PROPERTIES OF BITUMINOUS MIX AND BINDER MODIFIED WITH WASTE POLYETHYLENE TEREPHTHALATE

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DISERTATION SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

FACULTY OF ENGINEERING

UNIVERSITY OF MALAYA

2012

DECLARATION

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ABSTRACT

Waste materials can be recycled to produce valuable construction materials for pavements. Many different types of waste materials have been and are currently being used in this application. The challenge is to recognize potential uses of the various waste materials and to apply engineering solutions for their use in pavement construction. Using PET-modified (Polyethylene Terephthalate) binders also contribute to the recirculation of plastic waste, as well as to the protection of the environment.

The purpose of this research is to investigate the possibility of using waste material in road construction and also to study the effect of waste polyethylene terephthalate on the rheological properties of the binder.

The research methodology involves a series of tests, which are separated into two parts:

- The first part is binder tests on bitumen modified with PET
- The second part is IDT (Indirect Tensile) and Marshall test on PET modified bituminous mixes

A statistical analysis was also done to compare the results and present the significant differences between results.

The results showed that the decreased penetration and increased softening point temperature increased the stiffness (hardness) of the PMBs (polymers modified bitumen). The results demonstrate that the asphalt mixtures prepared with the PET (Polyethylene Terephthalate) may be less sensitive to permanent deformation. Along with the parameters

related to penetration and softening point test the increased viscosity values and indices also indicated the stiffening effect of PET modification.

It may also be inferred that PET-modified bituminous binders provide better resistance against permanent deformations due to their higher complex shear modulus and lower phase angle as compared to conventional binder.

The results of the Marshall test indicated that the modified mixture have a higher stability compared to non-modified mixtures. This would positively influence the rutting resistance of these mixtures. The air void contents of the modified mixture decreases with increasing binder content. VIM (Void in Air) in all binder contents decreases as the amount of PET used increases. Air void proportion around 4% is enough to provide room for the expansion of asphalt binder to prevent bleeding or flushing that would reduce the skid resistance of the pavement and increase fatigue resistance susceptibility.

ABSTRAK

Bahan buangan yang dikitar semula boleh digunapakai sebagai bahan yang penting untuk sesuatu projek pembinaan. Pelbagai jenis bahan buangan telah dan sedang digunakan pada masa ini khususnya dalam pembinaan terutamanya jalan raya.

Setiap bahan buangan mempunyai potensi yang berlainan dan di antara cabaran-cabaran yang dihadapi oleh jurutera dan pengeluar ialah untuk mengenal pasti bahan buangan yang dapat memenuhi keperluan dan kegunaan di dalam pembinaan khususnya jalan raya.

PET-modified (Polyethylene Terephthalate) adalah di antara salah satu bahan buangan yang berpotensi sebagai bahan binaan, dan ia dikatakan dapat menyumbangkan kepada proses edaran semula bahan buangan plastik serta perlindungan persekitaran.

Objektif projek ini adalah untuk menyelidik kemungkinan sama ada "PET-modified" (bahan buangan kitar semula) dapat digunakan sebagai bahan ganti dalam pembinaan jalan raya dan juga kesan bahan buangan polyethylene terephthalate pada ciri – ciri aliran pengikat.

Metodologi penyelidikan ini dibahagikan kepada dua bahagian iaitu:

- Bahagian pertama ialah merguiji bitumen yang telah diubah suai dengan PET
- Bahagian kedua ialah menjalankan ujian IDT dan Marshall pada campuran bitumen dan PET

Analisis secara stastik dibuat untuk membandingkan keputusan yang diperolehi melalui ujian makmal sama ada ia memberi perbezaan yang besar atau tidak. Hasil daripada ujikaji menunjukkan, pengurangan penembusan dan penambahan suhu takat lembut telah

menyebabkan bertambahnya kekerasan PMBs (polimer-polimer menerangkan bitumen), dan telah menunjukkan campuran-campuran asphalt yang disediakan dengan PET (Polyethylene Traphthalate) mungkin kurang sensitif untuk ubah rupabentuk kekal. Bersama dengan parameter yang berkaitan dengan penembusan dan takat lembut, penambahan di dalam kelikatan dan indeks telah menunjukkan kesan kekerasan yang tinggi kepada "PET-modified".

Selain daripada itu, pengikat "bitumen PET-modified" dapat menyediakan rintangan yang lebih baik untuk menentang perubahan rupa bentuk kekal yang disebabkan oleh modulus ricih kompleks yang tinggi dan sudut fasa yang jauh lebih rendah berbanding dengan pengikat bitumen konvensional. Hasil daripada ujian Marshal menunjukkan campuran yang diubah suai mempunya kestabilan yang lebih tinggi berbanding dengan campuran yang tidak diubah suai.

Ini akan secara positif mempengaruhi rintangan terhadap 'aluran' bagi campuran – campuran ini. Kandungan udara bagi campuran yang diubah suai menurun dengan pertambahan dalam pengikat bitumen. Kandungan VIM (Void in Air) di dalam pengikat bitumen berkurang dengan peningkatan penggunaan PET-modified. Kandungan VIM sebanyak 4% adalah memadai untuk menyediakan ruang bagi proses pengembangan bitumen dan mengelakkan daripada 'pendarahan' atau 'curahan' yang akan menyebabkan kepada kegelinciran dan meningkatkan kerentanan rintangan.

ACKNOWLEDGEMENT

First and foremost, I would like to express my appreciation to my supervisors, Professor Ir. Mohamed Rehan Karim and Dr. Abdelaziz Mahrez for their invaluable advice and guidance, as well as their understanding and patient assistance in the preparation of this dissertation.

I would also like to acknowledge the financial support provided by the Institute of Research Management and Consultancy of the University of Malaya (Institut Pengurusan Penyelidikan dan Perundingan, IPPP).

Words are incapable of expressing my appreciation and respect to my beloved parents for their unsparing support and understanding and also my brother whose continued encouragement helped me to complete my study. I thank the Highway Laboratory technicians for their help during the practical part of my study and my friends Mr. Mario Oettler and Mr. Walter Heck for their help during writing of this dissertation

Last but not least, I extend my gratitude to all my friends who have been supportive and helpful during my study in Malaysia.

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ABBREVIATIONS AND SYMBOLS

ACW 14: Asphaltic Concrete Wearing Course with 14 mm Nominal Size

CDM: Density of the Compacted Mix

C&D: Construction and Demolition Debris

CRM: Crum Rubber Modified

DSR: Dynamic Shear Rheometer

E: Elastic Modulus

EPDM: Ethylene propylene Diene Monomer

EVA: Ethylene Vinyl Acetate

G*: Complex Shear Modulus

Ǵ: Storage Shear Modulus and its equal to G*cosδ

Ǵ′: Loss Shear Modulus and its equal to G*sinδ

HDPE: High Density Polyethylene

HMA: Hot Mix Asphalt

IDT: Indirect Tensile Test

LDPE: Low Density Polyethylene

LVDT: linear Variable Differential Transformers

mm: Millimeter

M_R: Resilient Modulus

MPa: Megapascal

MS: Mean Square

MQ: Marshall Quotient

N: Newton

PET: Polyethylene Terephthalate

δ : Phase Angle

PI: Penetration Index

PMA: Polymer Modified Asphalt

RAP: Reclaimed Asphalt Pavement

RV: Rotational Viscometer

UMATTA: Universal Materials Testing Apparatus

VIM: Void in Mix

VMA: Voids in the Mineral Aggregate

CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

In the last two decades the paved roads are under serious study in most research laboratories and universities. The main objective of these researches is how to correct, rehabilitate or reconstruct the damaged roads. Although material quality, mix design and construction practices are maintained to some extent, increasing traffic loading and severe environmental conditions justify a new mix design concept altogether.

The bituminous binder is considered as one of the essential material of construction in road pavement, and the performance of road pavement is related to the performance of a bituminous binder.

On the other hand, the use of plastic bottles throughout the world is on the increase. Both the creation and the recycling procedures of plastic bottles are detrimental to the environment. Plastics do not decompose naturally and so in other to recycle the plastic alternative methods need to be implemented.

The performance of road surfaces can be improved by modifying bitumen. There are numerous modifiers that can be used to improve the properties of road surfaces, but most of these are virgin materials. Virgin materials are difficult to find and are uneconomical when used as a modifier. Therefore using waste plastic bottles as modifier in road surfaces, can potentially help reduce material wastage and improve the performance of road surfaces

at the same time.

Therefore, research on the use of PET as an additive to bituminous binder has found to be suitable for use in bituminous mix for road constructions, since a small amount of PET into bitumen showed an improvement in the properties of the binder, hence in the bituminous mix (Hesp and Woodhams, 1991).

1.2 OBJECTIVES OF STUDY

The main objectives of this study are as follows:

1. To determine the effects of waste PET on rheological and physical properties of the base binder using different portion of the PET

2. To assess the engineering properties of mixture produced with and without the PET additive

3. To determine and compare some fundamental mix properties such as the resilient modulus

1.3 SCOPE OF STUDY

This research may lead to the discovery of new pavement material, where we hope that its properties can be used to solve some pavement problems or at least provide answers for some particular questions and it contributes to reciycling of plastic wastes as well as to protection of the environment. This research examines the properties of asphalt mixed with waste plastic as a bitumen-modifier. Four different proportions of binder and waste plastic powders (PET) are used in this research. The laboratory test includes binder tests (penetration, softening point, viscosity, DSR) resilient modulus and Marshal Test.

1.4 ORGANISATION OF DISSERTATION

The work document herein is presented in the following chapters:

Chapter 2: This chapter highlights the history and benefits of using polymers in asphalt. It also presents a literature review of various studies undertaken elsewhere using different polymers as modifier in bituminous mix.

Chapter 3: Review of some studies in using solid waste material in pavement. The studies on using the municipal solid waste such as glass, plastics, steel slag, construction and demolition debris and reclaimed asphalt pavement have been reviewed

Chapter 4: Presents the detailed laboratory testing methods and the basic experimental approaches that were employed in this research to investigate the main characteristics and properties of PET modified bituminous binder and mixes. Testing methodology comprises routine binder tests such as penetration test, softening point test, Brookfield viscosity tests

and dynamic shear rheometer. Whereas the testing methodology for bituminous mix comprises of Marshall and resilient modulus tests.

Chapter 5: This chapter presents the interpretation and analysis of data acquired using conventional binder tests. It also included the discussion and comparison of test results with previous studies. The analysis of ANOVA on tests results is also reported.

Chapter 6: Presents the interpretation and analysis of data acquired using IDT and Marshall tests. It also included the discussion and comparison of test results with previous studies. The analysis of ANOVA also has been done.

Chapter 7: Presents the major conclusions derived from the previous chapters and recommendations for the future work.

CHAPTER 2: LITERATURE REVIEW

2.1 HISTORY OF USING POLYMER IN ASPHALT

Synthetic and natural polymers have been used in asphalt as a modifier as early as 1843. In the 1930s the project was underway in Europe and North America began to use rubber latex in 1950s. Europe was using modified asphalts ahead of the United States which were limited to use PMA because of its high expenses in the late 1970s (Attaelmanan et al., 2011, Yildirim, 2005). In the mid-1980s, US began to use new developed polymers and European technologies. Currently in Australia, polymer modified binders is included in the guides and specifications of National Asphalt Specification (Yildirim, 2005).

In the survey of State departments of transportation in 1997, 47 states of US reported that in the near future they would be using modified asphalts and 35 states reported that they would need bigger portions. Several investigations all around the world have researched and evaluated benefits of modifying polymers on the performance of pavement, and developing the specifications and tests for binders are still continuing (Yildirim, 2005).

Over the last decade, USA is the country where most of the research is done, followed by China, Canada and some European countries. Among the companies that have been filing patents on PMA over the last decade, Marathon Ashland Petroleum LLC is the leading one. The Goodyear Tire and Rubber Company, Fina Technology, Polyphalt LLC, BASF Corporation and Ergon Incorporated are also reported. There have been lots of movements

in the marketing area. The interest for polymer modified asphalt (PMA) technology has been increasing, and so the number of companies will commercialize it (Beker et al., 2001).

The United States, China, France and Italy are leaders in polymer modified asphalt (PMA) research and development activities, even though considerable work has also been done in Japan, Germany, Russia, Great Britain, and Canada (Beker et al., 2001).

2.2 THE BENEFITS OF USING POLYMER IN ASPHALT

Bitumen is one of the viscoelastic materials and the only deformable element of pavement and has a very important role in pavement performance (Beker et al., 2001). Bitumen has a good adhesion and cohesion with aggregates therefore it has been used for roofing and paving purposes (González et al., 2002).

One of the most important properties of the bituminous mixture is its stability. The optimum stability is the one that can handle traffic sufficiently and also it is not higher than traffic condition needed. If the stability is lower than the traffic remand, it will cause shoving and flow of the road surface (Hinisliglu and Agar, 2004). To prevent a sub grade pavement from cracking the flow should be low. Flow can be considered as opposite property to the stability (Kulogçlu, 1999).

In hot climates, rutting, and in cold climates, cracking, depend on the sensitivity of the asphalt pavement to the temperature change and the traffic load (Perez-Lepe et al., 2003). If the volume of tyre pressure, heavy vehicle and traffic increases higher performance pavement will be demanded which requires bitumen with low susceptibility to temperature changes and has high cohesion to aggregates.

Some improvements in asphalt properties have been gained by selecting proper starting crude, or tailoring the refinery processes used to make asphalt. Unfortunately, there are only a few crudes that can produce very good asphalts, and only a limited number of actions that can be taken to control the refining process to make improved asphalts (Beker et al., 2001). The next step taken by the industry was to modify the asphalt. Air blowing makes asphalt harder. Fluxing agents or diluent oils are sometimes used to soften the asphalt. Another method that can significantly improve asphalt quality is the addition of polymers (Beker et al., 2001).

Modifying synthetic and natural polymers to the asphalt can improve the performance of roads (Hinisliglu and Agar, 2004 and González et al., 2002). Several researches on PMA (polymer modified asphalt) mixture have been conducted for the past two decades. Addition of polymers to asphalt in order to enhance properties of asphalt over different temperature ranges in paving applications was contemplated a long time ago (Abdel-Goad, 2006). Polymers can significantly improve the asphalt pavements performance at low, intermediate and high temperatures. They can increase the resistance of mixture to permanent deformation, thermal fracture and fatigue cracking at low temperature, decrease plastic flow and increase shear modulus at high temperature (Aflaki and Tabatabaee, 2008) and (González et al., 2002). The researchers reported that by modifying bitumen with even small amounts of polymers, the road pavement life span may be increased (Hesp and Woodhams, 1991).

Improvement in engineering properties including thermal cracking, stripping, rutting resistance, temperature susceptibility and fatigue damage, have led polymer modified binders to be a substitute for asphalt in paving and maintenance application, such as cold

mix, cold and hot crack filling, slurry seal, patching, hot mix, chip seals and recycling. They also can be used to cut down the costs of life cycle (Beker et al., 2001).

2.3 THE USE OF WASTE POLYMER INSTEAD OF VIRGIN POLYMER

The uses of virgin polymers in bitumen to improve the characteristics of resulting polymer modified bitumen have been accomplished for many years (González et al., 2002). However, there are some concerns of replacing virgin materials with recycled polymers (González et al., 2002). Virgin polymer is polymer that has never been made into a finished product. It is the "new" polymer that a factory uses directly from the polymer manufacturer.

Regarding to high cost of polymers, the amount of polymer used to improve the road pavements must be small. Recycled polymer can show almost the same result in improving the roads performance compared to virgin polymers. From economic and environmental point of view using the waste polymer as a modifier is beneficial because it may help to improve the performance of pavement and quality of the roads and also to solve waste disposal problem (González et al., 2002). Many polymers have been used as binder modifiers, and they can be classified into five groups. Table 2.1 presents a summary of these polymers and their advantages and disadvantages as asphalt modifiers (Beker et al., 2001).

The polymers used to modify bitumen can be divided into class, elastomers and plastomers. Plastomers include ethylene vinyl acetate, polyethylene and various compounds based on polyethylene (Awwad & Shbeeb, 2007), (Al-Hadidy and Yi-qiu, 2009) and (Aire 2002). At normal temperature condition these polymers can increase the stiffness of bitumen and

provide a mix with high viscosity. Depends on the mixing method, they might need high shear mixing (Awwad & Shbeeb, 2007).

Table 2.1 Characteristics of polymers used to modify bitumen (Beker et al., 2001)

Polymer	Advantages	Disadvantages	Uses
Polyethylene (PE)	High temperature resistance Aging resistance High modulus Low cost	Hard to disperse in the bitumen Instability problems High polymer contents are required to achieve better properties No elastic recovery	Industrial uses Few road applications
Polypropylene (PP)	No important viscosity increase even though high amounts of polymer are necessary (ease of handling and layout) Low penetration Widens the plasticity range and improves the binder's load resistance	Separation problems No improvement in elasticity or mechanical properties Low thermal fatigue cracking resistance.	Isotactic PP is not commercially applied Atactic PP is used for roofing
PVC	Lower cracking PVC disposal	Acts mostly as filler	Not commercially applied
Styrene-butadiene block copolymer (SBS) Styrene-isoprene block copolymer (SIS)	Higher flexibility at low Temperatures Better flow and deformation resistance at high temperatures Strength and very good elasticity Increase in rutting resistance Higher aging resistance Better asphalt-aggregate adhesivity Good blend stability, when used in low proportion.	High cost Reduced penetration resistance Higher viscosity at layout temperatures Resistance to heat and to oxidation is lower than that of polyolefins (due to the presence of double bonds in the main chain) Asphalts suitable for SBS blends, need an asphalt with a high aromatic and a low asphaltene content	Paving and roofing

2.4 POLYETHYLENE

Polyethylene is one of the most effective polymer additives (Hinisliglu and Agar, 2004) and the most popular plastic in the world. Polyethylene has very good chemical and wear resistance and fatigue. It is a semi-crystalline material with a simple and light structure. A molecule of polyethylene is a long chain of carbon atoms, with two hydrogen atoms attached to each carbon atom (Awwad and Shbeeb, 2007).

Polyethylene terephthalate (PET) is a linear, aromatic polyester (Bing et al., 2006). PET is commonly recycled, and has the number "1" as its recycling symbol (Figure 2.1). In 1999 PET accounted for 48% of plastic bottle resin sales, making it the most widely used resin in plastic bottles. The chemical structure of PET is shown in Figure 2.2.

Figure 2.1 PET recycling symbol (http://scifun.chem.wisc.edu)

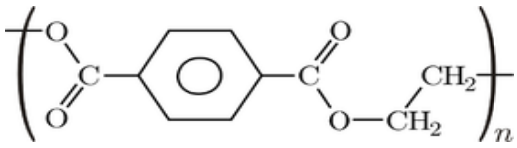

Figure 2.2 Chemical structure of polyethylene terephthalate (Bing et al., 2006)

2.5 HOW POLYMERS ARE INCORPORATED INTO THE ASPHALT

There are two common methods used to incorporate polymer into the asphalt:

- Wet method (Addition of latex polymer into the asphalt)
- Dry method (Addition of solid polymers into the asphalt)

Wet method is relatively easy and free of trouble. In this method solid polymer mixes with bitumen in high temperature than the binder will be used into the mix. Mixing temperature

and mixing time depend on the type of polymer and bitumen. For example Naskar et al., (2010) investigated the effect of waste plastic as modifier on thermal stability and degradation kinetics of bitumen. They mixed different waste plastics with 60/70 penetration grade bitumen for 45 min at 180 °C. Garcia-Morales et al. (2005) used four different types of waste polymers to mix with 60/70 penetration grade bitumen. Their samples were processed for 6 h, at 180 °C. Shell report suggests that the mixing temperature should not exceed 185 °C otherwise the bitumen would burn and the mixing time should be adequate enough for homogeneous dispersion of the waste plastic within the bitumen matrix.

Dry method normally requires substantial mixing and shearing in order to uniformly disperse the polymers. In dry method polymer will be mixed with the aggregates as a solid form like granules or chips first then bitumen will be added. Awwad and Shbeeb (2007) used the dry method for their study, whit two types of polyethylene used, high density polyethylene and low density polyethylene. The polymers were added to the mixture in two states (Grinded and not Grinded).

2.6 ASPECTS THAT INFLUENCE THE PROPERTIES OF POLYMER-ASPHALT BLENDS

2.6.1 Polymer Characteristics

The most effective mixture happens when polymer blend with the bitumen and increase its rutting resistance at high temperatures without making it too viscous for the mixing procedure or too brittle at low temperatures. The modifier should be sufficiently

compatible with the asphalt so as not to cause phase separation during the storage, transportation, application and service.

The polymer content range is between 2 and 10% by weight of the bitumen. In the last decade the most common proportions were about 5 or 6% but few years ago the polymer content has been reduced to 2 or 3%. Now using waste materials (due to their low cost, they can be added in higher proportions), or mixes of two different polymers (as mentioned before) are being considered (Giavarini et al., 1996). Polymer parameters such as polymer content, chemical composition, structure, average molecular weight, molecular weight distribution, degree of branching, crystallinity, etc. affect the modification process (Morgan and Mulder, 1995), (Giavarini et al., 1996).

Ali et al. (1994) found that, original grade of asphalt affects the mechanical properties of mixtures at low temperatures, while adding modifiers does not have statistically significant affect on stiffness at low temperatures. Therefore, low temperature cracking should not be adversely affected by the addition of modifiers. However, at high temperature the effect of modifier on stiffness of mixture increases so the modified mixture has higher modulus value compared to conventional mixture. Thus, addition of modifiers may actually improve the temperature susceptibility of the binders.

2.6.2 Bitumen Characteristics

Binder's mechanical properties and its micromorphology, as well as stability of the blend are influenced by bitumen nature. As mentioned before, the polymer must be compatible with the bitumen and maintain this compatibility during storage and use. This is a difficult task, because of the big difference in molecular weight and structure, viscosity and density of PMA constituents (Giavarini et al., 1996). Moreover, bitumen differences

depend not only on the composition of the original crude, but also on the production process (Lu and Isacsson, 1997).

The general conclusion from the studies on the nature of the asphalt is that to dissolve and expand the polymer asphalt should contain enough oil fractions. It should also have a high content of condensed ingredients like aromatics hydrocarbons which mix especially well with polar aromatic polymers. The PMA blends with the condensed ingredients in their asphalt are more endurable (Zielinski et al., 1995)

For low polymer content, the continuous asphalt phase is enriched with resins and asphaltenes, thus leading to an increase in the consistency and the elastic properties of the binder. Generally, a thermoplastic polymer modified asphalt which is resulted from physical mixing of the constituents without chemical interactions, can consequently be a two-phase system. One phase is a swollen polymer and another phase grouping the constituents of the asphalt not intervening in the solvation. Increasing the polymer contact, the physical properties of the blend will significantly change. The result is a significant increase in the plasticity interval, tensile strength and elastic properties, and a reduction in thermal sensitivity (Beker et al., 2001).

Vonk and Bull (1989) study has shown that elastomer of a thermoplastic rubber copolymer can absorb almost all the bitumen components except the asphaltnes (Morgan and Mulder, 1995). Therefore the asphaltnes content of the bitumen should not be too high otherwise addition of a thermoplastic rubber can result in asphaltene precipitation or gelation and will result in phase separation so the blend becomes unworkable. On the other hand if the asphaltene content is low a single phase blend may be obtained.

The permissible level of the asphaltene concentration is dependent upon:

- polymer content
- polymer molecular weight
- asphaltene molecular weight
- aromaticity

In order to produce a stable bitumen-thermoplastic blend, balancing of the aromatic content is important. Such blends are termed as "compatible" blends (Morgan and Mulder, 1995).

2.6.3 Mixing Conditions

The mixing process is influenced by following parameters:

I. Nature of the polymer

The proper mixing time to achieve a homogeneous blend of the bitumen and polymer depends on the type, molecular weight and chemical composition of polymer. A polymer with higher molecular weight needs longer time to blend with bitumen and vice versa (Morgan and Mulder, 1995).

II. Physical form of the polymer

Smaller particle size has larger surface area per unit mass of polymer. Thus the swelling of the polymer is easier and the penetration of the bitumen is facilitated. It means more rapid dissolution is completed. Powdered polymers will therefore disperse and dissolve more rapidly than porous pellets (Morgan and Mulder, 1995).

III. Nature and grade of the bitumen.

Bitumen's composition and its viscosity affect the blending process in more than one way. In general asphalt should contain enough old fractions to dissolve and expand the polymer. It also needs to content condensed ingredients in order to guarantee the PMA blends endurance (Zielinski et al., 1995)

On the other hand, bitumen with low viscosity can pre-disperse the polymer in itself and speed the penetration and swelling of the polymer particles. A low bitumen viscosity at the blending temperature can also improve the disintegration of the polymer at the mill (Morgan and Mulder, 1995).

IV. Type of mixing equipment.

There are two main methods for mixing the bitumen with polymer, high shear and low shear mixing. Low shear mixer is a simple mixing tank with a paddle stirrer. It can be used to mix the bitumen with powdered modifier. Mixing process is limited to the swelling and dissolving the bitumen with polymer. The temperature is fixed during the mix.

High shear mixer reduces the polymer particles size by mechanical and hydrodynamic shear. The temperature will increase during the mix in order to dissolve polymer in to the bitumen and make a homogenous blend.

V. Time-temperature profile during mixing.

Practically, time and temperature during the mixing depends on the type of bitumen and its requirement to achieve mobility and initial swelling of the polymer. For example to avoid the thermal effects on SBS during the mixing process, the temperature should be kept lower than 190°C (Beker et al., 2001). However the ideal mixing process should be

undertaken at the lowest possible temperature for the shortest possible time, corresponding to the complete incorporation of the polymer into the bitumen both from an economic standpoint and to minimize any thermal effect on the polymer.

Structure and properties of PMA is a function of blending conditions. It means the longer the mixing time, the finer the microstructure will be and the higher the temperature, the more rapid this process is done (Beker et al., 2001).

2.6.4 Compatibility and Stability

A polymer may be incompatible, slightly compatible or compatible with bitumen.

i. Incompatible polymers

The result of mixing an incompatible polymer with bitumen is a heterogeneous mixture. In this case the polymer affects the chemical equilibrium of the bitumen. Therefore the mixture doesn't have enough cohesion and ductility.

ii. Slightly compatible polymers

Slightly compatible polymers can improve the bitumen properties under special mechanical, thermal and chemical processes. For instant they require high shear mixer with reasonably high temperature to mix with bitumen homogeneously.

iii. Compatible polymers

Compatible polymers require conventional mixing techniques and it results a physically stable blend. These kind of polymers may or may not improve the physical properties of the bitumen.

Compatibility between polymer and bitumen should be high enough to avoid the phase separation in the bitumen and to achieve a proper pavement with good quality. The separation may happen during storing, pumping and application of the asphalts. If the storage stability is poor the polymer modified asphalt won't be suitable to use in roofing and paving applications, and other industrial specialty products.

There are some compatibilization processes to improve the compatibility and stability of the polymer-asphalt blends. For example Exxon Research and Engineering Co. (Beker et al., 2001), blend the bitumen and the polymer which both are in contact with sulfonate or sulfonic acid groups. TexPar Energy, Inc. adds an additive called ButaphaltTM, to the mixture for compatibility purposes (Beker et al., 2001). In this case the addition of an acid will be done after the polymer has been added to the bitumen. According to Ergon Incorporated the storage stability of bitumen can be improved, if the acid is added to the bitumen before the polymer.

Cross-linking agents such as sulfur also helps to improve the stability of polymer-bitumen compositions. It has been investigated that the sulfur chemically couples the polymer and the bitumen through sulfide or polysulfide bonds. Even though bitumen itself contains varying amounts of native sulfur, the addition of extraneous sulfur is required to improve the stability.

A homogeneous and compatible blend will happen when polymers completely disperse in the bitumen. UV microscopy is used to determine the completeness of blending and compatibility of polymer-modified bitumen. The pictures are taken from the samples which are seen under a fluorescence microscope. In order to see in which degree polymer is incorporated in the bitumen matrix, the pictures are taken every one hour.

Figures 2.3 and 2.4 (Beker et al., 2001) show a micrograph of a compatible system and an incompatible system respectively. As shown in Figure 2.4, in an incompatible system the mixture does not seem homogeneous.

The softening point variation test is another way to find out if incompatibility or phase separation is present. For this test, PMA is poured into a metal toothpaste tube and left in an oven for three days at 160°C. Then samples are taken from the bottom portion the top portion of the blend, and softening points between these two samples are compared. The difference between the softening point of the top portion and the bottom portion should not be more than 4°C. A difference of more than 4°C is considered as absence of storage stability and in this case the substantial phase separation may happen. The same samples are also examined using fluorescence microscopy to compare their microstructures. For true stability, the top portion of the blend should have the same continuous phase as the bottom portion.

Figure 2.3 Compatible system with 4% SBS (Beker et al., 2001)

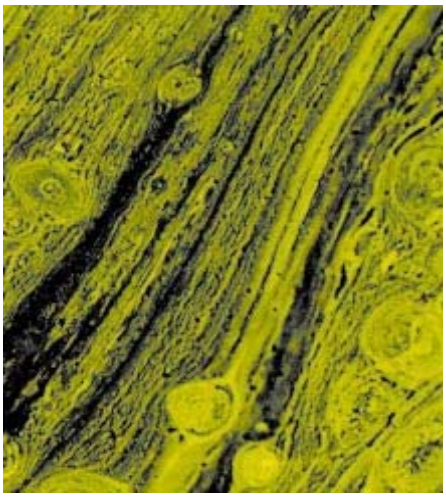

Figure 2.4 Incompatible system with 4% SBS (Beker et al., 2001)

2.7 GENERAL STUDIES ON USING POLYMERS IN ASPHALT

In last decade many studies have focused on using polymers in asphalt. There are several kinds of polymers that can be recycled in bitumen (Murphy et al., 2001) and (Satapathy et al., 2010) such as polypropylene (PP) which is used in straw, furniture and wrapping industries, high density polyethylene (HDPE) which is used in packaging and plastic bottles, low density polyethylene (LDPE) used widely in soft drink and mineral water bottles (Zheng et al., 2009), polyvinyl chloride (PVC), used in plumbing pipes and fittings; polyethylene terephthalate (PET), widely used in water and soft drink bottles and acrylonitrile butadiene styrene (ABS), used in electronic devices such as laptops and mobile phones. Not all of these polymers are suitable to modify with bitumen although there is sufficient amount of them available for this purpose (Casey et al., 2008).

Perez-Lepe et al. (2003) studied the influence of processing conditions on the rheological behaviour of polymer-modified bitumen. They concluded that, polymer type and the mixing method affect the engineering properties of modified binder. In Perez-Lepe et al. study binders modified with HDPE which were prepared with a rotor-stator devise show better results compared to binders which were modified with different polymer such as LDPE and SBS. The binders prepared using, as modifying agent, blends of polyethylene and EPDM show that the major component in the polymer blend mainly determine the rheological behaviour of the binder, and the influence on the rheological behaviour of the interactions among the molecules of EPDM and LDPE was less important than the interactions among the molecules of EPDM and HDPE (Perez-Lepe et al., 2003).

In 2004 Hinisliglu and Agar used different waste plastics containing HDPE as a polymer modifier. They studied the effects of various mixing time, temperature and HDPE content

in binders on Marshall test parameters. In their study HDPE was used in 3 different percentages of 4%, 6 %and 8% by weight of bitumen. The temperature of mixing were 145 °C, 155 °C and 165°C and the mixing time were 5 min, 15 min and 30 min. They reported that binders which were modified with HDPE have higher stability and strength and also the Marshal quotient value were higher which means they are more resistant to permanent deformation. The optimum result for Marshal stability, Marshal quotient and flow happened in the binder with 4% HDPE, 30 min of mixing time at 165°C of mixing temperature. In this binder Marshal quotient increased 50% compared to the control binder. In their study it has been concluded that due to waste HDPE modified asphalt high Marshall quotient and stability, binders have higher resistance against permanent deformations (Hinisliglu and Agar, 2004).

Another investigation on the rheology of recycled polymers modified bitumen has been done by Garcia-Morales et al. in 2005. They studied flow behavior of bitumen which was modified with 5% and 9% waste EVA/LDPE at high temperature and linear viscoelasticity, at low and intermediate temperature. In their study waste polymers were mix with the 60/70 penetration grade bitumen with a four blade propeller. The test results showed that the performance of modified bitumen was improved. They concluded that modified recycled EVA/LDPE bitumen has better mechanical properties and polymer improves the performance of road surface .It also contribute to solve the disposal of waste plastic problem (Garcia-Morales et al., 2005).

Polacco et al. (2005) studied the effect of different polymers on the rheology of modified bitumen. They used several polymers such as polyethylene and polyethylene-based polymers in their study. They numbered the polymer modified asphalts from M1 to M8 (Table 2.2) after their softening point and storage stability results and morphological

analysis. M1 and M2 are the binders which are modified with low-density polyethylenes with different molecular weights. M4 is a component of 90% of M1 and 10% of another kind of polymer. Figure 2.5 compared the morphology of the PMAs. In 2.5a, 2.5b and 2.5c polymer-based phase is dispersed in a dark asphaltic phase. Comparing the morphologies of Figures 2.5a and b, larger diameter of spheres are expected since polymer used in M2 has a higher molecular weight than polymer used in M1. In Figure 2.5c the dimensions of the particles are smaller than those reported in Figure 2.5b (Polacco et al., 2005).

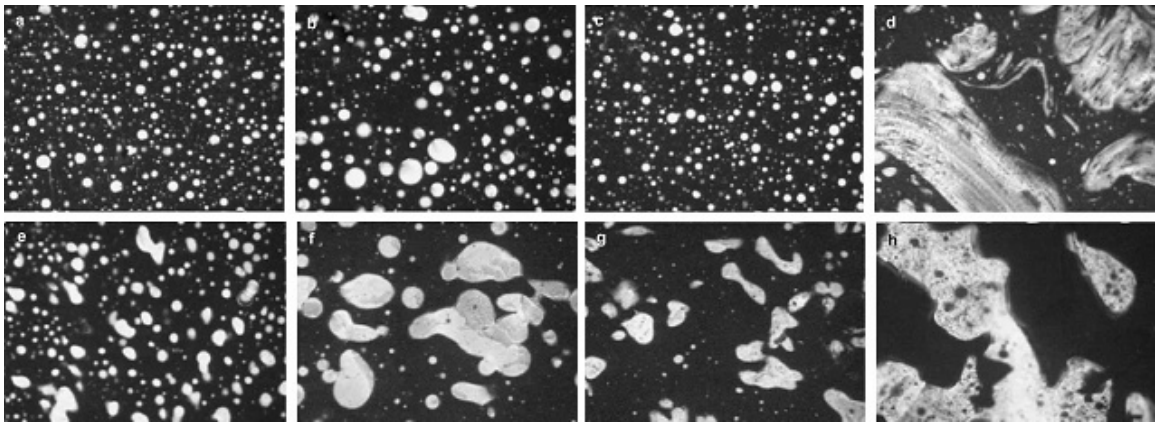

Figure 2.5. (a) M1 30 min, (b) M2 30 min, (c) M4 30 min, (d) M4 24 h, (e) M7 30 min mix, (f) M7 24 h curing, (g) M7 48 h curing, and (h) M8 2 h mix (Polacco et al., 2005)

Table 2.2 PMAs content and softening point (Polacco et al., 2005)

Mix `	Polymer (6% by weight)	Temperature (°C)	Mixing time (min)	T_{RandB}(°C)	
				After mix	After cure
M1	Riblene FF20	180	30	53.0	–
M2	Riblene FC20	180	30	53.7	–
M3	Escor 5100	180	30	49.4	–
M4	Lotader AX8930 (10%) Riblene FC20 (90%)	180	30	52.6	66.0
M5	Lotader AX8840 (7%) Riblene FC20 (93%)	180	30	53.8	58.1
M6	PEGMA1	180	30	59.2	73.6
M7	PEGMA2	190	120	52.3	68.9
M8	Flexirene FF25	190	120	120.5	–

Gonzalez et al. (2006) used m-LLDPE (Linear Low Density Polyethylene) and HDPEs modified with bitumen and investigated the stability and the rheological properties of blends. They added three different kinds of m-LLDPE and two types of HDPE. This work is similar to what Polacco et al. (2005) did and the results are almost same. They concluded that better stability results are obtained using m-LLDPEs than conventional polyethylenes like HDPEs, in bitumen/polyethylene blends.

Awwad and Shbeeb (2007) experienced adding two types of polyethylene to modify bitumen in hot asphalt mix. The polymers they used were LDPE and HDPE. They used two different shapes of grinded polymers and not grinded one. They used crushed limestone as aggregate and silica as filler. Marshall mix design was used, first to determine the optimum bitumen binder content and then further to test the modified mixture properties. Polyethylene of each type was added to the binder in 7 different portions of 6, 8, 10, 12, 14, 16 and 18% in both grained and not grained state. The optimum asphalt content was 5.4%. The results of tests which were bulk density, stability and flow showed that the modified mixture have a higher VMA percentage and higher stability compared to the control mix. This means that the mix is more resistant against rutting. But the air void contents of the modified samples are almost the same as the non-modified ones. To provide enough space for the expansion of binder and prevent flushing or bleeding air void proportion should be around 4%. Flushing in the mix would reduce the skid resistance and increase rutting susceptibility of the pavement. In this study it is concluded that asphalt modified by polyethylene is much more resistant against fatigue and deformation and it also provide better adhesion between the asphalt and the aggregate (Awwad and Shbeeb, 2007).

In Casey et al. (2008) research the binder with 4% of waste HDPE has the best result compared to the other modified binders. The optimum mixing process was chosen

according to the type of modifier, mixing time and mixing temperature. Results of this study were used to compare the performance of modified binder with recycled polymer with the traditional binders which already had been used in road construction. Fatigue and wheel track test result show that the polymer modified binder do better than traditional binders used in asphalt.

In 2009 in China, Al-Hadidy and Yi-qiu studied the effect of polyethylene on life of flexible pavements. In that investigation the modifier used was LDPE (low density polyethylene). In the first step the polymer was grind very fine with the thermal degradation apparatus which is shown in figure 2.6 and then the powder polymer was added to bitumen in different percentages of 2, 4%, 6% and 8%. The polymers were mixed with bitumen 3 to 5 minutes in high-speed stirrer rotating at 160± 5°C and at speed of 1750 rpm (Al-Hadidy and Yi-qiu, 2009).

The tests that had been done in Al-Hadidy and Yi-qiu study were as follows:

- Rheological tests include: softening point (ASTM D-36), ductility (ASTM D-113), penetration (ASTMD-5)
- LDPE modified SMA mixture tests such as Marshall test (ASTM D1559) and Indirect tensile strength test (ASTM D4124)
- Short-term aging test (TFOT) (ASTM D-1754), which used the thin film oven
- Temperature susceptibility
- Compatibility test.

As it is known, softening point has the direct relationship with asphalt deformation (Al-Hadidy and Yi-qiu, 2009). They study showed that the binders which had been modified with LDPE had higher softening point which means they were more resistant to the

deformation. Ductility results were at the minimum range up to 6% LDPE and the durability of bitumen were increased since the percentage of loss of weight was decreased. It can be concluded that addition of LDPE in the asphalt mix improved the performance of mix at both high and low temperatures. (Al-Hadidy and Yi-qiu, 2009).

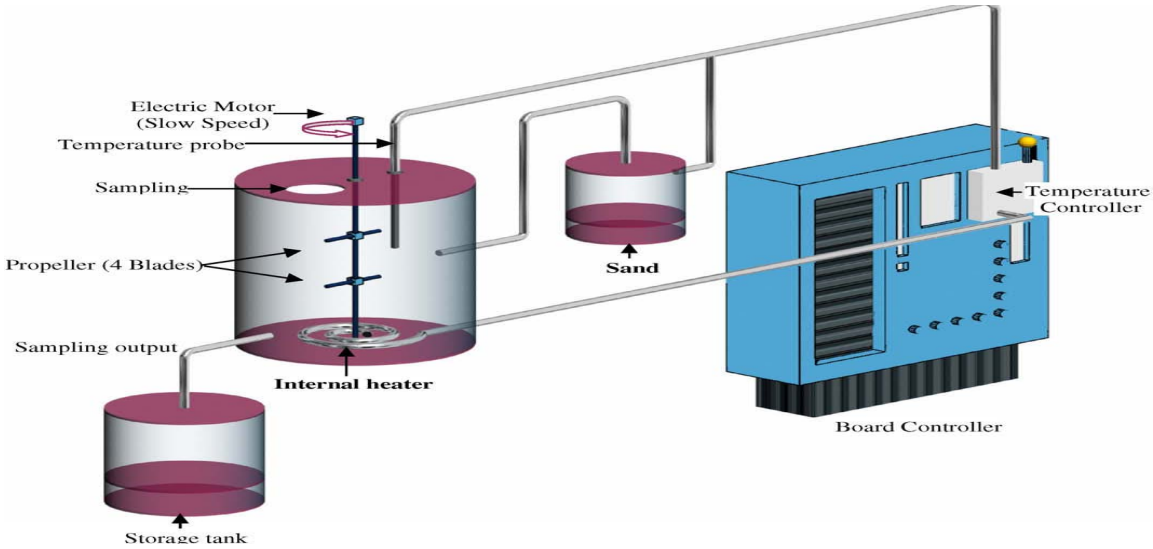

Figure 2.6 Schematic diagram of the thermal degradation apparatus (Al-Hadidy and Yi-qiu, 2009)

Polypropylene fibers can improve the mechanical and physical properties of asphalt mixture (Tapkın et al., 2010). They studied on a neural networks application to predict the Marshall test results for bitumen mixtures modified with polypropylene. In their research the flow and Marshall stability tests on binders which were modified with different type of waste polypropylene and polypropylene fiber were carried out. The binder content in this study was the optimum bitumen content. From the Marshal test results it is obvious that polypropylene fibers modified in bituminous mix can improve Marshall quotient and Marshall stabilities values, which is a kind of pseudo stiffness (Tapkın et al., 2010).

CHAPTER 3: WASTE MATERIAL IN PAVEMENT

3.1 INTRODUCTION

With increasing world population, the amount of waste generation grows rapidly. This amount of waste causes a huge rise in the cost of waste disposal and also is filling the future sites for land fields. To solve the problem, considerable effort is being put into recycling waste, turning it into re-usable by products (Paranavithana and Mohajerani, 2006). Reusing is a kind of recycling which can reduce the amount of waste, reduce the cost for transport and production energy, lessen the demands for new resources and contribute to solve the disposal of waste problem (Tam and Tam, 2006).

Under the Environmental Public Health Act (EPHA), ‘‘waste’’ is defined as any substance or article which requires to be disposed of as being broken, worn out, contaminated or otherwise spoiled, and for the purpose of this Act anything which is discarded or otherwise dealt with as if it were waste shall be presumed to be waste unless the contrary is proved (Bai and Sutanto, 2002).

Recently environmental issues became more and more important in our society. Social life scientists, politicians and economists are becoming more and more concerned about the environment. In most developed countries the way of living has been changed and due to these changes recycling, reusing and conservation of resources are becoming one of the important issues in society.

Many studies are going on to research about advantages of reusing waste material in an economically and environmentally sustainable way (Aubert et al., 2006). Many

investigations on the effect of reusing hazardous material on the construction material properties and its environmental impacts have been done (Xue et al., 2009). Due to the lack of raw material and natural resources, using waste solid material in civil engineering projects specially roads construction has become a considerable issue (Xue et al., 2006, Huang et al., 2006, Auber et al., 2006 and Xue et al., 2009).

3.2 HISTORY

The safe disposal of waste materials is increasingly a major concern around the globe. Unfortunately even with the big advertising that has been done for importance of recycling the amount of waste material continues to grow.

Between 1980 and 1988 the annual amount of waste recycled grew by 9 million tons; however, the amount of waste generated increased by 30 million tons per year. In 1994, the total amount of waste produced in the U.S. reached 4,500 million tons per year (U.S. Army, 1999). At the same time that existing disposal facilities are reaching capacity, approval of additional facilities for waste disposal or treatment are becoming more difficult to obtain. Increasingly restrictive environmental regulations have made waste disposal more difficult. Together, these factors have significantly increased the cost of disposal of waste materials (U.S. Army, 1999).

Using the waste material instead of new material in the roads construction has two major benefits. One is the significant savings and reducing the costs and the second is cutting down on the volume of wastes that will be disposed of in the landfills and can solve the costly disposal problem.

Historically, because of the huge amount of materia1s needed for construction, pavements have been suitable structures to recycle a wide range of waste materials. Initially, this kind of recycling was limited to the reusing of previous pavements materials which are removed from the road construction. For instance recyclable asphalt pavement, recyclable Portland cement concrete, and various base course materials. Recently, various other materials, not originating or historically associated with pavements, have come into use, for example various latex materials added to the asphalt cement (U.S. Army, 1999).

3.3 SOLID WASTE MATERIAL (SWM)

Definition of solid waste material is solid or semi-solid, non-soluble material (including gases and liquids in containers) such as agricultural refuse, demolition waste, industrial waste, mining residues, municipal garbage, and sewage sludge.

In general waste materials can be categorized as industrial, agricultural, mineral, and domestic waste. With developing technology and changes with time, new material will appear while some of these materials will disappear.

Waste materials can be resources which are displaced. They can either be recycled or reused. In most developed countries waste materials used in construction are known as industrial byproducts, road byproducts and demolition byproducts. Steel slag and coal fly ash are industrial byproducts. The example for road byproduct can be reclaimed asphalt pavement materials and reclaimed concrete pavement materials and crushed concrete, tiles, and bricks are demolition byproducts. The use of these by products in pavement or in general road contraction will help to reduce the amount of disposed waste in to the landfills

and it also can cut down on the transportation and new material costs in the construction project (Chiu et al., 2008).

3.4 MUNICIPAL SOLID WASTE (MSW)

Municipal solid waste is made by household activities like use of plastic carry bags, cooking, cleaning, packaging and repairing empty containers. Many times these waste gets mixed with biomedical waste from hospitals and clinics. There is no system of separation of organic, recyclable wastes and inorganic at the household level.

3.4.1 Glass

The recycling of waste glass causes a big problem for municipalities worldwide. In 1994, in the United States, about 9.2 million metric tons of postconsumer glass was disposed in the municipal waste stream. Approximately 8.1 million metric tons or 80% of this waste was container glass (Shi and Zheng, 2007). New York City alone collects more than 100,000 tons annually and pays Material Recycling Facilities (MRF's) up to $45 per ton for the disposal of the glass, mixed with metals and plastics (Shi and Zheng, 2007).

Waste glass, from an economical standpoint, should probably be used only to make more glass because recycling glass reduces energy consumption, wear and tear on machinery and raw materials use (Shi and Zheng, 2007). But not all waste glasses are good to recycle because either they are not pure and clean or they are mixed colored. The cost of recycling is also an important issue. This leaves a substantial amount of waste glass available for use in pavement applications (U.S. Army, 1999).

There are many studies investigating on the use of waste glasses in concrete as a cement replacement or aggregates (Shao et al., 2000), (Federico and Chidiac, 2009), (Wang and Huang 2010), (Bazant et al., 2000), (Davraz and Gunduz, 2005), (Karamberi et al., 2006), (Shayan and Xu, 2004), (Shi et al., 2004), (Shayan and Xu, 2006) and (Topcu and Canbaz, 2004).

In the paving industry, crushed glass (cu1let) has been used as a replacement for aggregate in hot-mix asphalt mixtures, known as glasphalt (U.S. Army, 1999). Experience has shown that the cullet can replace up to 15 percent by weight of total aggregate in hot-mix asphalt. These mixes should not be used in surface courses (U.S. Army, 1999). The mixtures containing cu1let have been shown to be susceptible to moisture damage. This effect is only somewhat offset by the use of antistripping agents. The laboratory studies investigated the use of cullet as an aggregate replacement for subbase, base and embankment structures. They concluded that the cullet as an aggregate was strong, clean, safe and economical. Compaction results with some cullet gradations showed a flatter maximum dry density versus moisture curve indicating, that in field construction, compaction could occur over a wide range of moisture conditions (U.S. Army, 1999).

3.4.2 Plastics

Plastic has become an integral and inseparable part in our lives. The volume of consuming plastics is growing steadily because of its light weight, strength, fabrication capabilities, low density, low cost, user friendly designs and long life. Plastic has been used in industrial applications like automotive and packaging, healthcare applications such as artificial implants and medical delivery systems. Other applications are, housing, soil conservation, distribution and preservation of food, water desalination, flood

prevention, communication materials and other uses. Contrition of plastic in the category of solid waste material is increasing due to a wide range of applications. In 1996, in United States 12% of municipal solid waste (MSW) were plastics (Siddique et al., 2008). The plastics that are collected from the solid wastes material contaminate with other types of plastics thus the purification, segregation and identification of the various kinds of plastics is challenging. PET or in general polyethylene forms are the largest stream in the plastic wastes. The amounts of waste PET along with other plastics in municipal solid waste in United States are given in Table 3.1 (Subramanian, 2000). Plastic material consumption has increased from nearly 5 million tons to about 100 million tons from 1950s to 2001 in the world (Siddique, 2008).

Table 3.1 Quantities and types of plastics in MSW in the USA (Subramanian, 2000)

Type of plastic	Quantity (1000 tons)
Low density polyethylene (LDPE)	5010
Polyethylene terephthalate (PET)	1700
High density polyethylene (HDPE)	4120
Polystyrene (PS)	1990
Polypropylene (PP)	2580
Others	3130

LDPE has been used for many years as an asphalt modifier in hot-mix asphalt mixes and other asphalt paving applications. LDPE has been shown to be effective in reducing low temperature cracking and reducing rutting at high temperatures (U.S. Army, 1999), (Al-Hadidy and Yi-qiu, 2009), (Garcia-Morales et al., 2005) and (Hinisliglu and Agar, 2004). At low temperatures LDPE mixtures may be more susceptible to fatigue problems; however, the high temperature performance has usually been exceptional (Awwad and Shbeeb, 2007). It has been studied that using LDPE improved stability and viscoelastic properties of bitumen (prez-lepe et al., 2003), (Gonzalez et al., 2005) and (Polacco et al.,

2005). HDPE has also been used as a bitumen modifier in pavement construction (Casey et al., 2008). PET bottles have been used to produce geotextiles and, when chemically modified to a thermoset polyester, they have been used to produce a polymer concrete. PET chips have been used as aggregate in some studies (Frigione, 2010).

3.4.3 Steel slag

Steel slag is a byproduct of most metallurgical applications, which is cooled (granulated, pelletized, air or foamed) subsequently for use, and unfortunately disposed. Blast furnace slag (BFS), is a nonmetallic by product from iron making. BFS is relatively well known to be used in most highway construction applications such as granular base, supplementary cementitious materials and hot mix or concrete asphalt aggregate. Using the steel slag from other furnace process like basic oxygen furnace or electric arc furnace in the construction can result instability due to the containing CaO which may cause expansion. To avoid this problem and ensure the slag is appropriate to use in construction, it should go through quality control, appropriate steel slag aging and testing (Wang et al., 2010).

Many researchers have been done by civil engineers and material scientists to investigate possibility of using steel slag in construction applications. The studies indicate that steel slag is suitable to be used in construction applications' broad areas such as, in blended cement manufacturing (Tsakiridis et al., 2008), an aggregate in pavement surfaces or asphalt mixes (Ahmedzade and Sengoz, 2009), (Xue et al., 2006) and (Huang et al., 2007), and granular material in road subbase or base courses (Motz and Geiseler, 2001). In each named applications there are some advantages but using steel slag as a granular

material for following reasons has the best results compared to the other applications (Wang et al., 2010):

- Steel slag as a granular material can be used in larger quantities in unbound conditions, like road subbase or base, to compare with other usage.
- The process of using steel slag as granular and the volume expansion test method is technically developed and simple.
- The long term stability of highway granular subbase and base in unlimited condition is less concerned.

The technology of processing and treating steel slag to be useful as granular subbase and base in freeway construction in big quantities has been developed for the last two decades (Wang et al., 2010) and (Shen et al., 2009). But, the fact is that it has not been used in construction, as a granular material extensively. In United States, approximately 13 million metric tons (mt) of steel slag was disposed, only 1.7 million metric tons (mt) was used in construction in 2000 (Wang et al., 2010).

3.4.4 Construction and demolition debris (C&D)

The promotion of environmental management and the mission of sustainable development have exerted the pressure demanding for the adoption of proper methods to protect the environment across all industries including construction.

Construction is not an environmental-friendly activity by nature (Tam and Tam, 2006). Construction and demolition waste (C&D) is one of the largest waste streams on the earth. In China 30% to 40% of urban waste is construction and demolition waste. This is due to accelerating the city rebuilding and urbanization which led to more and more

construction and demolition activities (Zhao et al., 2010). In Finland one million tons of concrete, bricks and other mineral demolition wastes are produced every year which most of them are land filled (Wahlstrom, et al., 2000).

A proper and detailed demolition plan is very important in order to provide suitable material for use in roads construction. The quality of waste material will improve by selective constructions and demolition of buildings. By introducing the taxes on the waste land filling, recycling of mineral demolition wastes will be encouraged. Crushed concrete can be used in road bases or reused as an aggregate in concrete.

Typical emissions from land filling construction and demolition waste are chemicals leaching from concrete, drywall and wood (Symonds, 1999) and (Reinhart et al., 2004). The materials that are not recyclable will be disposed of in a landfill.

From economic and environmental point of view, recycling of construction and demolition waste not only has environmental benefits, but also has major effect on the resources conservation for the whole society, because it avoids producing of raw materials and provides substitution for materials like plastics and cement which require a significant amount of funding, energy and raw material to produce.

Generally, however there is not any uniform definition of construction and demolition in the world, it is mostly classified based on the composition and origin of construction and demolition waste. In the United States, construction and demolition waste is a waste material which is produced in the demolition of structures, renovation, or process of construction. Structures include bridges, roads and buildings, both residential and non-residential. Typically components of construction and demolition debris include gypsum wallboard, asphalt, metals, concrete, wood and roofing (Zhao et al., 2010).

3.4.5 Reclaimed asphalt pavement (RAP)

Increasing energy cost and environmental concerns have encouraged the development of using pollution-free, recyclable engineering materials that consume less energy to manufacture. Generally, there is a vast amount of material used in constructing a roadway. Different materials are used in different ways to fully exploit their potentials. For example, the best part of the soil–rock mixture can be used as the aggregates of the asphalt or concrete, the part with average quality can be used as road embankment filler, and the remaining part can be stabilized and used as the material of road bed (Chiu et al., 2008).

Recycling of asphalt pavements is increasingly used as one of the major rehabilitation methods for road and airport pavements worldwide in the light of the increasing cost of asphalt, the scarcity of quality aggregates, the pressing need to protect the environment and the increasing disposal costs of old asphalt pavements (Shoenberger and DeMoss, 2005), (James and Tere, 2005), (Chen et al., 2007) and (Chiu et al., 2008). Al-Qadi et al. in a study in 2007 reported that recycling asphalt pavement (RAP) in the hot mix asphalt (HMA) can save a substantial cost in construction (Al-Qadi et al., 2007) and (Su, et al., 2009).

CHAPTER 4: METHODOLOGY

4.1 INTRODUCTION

This chapter reviews detailed tests and the basic experimental approaches used in this research to investigate the main characteristics and properties of polyethylene terephthalate (PET) modified bituminous mixes. Testing will be done on the bituminous binder with and without PET as well as on the bituminous mixes with and without PET. The physical and engineering properties of the mixtures were determined from the relevant tests. These will be done by some laboratory test methods in compliance with the American Society of Testing and Materials (ASTM). These laboratory testing methods measure a number of parameters that takes into account the structural adequacy of the material as well as ensuring a satisfactory long term performance of the bituminous mix.

The testing methodology involved in this study can be divided into two major parts:

Part - I -: The first task focuses on the properties of PET modified bituminous binders.

Part - II -: The second task focuses on the properties on the PET modified bituminous mixes.

The obtained results were analysed using the statistical analysis, namely Analysis of Variance (ANOVA)

4.2 MATERIALS USED

All the experimental materials used in the tests came from the same source to ensure consistency characteristics of the materials. Below are the detail descriptions of the materials.

4.2.1 Bitumen Selection

Bitumen with 80/100 penetration grade and average softening point of 46 °C was used. It had been adopted as a pavement binder material for more than twenty years in Malaysia.

4.2.2 Aggregate Gradation

The aggregates used were asphaltic concrete wearing course with 14 mm nominal size (ACW 14). Selected gradation is shown in Appendix A.

4.2.3 Percentage of the Binder in the Mix and Mixing Temperature

Percentages of the binder in the mix were 4.5%, 5%, 5.5% and 6 % by weight of aggregate. Mixing temperature was 160-180 °C.

4.2.4 Gradation of PET in the Mix

In this investigation, waste PET in the powdered form of 2%, 4%, 6%, 8% and 10% by the weight of bitumen was used as a modifier. About 200 waste mineral water bottles were used as raw material. They where crashed in a crusher machine and then sieved. The gradation of PET is presented in Appendix A.

PART- I -: PET MODIFIED BITUMINOUS BINDER

4.3 TESTING OF PET MODIFIED BITUMINOUS BINDERS

The binder tests in addition to their significance and importance were specifically considered on the basis of the specimen's preparation. Meaning that the tests in which the specimens were workable, reliable and can easily be prepared would be considered.

Binders were characterised by using a number of standard physical tests. The following list shows the tests which were conducted in this study on PET modified binders

- Standard Test Method for Penetration of Bituminous Materials (ASTM D5 - 06e1) (1987)
- Standard Test Method for Viscosity Determination Using the Brookfield Thermosel Apparatus (ASTM D4402-87) (1987)
- Standard Test Method for Softening Point of Bituminous Materials (ASTM D36/ D36M) (1989)
- Proposed test method for determination the rheoligical properties of bituminous binder for specification purposes using a Dynamic Shear Rheometer (DSR) (ASTM D7175) (1995)

4.4 PREPARATION OF BINDER

In this study dry mix was used. The bitumen contained in 1-liter cylindrical container was put into the oven and heated until it became liquid. The molten bitumen was poured in to six small empty cylindrical containers with volume of 250 ml. The net weight of bitumen in each small tin was 120 g. Before mixing the waste PET with bitumen in small tins, bitumen was heated up to about 160°C first. To achieve this place, small tins of bitumen were heated into the oven for about 1 hour. After that, waste PET in percentage of 2%, 4%, 6%, 8% and 10% was added into the tins and were mixed manually for about 2 minutes.

Immediately after mixing, the mixture was placed in viscosity sample chambers. Following this, softening point rings, penetration cups and then DSR test specimens were prepared. After having cooled in room temperature for 1 day, samples were tested.

4.5 PENETRATION TEST

4.5.1 Definition and Test Conditions

The first equipment for penetration test which was published in 1959, explained the following procedure:

- Penetration of a standard needle into the asphalt binder sample under the following conditions was measured:
  - Time = 5 seconds
  - Load = 100 grams
  - Temperature = 25° C (77° F)

- Asphalt binder sample under controlled conditions was melted and cooled

The depth of penetration was measured in units of 0.1 mm and reported in penetration units (e.g., if the needle penetrates 10 mm, the asphalt penetration number is 100). Penetration grading was based on the penetration test (Pavement Interactive).

4.5.2 Test Procedure

The bitumen had been heated until it became fluid then had been poured it in a container to a depth such that when cooled, the depth of the sample was at least 10mm greater than the expected penetration. the samples had been left in a room temperature for 24 hours and then the samples in had been placed a water bath with 25°C one hour before the test.

The needle on bitumen had been mounted by slowly lowering until its tip touched the surface of the bitumen. The pointer had been bringed to zero and the needle had been allowed to penetrate freely for 5 seconds. At least three readings had been taken. The result is the grade of bitumen.

Test condition and the method of specimen preparation are important for accurate results so that the appropriate standard requirements must be rigidly adhered to. Table 4.1 presented the maximum difference between the lowest and highest readings.

Table 4.1 the maximum difference between penetration test results (ASTM D5 - 06e1)

Penetration (d-mm)	0-49	50- 149	150 - 249	250-500
Maximum Difference	2	4	12	20

4.6 SOFTENING POINT (RING AND BALL)

4.6.1 Definition and Test Conditions

The softening point is defined as the temperature at which a bitumen sample can no longer support the weight of a 3.5 g steel ball. Basically, two horizontal disks of bitumen, cast in shouldered brass rings were heated at a controlled rate in a liquid bath while each supported 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).

4.6.2 Preparation of the Specimen

The bitumen sample had been heated between 75 and 100^{o}C and it had been stirred slowly to remove air bubbles. The rings had been heated and some glycerine had been applied on the surface which the samples will be on. Glycerin helps for removing the samples from the surface. Then the bitumen had been filled in it and had been cooled for at least 30 minutes.

4.6.3 Test Procedure

The apparatus with the specimen rings, ball centering guides and thermometer had been assembled in position then the bath had been filled so that the liquid depth was 105±3 mm with the apparatus in place. The ice had been used to reach the proper starting temperature which should be below 5°C then had been left for 15 min.

The two steel balls had been placed in the bottom of the bath so they could reach the same starting temperature as the rest of assembly. The ball had been placed from the bottom of bath in each ball centering guides and the bath had been heated by using a gas burner

from below with a rate of 5°C/min and the liquid had been stirred constantly. For each ring and ball the temperature indicated by the thermometer at the instant when the bitumen surrounding the ball touches the bottom plate had been recorded. If the difference between the temperatures that each ball touched the bottom exceeded 1°C the test had been repeated.

4.7 VISCOSITY DETERMINATION USING THE BROOKFIELD THERMOSEL APPARATUS

4.7.1 Definition and Test Conditions

The Brookfield Thermosel viscometer was used to determine the viscosity of binders at elevated temperatures. The viscosity test can be applied at different temperatures, but since construction and manufacturing temperatures are quiet similar regardless of the environment, the test for bitumen binder specification was conducted at 135°C. The viscosity test ensured that the bitumen binder was fluid enough for mixing and pumping (Roberts et al., 1996).

The basic viscosity test determines the torque which is required to keep a fixed rotational speed of a cylindrical spindle (20 rpm) while submerged in a bitumen binder at a fix temperature. Then this torque will be converted to a viscosity and automatically displayed by the Brookfield thermosel viscometer. The viscosity of bitumen binder at elevated temperatures is important in order to be able to control the following:

- Workability which is the ability of the bituminous mix to be compacted and placed with reasonable effort

- Mixability which is the ability of the bitumen binder to properly coat and mixed with the aggregate.
- Pumpability which is the ability of the bitumen binder to be pumped into the bituminous mix and between storage facilities (pavement interactive).

4.7.2 Preparation of the Specimen

The bitumen had been heated for maximum 30 min then 10± 0.5 gr of bitumen had been poured into viscosity sample chambers. The samples had been allowed to cool at room temperature. For this dissertation, the temperature range was 90 to 170°C. Spindle number used was 27 and the rotation speed was 20 rpm.

4.7.3 Procedure of the Test

The Thermosel power had been turned on and the temperature of the controller had been set to 90°C. By using an extracting tool the viscosity sample chamber had been put into the Brookfield Thermosel viscometer container. The samples had been come to the equilibrium temperature after one to one and half hours. By using the coupling the selected spindle (No. 27) had been attached to the viscometer then the spindle had been lowered into the sample in the Thermosel until the liquid level was approximately 3 mm (1/8 inch) above the upper conical spindle shaft. The viscometer had been started at a 20 rpm setting. If the required speed of 20rpm was not attainable because the sample was too hard, the temperature had been increased to the next with 10°C and had been tried to get the speed required. The torque reading had been stabilised before taking the reading for viscosity and shear stress. The temperature had been increased every time with 10°C and the torque reading had been stabilised again before taking the reading.

4.8 DYNAMIC SHEAR RHEOMETER (DSR) TEST (ASTM D7175)

4.8.1 Definition and Test Conditions

The test is used to determine the elastic and viscous behavior of bitumen binders at various temperatures.

The basic dynamic shear rheometer test uses a thin bitumen binder sample formed between two parallel plates. To make a shearing action, the upper plate oscillates at 1.59 Hz across the sample while the lower plate was fixed. DSR tests were conducted on PAV aged; RTFO aged and unaged bitumen binder samples. The test is mostly controlled by software.

Bitumen is a viscoelastic material which means it behaves partly like a viscous liquid and partly like an elastic solid. Deformation in viscous material due to loading is not recoverable. It means that after removing the load the material is not able to return to the original form whereas deformation in elastic solid material is recoverable which means after removing the load it can return to its original shape.

The DSR test is suitable to characterize bitumen binder in the wide temperature range and quantify the viscous and elastic properties because it has been used in the plastics industry for years.

The DSR test covers the determination of the complex shear modulus (G*) and phase angle (δ). G* is an indicator of the stiffness or resistance of bitumen binder to deformation under traffic loads while δ is the lag between the resulting shear strain and the applied shear stress. This means more viscous material has larger phase angle. Phase angle is limited as following:

- 100% elastic material: $\delta = 0$ degrees

- 100% viscous material: $\delta = 90$ degrees

4.8.2 Preparation of the Specimen

The sample had been heated until it became fluid to pour (typically 100-150°C). The sample had been stirred during the heating process to ensure homogeneity and to remove air bubbles. The pre-calculated amount of sample had been poured directly into a metal mold with 1 mm thickness. Both surface of the mold had been covered with an oily paper before pouring the bitumen in to the mold. The sample had been cooled, cut and replaced on upper plate of DSR machine.

4.8.3 Procedure of the Test

As it has been mentioned before, the test is largely software controlled. The test was conducted using a temperature sweep. For this dissertation the range starts from 30°C to 80°C. The removable upper palate of the rheometer had been fastened firmly to ensure that the specimen will adhere to both plates strongly. The temperature of the water bath had been set to 30°C. By using the computer software the rheometer had been at zero point automatically, and then the upper plates which had been removed to prepare the specimen had been replaced. The plates had been moved together to squeeze the specimen until the gap was 1mm. when measurement position had been achieved, the water had been opened to fill the environmental chamber and the test had been started.

This test was conducted by measuring 25 values of complex shear modulus and phase angle. The frequency used was 1.59 Hz.

Part - II -: PET MODIFIED BITUMINOUS MIXES

4.9 TESTING OF PET MODIFIED BITUMINOUS MIXES

Specimen mixes were characterised by using a number of standard physical tests. The tests conducted on bituminous mixes modified by PET follows as:

- Marshall test
- Indirect Tensile Test (IDT)

4.10 PREPERATION OF THE MIX SPECIMEN

The weighed aggregates and the bitumen had been heated separately up to 200^{o}C and 160^{o}C respectively. Meanwhile the specimen mould had been prepared, cleaned it and placed a piece of filter paper in the bottom of the mould. The aggregate had been mixed and bitumen at the temperature of 160-180°C rapidly until all the aggregate was thoroughly coated. The entire mixture had been placed in the mould and had been spaded with a heated spatula, and then a piece of filter paper had been put on the top. The thermometer had been placed in the mixture until the mixture temperature had decreased to 140°C. After that the mould had been placed on the compaction pedestal then the specimen had been compacted by applying 75 blows in each face. The mould had been taken with the specimen and had been cooled in room temperature then the specimen had been removed from the mold. The specimen had been marked and cured it at the room temperature overnight.

4.11 MARSHALL TEST (ASTM D1559-89)

4.11.1 Definition and Test Conditions

Marshal test can be applied to hot bituminous mix designs made of bitumen and aggregates up to a maximum size of 25mm. In this test, cylindrical specimen was loaded at 5 cm per min then resistance to plastic deformation was measured. Marshal test procedure was used in evaluating and designing bituminous mixes and for paving jobs. Marshall method of designing mixes has two major features which are:

1) Stability – flow tests

2) Density – voids analysis

Definition of Marshall stability is the maximum load that a compacted specimen can carry at a standard test temperature of 60ºC. During the loading, deformation of specimen was measured and recorded as flow value at the exact time when the maximum load was applied. The flow value was shown in 0.25 mm.

4.11.2 The Marshal Test Parameters

The major properties of bituminous mix to be suitable for paving applications are stability, flexibility, durability, and skid resistance. Traditional mix design methods are established to measure the optimum bitumen content which would have optimum performance due to its optimum stability and durability. There are a lot of mix design methods used around the world, for example Asphalt Institute triaxial mix design method, Marshall mix design method, Hveem mix design method and Hubbard-field mix design method. Out of these four, only Hveem mix design method and Marshall mix design

method are accepted. In this study, Marshall mix method of design was used to design the bituminous mixes.

Marshall test on the effect of the PET at different portions in bituminous mix has been carried out. The PET was mixed into the bituminous mixes in 5 different concentrations (2%, 4%, 6%, 8% and 10%) by weight of the bitumen in the mix. In determining the properties of the PET bituminous mixes a comparison has been made with the control mix. The following parameters were considered.

- Marshall stability
- Marshall flow
- Density of the compacted mix
- Void in the mix
- Optimum binder content

4.11.2.1 Marshall Stability and Flow

The stability is a measure of the ability of the bituminous mixture to resist deformation from imposed loads. And it depends on both the internal friction and cohesion within the material.

During the loading, deformation of specimen was measured and recorded as flow value at the exact time when the maximum load was applied. The flow value is shown in mm units.

4.11.2.2 Density

Density is the ratio of the mass in air of a unit volume of a permeable material at room temperature to the mass in air (of equal density) of an equal volume of water. This value

is used to determine the weight per unit volume of the compacted mixture. It is very important to measure density as accurately as possible. Since it is used to convert weight measurements to volumes, any small errors in density will be reflected in significant volume errors, which may go undetected. The corresponding densities of the specimens were determined from Eq. 4.1.

$$\text{Density} = \frac{W_{air}}{W_{surface\ dry} - W_{water}} \qquad (4.1)$$

Where W_{air} = weight of specimen in air (gram)

W_{water} = weight of specimen in water (gram)

$W_{surface\ dry}$ = weight of specimen with surface dry (gram)

4.11.2.3 Voids in the Mix

The total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, is expressed as a percent of the bulk volume of the compacted paving mixture. Porosity relates to the amount of air voids in the mix. The amount of air voids in a mixture is extremely important and closely related to stability and durability. It should not be too high otherwise it may affect the durability and stability of the mixture. However there must be sufficient porosity in a mix to allow the binder to expand and provide enough space for further compaction due to the effect of traffic loads. Porosity was determined from Eq. 4.2.

$$VIM = 100 - \left\{ \frac{P_{bitumen}}{SG_{bitumen}} + \frac{P_{aggregate}}{SG\ aggregate} \right\} * D \qquad (4.2)$$

where: VIM = voids in the mix (porosity)

SG = specific gravity of the material

P = proportion of the material in the mix

D = density of the specimen ($gr/cm^{3)}$

4.11.2.4 Determination of Optimum Binder Content

The design of a bituminous mix consists of the determination of an economical blend and gradation of aggregates together with the necessary content of bitumen to produce a mixture that will be durable, have the stability to withstand traffic loads, and be workable for placement and compaction with the construction equipment available. To achieve this goal, determination of optimum binder content in mix is necessary.

In this study the parameters that are averaged to obtain the bitumen binder content are maximum stability, flow and porosity. These parameters were determined by reading off the appropriate values from the curves that satisfy the limiting criteria set by the Asphalt Institute (1990) as shown in Table 4.2.

Table 4.2 The Asphalt Institute design criteria (Asphalt Institute 1990)

Mix Criteria	Light traffic		Medium traffic		Heavy traffic	
	Min	Max	Min	Max	Min	Max
Compaction	35		50		75	
Stability (KN)	≥ 3.34		≥ 5.34		≥ 8	
Flow (mm)	2.0	4.5	2.0	4.0	2.0	3.5
Air Voids (%)	3	5	3	5	3	5

Maximum size of aggregate (mm)	Minimum voids in mineral aggregate (%)
19	14
12.5	15
9.5	16
4.75	18
2.36	21
1.18	23.5

4.11.3 Procedure of the Test

The empirical Marshall test is to define the stability and flow of a bituminous mix.

According to the Asphalt Institute (1990), in Marshall method each specimen is subjected to the following tests.

i. Stability and Marshall flow test

ii. Bulk specific gravity determination

iii. Density and voids analysis

iv. Optimum binder content

Before the Marshall test, the thickness, diameter, weight in air, weight in water and dry surface weight of each specimen had been measured. Each specimen had been kept in water bath at temperature of 60°C for 40 min and then the specimen had been placed in Marshall

test apparatus.

Stability and flow on the apparatus had been checked to be zero then the run button had been pressed. The specimen had been compressed radially at a constant rate of strain (51mm per min). The stability and flow of the specimen on Marshall test apparatus had been checked.

Bulk specific gravity of mixture, density and voids analaysis were determined for each specimen.

According to the Asphalt Institute (1990) the methodology for selecting the optimum binder content procedure are as follows:

a. The average of the binder contents required for maximum stability, density and midpoint of selecting range of VMA had been obtained.

b. From the test plots the value of stability, flow, VIM and VMA, corresponding to the average binder content calculated in 1 had been obtained.

c. The values determined in 2 comply with acceptability criteria had been verified.

4.12 INDIRECT TENSILE MODULUS TEST (ASTM D693-07)

4.12.1 Definition and Test Conditions

The Universal materials testing apparatus (UMATTA) for asphalt specimens is a testing system used to determine the elastic modulus, and also the permanent and elastic deformations of the Marshall specimens. The loading device is a 100-kN capacity

electromechanical test frame, Instron Corporation Model 5583. The system operates automatically and is computer controlled using the software UMAT. The parameters such as the applied load level, load repetition, the time to reach the maximal loading level were specified before the test. While the test was being carried out at predefined intervals, the elastic and plastic deformations are recorded and tensile stress, resilient strain and elastic modulus values were calculated. The experiment was conducted in a temperature-controlled environment with the interior and surface temperature of the specimen continuously recorded.

The stiffness modulus of the material is calculated using the E.q. 4.3.

$$\mathbf{M_R} = \frac{\mathbf{P(\nu+0.27)}}{\mathbf{tH}} \quad (4.3)$$

where

M_R= Resilient modulus (MPa)

P = Repeated peak load (N)

ν = Poisson's ratio

t = Specimen thickness (mm)

H = Total recoverable horizontal deformation (mm)

Although the elastic moduli of various different HMA mixes are well defined, these tests are still used to determine how elastic and resilient modulus varies with different modifiers and temperatures.

4.12.2 Test Equipment

The indirect tensile test consists of Resilient Modulus Testing Machine, Temperature Control System, Measurement System, Deformation Measurement, Load Measurement and Loading strips.

Resilient modulus testing machine is a pneumatic repeated loading device with control. The loading device is a 100-kN capacity electromechanical test frame, Instron Corporation Model 5583.

Temperature control system includes digitally controlled refrigeration and heating system capable of achieving temperatures in the range of 5 to 40°C. The chamber was also capable of storing specimens prior to testing. It includes a viewing window, system for keeping the air dry, interior lights, and an interface for remote control. Measurement system was a display that presents the value of the repeated load magnitude and the value of the recoverable horizontal deformation.

Deformation measurement consists of linear variable differential transformers (LVDTs) with a resolution of 0.000125 mm. The linear variable differential transformer (LVDT) is a type of electrical transformer used for measuring linear displacement. The transformer has three solenoidal coils placed end-to-end around a tube. The center coil is the primary, and the two outer coils are the secondaries. A cylindrical ferromagnetic core, attached to the object whose position is to be measured, slides along the axis of the tube.

Load measurement was an electronic load cell with a resolution of 5 Newton. Loading strips were two metal strips with a concave surface having a radius of curvature equal to the nominal radius of the test specimen.

4.12.3 Testing Parameters

- Temperature : 25°C
- Force : 20 * specimen thickness
- Pulse period : 1s
- Poisson ratio : 0.35
- Rise time : 70ms

4.12.4 Test Procedure

The repeated load indirect tension test for resilient modulus was conducted by applying a Trigonometry, or other suitable waveform, with a load applied vertically in the vertical diametral plane of a cylindrical specimen of mix asphalt. The resulting horizontal deformation of the cylindrical specimen was measured and, with an assumed Poisson's ratio, was used to calculate the resilient modulus of the compacted mixture.

The test specimens had been placed in a controlled temperature cabinet and had been brought to the specified test temperature. After the required test temperature was reached, the specimen had been placed into the loading apparatus positioned on the concave loading strips. The electronic measurement system had been adjusted and balanced as required then the load magnitude, loading frequency, load duration, and test temperature had been selected. In the indirect tensile test a pulsed diametral loading force was applied to a specimen and the resulting total recoverable diametral strain was then measured from axes 90 degrees from the applied force. Strain in the same axes was not measured, thus a value of 0.35 for Poisson's ratio was used as a constant. Poisson's ratio (ν) can be assumed to take on the following values for various temperatures (Table 4.3).

Table 4.3 Poisson's ratio for various temperatures

Temperature, °C	Poisson's Ratio, ν
5	0.30
25	0.35
40	0.40

4.13 ANOVA

ANOVAs form a set of analytical tests which can be used to identify possible differences in the mean value of more than two data samples. It is a useful and powerful tool for determining if differences are statistically significant or not. In this investigation two type of ANOVA were performed.

- One-way ANOVA (also known as single factor ANOVA) was used to determine if there's a statistically significant difference between three or more alternatives.

- Two way ANOVA (also known as two factor ANOVA) was used to determine if two factors have the same mean or average. This is a form of "hypothesis testing."

For both types of ANOVA the null hypothesis (H_0) is that the means are equal and the alternate hypothesis (H_a) is that the means are different. Interpretation of the test result is presented in Table 4.4. It also indicated where the null hypothesis is accepted or rejected.

Table 4.4 Interpreting the ANOVA test result

If	Then
F-ratio> F-critical	Reject the null hypothesis
F-ratio< F-critical	Accept the null hypothesis
P value < a	Reject the null hypothesis
P value > a	Accept the null hypothesis

To assess the effect of PET on the penetration, softening point, viscosity, complex shear modulus and phase angle, the ANOVA test at 5% significance level was conducted.

CHAPTER 5: BINDER TESTS RESULT AND ANALYSIS

5.1 INTRODUCTION

Bitumen's are mixtures of aliphatic, aromatic and naphthenic hydrocarbons. They are widely used to provide waterproofing and protective coating and as binders in road construction. During the life service of asphalt binders, there are many types of failures, e.g. rutting, fatigue cracking and thermal cracking, which can reduce the quality and performance of pavements. Temperature susceptibility characteristics and the physical properties of asphalt bitumen at high and low field-operating temperatures can affect the final performance of the mixture. For the past two decades significant research has been conducted on polymer modified asphalt mixtures. Polymers can successfully improve the performance of asphalt pavements at low, intermediate and high temperatures by increasing mixture resistance to fatigue cracking, thermal cracking and permanent deformation.

Since there are almost infinite variety grades of bitumen that can be produced, it is necessary to adopt a convenient method of describing them. The most obvious need is the measurement of hardness. Since consistency and temperature of bitumen are dependent parameters, it is necessary to measure the consistency at a fixed temperature or determine the temperature at when a fixed consistency occurs. Therefore the industry had developed a number of physical and rheological property tests for the asphalt specifications such as penetration, softening point, viscosity and dynamic shear rheometer.

This chapter discusses the results of laboratory tests. Binders are characterised by using a number of standard physical tests such as penetration test (temperature, load and time are

25ºC, 100g and 5sec respectively), softening point test, viscosity test using Brookfield viscometer (temperature range from 90 to 170 ºC, spindle No.27, and a rotating speed of 20rpm), and also rheological measurements by using a dynamic shear rheometer (tests conducted by using a temperature range of 30 ºC to 80 ºC, and a frequency of 1.59 Hz).

5.2 PENETRATION TEST RESULTS

Penetration test is the most widely used method to evaluate the consistency of a bituminous material at a certain temperature. This test only classified the material and do not measure the quality. The consistency is an engineering term which measures the resistance of a fluid under shearing stress against deformation. The consistency is a relative proportion of resins, asphaltenes and oils. Resin is responsible for ductility and adhesion, asphaltenes are high molecular weight part of bitumen and is responsible for stiffness and strength, and oil is low molecular weight that is responsible for fluidity and viscosity. The amount and type of these constituents are determined by the method of processing at the refinery and the source petroleum (Whiteoak, 1990).

Test condition and the method of specimen preparation are important for accurate results so that the appropriate standard requirements must be rigidly adhered to. Table 4.1 has reported the maximum difference between the lowest and highest readings.

Table 5.1 consists of penetration test result for six different binder contents and each binder has nine reading. The results show that the penetration decreases with increasing the amount of PET. It appears clearly from Figure 5.1 that the penetration value of modified bitumen is lower than unmodified bitumen and more over the increasing of PET portion in

bitumen the penetration value decreases. The rate of decrease is about 2.4%, 4.9%, 8.5%, 11% and 14.6% with the addition of 2%, 4 %, 6%, 8% and 10% of PET, respectively, as compared to the original bitumen. This means that the addition of PET makes the modified bitumen harder and more consistent.

This is confirmed by the statistical analysis which shows that PET content on the penetration values has significant effect. Statistical analysis using single factor ANOVA at a confidence level of 95% has been carried out on penetration test result. According to the penetration ANOVA test result, F-ratio value is 26.7 which is much higher than F-critical (2.4) and also P-value is much lower than 0.05 which satisfy the alternate hypothesis (H_a). A summary of ANOVA results is given in Appendix B.

Previous researches have also shown that polymer modification has a significant effect on properties of bitumen. Sengoz and Isikyakar (2008) analysed the effect of styrene-butadiene-styrene polymer on modified bitumen using conventional test methods. They concluded that adding SBS polymer in bitumen as a modifier reduces penetration value of the bitumen. Results from Casey et al. (2008) study also show the effect of the recycled polymer on the penetration value of the binder, and it can be seen in all cases increasing quantities of polymer leads to a reduction in the measured penetration value. Al-Hadidy and Yi-qiu (2009) have similar results on the effect of LDPE on bitumen penetration value. According to their work, results with addition of 8% LDPE, penetration value decrease to half compared to unmodified bitumen. Another investigation that has been done with Sengoz et al. (2009) shows reduction in penetration with increasing polymer content in all specimens.

Table 5.1 Penetration Results (0.1 mm)

Unmodified binder	2% PET	4% PET	6% PET	8% PET	10% PET
85	77	77	69	82	67
81	78	78	74	74	68
84	79	80	74	72	69
82	78	76	75	70	68
80	83	79	76	70	73
83	80	77	75	74	70
80	81	77	77	73	71
80	80	78	76	73	70
84	86	80	77	72	76

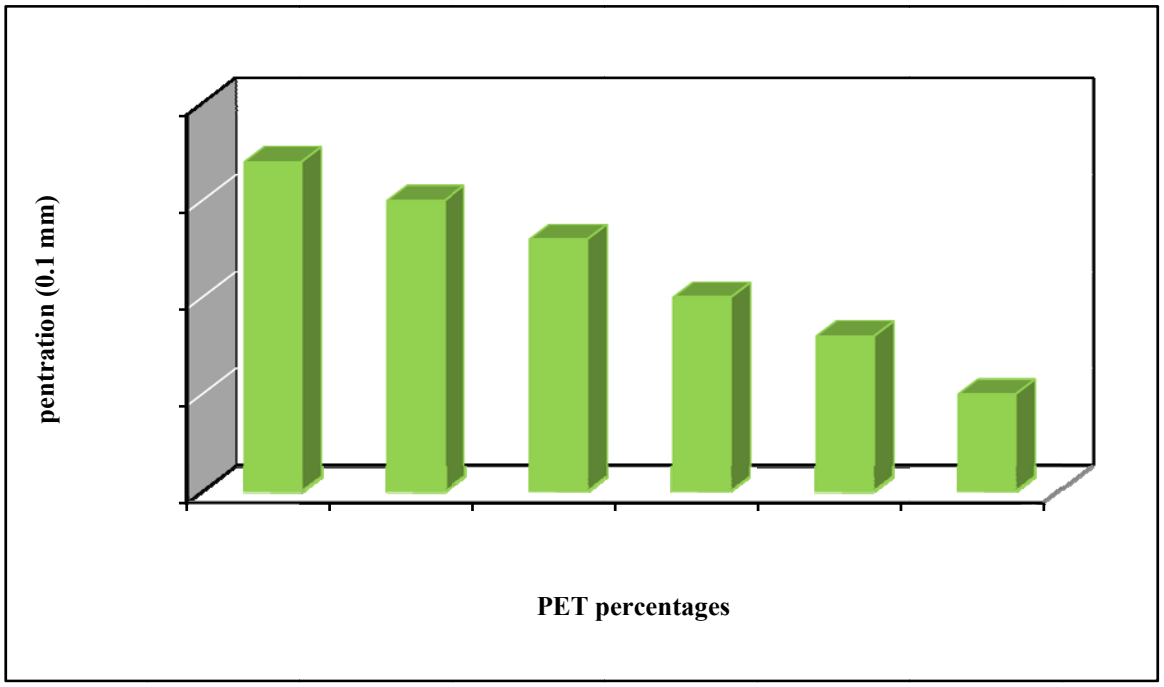

Figure 5.1 Penetration vs. Different Portion of PET

5.3 SOFTENING POINT TEST RESULTS

The softening point is a measure of the temperature at which bitumen begins to show fluidity. It is also defined as the temperature at which a bitumen sample can no longer support the weight of a 3.5 g steel ball. Basically, two horizontal disks of bitumen, cast in shouldered brass rings are heated at a controlled rate (5°C per min) in a liquid bath while each supports a steel ball.

Softening point test results are presented in Table 5.2. Figure 5.2 shows that softening point increases with increasing PET content. The results clearly show that the addition of PET to bitumen increases the softening point value, and as the PET content increases the softening point also increases. This phenomenon indicates that the resistance of the binder to the effect of heat is increased and it will reduce its tendency to soften in hot weather. Thus, with the addition of PET the modified binder will be less susceptible to temperature changes.

Casey et al. (2008) reported that the softening point of modified bitumen can give an indication of the improvement in temperature susceptibility of the binder achieved through the addition of the polymer. The effect of softening point of a binder on resistance to permanent deformation, of bituminous pavement mixes, has been studied by various researchers. An example is hot rolled asphalt where it was found that the rate of rutting in the wheel tracking test at 45°C, was halved by increasing softening point by approximately 5ºC (Fernando and Guirguis, 1984).Therefore it is expected that by using the PET in the bituminous mix the rate of rutting will decrease due to the increase in softening point.

Comparing to previous researches, Sengoz and Isikyakar (2008), Casey et al. (2008), Sengoz et al. (2009), Al-Hadidy and Yi-qiu (2009) and Polacco et al. (2005) achieved

similar results in their works. Sengoz and Isikyakar (2008) reported that by adding 6% SBS in bitumen the softening point increases by 20°C compared to unmodified bitumen. Casey et al. (2008) have tested the softening point of three different polymer (PP, LDPE, HDPE) modified bitumen in four different percentage of polymer by weight of bitumen. According to their test results the softening point of all modified specimens increased compared to base binder and with increasing the polymer content the softening point increases. It was also noticed that higher density of polymer has higher softening point and lower penetration value. In Sengoz et al. (2009) study, the softening point of specimen 60% increased compare to base binder with the addition of 6% Ethylene Butyl Acrylate (EBA).

Single factor ANOVA at the confidence level of 95% has been done for softening point test results and showed significant effect of PET contents on softening point values. In this case F-ratio obtained is 19.2 which is higher than F-critical (2.8). Also P-value is lower than α which means the H_0 is rejected. A summary of ANOVA results is given in Appendix B.

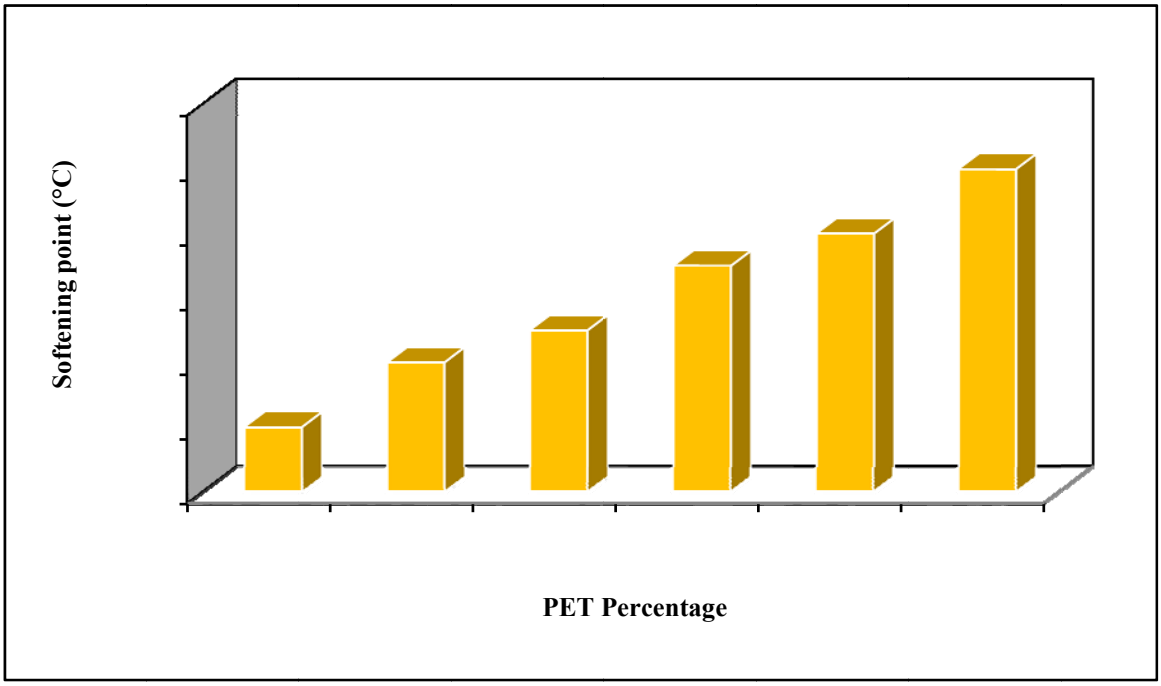

Figure 5.2 Softening Point vs. Different Portion of PET

Table 5.2 Softening Point Results (°C)

Unmodified binder	2% PET	4% PET	6% PET	8% PET	10% PET
46	47	47.5	48.5	49	50
45	48	47	49	51	50
46.5	46	48	48	49	51
46	47	47.5	48.5	49	49

5.4 PENETRATION INDEX (PI)

The temperature susceptibility of the modified bitumen samples has been calculated in terms of penetration index (PI) using the results obtained from penetration and softening point tests. Temperature susceptibility is defined as the change in the consistency parameter as a function of temperature.

A classical approach related to PI calculation has been given in the Shell bitumen handbook (Zhang et al., 2009) as shown with the following Eq.

$$\mathrm{PI} = \frac{1952 - 500\log(\mathrm{Pen25}) - 20 \times \mathrm{SP}}{50\log(\mathrm{Pen25}) - \mathrm{SP} - 120} \qquad (5.1)$$

Where Pen25 is the penetration at 25 °C and SP is the softening point temperature of polymer modified bitumen (PMB).

Figure 5.3 shows a nomograph which enables the PI to be measured from the penetration at 25°C and the softening point temperature. Typical values of PI are presented in Table 5.3.

Table 5.3 Typical Values of PI (Whiteoak, 1990)

Bitumen type	PI
Temperature susceptible bitumen (Tars)	<2
Conventional paving bitumen	-2 to +2
Blown bitumen	>-2

To deduce the PI from Figure 5.3 draw a line between the softening point (line 'A') and penetration (line 'B') values. The intercept on line 'C' is the PI of the bitumen.

From Figure 5.3 we can see that PI for all the binders in this study are between -1 and +0, therefore the bitumen type is conventional paving bitumen. The intercept on line C and the red line is the PI of original bitumen which is 0 and the intercept on line C and the blue line is the PI of modified bitumen with 10% PET. As we can see PI of modified bitumen is less than PI of unmodified one. It means that polymer modification reduces temperature susceptibility (as determined by the penetration index-PI) of the bitumen. Lower values of PI indicate higher temperature susceptibility. As reported by Isikyakar and Sengoz, 2008 asphalt mixtures containing bitumen with higher PI were more resistant to low temperature cracking as well as permanent deformation

PI values can be used to measure the stiffness of bitumen (modulus) at any loading time and temperature. It can also be used to classify different types of bituminous material.

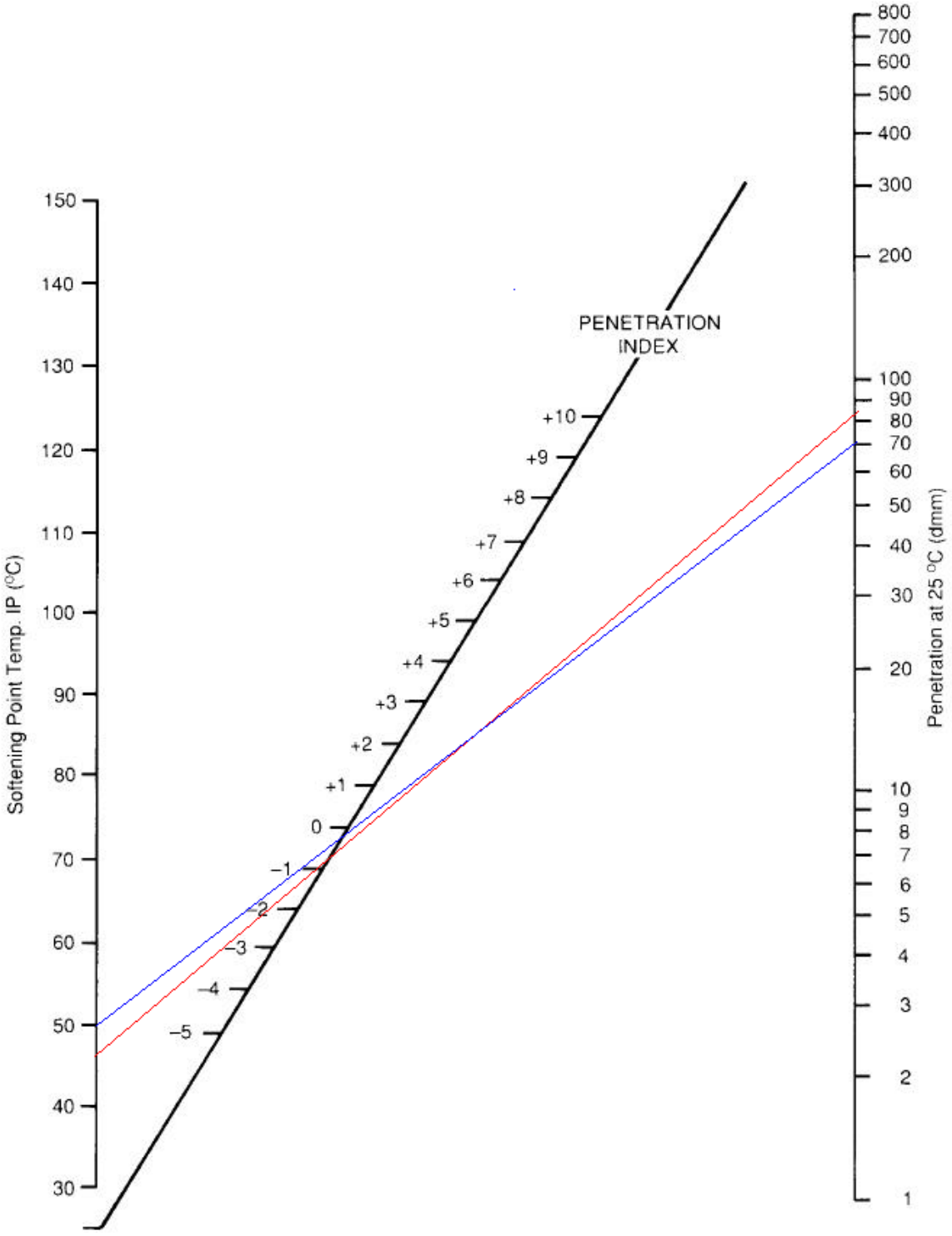

Figure 5.3 Nomograph for the IP of Bitumen (Whiteoak, 1990)

5.5 VISCOSITY TEST RESULTS

The viscosity of asphalt binder at high temperature is considered to be one of the important properties since it represents the binder's ability to be pumped through an asphalt plant, thoroughly coat the aggregate in asphalt concrete mixture, and be placed and compacted to form a new pavement surface.

5.5.1 The Effect of Temperature on the Viscosity

Figure 5.4 shows that the viscosity of all samples (unmodified and modified bitumen) decreases as the temperature increase. This means that the viscosity for unmodified bitumen is equal to the viscosity of PET modified bitumen at higher temperature.

Proper mixing temperature of the aggregate with the binder can be identified by viscosity of the binder since the viscosity is related to the temperature. This is the temperature which the binder would maintain an acceptable viscosity in order to coat the aggregate effectively before the binder gets too viscous. Some problems related to lack of adhesion may occur if the binder is not viscous enough. In this case the air void will increase and cause increasing possibility of oxidative hardening of the binder, and therefore durability of the bituminous pavement will reduce.

Previous researches show similar results. Akisetty et al. (2009) have done viscosity test on rubberized binder at two temperatures of 120°C and 135°C. They concluded that viscosity at 135°C is lower than viscosity at 120°C in all modified and unmodified binders. Aflaki and Tabatabaee (2008) also have similar experience. They have done viscosity test on different kinds of modified binders at temperatures of 95-175°C. Modifiers used were crumb rubber, gilsonite, polyphosphoric acid, and styrene–

butadiene–styrene (SBS). From their results all the binders showed a decrease in viscosity with increasing temperature.

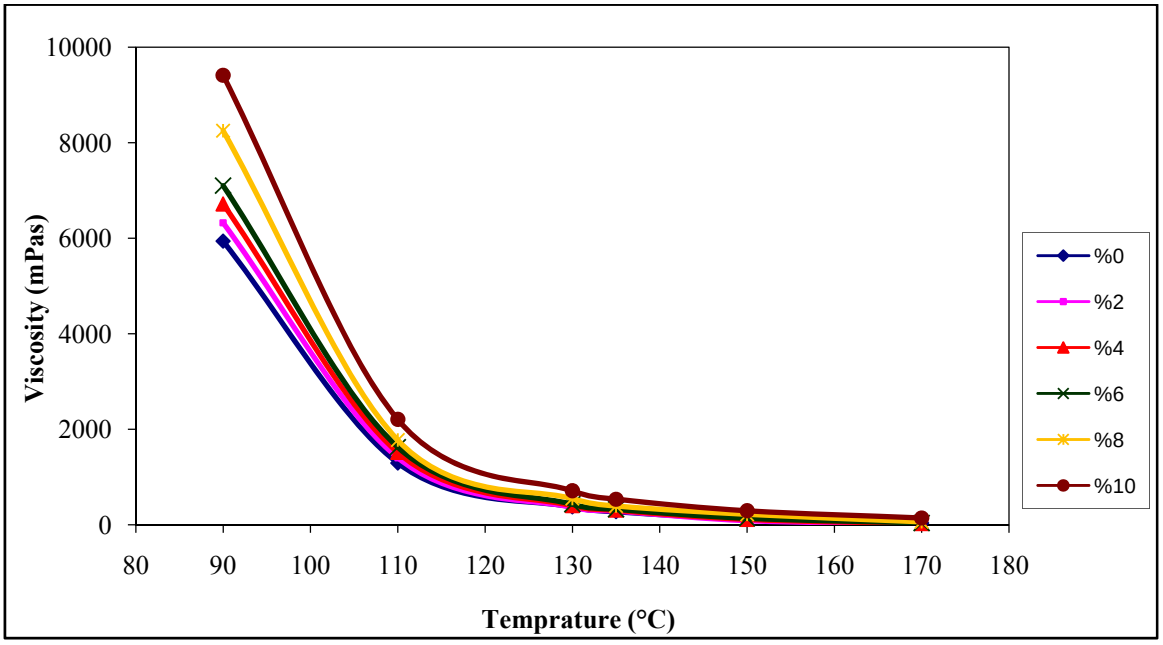

Figure 5.4 Viscosity vs. Temperature

5.5.2 The Effect of PET Content on Viscosity

Modified asphalt binders are usually more viscous than unmodified ones. Figure 5.5 shows that as the PET content increases, the viscosity increases. The addition of 2%, 4%, 6%, 8% and 10% of PET into the binder increase the viscosity of the bitumen by 5.4%, 10.9%, 18.2%, 43.3% and 95.6% respectively, as compared to the original bitumen. In the extreme case of adding 10 % PET to the base binder, the viscosity increased from 275 mPas to 538 mPas (Table 5.4). This value is less than 3000 mPas and therefore satisfies the ASTM D6373 criterion for asphalt binder workability.

Numerous works have been done on effect of bitumen modifier content on the viscosity and all reported the similar results. Aflaki and Tabatabaee (2008) mixed granulated SBS in 1%, 2%, and 3% concentrations with the base bitumen at 160 °C. Their work results show that viscosity at 135°C for 1%, 2% and 3% SBS binder content was 1.3, 1.7 and 2.1 times respectively higher than unmodified binder. Lee et al. (2009) study clearly demonstrated that the addition of Sasobit (a crystalline, long chain aliphatic polymethylene hydrocarbon produced from natural gas) into recycled binders decreased the binder's viscosity, compared to the control recycled binder. Jeong et al. (2010) and Thodesen et al. (2009) have done similar work on crumb rubber modified binder viscosity. In both studies the viscosity measured at 135°C and CRM was 5%, 10%, 15% and 20% by weight of bitumen. Both work results clearly showed that with increasing the rubber in binder content the viscosity increases significantly.

To check the statistical significance of the viscosity results, two factor ANOVA analyses were carried out. From ANOVA test result it can be stated with 95 percent confidence that the addition of PET resulted in an increase in binder stiffness. Both PET content and temperature have significant effect on the viscosity of the binder as demonstrated by the obtained F-ratio values of 2.7 and 198.1 respectively which is higher than F-critical (2.6). A summary of ANOVA results is given in Appendix B.

Table 5.4 Viscosity Results (mPas)

Temp °C	PET					
	0%	2%	4%	6%	8%	10%
90	5938	6324	6715	7100	8250	9412.5
110	1294	1404	1515	1625	1775	2206.5
130	375	368.5	400	431.5	550	712.5
135	275	290	305	325	394	538
150	118.75	87.5	112.5	137.5	219	294
170	37.5	18.75	25	37.5	62.5	144

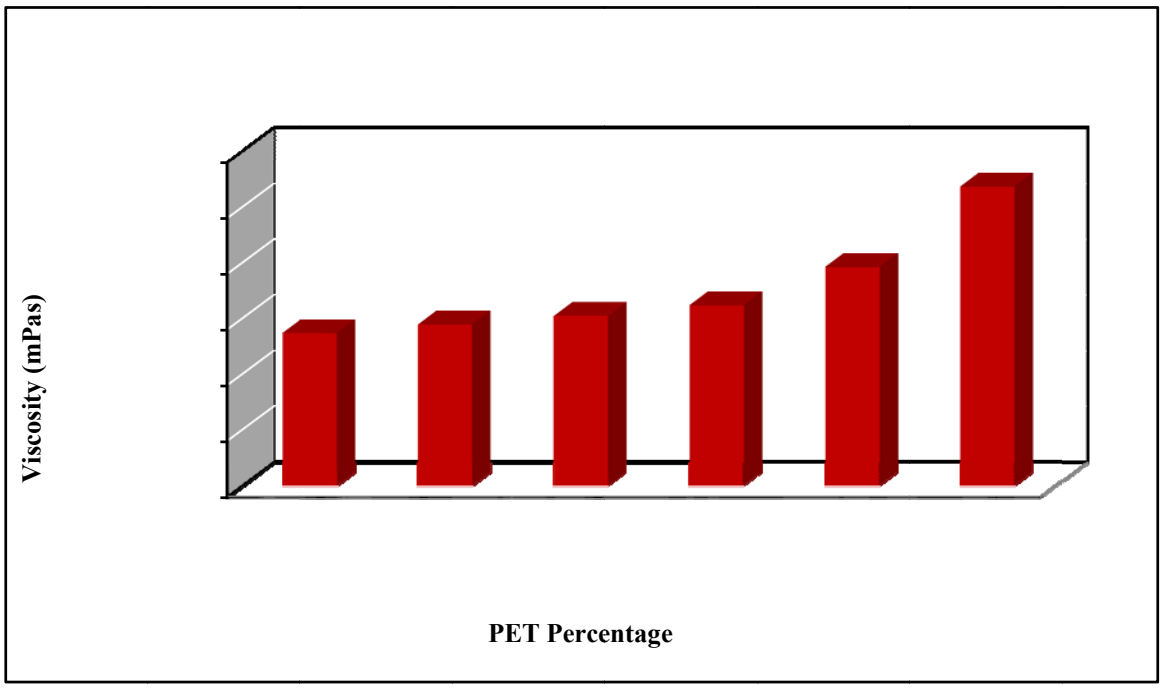

Figure 5.5 Viscosity vs. Different Portion of PET @ 135°C

5.6 VISCOSITY- SOFTENING POINT RELATIONSHIP

The viscosity of the 24 samples at 135°C varied from 275 to 538 mPa.s with the softening point ranging from 46°C to 50°C respectively is presented in Figure 5.6. The empirical equation gave a very good representation of the softening point -viscosity relationship for the range of bitumen of 40-50°C softening point.

The increase in viscosity in all the binders due to the addition of PET content follows a similar pattern as the increase in softening point of the same binders due to the addition of PET. Karim and Samsuri (1997) reported that there is a linear relationship between the viscosity and the softening point. Oyekunle (2000) has also reported that the model equation of viscosity with softening point contains two empirical parameters which were determined by linear regression.

In our case the regression line is plotted for all the data, where the function and the coefficients of correlation (R^2) are mentioned in the Figure 5.6.

The data in the Figure 5.6 confirmed that, the increase in the viscosity due to PET content is followed by the increase in the softening point. The increase of viscosity means that the binder became harder and more resistant to flow. The increase in softening point means that the binders provide less tendency to flow and its stiffness is higher. These two facts are almost the same and confirm the linear relationship between the viscosity and the softening point for the same binder.

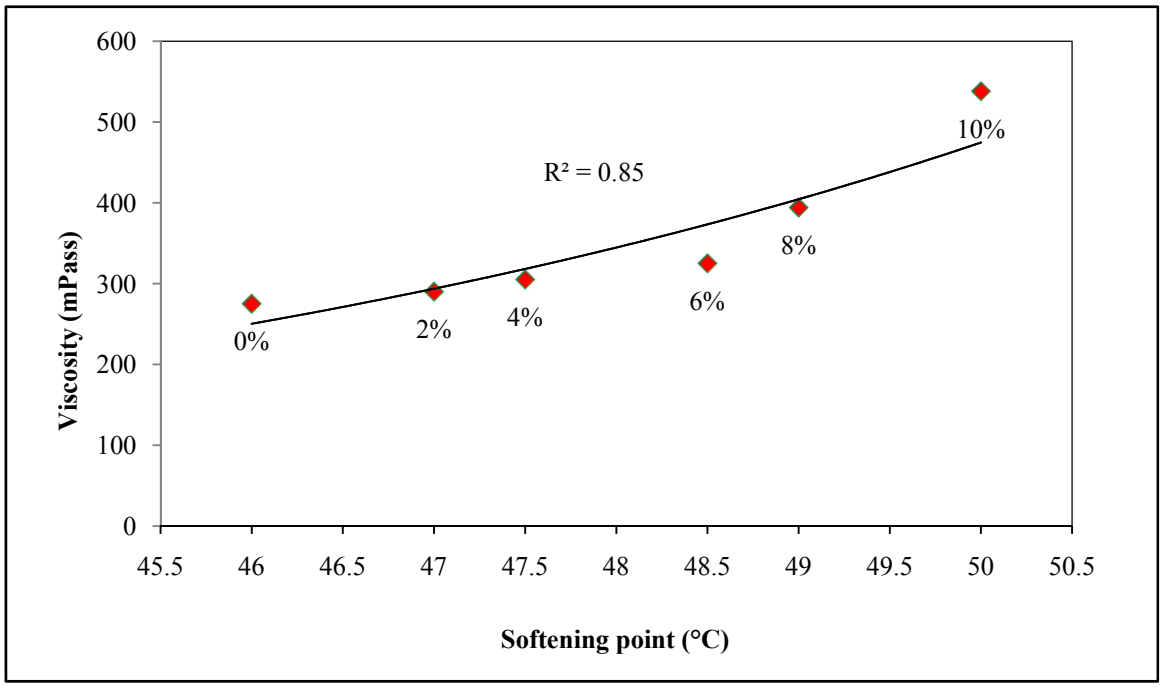

Figure 5.6 Viscosity @ 135 °C vs. Softening Point

5.7 D.S.R TEST RESULTS

The basic dynamic shear rheometer test uses a thin bitumen binder sample formed between two parallel plates. To make a shearing action, the upper plate oscillates at 1.59 Hz across the sample while the lower plate was fixed.

In the dynamic shear rheometer test, the value of the phase angle (δ) and the complex shear modulus (G*) of the bitumen material were determined. Viscous and elastic components and the total complex shear modulus of the bitumen material can be conducted by measuring the complex shear modulus (Eq. 5.2, 5.3 and 5.4). According to Eq. (5.5), the phase angle is the time lag between the applied shear stress and the resulting shear strain converted into degrees.

$$\tau_{max} = \frac{2T}{\pi r^3}$$

(5.2) (Al-Khatib and Al-Akhras, 2011)

$$\gamma_{max} = \frac{\theta r}{h}$$

(5.3) (Al-Khatib and Al-Akhras, 2011)

$$G^* = \frac{\tau_{max}}{\gamma_{max}}$$

(5.4) (Al-Khatib and Al-Akhras, 2011)

$$\delta = 360\,(t)(f)$$

(5.5) (Al-Khatib and Al-Akhras, 2011)

where τ_{max} is the maximum applied shear stress; T the maximum applied torque; r the radius of binder specimen (12.5 mm); γ_{max} the maximum resulting shear strain; θ the deflection (rotation) angle; h the specimen height (1 mm); G* the complex shear modulus; δ the phase angle (°); t the time lag (s); and f is the loading frequency (1.59 Hz).

The G* value can be from about 500 Pa to 6000 Pa (0.07 psi to 0.87 psi), while δ range from about 50° to 90°. A material with δ of 90° essentially has a complete viscous behavior and a material with δ of 0° essentially has a complete elastic behavior. Generally PMA binders have lower δ and higher G* which means that they are usually more elastic and stiffer compare to unmodified asphalt binders.

The phase angle value (δ) and the complex shear modulus value (G*) were obtained for all the binders at the eight test temperatures. G* and δ values are reported in Table 5.5 and 5.6 respectively.

Table 5.5 Complex Shear Modulus Result (kPa)

Tem °C	0% PET	2% PET	4% PET	6% PET	8% PET	10% PET
30	118.76	221.34	268.60	305.30	330.00	376.50
40	25.88	49.14	60.60	69.88	71.00	88.26
50	7.50	12.90	16.00	18.55	22.00	28.50
60	5.50	10.15	12.20	13.98	15.76	21.52
70	2.38	3.06	4.50	5.91	8.76	11.76
76	1.40	1.70	2.25	3.47	5.60	8.90
80	0.75	0.66	1.00	1.61	2.50	5.76

Table 5.6 Phase Angle Result (°)

Tem °C	0% PET	2% PET	4% PET	6% PET	8% PET	10% PET
30	80.00	76.00	73.00	71.00	71.60	70.00
40	87.00	85.00	81.00	80.80	80.00	79.80
50	88.00	87.00	86.00	85.30	83.80	82.00
60	89.00	88.50	88.30	87.80	85.90	85.00
70	89.50	89.20	89.00	88.90	88.20	88.00
76	89.70	89.60	89.50	89.00	88.40	88.20
80	89.90	89.90	89.90	89.90	89.90	89.90

5.7.1 Effect of Temperature and PET Content on the Complex Shear Modulus (G*)

The temperature dependence of G* is lowest for the unmodified bitumen compared to modified bitumen. It is observed that in all samples (unmodified and modified bitumen) the complex shear modulus G* decreases as the temperature increase (Figures 5.7, 5.8 and 5.9). Complex shear modulus results are tabulated in Table 5.5.

From the graphs we can also see that as PET content increases the complex shear modulus G* increases. This can be clearly seen from the Figure 5.9 since the graphs of G* follow a certain order. It can be seen that the lowest graph is for the original sample (without PET) and the highest one is for the sample with 10% PET.

The lower slope of the complex shear modulus G* means that the asphalt is softer, and

can deform without developing large stresses. Also, a higher complex shear modulus G* is beneficial since it reduces rutting problems (deformations) in the asphalt.

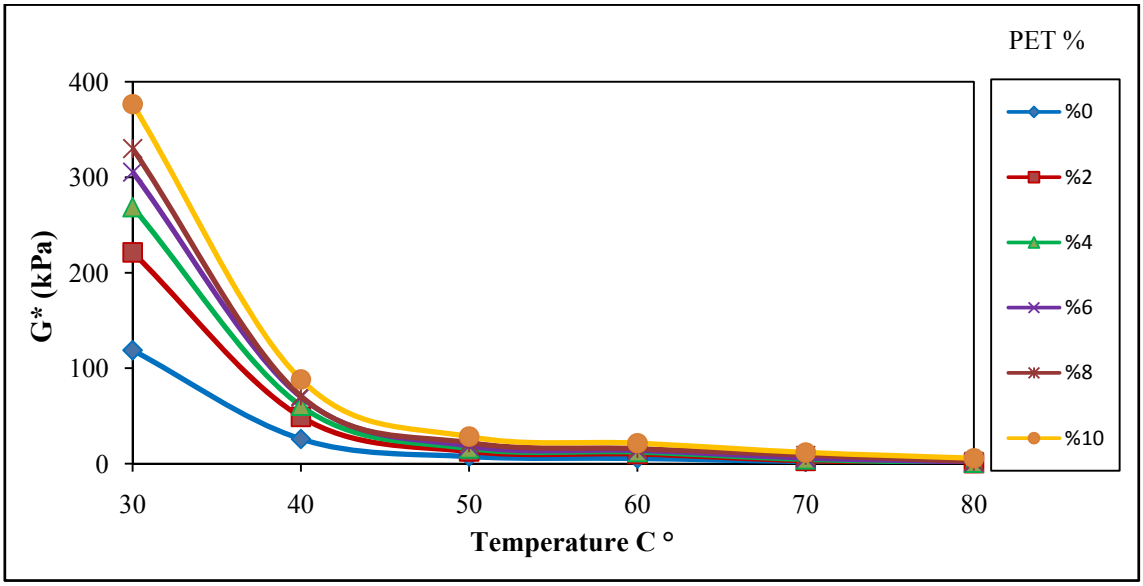

Figure 5.7 Complex Shear Modulus vs. Temperature (30-80 °C)

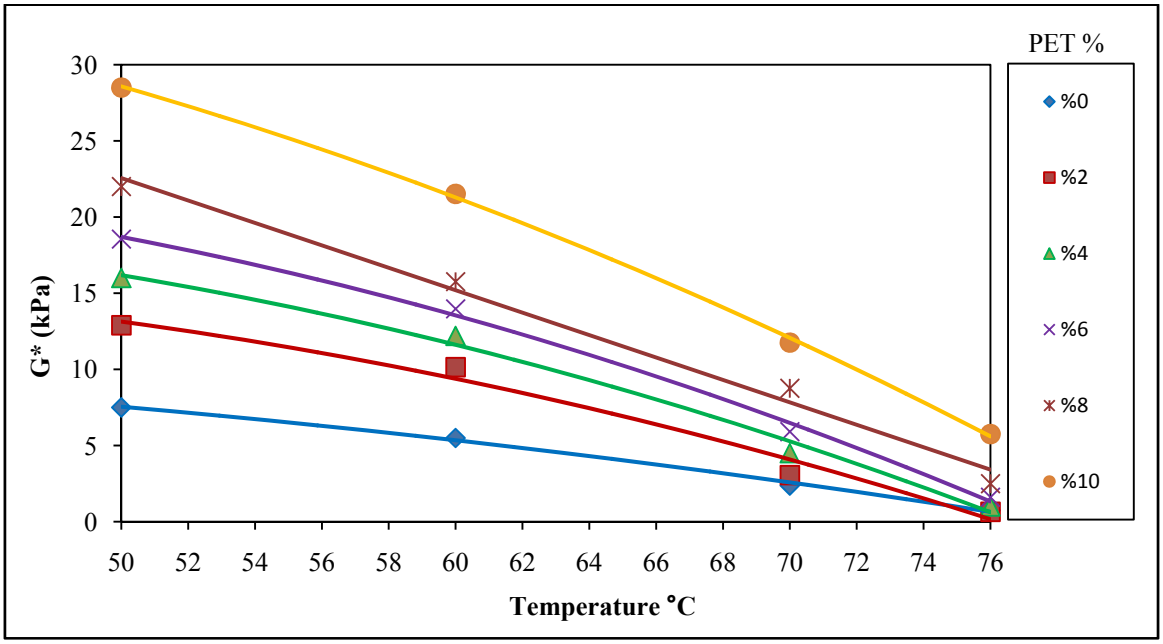

Figure 5.8 Complex Shear Modulus vs. Temperature (50-76 °C)

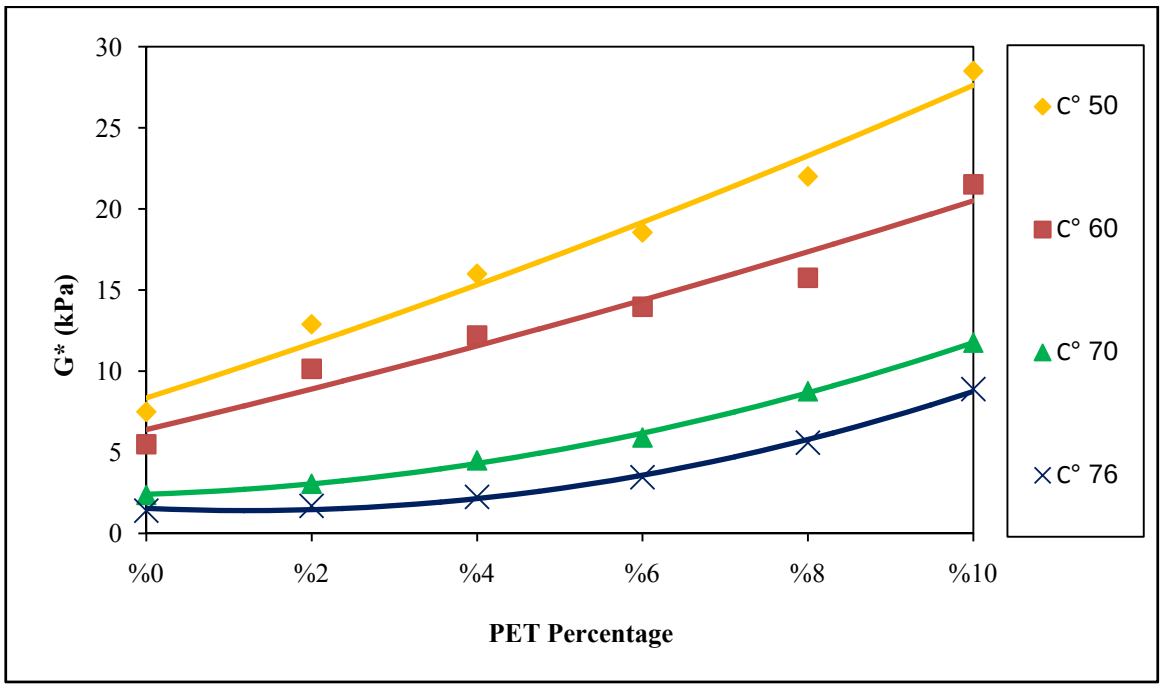

Figure 5.9 Complex Shear Modulus vs. Different Portion of PET

5.7.2 Effect of Temperature and PET Content on the Phase Angle (δ)

Figures 5.10 and 5.11 show that the phase angle δ for the unmodified bitumen is higher than modified bitumen. Table 5.6 presents the phase angle test results.

Generally as PET content increases the phase angle δ decreases and we can verify this by doing the same comparison as before concerning the order of the graphs for the samples. We can also see from the unmodified and modified samples that as the temperature increases the phase angle δ also increases.

The lower slope of phase angle δ means that the asphalt is more elastic than viscous, and will recover to its original condition without dissipating energy. Also, at high temperatures, a low phase angle δ is desirable since this reduces permanent deformation.

At high temperatures δ approaches a limiting value of 90º. This means that the material response is almost totally out of phase with the load and complete viscous behavior (complete dissipation of energy) is approached. The bitumen tends toward Newtonian fluid behaviour and it is normally characterised in terms of dynamic viscosity.

ANOVA results confirm that binder content and PET content have significant effects on the G* and δ values of modified binders at 95% confidence level. For G* all the samples with different temperature showed an F-ratio of 53.98 which is higher than F-critical of 2.42 and for different PET content the results is F-ratio of 2.67 that is slightly higher than F critical of 2.53. For δ all the samples with different temperature showed an F-ratio of 89.37 which is much higher than F-critical of 2.42 and for different PET content the results is F-ratio of 8.07 that is higher than F critical of 2.53 A summary of ANOVA results is given in Appendix B.

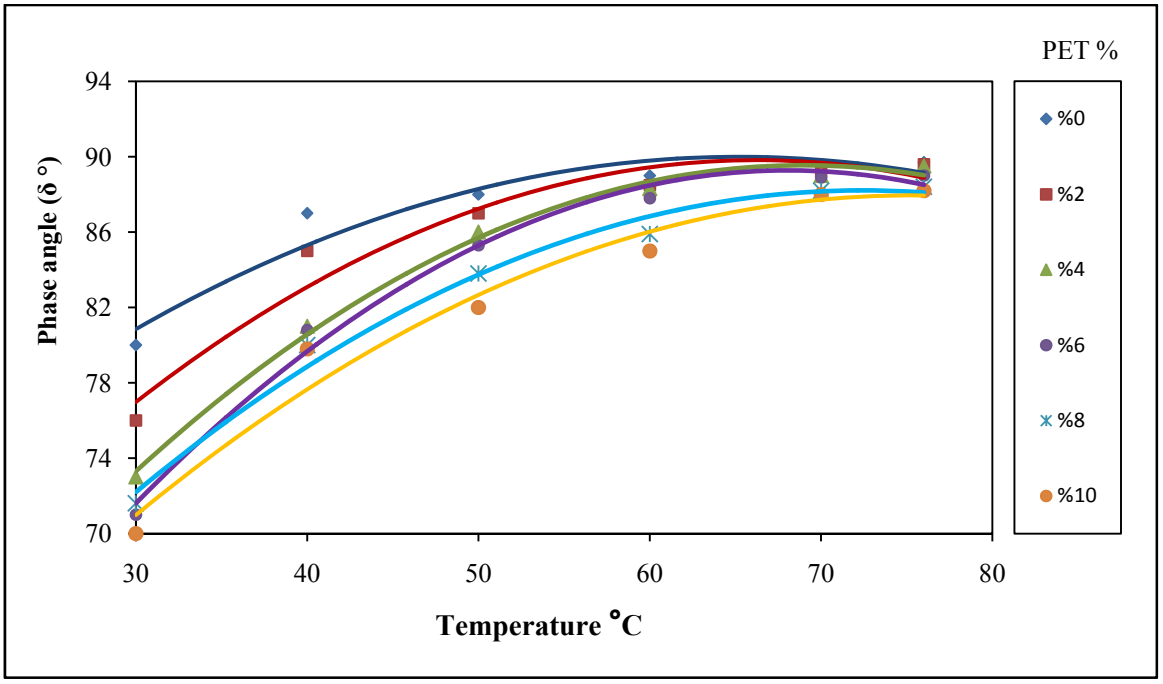

Figure 5.10 Phase Angle vs. Temperature (50-80 °C)

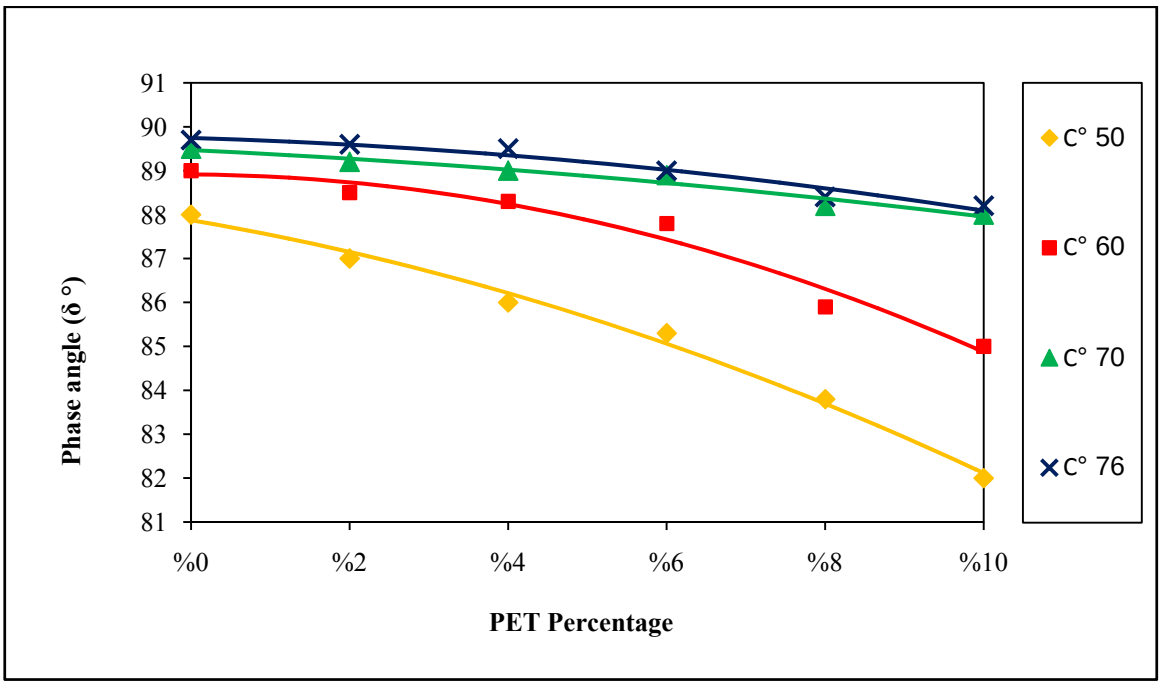

Figure 5.11 Phase Angle vs. Different Portion of PET

5.7.3 Rutting and Fatigue Prevention

G*/sin δ value is the parameter that is highly correlate with permanent deformation or rutting of bituminous pavements in the Superpave specification. A bitumen binder that is resistant to rutting need to be stiff enough not to deform too much and elastic enough to return to the original form after removing the load. Therefore, G*/sin δ, the complex shear modulus elastic portion, should be large. Usually during the early and midlife of pavements rutting is a big concern so for that a minimum value for the elastic component of the complex shear modulus is specified. Binders with higher G* value are stiffer which means they are able to resist deformation and ones with lower δ value have greater elastic portion of G* which make them more elastic and flexible (http://pavementinteractive.org).

Basically rutting is a cyclic loading phenomenon. It means with each traffic cycle, the pavement surface is being deformed. Part of this deformation is recovered by the elastic rebound of the pavement surface and part of it will dissipate in the form of heat crack propagation, permanent deformation and cracking. Therefore, in order to minimize rutting, the amount of work dissipated per loading cycle should be minimized. The work dissipated per loading cycle at a constant stress can be expressed as in Eq. (5.6)

$$W_c = \pi\sigma_0 \left[\frac{1}{G^*/\sin\delta} \right] \qquad (5.6)\ (\text{http://pavementinteractive.org})$$

Where W_c is work dissipated per load cycle, σ = stress applied during load cycle, G* complex modulus and δ is phase angle.

In order to minimize the work dissipated per loading cycle, the parameter G*/sin δ should be maximized. Therefore, minimum values for G*/sin δ for the DSR tests conducted on asphalt binder are specified. The Superpave specifications specify a minimum value of 1.0 kPa for the G*/sin δ of original asphalt binders at the high performance grade temperature (Table 5.7).

Table 5.7 Performance Graded Asphalt Binder DSR specifications

Material	Value	Specification	HMA Distress of Concern
RTFO* residue	G*/sin δ	$\geq$ 2.2 k Pa (0.319 psi)	Rutting
Unaged binder	G*/sin δ	$\geq$ 1.0 k Pa (0.145 psi)	Rutting

* Rolling Thin-Film Oven

The G*/sin δ values were plotted against the different portion of PET in binders at the different temperatures as shown in Figure 5.12. A similar relationship to the G* value-PET relationship was obtained in this case. It appears clearly from Figure 5.12 that with increasing percentage of PET in binder, G*/sin δ value increase as well and it means that with addition of polymer in asphalt, the resistance of asphalt against rutting increases. In general, the addition of the PET to the asphalt material improves the G*/sin δ value at all temperatures. In addition to this, the PET improves the high performance grade temperature of asphalt binders; i.e., asphalt binders mixed with PET can pass the Superpave specifications for G*/sin δ value at higher temperatures. Consequently, hot-mix asphalts with high rutting resistance are produced as a result of the addition of PET at relatively high pavement service temperatures such as 76 °C. According to performance graded asphalt binder specifications (AASHTO, 2001) and Table 5.8 PG for all binder is 76. The specification Table is in Appendix A. The fatigue resistance parameter in the Superpave specification, also based on DSR test result is G* sing δ, the storage modulus for cyclic loading. It is a measure of the energy dissipation which determines fatigue damage and is limited to 5.0 MPa based on observations of test pavements in service. Table 5.9 shows that G* sin δ for all the binders except the one with 10% PET content is less than 5 MPa.

Table 5.8 Complex Shear Modulus Elastic Portion Result (KPa)

Tem °C	0% PET	2% PET	4% PET	6% PET	8% PET	10% PET
30	120.59	228.12	280.87	322.89	347.78	400.66
40	25.92	49.33	61.36	70.79	72.10	89.68
50	7.50	12.92	16.04	18.62	22.13	28.78
60	5.50	10.15	12.21	13.99	15.80	21.60
70	2.38	3.06	4.50	5.91	8.76	11.77
76	1.40	1.70	2.25	3.47	5.60	8.90
80	0.75	0.66	1.00	1.61	2.50	5.76

Table 5.9 Storage modulus for cyclic loading (MPa)

Tem C °	0% PET	2% PET	4% PET	6% PET	8% PET	10% PET
30	116.96	214.77	256.86	288.67	313.13	353.79
40	25.84	48.95	59.85	68.98	69.92	86.87
50	7.50	12.88	15.96	18.49	21.87	28.22
60	5.50	10.15	12.19	13.96	15.72	21.44
70	2.37	3.06	4.50	5.91	8.76	11.75
76	1.40	1.70	2.25	3.47	5.60	8.90
80	0.75	0.66	1.00	1.61	2.50	5.76

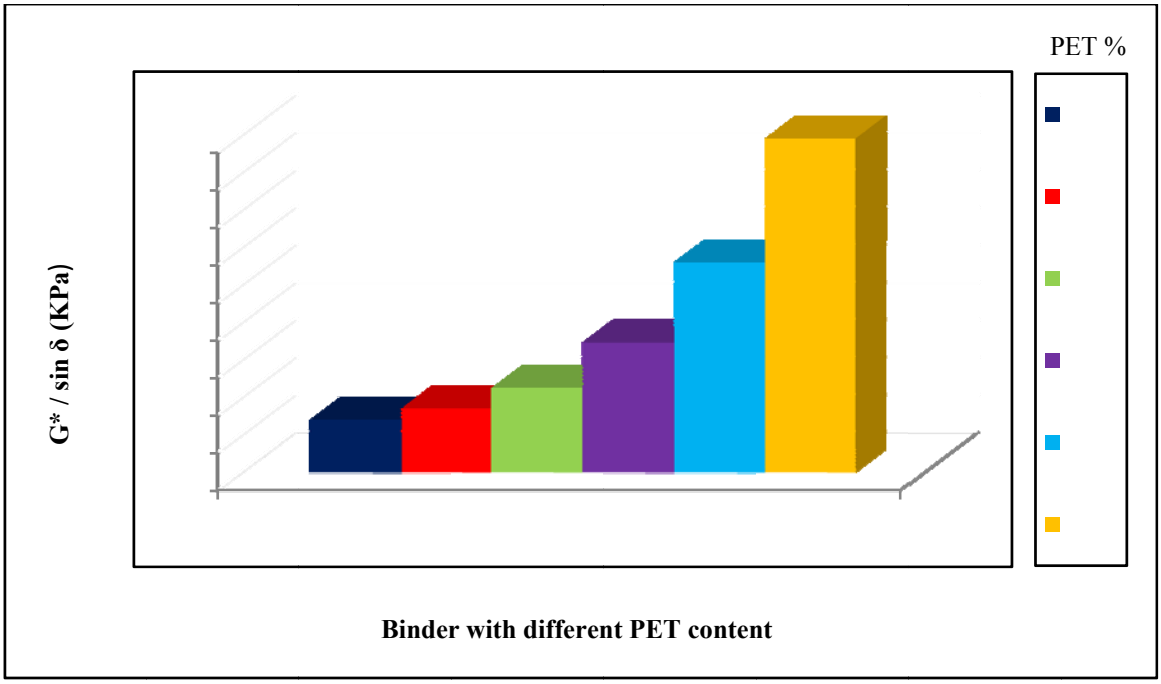

Figure 5.12 Complex Shear Modulus Elastic Portion vs. Different Portion of PET @ Temperature of 76 °C

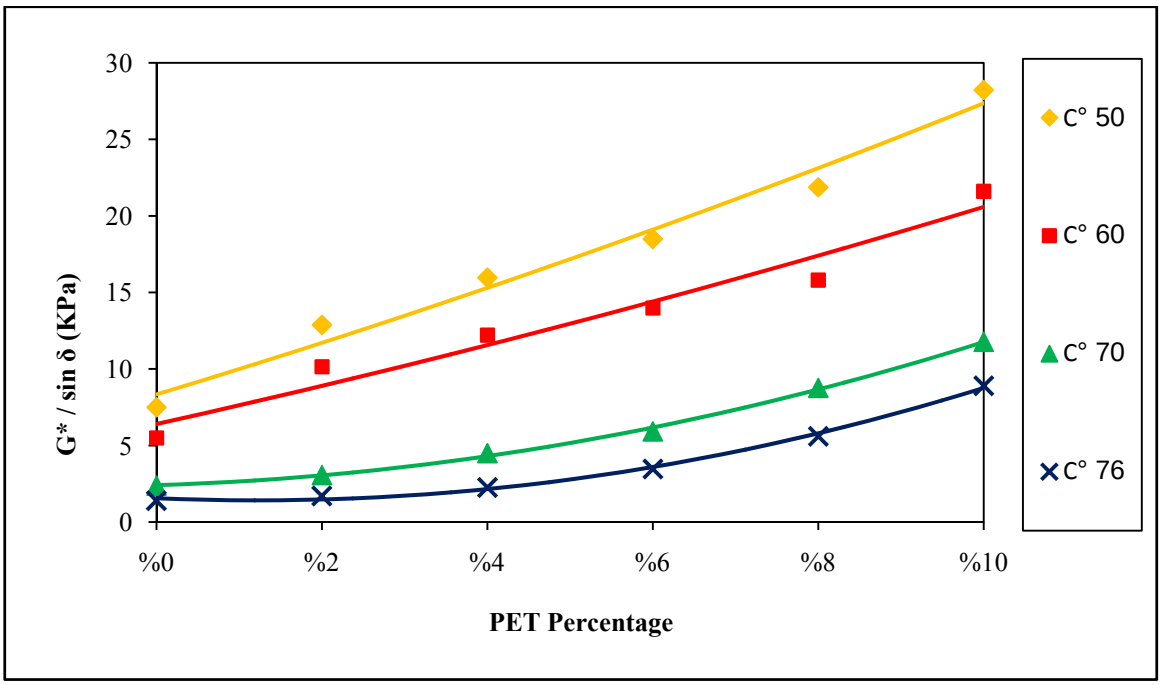

Figure 5.13 Complex Shear Modulus Elastic vs. Different Portion of PET @ Four Different Temperatures

5.8 D.S.R – SOFTENING POINT RELATIONSHIP

Figures 5.14, 5.15, 5.16 and 5.17 show plotted G*, δ, Tan δ and G*/Sin δ versus the softening point respectively for all the binders. Figures 5.14 and 5.17 show an increase in G* and G*/Sin δ respectively as softening point increases, while the figures 5.15 and 5.16 show a decrease in δ and Tan δ as the softening point increases.

The increase in G* means that the resistance of the binder to the deformation when sheared increases. From the Figure 5.14 we see that as the softening point increases which means that the binder is stiffer and harder, the G* increases therefore binder is less susceptible to be deformed.

From the Figures 5.15 and 5.16, we see that as the softening point increases there is a

decreasing in both of δ and Tan δ, decreasing the δ means that the binder became more elastic than viscous. Thus the increasing of softening point is followed by more elastic behaviour of the binder, which can be understood by a less susceptibility of the binder to flow and this is logical in terms of binder properties comparing to softening point data.

It is interesting to see what is the relation between rutting parameters Tan δ and G*/Sin δ with the softening point, for that purpose the Figures 5.16 and 5.17 are plotted. Table 5.8 presents G*/Sin δ data. The strategic highway research program (SHRP) parameter G*/sin δ is used as an indicator of rut (deformation) resistance. The parameter Tan δ is equivalent to the (energy absorbed/cycle or pulse) / (energy stored elastically/cycle or pulse) might be expected to be a good predictor of rutting rate (Oliver et al., 1996). For the figure 5.17 the increase means that the rut resistance increase as the softening point increase. This is similar to complex shear modulus result since it depends on that.

Material with high value of Tan δ are predominantly viscous, and deformation under loading will not be recovered and rutting will happen (Oliver et al., 1996). Figure 5.16 clearly shows that with increasing softening point and percentage of PET in binder Tan δ decrease therefore resistance to rutting increases. Fernandes et al. (2008) has found similar result with modifying the SBS with bitumen.

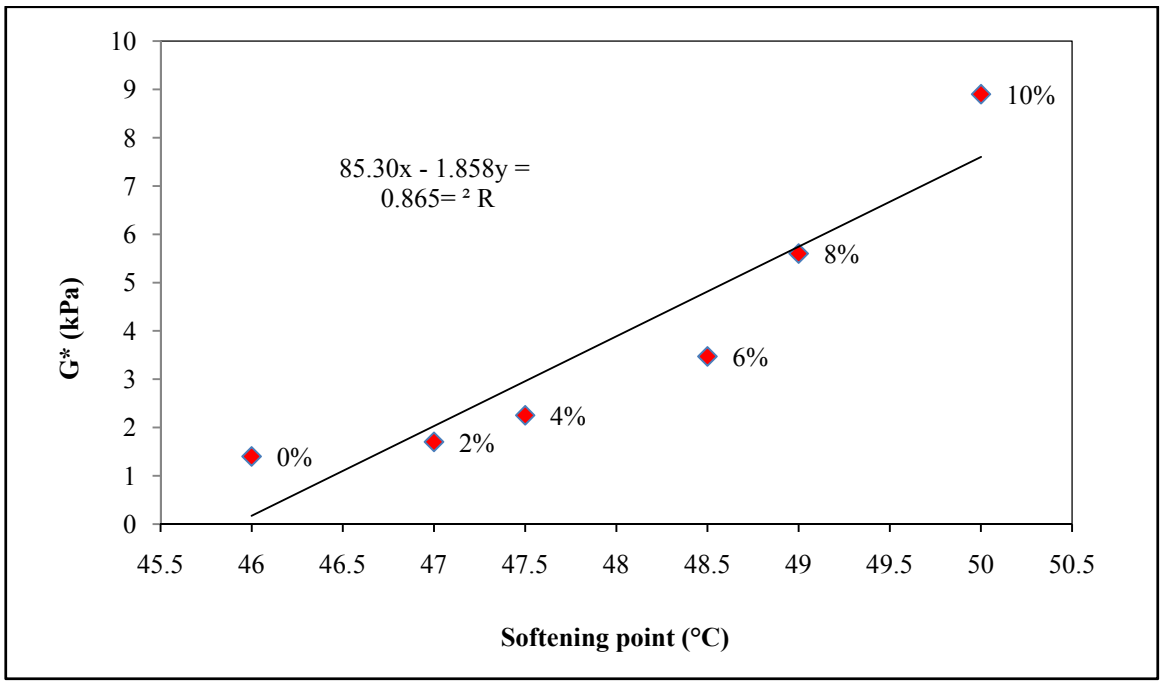

Figure 5.14 Complex shear modulus @ 76 °C vs. Softening Point

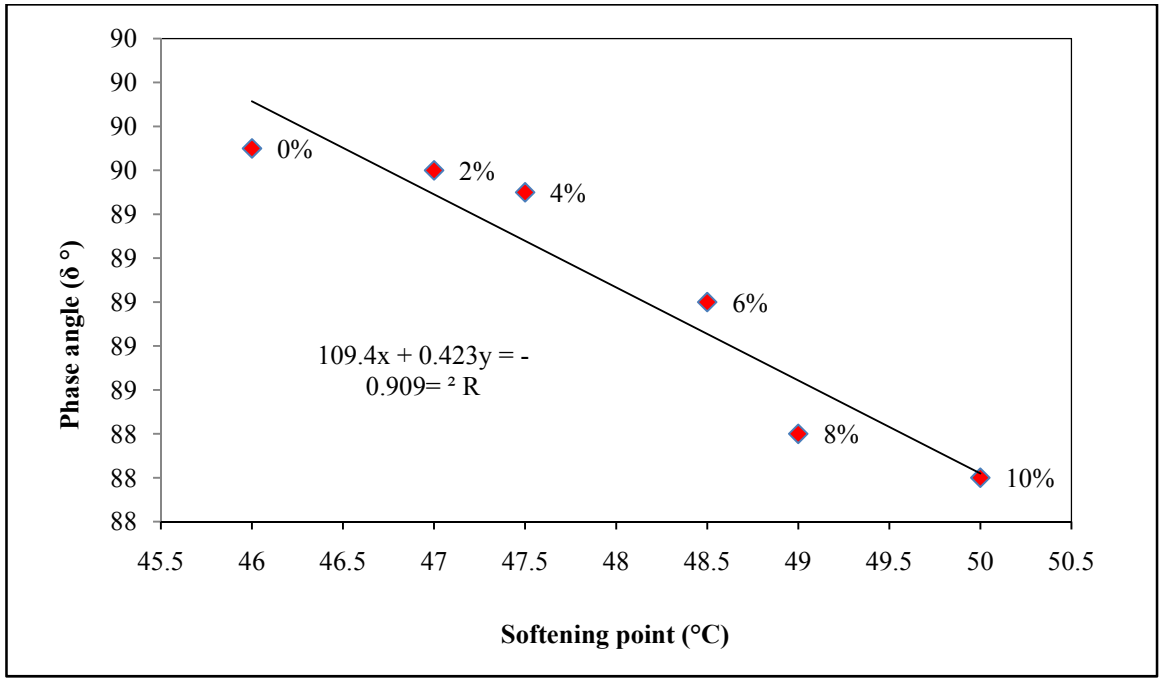

Figure 5.15 Phase Angle @ 76 °C vs. Softening Point

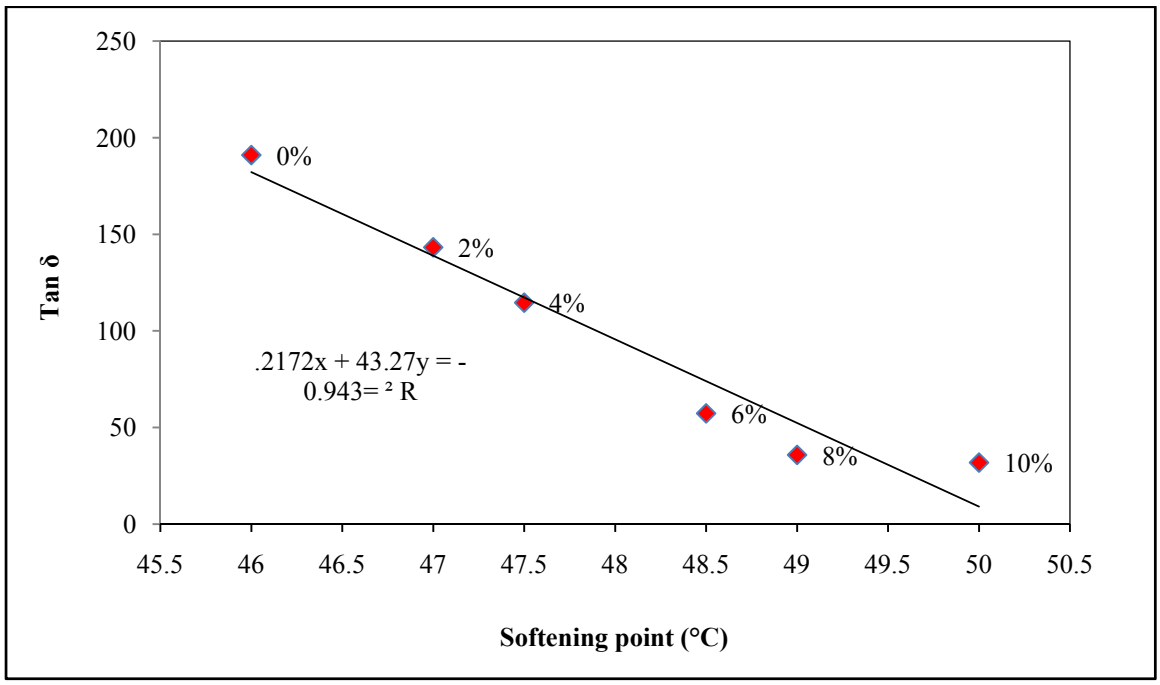

Figure 5.16 Tan Phase Angle @ 76 °C vs. Softening Point

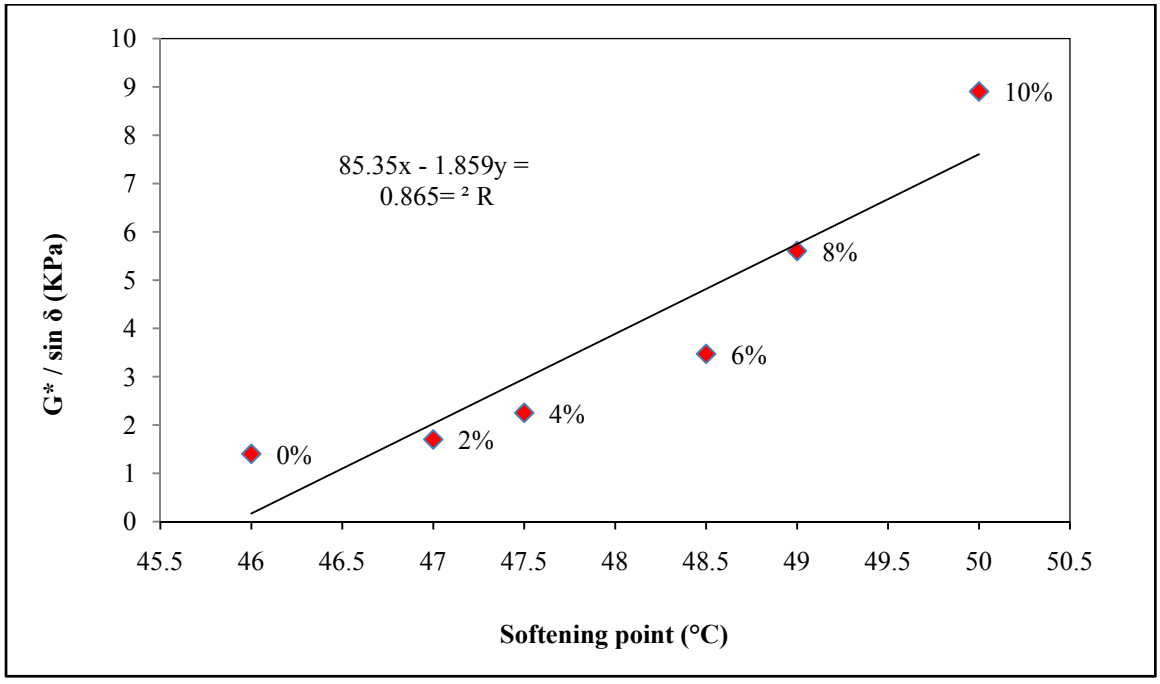

Figure 5.17 Complex Shear Modulus Elastic Portion vs. Softening Point

CHAPTER 6: MIX TESTS RESULTS AND ANALYSIS

6.1 INTRODUCTION

This chapter discusses the results of the indirect tensile test (IDT) and Marshal test. The incorporation of PET into the bituminous binders has been found to alter the rheological properties of the bitumen. PET contents effects on the binder properties were determined using data from the standard tests which has been dealt with in chapter 5. Investigation on the properties of PET bituminous mixes is necessary and is a complementary to those binder properties.

The indirect tensile test can be considered as the most convenient tool for measuring the stiffness modulus of bituminous mixtures in the laboratory. One of the material stiffness test is the resilient modulus test (M_R). In 1807 Thomas Young published the concept of elastic modulus that's why it is sometimes called as Young's modulus. An estimate of a material modulus of elasticity is its resilient modulus (Pavement Interactive).

It can be measured for all solid material and show a constant ratio of strain and stress. An elastic material is one that has the ability of returning to its original size or shape after being release from the load or pressure. All materials can be elastic to some degrees if the load or pressure does not cause permanent deformation. Basically the modulus of elasticity (E) of any material is the slope of its strain-stress plot within the elastic range therefore the flexibility of any structure or material depends on its geometric shape and elastic modulus (Pavement Interactive).

Marshall test is a laboratory semi-empirical method. Around 1939 Bruce Marshall of the Mississippi Highway Department developed the basic concepts of the Marshall mix design method and then refined by the U.S. Army. The Marshall method seeks to select the asphalt binder content at a desired density that satisfies minimum stability and range of flow values (Pavement Interactive). The mechanical properties of the Marshall test which are stability and flow do not directly measure fundamental properties. They provide empirical relationships that have been found to correlate with asphalt mixes. (AAPA National asphalt specification 2nd edition April 2004).

6.2 THE INDIRECT TENSILE TEST RESULTS (IDT)

In pavement industry the resilient modulus test typically is used to design the sub-base and base layers of pavement under repetitive loads. One of the most important characters of the base and sub-base layers performance is its stiffness. The mechanical performance of pavement structure depends on aggregate materials and the stiffness of sub surface. Therefore the modulus of subgrade, base course and sub-base layers of pavement structure must be characterized (Schuettpelz et al., 2010).

This test is a fundamental measure of the load-spreading ability of the bituminous layers. It controls the level of traffic induced tensile strains at the underside of the base and the compressive strains induced in the subgrade. Tensile strains at the base are responsible for fatigue cracking and compressive strains can lead to permanent deformation in asphalt.

6.2.1 Effect of PET Content on the Resilient Modulus

The laboratory results on the resilient modulus by using ASTM D4123-82 carried out by using UMATTA machine at the temperature of 25 °C are presented in Table 6.1 and Figures 6.1 and 6.2.

From the Figure 6.2 it is noted that the 6% PET modified bituminous mixes have the highest modulus values and this is true for the all binder content in mix. This means that by using PET in the bituminous mix the resilient modulus of mix increases. Hence it increases the resistance to flow and rutting, therefore improve the resistance to deformation of the bituminous mix and increase the adhesion.

Resilient modulus of the mixes with more than 6% PET decreases with increasing the PET portion. This phenomenon may be led to the decreases in the adhesion.

From Figure 6.1 it is apparent that in 5% binder content by weight of aggregate all the mixes have the maximum stiffness modulus. There is an increase in resilient modulus (stiffness) as the binder content increase up to an optimum value. Further addition of the binder content resulted in decreasing resilient modulus. The properties of PET mixtures at the optimum condition showed that modified mix with 2%, 4% and 6% of PET by weight of bitumen had higher stiffness modulus than the unmodified mix. It revealed that with 6% PET in the 5% binder mix enhanced the stiffness properties of mix by about 17.6% as compared to control mix. Rutting, fatigue, and low temperature cracking are three major distresses mechanism.

Many research works have been conducted to relate the asphalt pavements performance to the tensile strength of asphalt mixtures (Rogue et al., 1999) and (Zhang et al., 2001). In

2005 Tayfur et al. investigate using LDPE as a modifier in bituminous mixes and the results show that quality of mix and bitumen binder properties is improved. They concluded that in modified binders and modified mixtures the indirect tensile strength values were much higher than the control mix. This means that under static loading the mixtures modified with polymer additives have higher values of tensile strength at failure indirect tensile strength. This would further imply that modified mixtures appear to be capable of withstanding larger tensile strains prior to cracking.

Simpson et al. (1994) studied on bituminous mixtures modified with polymers, polyester fibers and polypropylene in Somerset, Kentucky. Two proprietary blends of modified binder were also evaluated. An unmodified mixture was used as a control sample. Indirect tensile strength test results show that the control mix and polypropylene mixtures are more resistance against thermal cracking and the samples containing polypropylene fibers have higher resistant to cracking due its higher tensile strengths.

Statistical analysis using two factor ANOVA at a confidence level of 95% has been carried out on IDT test result. According to the IDT ANOVA test result, F-ratio value for both PET content and binder content is much higher than F-critical and also P-value is much lower than 0.05 which satisfy the alternate hypothesis (H_a). A summary of ANOVA results is given in Appendix B.

Table 6.1 Resilient modulus results (MPa)

Binder content	Percentage of PET					
	0%	2%	4%	6%	8%	10%
4.5%	5505	5568	4746	6262	4323	3398
4.5%	5254	6099	4977	6281	5355	4642
4.5%	3860	5583	6894	5864	4663	4975
4.5%	5326	4492	5994	6584	4149	4018
5%	5695	6286	6135	7442	5198	4940
5%	4934	6807	6265	5877	4560	5190
5%	6274	4934	5458	6463	4585	4879
5%	5108	5166	6546	6145	7018	5068
5.5%	4726	4874	4979	5418	4786	4081
5.5%	4235	5266	5274	5702	4238	4118
5.5%	4297	5581	5127	6509	4246	4042
5.5%	4341	4663	5153	5881	4200	4604
6%	3941	4487	4958	5278	3627	3891
6%	3876	4864	4327	5863	4084	3807
6%	4051	5008	4875	4574	4953	3672
6%	4628	4198	5186	6252	3820	3336

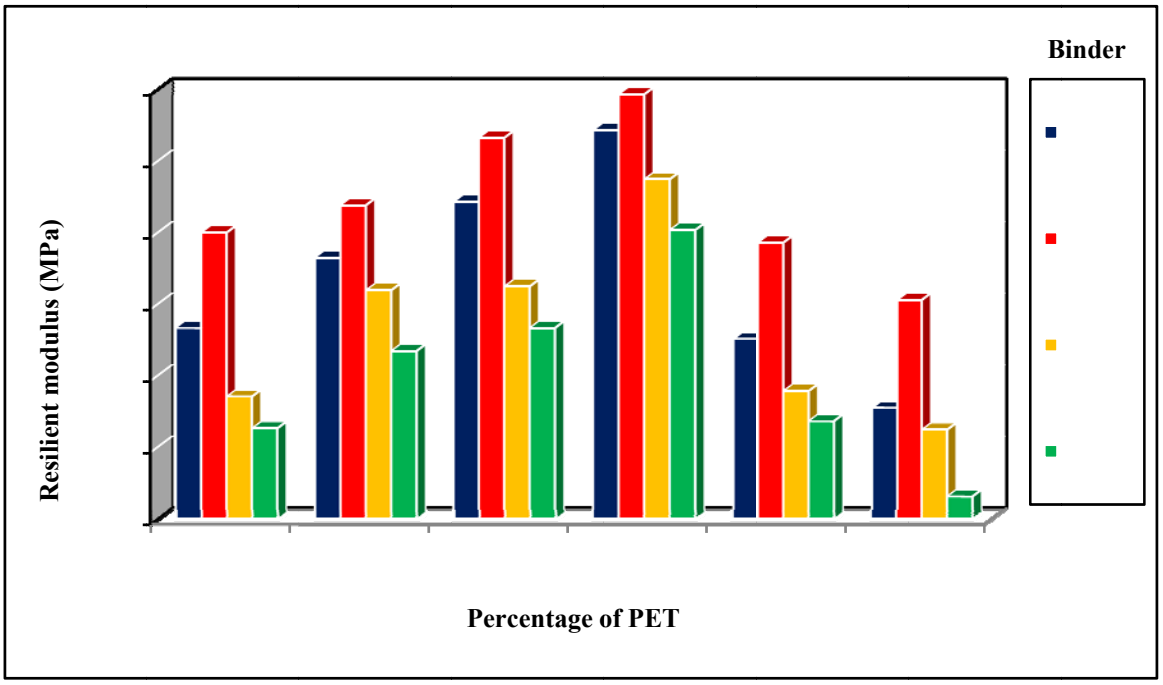

Figure 6.1 Resilient Modulus vs. Percentage of PET

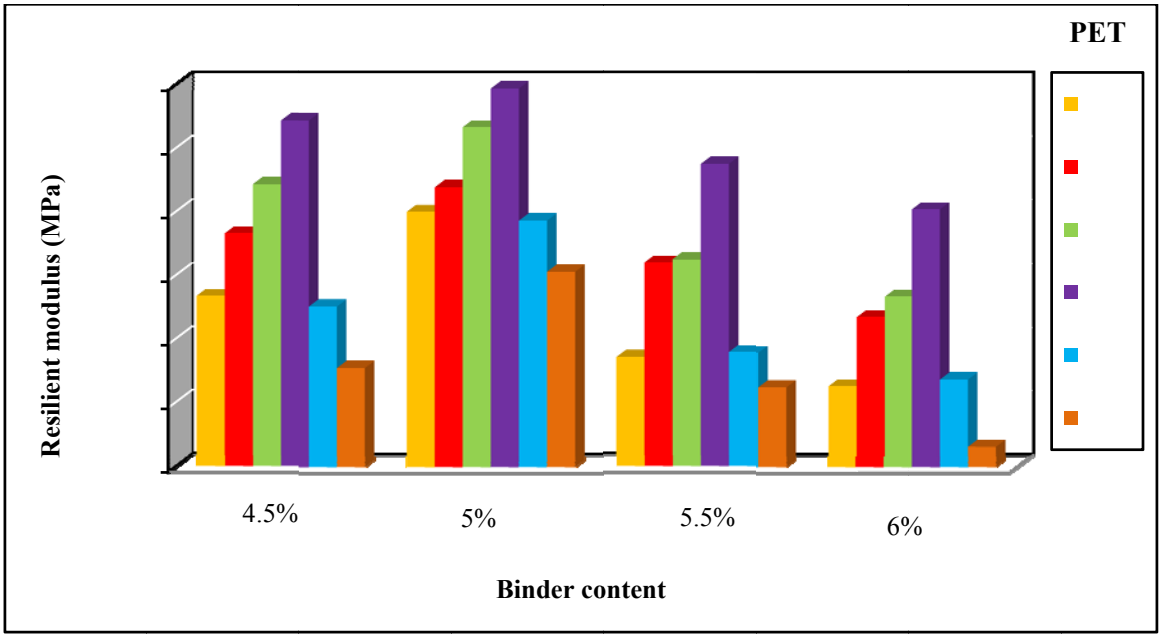

Figure 6.2 Resilient Modulus vs. Binder Content

6.3 THE MARSHAL TEST RESULTS

6.3.1 Marshall Stability

The Marshall stability values for four different binder content and six different PET portion in mix are presented in Table 6.2. Figure 6.3 shows the plot of Marshall stability versus PET portion, and Figure 6.4 shows the plot of Marshall stability versus binder content. In all samples the stability value increases as the binder content increases up to an optimum value, and with further addition of binder causes in decreasing of the stability value. It is noticed that the maximum stability value require different amount of bitumen in mixes. The stability in all mixes increases with increasing the PET content until a certain percentage and with addition of waste PET it decreases. The decreases in stability while increasing

PET content may be attributed to the decrease in the adhesion between aggregate and bitumen.

Previous researches also obtained that PMA stability is higher than control mixture. Hinisliglu and Agar (2004) have investigated on use of waste high density polyethylene as bitumen modifier in asphalt concrete mix and they achieved similar results. Tapkin (2008) investigated the effect of polypropylene fibers on asphalt performance. This study presented that stability and flow have significantly improved by 58% increase and 142% decrease respectively which may help the pavement industry to generate high performance paving products. Sengoz and Isikyakar's (2008) study presented a laboratory work on bitumen modified with ethylene vinyl acetate (EVA) copolymers and styrene–butadiene–styrene (SBS). In their report they concluded that the stability of mixtures modified with SBS is higher compared to the stability of the control mix. The stability test results of mixtures modified with EVA did not correlate well with the conventional bitumen tests conducted on EVA polymer modified asphalt.

To check the statistical significance of the Marshall stability results, two factor ANOVA analyses was carried out. F-ratio of PET content is 25.5 which is higher than F-critical of 2.90 and its P-value is 7.82E-07 which is much lower than 0.05. For binder content the F-ratio is 38.58 which is higher than F-critical of 3.29 and its P-value is 2.73E-07 which is much lower than 0.05. This result satisfies the alternate hypothesis (H_a). A summary of ANOVA results is given in Appendix B.

Table 6.2 Marshall stability results (KN)

PET %	Binder content 4.5%	5.0%	5.5%	6.0%
0%	9.80	10.70	12.10	11.30
2%	10.20	11.00	12.30	12.00
4%	10.90	11.20	12.60	11.90
6%	11.30	11.60	13.60	13.00
8%	9.80	10.50	11.20	10.90
10%	9.60	10.20	10.80	10.00

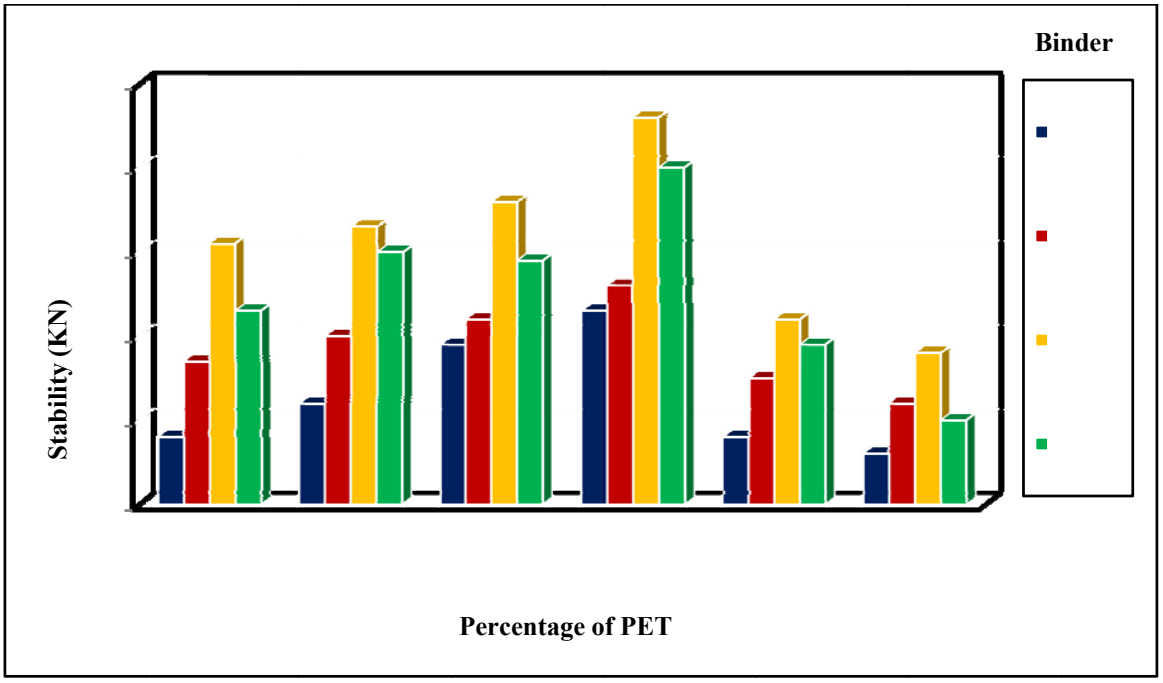

Figure 6.3 Marshall Stability vs. Percentage of PET

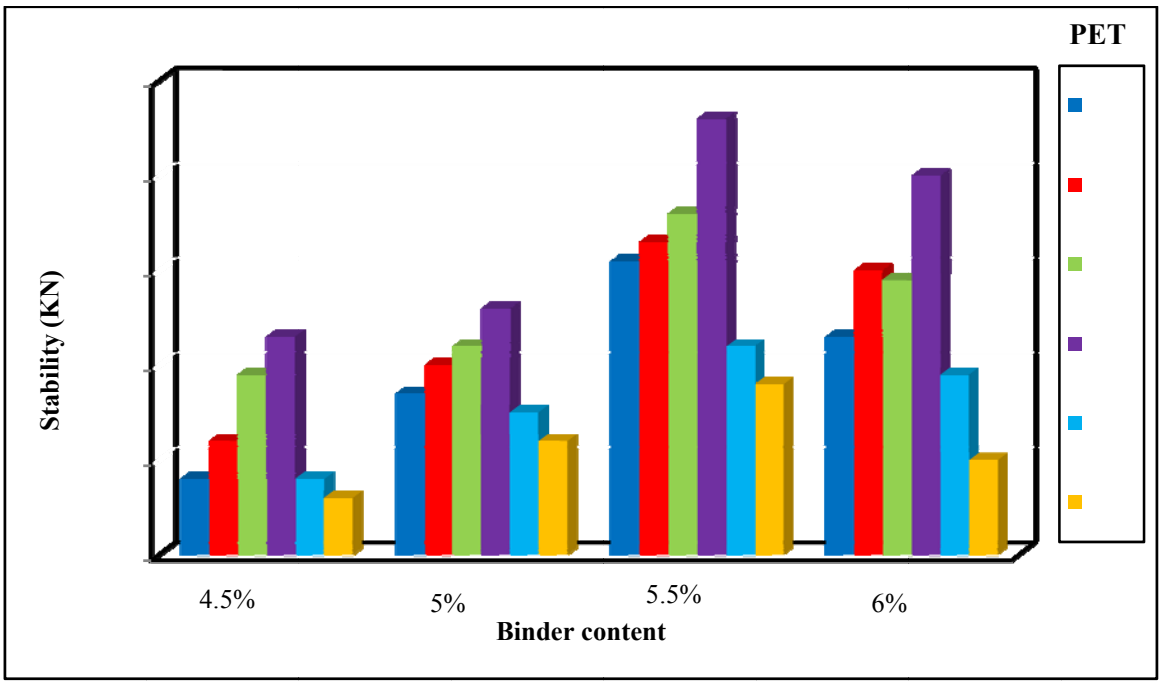

Figure 6.4 Marshall Stability vs. Binder Content

6.3.2 Marshall Flow

The Marshall flow values results followed a special trend. The results are tabulated in Table 6.3. Figures 6.5 and 6.6 show that flow values increase with increasing binder content with 0% PET. The addition of 2% PET increases the flow value for all binder content compare to the conventional samples, but increasing the PET portion up to 8% the flow decreases. In all modified samples the lowest flow happens at 5.5% binder content. The highest flow belongs to 6% binder content unmodified sample and the lowest one is for the 8% PET modified 5.5% binder content. The flow value decrease in 8% PET modified 5.5% binder content is approximately 17%. Hence it appears that adding PET to the mix has a remarkable effect in decreasing the flow of the mix.

Tapkin (2008) and Haddadi et al. (2008) showed similar result in their studies. In Haddai et al. (2008)'s work, the flow decreases by increasing the EVA content but this trend is reversed since the EVA content reached 7%. Then, the flow values become higher than the control specimen.

Statistical analysis using two factor ANOVA at a confidence level of 95% has been carried out on Marshall flow test result. ANOVA test result shows that, F-ratio value for PET content and binder content is 9.56 and 8.60 respectively and both are higher than the F-critical and also P-value is much lower than 0.05 which satisfy the alternate hypothesis (H_a). A summary of ANOVA results is given in Appendix B.

Table 6.3 Marshall flow results (mm)

PET %	Binder content 4.5%	5.0%	5.5%	6.0%
0%	3.37	3.43	3.57	3.85
2%	3.83	3.80	3.55	3.80
4%	3.43	3.40	3.40	3.77
6%	3.33	3.40	3.33	3.50
8%	3.35	3.23	3.20	3.55
10%	3.40	3.37	3.27	3.47

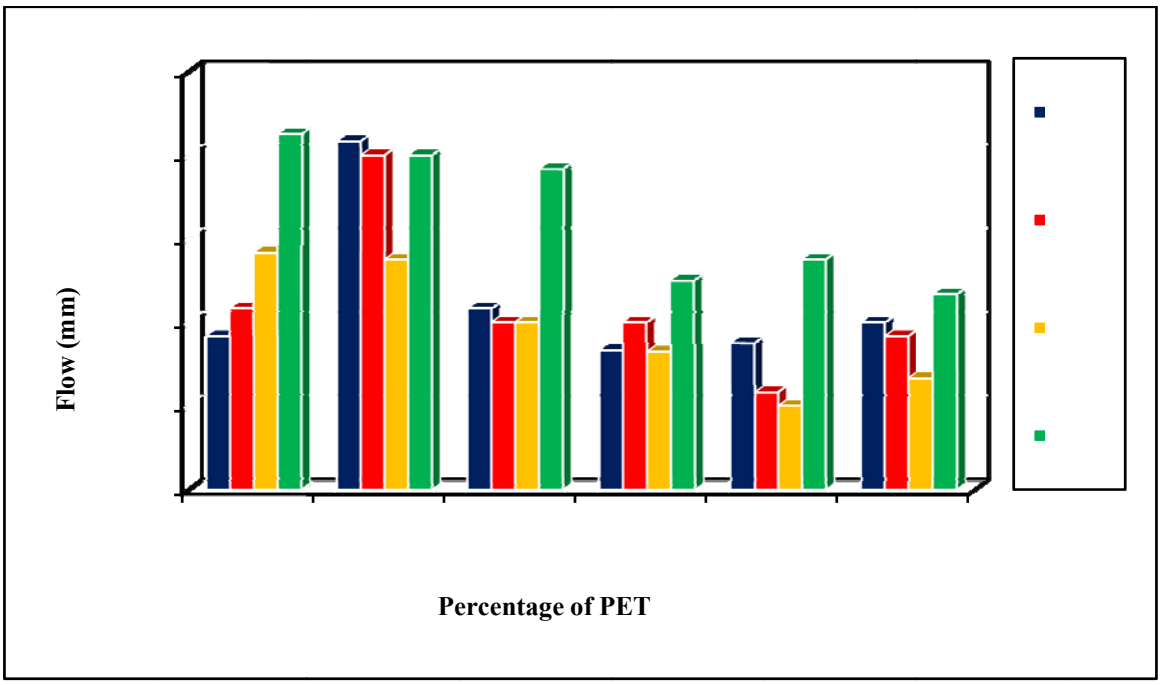

Figure 6.5 Marshall Flow vs. Percentage of PET

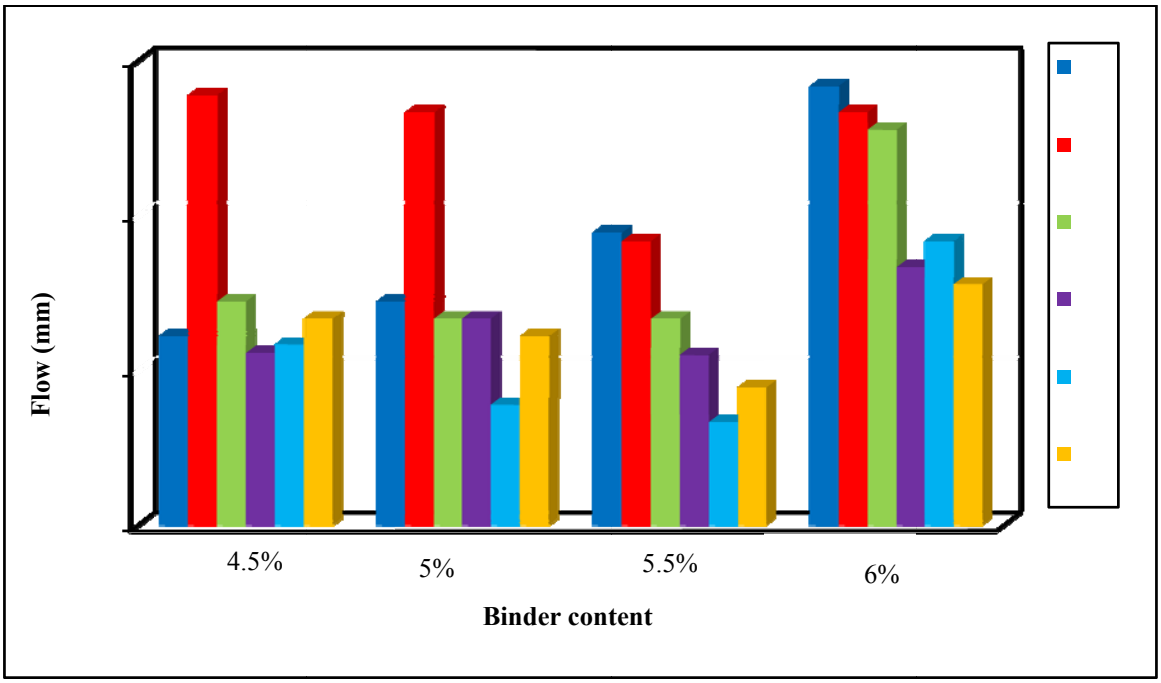

Figure 6.6 Marshall Flow vs. Binder Content

6.3.3 Density of the Compacted Mix (CDM)

In general adding a certain amount of PET to a mix increase CDM to its maximum level and adding more PET will have an opposite effect in the properties of the mix.

Data in Table 6.4 indicate that both PET content and binder content influence the compaction characteristics of the mix, thus having a significant effect on the mix density. Figures 6.7 and 6.8 show that for any specific PET content, the density of the compaction mix progressively increases as the bitumen content of the mix increases. This is due to the bitumen filling in the void space of the aggregate particles.

Statistical analysis using two factor ANOVA at a confidence level of 95% has been carried out on CDM test results. According to the ANOVA test result, F-ratio value for PET content is 14.19 and for binder content is 41.87, which are both higher than their F-critical of 2.90 and 3.29 respectively and also P-value is much lower than 0.05 which satisfy the alternate hypothesis (H_a). A summary of ANOVA results is given in Appendix B.

Table 6.4 Density of the compacted mix (CDM) results (g\ml)

PET %	Binder content 4.5%	5.0%	5.5%	6.0%
0%	2.23	2.26	2.27	2.29
2%	2.23	2.28	2.31	2.33
4%	2.26	2.30	2.32	2.34
6%	2.28	2.29	2.29	2.33
8%	2.24	2.26	2.28	2.29
10%	2.23	2.25	2.27	2.28

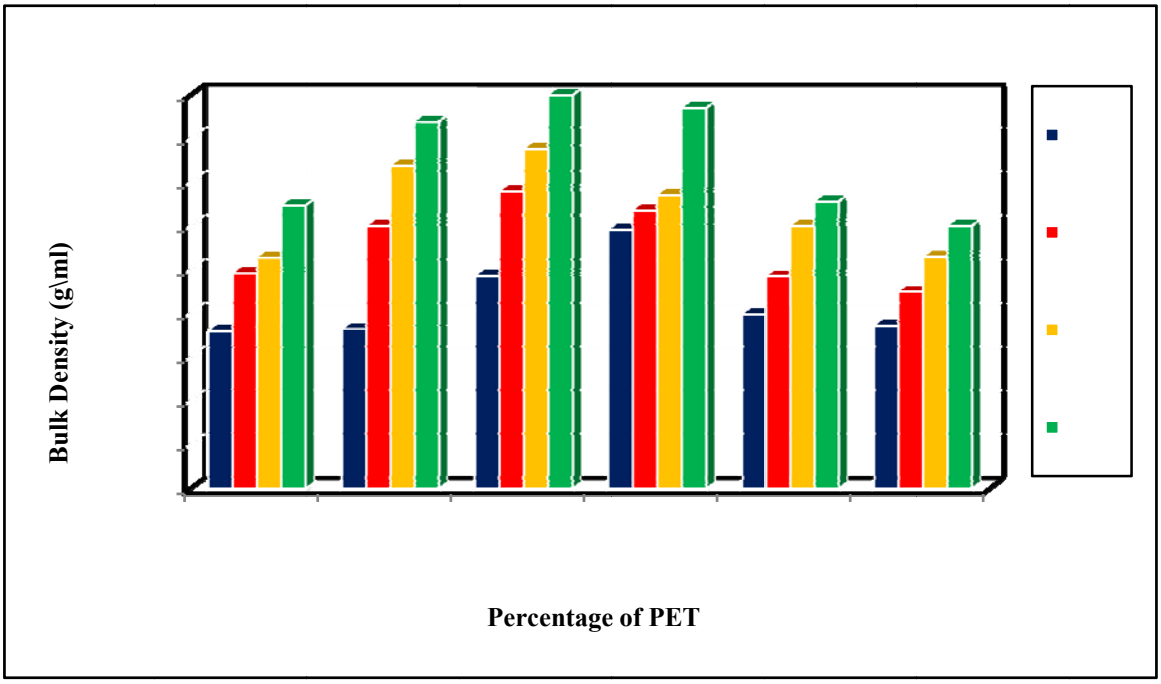

Figure 6.7 Bulk Density vs. Percentage of PET

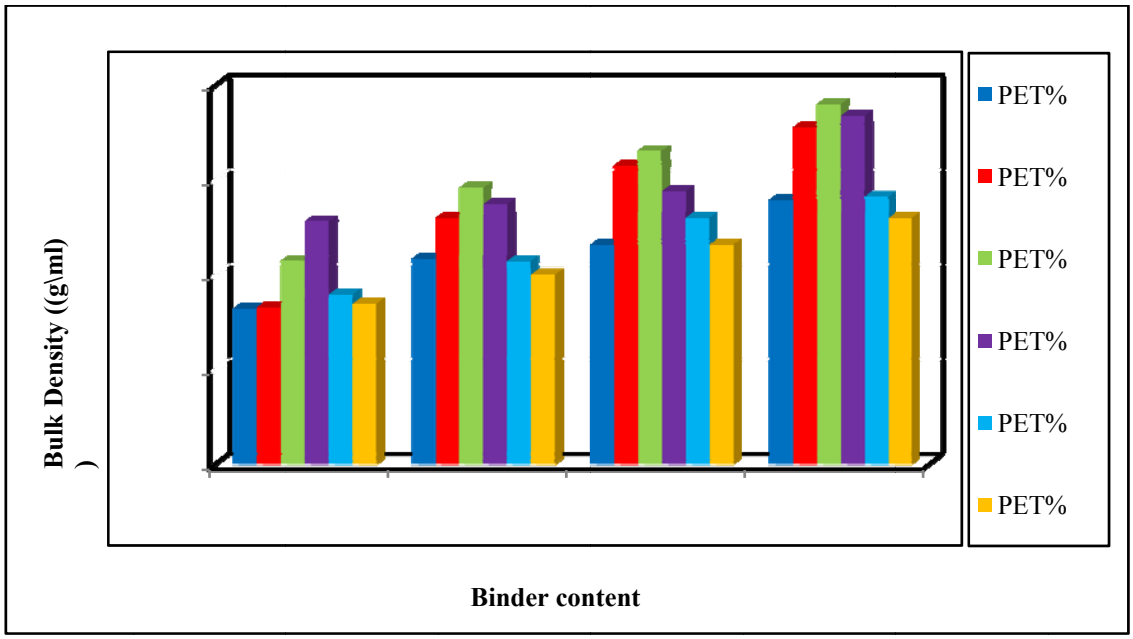

Figure 6.8 Bulk Density vs. Binder Content

6.3.4 Void in the Mix (VIM)

The durability of the bituminous mix has a relationship with the voids in the mix (VIM) or porosity. The lower the porosity, the more durable is the mix and vice versa. Higher porosity will provide passageways through the mix for entrance of air and water. Too low porosity can lead to flushing where the excess bitumen flow out of the mix to the surface. Therefore the mix should be low enough in voids to be durable and impermeable and high enough to prevent the bitumen pumping under the action of traffic and high temperature.

Figures 6.9 and 6.10 show the effect of the PET content and binder content on the porosity of the mix. Generally for any PET content, with increasing the binder content, the VIM decreases. This is due to the presence of the big amount of binder which fills all the voids between aggregates. In Figure 6.9 for any binder content, increasing the PET content cause decrease in voids until a certain point and adding more PET shows opposite results. This is because after a certain amount of PET the contact point between aggregates becomelower and also the PET absorb the bitumen that the mix needs to fill the voids between aggregates. The Marshall flow results is presented in Table 6.5.

Statistical analysis using two factor ANOVA at a confidence level of 95% has been carried out on VIM test results. F-ratio of PET content is 13.20 which is higher than the F-critical of 2.90 and its P-value is 4.78E-05 which is much lower than 0.05. For binder content, the F-ratio is 144.61 which is higher than F-critical of 3.29 and its P-value is 2.72E-11 which is much lower than 0.05. These results satisfy the alternate hypothesis (H_a). A summary of ANOVA results is given in Appendix B.

Table 6.5 Void in the mix (VIM) results

PET %	Void in the mix (%) Binder content 4.5%	5.0%	5.5%	6.0%
0%	10.41	8.67	7.71	6.06
2%	10.18	8.33	6.00	5.33
4%	9.40	7.17	5.69	5.03
6%	8.56	7.51	6.55	5.23
8%	10.11	8.74	7.33	5.99
10%	10.31	9.02	7.70	6.47

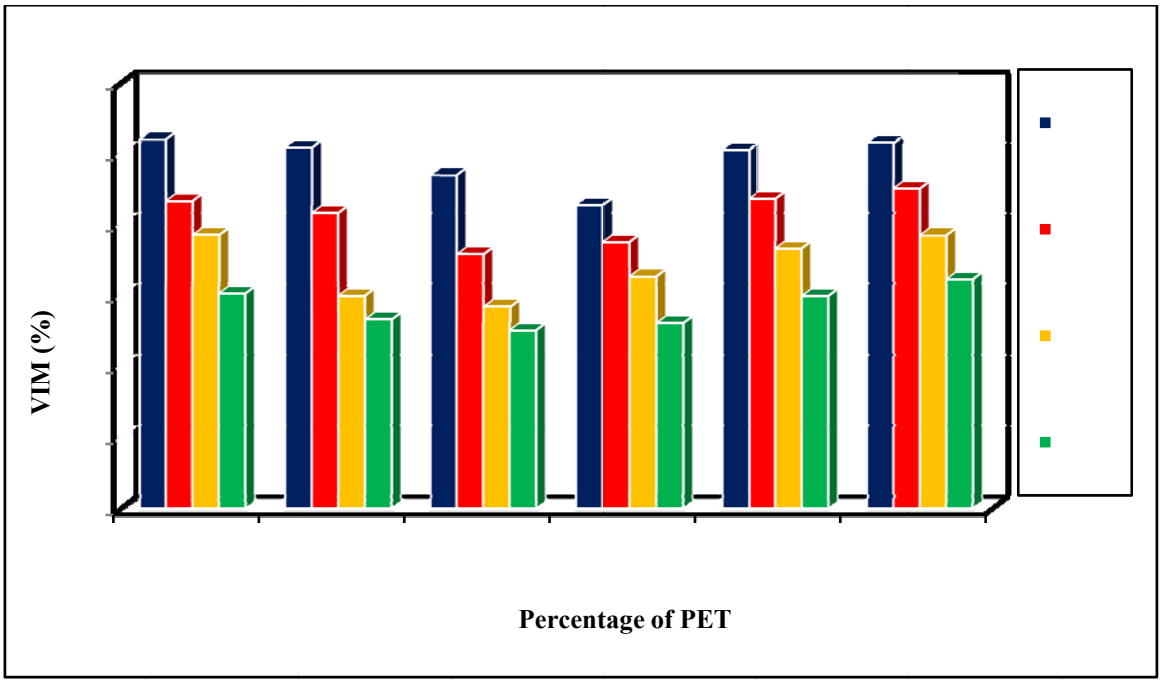

Figure 6.9 Voids in Mix vs. Percentage of PET

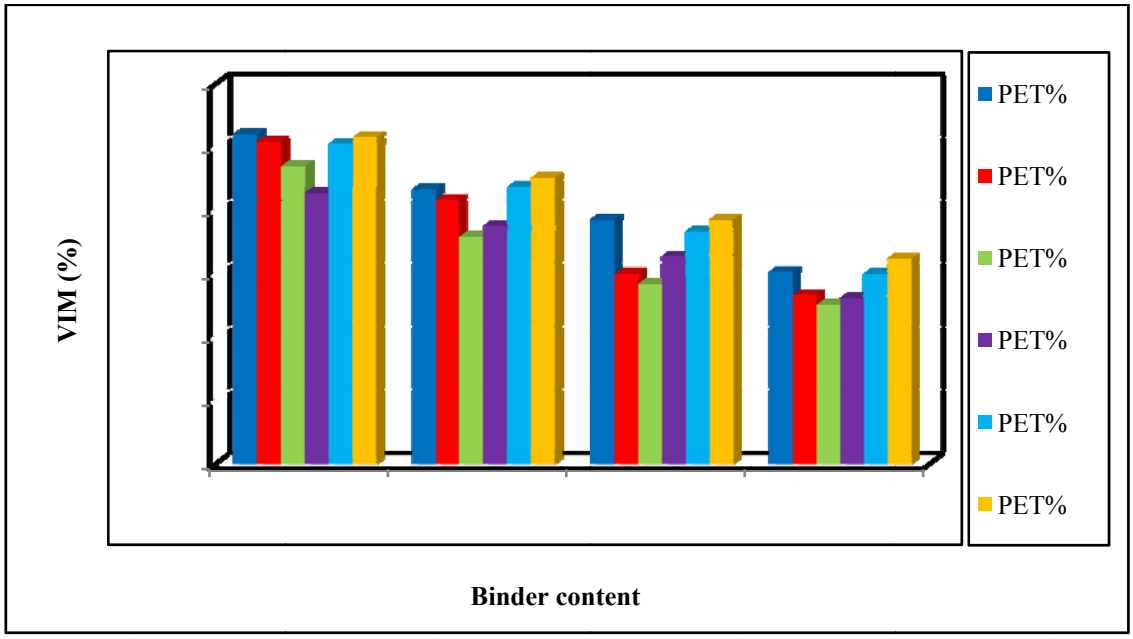

Figure 6.10 Voids in Mix vs. Binder Content

6.3.5 Optimum Binder Content

From the test parameters, the optimum binder contents (OBC) obtained for the mixes with different PET contents is tabulated in Table 6.6. It is evident that the PET incorporated mixture exhibited a greater demand for the bitumen at the optimum condition. Each of the modified mixtures has higher optimum binder content than the control.

Table 6.6 Optimum binder content results

	Percentage of PET					
	0%	2%	4%	6%	8%	10%
OBC %	5.3	5.6	5.6	5.6	5.6	5.6

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDIES

7.1 CONCLUSIONS

From the analysis of the various tests results, the following conclusions can be derived.

7.1.1 Effect of PET Content in the Binders

The effect of the PET content was very noticeable in most of the tests. Especially with higher percentage of PET which resulted greater difference than the lower portions. As ANOVA test result shows, the effect of PET on the penetration and softening point of binder is very significant. F-ratio in penetration ANOVA result is 11 times higher than F critical and in softening point is almost 7 times bigger which means the data has a significant difference.

The difference in viscosity test and dynamic shear rheometer tests are less significant than in penetration and softening point tests.

Binder tests results showed that adding PET to bituminous binder resulted in a decrease of penetration and an increase in softening point and viscosity. This indicate that the PET modified bituminous binder is stiffer and more resistant to flow as compared to normal bitumen.

From the visco-elastic properties, generally as the PET content increases the complex shear modulus G* increases and the phase angle δ decreases.

7.1.2 Relationship between the Binder Properties

A good relationship was found between the viscosity and softening point data. The viscosity of the modified binder increases due to binder content, followed by the increase in the softening point. The relationship is almost linear between the two properties.

There is also a linear relationship between softening point and G*. As the softening point increases which means that the binder is stiffer and harder, the G* increases therefore binder is less susceptible to be deformed.

Results showed that as the softening point increases there is a decrease in both of δ and tan δ, decreasing the δ means that the binder became more elastic than viscous. Thus the increasing of softening point is followed by more elastic behaviour of the binder, which can be understood by a less susceptibility of the binder to flow and this is logical in terms of binder properties compared to softening point data.

Relation between rutting parameters, Tan δ and G*/sin δ, with the softening point shows that with increasing softening point and percentage of PET in binder Tan δ decrease therefore resistance to rutting increases.

7.1.3 Effect of PET Content on the Mix

The incorporation of the PET in bituminous mixes increased the stability of the mix, lower Marshall flow exhibited than the normal specimen. Marshall stability and flow improved gradually as the PET content increased.

The data obtained at the optimum condition showed that the modified mixes had slightly higher than the control. Since in ANOVA test F-ratio is much higher than F critical in all tests, it is clear that PET content has a significant effect on the mix stiffness modulus.

Generally adding a certain amount of PET to a mix increases CDM to its maximum level and decrease VIM to its minimum level. Addition of more PET into the mix will have opposite effect of decreasing CDM and increasing VIM values.

Modified binder with 6% PET content showed better and higher quality performance compare to other samples

7.1.4 Environmental and Economical Considerations

While planning any pavement project, any possible effect of using waste materials on environment have to be considered. These effects could be the effects of constructing and using pavements, as well as the effects of preparing the materials for use. Investigations have been conducted into the environmental effects of many waste materials during pavement applications. Many of these materials are considered as hazardous material when used in non pavement applications or stockpiled so they require special consideration.

From economical point of view using waste material in road construction and pavement is beneficial in different ways. It can be obtained by improving the performance of pavement or from reduced landfills. Consideration must be given to the effect that waste materials may have on pavement once it deteriorates to the point of requiring rehabilitation.

Most of the cost savings are only claimed on initial and not on the life-cycle analysis. The accurate cost saving assessment for life-cycle is difficult for most waste materials because there are only few numbers of particular material applications. True life-cycle analysis must include the initial cost, increased performance, and the effects of the waste-material recyclability of the pavement materials at the conclusion of its useful life.

7.2 RECOMMENDATION FOR FUTURE STUDIES

Valuable materials for pavement construction can be produced by using recycled waste materials. In this application various types of waste materials are currently being and have been used. But still to recognize the best usage of different wastes and find a best way to apply them in pavement structure is a big challenge.

For future improvements of this study, the following suggestions are recommended:

1 The use of different penetration grade bitumen,

2 Use of aged bitumen and compare the result with normal bitumen The use of different types of aggregate and gradations

3 The use of different mixing method such as dry and wet and different mixing equipment and compare the results

4 Selecting other type of waste polymers as a modifier and different size and gradation

5 Using PET chips as a aggregate in the mix in order to have a light asphalt

6 Selecting different type of waste material for use in pavement such as waste cooking oil, waste glass, etc.

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APPENDIX A

AGGREGATE GRADATION

And

GRADATION OF PET IN THE MIX

Aggregate proportion for ACW14 specimen

B.S SIEVE	PASSING %	RETAIN %	WAIGHT (gm)
20	100	0	0
14	87.5	12.5	140.6
10	79	8.5	95.6
5	62	17	191.3
3.35	53.5	8.5	95.6
1.18	37.5	16	180
425	23.5	14	157.5
0.150	11.5	12	135
0.075	7	4.7	50.6
PAN	0	7	78.8
Total		100	1125

Gradation of PET

Sieve size	Percent passing
701 µm	100
450 µm	0

Performance Graded Asphalt Binder Specification (from AASHTO MP 1)

Performance Grade	PG 46			PG 52							PG 58					PG 64						PG 70						PG 76					PG 82				
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40	10	16	22	28	34	40	10	16	22	28	34	40	10	16	22	28	34	10	16	22	28	34
Average 7-day Maximum Pavement Design Temperature, °C[a]	< 46			< 52							< 58					< 64						< 70						< 76					< 82				
Minimum Pavement Design Temperature, °C[a]	-34	-40	-46	-10	-16	-22	-28	-34	-40	-46	-16	-22	-28	-34	-40	-10	-16	-22	-28	-34	-40	-10	-16	-22	-28	-34	-40	-10	-16	-22	-28	-34	-10	-16	-22	-28	-34
ORIGINAL BINDER																																					
Flash Point Temp, T 48, Minimum (°C)	230																																				
Viscosity, ASTM D 4402:[b] Maximum, 3 Pa*s, Test Temp, °C	135																																				
Dynamic Shear, TP 5:[c] G*/sinδ[f], Minimum, 1.00 kPa Test Temp @ 10 rad/s, °C	46			52							58					64						70						76					82				
ROLLING THIN FILM OVEN RESIDUE (T 240)																																					
Mass Loss, Maximum, percent	1.00																																				
Dynamic Shear, TP 5: G*/sinδ[f], Minimum, 2.20 kPa Test Temp @ 10 rad/s, °C	46			52							58					64						70						76					82				
PRESSURE AGING VESSEL RESIDUE (PP 1)																																					
PAV Aging Temperature, °C[d]	90			90							100					100						100 (110)						100 (110)					100 (110)				
Dynamic Shear, TP 5: G*sinδ[f], Maximum, 5000 kPa Test Temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16	34	31	28	25	22	19	37	34	31	28	25	40	37	34	31	28
Physical Hardening[e]	Report																																				
Creep Stiffness, TP 1 Determine the critical cracking temperature as described in PP 42	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24
Direct Tension, TP 3 Determine the critical cracking temperature as described in PP 42	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24

a. Pavement temperatures are estimated from air temperatures using an algorithm contained in the LTPP Bind program, may be provided by the specifying agency, or by following the procedures as outlined in MP 2 and PP 28.

b. This requirement may be waived at the discretion of the specifying agency if the supplier warrants that the asphalt binder can be adequately pumped and mixed at temperatures that meet all applicable safety standards.

c. For quality control of unmodified asphalt binder production, measurement of the viscosity of the original asphalt cement may be used to supplement dynamic shear measuremments of G*/sinδ at test temperatures where the asphalt is a Newtonian fluid.

d. The PAV aging temperature is based on simulated climatic conditions and is one of three temperatures 90°C, 100°C or 110°C. The PAV aging temperature is 100°C for PG 58- and above, except in desert climates, where it is 110°C.

e. Physical hardening – TP 1 is performed on a set of asphalt beams according to Section 12, except the conditioning time is extended to 24 hours ± 10 minutes at 10°C above the minimum performance temperature. The 24-hour stiffness and *m*-value are reported for information purposes only.

f. G*/sinδ = high temperature stiffness and G*/sinδ = intermediate temperature stiffness

APPENDIX B

ANOVA TEST

RESULTS

ANOVA: Single Factor for Penetration Test

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Binder content	899.8	5	179.96	26.7	8E-13	2.409
Within Binder content	323.6	48	6.7407			
Total	1223	53				

ANOVA: Single Factor for Softening Point Test

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Binder content	48.96	5	9.79	19.18	1.2E-06	2.77
Within Binder content	9.18	18	0.51			
Total	58.15	23				

ANOVA: Two-Factor Without Replication for Viscosity Test

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Temperature 90	6	43739.5	7289.9	1710878.242
Temperature 110	6	9819.5	1636.6	106067.8417
Temperature 130	6	2837.5	472.92	18172.94167
Temperature 135	6	2127	354.5	9806.7
Temperature 150	6	969.25	161.54	6228.610417
Temperature 170	6	325.25	54.208	2160.010417
0% PET	6	8038.25	1339.7	5279425.46
2% PET	6	8492.75	1415.5	6034191.66
4% PET	6	9072.5	1512.1	6786876.042
6% PET	6	9656.5	1609.4	7564284.542
8% PET	6	11250.5	1875.1	10125420.64
10% PET	6	13307.5	2217.9	12970628.94

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Temperature	2.38E+08	5	5E+07	198.1524484	2.8706E-19	2.602987402
PET Content	3266050	5	653210	2.721471679	0.04268221	2.602987402
Error	6000522	25	240021			
Total	2.47E+08	35				

ANOVA: Two-Factor Without Replication for G*

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Temperature 30	6	1620.5	270.0833	8286.318307
Temperature 40	6	364.755	60.7925	459.1697775
Temperature 50	6	105.452	17.57533	53.15218517
Temperature 60	6	79.105	13.18417	29.19352417
Temperature 70	6	36.37	6.061667	12.95991417
Temperature 76	6	23.32	3.886667	8.377266667
Temperature 80	6	12.27875	2.046458	3.77859401
0% PET	7	162.165	23.16643	1851.931873
2% PET	7	298.9463	42.70661	6486.870453
4% PET	7	365.15	52.16429	9533.613929
6% PET	7	418.6995	59.81421	12272.5988
8% PET	7	455.62	65.08857	14188.67838
10% PET	7	541.2	77.31429	18204.27196

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	343420.2	6	57236.71	53.98406564	9.66E-15	2.42052319
Columns	12457.19	5	2491.438	2.679855246	0.044972	2.53355455
Error	31807.56	30	1060.252			
Total	387685	41				

ANOVA: Two-Factor Without Replication for δ

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Temperature 30	6	441.6	73.6	14.16
Temperature 40	6	493.6	82.26667	8.970666667
Temperature 50	6	512.1	85.35	4.759
Temperature 60	6	524.5	87.41667	2.549666667
Temperature 70	6	532.8	88.8	0.34
Temperature 76	6	534.4	89.06667	0.414666667
Temperature 80	6	539.4	89.9	2.42338E-28
0% PET	7	613.1	87.58571	12.25809524
2% PET	7	605.2	86.45714	24.19952381
4% PET	7	596.7	85.24286	38.62285714
6% PET	7	592.7	84.67143	46.00571429
8% PET	7	587.8	83.97143	40.86904762
10% PET	7	582.9	83.27143	47.22904762

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	1188.61	6	198.1017	89.37493286	8.93E-18	2.42052319
Columns	89.47429	5	17.89486	8.073388188	6.41E-05	2.53355455
Error	66.49571	30	2.216524			
Total	1344.58	41				

ANOVA: Two-Factor Without Replication for IDT Test

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
4.5% Binder	6	31137.48	5189.581	499937.9
5% Binder	6	34299.38	5716.564	272851.2
5.5% Binder	6	28979.18	4829.864	433288.1
6% Binder	6	27011.14	4501.857	425770.8
0% PET	4	18830.71	4707.677	367415.1
2% PET	4	20799.7	5199.925	182223.9
4% PET	4	21846.17	5461.542	354895.1
6% PET	4	24086.08	6021.521	170312.1
8% PET	4	18773.03	4693.258	299353.4
10% PET	4	17091.5	4272.875	325542.7

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Binder content	4874115	3	1624705	108.2597	2.18E-10	3.287382
PET content	7934128	5	1586826	105.7356	3.79E-11	2.901295
Error	225112.2	15	15007.48			
Total	13033355	23				

ANOVA: Two-Factor Without Replication for Stability test

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
0% PET	4	43.9	10.98	0.94
2% PET	4	45.5	11.38	0.92
4% PET	4	46.6	11.65	0.58
6% PET	4	49.5	12.38	1.22
8% PET	4	42.4	10.60	0.37
10% PET	4	40.6	10.15	0.25
4.5% Binder	6	61.6	10.27	0.47
5% Binder	6	65.2	10.87	0.25
5.5% Binder	6	72.6	12.10	1.01
6% Binder	6	69.1	11.52	1.06

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
PET content	12.50	5	2.50	25.50	7.82E-07	2.90
Binder content	11.35	3	3.78	38.58	2.73E-07	3.29
Error	1.47	15	0.10			
Total	25.33	23				

ANOVA: Two-Factor Without Replication for Marshall flow test

SUMMARY	*Count*	*Sum*	*Average*	*Variance*		
0% PET	4	14.22	3.55	0.04581		
2% PET	4	14.98	3.75	0.017292		
4% PET	4	14.00	3.50	0.031852		
6% PET	4	13.56	3.39	0.006336		
8% PET	4	13.33	3.33	0.025		
10% PET	4	13.50	3.38	0.006944		
4.5% Binder	6	20.72	3.45	0.036046		
5% Binder	6	20.63	3.44	0.036185		
5.5% Binder	6	20.31	3.39	0.022341		
6% Binder	6	21.93	3.66	0.028407		
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
PET content	0.47	5	0.093595	9.56	0.000296	2.90
Binder content	0.25	3	0.08426	8.60	0.001464	3.29
Error	0.15	15	0.009795			
Total	0.87	23				

ANOVA: Two-Factor Without Replication for VIM

SUMMARY	*Count*	*Sum*	*Average*	*Variance*		
0% PET	4	32.86	8.21	3.31		
2% PET	4	29.84	7.46	4.94		
4% PET	4	27.28	6.82	3.76		
6% PET	4	27.85	6.96	2.01		
8% PET	4	32.17	8.04	3.15		
10% PET	4	33.51	8.38	2.75		
4.5% Binder	6	58.97	9.83	0.51		
5% Binder	6	49.44	8.24	0.55		
5.5% Binder	6	40.98	6.83	0.77		
6% Binder	6	34.11	5.68	0.32		
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
PET content	8.79	5	1.76	13.20	4.78E-05	2.90
Binder content	57.76	3	19.25	144.61	2.72E-11	3.29
Error	2.00	15	0.13			
Total	68.55	23				

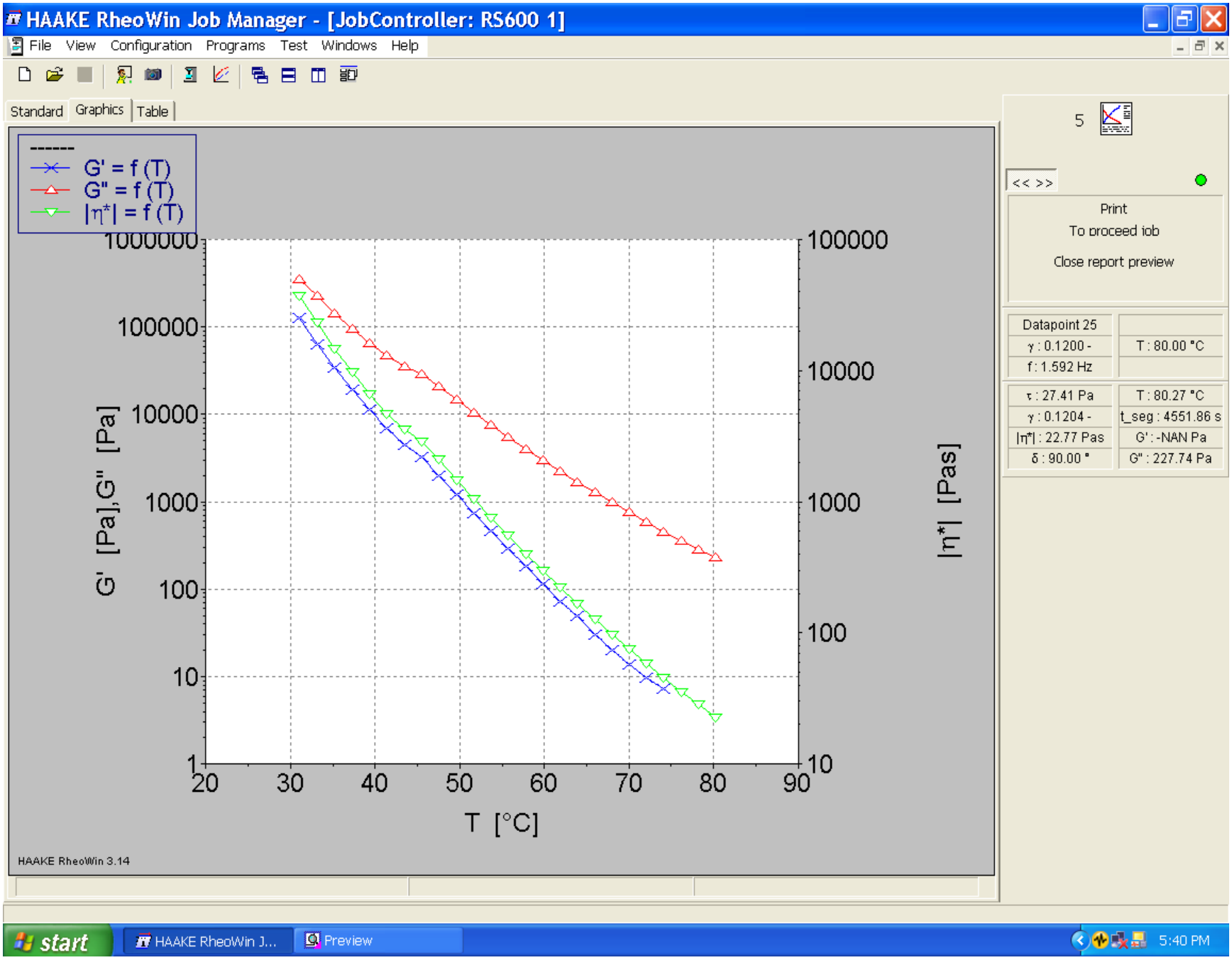
ANOVA: Two-Factor Without Replication for DCM

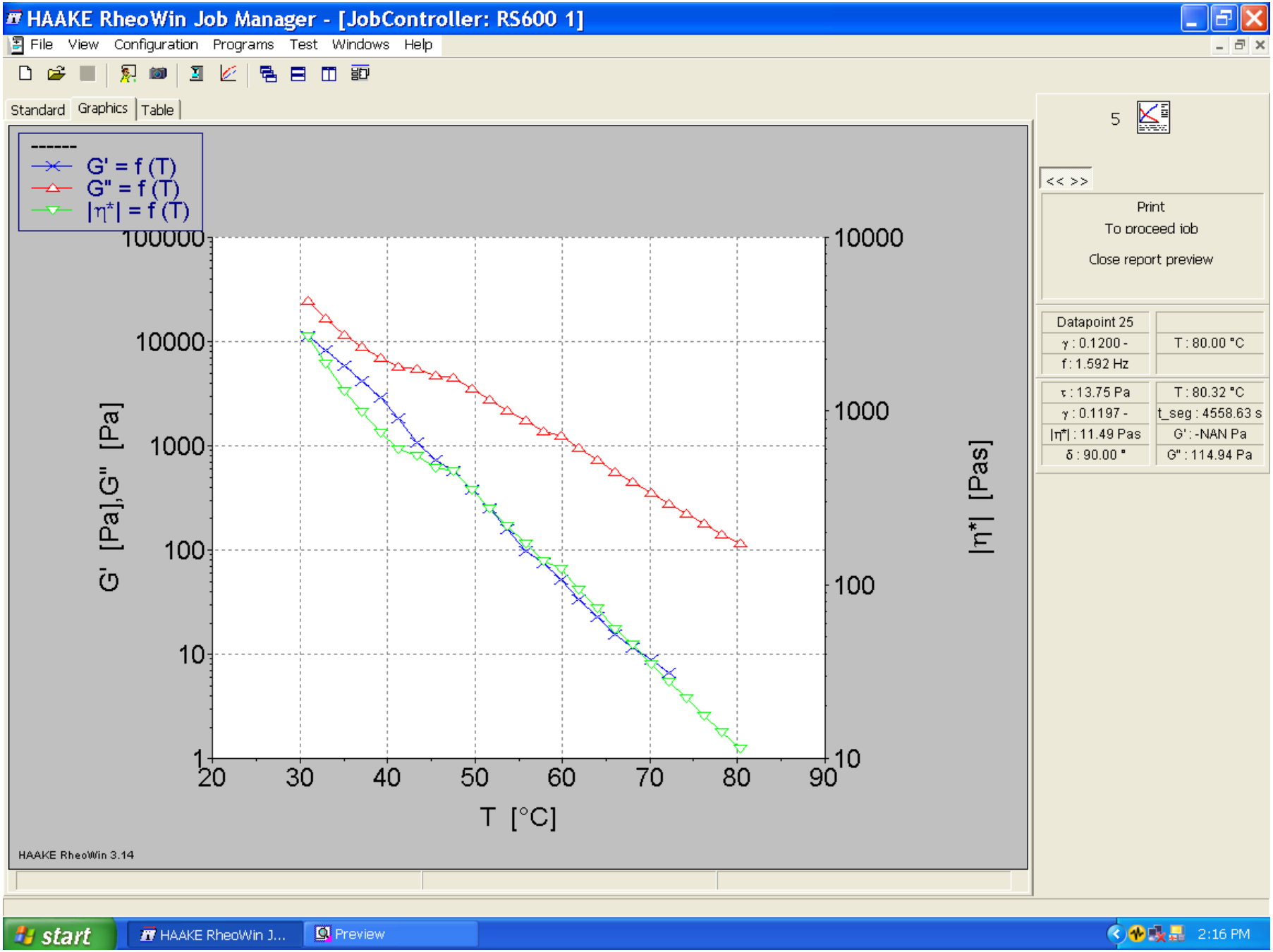
SUMMARY	*Count*	*Sum*	*Average*	*Variance*		
0% PET	4	9.05	2.26	0.000557		
2% PET	4	9.15	2.29	0.001691		
4% PET	4	9.21	2.30	0.00122		
6% PET	4	9.19	2.30	0.000605		
8% PET	4	9.07	2.27	0.000533		
10% PET	4	9.03	2.26	0.000387		
4.5% Binder	6	13.47	2.25	0.000341		
5% Binder	6	13.63	2.27	0.000351		
5.5% Binder	6	13.73	2.29	0.000446		
6% Binder	6	13.86	2.31	0.000693		
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
PET content	0.007557	5	0.001511	14.19	3.12E-05	2.90
Binder content	0.013381	3	0.00446	41.87	1.58E-07	3.29
Error	0.001598	15	0.000107			
Total	0.022536	23				

APPENDIX C

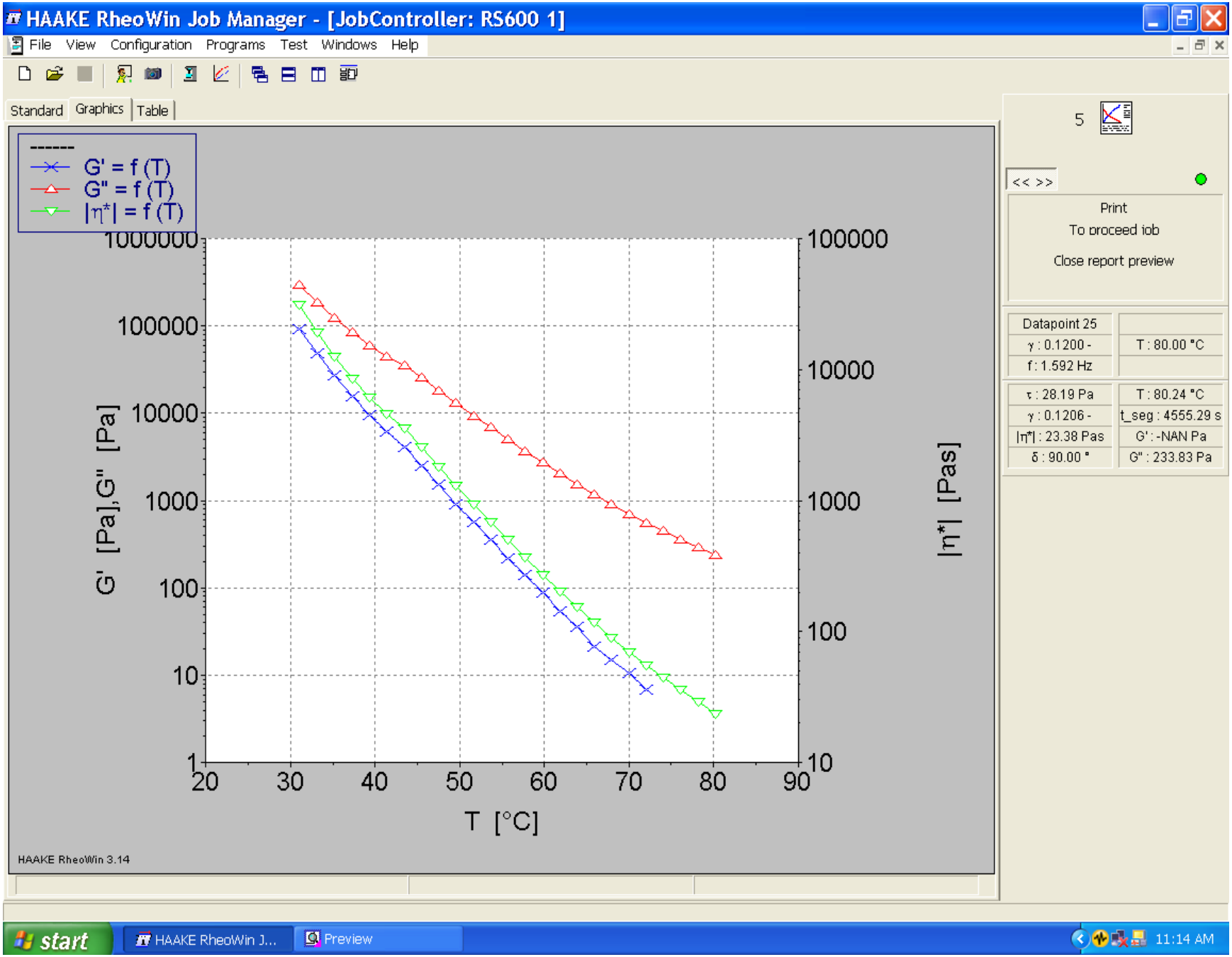
DSR TEST

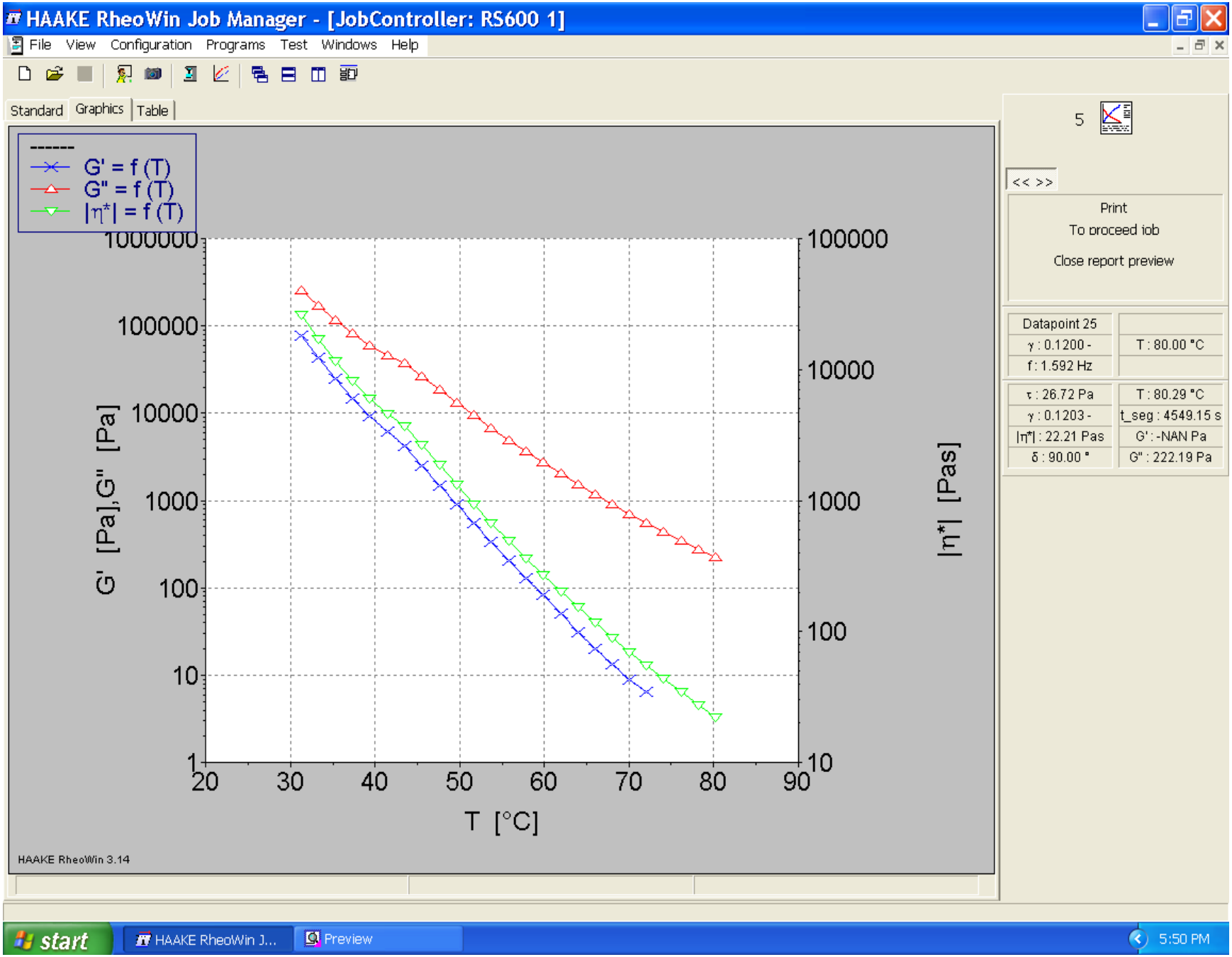
OUTPUT


HAAKE RheoWin Job Manager - [JobController: RS600 1]
File View Configuration Programs Test Windows Help
Standard Graphics Table
G' = f (T)
G" = f (T)
|η*| = f (T)
G' [Pa],G" [Pa]
|η*| [Pas]
T [°C]
HAAKE RheoWin 3.14
5
<< >>
Print
To proceed iob
Close report preview
Datapoint 25
γ : 0.1200 -
T : 80.00 °C
f : 1.592 Hz
τ : 27.41 Pa
T : 80.27 °C
γ : 0.1204 -
t_seg : 4551.86 s
|η*| : 22.77 Pas
G' : -NAN Pa
δ : 90.00 °
G" : 227.74 Pa
start
HAAKE RheoWin J...
Preview
5:40 PM

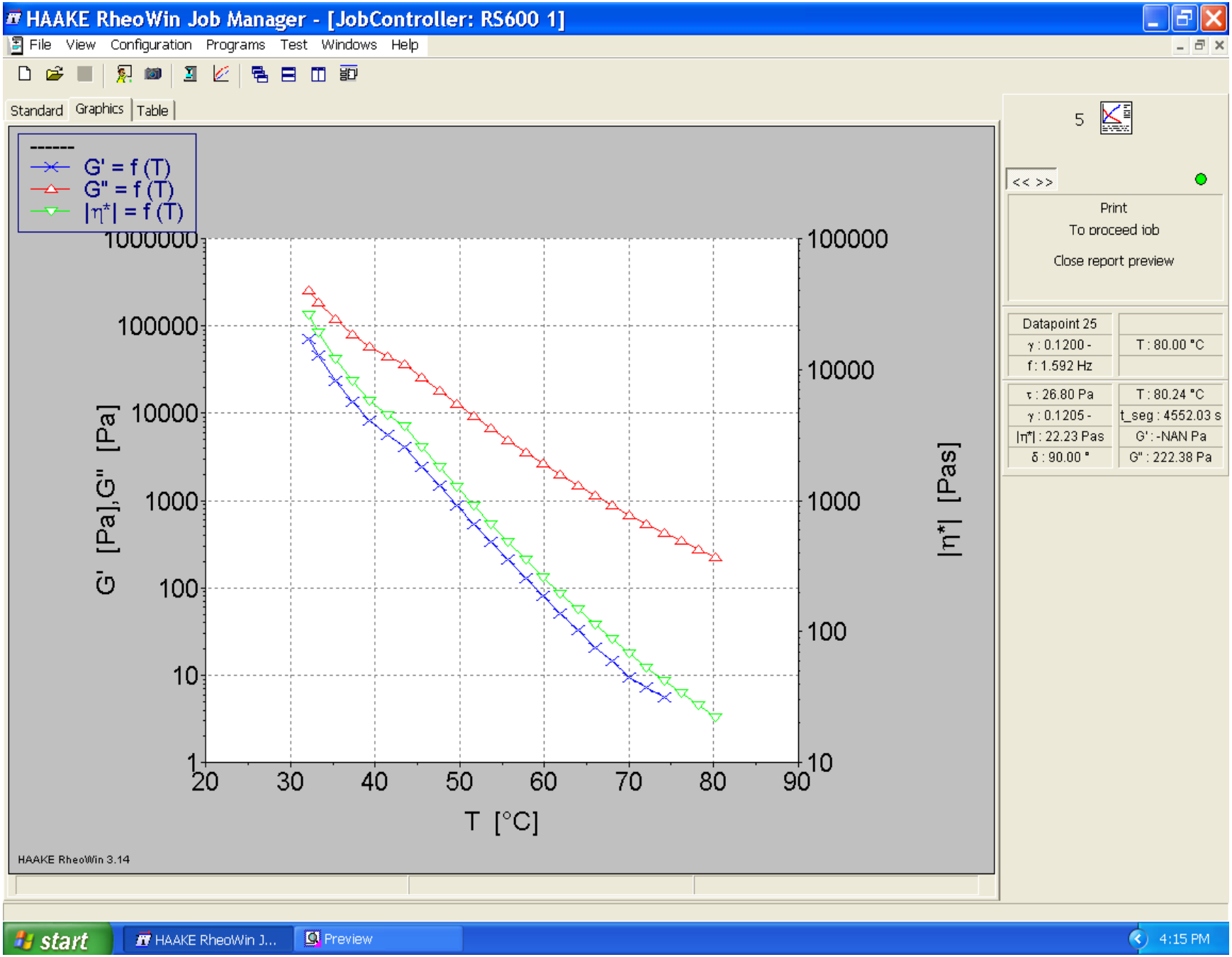

HAAKE RheoWin Job Manager - [JobController: RS600 1]
File View Configuration Programs Test Windows Help
Standard Graphics Table

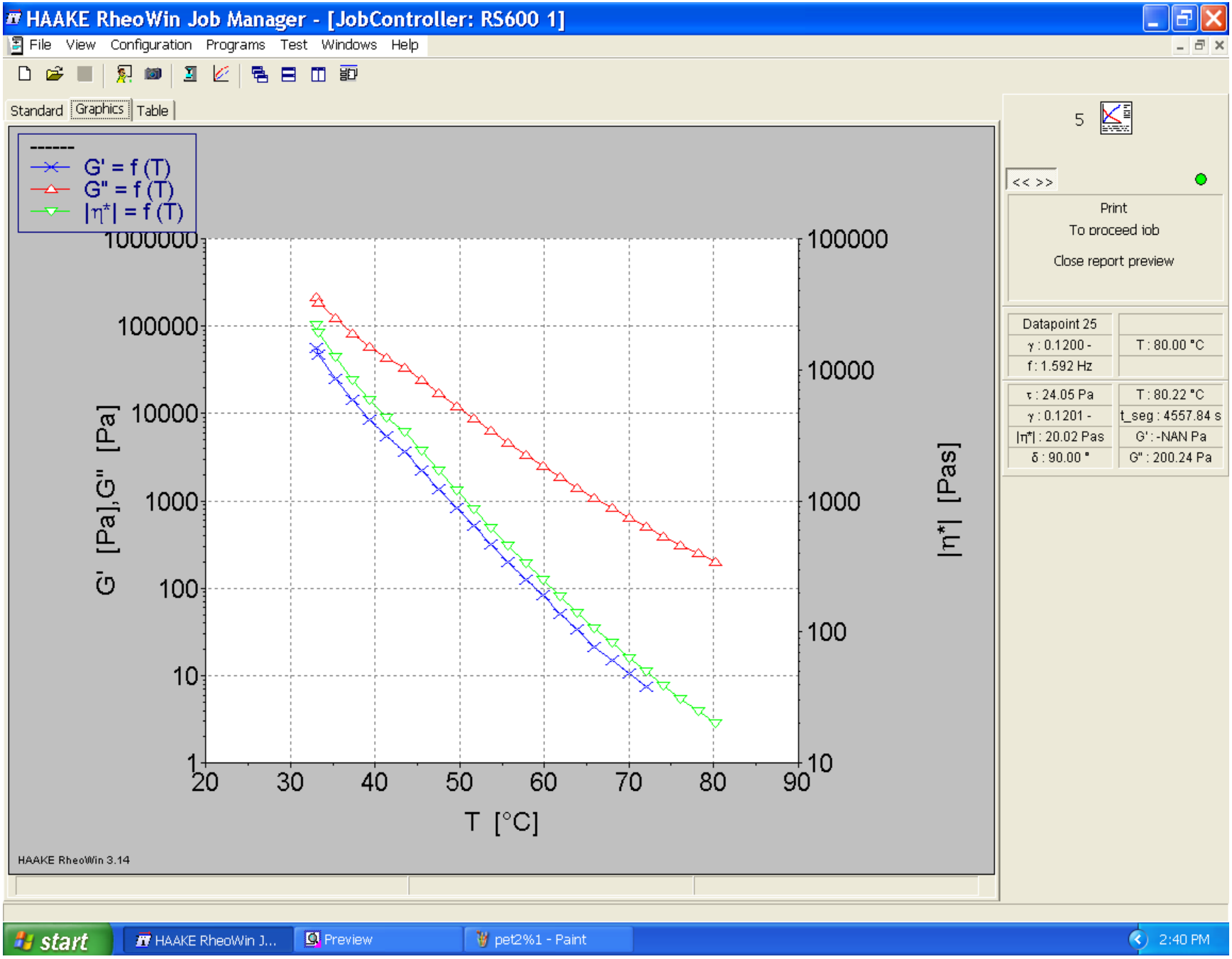
G' = f (T)
G" = f (T)
|η*| = f (T)
100000
10000
1000
100
10
1
10000
1000
100
10
20 30 40 50 60 70 80 90
G' [Pa],G" [Pa]
|η*| [Pas]
T [°C]
HAAKE RheoWin 3.14
5
<< >>
Print
To proceed iob
Close report preview
Datapoint 25
γ : 0.1200 -
T : 80.00 °C
f : 1.592 Hz
τ : 13.75 Pa
T : 80.32 °C
γ : 0.1197 -
t_seg : 4558.63 s
|η*| : 11.49 Pas
G' : -NAN Pa
δ : 90.00 °
G" : 114.94 Pa
start
HAAKE RheoWin J...
Preview
2:16 PM

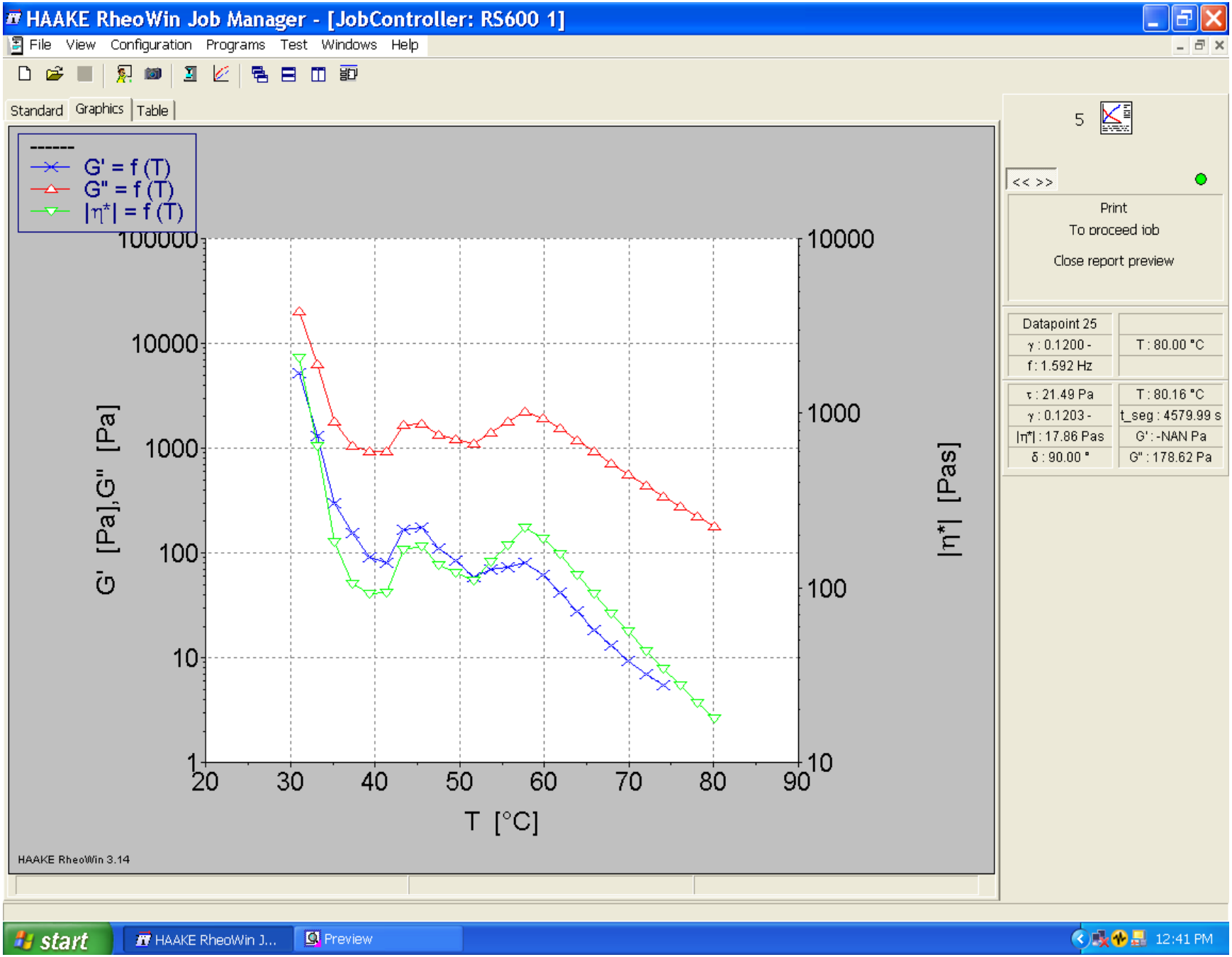

HAAKE RheoWin Job Manager - [JobController: RS600 1]
File View Configuration Programs Test Windows Help
Standard Graphics Table
G' = f (T)
G" = f (T)
|η*| = f (T)
1000000
100000
10000
1000
100
10
1
G' [Pa],G" [Pa]
100000
10000
1000
100
10
|η*| [Pas]
20 30 40 50 60 70 80 90
T [°C]
HAAKE RheoWin 3.14
5
<< >>
Print
To proceed iob
Close report preview
Datapoint 25
γ : 0.1200 -
T : 80.00 °C
f : 1.592 Hz
τ : 28.19 Pa
T : 80.24 °C
γ : 0.1206 -
t_seg : 4555.29 s
|η*| : 23.38 Pas
G' : -NAN Pa
δ : 90.00 °
G" : 233.83 Pa
start
HAAKE RheoWin J...
Preview
11:14 AM


HAAKE RheoWin Job Manager - [JobController: RS600 1]
File View Configuration Programs Test Windows Help
Standard Graphics Table

G' = f (T)
G" = f (T)
|η*| = f (T)
1000000
100000
10000
1000
100
10
1
G' [Pa],G" [Pa]
100000
10000
1000
100
10
|η*| [Pas]
20 30 40 50 60 70 80 90
T [°C]
HAAKE RheoWin 3.14
5
<< >>
Print
To proceed iob
Close report preview
Datapoint 25
γ : 0.1200 -
T : 80.00 °C
f : 1.592 Hz
τ : 26.72 Pa
T : 80.29 °C
γ : 0.1203 -
t_seg : 4549.15 s
|η*| : 22.21 Pas
G' : -NAN Pa
δ : 90.00 °
G" : 222.19 Pa
start
HAAKE RheoWin J...
Preview
5:50 PM


HAAKE RheoWin Job Manager - [JobController: RS600 1]
File View Configuration Programs Test Windows Help
Standard Graphics Table
G' = f (T)
G" = f (T)
|η*| = f (T)
G' [Pa],G" [Pa]
|η*| [Pas]
T [°C]
1000000
100000
10000
1000
100
10
1
20 30 40 50 60 70 80 90
HAAKE RheoWin 3.14
5
<< >>
Print
To proceed iob
Close report preview
Datapoint 25
γ : 0.1200 -
T : 80.00 °C
f : 1.592 Hz
τ : 26.80 Pa
T : 80.24 °C
γ : 0.1205 -
t_seg : 4552.03 s
|η*| : 22.23 Pas
G' : -NAN Pa
δ : 90.00 °
G" : 222.38 Pa
start
HAAKE RheoWin J...
Preview
4:15 PM


HAAKE RheoWin Job Manager - [JobController: RS600 1]
File View Configuration Programs Test Windows Help
Standard Graphics Table
G' = f (T)
G" = f (T)
|η*| = f (T)
G' [Pa],G" [Pa]
|η*| [Pas]
T [°C]
HAAKE RheoWin 3.14
5
<< >>
Print
To proceed iob
Close report preview
Datapoint 25
γ : 0.1200 -
T : 80.00 °C
f : 1.592 Hz
τ : 24.05 Pa
T : 80.22 °C
γ : 0.1201 -
t_seg : 4557.84 s
|η*| : 20.02 Pas
G' : -NAN Pa
δ : 90.00 °
G" : 200.24 Pa
start
HAAKE RheoWin J...
Preview
pet2%1 - Paint
2:40 PM


HAAKE RheoWin Job Manager - [JobController: RS600 1]
File View Configuration Programs Test Windows Help
Standard Graphics Table

G' = f (T)
G" = f (T)
|η*| = f (T)
100000
10000
1000
100
10
1
10000
1000
100
10
20 30 40 50 60 70 80 90
G' [Pa],G" [Pa]
|η*| [Pas]
T [°C]
HAAKE RheoWin 3.14
5
<< >>
Print
To proceed iob
Close report preview
Datapoint 25
γ : 0.1200 -
T : 80.00 °C
f : 1.592 Hz
τ : 21.49 Pa
T : 80.16 °C
γ : 0.1203 -
t_seg : 4579.99 s
|η*| : 17.86 Pas
G' : -NAN Pa
δ : 90.00 °
G" : 178.62 Pa
start
HAAKE RheoWin J...
Preview
12:41 PM

HAAKE RheoWin Data Manager

File View Layout Configuration Analysis Programs Windows Help

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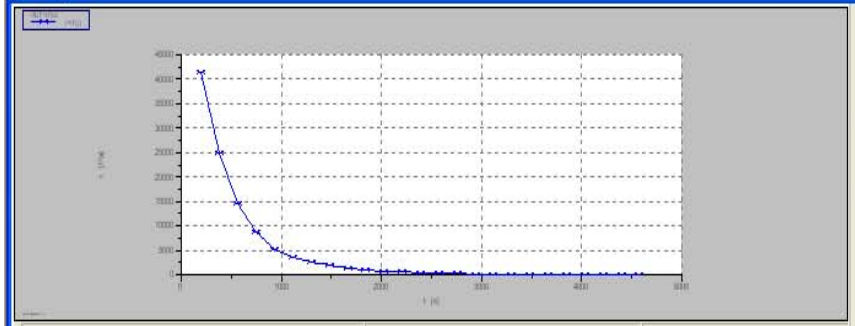

PET10%3.rwd

	t [s]	t_seg [s]	τ [Pa]	T [°C]	|G*| [Pa]	δ [°]
1 | 1	201.9	180.6	41500	31.14	343800	71.43
1 | 2	384.1	362.9	24960	33.17	206300	74.92
1 | 3	568.4	547.2	14630	35.25	121400	77.38
1 | 4	750.5	729.3	8767	37.31	72760	78.95
1 | 5	932.7	911.4	5347	39.37	44300	79.75
1 | 6	1115	1093	3553	41.42	29570	79.81
1 | 7	1297	1276	2585	43.46	21490	79.69
1 | 8	1479	1458	1961	45.51	16290	79.65
1 | 9	1661	1640	1461	47.55	12160	80.64
1 | 10	1843	1822	1074	49.61	8920	82.06
1 | 11	2025	2004	789.2	51.64	6569	83.42
1 | 12	2207	2186	583.6	53.68	4844	84.55
1 | 13	2390	2368	430.3	55.73	3576	85.49
1 | 14	2572	2551	323.6	57.78	2696	86.24
1 | 15	2754	2733	244.2	59.83	2029	86.74
1 | 16	2936	2915	186.2	61.88	1541	87.00
1 | 17	3118	3097	141.5	63.92	1183	87.35
1 | 18	3300	3279	109.9	65.98	915.8	87.61
1 | 19	3483	3461	86.53	68.00	725.3	87.78
1 | 20	3665	3643	69.46	70.05	579.5	87.97
1 | 21	3846	3825	55.83	72.09	465.9	88.26
1 | 22	4028	4007	45.07	74.09	376.9	88.41
1 | 23	4212	4191	36.89	76.15	306.8	88.52
1 | 24	4394	4373	30.63	78.17	256.4	88.57
1 | 25	4576	4555	25.36	80.22	211.5	90.00

Files:
1: PET10%3.rwd
==========
Filename: PET10%3.rwd
Job: C:\Program Files\RheoWin3\JOBS\Original Binder 30-80°C.rwj
Version: 314

Company: UM
Operator: Makmal Lebuhraya
Comment:

Date/Time: 28.01.2010/14:15:51 PM
Name: cewing cum
Sample no: 17
Description:

Notes:

Measure device: RS600 1 (RheoStress RS600)
Driver version: 1.03
Firmware version 1: 209010
Firmware version 2: 200013
Inertia: 9.7912e-06 kgm²
Options: HT
Serial number: 1200403739002
Last Service: 12/10/2004
Last Calibration: 12/10/2004
Thermal expansion coefficient: 1.100 µm/K
Check G': [X]
Oscillation raw data: [---]
Use MicroStressControl: [X]
Inertia correction Osc: [X]
Inertia correction Ramp: [X]
Use Halfwave: [Automatic]
Autostrain: [X]
Accept data against set direction: [---]
Upload mode: [---]
Communication log: [---]

Temperature device: DC30 (DC30)
Driver version: 1.28
Firmware version 1: 20

Sensor: PP25
A-factor: 325900.000 Pa/Nm
M-factor: 12.518 (1/s)/(rad/s)
Inertia: 8.500e-07 kg m²
Damping: 30.00
Gap: 0.999 mm
Driver version: 1.19

Element definition:
ID 13: 30.00 °C, t 300.00 s, CS, 0.00 Pa,
ID 18: CD lin, prev °C - 80.00 °C, 0.12 -, f 1.592 Hz, #25
ID 14: Measurement.LST

Evaluation:
==========

HAAKE RheoWin Data Manager

File View Layout Configuration Analysis Programs Windows Help

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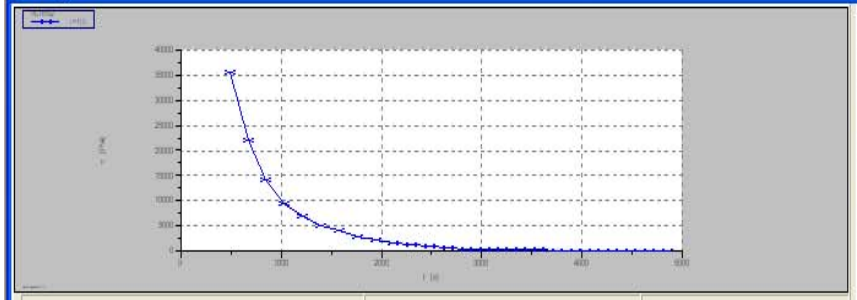

PET8%2.rwd

	t [s]	t seq [s]	τ [Pa]	T [°C]	|G*| [Pa]	δ [°]
1 | 1	483.8	181.5	35700	31.32	296400	73.46
1 | 2	665.0	362.7	22000	33.27	182400	76.50
1 | 3	846.9	544.6	14090	35.33	117200	78.77
1 | 4	1029	726.3	9575	37.38	79330	80.43
1 | 5	1211	908.5	6851	39.43	57250	81.75
1 | 6	1393	1090	5159	41.48	43260	82.85
1 | 7	1574	1272	4121	43.51	34380	83.66
1 | 8	1757	1455	2926	45.58	24450	84.60
1 | 9	1939	1636	2098	47.63	17420	85.33
1 | 10	2120	1818	1495	49.67	12410	85.89
1 | 11	2302	2000	1075	51.71	8924	86.47
1 | 12	2482	2180	775.3	53.76	6466	86.93
1 | 13	2664	2362	565.3	55.81	4713	87.33
1 | 14	2847	2545	418.6	57.86	3478	87.61
1 | 15	3028	2726	309.9	59.90	2591	87.93
1 | 16	3210	2908	234.5	61.94	1951	88.24
1 | 17	3392	3090	178.5	63.95	1489	88.43
1 | 18	3574	3272	137.0	66.02	1142	88.56
1 | 19	3756	3454	106.3	68.04	889.8	88.73
1 | 20	3938	3636	83.48	70.10	694.1	88.77
1 | 21	4120	3818	65.35	72.15	542.2	88.84
1 | 22	4303	4000	51.40	74.19	429.1	88.82
1 | 23	4486	4183	41.53	76.19	348.3	88.80
1 | 24	4667	4365	33.69	78.20	281.3	88.64
1 | 25	4851	4548	27.02	80.34	226.0	90.00

Files:
1: PET8%2.rwd
==========
Filename: PET8%2.rwd
Job: C:\Program Files\RheoWin3\JOBS\Original Binder 30-80°C.rwj
Version: 314

Company: UM
Operator: Makmal Lebuhraya
Comment:

Date/Time: 31.12.2009/15:53:11 PM
Name: cewing cum
Sample no: 8
Description:

Notes:

Measure device: RS600 1 (RheoStress RS600)
Driver version: 1.03
Firmware version 1: 209010
Firmware version 2: 200013
Inertia: 9.7912e-06 kgm²
Options: HT
Serial number: 1200403739002
Last Service: 12/10/2004
Last Calibration: 12/10/2004
Thermal expansion coefficient: 1.100 µm/K
Check G': [X]
Oscillation raw data: [---]
Use MicroStressControl: [X]
Inertia correction Osc: [X]
Inertia correction Ramp: [X]
Use Halfwave: [Automatic]
Autostrain: [X]
Accept data against set direction: [---]
Upload mode: [---]
Communication log: [---]

Temperature device: DC30 (DC30)
Driver version: 1.28
Firmware version 1: 20

Sensor: PP25
A-factor: 325900.000 Pa/Nm
M-factor: 12.496 (1/s)/(rad/s)
Inertia: 8.500e-07 kg m²
Damping: 30.00
Gap: 1.000 mm
Driver version: 1.19

Element definition:
ID 13: 30.00 °C, t 300.00 s, CS, 0.00 Pa,
ID 18: CD lin, prev °C - 80.00 °C, 0.12 -, f 1.592 Hz, #25
ID 14: Measurement.LST

Evaluation:
==========

HAAKE RheoWin Data Manager

File View Layout Configuration Analysis Programs Windows Help

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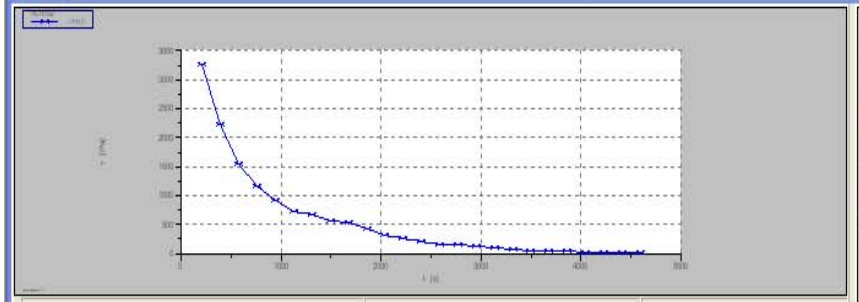

PET6%2.rwd

	t [s]	t_seg [s]	τ [Pa]	T [°C]	|G*| [Pa]	δ [°]
1 | 1	213.6	180.8	3269	30.88	27000	65.39
1 | 2	395.9	363.1	2241	32.97	18660	63.78
1 | 3	577.6	544.8	1557	35.02	12980	62.96
1 | 4	758.9	726.1	1175	37.11	9848	64.75
1 | 5	940.8	908.0	911.4	39.16	7560	67.44
1 | 6	1129	1097	718.1	41.24	6010	72.36
1 | 7	1311	1279	661.2	43.36	5531	78.81
1 | 8	1494	1461	571.4	45.50	4731	81.12
1 | 9	1675	1642	543.6	47.56	4513	82.71
1 | 10	1857	1824	422.4	49.62	3539	83.79
1 | 11	2039	2007	326.8	51.66	2745	84.80
1 | 12	2222	2189	261.0	53.71	2182	85.85
1 | 13	2405	2372	208.4	55.77	1740	86.75
1 | 14	2587	2554	163.4	57.83	1366	86.83
1 | 15	2769	2736	148.4	59.88	1239	87.62
1 | 16	2951	2918	113.1	61.91	941.3	87.96
1 | 17	3133	3100	87.53	63.96	730.2	88.19
1 | 18	3315	3283	66.99	66.02	558.2	88.40
1 | 19	3498	3465	54.34	68.06	452.2	88.52
1 | 20	3680	3647	42.11	70.11	351.8	88.56
1 | 21	3862	3830	33.53	72.14	278.1	88.64
1 | 22	4044	4012	26.60	74.18	221.6	90.00
1 | 23	4227	4194	21.17	76.24	176.8	90.00
1 | 24	4408	4375	17.09	78.28	141.8	90.00
1 | 25	4591	4559	13.75	80.32	114.9	90.00

Files:
1: PET6%2.rwd
==========
Filename: PET6%2.rwd
Job: C:\Program Files\RheoWin3\JOBS\Original Binder 30-80°C.rwj
Version: 314

Company: UM
Operator: Makmal Lebuhraya
Comment:

Date/Time: 31.12.2009/12:55:49 PM
Name: cewing cum
Sample no: 6
Description:

Notes:

Measure device: RS600 1 (RheoStress RS600)
Driver version: 1.03
Firmware version 1: 209010
Firmware version 2: 200013
Inertia: 9.7912e-06 kgm²
Options: HT
Serial number: 1200403739002
Last Service: 12/10/2004
Last Calibration: 12/10/2004
Thermal expansion coefficient: 1.100 µm/K
Check G': [X]
Oscillation raw data: [---]
Use MicroStressControl: [X]
Inertia correction Osc: [X]
Inertia correction Ramp: [X]
Use Halfwave: [Automatic]
Autostrain: [X]
Accept data against set direction: [---]
Upload mode: [---]
Communication log: [---]

Temperature device: DC30 (DC30)
Driver version: 1.28
Firmware version 1: 20

Sensor: PP25
A-factor: 325900.000 Pa/Nm
M-factor: 12.509 (1/s)/(rad/s)
Inertia: 8.500e-07 kg m²
Damping: 30.00
Gap: 0.999 mm
Driver version: 1.19

Element definition:
ID 13: 30.00 °C, t 300.00 s, CS, 0.00 Pa,
ID 18: CD lin, prev °C - 80.00 °C, 0.12 -, f 1.592 Hz, #25
ID 14: Measurement.LST

Evaluation:
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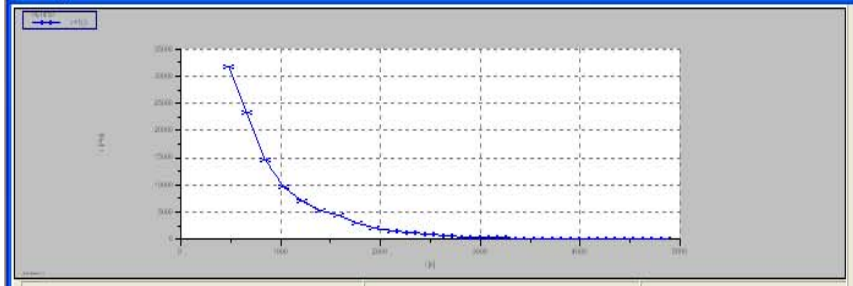

PET4%1.rwd

	t [s]	t seg [s]	τ [Pa]	T [°C]	|G*| [Pa]	δ [°]
1 | 1	483.3	181.2	31860	32.13	263000	74.61
1 | 2	665.8	363.7	23190	33.23	191900	76.38
1 | 3	847.3	545.2	14710	35.30	121600	78.76
1 | 4	1030	728.3	9748	37.36	81130	80.43
1 | 5	1213	910.9	6952	39.40	58090	81.77
1 | 6	1395	1093	5403	41.44	45200	82.81
1 | 7	1577	1275	4368	43.46	36620	83.67
1 | 8	1759	1457	3098	45.53	25670	84.57
1 | 9	1942	1640	2179	47.58	18070	85.35
1 | 10	2124	1821	1535	49.62	12780	86.05
1 | 11	2305	2003	1101	51.67	9149	86.67
1 | 12	2488	2185	799.0	53.71	6623	87.10
1 | 13	2670	2368	578.6	55.75	4830	87.52
1 | 14	2852	2550	428.3	57.81	3553	87.94
1 | 15	3034	2731	315.2	59.88	2620	88.25
1 | 16	3215	2913	235.5	61.90	1953	88.52
1 | 17	3397	3095	179.3	63.96	1487	88.73
1 | 18	3580	3278	136.1	66.01	1131	88.94
1 | 19	3762	3460	104.9	68.03	872.6	89.06
1 | 20	3943	3641	81.14	70.07	677.7	89.21
1 | 21	4125	3823	64.03	72.12	533.0	89.21
1 | 22	4307	4005	50.70	74.16	423.7	89.25
1 | 23	4490	4188	41.12	76.16	342.2	90.00
1 | 24	4672	4370	33.18	78.19	276.2	90.00
1 | 25	4854	4552	26.80	80.24	222.4	90.00

Files:
1: PET4%1.rwd
==========
Filename: PET4%1.rwd
Job: C:\Program Files\RheoWin3\JOBS\Original Binder 30-80°C.rwj
Version: 314

Company: UM
Operator: Makmal Lebuhraya
Comment:

Date/Time: 30.12.2009/14:50:30 PM
Name: cewing cum
Sample no: 3
Description:

Notes:

Measure device: RS600 1 (RheoStress RS600)
Driver version: 1.03
Firmware version 1: 209010
Firmware version 2: 200013
Inertia: 9.7912e-06 kgm²
Options: HT
Serial number: 1200403739002
Last Service: 12/10/2004
Last Calibration: 12/10/2004
Thermal expansion coefficient: 1.100 µm/K
Check G': [X]
Oscillation raw data: [---]
Use MicroStressControl: [X]
Inertia correction Osc: [X]
Inertia correction Ramp: [X]
Use Halfwave: [Automatic]
Autostrain: [X]
Accept data against set direction: [---]
Upload mode: [---]
Communication log: [---]

Temperature device: DC30 (DC30)
Driver version: 1.28
Firmware version 1: 20

Sensor: PP25
A-factor: 325900.000 Pa/Nm
M-factor: 12.504 (1/s)/(rad/s)
Inertia: 8.500e-07 kg m²
Damping: 30.00
Gap: 1.000 mm
Driver version: 1.19

Element definition:
ID 13: 30.00 °C, t 300.00 s, CS, 0.00 Pa,
ID 18: CD lin, prev °C - 80.00 °C, 0.12 -, f 1.592 Hz, #25
ID 14: Measurement.LST

Evaluation:
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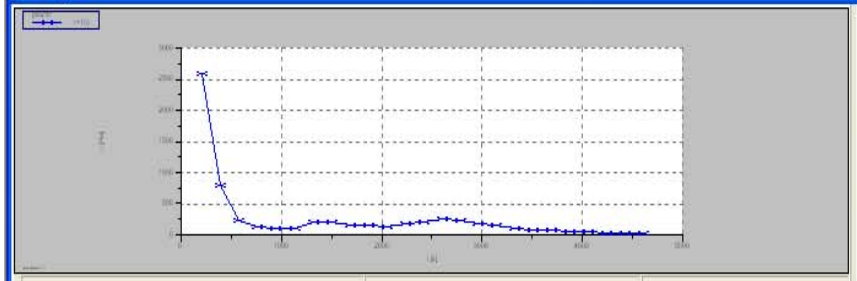

pet2%1.rwd

	t [s]	t seg [s]	τ [Pa]	T [°C]	|G*| [Pa]	δ [°]
1 | 1	207.2	181.3	2588	31.03	20900	75.55
1 | 2	388.3	362.4	794.2	33.13	6502	78.40
1 | 3	569.4	543.4	226.2	35.21	1831	80.55
1 | 4	754.4	728.5	127.5	37.28	1063	81.58
1 | 5	936.6	910.7	112.0	39.34	928.7	84.41
1 | 6	1133	1107	113.0	41.37	935.3	85.05
1 | 7	1318	1292	200.2	43.42	1663	84.20
1 | 8	1500	1474	208.9	45.48	1725	84.14
1 | 9	1687	1661	163.1	47.53	1352	85.33
1 | 10	1868	1842	147.7	49.57	1224	86.09
1 | 11	2050	2025	133.0	51.61	1101	86.91
1 | 12	2233	2207	167.8	53.65	1410	87.19
1 | 13	2419	2393	211.2	55.71	1768	87.66
1 | 14	2601	2575	265.2	57.76	2218	87.94
1 | 15	2783	2757	230.1	59.81	1928	88.18
1 | 16	2965	2939	186.0	61.84	1560	88.48
1 | 17	3148	3122	143.9	63.90	1194	88.67
1 | 18	3331	3305	110.3	65.93	919.8	88.86
1 | 19	3513	3487	85.85	67.95	716.4	88.95
1 | 20	3695	3669	67.11	69.97	561.0	89.04
1 | 21	3878	3852	52.42	72.03	437.4	89.08
1 | 22	4060	4034	41.20	74.06	343.8	89.09
1 | 23	4242	4216	33.08	76.07	275.4	90.00
1 | 24	4424	4398	26.39	78.13	220.5	90.00
1 | 25	4606	4580	21.49	80.16	178.6	90.00

Files:
1: pet2%1.rwd
==========
Filename: pet2%1.rwd
Job: C:\Program Files\RheoWin3\JOBS\Original Binder 30-80°C.rwj
Version: 314

Company: UM
Operator: Makmal Lebuhraya
Comment:

Date/Time: 30.12.2009/11:04:06 AM
Name: cewing cum
Sample no: 1
Description:

Notes:

Measure device: RS600 1 (RheoStress RS600)
Driver version: 1.03
Firmware version 1: 209010
Firmware version 2: 200013
Inertia: 9.7912e-06 kgm²
Options: HT
Serial number: 1200403739002
Last Service: 12/10/2004
Last Calibration: 12/10/2004
Thermal expansion coefficient: 1.100 µm/K
Check G': [X]
Oscillation raw data: [---]
Use MicroStressControl: [X]
Inertia correction Osc: [X]
Inertia correction Ramp: [X]
Use Halfwave: [Automatic]
Autostrain: [X]
Accept data against set direction: [---]
Upload mode: [---]
Communication log: [---]

Temperature device: DC30 (DC30)
Driver version: 1.28
Firmware version 1: 20

Sensor: PP25
A-factor: 325900.000 Pa/Nm
M-factor: 12.891 (1/s)/(rad/s)
Inertia: 8.500e-07 kg m²
Damping: 30.00
Gap: 0.970 mm
Driver version: 1.19

Element definition:
ID 13: 30.00 °C, t 300.00 s, CS, 0.00 Pa,
ID 18: CD lin, prev °C - 80.00 °C, 0.12 -, f 1.592 Hz, #25
ID 14: Measurement.LST

Evaluation:
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File View Layout Configuration Analysis Programs Windows Help

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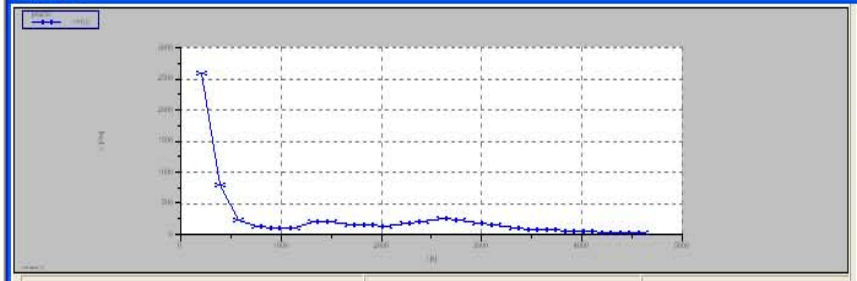

pet2%1.rwd

	t [s]	t seq [s]	τ [Pa]	T [°C]	|G*| [Pa]	δ [°]
1 | 1	207.2	181.3	2588	31.03	20900	75.55
1 | 2	388.3	362.4	794.2	33.13	6502	78.40
1 | 3	569.4	543.4	226.2	35.21	1831	80.55
1 | 4	754.4	728.5	127.5	37.28	1063	81.58
1 | 5	936.6	910.7	112.0	39.34	928.7	84.41
1 | 6	1133	1107	113.0	41.37	935.3	85.05
1 | 7	1318	1292	200.2	43.42	1663	84.20
1 | 8	1500	1474	208.9	45.48	1725	84.14
1 | 9	1687	1661	163.1	47.53	1352	85.33
1 | 10	1868	1842	147.7	49.57	1224	86.09
1 | 11	2050	2025	133.0	51.61	1101	86.91
1 | 12	2233	2207	167.8	53.65	1410	87.19
1 | 13	2419	2393	211.2	55.71	1768	87.66
1 | 14	2601	2575	265.2	57.76	2218	87.94
1 | 15	2783	2757	230.1	59.81	1928	88.18
1 | 16	2965	2939	186.0	61.84	1560	88.48
1 | 17	3148	3122	143.9	63.90	1194	88.67
1 | 18	3331	3305	110.3	65.93	919.8	88.86
1 | 19	3513	3487	85.85	67.95	716.4	88.95
1 | 20	3695	3669	67.11	69.97	561.0	89.04
1 | 21	3878	3852	52.42	72.03	437.4	89.08
1 | 22	4060	4034	41.20	74.06	343.8	89.09
1 | 23	4242	4216	33.08	76.07	275.4	90.00
1 | 24	4424	4398	26.39	78.13	220.5	90.00
1 | 25	4606	4580	21.49	80.16	178.6	90.00

Files:
1: pet2%1.rwd
==========
Filename: pet2%1.rwd
Job: C:\Program Files\RheoWin3\JOBS\Original Binder 30-80°C.rwj
Version: 314

Company: UM
Operator: Makmal Lebuhraya
Comment:

Date/Time: 30.12.2009/11:04:06 AM
Name: cewing cum
Sample no: 1
Description:

Notes:

Measure device: RS600 1 (RheoStress RS600)
Driver version: 1.03
Firmware version 1: 209010
Firmware version 2: 200013
Inertia: 9.7912e-06 kgm²
Options: HT
Serial number: 1200403739002
Last Service: 12/10/2004
Last Calibration: 12/10/2004
Thermal expansion coefficient: 1.100 µm/K
Check G': [X]
Oscillation raw data: [---]
Use MicroStressControl: [X]
Inertia correction Osc: [X]
Inertia correction Ramp: [X]
Use Halfwave: [Automatic]
Autostrain: [X]
Accept data against set direction: [---]
Upload mode: [---]
Communication log: [---]

Temperature device: DC30 (DC30)
Driver version: 1.28
Firmware version 1: 20

Sensor: PP25
A-factor: 325900.000 Pa/Nm
M-factor: 12.891 (1/s)/(rad/s)
Inertia: 8.500e-07 kg m²
Damping: 30.00
Gap: 0.970 mm
Driver version: 1.19

Element definition:
ID 13: 30.00 °C, t 300.00 s, CS, 0.00 Pa,
ID 18: CD lin, prev °C - 80.00 °C, 0.12 -, f 1.592 Hz, #25
ID 14: Measurement.LST

Evaluation:
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APPENDIX D

IDT TEST

OUTPUT

APPENDIX E

MARSHAL TEST

RESULTS

	Binder %		4.5%			5.0%			5.5%			6.0%		
	PET %		0% 1	0% 2	0% 3	0% 1	0% 2	0% 3	0% 1	0% 2	0% 3	0% 1	0% 2	0% 3
a	temperature compaction	C	140	140	140	140	140	140	140	140	140	140	140	140
b	Diameter	mm	101.1	101.2	100.6	101.1	101.4	101.1	100.8	101.3	101.2	101.2	101.2	101.2
c	Thickness	mm	63.7	64.2	65.6	64.2	63.5	63.7	64.7	63.8	64.3	65.2	64.5	64.1
d	Weight in air	g	1145.2	1156.7	1157.7	1161.6	1143.3	1164.2	1178.9	1168.9	1174.6	1177.6	1170.3	1173
e	Wt. in water	g	632.3	641.2	638.7	647.3	633.6	655	662.4	655.7	653.2	657.4	663.3	664.6
f	Wt. surface dry	g	1145.7	1158.6	1157.8	1162.3	1145.3	1164.3	1179.4	1169.3	1177.4	1178.5	1171	1173.8
g	Volume,[f-e]	ml	513.4	517.4	519.1	515	511.7	509.3	517	513.6	524.2	521.1	507.7	509.2
h	binder content	%	4.5	4.5	4.5	5	5	5	5.5	5.5	5.5	6	6	6
i	bulk density,CDM,[d/g]	g/ml	2.23	2.24	2.23	2.26	2.23	2.29	2.28	2.28	2.24	2.26	2.31	2.30
j	SGM,[100/{(h/t)+((100-h)/u)}]	g/ml	2.49	2.49	2.49	2.47	2.47	2.47	2.46	2.46	2.46	2.44	2.44	2.44
k	Vol. of bitumen,[h*i/t]	%	9.75	9.77	9.74	10.95	10.85	11.10	12.18	12.15	11.97	13.16	13.43	13.42
l	Vol. of aggregate [(100-h)*i/u]	%	79.78	79.96	79.77	80.25	79.50	81.33	80.71	80.55	79.31	79.56	81.15	81.10
m	VMA ,[100-L]	%	20.22	20.04	20.23	19.75	20.50	18.67	19.29	19.45	20.69	20.44	18.85	18.90
n	VIM [100-(K+l)]	%	10.47	10.27	10.49	8.80	9.66	7.57	7.12	7.30	8.73	7.28	5.42	5.48
o	VFB, [100*K/M]	%	48.21	48.74	48.16	55.45	52.90	59.44	63.11	62.49	57.82	64.40	71.25	71.00
p	Measured stability	KN	10	11.5	10.8	11.6	7.7	12	11.7	12.3	8.6	8.62	12.2	12.7
q	Corrected stability	KN	9.8	11	9.9	11.1	7.7	11.8	11	12.1	8.2	8	11.5	12
r	Flow	mm	3.3	3	3.8	2.7	3.8	3.8	3.5	3.4	3.8	3.6	4.1	4.5
s	Quotient, [q/r]	KN/mm	3.0	3.7	2.6	4.1	2.0	3.1	3.1	3.6	2.2	2.2	2.8	2.7
t	S.G. of binder		1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
u	S.G. of aggregate		2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67

	Binder %		4.5%			5.0%			5.5%			6.0%		
	PET %		2% 1	2% 2	2% 3	2% 1	2% 2	2% 3	2% 1	2% 2	2% 3	2% 1	2% 2	2% 3
a	temperature compaction	C												
b	Diameter	mm	101.8	101.5	102.0	101.2	101.4	101.7	101.0	100.1	101.8	101.3	100.7	101
c	Thickness	mm	64.6	65.0	63.1	64.4	64.3	64.4	63.8	64.0	62.9	62.1	63.0	62.5
d	Weight in air	g	1158.2	1149.2	1157.3	1157.6	1149.7	1166.0	1172.7	1176.0	1170.0	1177.5	1170.3	1178.3
e	Wt. in water	g	638.6	629.8	646.7	644.4	637.5	650.5	665.9	665.0	663.9	670.5	667.9	673.9
f	Wt. surface dry	g	1158.6	1149.6	1158.7	1158.2	1149.8	1166.6	1172.8	1176.3	1170.5	1178.2	1170.4	1178.5
g	Volume,[f-e]	ml	520.0	519.8	512.0	513.8	512.3	516.1	506.9	511.3	506.6	507.7	502.5	504.6
h	binder content	%	4.5	4.5	4.5	5	5	5	5.5	5.5	5.5	6	6	6
i	bulk density,CDM,[d/g]	g/ml	2.23	2.21	2.26	2.25	2.24	2.26	2.31	2.30	2.31	2.32	2.33	2.34
j	SGM,[100/{(h/t)+((100-h)/u)}]	g/ml	2.49	2.49	2.49	2.47	2.47	2.47	2.46	2.46	2.46	2.44	2.44	2.44
k	Vol. of bitumen,[h*i/t]	%	9.73	9.66	9.88	10.94	10.89	10.97	12.35	12.28	12.33	13.51	13.57	13.60
l	Vol. of aggregate [(100-h)*i/u]	%	79.67	79.08	80.85	80.16	79.85	80.39	81.88	81.41	81.74	81.65	81.99	82.21
m	VMA ,[100-L]	%	20.33	20.92	19.15	19.84	20.15	19.61	18.12	18.59	18.26	18.35	18.01	17.79
n	VIM [100-(K+l)]	%	10.60	11.26	9.28	8.90	9.26	8.65	5.77	6.31	5.93	4.84	4.44	4.19
o	VFB, [100*K/M]	%	47.86	46.17	51.56	55.14	54.06	55.91	68.18	66.05	67.54	73.64	75.34	76.46
p	Measured stability	KN	9	9.7	12	9.2	9.7	10.9	12.5	12.3	11.1	13.3	12.6	13.8
q	Corrected stability	KN	8.6	9	12.2	8.7	9.3	10.3	12.3	11.8	11.3	13.8	12.8	14.1
r	Flow	mm	4.7	3	3.8	3.7	3.9	4.2	3.4	3.7	4.4	4.2	3.6	3.8
s	Quotient, [q/r]	KN/mm	1.8	3.0	3.2	2.4	2.4	2.5	3.6	3.2	2.6	3.3	3.6	3.7
t	S.G. of binder		1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
u	S.G. of aggregate		2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67

	Binder %		4.5%			5.0%			5.5%			6.0%		
	PET %		4% 1	4% 2	4% 3	4% 1	4% 2	4% 3	4% 1	4% 2	4% 3	4% 1	4% 2	4% 3
a	temperature compaction	C												
b	Diameter	mm	101.2	102	101.1	101.3	101.7	101.5	101.5	100.9	101.2	101.4	101.1	101.6
c	Thickness	mm	64.1	63.7	65.1	64.3	63.2	64	63.9	62	63.5	64.9	63.5	64.3
d	Weight in air	g	1164.6	1162.5	1169.8	1156.8	1177.4	1166.1	1180.7	1125.7	1170.5	1181.4	1175	1189.7
e	Wt. in water	g	652.7	648.2	650.8	655.6	668.5	657.3	672.3	642.7	663.7	669.3	671	675.1
f	Wt. surface dry	g	1165.7	1163.2	1172	1159.6	1178.4	1168	1181.1	1127.9	1171.4	1182.1	1175.4	1190
g	Volume,[f-e]	ml	513.0	515.0	521.2	504.0	509.9	510.7	508.8	485.2	507.7	512.8	504.4	514.9
h	binder content	%	4.5	4.5	4.5	5	5	5	5.5	5.5	5.5	6	6	6
i	bulk density,CDM,[d/g]	g/ml	2.27	2.26	2.24	2.30	2.31	2.28	2.32	2.32	2.31	2.30	2.33	2.31
j	SGM,[100/{(h/t)+((100-h)/u)}]	g/ml	2.49	2.49	2.49	2.47	2.47	2.47	2.46	2.46	2.46	2.44	2.44	2.44
k	Vol. of bitumen,[h*i/t]	%	9.92	9.86	9.81	11.14	11.21	11.08	12.39	12.39	12.31	13.42	13.57	13.46
l	Vol. of aggregate [(100-h)*i/u]	%	81.20	80.74	80.28	81.67	82.16	81.24	82.13	82.11	81.60	81.11	82.01	81.35
m	VMA ,[100-L]	%	18.80	19.26	19.72	18.33	17.84	18.76	17.87	17.89	18.40	18.89	17.99	18.65
n	VIM [100-(K+l)]	%	8.88	9.40	9.92	7.19	6.63	7.67	5.48	5.50	6.09	5.47	4.42	5.20
o	VFB, [100*K/M]	%	52.75	51.20	49.72	60.77	62.83	59.09	69.35	69.27	66.90	71.04	75.44	72.15
p	Measured stability	KN	13.4	9.15	9.7	12.6	11.3	11.8	12.4	10	12.3	11.6	12.7	13.1
q	Corrected stability	KN	12.7	9	9	12	11.4	11.4	11.7	10.4	12.3	10.9	12.7	12.1
r	Flow	mm	3.6	3.9	2.8	3.2	3.5	3.5	5.6	2.7	4.1	3.4	4	3.9
s	Quotient, [q/r]	KN/mm	3.5	2.3	3.2	3.8	3.3	3.3	2.1	3.9	3.0	3.2	3.2	3.1
t	S.G. of binder		1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
u	S.G. of aggregate		2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67

	Binder %		4.5%			5.0%			5.5%			6.0%		
	PET %		6% 1	6% 2	6% 3	6% 1	6% 2	6% 3	6% 1	6% 2	6% 3	6% 1	6% 2	6% 3
a	temperature compaction	C												
b	Diameter	mm	101.5	101.7	101.5	101.4	101.7	101.7	101.1	101.4	102.1	101.4	101.1	101.2
c	Thickness	mm	64	64.3	64.5	64.3	63.8	64.7	63	64.7	63.5	63	64	63.2
d	Weight in air	g	1164.2	1166.3	1157.4	1173.1	1177.2	1172.4	1161.4	1185.6	1171.4	1170.7	1177.9	1181
e	Wt. in water	g	659.8	660	640.2	663.1	666.8	657.3	660.4	669.5	656.8	670.8	674.8	672.6
f	Wt. surface dry	g	1165.2	1167.4	1158.6	1174.5	1177.8	1175.1	1161.9	1186.3	1172.2	1170.8	1178.1	1181.6
g	Volume,[f-e]	ml	505.4	507.4	518.4	511.4	511.0	517.8	501.5	516.8	515.4	500.0	503.3	509.0
h	binder content	%	4.5	4.5	4.5	5	5	5	5.5	5.5	5.5	6	6	6
i	bulk density,CDM,[d/g]	g/ml	2.30	2.30	2.23	2.29	2.30	2.26	2.32	2.29	2.27	2.34	2.34	2.32
j	SGM,[100/{(h/t)+((100-h)/u)}]	g/ml	2.49	2.49	2.49	2.47	2.47	2.47	2.46	2.46	2.46	2.44	2.44	2.44
k	Vol. of bitumen,[h*i/t]	%	10.06	10.04	9.75	11.14	11.18	10.99	12.37	12.25	12.14	13.64	13.63	13.52
l	Vol. of aggregate [(100-h)*i/u]	%	82.39	82.22	79.86	81.62	81.97	80.56	81.97	81.20	80.44	82.43	82.39	81.69
m	VMA ,[100-L]	%	17.61	17.78	20.14	18.38	18.03	19.44	18.03	18.80	19.56	17.57	17.61	18.31
n	VIM [100-(K+l)]	%	7.54	7.74	10.39	7.25	6.85	8.45	5.67	6.55	7.42	3.93	3.97	4.80
o	VFB, [100*K/M]	%	57.16	56.47	48.42	60.58	62.02	56.54	68.57	65.15	62.05	77.63	77.44	73.80
p	Measured stability	KN	13.2	13.4	11.2	12	11.9	9.6	13.7	13.6	9.8	13.2	13.4	12.6
q	Corrected stability	KN	12.6	12.8	10.6	11.4	11.6	9	13.9	12.8	9.8	13.3	12.9	12.7
r	Flow	mm	3.1	2.9	4	2.7	3.6	3.9	3.2	3.5	3.9	3.2	3.3	4
s	Quotient, [q/r]	KN/mm	4.1	4.4	2.7	4.2	3.2	2.3	4.3	3.7	2.5	4.2	3.9	3.2
t	S.G. of binder		1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
u	S.G. of aggregate		2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67

	Binder %		4.5%			5.0%			5.5%			6.0%		
	PET %		8% 1	8% 2	8% 3	8% 1	8% 2	8% 3	8% 1	8% 2	8% 3	8% 1	8% 2	8% 3
a	temperature compaction	C												
b	Diameter	mm	101.8	101.5	101	101.3	101.2	101.9	101.1	101.3	101.3	101.2	100.8	101.2
c	Thickness	mm	64.6	64.6	64.5	64.7	65.5	64.7	65.4	64.5	64.8	63.3	64.8	64.2
d	Weight in air	g	1163	1160.1	1154.7	1169.6	1164.9	1165.2	1180.9	1170.6	1174.6	1174.7	1177.4	1173.3
e	Wt. in water	g	642.7	642.3	644.6	652.8	648.8	654	657.8	653.1	661.3	665.8	660	663.8
f	Wt. surface dry	g	1164.3	1161.5	1156.7	1171.6	1166.4	1168.2	1183.2	1171.2	1176.7	1174.9	1178.6	1174.9
g	Volume,[f-e]	ml	521.6	519.2	512.1	518.8	517.6	514.2	525.4	518.1	515.4	509.1	518.6	511.1
h	binder content	%	4.5	4.5	4.5	5	5	5	5.5	5.5	5.5	6	6	6
i	bulk density,CDM,[d/g]	g/ml	2.23	2.23	2.25	2.25	2.25	2.27	2.25	2.26	2.28	2.31	2.27	2.30
j	SGM,[100/{(h/t)+((100-h)/u)}]	g/ml	2.49	2.49	2.49	2.47	2.47	2.47	2.46	2.46	2.46	2.44	2.44	2.44
k	Vol. of bitumen,[h*i/t]	%	9.74	9.76	9.85	10.94	10.93	11.00	12.00	12.06	12.17	13.44	13.23	13.37
l	Vol. of aggregate [(100-h)*i/u]	%	79.75	79.92	80.65	80.21	80.08	80.63	79.55	79.97	80.66	81.23	79.93	80.82
m	VMA ,[100-L]	%	20.25	20.08	19.35	19.79	19.92	19.37	20.45	20.03	19.34	18.77	20.07	19.18
n	VIM [100-(K+l)]	%	10.51	10.32	9.50	8.84	9.00	8.37	8.45	7.97	7.17	5.32	6.85	5.81
o	VFB, [100*K/M]	%	48.11	48.61	50.91	55.31	54.84	56.78	58.69	60.23	62.93	71.63	65.89	69.72
p	Measured stability	KN	9.1	12.1	10.3	12.7	9.7	8.7	11.2	11.2	10.6	14.8	11	11.3
q	Corrected stability	KN	8.7	11.6	9.8	11.9	8.9	8.1	10.3	10.6	9.9	14.9	10.3	10.8
r	Flow	mm	4.4	4	3.1	2.9	3	3.8	3	3.3	3.3	4	3.4	4.5
s	Quotient, [q/r]	KN/mm	2.0	2.9	3.2	4.1	3.0	2.1	3.4	3.2	3.0	3.7	3.0	2.4
t	S.G. of binder		1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
u	S.G. of aggregate		2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67

	Binder %		4.5%			5.0%			5.5%			6.0%		
	PET %		10% 1	10% 2	10% 3	10% 1	10% 2	10% 3	10% 1	10% 2	10% 3	10% 1	10% 2	10% 3
a	temperature compaction	C												
b	Diameter	mm	101.6	100.9	101.1	101.6	101.2	101.3	101.6	101.4	101.6	101.4	101.3	101.1
c	Thickness	mm	63.8	65.5	65.2	64.4	64.8	64.2	64.7	64.3	64.4	64.6	64.4	64.4
d	Weight in air	g	1164.2	1164.2	1160.3	1165.1	1165.5	1161.6	1180.8	1175.3	1179.1	1177.7	1179.6	1171.8
e	Wt. in water	g	646.4	642	641.8	647.3	647.4	648.6	660.3	656	663.1	660.4	663.3	660
f	Wt. surface dry	g	1165	1165.5	1161	1166.2	1165.9	1163.3	1182.1	1176.6	1180.9	1178.2	1180.5	1173.2
g	Volume,[f-e]	ml	518.6	523.5	519.2	518.9	518.5	514.7	521.8	520.6	517.8	517.8	517.2	513.2
h	binder content	%	4.5	4.5	4.5	5	5	5	5.5	5.5	5.5	6	6	6
i	bulk density,CDM,[d/g]	g/ml	2.24	2.22	2.23	2.25	2.25	2.26	2.26	2.26	2.28	2.27	2.28	2.28
j	SGM,[100/{(h/t)+((100-h)/u)}]	g/ml	2.49	2.49	2.49	2.47	2.47	2.47	2.46	2.46	2.46	2.44	2.44	2.44
k	Vol. of bitumen,[h*i/t]	%	9.81	9.72	9.76	10.90	10.91	10.96	12.08	12.06	12.16	13.25	13.29	13.30
l	Vol. of aggregate [(100-h)*i/u]	%	80.29	79.54	79.93	79.89	79.98	80.30	80.09	79.90	80.60	80.07	80.30	80.39
m	VMA ,[100-L]	%	19.71	20.46	20.07	20.11	20.02	19.70	19.91	20.10	19.40	19.93	19.70	19.61
n	VIM [100-(K+l)]	%	9.90	10.74	10.30	9.21	9.11	8.74	7.82	8.04	7.25	6.68	6.42	6.31
o	VFB, [100*K/M]	%	49.77	47.50	48.66	54.20	54.50	55.61	60.70	59.99	62.66	66.49	67.43	67.82
p	Measured stability	KN	12.8	11.8	10.3	12.1	11	10.3	12.5	10.6	10.7	10.4	10.8	10.5
q	Corrected stability	KN	12.6	10.8	9.6	11.4	10.3	9.8	11.8	10.2	10.1	9.9	10.2	9.9
r	Flow	mm	3.3	3.9	3	3.1	3.7	3.3	3.4	3.2	3.2	3.3	3.6	3.5
s	Quotient, [q/r]	KN/mm	3.8	2.8	3.2	3.7	2.8	3.0	3.5	3.2	3.2	3.0	2.8	2.8
t	S.G. of binder		1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
u	S.G. of aggregate		2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67

APPENDIX F

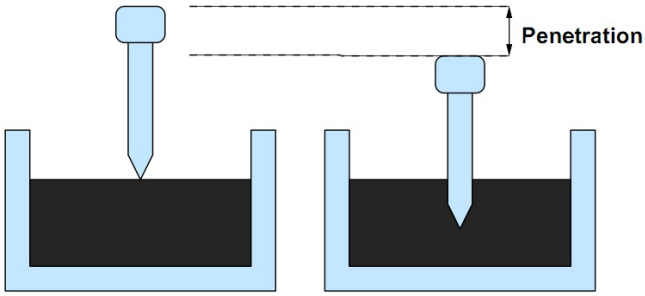
MATERIAL AND

EQUIPMENT

PHOTOGRAPHS

Penetration Test Apparatus

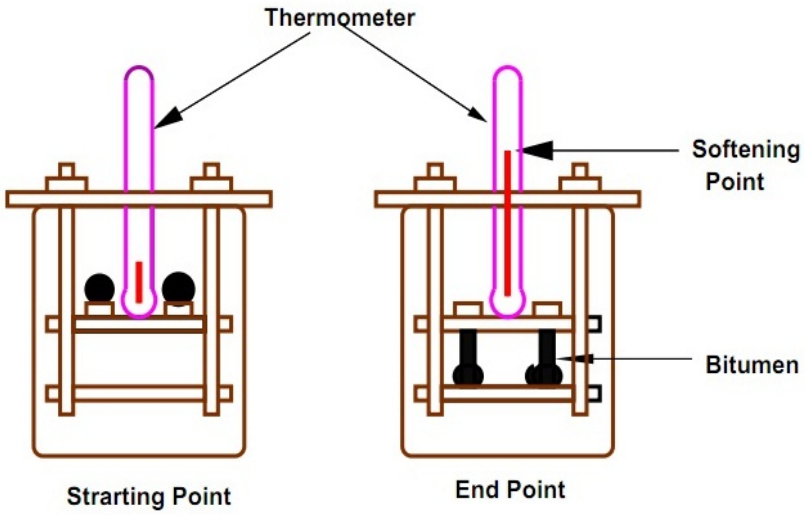
Penetration Test Samples



Penetration Test Set up

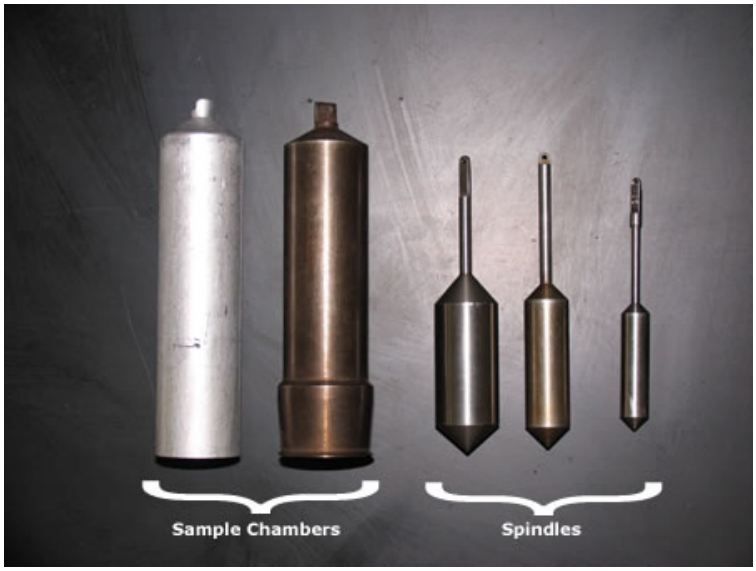
Softening Point Test Apparatus

Softening Point Test Simples



Softening Point Test Set up

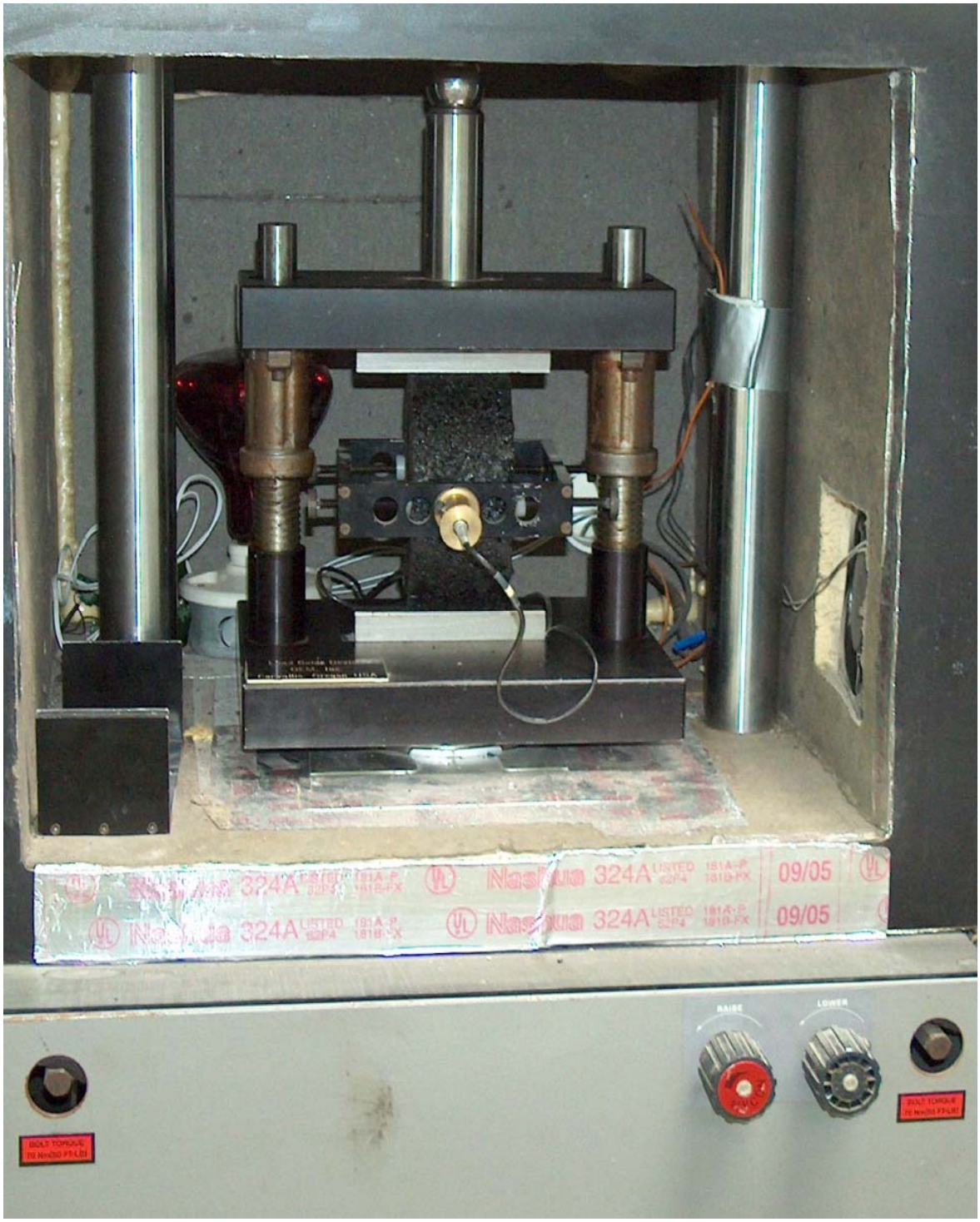
Viscosity Test Apparatus



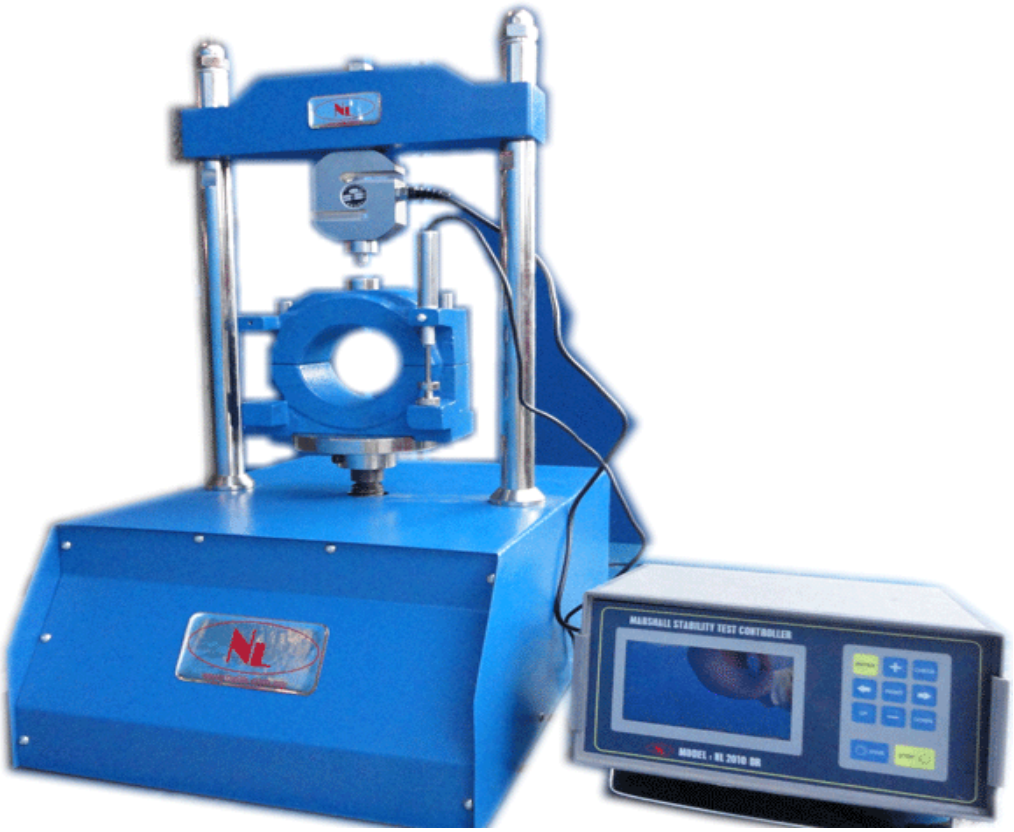
Viscosity Test Sample Chambers and Spindles

DSR Test Apparatus

DSR Test Samples



Indirect Tensile (IDT) Test Apparatus



Marshall Test Apparatus

Indirect Tensile and Marshall Test Samples

Crasher Apparatus

PET Samples