Hybrid Reinforcement of Asphalt-Concrete Mixtures Using Glass and Polypropylene Fibers

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Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the Degree of

Master of Science
in
Civil Engineering

Eastern Mediterranean University
June 2010
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

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ABSTRACT

In recent years, research has been devoted to modify the properties of bitumen and improve the performance of the flexible pavements. Use of different fibers in mixtures is known as beneficial HMA (hot mix asphalt) modifier. Although applying these modifiers increases the initial cost, they may increase pavement resistance for rutting therefore, postpone the rehabilitations and decrease maintenance cost.

In this research, effect of polypropylene (pp) additive at two lengths (6 and 12mm) on properties of asphalt cement was examined. Three percent of pp were used: 2, 4 and 6% by weight of asphalt were added to unmodified asphalt (wet base) at optimum asphalt content of 4.3%. Penetration, softening point and ductility tests were applied to pp modified asphalt cement and the results were compared with unmodified asphalt cement. Also, three different percent of glass fiber: 0.05, 0.1 and 0.2% by weight of aggregate with 12mm length was selected as a second fiber for the pp modified bitumen mixture (dry base).

Since glass fiber has smooth surface area with extreme tensile strength potential (more than 60000MPa) and pp provides good adhesion with asphalt cement, glass fiber was added to pp modified asphalt mix to increase the internal friction of glass fiber with other materials. All of the specimens were made and compacted by Superpave Gyratory Compactor (SGC) apparatus and then analyzed by Marshall Method and finally tested by Marshall Stability test.

Results indicate that pp modified bitumen reduced penetration value and increased softening point value compared to unmodified asphalt, which may result in increased rutting resistance of the modified mixtures and resistance to traffic-induced deformation at high temperatures. Also, pp additive caused ductility value to decrease.

Marshall test indicated that pp additive can affect the properties of the mix. Use of 0.1% glass fiber plus 6%pp presented the best hybrid reinforcement by increasing stability and decreasing flow value for both of pp lengths.

Keywords: Polypropylene (pp), Glass Fiber, Marshall Stability, Hybrid Reinforcement.

ÖZ

Son yıllarda asfalt çimentosu özelliklerini artırmaya yönelik ve asfaltın esnekliğini geliştirmeye yönelik araştırmalar yapılmıştır. Karışımlarda farklı liflerin kullanılması asfalt karışımına faydalar sağlamıştır. Bu malzemenin karışıma eklenmesiyle birlikte ilk fiyatı değerinde artış olmakta fakat ağır vasıta yükleri altında gösterdiği yüksek performans onun zaman içerisinde bakım ve onarıma gidecek olan giderini düşürecektir.

Bu çalışmada iki farklı uzunluktaki (6 ve 2 m) polypropylene liflerini asfalt özelliklerine yaptığı etki araştırılmıştır. Ağırlıkça asfaltın 2, 4 ve 6 % si kadar lifler 4.3 % asfalt karışıma katılmıştır. Bu asfalt karışımlarına penetrasyon, yumuşama noktası ve düktilite deneyleri yapılmış ve normal asfalt karışımı ile sonuçları karşılaştırılmıştır. Ayrıca ikinci lif olarak agrega ağırlığının yüzdelikce 0.05, 0.1 ve 0.2 % oranında 12 mm uzunluğunda cam liflerde karışıma eklenmiştir. Cam liflerinin yüzeyinin düzgün olmasından ve gerilme gücü potansiyelinin 60000 MPa dan daha fazla ve pp liflerinin asfalt ile sağladığı iyi referans ile birlikte pp liflerinin karışıma eklemesi ile cam liflerinin diğer karışım malzemeleri arasındaki bağ gücünü artırmıştır. Tüm numuneler Superpave Sıkıştırma cihazı ile sıkıştırıldı. Marshall metodu ile analiz edilip son olarak Marshall Stabilite ve akma deneyine tabii tutulmuştur. Sonuç olarak görülüyor ki pp modifiyeli karışımların geçirgenlik değerinin düşük olduğu ve yumuşama noktası değeri normal asfalt ile karşılaştırıldığında pp modifiyeli asfaltın değeri normal asfalt ile karşılaştırıldığında pp modifiyeli asfaltın değeri yüksek olduğu ve bu sonuçla birlikte pp modifiyeli asfaltın tekerlek izi direnci yüksek sıcaklık altında deformasyon resistansının yüksek olması beklenmektedir. Ayrıca pp lifleri duktiliteyi azaltmaktadır.

Marshall testi sonuçlarına göre pp katkısı karışımın özelliklerini etkilemektedir. Karışımda 0.1 % cam lifi ve 6 % oranında pp lifi kullanılması karışımının stabilitesini artırmakta ve her iki farklı pp uzunluğunda karışımın akış değerinin düştüğü görülmüştür.

Anahtar kelimeler: Polypropylene, Cam lif, Marshall Stabilite ve Akma, Hibrid Donatı

To

My Family

ACKNOWLEDGMENTS

I would like to thank my supervisor Asst. Prof. Dr. Mehmet M. Kunt for his support in the preparation of this study, appreciate Asst. Prof. Dr. S. Mahdi Abtahi, my co-supervisor, and PhD student S. Mahdi Hejazi for their help in various issues of this thesis.

Ogun Kilic, laboratory engineer who helped me a lot in the laboratory during this study. A number of friends had always been around to support me and I should appreciate them for their help and also, Highway Department of North Cyprus for providing Asphalt cement for this experiments.

I owe quite a lot to my family who supported me all throughout my studies, I like to dedicate this study to them as an indication of their significance in this study as well as in my life.

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Chapter 1

INTRODUCTION

1.1 Introduction

Hot mix asphalt is one of the common flexible pavement types used for most pavement constructions. Approximately 96% of all the paved surfaces are constituted by hot mix asphalt (HMA) in the United States (Copeland , A.R, 2007). The asphalt cement concrete mixtures included aggregate to tolerate the anticipated traffic loads and asphalt cement to bind all materials in the mix and provide flexibility to the mixture.

Many studies were carried out to find out the effect of different shapes and types of aggregate on the mixtures; Chen *et al.,* (2001) examined consequence of various shape of aggregate on the performance of the mix. They found that cubical particles have the highest rutting resistance. In another research, Huang *et al.* (2009) mentioned that by increasing coarse aggregate fractured faces, rutting resistance of mix will increase. Moreover, various types of gradation such as stone matrix asphalt (SMA) were introduced to develop the performance of asphalt mixtures.

On the other hand, role of asphalt cement in the performance of mixtures is undeniable. The grade of asphalt cement which can be obtained by penetration or viscosity is so important factor to select proper asphalt cement according to climate and environmental condition. It should be mentioned that most of the distresses in asphalt pavements are derived from some weak properties of the asphalt cement. Many studies have been carried out to modify the asphalt cement properties. Various types of polymers were applied to modify the bitumen characteristics. They are called polymer modified asphalt (PMA). In addition, use of different fibers to improve the performance of the mixtures has been increased in over last decade. Most of the fiber-reinforcement asphalt concrete (FRAC) can improve the tensile strength and stiffness of the mixtures and also increase cohesion bond of the asphalt cement. The common fibers which are used to improve the properties of mixtures are asbestos, polyester, polypropylene, carbon, glass, nylon (Abtahi, S. M., Sheikhzadeh, M., Hejazi, S. M., 2009b). Previous studies illustrate that use of two fibers simultaneously in the asphalt-concrete pavement have been not examined, these fibers may improve weak properties of the mix and assist to improve the performance of the mixture.

1.2 Objectives and Scopes

The purpose of this study is, improving workability and performance of the hot mix asphalt (HMA), by using polypropylene (pp) additive and glass fiber to increase stability and decrease the flow value. Use of pp in wet base was examined by Tapkin *et al.*, (2009). The results indicated that addition of pp increased Marshall Stability and stiffness of the specimens and also increased the life of samples under creep testing. In a research program, Hejazi found that pp has excellent performance due to low melting point in the asphalt concrete. This result, which was proved by Artificial Neural Network (ANN) and matched with his experiment, showed a phenomenon called "tackiness", glues pp fiber to the matrix (Hejazi, , 2007).

On the other hand, properties of the glass fiber indicate an extremely high tensile modulus (more than 60000 MPa) that can influence the properties of the asphalt concrete. However, it seems that all potential of tensile strength of the glass fiber does not properly participate in the mix due to smooth and brittle surface of the glass fiber which causes low internal friction between aggregate and the fiber.

In this thesis the effect of pp (wet method) on HMA will be investigated to answer these two important and vital questions:

-Will the pp fiber enhance the asphalt binder properties and cause aggregate particles and glass fibers glue together to improve the tensile strength and consequently increase the stability of mixture?

-Will the use of these fibers (pp-glass) improve the performance and workability of the composite?

1.3 Organizations

Chapter 1: The introduction, objectives and scopes.

Chapter 2: This chapter contains literature review concerning brief explanation about asphalt and aggregate, also Hot Mix Asphalt (HMA), and effect of polymers and fibers especially polypropylene additive and glass fiber-reinforcement on the asphalt concrete.

Chapter 3: Present methodologies includes different tests which have been accomplished on aggregates, asphalt, modified asphalt, and hot-mix asphalt, mix design and procedure of using polypropylene and glass fiber.

Chapter 4: This chapter consists analysis of the data, tables and figures.

Chapter 5 is about discussion and conclusion.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter is focused on describing asphalt cement and aggregates, their use in pavements and applicable tests. Some important distresses such as rutting, raveling and various types of cracks will be discussed briefly. Then, two methods: use of polymers and fibers for modification and improvement of the properties of the asphalt cement and HMA mixture will be introduced. Finally, effect of two useful fibers polypropylene (pp) and glass fiber on HMA will be examined.

2.2 Asphalt

Asphalt cement is one of the old materials that have been used since about 6000 B.C in Sumeria (Roberts *et al*., 1991). From that time up to now, asphalt cement has been applied for various applications such as thriving shipbuilding, mortar in building, waterproofing in very different purpose and road (Asphalt Institute, 1989)

Asphalt is either obtained from refining crude oil or from natural source. Nowadays, because of the good quality of refined asphalt almost all of the asphalt types, which are used in the field, are obtained by petroleum distillation (Roberts *et al*., 1991).

2.2.1 Consistency

Consistency of the asphalt cement is one of the important properties of asphalt cement. Since the consistency of asphalt cement changes with changing of the temperature, it is necessary to measure and determine the grade of bitumen (consistency). There are some tests for measuring the consistency of the asphalt cement such as viscosity and penetration.

2.2.1.1 Penetration Test

According to ASTM D5 penetration test is an empirical test to determine the consistency of asphalt cement. A container filled with asphalt cement is placed in a water bath to reach the specified temperature which is usually 25ºC (77 ºF) because it is near to the average service temperature of HMA mixtures. The container is placed under a specified needle which is weighted with 100 grams. The needle is permitted to penetrate the asphalt cement for exactly 5 seconds. The distance that needle is penetrated into the sample is measured in units of 0.1 mm. Five common penetration grades for asphalt cement are: 40-50, 60-70, 85-100, 120-150, and 200-300. The asphalt cement with penetration of 40-50 is hardest and the softest asphalt is 200-300 (Roberts *et al*., 1991).

2.2.1.2 Viscosity Test

It is clear that the viscosity of the asphalt cement is very essential to distinguish, since the viscosity plays the main role in selection of the mixing and compaction temperature. The viscosity of asphalt cement is measured at two different temperatures; Absolute viscosity at 60ºC (140ºF) and Kinematic viscosity at 135ºC (275ºF).

The temperature of the absolute viscosity was selected at 60ºC (140ºF), because "this temperature approximates the maximum HMA pavement surface temperature during the summer in the United States. (Roberts *et al*., 1991, p.21) Some specified viscometers are used to determine the absolute viscosity such as "Saybolt Furol Viscometer" (Garber, N., Hoel, A., 2010) "Cannon-Manning vacuum viscometer and the Asphalt Institute vacuum viscometer." (Roberts *et al*., 1991).According to the ASTM D2171 the time in which asphalt cement flows between two certain lines (timing marks) is recorded in seconds. By multiplying the recorded time by the calibration factor, which is obtained from a standard material, the viscosity of the asphalt cement is calculated in poises. The following relation is applied to find the viscosity:

$$V_2 = (—)\ T_2 \qquad (2.1)$$

Where,

V_1= viscosity of standard material;

T_1= time for standard material to pass through the tube;

V_2= viscosity of unknown material

T_2= time for unknown material to pass through the same tube

The procedure of the Kinematic viscosity is similar to Absolute viscosity according to ASTM D2170 the time required for asphalt cement at 275ºF to pass the distance between two timing marks are measured in seconds. The viscosity of the asphalt cement is calculated in centistokes by multiplying the calibration factor to the recorded time. It should be mentioned that the selected temperature (275 ºF) is close to mixing and compaction temperature and it can help to estimate the consistency of the asphalt cement at mixing and laydown condition (Roberts *et al*., 1991).

2.2.1.3 Softening Point

Softening point or ring and ball test is applied to determine at what temperature the phase change happens in the asphalt cement. According to the ASTM D36 brass ring is filled with a sample of asphalt cement. A steel ball with specified diameter and weight is loaded on the center of the ring. The ring is suspended in a beaker filled with water that is maintained at 5ºC. The beaker is heated by rate of 5 ºC/min. By increasing the temperature, asphalt cement becomes softer and the steel ball gradually sinks to the asphalt cement, at the moment asphalt cement completely sinks and touches the plate the temperature is recorded as the softening point (Garber, N., Hoel, A., 2010).

2.2.2 Aging Test

Aging phenomenon is a very important rheological property in asphalt cement. The main factors which cause age hardening in asphalt cement are:

- Oxidation
- Volatilization
- Polymerization
- Thixotropy
- Syneresis
- Separation

There are two methods to find the short-aging test of the asphalt cement; Thin Film Oven Test (TFO) and Rolling Thin Film Oven Test (RTFO) (Roberts *et al*., 1991).

2.2.2.1 Thin Film Oven Test (TFO)

According to ASTM D1754, 50 grams of asphalt cement is placed in a thin cylindrical pan. The pan is placed in an oven to keep temperature at 162.8°C (325 ºF). Then, samples start to rotate with an approximate rotation of 5 to 6 revolutions per minute (RPM), which is continued for 5 hours. When the test is completed, the penetration, viscosity and weight of the aged asphalt cement are measured. All of these parameters should be in a specified range according to ASTM (Roberts *et al*., 1991).

2.2.2.2 Rolling Thin Film Oven Test (RTFO)

The purpose of this test is the same with thin film oven test. The known amount of the asphalt cement is poured in the bottles which are in the oven at 162.8°C (325 ºF). The bottles are rotated and correspondingly, opening of each bottle is passed from the heated air jet. The time of the test is 75 min which is less than the TFO. At the end the viscosity, penetration and weight should be measured. The retained penetration, the viscosity of the aged asphalt and the gaining and losing of the weight must satisfy all the limitations and ranges according to ASTM D2872. (Roberts *et al*., 1991)

2.2.3 Purity Test

According to ASTM D2042 for measuring the purity of asphalt cement a known weight of asphalt cement is dissolved in trichloroethylene, and then it is passed through a glass fiber pad. Retained material should be washed and dried and weighted .the weight of the insoluble materials should not be exceeded 1 percent (Asphalt Institute, 1989).

2.2.4 Safety Test

Since by heating the asphalt cement some volatiles are released and these volatiles can produce flash in the presence of an open flame, it is necessary to determine the temperature at which asphalt cement can be heated without any dangerous of instantaneous flash.

Asphalt cement is poured in a specified open cup. While the asphalt cement is heating, a flame is passed over the surface of the asphalt cement occasionally. When the vapors cause a flash occurs, the temperature should be recorded as the flash point. (Placeholder2)

2.2.5 Other Tests

2.2.5.1 Ductility

Ductility test is an important property of the asphalt cement and there is a special extension type of machine to determine this property. According to ASTM D113 the temperature of the test is usually 25ºC (77ºF). Asphalt cement is poured to a standard mold and then placed in the ductility machine test. The extension with rate of 5 cm/min is applied until rupture. The specific gravity of water is supposed to be equal to the asphalt cement specific gravity to avoid sinking and floating of sample. For this purpose, it can be used alcohol to decrease or salt to increase the specific gravity of the water (Roberts *et al*., 1991).

2.2.5.2 Specific Gravity

The pycnometer method is commonly used to determine the specific gravity. Usual temperature of the specific gravity test is 25ºC (77ºF). The specific gravity of the materials gives the relation between volume and weight of the materials and defines as the ratio of the weight of the given volume of the material at specified temperature to the weight of an equal volume of water at the same temperature.

2.3 Aggregate

Aggregate plays a major role in pavements by occupying about 85 percent of the mixture by volume. Aggregate particles are in charge of load bearing in the HMA mixture. Therefore, physical and chemical properties of the aggregate are significantly important and will have considerably effect on the behavior and life of the HMA (Asphalt Institute, 1989).

The physical property is related to length, width dimension, mass, volume of the aggregate particles. There are some significant properties which are reported as physical property of aggregate such as particle shape, maximum particle size, particle surface texture, absorption, permeability, specific gravity, void in aggregate mixture, resistance to Wetting-drying, resistance to freezing-thawing, deleterious substances (Barksdale, R., 1991)

On the other hand, it should be noticed that the chemical properties of the aggregate such as solubility, surface charge, resistance to attack by chemicals, chemical compound reactivity is important and trigger the performance of the HMA (Barksdale, R., 1991).

2.3.1 Type of Aggregate

Most of aggregates used in the pavements are natural and crushed rock aggregate (Barksdale, R., 1991). The three common natural rocks are Igneous, Sedimentary, and Metamorphic which are applied in construction industry. Moreover, other types of aggregate, called artificial aggregate, are occasionally used in HMA. Slag and lightweight aggregate are two popular types of artificial aggregate (Roberts *et al*., 1991).

2.3.1.1 Igneous Rocks

By the cooling and solidification of the hot molten magma on the surface of the earth, igneous rocks are shaped. These types of rocks generally are crystalline and can be found either basic or acidic. Granit, Gabbro, Basalt are some examples of igneous rock. The igneous rocks can be discriminated by determining their composition (Roberts *et al*., 1991).

Table 1: Classification of Igneous Rocks

	Acidic	Intermediate	basic
Silica	>66	55-66	<55
Specific Gravity	<2.75	_	>2.75
Color	light	_	Dark
Presence of free quartz	yes	_	No

Source: (Roberts *et al*., 1991)

2.3.1.2 Sedimentary Rocks

Sedimentary rocks can be formed by the deposition of the remains of animals and planets or sediment of the collapse of other rocks; or result of chemical action. Sedimentary rocks are categorized base on the mineral aggregate such as calcareous and siliceous (Asphalt Institute, 1989).

2.3.1.3 Metamorphic Rocks

Metamorphic rocks are created by igneous and sedimentary rocks when they have been under severe pressure and excessive heat by earth movement. These processes result in changing property of mineral structure of igneous and sedimentary rocks and bring about different material called metamorphic rock (Roberts *et al*., 1991).

2.3.1.4 Slag

Generally slag is generated during the production of the steel. Most properties of the slag are similar to igneous racks, these slag aggregate is used commonly in the mixtures. The asphalt content increases when slag is used as aggregate in the mix, compare with the usual aggregates.

2.3.2 Aggregate Property

2.3.2.1 Chemical Properties of Aggregate

The chemical properties of aggregate impact the amount of asphalt cement around the aggregate particles in a mix and play a significant role in stripping asphalt cement from surface of aggregate particles. The Aggregate is divided to two categories in this area: Hydrophilic and Hydrophobic.

Hydrophilic aggregates show more compatibility to water than the asphalt cement and tend to absorb moisture in the presence of water. Hydrophilic or water-loving aggregates have high potential to become stripped in HMA. In contrast, hydrophobic aggregates have high attraction to the asphalt cement than water. Stripping resistance of hydrophobic or water-hating aggregate is better than the hydrophilic aggregate. It should be mentioned that electric charge of aggregate surface can significantly affect stripping resistance of aggregate particles and mixture (Roberts *et al*., 1991).

2.3.2.2 Physical Properties of Aggregate

Generally, aggregate particles are divided to fine and coarse aggregate by using sieve number 4. Coarse aggregate can be defined as particles larger than No.4 (4.75 mm) sieve and fine aggregate as smaller particles passing No.4 sieve.

All aggregate particles should satisfy some specified standard test level to be suitable for applying in HMA. Some of the important tests are:

- Toughness and abrasion resistance
- Durability and soundness
- Particle shape and surface texture
- Plasticity index
- Sand equivalent test
- etc

Aggregate particles should be in the specified range for each test according to ASSHTO or ASTM to be desired for HMA (Roberts *et al*., 1991).

One of the vital physical properties of aggregate is specific gravity and absorption of coarse and fine aggregates which can be defined as “the ratio of the weight of a unit volume of material to the weight of the same volume of water at 20 to 25°C (68 to 77°F)” (Asphalt Institute, 1989). Specific gravity and absorption of aggregates is essential to measure for obtaining the weight-volume relationship of the HMA. Apparent (G_{sa}), Bulk (G_{sb}) and Effective specific gravity(G_{se}) of the aggregates can be achieved for both coarse and fine aggregate by applying some tests and simple calculations accordance with ASTM C127 and ASTM C128, respectively.

2.3.2.3 Size and Gradation

Aggregate size and gradation is one of the important factors in pavements and can influence most properties of HMA mixture. Gradation or distribution of particle sizes can be achieved by passing the aggregate particles through the standard sieve stacked and calculating the percent of retained aggregate on each sieve (US Army Corps of engineers, 2000, p. 16).Control the material and select desirable size, minimize cost, and optimize use of local available aggregate are some main aims of the gradation. (Asphalt Institute, 1989). The 0.45 power chart is used to provide best gradation for maximum density (Asphalt Institute, 1996). A few common terms are described to classify aggregate gradation:

Well-graded or Dense-graded: well-graded gradation is common gradation which is used in the United States. It is permissible that densest gradation presents increase in stability and reduction in void. The range of nominal maximum size for well-graded gradation changes in 12.5mm to 19.0mm (US Army Corps of engineers, 2000, pp. 3-4).

Open-graded or Uniformly-graded: open-graded refers to gradation that contains a narrow size of particle aggregate (uniform grading). Generally, Amount of Air void is high in this gradation because of lack of small particles to fill the void between larger particles. The main purpose of open-graded gradation is preparation a drainage layer at the pavement surface. The major difference production between open-graded and dense –graded is lower temperature compaction. The lower compaction effort is applied for open-graded to prevent draindown of the asphalt cement. It should be mentioned that use of polymers and fibers in open-grade mixes can reduce draindown and develop durability of mixtures (US Army Corps of engineers, 2000).

Gap-graded: gap-graded refers to gradation that contains coarse and fine aggregate with some intermediate size missing. Gap-graded mixes are like dense-graded mixes to provide impervious layers when compacted appropriately (US Army Corps of engineers, 2000). The following figure shows different aggregate classification:

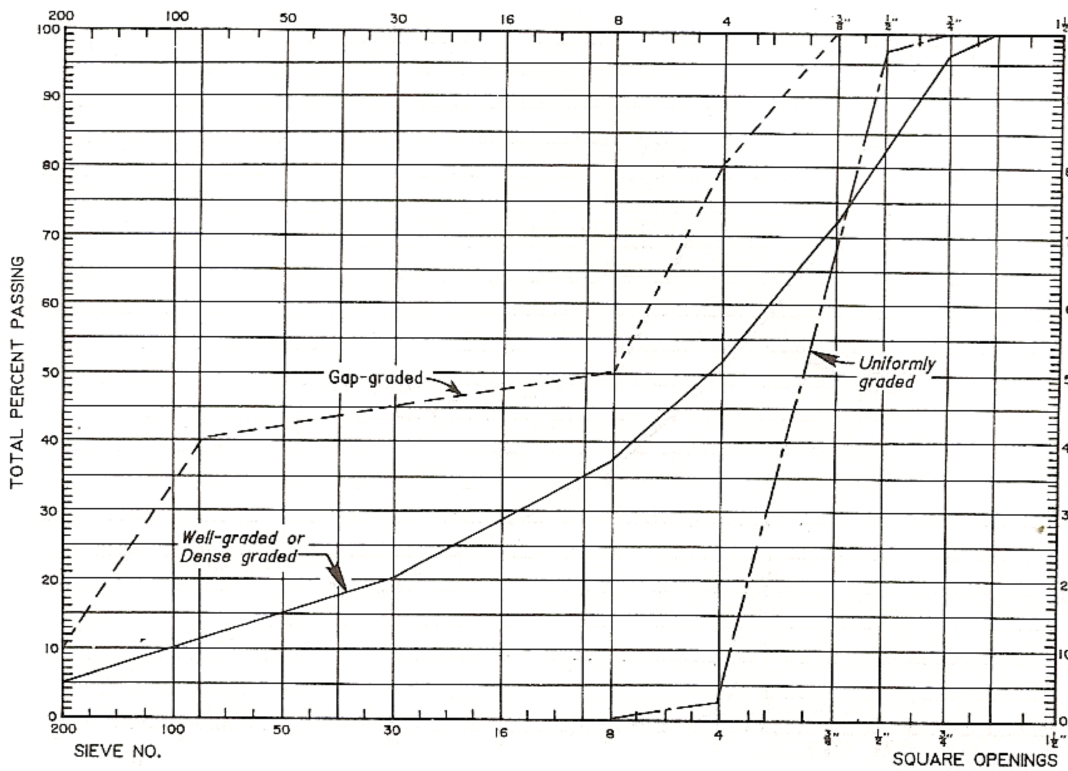


Figure 1: Typical Terms Used to Identify Aggregate Gradations
Source:(Roberts et al., 1991**).**

2.4 Distress in HMA

HMA, like other kind of paving materials experiences different distress during its service life. These various distresses can extend due to traffic load repetitions or different environmental conditions such as temperature, moisture, etc.

Some common types of distresses that may occur during the life of flexible pavements will be briefly described and discussed below.

2.4.1 Stripping

Moisture induced damage or stripping can be defined as loss of adhesive bond between asphalt film thickness and aggregate surface in the presence of water (Roberts *et al*., 1991). As it can be seen in below figure by penetrating water between aggregate and asphalt cement breaking adhesive bond occurs.

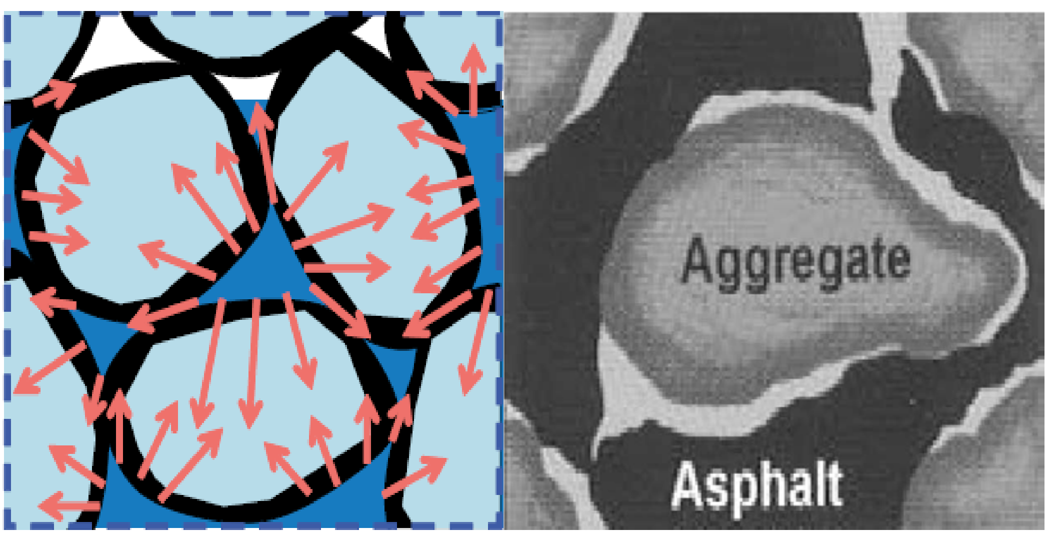


Figure 2: Loss Of Adhesive Bond in The Presence of Water Between Aggregate and Asphalt
Surce:(Logaraj, .S, 2004)

Generally, stripping starts at the bottom of the asphalt mixture layer and develops through upward. Stripping is a complex distress and it is not easy to be recognized because surface of HMA can take many forms such as rutting, raveling, corrugations or cracking. Hence, the best precise way to recognize this distress is to open up the pavement surface layer and consider the material from cross-section (Roberts *et al*., 1991). Many variables can effect on the moisture damage: aggregate and asphalt characteristics, weather condition, compaction, air void, testing method and etc (Abo-Qudais, 2005). Many investigations were carried out to prevent or minimize the stripping potential in the HMA mixtures. Using hydrophobic aggregates (water-hating) which show great affinity to the asphalt than water, like limestone, instead of hydrophobic aggregate (water-loving) like siliceous aggregates, may reduce amount of stripping potential in the pavement mixtures. In addition, numerous investigators have been mentioned that applying anti-stripping agent can minimize stripping (Atakan,et al,. 2004; Hao, P.; Liu, H, 2006; Tienfuan. et al,. 2005). In North Cyprus generally crushed lime stone is used in HMA.

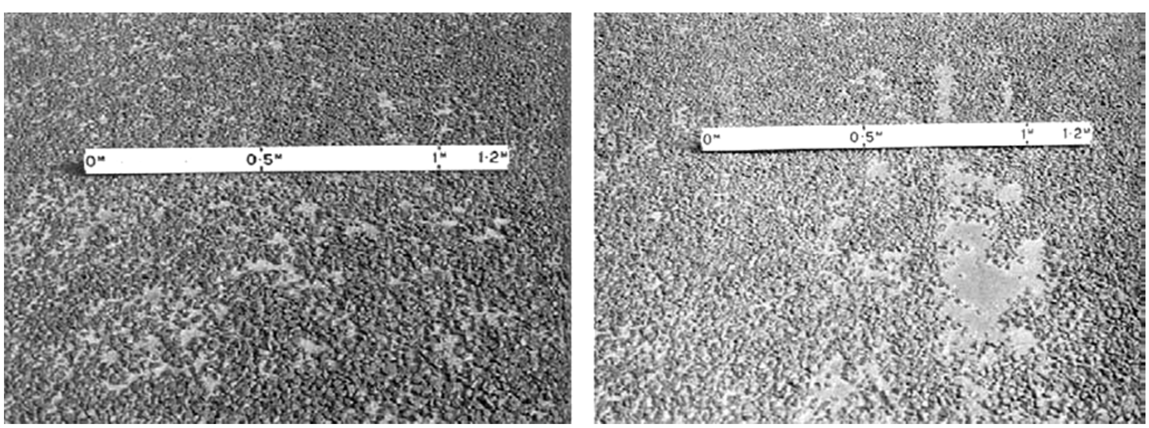


Figure 3: Stripping in Flexible Pavements
Source: (Taylor&Francis & T.F.FWA, 2006)

2.4.2 Raveling

Raveling is a breakup of the materials consist aggregate particles and binder from each other in the surface of HMA. Loss of asphalt binder starts at the surface of pavements and progresses downward. Raveling may occur due to a) inadequate asphalt content b) lean asphalt mix design c) insufficient compaction (high percent of air void) and also it should be mentioned that aging and particularly oxidation can cause asphalt cement to become brittle and results in raveling distress (Roberts *et al*., 1991).

Figure 4: Loss of Coarse Aggregate
Source: (Miller ; Bellinger, 2003)

Figure 5: High Severity Raveling
Source**:** (Miller ; Bellinger, 2003)

2.4.3 Cracking

Various reasons cause cracks occur during the service life of HMA mixture. Some of these reasons could be axle load stresses, temperature changes in HMA and underlying layers, moisture, etc. In order to different types of cracks, it is essential to identify accurate cause of each crack to select proper technique for repairing. Some of common and important types of cracks will be discussed in next section (Roberts *et al*., 1991).

2.4.3.1 Fatigue cracking (Alligator cracking)

Fatigue distress cracking is one of the major reasons for the failure of structural components of pavements. Fatigue cracking is usually called alligator cracking because this kind of crack is similar to alligator's back. Cracking can be divided into two categories: load associated cracking and non-load associated cracking.

Fatigue cracking is typically associated with load, this type of failure occurs when either too heavy loads are applied on the pavement or asphalt concrete experiences too repetitive axle load applications which do not exceed in strength of materials. Consistency of the asphalt cement in mixture, amount of the asphalt cement content, air void, aggregate characteristics, traffic load and some local conditions such as temperature and moisture can effect on developing of fatigue cracking (Roberts *et al*., 1991). One of the main parameters for designing flexible pavements is to limit the tensile stress particularly at the bottom of pavement layer, to minimize the fatigue distress cracking (Dong-Yeob, P., Neeraj ,B., Young-Chan ,S., 2001). The process of fatigue failure is difference in thin and thick asphalt pavements. In pavements with less than 2 in thickness (thin pavement), high tensile strain at the bottom layer of the HMA cause to fatigue cracking start to develop upward to the top of HMA, whereas in pavements with more than 6 in thickness (thick pavement), high tensile stress at the surface of HMA generates fatigue cracking.

Fatigue cracking starts with one or more longitudinal parallel cracks at the surface of pavement and under repeated loading, cracks extend and connect to each other and alligator cracking is formed. When cracks occurred, moisture can easily penetrate into structural component and deteriorate in other failures. Fatigue cracking may cause to the development of potholes by separating and dislodging materials at the surface of HMA under traffic loads, if no repair strategy is considered for fatigue cracking failure (Roberts *et al*., 1991). Next figure shows a pothole which is generated by developing the alligator cracking.

Figure 6: Pothole Surrounded by Alligator Cracking
source: (Federal Highway Administration, 2006-2009)

Figure 7: Low Severity Alligator Cracking
Source:(Federal Highway Administration, 2006-2009)

Fatigue cracking is classified in three severity levels: low, medium, and high. A combination of crack width and crack form should be applied for determining severity level of alligator cracking (Federal Highway Administration, 2006-2009).

Low severity: cracks are less than 0.25 in (6mm) mean width with very few interconnecting cracks, Figure 7 illustrates low severity alligator cracking.

Medium severity: interconnected cracks are distinguished; cracks are more than 0.25 in (6mm) and less or equal than 0.75 in (19 mm). Figure 8 shows medium severity alligator cracking.

Figure 8: Medium Severity Alligator Cracking
Source: (Opus Consultants International (Canada) Limited, 2009)

High severity: as it can be seen in Figure 9 (high severity alligator cracking) interconnecting cracks are obviously complete and cracks are more than 0.75 in (19mm).

Figure 9: High Severity Alligator Cracking
Source: (Opus Consultants International (Canada) Limited, 2009)

2.3.3.2 Low Temperature cracking (thermal cracking)

Low temperature cracking is one of the nonload associated cracking types. Investigations have been indicated that thermal cracking begins at the surface of the pavement and extends to down layers with time. Temperature difference between surface layer and underlying layers of the HMA pavements develops tensile stresses. When these tensile stresses exceed the strength of HMA pavement materials, thermal cracking will be occurred.

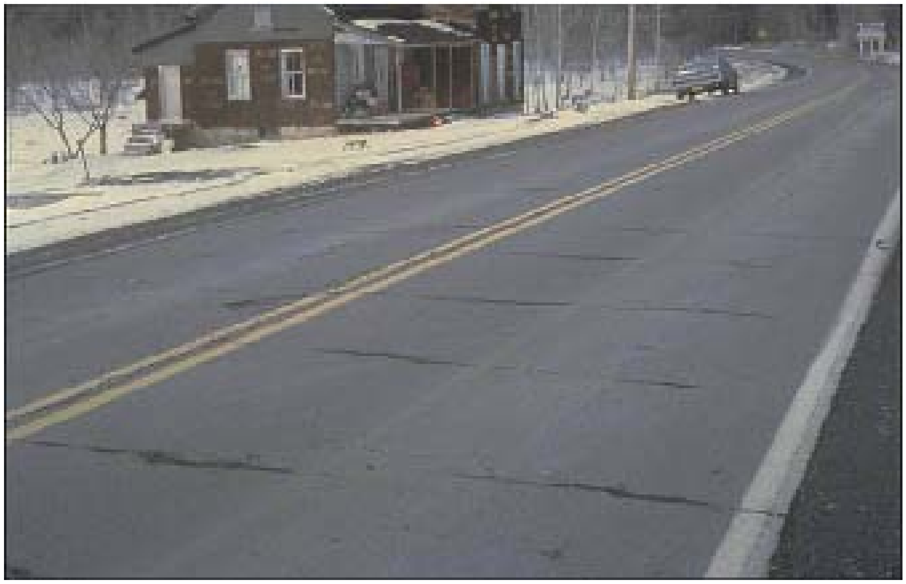


Figure 10: Low Temperature Cracking
Source: (Federal Highway Administration, 2010)

HMA mixes with low penetration and high viscosity (high stiffness modules) at low temperature are prone to cracking. The asphalt cement stiffness plays main role in mixes at low temperature, while mix stiffness is dependent on the asphalt cement stiffness.

It should be mentioned that low temperature cracks are perpendicular to the centerline of the roads and are approximately in equal spaced as it is shown in Figure 10 (Roberts *et al*., 1991).

2.4.3.3 Longitudinal Cracking

Longitudinal cracks are parallel to centerline of the road and are located either at edge of wheel path or at the lane line pavement joint. The longitudinal cracks near wheel path are associated by heavy traffic loads. Repeating heavy loads result in generating a residual stresses at adjacent wheel path. While these residual stresses go over tensile strength of HMA, cracks are occurred. However, longitudinal cracks at lane line pavement joint are typically nonload associated cracking. Low temperature and difference in density of lane joint are the main reasons for occurring lane line longitudinal cracks (Roberts *et al*., 1991).

Longitudinal cracks are divided into three severity levels: low, medium, and high (Federal Highway Administration, 2006-2009).

Figure 11: Low severity longitudinal cracking
Source: (Opus Consultants International (Canada) Limited, 2009)

Low severity: cracks are very little and narrow. The mean width of cracks is less than 0.25 in (6 mm). Low severity longitudinal cracks between adjacent lanes and at edge of wheel path can be seen in Figure 11 on right and left respectively.

Medium severity: cracks are larger than low severity with the mean width more than 0.25 in (6mm) and less than 0.75 in (19 mm). Some low severity cracks may be connected to main cracks. Medium severity longitudinal cracks between adjacent lanes and at edge of wheel path can be seen in Figure 12 on right and left respectively.

Figure 12: Medium Severity Longitudinal Cracking
Source: (Opus Consultants International (Canada) Limited, 2009)

High severity: pieces are missing along the cracks and the mean width of cracks is more than 0.75 in (19 mm). Figure 13 shows high severity longitudinal cracks.

Figure 13: High Severity Longitudinal Cracking
Source: (Opus Consultants International (Canada) Limited, 2009)

2.4.3.4 Transverse Cracking

Transverse cracks extend perpendicular to the pavement centerline and can be happened due to shrinkage caused by low temperature or asphalt cement hardening or reflecting cracking. They can be partly or completely across the roadway (Huang yang, H., 2004).Transverse cracks are classified in three severity levels similar to longitudinal cracking: low, medium, and high, with same specifications. Figure 14 indicates various level of transverse cracking.

Figure 14: Low, Medium, High Severity Transverse Cracking From Left to Right Respectively
Source:(Opus Consultants International (Canada) Limited, 2009)

2.4.4 Rutting (permanent deformation)

Rutting is one of the main distresses in the asphalt cement pavement mixtures. Rutting is a depression or movement of materials due to repetitive traffic loads. This distress can be occurred either in HMA surface layer or underlying base.

Permanent deformation can be occurred through three main factors: consolidation, mechanical deformation and plastic flow.

1. ***Consolidation*****:** consolidation is further compaction after construction of HMA pavement by wheel loads. Generally, it happens when compaction is not sufficient and amount of air void content is higher than standard range (3-5%). By applying traffic on deficient compacted pavement, HMA becomes dense and compacted. Therefore, shape of surface becomes similar to channel in wheel track area as it can be seen in Figure 15.

Figure 15: Rutting Due to Consolidation of Asphalt Concrete
Source: (Huang, 2004)

2. ***Mechanical Deformation***: mechanical deformation occurs when layers under surface HMA, such as base, subbase, subgrade, loss their stability and displaced under traffic loads. Many reasons can assist mechanical deformation; the important factors are poor drainage and weak subgrade. Figure 16 illustrates rutting at underlying layers (Huang, 2004).

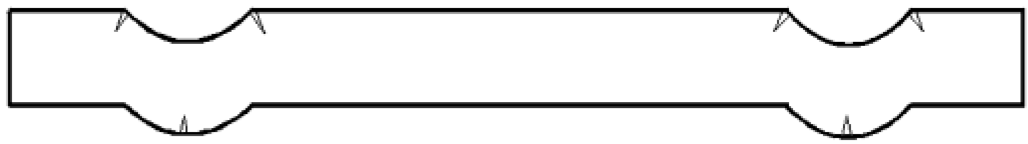


Figure 16: Deformation at Underlying Layers
source (Huang, 2004)

3. ***Plastic flow:*** the main reasons that plastic flow happens is excessive amount of asphalt cement in the mixtures, extreme amount of asphalt cement causes the loss of internal friction between aggregate particles and results in the responsibility of the load bearing is switched to the asphalt cement instead of aggregates. Plastic flow can be minimized by applying large size of aggregate, using rough and angular aggregate rather than smooth aggregate or too many fine aggregate in the HMA mix. Figure 17 shows rutting due to plastic flow.

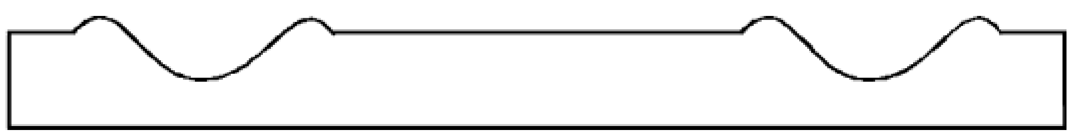


Figure 17: Rutting Due to Plastic Flow
Source: (Huang, 2004)

Many researchers indicated that mix design and gradation and especially physical properties of aggregate such as texture, particle size and shape, play main role in rut resistant and performance of HMA mixtures: angularity of aggregate (coarse and fine) and rough aggregate (surface texture) are two very important parameters may affect rut resistant (Fletcher, T., Chandan, C., Masad, E., Sivakumar, K, 2002). Huang *et al.* (2009) mentioned that by increasing coarse aggregate fractured faces, rutting resistance of mix will increase. Chen *et al.*, (2001) examined effect of various shape of aggregate (cubical, blade, rod, and disk). They found that "cubical particles possess the highest rutting resistance, following by rod, dense, disk and blade particles."

According to *Distress identification manual for the NPS road inventory program cycle 4, 2006-2009* rutting is classified into three severity level; low severity, medium severity, high severity.

Low severity: the rut depths is more than or equal to 0.2" (≥ 0.2") and less than or equal to 0.49 (≤ 0.49").

Figure 18: Low Severity Rutting
source: (Federal Highway Administration, 2006-2009)

Medium severity: the rut depths is more than and equal to 0.50” (≥ 0.50”) and less than or equal to 0.99 (≤ 0.99”).

High severity: ruts with more than 1.00” depths are classified in high severity level. The following figures illustrate various severity level of rutting.

Figure 19: Medium Severity Rutting
Source: (Federal Highway Administration, 2006-2009)

Figure 20: High Severity Rutting
Source: (Opus Consultants International (Canada) Limited, 2009)

2.5 Mix design

HMA pavements are consisted of certain portion of aggregate and specified amount of asphalt cement. HMA should be properly designed to provide sufficient durability and stability to carry the anticipated traffic loads accumulated during its service life and endures the environmental damages (Institute, 1995). The common mix design methods are Hveem Method, Marshall Method, and Superpave Method.

Hveem Method: this method was developed by Francis Hveem of the California Division of Highway and it has been used by that organization since the early 1940s (US Army Corps of engineers, 2000). ASTM D 1561 contains a detailed account of the laboratory using of Hveem method.

Marshall Method: Bruce Marshall was the first person who designed and formulated the concept of Marshall Method for paving mixtures. During the World War II the US Army Crops of Engineers (USACE) developed the Marshall Method for airfield pavements then, the procedure of modified Marshall Method was adapted by asphalt institute for designing highway pavements (US Army Corps of engineers, 2000). In this method, amount of the asphalt content is selected base on some important factors such as air void, stability and density. These parameters plus voids in mineral aggregate, voids filled with asphalt and flow should be in certain criteria according to standard codes. More details, like preparing samples and compaction, have been given in ASTM D 1559 (US Army Corps of engineers, 2000).

Superpave Method: since both Marshall and Hveem Methods are based on empirical relationships, strategic highway research program (SHRP) began developing a test system which be based on the fundamental properties in 1987 (Roberts *et al*., 1991).

Following information about superpave is presented from Asphalt Institute in Superpave Mix Design manual; Superpave Series No. 2 (SP – 2). One main purpose of developing this new test system was better simulation filed conditions in the lab which asphalt cement will meet in its service life. Finally, SHRP introduced the new system which is called Superpave, acronym for Superior Performing Asphalt Pavements.

The test equipment which is used in Superpave mix design for preparing the samples is Superpave Gyratory Compactor (SGC). This compactor equipment was developed because compaction in the other mix design methods was not precisely compatible with filed condition. SHRP tried to have equipment to compact samples in realistic conditions close to filed conditions. For achieving this aim some parameters were defined in compaction of specimens instead of kneading and blowing the samples. Pressure, angle of applied pressure and rotation were considered for compaction of specimen. As it can be seen in Figure 21 obviously, the pressure which is applied for samples is 600 kpa and the rotation and angle of machine during the compacting action is 30 revaluations per minute and 1.25 degree respectively.

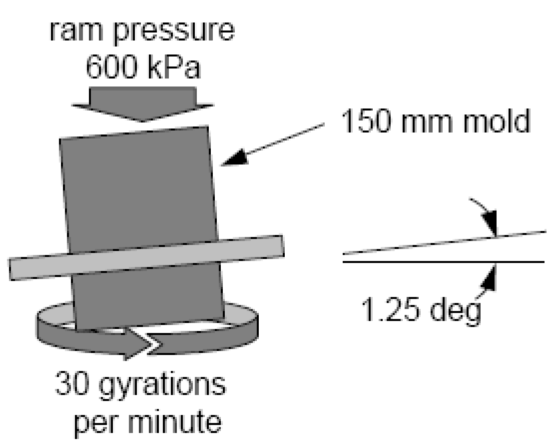


Figure 21: SGC Mold Configuration
source: (Asphalt Institute, 1996)

There are three gyration levels of compaction:

- The initial number of gyrations (N_{ini})

- The design number of gyrations (N_{des})

- The maximum number of gyrations (N_{max})

The design number of gyrations (N_{des}) is dependent on the traffic and climate as it is shown in Table 2.

Table 2: Superpave Design Gyratory Compactive Effort

Design	**Average Design High Air Temperature**											
ESAls	<39° C			39 – 40° C			41 – 42° C			43 – 44° C		
(millions)	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}
<0.3	7	68	104	7	74	114	7	78	121	7	82	127
0.3 – 1	7	76	117	7	83	129	7	88	138	8	93	146
1 – 3	7	86	134	8	95	150	8	100	158	8	105	167
3 – 10	8	96	152	8	106	169	8	113	181	9	119	192
10 – 30	8	109	174	9	121	195	9	128	208	9	135	220
30 – 100	7	126	204	9	139	228	9	146	240	10	153	253
>100	7	143	235	10	158	262	10	165	275	10	172	288

source: (Asphalt Institute, 1996)

Climate is defined as the average temperature for seven-day maximum air temperature for project conditions and traffic is described by the design ESALs. There are two other gyration levels beside of N_{des}; The initial number of gyrations (N_{ini}) represents mix reaction during initial compaction and the maximum number of gyrations (N_{max}) represents a traffic level higher than that for the project is designed. N_{ini} and N_{max} can be obtained from design number of gyrations:

$$\text{Log } N_{max} = 1.10 \text{ Log } N_{des} \qquad (2.2)$$

$$\text{Log } N_{ini} = 0.45 \log N_{des} \qquad (2.3)$$

2.6 Modification of Asphalt Binder

Asphalt cement is an important material which is being used in construction of roads as a binder for along time. By development of the industrial products and growth of the various automotive industries, there is a growing demand for the improvements of roads and transportation networks. Hot mix asphalt is one of the common flexible pavement types applied for most pavement constructions. Approximately 96% of all the paved surfaces are constituted by hot mix asphalt (HMA) in the United States (Copeland , A.R, 2007).

HMA pavements should be able to carry anticipated traffic loads accumulated during its service life. When environmental conditions are combined with these loads various distress such as high temperature rutting, fatigue cracking and etc, can cause the rapid deterioration of pavement structures as explained in section 2.4 (Zhang, F., Yu, J., 2009). These distresses in asphalt cement result in some limitations on its applications. Therefore, modifying asphalt cement engineering properties is essential and important (Vlachovicova, Z.,Wekumbura, C.,Stastna, J., Zanzotto, L., 2005). The popular methods for modifying asphalt binder are using polymers or applying fibers in mixtures. In the following section use of different types of polymers will be discussed briefly.

2.6.1 Polymer Modified Asphalt

The simplest definition of polymer could be “many parts or units”. The physical and chemical properties of a polymer depends on theses individual units (molecules) which are chained together (PB bitumen). Use of natural and synthetic polymers for modification of asphalt cement was patented as early as 1843 (Yildirim, 2005). Generally, polymers are added to asphalt cement to improve functional properties such as permanent deformation, fatigue and low temperature cracking, stripping, wear resistance and etc.

Although there are several types available for modification, there is only small number of polymer types suitable for modification of asphalt. The polymer modified asphalt (PMA) properties may change from one polymer to another and the characteristics of PMA are function of some factors: polymer properties and content, blending process and characteristics of the asphalt nature. It is necessary that polymers which are used as modifier, be compatible with natural asphalt cement in the process of blending and be able to keep their properties constant by passing time. A study indicates that amount of polymer which is added to a mixture usually is about 4-6% by weight of asphalt cement, in fact higher percentage of polymer is non-economical and may lead to other problems such as separation between polymer and asphalt particles (Al-Hadidy, A.I.,Yi-qiu , T., 2008b).

There are two types of modificative polymers: Elastomers and Plastomers. Elastomers are most popular polymer which is used in the asphalt cement. Elastomeric polymers assist elastic component in the asphalt cement and decline the viscosity behavior therefore they increase elastic response of the asphalt. Generally, elastomeric polymers reduce permanent deformation by improving the elastic recovery after eliminating stress and decrease risk of rutting developing as a result of the temperature susceptibility of PMA. The famous elastomeric polymers are Styrene-butadiene-styrene (SBS), Styrene-butadiene rubber (SBR) and Styrene-Ethylene- butadiene –Styrene (SEBS) (Robinson, 2004).

Plastomers are the second most common polymers which are applied to asphalt highway products. Plastomers will deform in a plastic or viscous mode at melting temperatures. They modify bitumen by creating a tough and rigid network within the binder. Unlike elastomeric polymers that improve ductility by reducing the stiffness, plastomers cause the bitumen stiffer and decrease the temperature susceptibility of bitumen. These factors may lead to reduction of rutting risk in the period of hot summer months. Ethylene Vinyl Acetate (EVA) and low and high density polyethylene (LDPE & HDPE) are other popular plastomer polymer types (Robinson, 2004).

In the following part some important polymers used in asphalt will be discussed briefly.

2.6.1.1 Rubber

Asphalt-rubber (AR) and crumb rubber modifier (CRM) are two names that refer to combination of the asphalt cement and ground recycled rubber. Properties of asphalt-rubber are function of the following factors; type and size of rubber crumbs, nature asphalt constitution, and time and temperature of reaction (Yildirim, 2005).

There are two methods for applying the crumb rubber to mixes; dry process and wet process. In the dry method crumb rubbers are applied as aggregate particle in HMA mixture whereas in wet method crumb rubber is added and mixed with asphalt cement for half an hour to two hours at high temperatures (175-220 ^{o}C), and then stored until the asphalt cement is added to mineral aggregate at mixing temperature. Many investigations indicate that use of ground rubber modifier enhance elastic behavior of asphalt cement in a mix and also it improves rutting resistance at intermediate temperature and reduces reflective cracking which cause the development of ductility (Xiao, *et al*,. 2008; Navarro, *et al*,.2004; Yildirim, 2005). Moreover, it should be mentioned that applying waste tire rubbers instead of new polymers has the advantage of higher cost savings and lower energy consumption and pollution (Navarro *et al*, 2004).

However, it can be said that use of crumb rubber has some negative aspects. Sensitive to decomposition and oxygen absorption plus the necessity of high temperatures and long digestion times for dispersion are some practical problems of applying rubber in the HMA (Yildirim, 2005).

2.6.1.2 Styrene-Butadiene-Rubber (SBR)

Styrene-butadiene-rubber is an elastomer polymer which has been added to bitumen for modifying the weak properties of bitumen. SBR usually is used as dispersion when exposed to asphalt in the form of latex (Yildirim, 2005). SBR latex can be used in asphalt concrete pavement and particularly in seal coats and presents improvement in low temperature ductility, adhesive and cohesive properties, elastic recovery test, increasing in viscosity and decreasing in rate of oxidation (Bates, R.,Worch ,R., 1987).

Yildirim mentioned that water based SBR is replaced with SBR gradually due to compatibility to wide range of asphalt and greater tensile strength. ((Shuler, Wardlaw & Scott, 1992); (Yildirim, 2005)) .

2.6.1.3 Styrene-Butadiene-Styrene (SBS)

Styrene-butadiene-styrene is an elastomeric polymer that improves the elasticity behavior of asphalt. SBS is black copolymer and probably the most suitable polymer for modifying asphalt cement (Yildirim, 2005). When SBS is mixed with bitumen, during the chemical reaction the bitumen swells up and a polymer network is shaped throughout the mixture and this polymer network affect the properties of bitumen (Gordon D.A, 2003).

Since SBS is more compatible with asphalt and shows higher tensile strength under stress than SBR, it is replacing SBR at present time (Abtahi, S. M., Ameri, M., Sheikhzadeh, M., Hejazi, S. M., Rahnama, E., 2009a). Many researches were carried out to investigate the effect of Styrene-Butadiene-Styrene on the asphalt mixtures. Results showed that SBS can enhance the mechanical and rheological properties of bitumen, SBS cause the flexibility increases at low temperature, and SBS is found useful for cracking resistance due to reduction in micro-damage accumulation (Bjorn, *et al*,. 2007; Fua, *et al*,. 2006; Yildirim, Y., 2005).

However, some reports indicated some drawbacks of this polymer: reduction in strength at high temperature, experiencing of severe oxidative age hardening and also poor performance probably due to not uniform distribution. The distribution of the SBS throughout the asphalt cement is so important and care should be taken during blending process to create a homogeneously mix (Yildirim, 2005).

It is evident that polymers can effect on the properties of asphalt cement and as it was mentioned before, they may improve fatigue resistance, rutting resistance, thermal cracking and temperature susceptibility. Polymers also show increasing in viscosity and elastic recovery than the unmodified asphalt cement. Use of polymer is with some disadvantages, the compatibility of polymers with asphalt cement plays an important role in properties of PMAs. Separation between asphalt and polymers particles during application or storage should be prevented otherwise poor performance and increasing cost without any desirable result will be appeared (Yildirim, 2005). By applying ring and ball softening point test simply can be realized the dispersion of the polymer throughout of binder since weak dispersion results in lower than expected softening point (Robinson, 2004). It should be added that some routine tests such as ductility, elastic recovery and resilience are inconsistent in performance level of the polymer modified binder and there are not desirable correlation between laboratory test result and field performance of PMAs (Yildirim, 2005).

2.6.2 Fiber-Reinforcement Asphalt-Concrete

The second case for improvement of asphalt pavements performance is fiber-reinforcement. Use of fibers to enhance the properties of materials is not novel. It was reported that “Use of fibers can be traced back to a 4000-year-old arch in China constructed with a clay earth mixed with fibers or the Great Wall built 2000 years ago”(Hongu & Philips, 1994, cited in Hejazi *et al.*,2008). However, the concept of using modern fiber reinforcement began in early 1960s (Serfass, J.P , Samanos, J., 1996). In 1989, Maurer mentioned that “reinforcement generally consists of incorporating certain materials with some desired properties within other material which lack those properties”. Different fiber has been applied in various mixtures such as HMA mixtures, Stone Mastic Asphalt (SMA), open grade mixtures, etc (Maurer & Geeald, 1989, cited in Abtahi *et al.,* 2009b). Typically, one of the main advantages of applying fiber can be the additional tensile strength and potentially improving cohesive bond to the mixture (Mahrez, A., Karim, M.R, Katman, H., 2005).

Hejazi *et al*., (2008) reported that performance of various fibers can be predicted by “Slippage theory”. An index λ can be achieved for each type of fiber base on the some specified fundamental properties:

$$\lambda = \underline{\qquad\qquad} \tag{2.4}$$

Where d_f, E_f, ε_f are diameter, Young's Modulus and strain at failure of fiber, respectively. L_f is length of fiber and τ is interfacial shear stress between fiber and asphalt mixture. They found that while slippage factor (λ) increases, the corporation between fiber and mixture will decrease (Hejazi *et al*., 2008). The performance of some fibers according to the slippage theory is shown in Table 3.

Table 3: The Performance of Some Fibers in Slippage Theory

Fiber type	**λ**
Glass	71.89T[a]
Nylon 6.6	115.577T
Polyester	286.25T
Polypropylene	709.22T

[a]T= 1/τ.
source: (Hejazi *et al*., 2008)

Previous researches illustrated that fibers be able to improve the performance of the mixtures [(Kaloush, K.E, Zeiada, W.A, Biligiri, K.P, Rodezno, M.C, Reed, J.); (Yea, Q., Wu, S., Li, N., 2009)]. In addition, fibers (polypropylene, polyester, asbestos and cellulose) can increase the stiffness of the asphalt cement and mixture and can also decrease the binder drain-down (particularly in cellulose fibers) (Tapkin *et al*., 2009).

There are plenty of fibers which can be used as reinforcement in asphalt cement matrix such as asbestos, polyester, polypropylene, carbon, glass, nylon to affect the behavior of asphalt cement. In the next part polypropylene fibers and glass fibers, will be discussed.

2.6.2.1 Polypropylene (pp)

Polypropylene is the synthetic fiber which is applied in Portland cement concrete mixtures. The polypropylene fiber creates a three-dimensional reinforcement and causes growth in toughness and durability in concrete. Polypropylene fibers are also used as a modifier in asphalt concrete. The use of polypropylene fiber for high-performance asphalt concrete was standardized in Ohio State Department of Transportation (ODOT) in the United Stated. This standard implies that the ratio of polypropylene to the asphalt mix must be 2.7 kg/ton, however this ratio can be decreased or increased to achieve the desired properties of mixture (Abtahi *et al*, 2009b). Physical properties of polypropylene according to ODOT are shown in Table 4.

Table 4: Physical Properties of Polypropylene Fibers as Specified by Ohio Department of Transportation

Characteristic	**Value**	**Standard**
Denier, grams per denier	4±1	ASTM D-1577
Length, mm	10±2	-
Tensile strength (minimum), MPa	276	ASTM D-638
Specific gravity, kg/m^3	910±4	ASTM D-792
Melting temperature, °C	160	-

Source:(Abtahi *et al*, 2009b)

The polypropylene (pp) fiber can be used in the asphalt concrete mixture in two ways; wet or dry base. In dry base, aggregate is heated at certain temperature (160-170°C) to be dried for 16-24h and then mixed with specified amount of pp. Then, the preheated asphalt cement is introduced to the aggregate and polypropylene and mixed together for 2 minutes. Tapkin in a study investigated the effect of using dry base polypropylene in asphalt concrete. In that research, 0.3, 0.5 and 1% of polypropylene was applied in the mixture. The results indicated that the specimen including 1% fiber showed the best performance and increased Marshall Stability test and decreased flow. Also, the fatigue life of the polypropylene modified asphalt concrete was improved (Tapkin.S, 2007).

Table 5: The Physical Properties of Polypropylene

Characteristic	**Value**	**Standard**
Homogeneity,%	100%	-
Color	Transparent	-
Length, mm	3-50	-
Melting point, °C	160	-
Specific gravity, kg/m^3	910	ASTM D-792
Fire point, °C	590	-
Glass transition temperature, °C	-18	-
Alkali resistance as % of strength	99.5	-
Retained after treatment in 40% NaOH solution at 20°C for 1000 h water absorption, %	0.01-0.02	ASTM D-570
Moisture retention, at 20 °C and 65% relative humidity	<0.1%	-
Rupture resistance, MPa	31-41	ASTM D-638
Elongation, %	>= 33	ASTM D-638
Elongation at rupture,%	100-600	ASTM D-638
Tensile strength, MPa	31-37	ASTM D-638
Compressive strength, Mpa	37-55	ASTM D-695
Bending strength, MPa	41-55	ASTM D-790
Tensile modulus, MPa	1137-1551	ASTM D-638
Bending modulus,73°F, MPa	1172-1723	ASTM D-790
Hardness, Rockwell	R80-R102	ASTM D-785
Thermal expansion, linear, m/m/°C	0.031-0.039	ASTM D-696

source: (Tapkin.S, 2007)

Another investigation revealed that specimens which were applied dry base polypropylene (12 mm length) with a ratio of 0.125% by weight of total mix showed better performance than the specimens which were constituted by SBS (Abtahi *et al.*, 2009a).

However, in the wet method, the polypropylene is added to the asphalt cement at the specified temperature and then mixed for a certain time mechanically or manually. Next, the modified asphalt is added to preheated-dried aggregate and blended together at mixing temperature for 2 minute. An investigation on wet polypropylene in asphalt cement is carried out by Tapkin (2009). Three lengths of fiber (3, 6, 9 mm) with a ratio of 0.3, 0.45 and 0.6% by weight of aggregate for each length were used. The asphalt test results indicated improvement in some properties of asphalt cement such as penetration, penetration index, ductility, softening point. The addition of polypropylene caused increase in Marshall Stability and increase 5-12 times lives of fiber modified specimens under creep loading test than conventional specimens (Serkan , T., Usar, Ü., Tuncan, A., Tuncan, M., 2009). In another case, pyrolisis polypropylene was used in asphalt mixture. The results showed that fiber modified asphalt decreased in penetration and increased in softening point which indicates the improvement in resistance to deformation. Also the fiber was effective and enhanced in stripping and draindown (Al-Hadidy, A.I., Yi-qiu, T., 2008a).

2.6.2.2 Glass Fiber

It is necessary to know that few published information concerning glass fiber modified asphalt is available. The history of using glass fiber is not certain. Glass fiber will not burn but it becomes soft at 815°C and its stability decreases at temperature above 315°C. Glass fibers do not absorb water and also they are brittle and sensitive to surface damage. One of the remarkable properties in this fiber is its high tensile modules (60014 MPa). The elongation of the fibers of glass is 3-4% while they have elastic recovery equal to 100% (Abtahi, *et al.*, 2009b; (Vasiliev,V., Morozov,E., 2007).

Mahirez *et al.* (2005) used glass fiber with 20mm length in the asphalt concrete. Glass fiber content was 0.1%, 0.2%, 0.3%, 0.4% and 0.5% by weight of total mix. Marshall Stability, Resilient Modulus, Dynamic Creep Test and Repeated Load Indirect Tensile Test have been applied in reinforced and control asphalt concrete specimens. The results illustrated that resilient modulus and fatigue performance significantly increased and permanent strains under dynamic creep loading test drastically decreased. However, Marshall Stability unexpectedly decreased and flow increased as the fiber content increased (Figure 22). It was concluded that the high percentage of fiber in the mix caused the contact points between aggregate decreased and therefore the stability decreased.

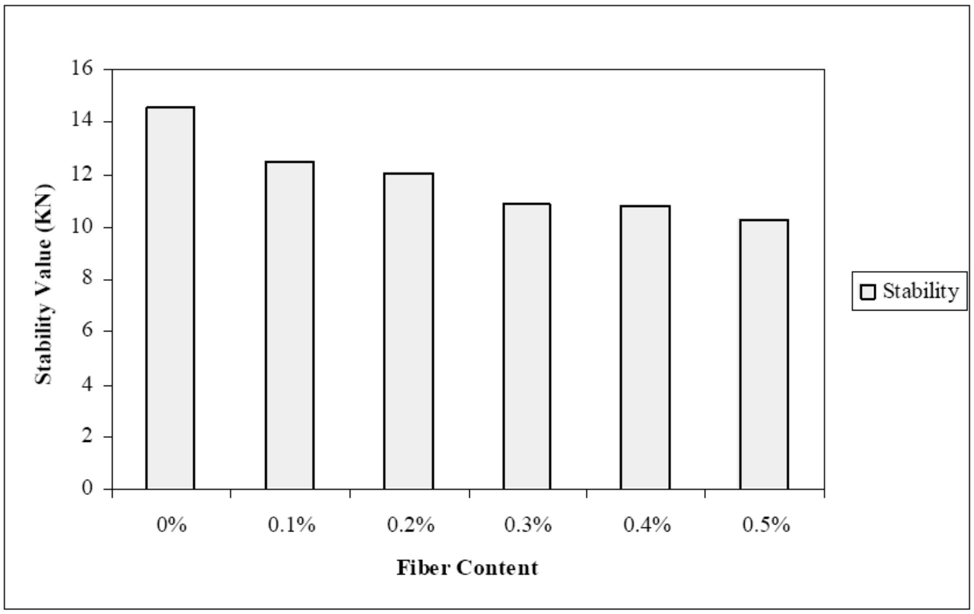


Figure 22: Marshall Stability in Different Fiber Content
source:(Mahrez *et al*., 2005).

In another research Najd *et al* .(2005) found that applying glass fiber in asphalt mixture is useful to impede rutting and bleeding phenomena in high temperature, because glass fiber reinforcement showed improvement in Marshall Stability and deformability of the asphalt concrete without any growth in asphalt cement content.

In a comparative study Hejazi *et al,* (2008) investigated effect of different fibers reinforcement on HMA asphalt. In this research, various fibers such as nylon6.6, polyester, polypropylene, and glass fiber with desirable content ratio (0.0625%, 0.125%, and 0.25% by weight of total mix) were applied in asphalt concrete. The physical properties of fibers were given in the Table 6. The results indicated that glass fiber and polypropylene had the highest Marshall stability among the tested fiber types as it can be seen through Figures 23-25.

The high stability in glass fiber reinforcement mixture could be due to low value of slippage factor (λ) and highest tensile modulus (60014 MPa) compared to nylon, polyester and polypropylene. Although polypropylene has the highest value of the slippage factor, its performance is excellent. Perhaps because of low melting point of polypropylene (160 °C), a phenomenon called "tackiness" causes the fiber to glue to the mixture completely and results in a great performance (Hejazi *et al.,* (2008)).

Table 6: Physical Properties of Fibers

Fiber type	**Modulus (MPa)**	**Finesse (denier)**	**Density (g/cm3)**	**Diameter (mm)**	**Strain (%)**	**Fiber length (mm)**	**slippage factor (λ)**
Nylon 6.6	5,214	1.6	1.14	0.014	38	12	71.89T[a]
Glass	60,014	2	2.59	0.010	2.875	12	115.577T
Polypropylene	6,840	3	0.92	0.021	118	12	286.25T
Polyester	15,703	2	1.39	0.014	31.25	12	709.22T

[a]T= $1/\tau$.

Source (Hejazi,*et al.*, 2008)

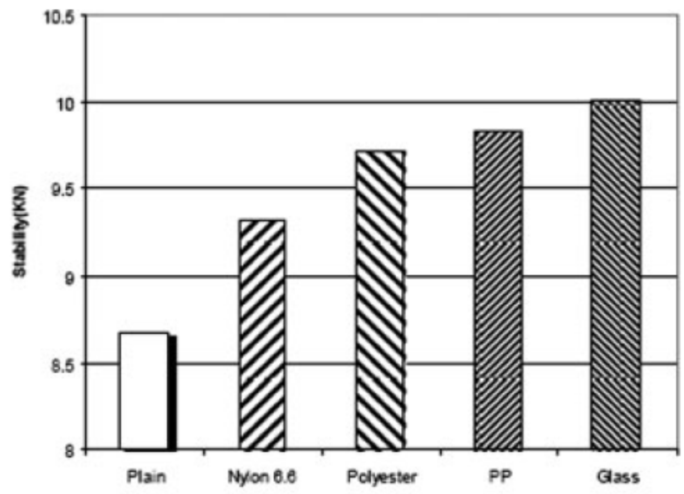


Figure 23:The Effect of Fiber Type (0.0625% and 12 mm) on Stability of the FRAC
Source(Hejazi *et al.*, 2008)

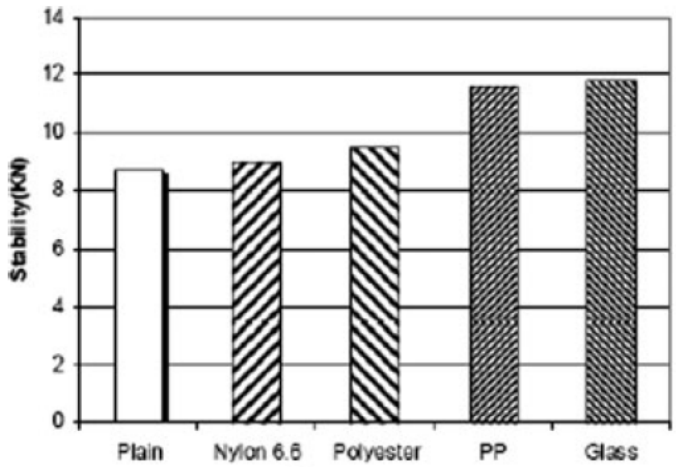


Figure 24:The Effect of Fiber Type (0.125% and 12 mm) on Stability of the FRAC
Source: (Hejazi *et al.*, 2008)

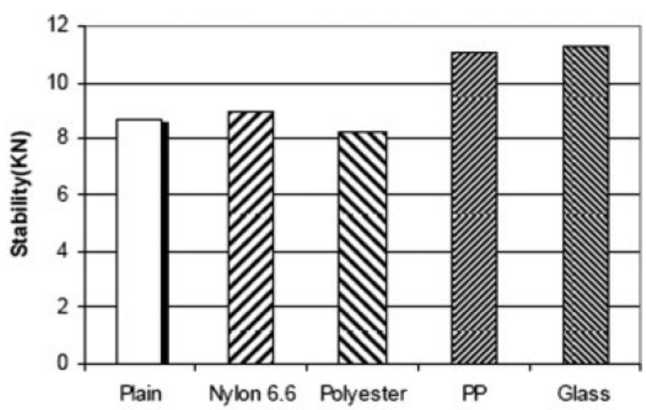


Figure 25: The Effect of Fiber Type (0. 25% and 12 mm) on Stability of the FRAC
source: (Hejazi *et al.*, 2008)

Chapter 3

METHODOLOGY

3.1 Introduction

In the following sections various test methods and results, which have been completed for this research will be explained. All the experiences are accordance to standard codes such as ASTM, AASHTO, Asphalt Institute and Turkish Highway Standard. This chapter will include:

- Aggregate test
- Normal asphalt test
- Mix Design Method
- Maximum Specific Gravity of Loose Mixture and;
- Procedure for Analyzing a Compacted Paving Mixture

3.2 Aggregate Tests

3.2.1 Gradation

All the aggregate particles (coarse, fine) used in this research were crushed limestone aggregate obtained from Cyprus Highway Department quarries in Beşparmak Mountains in TRNC (Tawfiq, 2002). The gradation was selected from Turkish Highway Standard of binder course which can be seen in the table below.

Table 7: Gradation of the Aggregate

	Range of Standard	**Used**
Sieve Size	Passing (%)	Passing (%)
25 mm (1 inch)	100	100
19 mm (3/4 inch)	82-100	91
12.5 mm (1/2 inch)	68-87	78
9.5 mm (3/8 inch)	60-79	70
4.75 mm (No.4)	46-65	56
2.36 mm (No.8)	34-51	43
0.425 mm (No.40)	17-29	23
0.180 mm (No.80)	9-18	14
0.075 mm (No.200)	2-7	5
Pan	0	0

3.2.2 Specific Gravity of the Aggregate

3.2.2.1 Specific Gravity of the Coarse Aggregate

The specific gravity of coarse aggregate was tested according to American Society for Testing and Materials (ASTM) C 127-07, to determine bulk specific gravity dry and saturated-surface dried (SSD), apparent specific gravity and Absorption. Table 8 shows the result of test for coarse aggregate.

Table 8: Specific Gravity and Absorption of the Coarse Aggregate

Items		**Size**			
		3/4 inch	**1/2 inch**	**3/8 inch**	**#4**
Wight of oven dried sample in air (g)	A	565.5	563.9	567.5	561.5
Weight of SSD sample in air (g)	B	568.9	566.8	570.8	565.8
Weight of sample in water (g)	C	366.8	364.5	367.9	366.4
Bulk Specific Gravity (Dry)	A/(B-C)	2.798	2.787	2.79	2.816
Bulk specific gravity (SSD)	B/(B-C)	2.815	2.802	2.813	2.838
Apparent Specific gravity	A/(A-C)	2.846	2.828	2.843	2.878
Absorption	[(B-A)/A]*100	0.60	0.51	0.58	0.766

The average specific gravity and absorption can be computed by the following equation:

$$G = \qquad (3.1)$$

Where:

G = average specific gravity.

G_1, G_2… G_n = appropriate average specific gravity for each size of fraction.

P_1, P_2… P_n = mass percentage of each size fraction percent in the original sample

The average absorption:

$$A = (P_1A_1/100) + (P_2A_2/100) + \ldots (P_nA_n/100) \qquad (3.2)$$

Where:

A = average absorption, %,

A_1, A2… A_n = absorption percentage for each size fraction, and

P_1, P_2... P_n = mass percentage of each size fraction present in the original sample.

Table 9 : Average Specific Gravity of Coarse Aggregate

Average bulk specific gravity (Dry)	2.799
Average bulk specific gravity (SSD)	2.818
Average Apparent specific gravity	2.850
Average Absorption, %	0.623

3.2.2.2 Specific Gravity of the Fine Aggregate

The specific gravity of fine aggregate was tested according to ASTM C 128-07, to determine the relative density (specific gravity), and absorption of fine aggregate. Table 10 presents the result of fine aggregate specific gravity.

Table 10: Specific Gravity and Absorption of Fine Aggregate

Weight of oven dried sample in air (g)	A	393.8
Weight of SSD sample in air (g)	S	400
Weight of Pycnometer with sample and water (g)	C	1603.3
Weight of Pycnometer with water (g)	B	1347.4
Bulk specific gravity (Dry)	A/(B+S-C)	2.727
Bulk specific gravity (SSD)	S/(B+S-C)	2.776
Apparent specific gravity	A/(B+A-C)	2.856
Absorption %	[(S-A)/A]*100	1.57

According to equations 3.1 and 3.2 the average value of specific gravity and absorption for combined coarse and fine aggregate were calculated and given in table 11.

Table 11: Overall Average Values for Specific Gravity and Absorption

Average bulk specific gravity (Dry)	2.758
Average bulk specific gravity (SSD)	2.794
Average Apparent specific gravity	2.853
Average Absorption, %	1.153

3.3 Asphalt

The type of asphalt cement, which was used in this research, was 50-70 penetration provided from Highway Department of North Cyprus.

3.3.1 Penetration Test

Penetration value of an asphalt cement specimen was obtained According to ASTM D5. A container filled with asphalt cement is placed in a water bath usually with a temperature of 25 °C (77 ºF). The container is placed under a specified needle which is weighted with 100 grams. The needle is permitted to penetrate to the asphalt cement for exactly 5 seconds. The distance that needle is penetrated into the sample is measured in units of 0.1 mm. the penetration result for normal asphalt in below table.

Table 12: Penetration Test Result

Sample No.	**Reading No.**	**Reading**	**Penetration (0.1 mm)**
1	1	76	76
	2	88	88
	3	81	81
	Average		**82**
2	1	80	80
	2	81	81
	3	80	80
	Average		**80**
3	1	90	90
	2	85	85
	3	82	82
	Average		**86**
	Total Average	**82.7**	

3.3.2 Softening Test

According to ASTM D36 a steel ball with specified diameter and weight is loaded on the center of the brass ring filled with asphalt cement. The ring is suspended in a beaker filled by water that is maintained at 5ºC. The beaker is heated by rate of 5 ºC/min. at the moment asphalt cement completely sinks and touches the plate the temperature is recorded as the softening point.

Table 13: Softening Point Test Result For Normal Asphalt Cement

	2% pp	**4% pp**	**6% pp**
6 mm	53	57	65.5
12 mm	56	61.5	68
Normal Asphalt cement		**48.5**	

3.3.3 Ductility Test

The ductility test was ran accordance with ASTM D113. The distance in centimeters that standard asphalt cement sample can stretch before rupture is measured and reported as ductility. Asphalt cement is poured to a standard mold and then placed in the ductility machine test usually at 25°C (77ºF). The extension with rate of 5 cm/min is applied until rupture. The specific gravity of water is supposed to be equal to the asphalt cement specific gravity to avoid sinking and floating of sample. For this purpose, it can be used alcohol to decrease or salt to increase the specific gravity of water. Table below shows the result of ductility test.

Table 14: Ductility Test Result

Sample No.	**Ductility of asphalt (cm)**
1	+100
2	+100

3.4 Hybrid Fiber-Reinforced Asphalt Concrete

In this study, two different length of fiber polypropylene (pp) 6 mm and 12mm plus glass fiber with 12mm length are added to asphalt concrete mixture to improve some properties of the mixture. Two methods were selected to add these fibers to the mixture; pp is added to the mix in dry base and glass fiber is mixed to the mixture in wet base. The properties of these fibers which are used in this research are given in Table 15 and Table 16.

Table 15: Physical Properties of Polypropylene Fiber

Specific Gravity	0.91 gr/cm^3
Diameter	22 µm
Cross Section	Round
Tensile Strength	350 – 400 Mpa
Melting Point	160 – 170
Acid & Salt Resistance	High
Akali Resistance	Excellent
Water Absorption	0
Thermal Conductivity	Low
Electrical Conductivity	Low
Length	3, 6, 9, 12 mm

Table 16: Physical Properties of Glass Fiber

Specific Gravity	2.59 gr/cm^3
Diameter	10 µm
finesse	2 denier
Tensile Modulus	60,014 MPa
Length	12mm

Three different types of polypropylene were used in this experiment ; 2%, 4% and 6% by weight of asphalt cement .The polypropylene is introduced to asphalt cement at the temperature of 151- 158 °C and mixed manually for 4-5 min (wet basis approach). Then, modified asphalt is introduced to preheated aggregate. However, glass fiber is added to the aggregate with temperature 170°C for less than 1 min (dry base) and then asphalt or modified asphalt can be added to mix of aggregate and glass fiber. The glass fiber content was selected 0.05, 0.1and 0.2 by weight of aggregate.

3.5 Mix Design Method

The method of mix design for this research is in accordance with ASTM D 1559 – 89. standard test method for resistance to plastic flow of bituminous mixtures using Marshall apparatus. Aggregate particles are placed at oven at 170°C, and then blended with different asphalt cement content. Five asphalt cement contents were selected 3.5%, 4.0%, 4.5%, 5.0%, and 5.5% by weight of mix. The aggregate particles or mix of aggregate and glass fiber are blended with asphalt cement (or modified asphalt cement) at compaction temperature of about 150°C.

The loose mixture is left in the oven at compaction temperature (150°C) for 2 hours for short term aging According to ASTM D 6925-09, preparation and determination of the relative density of HMA specimens by means of the superpave gyratory compactor. By finishing the short term aging, loose mixture should be placed in preheated mold quickly. Since Marshall Stability test was applied for measuring the stability of specimen, use of 100 mm (4 inch) diameter mold was essential. The initial, design and maximum number of gyration ($N_{ini,}$ N_{des}, N_{max}) were selected 8, 95, 150 respectively according to Department of Highway and Transportation of North Cyprus based on the design ESALs (Equivalent Single Axle Load) and average design high air temperature which were 1 – 3 millions and 39 – 40 °C, respectively. Table 17 shows the Compactive effort used in superpave gyratory compaction process. After preparing the samples by taking advantage of superpave gyratory compactor, the cool ready specimens are placed in water bath at 60±1°C (140 ± 1.8 °F) for 30 min before applying for Marshall Stability test. The marshal mix criteria are given in Table 18 (Ebrahimi, M., 2010).

Table 17Superpave Design Gyratory Compactive Effort

Design	**Average Design High Air Temperature**											
ESAls (millions)	<39° C			39 – 40° C			41 – 42° C			43 – 44° C		
	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}
<0.3	7	68	104	7	74	114	7	78	121	7	82	127
0.3 – 1	7	76	117	7	83	129	7	88	138	8	93	146
1 – 3	7	86	134	***8***	***95***	***150***	8	100	158	8	105	167
3 – 10	8	96	152	8	106	169	8	113	181	9	119	192
10 – 30	8	109	174	9	121	195	9	128	208	9	135	220
30 – 100	7	126	204	9	139	228	9	146	240	10	153	253
>100	7	143	235	10	158	262	10	165	275	10	172	288

Source (Asphalt Institute, 1996)

Table 18: Marshall Mix Design Criteria

Marshall Method Mix Criteria	**Traffic**					
	Light		Medium		Heavy	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Compaction, No. of blows/side	35		50		75	
Stability,. lb.	750	---	1200	---	1800	---
Flow (0.01 inch)	8	18	8	16	8	14
Air Voids, %	3	5	3	5	3	5
Voids in Mineral Aggregate	14	---	14	---	14	---

3.6 Maximum Specific Gravity of Loose Mixture

The maximum specific gravity of loose mixture is determined in accordance with ASTM D 2041 – 03a. The dry loose mixture with 5% asphalt cement content is weighted in air, and then placed in a bowel. The sufficient amount of water is poured to the bowel to cover the mixture, then vacuum is applied to the sample gradually until the residual pressure manometer reads 3.7 ± 0.3 kpa (27.5 ± 2.5mm) of Hg. After finishing vacuum time (15±2 min), container is placed in water bath to be full of water without storing any air voids. The recorded weights and calculation results are shown in Table 19 for mix with 5% Percent Asphalt content.

Table 19: Theoretical Maximum Specific Gravity 5% Asphalt

Weight of empty bowl (g)	B	4210
Weight of bowl and sample (g)	C	6747
Weight of sample (g)	A	2537
Weight of bowl and water (g)	D	19138
Weight of bowl and sample and water (g)	E	20690
Theoretical maximum specific gravity (G_{mm})	A/(A+D-E)	**2.576**

3.7 Procedure for Analyzing a Compacted Paving Mixture

In the following sections will go through to all formulas and calculations which are needed for analyzing a paving mixture. All these formulas and equations are borrowed from (American Society for Testing and Materials, 1989) and (Roberts *et al.*, 1991).

3.7.1 Effective Specific Gravity of Aggregate (G_{se})

Effective specific gravity is usually obtained from maximum specific gravity G_{mm} (void less loose mixture). G_{se} include all void spaces in the aggregate particle excluding those that absorb asphalt. G_{se} can be obtained from

$$= \qquad (3.3)$$

Where,

G_{se} = effective specific gravity of aggregate,

G_{mm} = maximum specific gravity of paving mixture (no air void),

P_{mm} = percent by mass of total loose mixture = 100,

P_b = asphalt content, percent by total mass of mixture,

G_b = specific gravity of asphalt.

3.7.2 Maximum Specific Gravity (G_{mm}) of Mixtures with Different Asphalt Contents

G_{mm} is specific gravity of mixture when there are no air void include in the mixture. G_{mm} is needed to calculate for all samples with different asphalt cement content. Since G_{mm} does not change noticeably by varying the amount of asphalt content, it can be considered constant. Maximum specific gravity obtained from lab test with asphalt content near to optimum and can be calculated for other asphalt content. G_{mm} is given as

$$= \frac{\quad}{\frac{\quad}{\quad} \;\; \frac{\quad}{\quad}} \tag{3.4}$$

Where,

G_{mm} = maximum specific gravity of paving mixture (no air void),

P_{mm} = percent by mass of total loose mixture = 100,

P_s = aggregate content, percent by total mass of mixture,

G_{se} = effective specific gravity of aggregate,

G_b = specific gravity of asphalt.

3.7.3 Asphalt Absorption of the Aggregate (P_{ba})

Asphalt absorption is defined as the percentage by mass of the asphalt that aggregate particles can absorb. P_{ba} is calculated

$$= 100 \times \frac{\quad}{\quad} \times \tag{3.5}$$

Where,

P_{ba} = absorbed asphalt, percent by mass of aggregate,

G_{se} = effective specific gravity of aggregate,

G_{sb} = bulk specific gravity of aggregate,

G_b = specific gravity of asphalt.

3.7.4 Effective Asphalt Content of the Paving Mixture (P_{be})

Effective asphalt content coats the aggregate particle and has a great deal with the performance of pavement. Effective asphalt content is difference between total asphalt content and the amount of asphalt which is absorbed into the aggregate particles. P_{be} can be calculated as

$$= \quad - \frac{\quad}{\quad} \times \tag{3.6}$$

Where,

P_{be} = effective asphalt content, percent by total mass of mixture,

P_b = asphalt content percent by total mass of mixture,

P_{ba} = absorbed asphalt, percent by mass of aggregate,

P_s = aggregate content, percent by total mass of mixture.

3.7.5 Bulk Specific Gravity of the Compacted Paving Mixture (G_{mb})

Bulk specific gravity can be obtained accordance with ASTM D 2726 – 08. The compacted mixture is weighted in air at room temperature (A) and then sample is submerged in water at 25 ± 1°C (77 ± 1.8°F) to record the weight in water (C) and finally the mass of saturated-surface dry is measured (B). The bulk specific gravity is given as

Bulk Specific Gravity= (3.7)

Where,

A = mass of the dry specimen in air, g;

(B – C) = mass of the volume of water for the volume of the specimen at 25°C;

B = mass of the saturated surface-dry specimen in air, g;

C = mass of the specimen in water, g.

3.7.6 Calculating the Percent of Air Voids in the Mineral Aggregate in the Compacted Mixture (VMA)

VMA is the void space in among of aggregate particles in the compacted mixture; include air voids plus volume of the asphalt not absorbed into the aggregates (V_{eff}). In Marshall Method, VMA can be obtained from following formula

= 100 ( ) (3.8)

Where,

= voids in mineral aggregate (percent of bulk volume),

= bulk specific gravity of aggregate,

= bulk specific gravity of compacted mixture,

= asphalt content.

3.7.7 Calculating the Percent Air Voids in the Compacted Paving Mixtures (Vtm, Va)

VTM is the small air volume space among of coated aggregates. In Marshall Method, VTM is calculated as

$$= \left(\qquad \frac{}{} \right) 100 \qquad (3.9)$$

Where,

Voids in total mix (air voids),

= bulk specific gravity of compacted specimen,

= maximum theoretical specific gravity of mixture.

3.7.8 Calculating the Percent of Voids Filled With Asphalt in the Compacted Mixture (VFA)

VFA is the percentage of void in mineral aggregate that is filled with asphalt (excluding the asphalt which is absorbed by aggregate) and in Marshall Method it can be determined by

For VFA:

$$= \frac{}{} \times 100 \qquad (3.10)$$

Where,

= voids filled with asphalt, percent of VMA

= voids in mineral aggregate (percent of bulk volume),

= air voids in compacted mixture, percent of total volume

Chapter 4

ANALYSIS AND RESULTS

4.1 Introduction

In this chapter results of asphalt cement tests, including penetration test, softening point and ductility, for normal asphalt test and three different percentage of polypropylene mixed with normal asphalt are discussed. Then, results of Marshall Mix Design for normal asphalt cement (unmodified), modified asphalt cement by pp, and mix of glass fiber plus modified asphalt cement are given in appropriate tables and figures.

4.2 Asphalt Cement Test Results

4.2.1 Penetration Test

Penetration value of an asphalt cement specimen was obtained According to ASTM D5 as it was mentioned before. The result of penetration for normal asphalt cement and three different percentage of pp; 2, 4 and 6% by weight of asphalt cement are shown in Table 20 through to Table 26.

As it can be seen from tables generally, penetration decreased by increasing the percent of additive (polypropylene) compare to normal asphalt cement. In 6 mm polypropylene length, penetration reduced 12%, 27.5% and 56% when 2%, 4% and 6% pp by weight of asphalt cement were used respectively. Longer lengths of additive made component stiffer and resulted in an appreciable decrease in penetration. In 12mm polypropylene length, 34%, 43% and 59% of decline in penetration was obtained by applying 2%, 4% and 6% pp in asphalt cement respectively. These results indicate that modified specimens are much stiffer than the normal asphalt and therefore the rutting resistance of the modified mixtures is expected to be high.

Table 20: Penetration Test Result for Normal Asphalt Cement

Sample No.	Reading No.	Reading	Penetration (0.1 mm)
1	1	76	76
	2	88	88
	3	81	81
		Average	**82**
2	1	80	80
	2	81	81
	3	80	80
		Average	**80**
3	1	90	90
	2	85	85
	3	82	82
		Average	**86**
	Total Average	**82.7**	

Table 21: Penetration Test Result fFor Modified Asphalt Cement with 2% Polypropylene (6mm)

Sample No.	Reading No.	Reading	Penetration (0.1 mm)
1	1	76	76
	2	74	74
	3	65	65
		Average	**71.7**
2	1	66	66
	2	70	70
	3	75	75
		Average	**70.3**
3	1	76	76
	2	72	72
	3	80	80
		Average	**76**
	Total average		**72.7**

Table 22 : Penetration Test Result for Modified Asphalt Cement with 4% Polypropylene (6mm)

Sample No.	Reading No.	Reading	Penetration (0.1 mm)
1	1	76	76
	2	49	49
	3	43	43
		Average	**56**
2	1	42	61
	2	28	59
	3	61	60
		Average	**60**
3	1	55	55
	2	70	70
	3	66	66
		Average	**63.7**
	Total Average		**59.9**

Table 23: Penetration Test Result for Modified Asphalt Cement with 6% Polypropylene (6mm)

Sample No.	Reading No.	Reading	Penetration (0.1 mm)
1	1	32	32
	2	23	23
	3	28	28
		Average	**27.7**
2	1	45	45
	2	43	43
	3	40	40
		Average	**42.7**
3	1	38	38
	2	43	43
	3	35	35
		Average	**38.7**
	Total average		**36.4**

Table 24: Penetration Test Result for Modified Asphalt Cement with 2% Polypropylene (12mm)

Sample No.	Reading No.	Reading	Penetration (0.1 mm)
1	1	36	36
	2	41	41
	3	50	50
	Average		**42.3**
2	1	52	52
	2	58	58
	3	62	62
	Average		**57.3**
3	1	69	69
	2	60	60
	3	66	66
	Average		**65.0**
	Total average		**54.9**

Table 25: Penetration test result for modified asphalt cement with 4% polypropylene (12mm)

Sample No.	Reading No.	Reading	Penetration (0.1 mm)
1	1	41	41
	2	45	45
	3	42	42
	Average		**42.7**
2	1	43	43
	2	46	46
	3	45	45
	Average		**44.7**
3	1	60	60
	2	47	47
	3	53	53
	Average		**53.3**
	Total average		**46.9**

Table 26: Penetration Test Result for Modified Asphalt Cement with 6% Polypropylene (12mm)

Sample No.	**Reading No.**	**Reading**	**Penetration (0.1 mm)**
1	1	22	22
	2	35	35
	3	27	27
		Average	**28.0**
2	1	32	32
	2	40	40
	3	35	35
		Average	**35.7**
3	1	43	43
	2	32	32
	3	41	41
		Average	**38.7**
	Total average		**34.1**

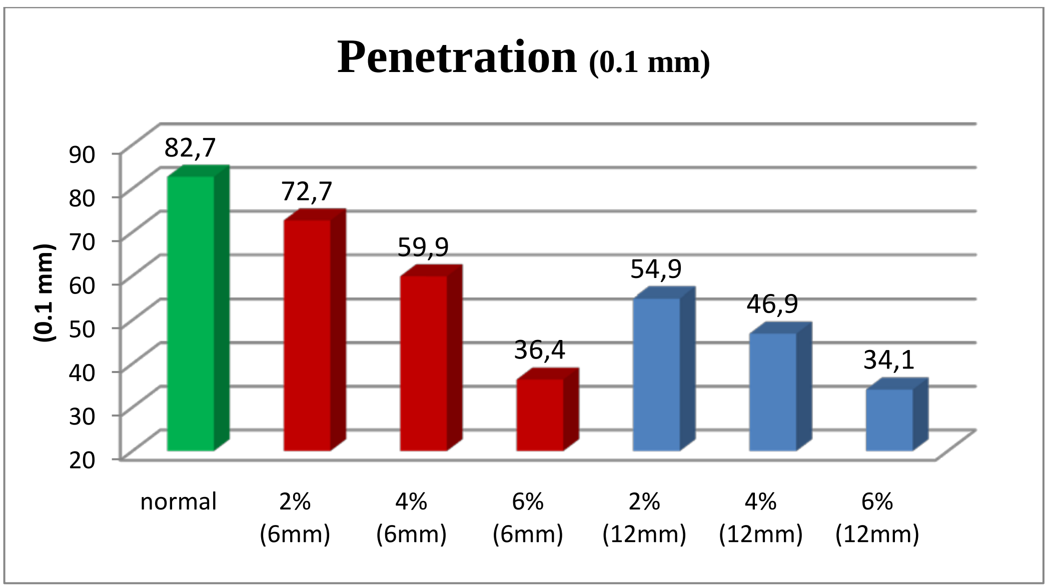


Figure 26: Penetration Test Result for Normal Asphalt and Polypropylene Modified Asphalt Cement

4.2.2 Softening Point

Softening point value of an asphalt cement specimen was obtained according to ASTM D36. The results indicate that softening point can be increased by applying polypropylene additive. Softening point value improved, by increasing the amount of pp additive in the asphalt cement. As it can be seen clearly from Figure 28 when 6% pp mixed with neat (normal) asphalt, softening point increased 35.4 and 40.6% for 6 and 12 mm polypropylene length as compared to control specimen. These results indicate that pp modified asphalt is less susceptible to traffic-induced deformation at high temperature compared to normal asphalt.

Table 27: Softening Point Test Result for Normal Asphalt and pp Modified Asphalt Cement

	2% pp	**4% pp**	**6% pp**
6 mm	53	57	65.5
12 mm	56	61.5	68
Normal Asphalt cement		**48.5**	

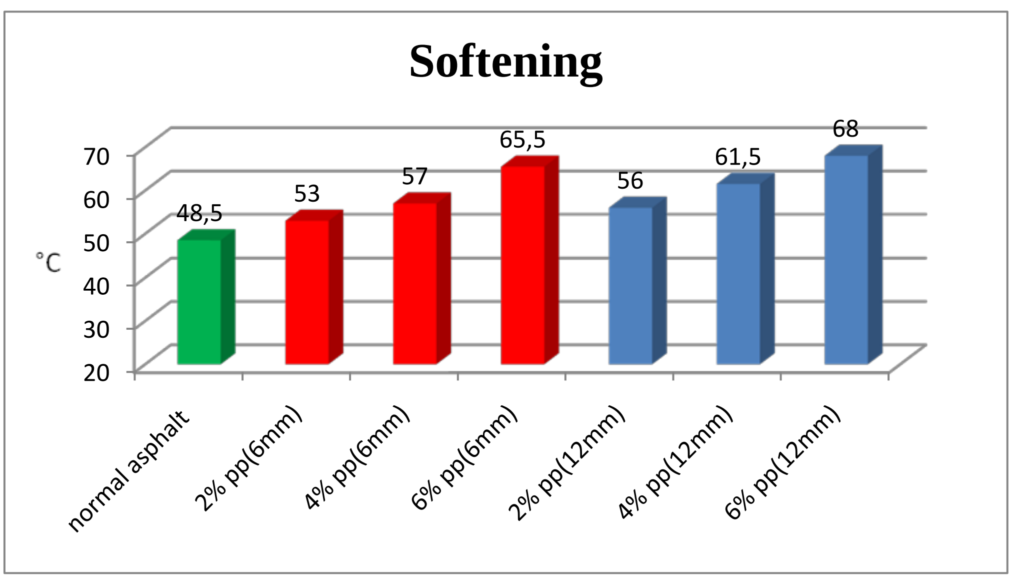


Figure 27: Softening Test Result for Normal Asphalt and Polypropylene Modified Asphalt Cement

4.2.2 Ductility

The ductility test was ran accordance with ASTM D113. The ductility test was obtained more than 100 cm for the normal asphalt and surprisingly less than 100 cm for modified asphalt. Results illustrate that ductility decreased considerably when amount of pp increased in the mixtures. The possible reason for this phenomenon could be; pp fibers placed in the cross-section of specimen in the process of stretching and prevent asphalt cement stretched easily and caused sample not be able to show a good performance in ductility test. Following table shows the ductility test for virgin (normal) asphalt and modified asphalt cement.

Table 28: Ductility Test Result for Normal Asphalt and pp Modified Asphalt

	2% pp	**4% pp**	**6% pp**
6 mm	47(cm)	40.5(cm)	36(cm)
12 mm	46(cm)	36(cm)	33(cm)
Normal Asphalt cement		**+100 cm**	

4.3 Marshall Analysis

Marshall Mix Design was used in this research according to ASTM D 1559. Five different percent of asphalt cement content 3%, 3.5%,4%, 4.5%, 5 % by weight of the mixture were applied to prepare the control group. The optimum amount of the asphalt content can be obtained base on either average of asphalt content at three important factors: 4% air void, highest stability and highest density or just 4% air void. The optimum asphalt content was obtained 4.3% base on 4%air voids in this research. Stability, flow, unit weight, voids in total mix (VTM), voids in mineral aggregate (VMA) and void filled with asphalt (VFA) was achieved at optimum asphalt cement (4.3%) from following figure 1800 kg, 5.8mm, 2494, 4%, 13.3% and 68.2% for normal asphalt cement mixture, respectively.

Two length of polypropylene 6 and 12mm with three different percentages 2%, 4% and 6% by weight of asphalt cement were added at optimum asphalt. Table 30 and Figure 30 show the results related to 6mm polypropylene, and Table 31 and Figure 31 illustrate the effect of 12mm length of pp on six parameters of Marshall Mix method.

Results prove that pp additive caused stability increased and flow decreased in modified asphalt mixtures as compared to the modified asphalt mixture. As it can be seen clearly from these figures in both 6 and 12mm length of pp, VTM (air voids) and VMA value increased whereas, VFA and Unit weight value decreased.

Table 29: Marshall Test Results (Control Group (normal asphalt))

			Mass in grams										Stability,(kg)		
NO.	%AC by wt. of mix	Spec. Height In (mm)	In Air	In Water	SSD In air	Bulk Volume (cc)	Bulk S.G Specimen	MAX. S.G (Loose Mix)	Unit Weight (Kg/m^3)	% Air Voids	% VMA	% VFA	Measured	Adjusted	Flow (mm)
1	3.0	65.62	1231.1	720.3	1232.7	512.4	2.403		2388.7	9.66	15.48	37.60	1533	1456	4.73
2	3.0	65.47	1226.7	717.7	1227.7	510.0	2.405		2385.6	9.59	15.42	37.81	1800	1715	3.71
3	3.0	65.825	1239.7	727.9	1240.9	513.0	2.416		2397.9	9.18	15.03	38.92	1892	1790	3.6
	Average						**2.408**	**2.660**	**2390.7**	**9.47**	**15.31**	**38.12**		**1654**	**4.01**
1	3.5	64.63	1242.1	737.0	1242.9	505.9	2.455		2448.6	6.97	14.10	50.57	1898	1846	3.42
2	3.5	64.31	1235.4	732.1	1236.6	504.5	2.449		2445.9	7.20	14.31	49.69	1986	1946	5.11
3	3.5	64.57	1240.0	735.6	1240.8	505.2	2.454		2445.1	7.01	14.14	50.42	1898	1847	4.12
	Average						**2.453**	**2.639**	**2446.5**	**7.06**	**14.18**	**50.23**		**1880**	**4.217**
1	4.0	64.56	1247.8	746.6	1248.8	502.2	2.485		2460.9	5.04	13.50	62.67	2145	2089	6.94
2	4.0	64.615	1244.9	745.0	1246.1	501.1	2.484		2453.1	5.08	13.54	62.48	2110	2051	5.14
3	4.0	64.17	1246.1	743.8	1247.1	503.3	2.476		2472.5	5.39	13.82	61.00	1808	1777	4.14
	Average						**2.482**	**2.617**	**2462.2**	**5.17**	**13.62**	**62.05**		**1972**	**5.41**
1	4.5	63.79	1250.6	753.4	1251.1	497.7	2.513		2496.2	3.23	12.98	75.12	1840	1827	6.64
2	4.5	64.24	1251.6	750.2	1252.7	502.5	2.491		2480.7	4.08	13.75	70.33	1507	1480	6.12
3	4.5	63.39	1242.0	747.1	1242.8	495.7	2.506		2494.7	3.50	13.23	73.54	1786	1720	5.12
	Average						**2.503**	**2.597**	**2490.5**	**3.60**	**13.32**	**73.0**		**1676**	**5.96**
1	5.0	64.18	1264.4	761.9	1264.5	502.6	2.516		2508.4	2.33	13.34	82.83	1585	1558	5.29
2	5.0	63.97	1257.5	758.2	1257.5	499.3	2.518		2502.9	2.25	13.27	83.04	1698	1678	7.50
3	5.0	63.79	1255.5	755.5	1255.9	500.4	2.509		2506.0	2.60	13.58	80.49	1416	1406	5.71
	Average						**2.519**	**2.576**	**2505.8**	**2.39**	**13.40**	**82.12**		**1547**	**6.17**

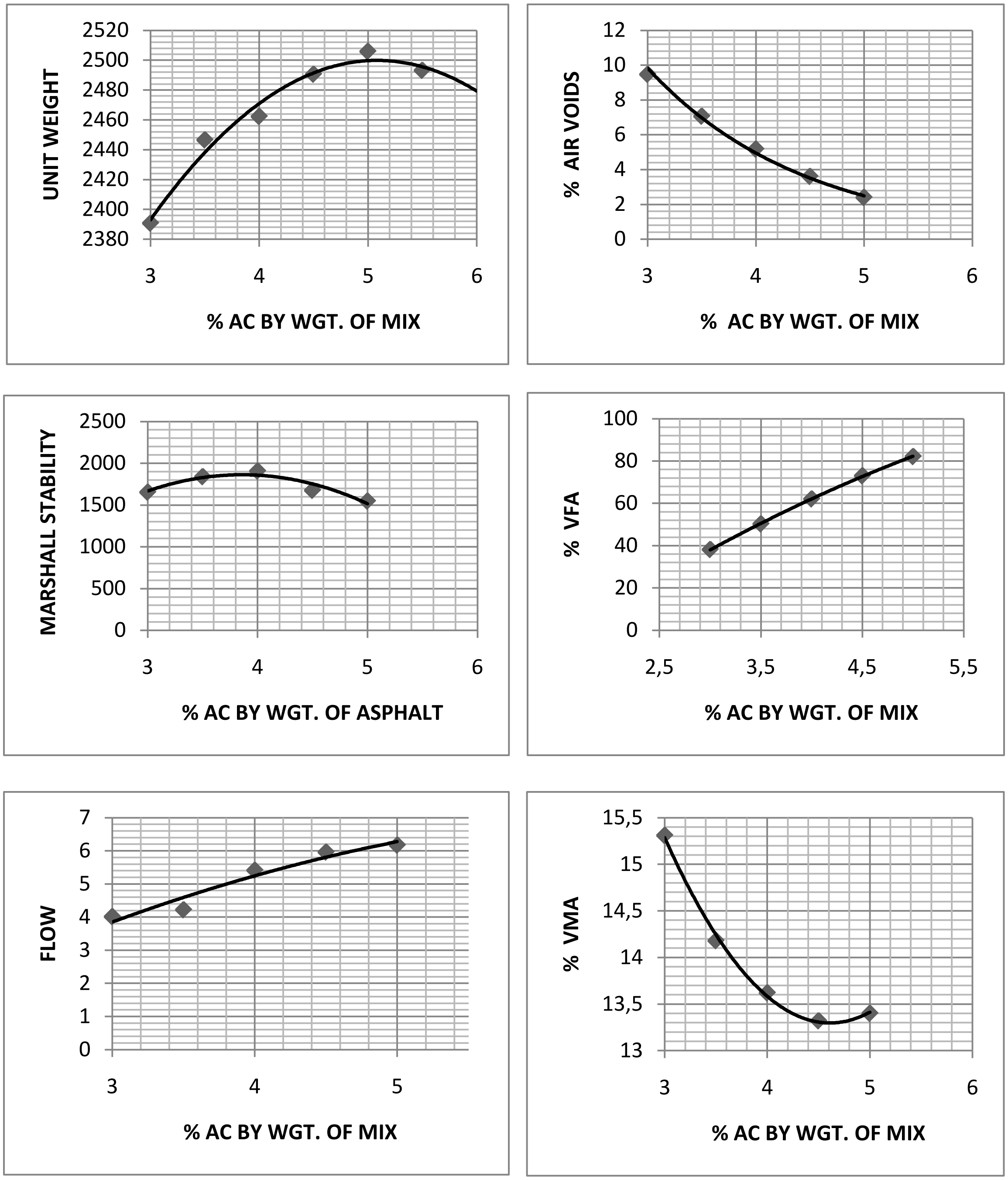


Figure 28: Graphical Illustration of HMA Design Data by Marshall Method (Control Group)

Table 30: Marshall Test Results (Polypropylene-6mm) at Optimum Asphalt (4.3%)

			Mass in grams										Stability,(kg)		
NO.	%PP by wt. of AC	Spec. Height In (mm)	In Air	In Water	SSD In air	Bulk Volume (cc)	Bulk S.G Specimen	MAX. S.G (Loose Mix)	Unit Weight (Kg/m^3)	% Air Voids	% VMA	% VFA	Measured	Adjusted	Flow (mm)
1	2.0	64.115	1247.2	745.9	1248.7	502.8	2.481		2476.8	4.76	13.91	65.78	1990	1960	6.07
2	2.0	64.13	1249.5	745.3	1250.8	505.5	2.472		2480.8	5.10	14.22	63.70	2260	2224	6.17
3	2.0	64.105	1248.8	746.3	1250.2	503.9	2.478	**2.605**	2480.3	4.87	14.02	65.25	2064	2033	5.16
	Average						**2.477**		**2479.3**	**4.91**	**14.05**	**64.91**		**2072**	**5.8**
1	4.0	64.86	1249.2	748.9	1250.7	501.8	2.489		2452.3	4.45	13.63	67.35	1956	1889	4.53
2	4.0	65.15	1245.5	742.7	1247.7	505.0	2.466		2434.3	5.34	14.43	63.00	2007	1925	5.61
3	4.0	64.74	1250.8	744.5	1251.8	507.3	2.466	**2.605**	2459.9	5.34	14.43	63.00	2144	2077	4.77
	Average						**2.474**		**2448.8**	**5.04**	**14.16**	**64.45**		**1964**	**4.97**
1	6.0	64.3	1237.2	736.1	1238.6	502.5	2.462		2449.8	5.49	14.66	62.55	2009	1969	4.95
2	6.0	65.45	1255.5	749.1	1256.9	507.8	2.472		2442.6	5.105	14.31	64.33	2079	1984	4.84
3	6.0	66.08	1246.5	741.8	1248.2	506.4	2.462	**2.605**	2401.8	5.49	14.66	62.55	1913	1802	5.44
4	6.0	65.20	1249.5	740.5	1251.0	508.8	2.456		2440.1	5.72	14.87	61.53	2038	1952	4.35
	Average						**2.463**		**2433.6**	**5.45**	**14.63**	**62.74**		**1927**	**4.90**

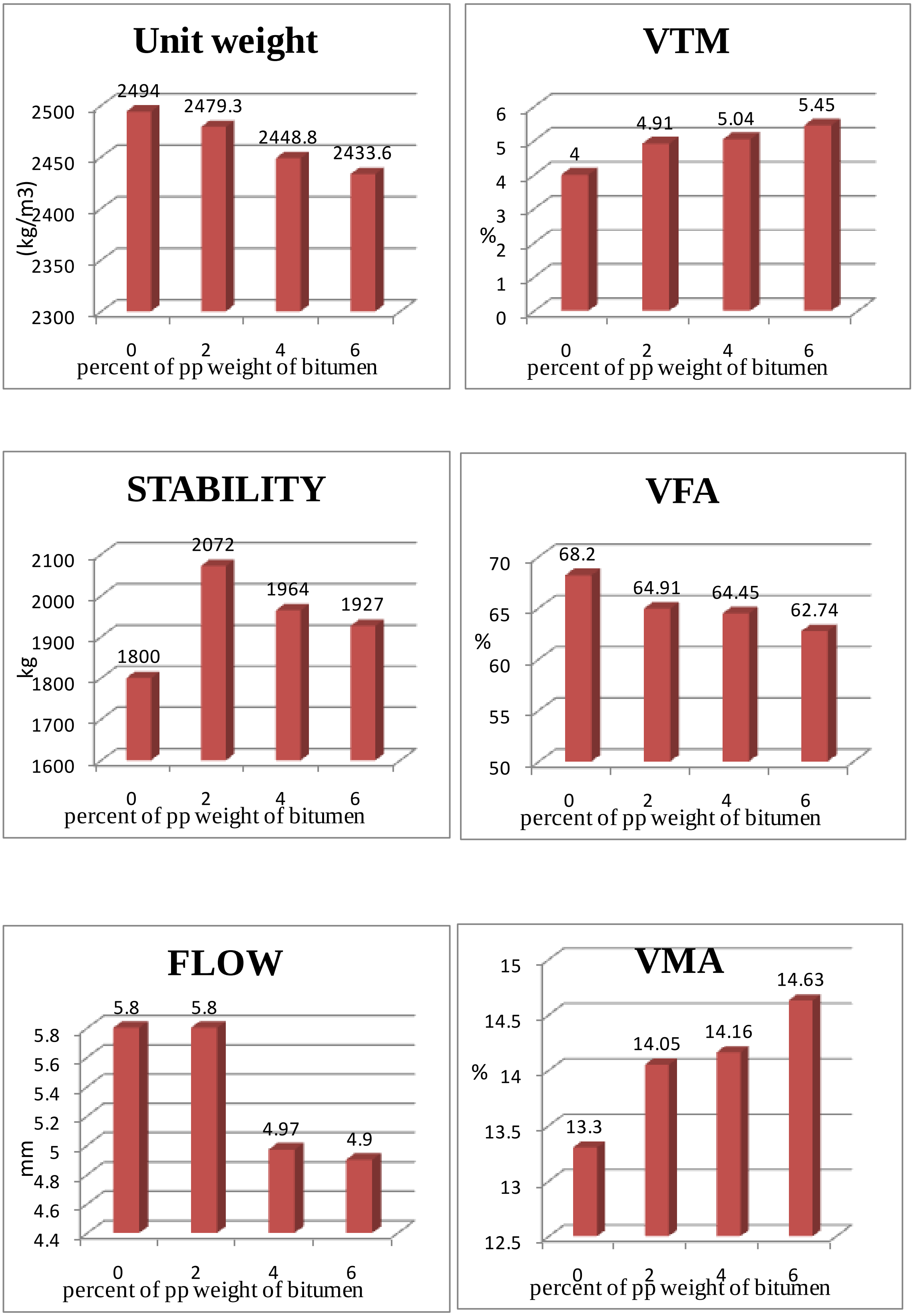


Figure 29: Unit Weight, Stability, Flow, VTM, VFA And VMA for Different Percent of Polypropylene(6mm) by Weight of Asphalt Cement at Optimum Asphalt

Table: 31Marshall Test Results (Polypropylene-12mm) at Optimum Asphalt (4.3%)

			Mass in grams										**Stability,(kg)**		
NO.	%PP by wt. of AC	Spec. Height In (mm)	In Air	In Water	SSD In air	Bulk Volume (cc)	Bulk S.G Specimen	MAX. S.G (Loose Mix)	Unit Weight (Kg/m^3)	% Air Voids	% VMA	% VFA	Measured	Adjusted	Flow (mm)
1	2.0	64.48	1249.9	747.7	1251.2	503.5	2.482		2468.1	4.72	13.97	66.19	1900	1854	4.56
2	2.0	64.04	1247.9	746.8	1248.7	501.9	2.486		2481.1	4.57	13.83	66.97	2098	2071	5.38
3	2.0	64.56	1250.3	750.2	1251.3	501.1	2.495	**2.605**	2465.8	4.22	13.52	68.76	1691	1647	7.61
4	2.0	64.91	1248.6	746.1	1250.0	503.9	2.478		2449.2	4.87	14.11	65.44	1920	1853	5.19
	Average						**2.485**		**2466.05**	**4.6**	**13.86**	**66.84**		**1856**	**5.69**
1	4.0	65.02	1247.6	741.5	1248.7	507.2	2.460		2443.1	5.57	14.73	62.21	1776	1709	4.91
2	4.0	65.3	1247.8	740.0	1249.1	509.1	2.451		2433	5.91	15.04	60.70	2058	1967	6.4
3	4.0	64.63	1251.8	748.4	1252.4	504.0	2.484	**2.605**	2466.1	4.64	13.90	66.58	2360	2294	4.04
	Average						**2.465**		**2447.4**	**5.37**	**14.56**	**63.16**		**1990**	**5.12**
1	6.0	65.09	1252.8	748.8	1253.7	504.9	2.481		2450.6	4.76	14.0	66.00	2789	2677	4.93
2	6.0	66.17	1248.3	737.7	1251.8	514.1	2.428		2402.0	6.79	15.84	57.10	1718	1615	4.5
3	6.0	64.685	1249.4	747.4	1250.4	503.0	2.484	**2.605**	2459.3	4.64	13.90	66.58	2323	2276	4.95
4	6.0	65.95	1248.5	738.0	1249.7	511.7	2.44		2410.4	6.33	15.42	58.93	1803	1702	5.26
	Average						**2.458**		**2430.1**	**5.63**	**14.79**	**62.15**		**2067**	**4.91**

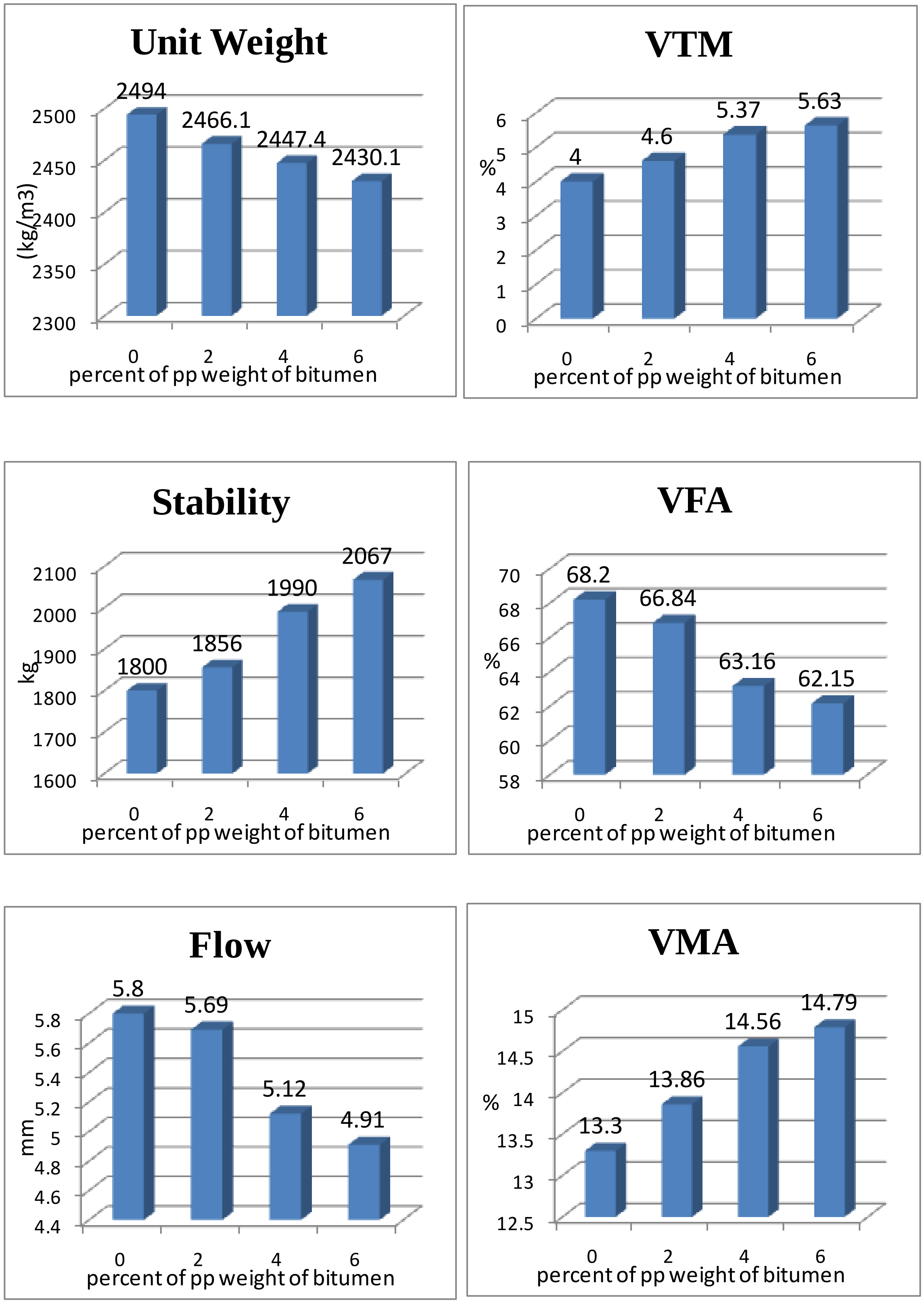


Figure 30: Unit Weight, Stability, Flow, VTM, VFA And VMA For Different Percent of Polypropylene(12mm) by Weight of Asphalt Cement at Optimum Asphalt

Glass fiber is the second fiber which is used in this research. Glass fiber with 12mm length was introduced to pp modified bitumen mixture based on dry method. Glass fiber mixed for 1 to 2 min with preheated aggregate before blending with modified bitumen. The following figures and tables illustrate the results of hybrid reinforcement of asphalt-concrete mixtures using glass and pp additive. Results indicate that by increasing the amount of pp additive stability increased in each the four glass fiber content levels (0, 0.05, 0.1 and 0.2%). In fact pp caused cohesion of the mix improve due to tackiness phenomenon and Therefore glass fibers can participate further in the mix and increase the stability due to its high tensile strength. Effect of this phenomenon can be seen obviously from stability result when 0.1% glass fiber added to 6% pp modified asphalt in both length of pp.

Also results show that flow, unit weight and void filled with asphalt (VFA) in all modified asphalt mixture presented a reduction trend compare to the normal asphalt mix. However, void in total mix (VTM) and Void in mineral aggregate (VMA) increased in all modified mixture as compared to unmodified mixture.

Table 32: Marshall Test Results (Polypropylene-12mm) + 0.05% Glass at Optimum Asphalt (4.3%)

			Mass in grams										**Stability,(kg)**		
NO.	%PP by wt. of AC	Spec. Height In (mm)	In Air	In Water	SSD In air	Bulk Volume (cc)	Bulk S.G Specimen	MAX. S.G (Loose Mix)	Unit Weight (Kg/m^3)	% Air Voids	% VMA	% VFA	Measured	Adjusted	Flow (mm)
1	2.0	64.77	1251.9	750.8	1252.7	501.9	2.494		2461	4.26	13.55	68.55	1653	1640	4.39
2	2.0	64.74	1250.7	748.5	1251.8	503.3	2.485		2459.7	4.61	13.86	66.77	2398	2320	5.32
3	2.0	64.72	1248.1	744.0	1248.5	505.5	2.469	**2.605**	2455.4	5.22	14.42	63.79	1882	1825	5.62
	Average						**2.483**		**2458.7**	**4.70**	**13.94**	**66.37**		**1928**	**5.11**
1	4.0	64.53	1250.2	748.0	1251.0	503.0	2.485		2467	4.60	13.86	66.77	2111	2056	3.03
2	4.0	64.90	1251.2	745.8	1252.7	506.9	2.468		2454.7	6.26	14.45	63.61	1884	1818.5	6.25
3	4.0	64.46	1248.7	748.2	1249.7	501.5	2.490	**2.605**	2466.5	4.41	13.69	67.75	2371	2314.	5.79
	Average						**2.481**		**2462.7**	**5.09**	**14.0**	**66.04**		**2063**	**5.02**
1	6.0	64.91	1249.3	743.4	1250.6	507.2	2.463		2450.6	5.45	14.63	62.73	1923	1856	3.76
2	6.0	65.31	1250.1	743.2	1251.3	508.1	2.460		2437.1	5.57	14.73	62.21	2300	2199	5.62
3	6.0	64.65	1249.5	746.5	1250.6	504.1	2.479	**2.605**	2460.8	4.84	14.07	65.53	2272	2206	4.93
	Average						**2.467**		**2449.5**	**5.29**	**14.48**	**63.49**		**2087**	**4.77**

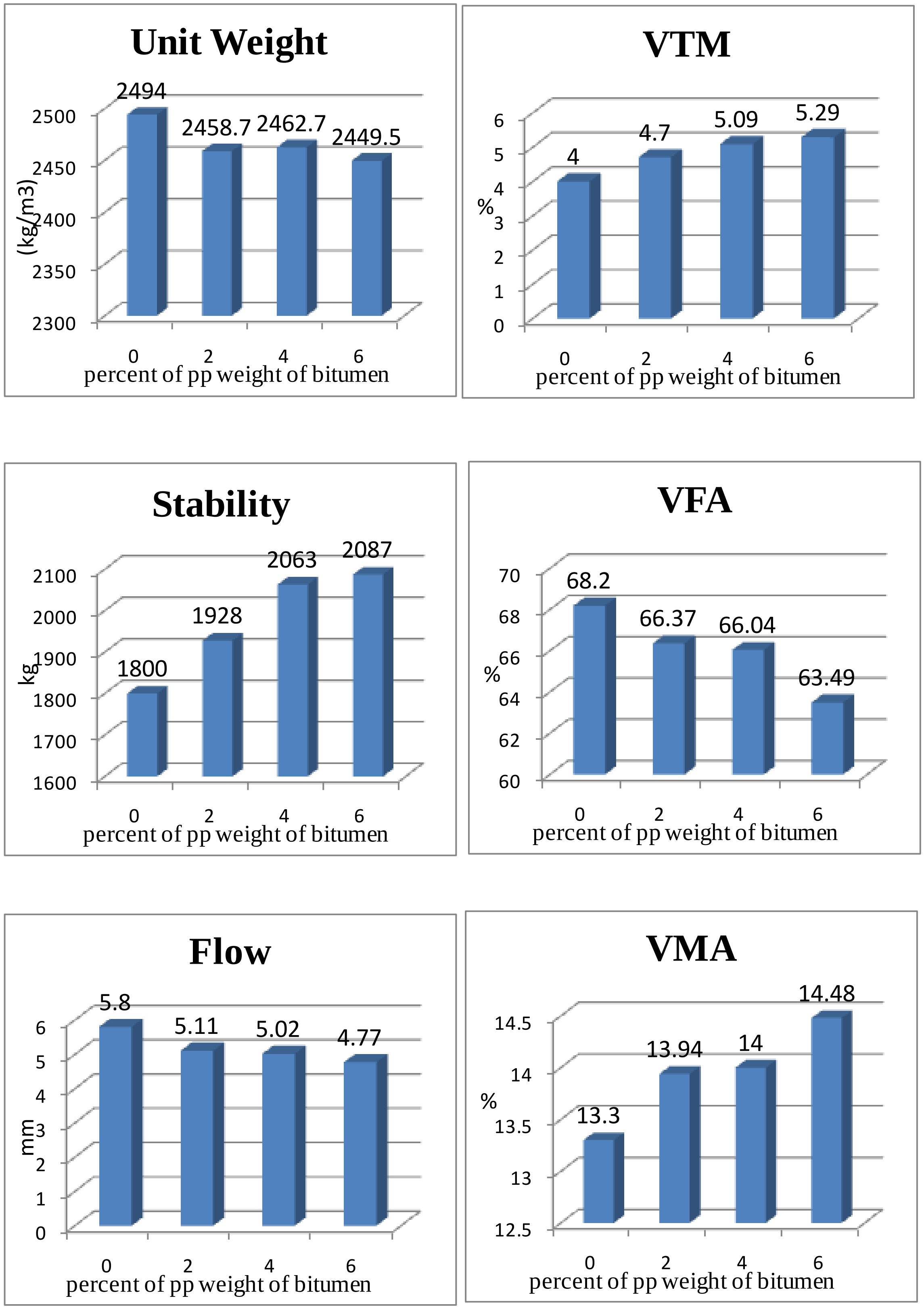


Figure 31: Unit Weight, Stability, Flow, VTM, VFA And VMA for Different Percent of Polypropylene(12mm) by Weight Of Asphalt Cement at Optimum Asphalt + 0.05% Glass Fiber

Table 33: Marshall Test Results (Polypropylene-12mm) + 0.1% Glass at Optimum Asphalt (4.3%)

			Mass in grams										Stability,(kg)		
NO.	%PP by wt. of AC	Spec. Height In (mm)	In Air	In Water	SSD In air	Bulk Volume (cc)	Bulk S.G Specimen	MAX. S.G (Loose Mix)	Unit Weight (Kg/m^3)	% Air Voids	% VMA	% VFA	Measured	Adjusted	Flow (mm)
1	2.0	64.30	1249	747.6	1250.3	502.7	2.485		2473.2	4.61	13.86	66.77	1698	1665	5.6
2	2.0	64.35	1248.5	746.0	1249.3	503.3	2.481		2470.3	4.76	14.0	66.00	1775	1738	5.22
3	2.0	65.0	1252.2	746.7	1253.4	506.7	2.471	**2.605**	2452.8	5.14	14.35	64.15	2268	2184	4.7
4	2.0	65.08	1252.3	746.0	1253.6	507.6	2.467		2450.0	5.30	14.49	63.43	2684	2578	4.02
	Average						**2.476**		**2461.6**	**4.95**	**14.18**	**65.09**		**2041**	**4.89**
1	4.0	64.83	1249.3	747.8	1250.7	502.9	2.484		2453.6	4.64	13.90	66.58	2348	2271	3.44
2	4.0	65.64	1252.3	742.5	1253.1	510.6	2.453		2429.0	5.83	14.97	61.03	2041	1939	4.54
3	4.0	64.84	1251.4	746.1	1252.3	506.2	2.472	**2.605**	2457.3	5.11	14.31	64.33	1952	1888	5.2
4	4.0	64.85	1249.8	745.6	1250.8	505.2	2.474		2453.8	5.03	14.24	64.70	2235	2159	5.38
	Average						**2.471**		**2448.4**	**5.15**	**14.36**	**64.16**		**2064**	**4.64**
1	6.0	66.14	1251.5	735.6	1252.3	516.7	2.422		2409.0	7.02	16.05	56.22	1870	1760	3.81
2	6.0	65.24	1253.7	743.5	1254.5	511.0	2.453		2446.8	5.83	14.97	61.03	2050	1962	5.08
3	6.0	65.58	1252.8	743.1	1253.8	510.7	2.453	**2.605**	2432.3	5.83	14.97	61.03	2098	1995	4.23
4	6.0	65.66	1253.9	743.0	1254.7	511.7	2.450		2431.5	5.95	15.08	60.53	3030	2879	4.83
	Average						**2.445**		**2429.9**	**6.16**	**15.27**	**59.70**		**2149**	**4.49**

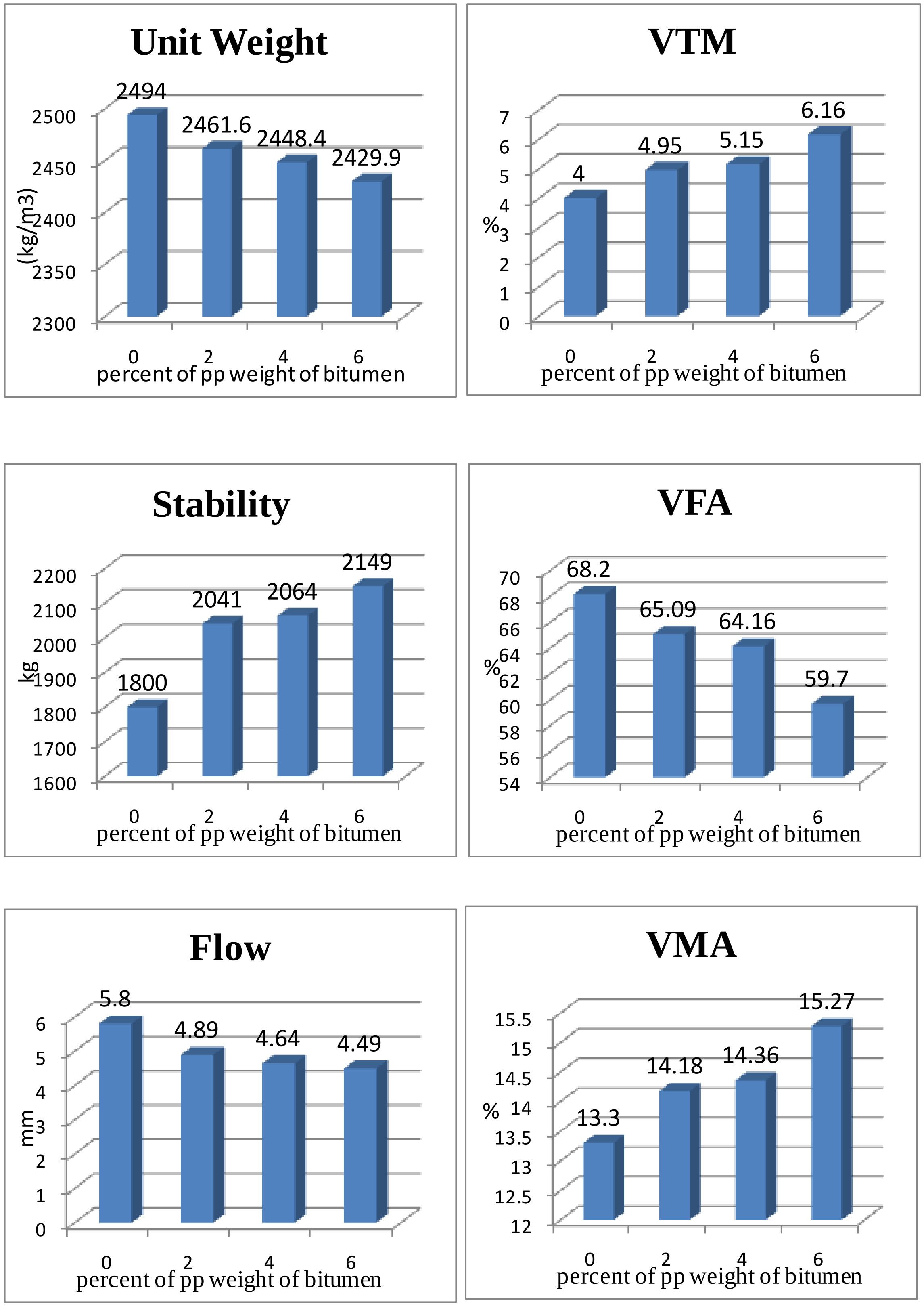


Figure 32: Unit Weight, Stability, Flow, VTM, VFA And VMA for Different Percent of Polypropylene(12mm) by Weight of Asphalt Cement At Optimum Asphalt + 0.1% Glass Fiber

Table 34: Marshall Test Results (Polypropylene-12mm) + 0.2% Glass at Optimum Asphalt (4.3%)

			Mass in grams										**Stability,(kg)**		
NO.	%PP by wt. of AC	Spec. Height In (mm)	In Air	In Water	SSD In air	Bulk Volume (cc)	Bulk S.G Specimen	MAX. S.G (Loose Mix)	Unit Weight (Kg/m^3)	% Air Voids	% VMA	% VFA	Measured	Adjusted	Flow (mm)
1	2.0	65.16	1254.3	744.5	1255.6	511.1	2.454		2450.9	5.80	14.94	61.19	1849	1774	4.08
2	2.0	65.05	1253.8	741.6	1254.4	512.8	2.445		2454.1	6.14	15.25	59.72	1625	1562	4.4
3	2.0	64.90	1255.6	745.1	1256.2	511.1	2.457	**2.605**	2463.3	5.68	14.83	61.70	1829	1765	4.46
4	2.0	65.22	1252	741.1	1252.7	511.6	2.447		2444.2	6.06	15.18	60.04	1568	1502	4.67
	Average						**2.451**		**2453.1**	**5.92**	**15.05**	**60.66**		**1651**	**4.40**
1	4.0	65.35	1255.6	743.5	1256.4	512.9	2.448		2446.3	6.03	15.15	60.21	1784	1704	3.8
2	4.0	65.32	1252.6	742.8	1253.1	510.3	2.454		2441.6	5.80	14.94	61.19	2031	1942	4.28
3	4.0	65.13	1253.7	741.7	1254.6	512.9	2.444	**2.605**	2450.9	6.18	15.28	59.56	1970	1889	3.65
4	4.0	65.27	1253.8	744.5	1254.7	510.2	2.457		2445.8	5.68	14.83	61.70	2074	1985	5.15
	Average						**2.450**		**2446.2**	**5.93**	**15.05**	**60.67**		**1880**	**4.22**
1	6.0	65.97	1252.6	739.2	1253.7	514.5	2.435		2417.6	6.53	15.60	58.16	1972	1861	3.52
2	6.0	65.66	1254.7	738.3	1255.9	517.6	2.424		2433.0	6.95	15.98	56.51	2059	1957	4.1
3	6.0	66.25	1253.9	733.1	1254.6	521.5	2.404	**2.605**	2409.8	7.72	16.67	53.72	2011	1886	4.67
4	6.0	65.92	1255.2	739.0	1256.0	517.0	2.428		2424.4	6.80	15.84	57.10	2212	2090	3.73
	Average						**2.423**		**2421.2**	**7.00**	**16.02**	**56.37**		**1949**	**4.0**

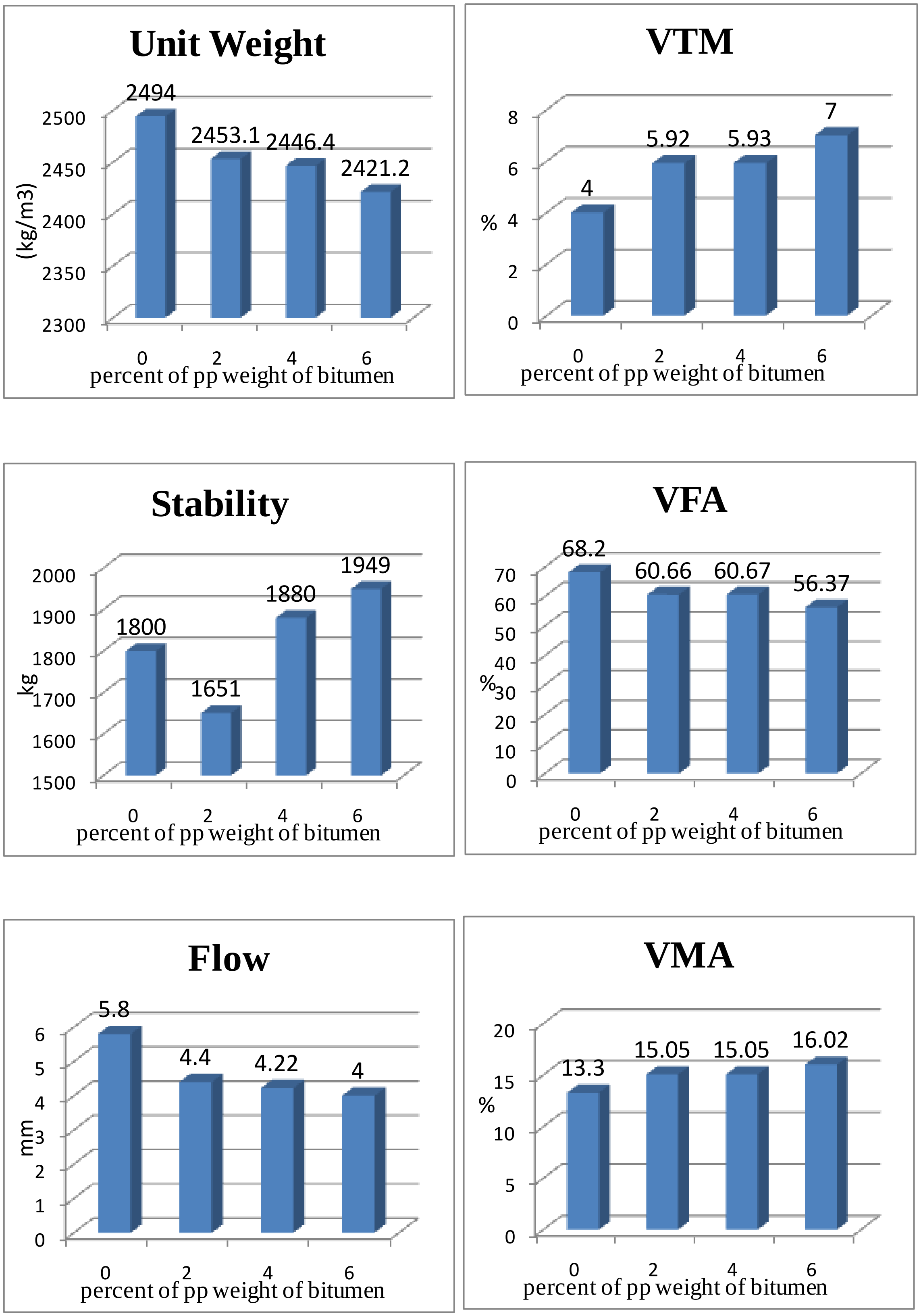


Figure 33: Unit Weight, Stability, Flow, VTM, VFA And VMA for Different Percent of polypropylene(12mm) by Weight of Asphalt Cement at Optimum Asphalt + 0.2% Glass Fiber

Table 35: Marshall Test Results (Polypropylene-6mm) + 0.05% Glass at Optimum Asphalt (4.3%)

			Mass in grams										**Stability,(kg)**		
NO.	%PP by wt. of AC	Spec. Height In (mm)	In Air	In Water	SSD In air	Bulk Volume (cc)	Bulk S.G Specimen	MAX. S.G (Loose Mix)	Unit Weight (Kg/m^3)	% Air Voids	% VMA	% VFA	Measured	Adjusted	Flow (mm)
1	2.0	64.89	1252.2	745.9	1253.3	507.4	2.468		2457.0	5.26	14.45	63.61	1988	1918	3.05
2	2.0	64.97	1252.3	748.3	1253.5	505.2	2.479		2454.2	4.84	14.07	65.63	2053	1977	3.86
3	2.0	64.33	1249.3	745.6	1250.2	504.6	2.476	**2.605**	2472.7	4.95	14.17	65.06	1869	1830	4.95
	Average						**2.474**		**2461.3**	**5.02**	**14.23**	**64.77**		**1908**	**3.95**
1	4.0	65.18	1252.6	746.4	1254.4	508.0	2.466		2446.9	5.34	14.52	63.26	2246	2154	3.75
2	4.0	65.41	1251.6	740.9	1252.5	511.6	2.446		2436.3	6.10	15.21	59.88	1654	1577	4.13
3	4.0	65.28	1254.2	745.6	1255.3	509.7	2.461	**2.605**	2446.2	5.53	14.69	62.38	2125	2034	3.38
	Average						**2.458**		**2443.1**	**5.66**	**14.81**	**61.84**		**1922**	**3.75**
1	6.0	65.36	1253.1	742.0	1254.5	512.5	2.445		2441.1	6.14	15.25	59.72	1760	1681	3.44
2	6.0	65.75	1255.0	742.1	1256.0	513.9	2.442		2430.3	6.26	15.35	59.25	2169	2056	3.13
3	6.0	65.24	1254.6	745.2	1255.7	510.5	2.458	**2.605**	2448.5	5.64	14.80	61.87	2346.	2245	4.55
	Average						**2.448**		**2440.0**	**6.01**	**15.13**	**60.28**		**1994**	**3.70**

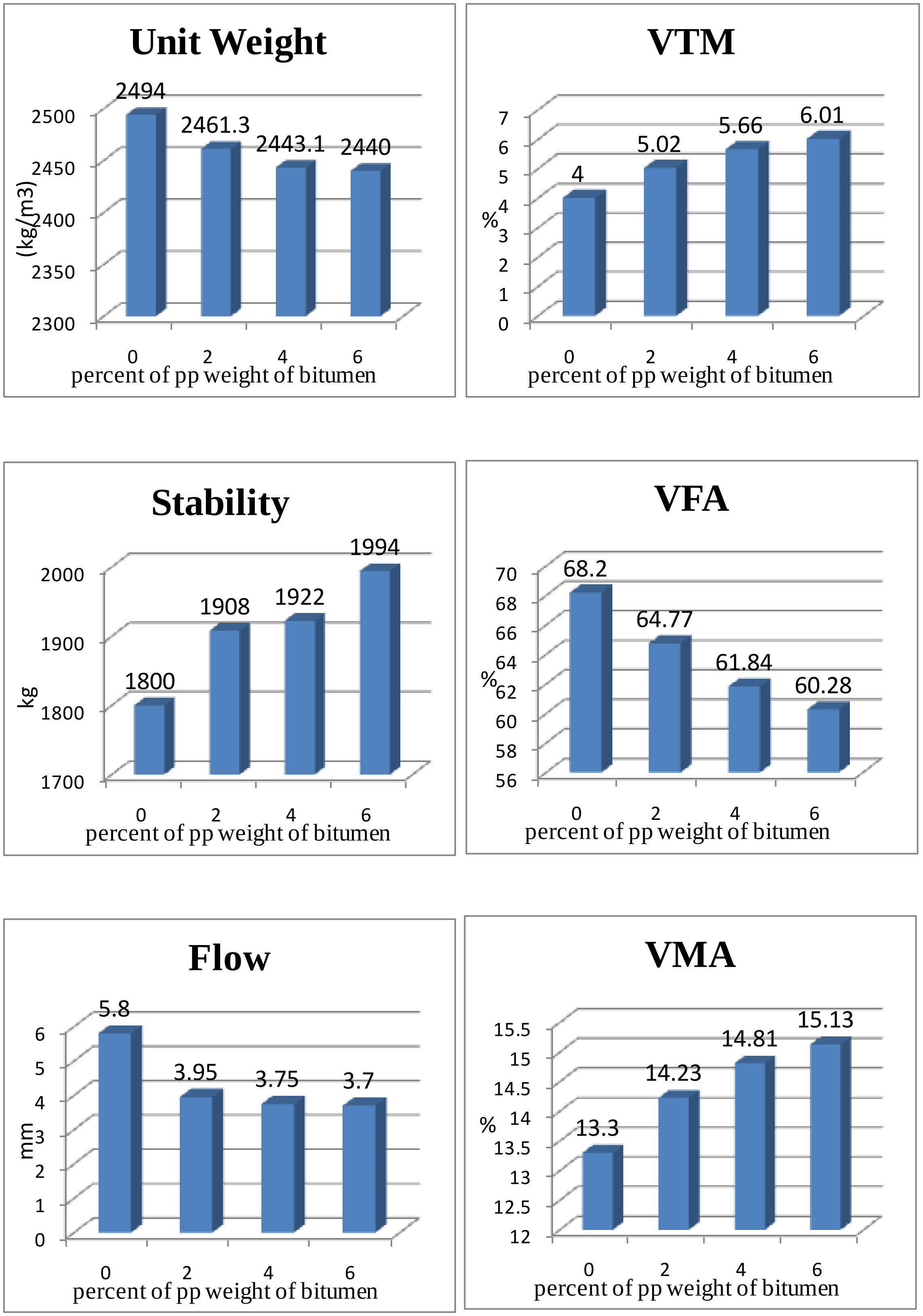


Figure 34: Unit Weight, Stability, Flow, VTM, VFA And VMA for Different Percent of Polypropylene(6mm) by Weight of Asphalt Cement at Optimum Asphalt + 0.05% Glass Fiber

Table 36: Marshall Test Results (Polypropylene-6mm) + 0.1% Glass at Optimum Asphalt (4.3%)

			Mass in grams										Stability,(kg)		
NO.	%PP by wt. of AC	Spec. Height In (mm)	In Air	In Water	SSD In air	Bulk Volume (cc)	Bulk S.G Specimen	MAX. S.G (Loose Mix)	Unit Weight (Kg/m^3)	% Air Voids	% VMA	% VFA	Measured	Adjusted	Flow (mm)
1	2.0	64.96	1252.8	745.0	1253.5	508.5	2.464		2455.5	5.41	14.59	62.90	1645	1586	3.64
2	2.0	64.74	1253.5	746.6	1254.1	507.5	2.470		2465.2	5.18	14.38	63.97	1933	1873	2.97
3	2.0	64.93	1250.3	741.8	1250.9	509.1	2.456	**2.605**	2451.8	5.72	14.87	61.53	1586	1529	3.88
	Average						**2.463**		**2457.5**	**5.44**	**14.61**	**62.8**		**1663**	**3.5**
1	4.0	65.01	1253.8	747.1	1254.9	507.8	2.469		2455.6	5.22	14.42	63.79	2107	2000	3.19
2	4.0	65.40	1252.8	743.1	1254.2	511.1	2.451		2439.0	5.91	15.04	60.70	1718	1837	2.67
3	4.0	65.14	1251.4	743.6	1252.0	508.4	2.461	**2.605**	2446.0	5.53	14.70	62.38	2120	2033	3.85
	Average						**2.460**		**2446.9**	**5.55**	**14.72**	**62.29**		**1957**	**3.24**
1	6.0	65.88	1261.1	749.4	1262.6	513.2	2.457		2437.3	5.68	14.83	61.70	2364	2234	3.18
2	6.0	65.70	1252.2	741.6	1253.0	511.4	2.449		2426.7	5.99	15.11	60.37	2802	2659	2.91
3	6.0	66.49	1252.3	743.1	1253.4	510.3	2.454	**2.605**	2398.1	5.80	14.94	61.19	2032	1898	3.52
	Average						**2.453**		**2420.7**	**5.82**	**14.96**	**61.09**		**2264**	**3.20**

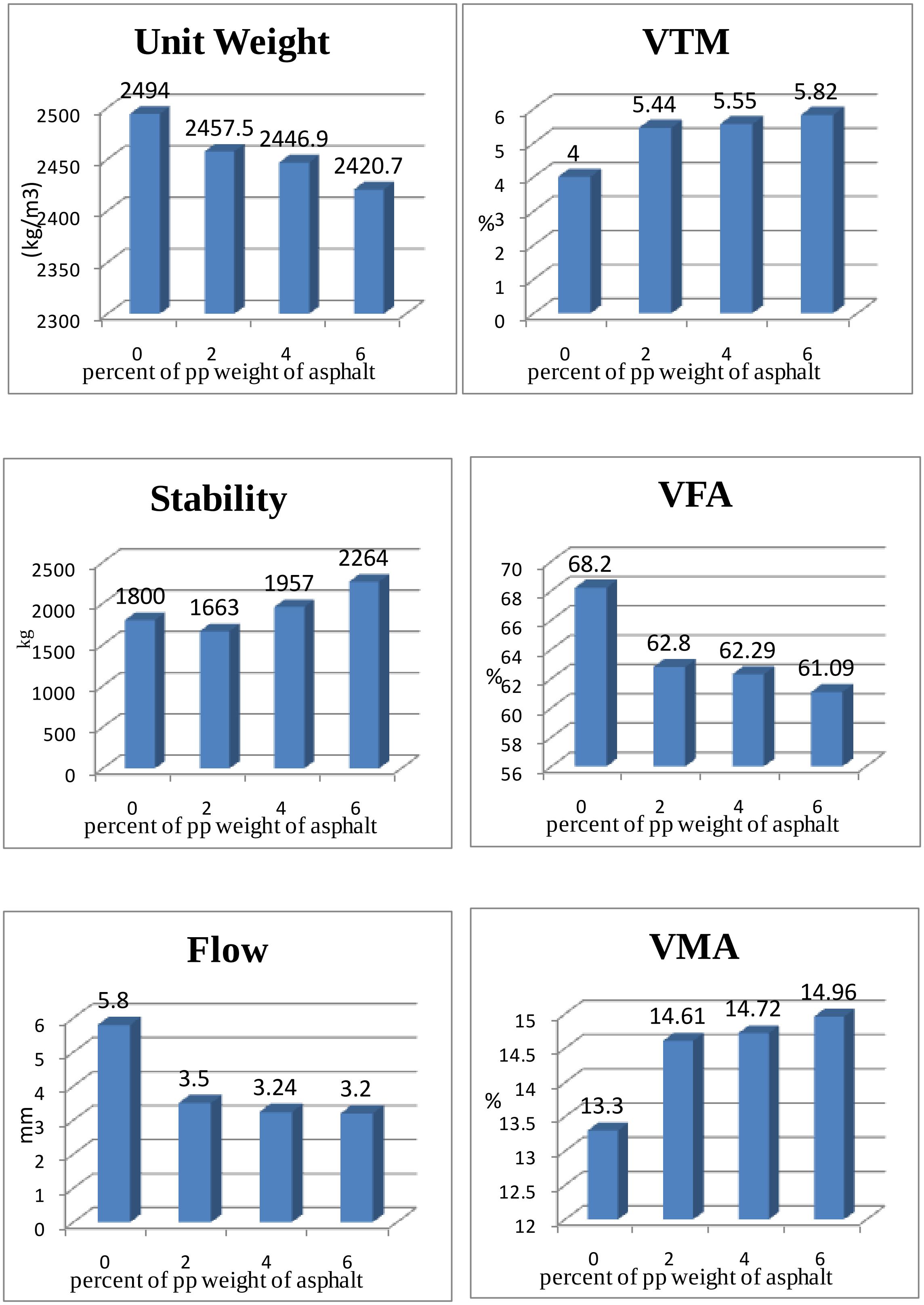


Figure 35: Unit Weight, Stability, Flow, VTM, VFA And VMA for Different Percent of Polypropylene(6mm) by Weight of Asphalt Cement at Optimum Asphalt + 0.1% Glass Fiber

Table 37: Marshall Test Results (Polypropylene-6mm) + 0.2% Glass at Optimum Asphalt (4.3%)

			Mass in grams										**Stability,(kg)**		
NO.	%PP by wt. of AC	Spec. Height In (mm)	In Air	In Water	SSD In air	Bulk Volume (cc)	Bulk S.G Specimen	MAX. S.G (Loose Mix)	Unit Weight (Kg/m^3)	% Air Voids	% VMA	% VFA	Measured	Adjusted	Flow (mm)
1	2.0	65.33	1254.4	746.0	1255.4	509.4	2.463		2444.7	5.45	14.63	62.73	1871	1789	4.1
2	2.0	65.59	1254.0	742.4	1255.2	512.8	2.445		2434.3	6.14	15.25	59.72	1676	1594	4.55
3	2.0	65.55	1254.2	744.1	1255.3	511.2	2.453	**2.605**	2436.2	5.83	14.97	61.03	1928	1835	3.9
	Average						**2.454**		**2438.4**	**5.81**	**14.95**	**61.16**		**1739**	**4.18**
1	4.0	65.9	1255.6	744.9	1257.0	512.1	2.452		2425.9	5.87	15.01	60.86	1692	1599	3.61
2	4.0	66.48	1254.2	738.8	1255.7	516.9	2.426		2402.1	6.87	15.91	56.81	1765	1849	4.2
3	4.0	66.29	1254.1	739.3	1255.4	516.1	2.430	**2.605**	2408.8	6.72	15.77	57.40	1957	1836	4.51
	Average						**2.439**		**2412.3**	**6.49**	**15.56**	**58.36**		**1761**	**4.11**
1	6.0	66.48	1253.8	737.7	1254.8	517.1	2.425		2401.3	6.91	15.94	56.66	1629	1722	3.01
2	6.0	66.70	1253.5	740.0	1255.6	512.8	2.431		2392.8	6.68	15.73	57.55	1662	1745	3.96
3	6.0	66.21	1254.5	742.7	1255.8	513.1	2.445	**2.605**	2412.4	6.14	15.25	59.72	2071	1945	2.56
	Average						**2.434**		**2402.2**	**6.58**	**15.64**	**57.98**		**1804**	**3.18**

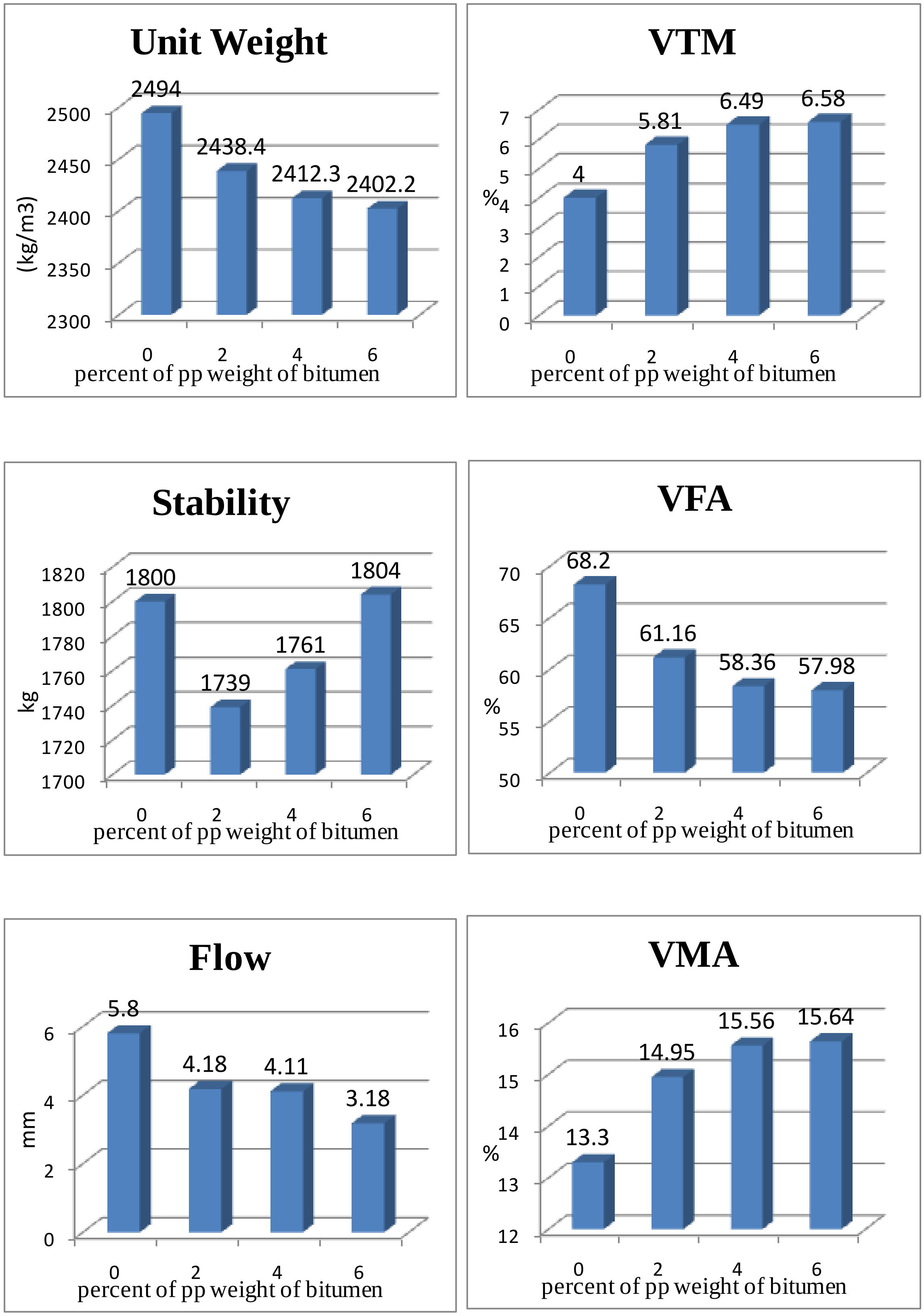


Figure 36: Unit Weight, Stability, Flow, VTM, VFA And VMA for Different Percent of Polypropylene(6mm) by Weight of Asphalt Cement at Optimum Asphalt + 0.2% Glass Fiber

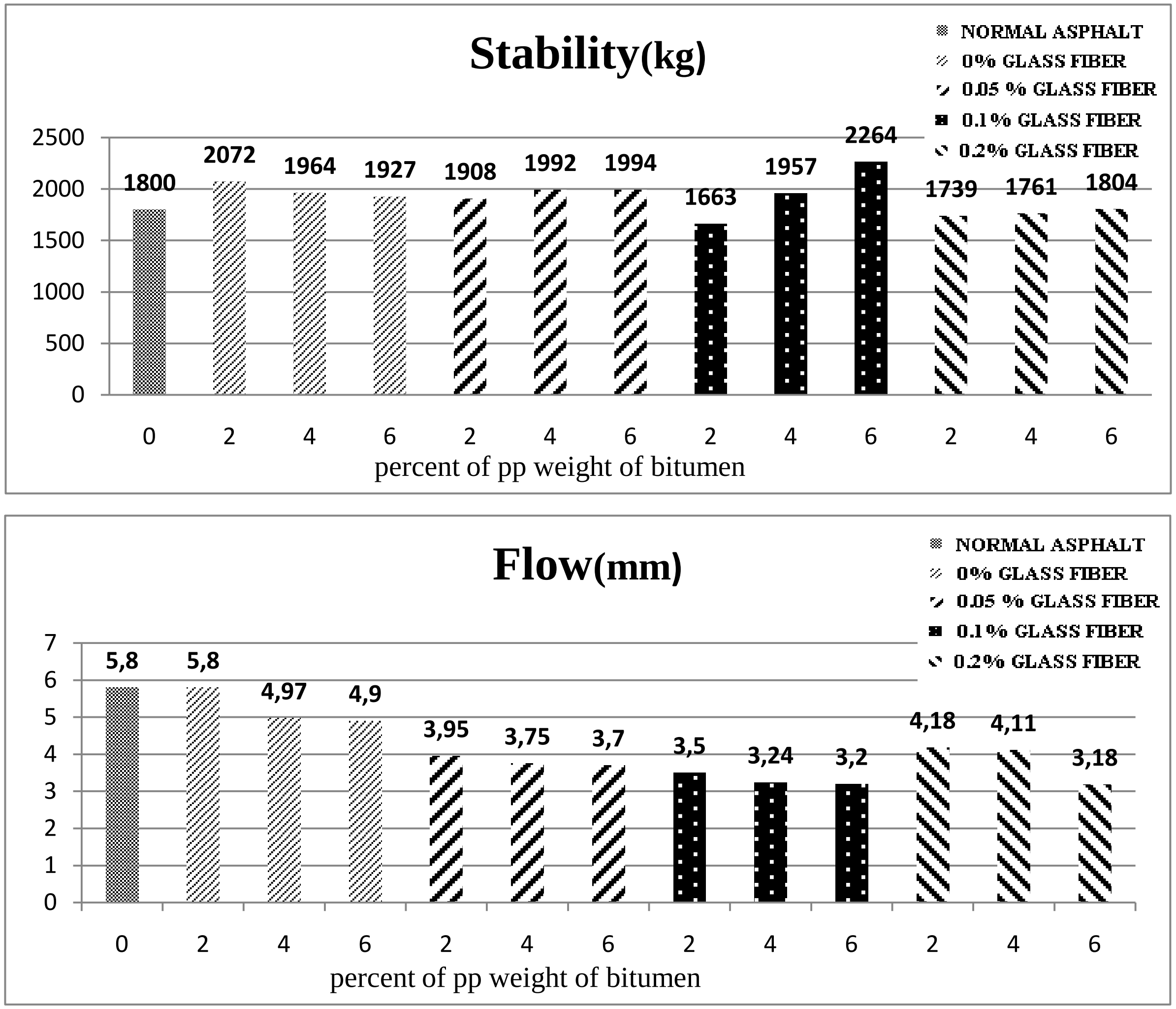


Figure 37: Stability and Flow for Different Percent of Glass Fiber(0.05,0.1 And 0.2%) and 6mm Polypropylene (2,4 And 6%)

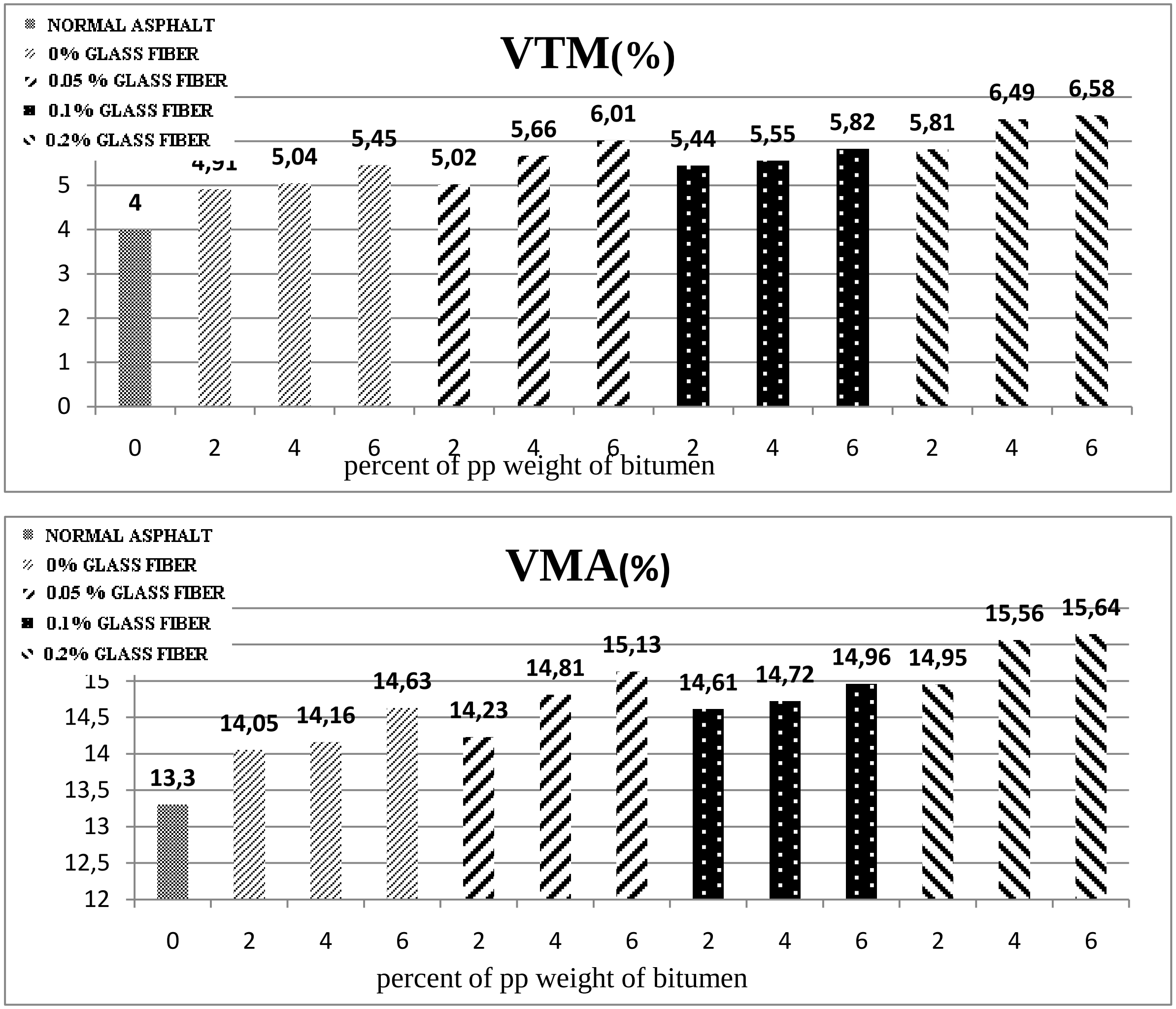
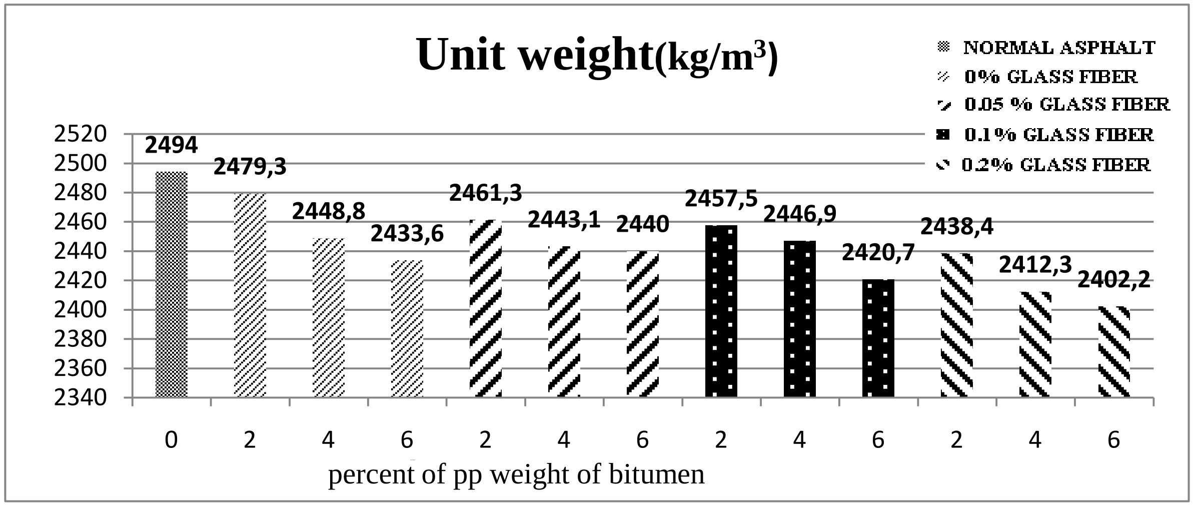


Figure 38: VTM and VMA for Different Percent of Glass Fiber(0.05,0.1 And 0.2%) and 6mm Polypropylene (2,4 And 6%)



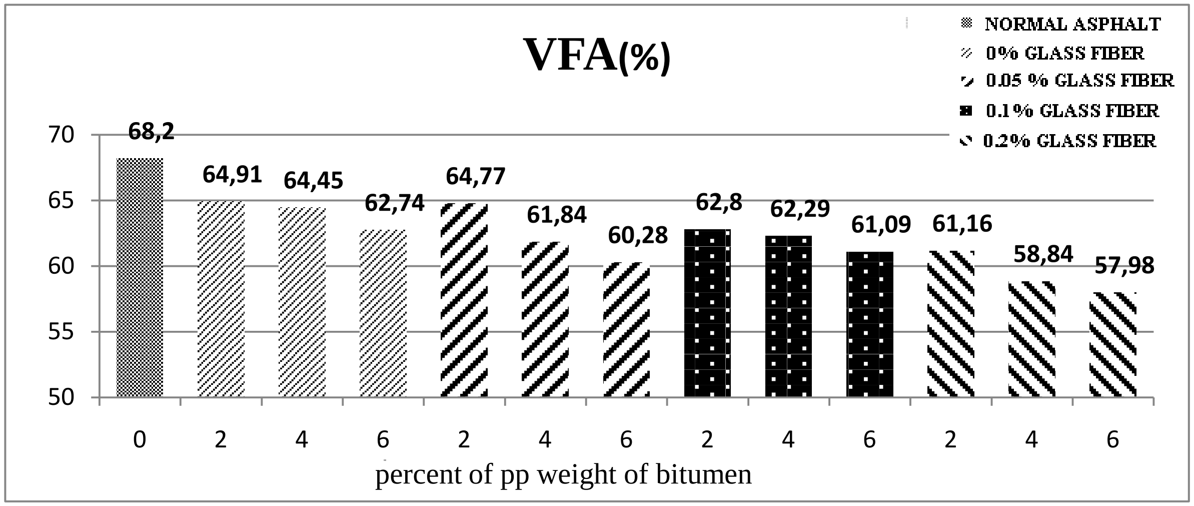


Figure 39: Unit Weight and VFA for Different Percent of Glass Fiber(0.05,0.1 And 0.2%) and 6mm Polypropylene (2,4 And 6%)

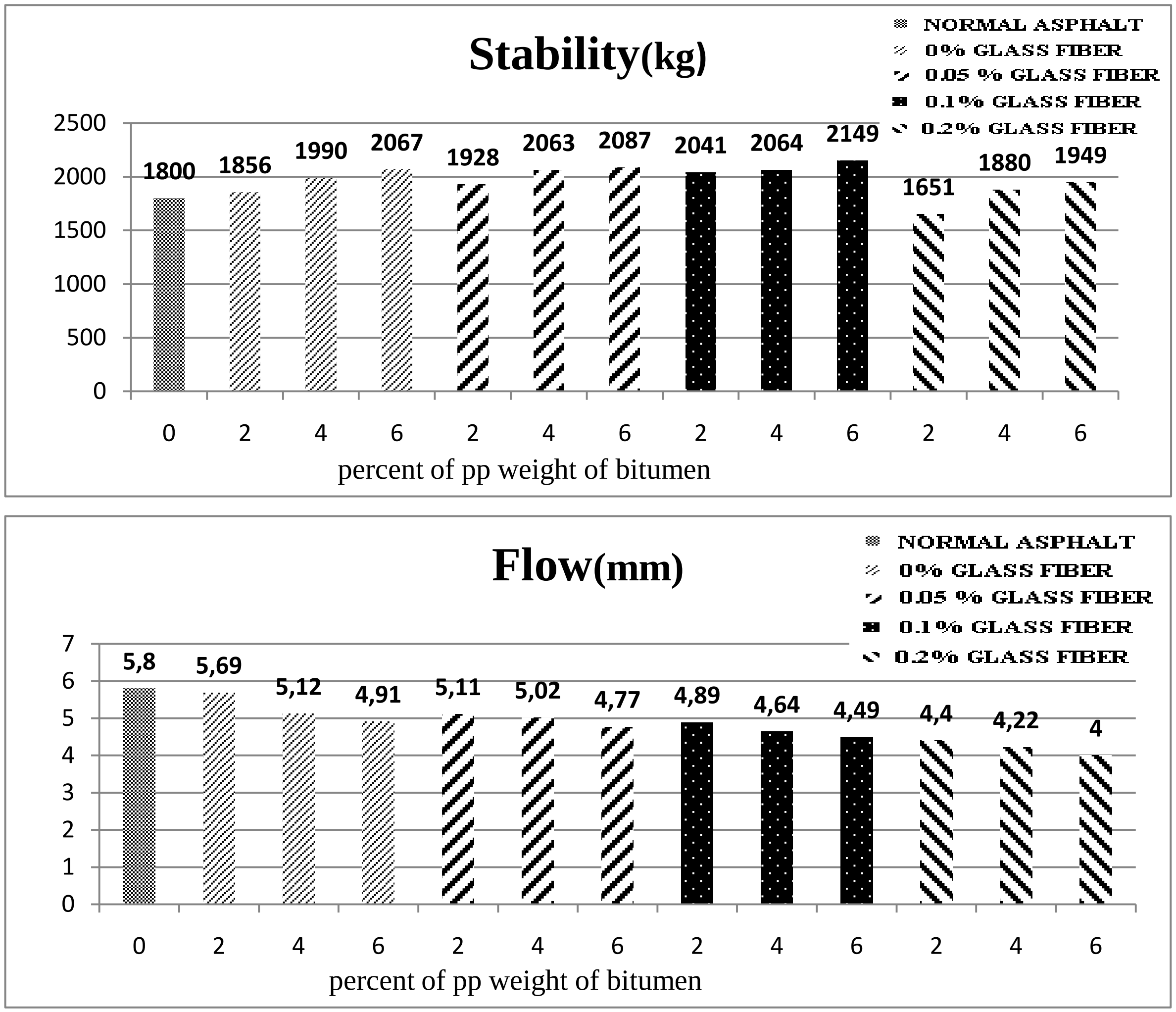


Figure 40: Stability and Flow for Different Percent of Glass Fiber(0.05,0.1 And 0.2%) and 12mm Polypropylene (2,4 And 6%)

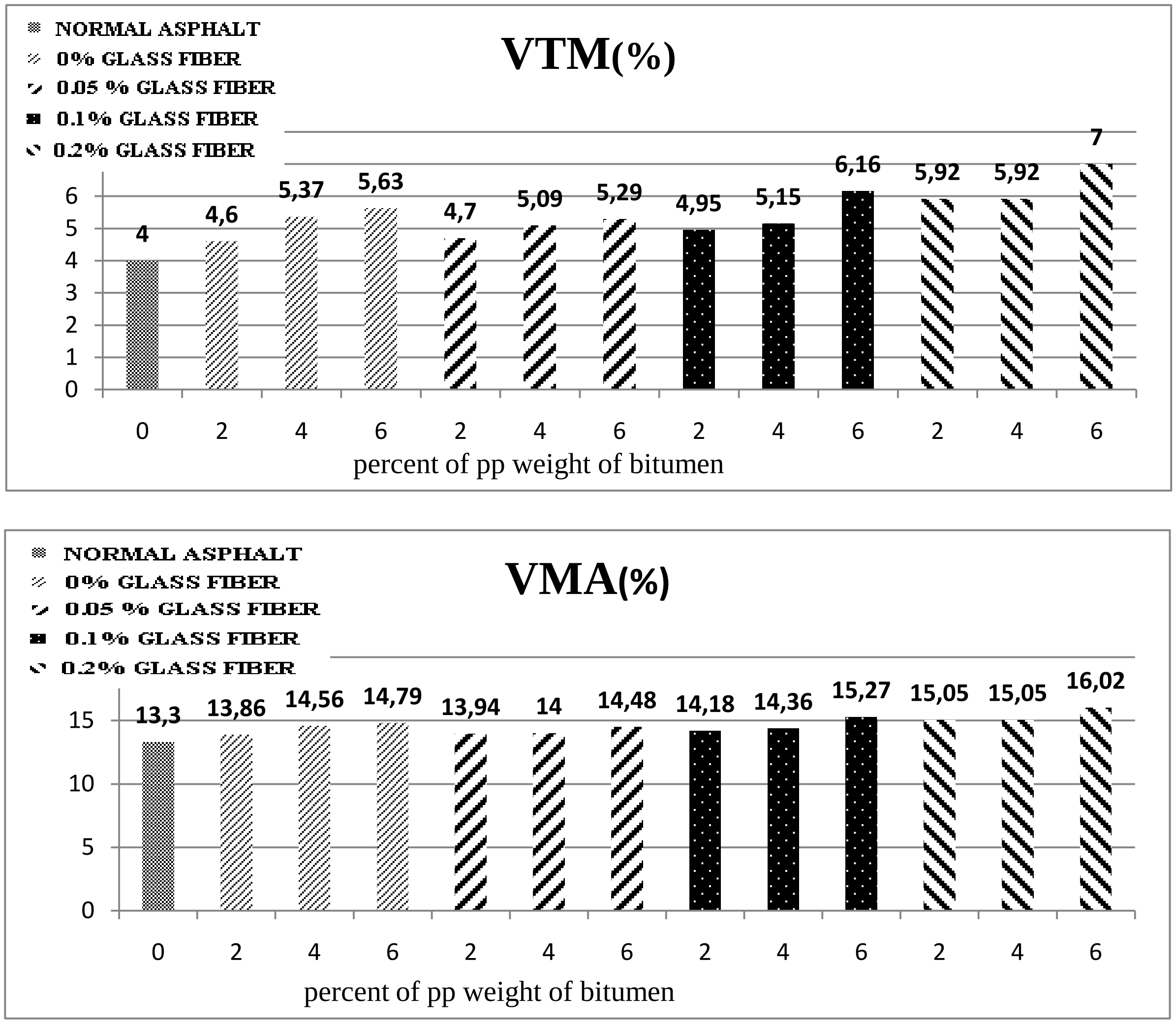
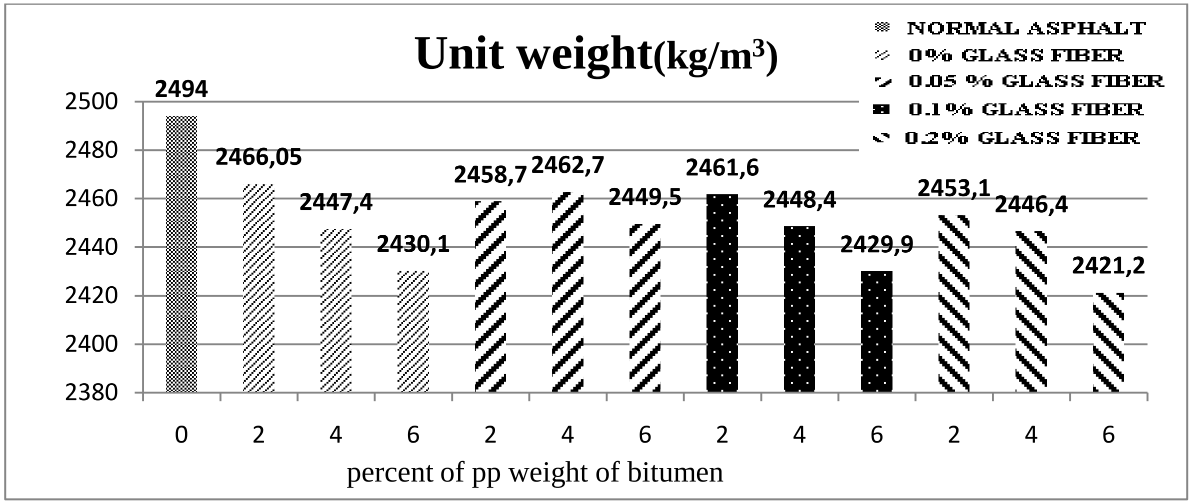


Figure 41: VTM and VMA for Different Percent of Glass Fiber(0.05,0.1 And 0.2%) and 12mm Polypropylene (2,4 and 6%)



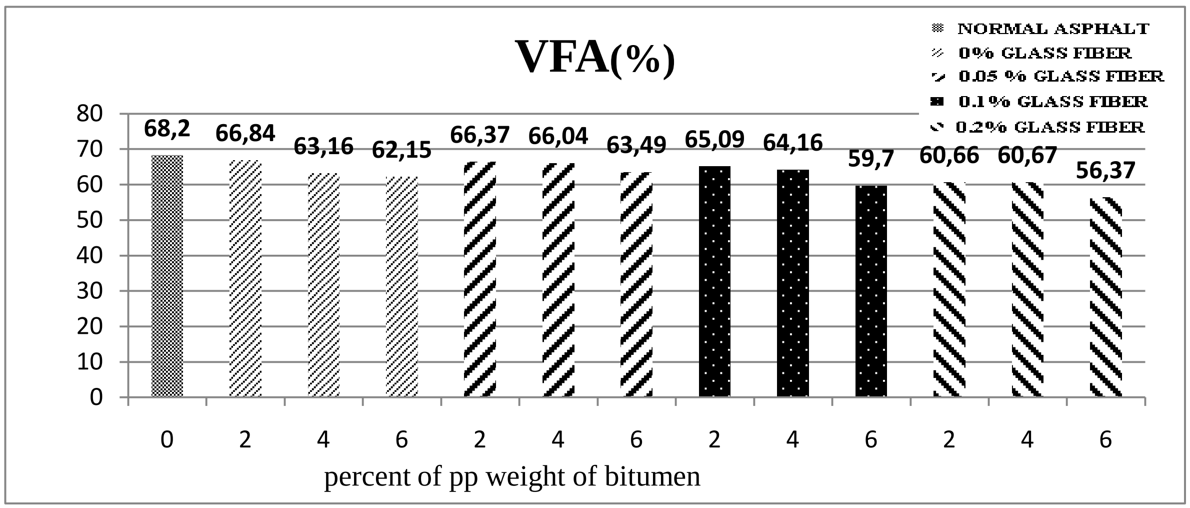


Figure 42: Unit Weight and VFA for Different Percent of Glass Fiber(0.05,0.1 And 0.2%) and 12mm Polypropylene (2,4 and 6%)

4.4 Results and Discussions

At least 3 samples were prepared for each type of modified and unmodified asphalt mixtures. As it was mentioned, optimum asphalt cement for normal mixture (unmodified) was obtained 4.3% base on 4% air voids. Stability, flow, unit weight VMA, VTM and VFA (according to Figure 29) were achieved as 1800 kg, 5.8mm, 2494 kg/m^3 , 4%, 13.3% and 68.2 % for normal asphalt cement mixture respectively.

Two different lengths (6 and 12 mm) of polypropylene with three percentages: 2%, 4% and 6% by weight of asphalt were applied in asphalt cement base on wet method. Polypropylene, by increasing the viscosity of asphalt and effect on some properties of the asphalt probably caused the performance of mixture increased. In both length of pp modified mixture Marshall Stability increased and flow decreased in comparison with unmodified mixture. Also, Unit weight and VFA reduced by increasing the amount of pp additive whilst, VTM and VMA value increased.

Glass fiber, which is brittle with smooth surface and high tensile strength, (more than 60000 MPa) was added to the modified asphalt cement mix with the purpose of increasing performance and strength of the mixture due to its high tensile strength. Three percentages of glass fiber: 0.05, 0.1 and 0.2% were added to the preheated aggregate.

For the hybrid reinforcement shown in Figure 38 to 43, the relationship between four different glass fiber contents (0, 0.05, 0.1 and 0.2%) and three percentages of pp content with two length (6 and 12mm) for six Marshall test factors were evaluated. It can be observed that by increasing the amount of pp additive stability increases in each the four glass fiber content levels. The maximum gain in stability was recorded at 0.1% glass and

6% pp while the lowest stability was at 0.1% glass fiber and 2% pp for 6mm pp and 0.2%glass fiber and 2%pp in 12mm pp according to Figure 37 and 40.

Polypropylene modifier causes glass fibers glue to other materials in the mix and contributes to increase in stability and decrease the flow value. As it shown in Figures 38 and 41 in both length of pp, addition of 0.1% glass fiber to 6%pp had the best performance on Marshall Stability result. However, addition of 0.2% glass fiber caused stability to decrease probably due to high percentage of fibers, which affect the contact points between aggregate particles. Stability and flow in 6% pp additive in 12mm polypropylene including 0.1% glass was 2149kg and 4mm, respectively which showed 4% and 16% increase in stability and 18.5% and 31% reduction in flow value as compared to pp modified mixture (6%) and normal asphalt mixture (control) respectively. Also, unit weight and VFA value reduced in comparison with the normal mixture. These values decreased for all percent of glass fiber by increasing the amount of polypropylene as well. In contrast, VMA and VTM value increased compare to the normal HMA and increased for all percent of glass fiber by increasing the percentage of polypropylene.

On the other hand, stability in 6% pp additive mixture with 6mm length including 0.1% glass fiber was 2264 kg which indicated highest stability with 14.89% raise compare to 6% pp (6mm) modified mixture and 20.5% when compared to the normal HMA. Also, flow value had the lowest value with 35% reduction compare to 6% pp (6mm-length) additive and 44.8% decrease as compared to the normal mixture. Overall, there was low flow value for fiber addition samples compared to the unmodified (normal) specimen which had a flow of 5.8mm. Also, unit weight and VFA value reduced compare to the normal mixture and decreased for all percent of glass fiber by increasing the amount of polypropylene as well. However, VMA and VTM value increased like 12mm pp compare to normal HMA and increased for all percent of glass fiber by increasing the percentage of polypropylene additive.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this research, two kinds of fiber were used; polypropylene with two different lengths (6 and 12 mm) and glass fiber (12mm). The purpose of this study was to examine the effect of polypropylene in wet method on the behavior and performance of the HMA.

Since high performance of glass fiber in terms of stiffness, resistance to distress, resistance to permanent deformation and fatigue life was proved and just decreasing in stability due to smooth surface and low internal friction was reported in recent research studies. This study attempted to answer the question: is polypropylene able to glue glass fiber to other materials of the mix to benefit from the high tensile strength of glass fiber (more than 60000MPa) and therefore increase the stability of the mixture?

Three different percentages of polypropylene 2%, 4% and 6% by weight of asphalt cement was selected in this study. All these percentages were added to the optimum asphalt cement (4.3%). Test results indicated that polypropylene had some effect on some properties of the asphalt cement and improved the performance of the mixture.

Penetration test results showed that, by increasing the percentage of additive (polypropylene), penetration decreased compared to normal asphalt cement. When 6 mm polypropylene was used, the penetration was reduced 12, 27.5 and 56% when 2, 4 and

6% pp by weight of asphalt cement were used, respectively. Longer length of additive made asphalt cement sample stiffer and resulted in a noticeable decrease in penetration. In 12mm polypropylene length 34%, 43% and 59% decline in penetration was obtained by applying 2, 4 and 6% pp in the optimum asphalt cement. These results indicate that modified specimens are much stiffer than the unmodified asphalt cement, and therefore the rutting resistance of the modified mixtures is expected to be high.

Softening point value improved, by increasing the amount of pp additive in asphalt cement. When 6% pp with 6 and 12mm length mixed with asphalt cement, softening point increased 35.4% and 40.6% as compared to control specimen, respectively. These results indicated that pp modified asphalt mixture is more resistant to traffic-induced deformation at high temperature compared to the normal HMA mixture.

Ductility test was performed for modified asphalt and unmodified asphalt cement. Results indicated that modified asphalt cement had ductility less than 100cm while, unmodified asphalt cement showed ductility more than 100cm. The possible reason for this phenomenon could be; pp fibers placed in the cross-section of specimen in the process of stretching and prevent asphalt cement stretch easily and cause sample not be able to show a good performance in ductility test.

Although ductility test results decreased by increasing the amount of additive (pp), previous studies and experiences indicate that use of fibers increased service life of the mix. Therefore, it may be concluded that some tests, such as ductility test do not provide real and suitable performance of modified bitumen properties.

Marshall Test results illustrated that pp in both lengths can affect performance of the mixture. In fact, polypropylene caused; VTM and VMA increased, while, flow, unit weight and VFA decreased compared to the value of unmodified asphalt mixtures.

Three percentages of glass fiber were selected. These percentages were 0.05, 0.1 and 0.2% by weight of aggregate which were added to pp modified asphalt mixture. According to the results, best performance was obtained when 6%pp and 0.1% glass fiber were used. Marshall Stability was affected by the type of aggregate and asphalt grade. Type of aggregate for this study was crushed limestone for all samples. Polypropylene decreased the penetration and increased viscosity of asphalt cement and caused increase in Marshall Stability. Also, pp additive provided a good cohesion between glass fiber and other materials which resulted in improving the stability of mixture. In 12 mm length pp, 6% polypropylene plus 0.1 % glass, stability increased 4% and 16% as compare to the pp modified mixture (6%) and normal asphalt HMA (control) respectively. Moreover, results show that pp with 6 mm length plus 0.1% glass had the highest stability. Stability increased 14.89% when compared to 6% pp modified mixture and 20.5% when compared to normal HMA.

Also, results indicate that flow decreased when amount of polypropylene increased. All the modified samples had the lower flow than unmodified (normal) samples which means that, modified mixtures have lower deformation under traffic loads than the normal HMA. Unit weight and VFA decreased in all modified mixtures compare to normal asphalt mixtures. In contrast, VTM and VMA increased in hybrid reinforcement mixture, than the normal HMA. This happened probably due to increase in surface area for aggregate and fiber (since the fibers behave like filler materials) which needs to be wetted by asphalt. Therefore, lower asphalt (effective asphalt) can fill the space between mineral aggregate and result in increase in VTM. Increasing VTM could be important for hot areas where flushing and bleeding mostly occur.

The price of polypropylene and glass fiber were around 2 € per kilogram. If it is assumed that initial price of HMA is 110 TL/ ton in North Cyprus, the initial price will raise by 12.7% (for 6% pp plus 0.1 %glass). However, it should be kept in mind that modified asphalt plus glass fiber showed desirable performance and previous researchers indicated that use of polypropylene and glass fiber individually increased the life of pavement. Therefore, use of this combination in HMA may postpone the rehabilitation needs and decrease and save maintenance cost.

5.2 Recommendations

Since applying two fibers correspondingly, polypropylene in wet base and glass fiber in dry base, is new research, there is a huge area to work on this field.

Because of lack of equipment in North Cyprus, all of the expected tests could not be accomplished.

Some tests such as Repeated Load Indirect Tensile Test to examine the fatigue performance of mixture, Dynamic Creep Test to consider the deformation behavior of the mixture can be considered in further studies. Also, optical or scanning electron microscopy could help to better understanding glass fiber and polypropylene position in the mixture.

Moreover, effect of changing the gradation types such as using SMA to reach higher stability could be done in future research as well.

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