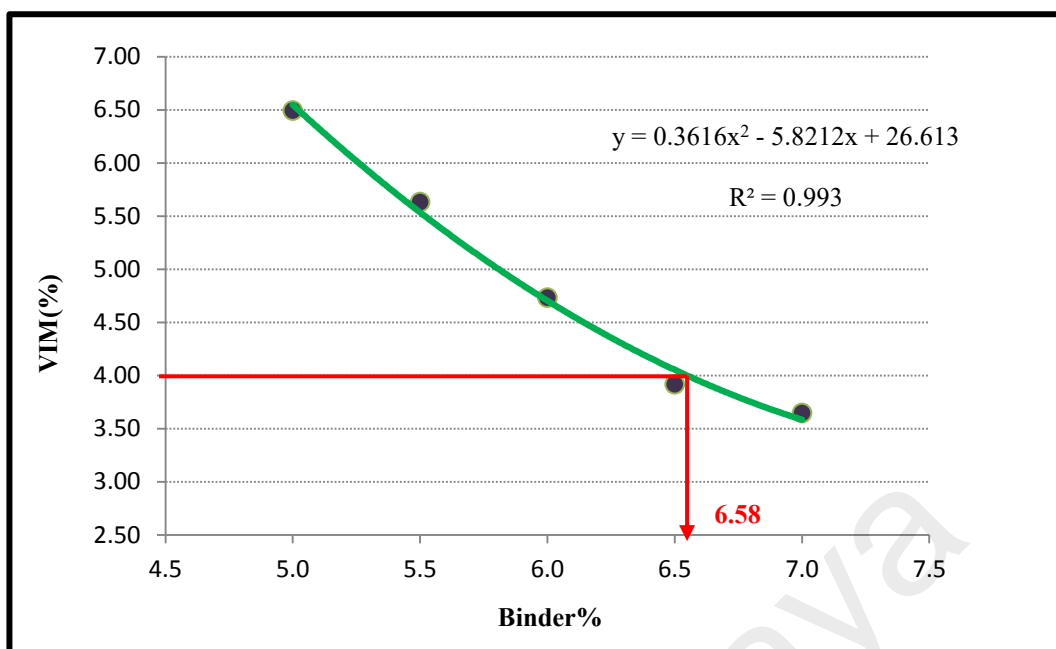


Figure 4.8.3: VIM curve with 4% air voids (mixture containing 4% PET)

- 4) And finally, the overall OBC was obtained from the average of these percentages. A summary of the obtained results is displayed in Table 4.10.

Table 4.10: The OBC of a mixture containing 4% PET

Property	OBC (for mixture containing 4% PET)
Peak of stability curve	5.74
Peak of density curve	6.35
4% air voids, from VIM curve	6.58
Average	6.22

For all PET contents, the same process was followed to obtain their OBC values a summary of which is available in Table 4.11.

Table 4.11: The OBCs for the mixes with various PET content

	PET content					
	0%	2%	4%	6%	8%	10%
OBC (%)	5.97	6.1	6.22	6.19	6.04	5.87

4.6 Performance Test Results

4.6.1 Resilient Modulus Test

The resilient modulus (MR) test is the most popular test used to measure stress–strain to assess and evaluate the elasticity properties of the bituminous mixture representing an applied stress ratio to the recoverable strain after removal of the applied stress (Xue et al., 2009). The modulus of asphalt is a fundamental design parameter during the application of the elastic-layered system theory for designing the structure of asphalt pavements. The current performance prediction models used in asphalt pavement projects also employ the modulus as a vital material parameter (Al-Hadidy and Tan, 2009, Ai et al., 2011). Therefore, it is desirable that the modulus of asphalt be predicted during the design stage of the asphalt mixture to improve the mixture design and for enhancement of the pavement performance prediction.

The MR was determined from tests on Marshall cylindrical specimens on both conventional (mixture with 0% PET) and PET-mixtures in indirect tension mode. Three specimens were prepared for each PET content and the conventional mixture and

were tested with a Universal Testing Machine . The test results are summarized in the table 4.12.

Figure 4.9 illustrates the MR value versus PET content. As the figure shows, after the addition of PET, the MR value increases until it reaches the maximum level, after which it starts to decrease. The MR values of mixtures containing PET were generally greater than the conventional mix (0% PET) and the achieved results indicate that the maximum value of MR was obtained by adding 6% PET, which showed that the MR had increased by 16% compared to the conventional mix.

As mentioned earlier (Marshall stability result section), the main cause of this result could be the PET remaining as a semi crystal material within the mixture, which results in a stiffer mixture.

Table 4.12: Resilient Modulus (MR) values for different PET contents.

	PET Content (%)					
	0	2	4	6	8	10
MR (MPa)	2587	2697	2914	2991	2872	2767

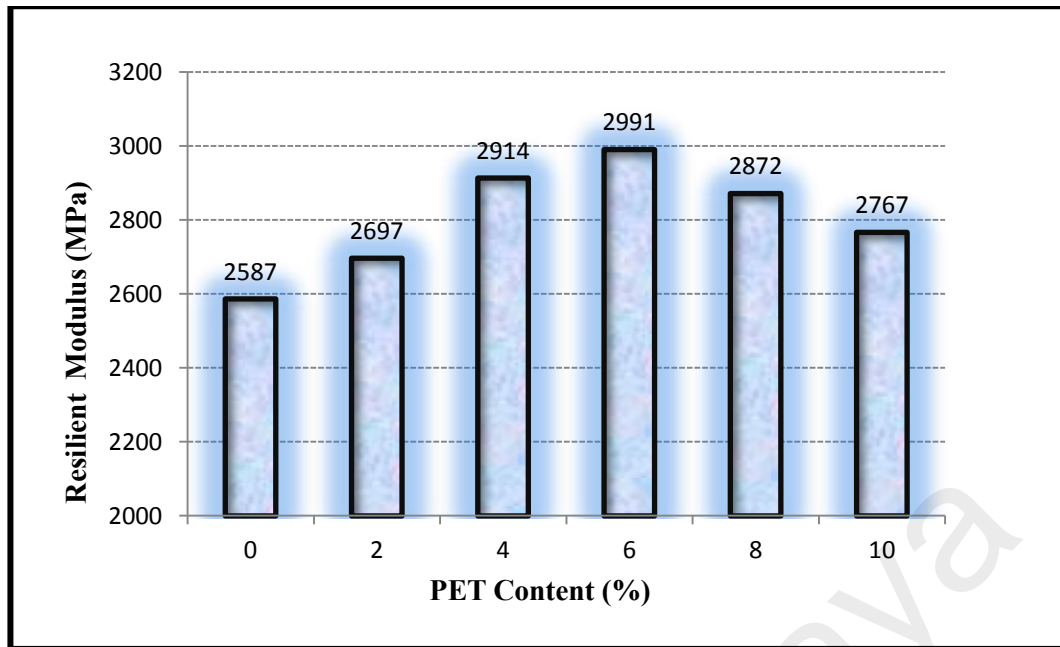


Figure 4.9: Resilient modulus (MR) test results.

4.6.2 Wheel tracking test

Resistance to rutting is one of the vital performance requirements for a bituminous mixture, especially in hot climates. In the literature, the typical tests used for testing and evaluating the rutting include the Marshall test, wheel track test, static and dynamic creep tests, and indirect tensile test (Tayfur et al., 2007, Moghaddam TB, 2011). However, the wheel tracking test is the most recommended one because of its features, which allow better field simulation (Lu and Redelius, 2007), particularly for the assessment of the performance of stone-skeleton mixtures or mixtures that include modified binders (Özen et al., 2008). In the present study, wheel track testing was used to evaluate the mixtures resistance against rutting. For this test, 18 specimens with 300×300×50 mm slab dimension were prepared and the results are summarized in the table 4.13.

The effect of waste PET on rutting resistance for mixtures is displayed in Figure 4.10. The results indicate that mixes containing waste PET have better permanent deformation resistance compared to the conventional mixture. Furthermore, Figure 4.10 indicates that the rut depth increases sharply for the first 15 min after which the increase becomes slower and more gradual. The rut depth for mixtures with 0%, 2%, 4%, 6%, 8% and 10% PET content after 45 min is 1.78mm, 1.50mm, 1.26mm, 1.35mm, 1.62mm and 1.56mm, respectively, which indicate that the minimum rut depth obtained for the mix with 4% PET could reduce the rut depth by 29% compared to the conventional mix. The results achieved can contribute to the formation of a stiffer mixture, which improves the rutting resistance of the mixture (Xiao et al., 2009, Hınıslioğlu and Ağar, 2004).

Table 4.13: Wheel track test results for different PET contents.

		Time (min)									
		0	5	10	15	20	25	30	35	40	45
PET Content	0%	0	1.02	1.43	1.60	1.66	1.70	1.73	1.74	1.76	1.78
	2%	0	0.78	1.21	1.29	1.3	1.39	1.42	1.45	1.47	1.5
	4%	0	0.4	0.67	0.81	0.89	0.99	1.12	1.18	1.24	1.26
	6%	0	0.91	1.08	1.16	1.19	1.24	1.27	1.29	1.32	1.35
	8%	0	0.53	0.92	1.07	1.27	1.38	1.47	1.57	1.61	1.62
	10%	0	0.64	1	1.25	1.33	1.39	1.44	1.47	1.49	1.56

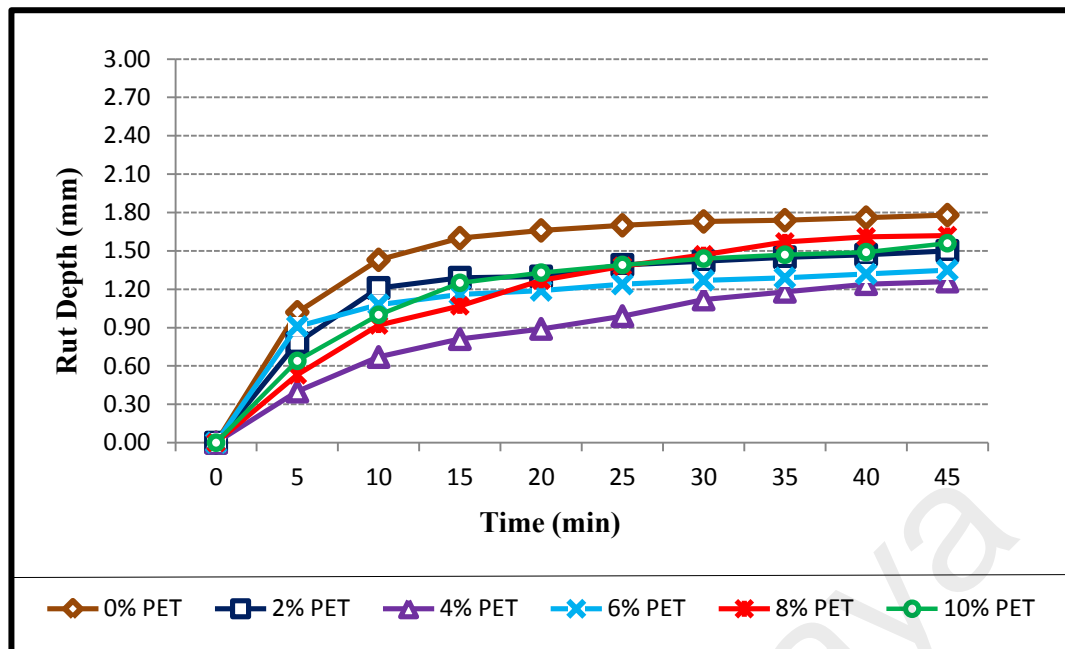


Figure 4.10: Wheel track test results.

4.6.3 Drain Down Test

SMA, like porous asphalt mixture, is subjected to binder drainage problems. Because SMA has a high optimal binder content, drainage problems may occur in the mixing, transporting and laying processes (Tayfur et al., 2007). The drain down test using the wire basket method, as suggested in AASHTO T305, was carried out on all the evaluated mixtures.

The results of the drain down test for the mixtures are displayed in figure 4.11 and table 4.14. Regardless of the content of the employed PET, the drain down value of the PET-mixes was lower than the drain down value of the control mixture, and, furthermore, any increase in PET content into the mixture reduces the value of the drain down. The reduction of drain down value can be as a result of the chopped PET used in the mixture, which remains in crystal form, thereby increasing the surface area. The

increased surface area, however, needs to be wetted with binder (Mahrez A, 2010) , which would finally lead to stabilizing and holding the binder on its surface and decrease the binder drain down.

Table 4.14: drain down values for different PET contents.

	PET Content (%)					
	0	2	4	6	8	10
Drain down (%)	0.298	0.285	0.269	0.253	0.236	0.229

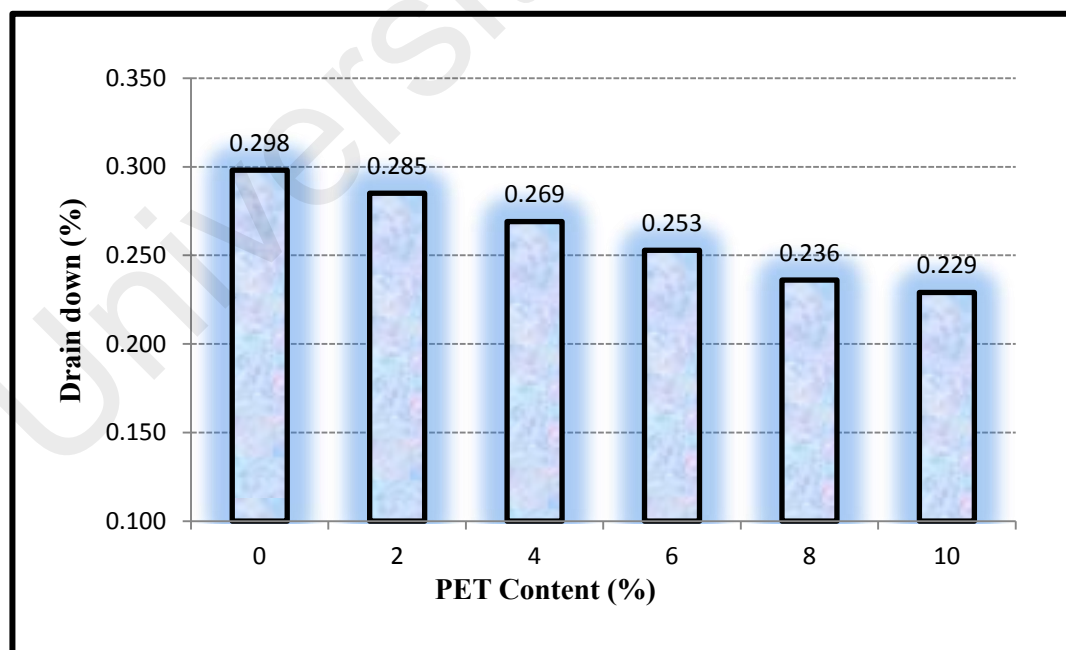


Figure 4.11: The drain down test results.

4.6.4 Moisture susceptibility test

The moisture susceptibility of bituminous mixtures is defined as the vulnerability of the asphalt mixture to be damaged by water. When moisture collects within the bituminous mixture, it can cause damage to the bond between the aggregates and asphalt binder, which, in turn, accelerates the development of other kinds of distress such as cracking and potholing (Ahmedzade and Yilmaz, 2008, Shen et al., 2008).

The moisture susceptibility test was carried out in accordance with the AASHTO T283 procedure on six SMA mixes, which were compacted to an average 7% air-void content. Three Marshall specimens for the dry group (unconditioned) and three specimens for the wet group (conditioned) were prepared. A tensile strength ratio (TSR) of the wet to dry group was calculated based on the outcomes of the indirect tensile strength test conducted at 25°C. It is noteworthy to mention here that the higher the TSR value the better the asphalt mixture resistance against moisture damage (Sung Do et al., 2008); a 70% or more TSR value is required for normal SMA specification (Al-Hadidy and Tan, 2009).

The results obtained from the tensile strength test of conventional mixture and the PET-mixes are presented in Figures 4.12.1 and 4.12.2, and summarized in the tables 4.15 and 4.16. As the results illustrate, the tensile strength and TSR values of the mixtures decrease with the addition of PET. TSR values between 70 – 80% have been set as the minimum requirement by AASHTO T 283 and ASTM D 4867 standards. As figure 4.12.2 shows, all values of TSR are above 70% indicating that all mixes may have adequate resistance against damage induced by moisture (Shen et al., 2008, Muniandy R, 2010). However, the addition of waste PET does not improve the moisture susceptibility of the mixture. This result could be attributed to the crystal form of PET

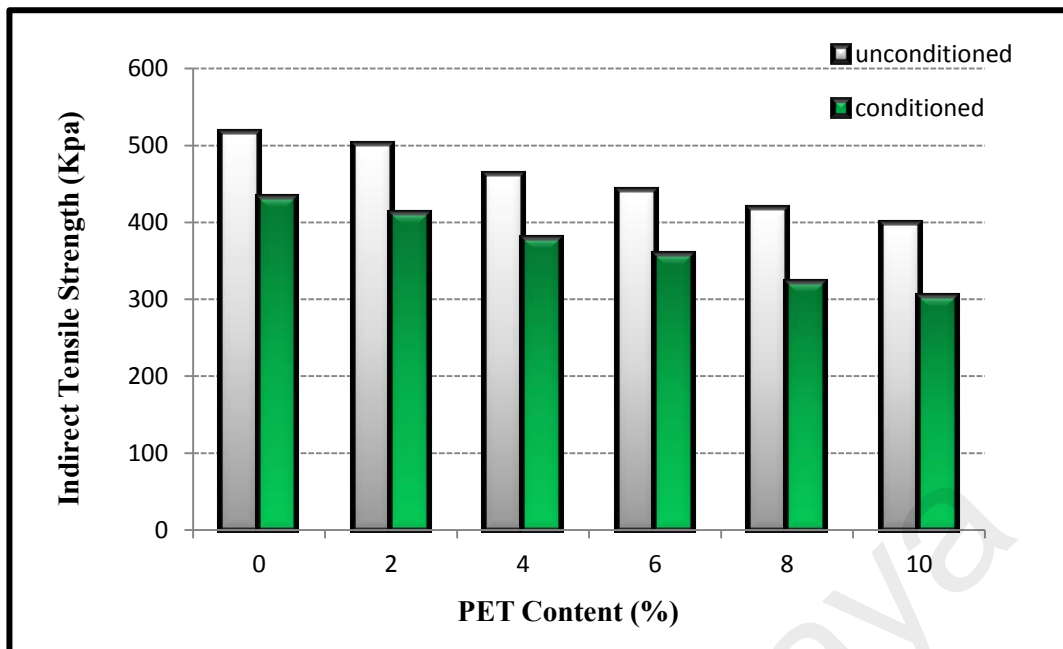
after mixing that holds the sticky binder on its surface and decreases the asphalt film thickness around the aggregate, which, in turn, results in a reduction to the resistance against damage induced by moisture.

Table 4.15: Indirect tensile Strength values for different PET contents.

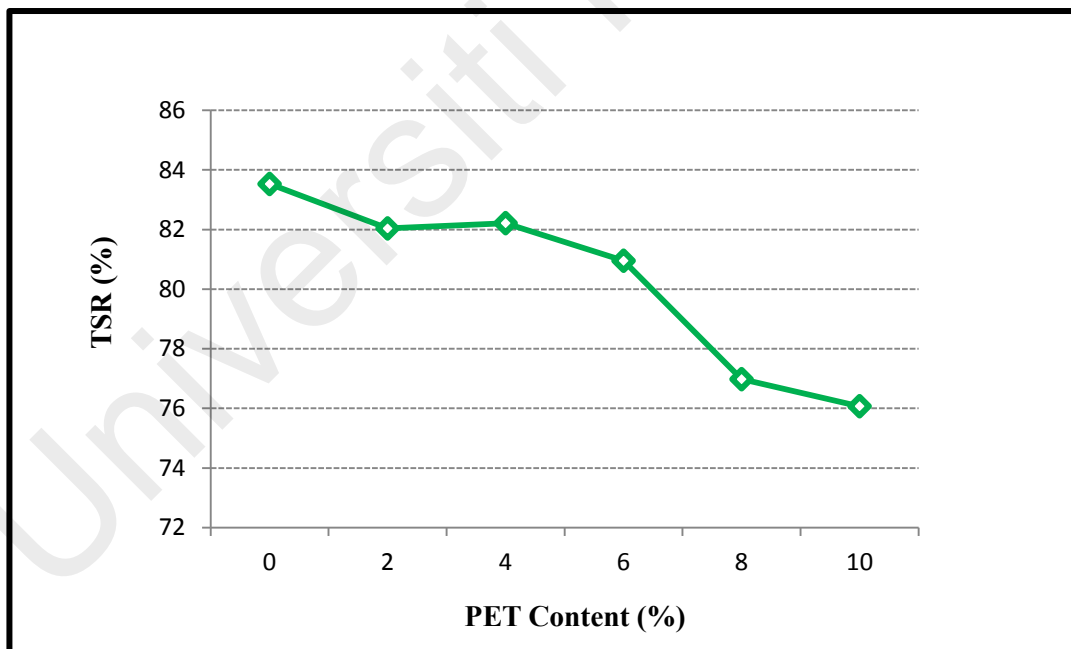
	PET Content (%)					
	0	2	4	6	8	10
Unconditioned	516	501	461	441	417	397
Conditioned	431	411	379	357	321	302

Table 4.16: Tensile strength ratio (TSR) values for different PET contents.

	PET Content (%)					
	0	2	4	6	8	10
TSR (%)	84	82	82	81	77	76



Figures 4.12.1: Indirect tensile strength of unconditioned and conditioned specimens.



Figures 4.12.2: TSR for asphalt mixtures with various PET content.

4.7 Summary

This chapter focused on the laboratory test results on the SMA properties enriched with waste PET as additives in the mixture. The first section of the chapter discussed the properties of the materials used, and then the Marshall test result, volumetric test result, and performance test results were evaluated.

According to the results obtained from the Marshall test, the addition of waste PET to the mixture resulted in an increase in both the Marshall stability and Marshall quotient of the mixtures. Moreover, the results confirm that the addition of waste PET results in a reduction of the bulk density and bitumen filled voids (VFB) of the mixture, however, it causes the air voids (VIM) and mineral aggregate voids (VMA) of the mixture to increase.

The ANOVA results show that the addition of PET has a significant effect on the Marshall data sets with 95% confidence level.

In addition, according to the results obtained from the overall test, the PET added mixtures had a higher level of Marshall stability, Marshall quotient, VIM, VMA, resilient modulus, resistance to rutting, resistance to binder drain down, but lower bulk density, lower VFB, lower resistance against damage induced by moisture.

Finally, during the experiments and tests carried out through this study, it was noticed that the PET content between 4-6% by weight of the bitumen resulted in the highest performance.

5. CONCLUSION

5.1 Conclusions of the Study

This study was divided into several parts to determine the impact of incorporating waste PET on the engineering properties of SMA. Based on the study conducted, the following conclusions can be derived:

1. The addition of PET into the SMA mixture increases its Marshall stability value. After adding PET, the stability value increased until it reached the maximum level, which was approximately 6% of the used PET, after which it started to decrease. Furthermore, overall, the Marshall stability values of the PET-mixes were higher than that of the control mixture. The mixture with 10% of PET was the only one with a lower value of stability than the control mix. The main reason for such an increase in the stability level is attributable to the existence of PET in a semi-crystal state within the mixture and making a stiffer mixture.

2. An increase in the PET content in the mix causes a slight decrease in its Marshall flow value until 4% of PET after which it reverses the direction and starts increasing. This can contribute to the formation of a stiffer mixture by adding PET into the mixture. However, a high percentage of PET results in an increase in the flow value while the stability decreases.

3. Concerning the relationship between the MQ and PET content, those cases that contain 2%, 4% or 6% of waste PET content showed higher MQ than the control

mixture. Therefore, we can conclude that as a result of the value of high MQ of the PET-added SMA, its resistance to serious damage and deformation resulting from heavy traffic loading is better than the control mixture.

4. For the same binder content, any increase in PET content resulted in a decrease in the bulk density of the mixture, and regardless of the PET content, the bulk density of the mixture was lower than that of the control mixture. However, the ensuing decrease of the value of the bulk density is due to the specific gravity of the waste PET, which is lower than the specific gravity of the mineral aggregates.

5. Increasing the PET content in the mixture results in an increase in air voids in the mixture since the PET remains in crystal form contributing to the increase in the surface area, which is required to be wetted with binder, and would finally lead to an increase in air voids in the mixture. Moreover, by using PET in the mixture, it seem to result in a reduction of the compact-ability of the mixture, which contributes to a higher value of air voids in the mixture .

6. Utilising the same binder content, all VMA values increased by increasing the PET content in the mixture. The test results showed that the VMA values of the PET-mixes were higher in comparison to the control mixture values. However, in the relationship between VFB and PET, with the same kind of binder, any increase in the PET content results in a slight decrease in the VFB value.

7. After the addition of PET to the mixture, the value of MR increases until the maximum level, however, after reaching this level, it reverses and begins to fall. The values of MR in mixtures with PET were greater overall than the conventional mixture

without PET. According to the achieved results, the maximum MR value was obtained by adding 6% of PET to the mixture, which resulted in a 16% increase in the value of MR in comparison to that of the conventional mixture. The main cause of this difference could be attributed to the presence of PET in the mixture in a semi crystal state, which, in turn, resulted in a stiffer mixture in the end.

8. The achieved results further indicate that mixtures with waste PET have better resistance to permanent deformation (rutting) than the conventional mixture. The minimum rut depth obtained for the mixture containing 4% PET, which could reduce the rut depth by 29% in comparison to the conventional mixture. The achieved results could contribute to the formation of a stiffer mixture, which improves the rutting resistance of the mixtures .

9. Regardless of the content of the used PET, the drain down values of the mixtures containing PET were lower than that for the conventional mixture. Furthermore, increasing the PET percentage in the mixture contributes to a significant decrease in its drain down value. The reduction of drain down value can result from the addition of chopped PET to the mixture since it remains in crystal form, contributing to a significant increase in the surface area. However, the surface area increases due to the added PET, which is required to be wetted with binder, ultimately leading to stabilization and holding the binder on its surface and decreasing the binder drain down.

10. The tensile strength and TSR values of the mixtures decrease with the addition of PET, however, all TSR values were above 70%, which indicates that all mixtures might gain adequate resistance to damage induced by moisture . However, the addition of PET does not improve the moisture susceptibility of the mixture due to the crystal status of

the PET, which helps hold the sticky binder on its surface and decreases the film thickness of asphalt around the aggregate. This, in turn, leads to a reduction in the resistance of the mixture to damage induced by moisture.

11. According to the overall conclusions resulting from the tests, adding PET to the mixture increases its values of Marshall stability, Marshall quotient, VIM, VMA, MR, resistance to rutting and binder drain down, and decreases its bulk density, VFB, and resistance against damage induced by moisture.

12. The optimum PET content determined during the tests was recommended to be between 4%-6% by weight of OBC.

13. According to the ANOVA analysis, the impact of PET on the properties of the mixture was significant.

14. The overall performance of the SMA with PET was acceptable and could satisfy the standard requirements

15. The conclusions achieved as a result of the current study contribute ultimately to the encouragement of the re-use and recycling of waste PET produced by industry and consumers. This kind of recycling contributes to solving environmental problems, particularly in the case of solid waste disposal, and reduces the expense of road construction and pavement projects.

5.2 Recommendations for Future Research

Considering the discussion, experiments, and conclusions elaborated upon above, and the new notions sparked in the mind of the researcher during the study, some suggestions are put forth here for the students and researchers interested in this kind of topic to consider in their initiation of related studies:

- Application of various type of aggregate such as limestone, basalt, etc., with different gradations (SMA 14, ACW, ...).
- Application of different mixing methods such as wet mixing method and compaction.
- Using bitumen with other penetration grades such as 60/70.
- Further research on this topic or in related areas may require other tests and standards to be taken into consideration to complete and highlight other aspects of the study.

Full-scale field-tests and in position performance monitoring is required to validate all the results achieved using the above-mentioned laboratory experiment. If an appropriate correlation can be established between the field and laboratory results, the achievements of this study can yield economic and environmental benefits to the contractors, taxpayers, and project owners as a result of the application of waste PET to the HMA used for pavement.

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