The Effect of Polypropylene Modification on Marshall Stability and Flow

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ABSTRACT

Asphalt concrete pavements because of their low initial cost are being preferred over portland cement concrete pavements. This advantage can be minimized if the mix design is not suitable for the road class and traffic composition. In North Cyprus use of unmodified asphalt cement in mix design causes unnecessary road maintenance on road section where traffic volume is high. In addition to extra cost of these repairs, the traffic disruptions also take place. The main surface distress types which cause these maintenance and disruption are rutting and fatigue cracking.

For solving these problems different studies have been carried out, ranged from changing gradation to adding polymers and fibers to asphalt mixture. In this study, polypropylene additive was selected as fiber additive because of low-cost situation and having good correlation with asphalt pavement according to various studies. Two type of polypropylene (PP) additive in length (6 & 12 mm) were selected, 6mm long PP was used at three different percentages (0.1%, 0.2%, and 0.3%) in asphalt concrete mixture with 3.5, 4.0, 4.5, 5.0 and 5.5% percent of asphalt by weight of total mix. 0.5% of 6 mm long PP and 0.3, 0.5% of 12 mm long PP were added to optimum percent of asphalt, to see the difference in asphalt characteristics. Asphalt specimens were made by Superpave Gyratory Compactor (SGC), and analyzed by both Marshall Analysis and Superpave Analysis and finally tested by Marshall Stability apparatus. Adding polypropylene increased Marshall Stability (26%), and decreased Flow (38%). This increase in the percentage of air void is important for hot regions where bleeding and flushing are common.

Keywords: Polypropylene fibers, Rutting, Marshall Stability and Flow.

ÖZ

Düşük yatırım maliyetlerinden dolayı portland çimentolu yol kaplamaları yerine asfalt betonu yol kaplamaları tercih edilmektedir. Asfalt betonunun karışım tasarımı kaplamanın kullanıldığı yol sınıfı için yeterli olmazsa bu avantaj azalacaktır. Kuzey Kıbrıs'ta trafik hacminin yüksek olduğu yol kısmlarında modifiye olmamış asfalt betonu kullanımı gereksiz yol bakım ve onarımına sebep olmaktadır. Fazla bakım onarımın gerektirdiği fazla maliyete ilaveten trafik akışı da etkilenmektedir. Bu bakım ve onarımlara sebep olan en önemli yüzey sorunları tekerlek izi ve yorgunluk çatlaklarıdır.

Bu sorunları çözmek için farklı yöntemlerin uygulandığı çalışmalar yapıldı. Bu çalışmalarda agrega gradasyonu değişikliği ve asfalt betonu karışımına polimer veya lif katkısı yapılmıştır. Bu çalışmada düşük maliyetinden dolayı polipropilen (PP) lifinin 6 ve 12 mm uzunluğu kullanılmıştır. Altı mm uzunluğundaki lif 0.1, 0.2 ve 0.3 ağırlık yüzdeliğinde seçilmiş ve bu yüzdelikler asfalt çimentosunun 3.5, 4.0, 4.5, 5.0 ve 5.5 yüzdelikleri ile kullanılmıştır. Aynı zamanda, 6 mm lif 0.5%, 12 mm lif 0.3, ve 0.5 yüzdeliğinde seçilmiş ve optimum asphalt çimentosu ile karışımda kullanılmıştır. Burada asphalt betonunun özelliklerinin nasıl etkilendiğine bakılmıştır. Asfalt betonu örnekleri Superpave Gyratory Compactor ile sıkıştırılmış, Marshall Stabilite ve Akma cihazı ile test edilmiştir. Polipropilen katkılı asfalt betonu Stabilitesi yüzde 26 artış gösterirken akım miktarı da yüzde 38 düşüş göstermiştir.

Anahtar kelimeler: Polipropilen lif, Tekerlek izi; Marshall Stabilite ve Akma.

To My Wife

And

My Family

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Chapter 1

INTRODUCTION

1.1 Introduction

The cost of rehabilitation and maintenance of asphalt concrete pavement is one of the major problems because of improper mix design (it can be because of aggregate gradation, type and etc.) and/or using improper asphalt either in amount or quality. Two important distresses which cause spending for maintenance and rehabilitation are permanent deformation (rutting) and fatigue cracking. In both of them, aggregate gradation and the percent of asphalt are playing important roles, which are explained in detail in Chapter 2. For solving these problems different efforts have been done like changing gradation to SMA (gap gradation) concluded in higher rutting resistance in SMA compare to dense-graded wearing course mixture (Mohamad, L. N., Huang, B., & Tan, Z. Z., 2001, p. 69), increasing coarse aggregate fracture faces showed an increase in rutting resistance, National Cooperative Highway Program 9-35 reports (Huang *et al*, 2009, p. 19). Changing aggregate gradation to coarser gradation, results in lower rut problem (Sebaaly, P. E., McNamara, W. M., Epps, J.A., 2000, p. 4). Increasing crushed coarse and fine aggregate fractures (instead of rounded aggregate like gravel) also increase shear resistance which result in higher resistance to rutting (WesTrack Forensic Team consensus Report, 2001, pp. 3-4) and also increase Marshall Stability (Carlberg, M., Berthelot, B., & Richardson, N., 2003, p. 5). Using cubical particles can increase internal friction which improves rutting resistance (Chen, J. S., Shiah, M. S., & Chen, H. J., 2001, p. 519). Strategic

Highway Research Program (SHRP) in summary report on permanent deformation in asphalt concrete indicates that shape of aggregate (rounded to angular) and size (increase in maximum size) will increase rutting resistance (Sousa, B. J., Craus, J., & Monismith, C. L., 1991, p. 13). As an utilizing additive for example using hydrated lime in many different studies has been performed like research of Burger & Huege which says that use of hydrated lime contributes to high performance asphalt pavement to mitigate moisture susceptibility, improving rut resistance and reducing fatigue cracking or The National Lime Association has confirmed using hydrated lime in asphalt mixture, make the pavement more resistant to rutting and fatigue cracking(National Lime Association, 2006). These distresses are common in North Cyprus because of improper mix design and traffic loading and there are few investigations in this area to improve roads performance.

1.2 Objectives and Scopes

The objective of this study is to improve mix design and workability of Hot Mix Asphalt (HMA), by using polypropylene (PP) fiber to increase stability of mixture and decrease flow. The reason of using polypropylene is because of economically occasion of this material, which can be obtained from Turkey by reasonable price. Different researches show an improvement in pavement in rutting and fatigue cracking by using this material. As a recent effort like Tapkin (2008) declared using polypropylene fiber increase Marshall Stability, or in the same study, “The fatigue life corresponding to the 50% elastic modulus drop of the polypropylene fiber-base specimens have increased by 27% when compared with reference specimen”. Another research which has been done by Al-hadidy &Yi-qui, 2008, indicates increasing in Marshall Stability and decreasing flow by using polypropylene. The difference between this study and the others which are mentioned is: all of the previous studies were conducted by Marshall Compaction, but in this study samples and the specification for degree of compaction will be prepared and specified by Superpave Mix Design Method which is more precise than Marshall because of better simulation of field condition.

1.3 Organization

The thesis contains the following chapters:

Chapter 1: The introduction, objectives and scopes.

Chapter 2: This chapter contains literature review about, asphalt, aggregate, different test in these area, Hot Mix Asphalt (HMA), gradation, and polypropylene additive.

Chapter 3 present methodology which is about different tests which has been done on aggregates and hot-mix asphalt, mix design and procedure of using polypropylene.

Chapter 4 is about analysis of the data, tables and graphs.

Chapter 5 is about conclusion and discussion.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses about two bituminous materials tar and asphalt, the difference between them, about aggregate and combination of asphalt and aggregate which is called asphalt cement. It goes through different tests which are important for qualifying materials used in pavement, asphalt cement, aggregate, and asphalt concrete, with brief explanation about each test. In this chapter we'll see different gradation for Hot Mix Asphalt (HMA) for different goals. Various distresses will be discussed and studies which has been carried out to solve these problems. And at the end there is an explanation about polypropylene additive used in this study as a material to solve HMA problems and also to decrease the cost of rehabilitation.

2.2 Asphalt

Bituminous materials are divided into asphalt cement and tar, most of the time these two types of materials are used instead of each other because of their similarity in appearance and also some parallel usage, but asphalt cement and tar are two different materials in sources and properties, both physical and chemical properties. Asphalt cement is dark brown to black material that can be produced naturally (like in Trinidad Lake on the island of Trinidad) or by petroleum distillation. But tar on the other hand is manufactured from destructive distillation of bituminous coal with very explicit odor, another difference between these two kinds of material goes back to their usage, asphalt cement is used principally in United State in paving work, but in vice versa, tar is hardly ever used because of, first tar has undesirable physical characters like high temperature susceptibility and second it is dangerous for health such as when eye and skin are exposed to its fumes (Roberts, F.L., Kandhal, P. S., 1991, p. 7).

The word "Asphalt" is derived from Accadian term "asphaltic", this phrase was adopted by the Homeric Greeks meaning "to make firm or stable". "Asphaltic" was brought over to Late Latin, French "asphalte", and finally English "asphalt." From its ancient past to the present, asphalt has been used for different purposes like ascement for bonding, coating and water-proofing objects in roof or as a pavement. At the moment asphalt is one of nature's most versatile products (Asphalt Institute, 1989, p. 2).

Asphalt has a wide consistency range, this sticky substance varies from solid to semisolid depends on air temperature, when heated sufficiently asphalt becomes soften and liquid and because of this trait it can covers aggregate particles during mix production. Asphalt is a waterproofing material and also it is unaffected by several acids, alkalies and salts, but asphalt lose some of its ability when it is heated and/or aged (Asphalt Institute, 1982, pp. 10-11). Asphalt is used generally in paving, but it is also consumed in the roofing industry, the kind of asphalt which is used in paving is called paving asphalt or asphalt cement to distinguish it from asphalt that is used in non-pave consumption. The paving asphalt is called thermoplastic material because it's hard when it is cooled and soft when it is heated, it means that when asphalt is heated it is soft enough to cover the aggregates and when asphalt is cooled it is strong enough to protect the aggregates against water and pressure. This character is fundamental reason for which asphalt is an important paving material. Commercial types of asphalt are classified into two categories:

1. Natural asphalts: found in geological strata in two phases, soft and hard. The soft asphalt material is typified in Trinidad Lake deposits on the island of Trinidad, in Bermudez Lake, Venezuelan and also in the extensive “tar sand” throughout western Canada. The hard phrase is friable, brittle black veins of rock formations, such as Glisonite (it’s a trademark of the American Gilsonite Company for a form of natural asphalt found in large amounts only in the Uintah Basin of Utah) includes asphaltites which are solid asphalts without impurities (silts, clays, etc).

2. Petroleum Asphalts: in early 1900’s and discovery of refining process and increasing in automobiles, large amount of asphalt were processed by the oil companies and asphalt became cheap and inexhaustible resource for smooth and modern road. (Roberts, F.L., Kandhal, P. S., 1991, p. 8)

2.2.1 Physical Properties of Asphalt

According to Asphalt Institute manual series No.22 in January 1983 page 17-20 the physical properties of asphalt cement are divided to:

- Durability

  Durability is the measure of how well asphalt can keeps its original characteristics when exposed to normal weathering and aging processes. Asphalt’s property also depends on pavement performance, because pavement performance is affected by mix design, aggregate characteristic, construction workmanship, and other variables as much as by the durability of the asphalt.

- Adhesion and Cohesion

  Adhesion is ability to stick to the aggregate in the paving mixture and cohesion means the ability of asphalt cement to hold the aggregate particles firmly in place in the finished pavement.

- Temperature Susceptibility

  As it was mentioned before asphalt cement is thermoplastic material, it becomes hard (more viscous) in cold area and soft (less viscous) in hot area, this characteristic is known as temperature susceptibility. It is important to know this trait, because it indicates the proper temperature for mixing and compacting asphalt on the roadbed.

- Hardening and Aging

  Asphalt is getting hard in the pavement during construction primarily because of oxidation (combination of asphalt and oxygen), the first significant hardening takes place in pugmill or drum mixer where asphalt cement has a high temperature and blended with aggregates, this category is also occurred in thin film asphalt, for example the asphalt which coat aggregate particles, hardening cause asphalt cement to have higher viscosity.(Asphalt Institute, 1982, pp. 17-20). As it can be seen in Figure 1 aged asphalt has higher viscosity and it means that asphalt after aging gets harder.

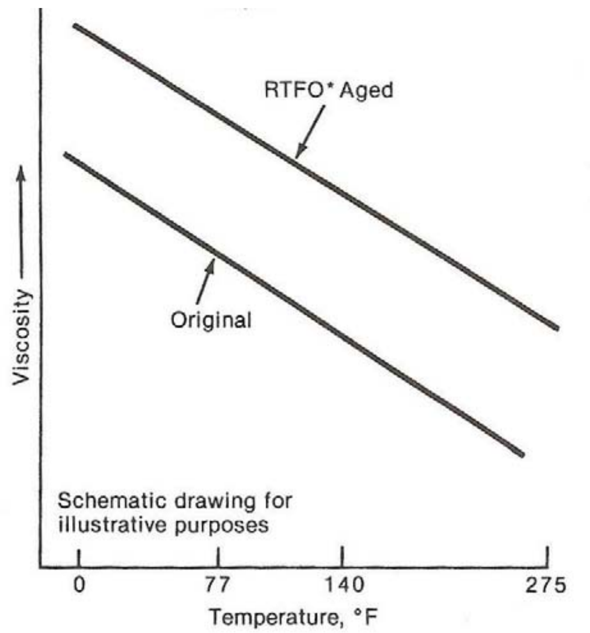

Figure 1: Hardening of Asphalt after Exposure to High Temperature (Asphalt Institute, 1982).

2.2.2 Refining Crude Petroleum

Crude petroleum changes from one source to another in composition and yield different amount of asphalt and other distillable fraction like gasoline, naphtha, kerosene….There is a classification to specify crude oils to estimate approximately the amount of asphalt in each source, this specification is called API (American Petroleum Institute) gravity. API gravity is an expression of a density (weight of unit volume) of asphalt cement in 60 °F and is obtained:

$$\text{API Gravity (deg)} = \frac{141.5}{\text{Specific Gravity}} - 13.5 \qquad (2.1)$$

The API gravity of water is equal to 10. Approximately asphalt has API gravity between "5 – 10", whereas the API gravity of gasoline (gasoline is the lightest product in refinery which stays at the top) is about 55. API gravity is divided in two levels:

1. Low API gravity crudes: API gravity for crude petroleum which have API gravity less than 25 that yield low percentages of distillable overhead

fraction and high percentages of asphalt cement, in industry they are known as heavy crudes (because asphalt is the heaviest product in refinery).

2. High API gravity crudes: API gravity for crude petroleum which have API gravity more than 25 that yield high percentages of distillable overhead fraction and low percentages of asphalt cement, in industry they are known as light crudes(Roberts, F.L., Kandhal, P. S., 1991, pp. 9-10).

2.2.3Characteristic of Asphalt Cement

There are three important properties or characteristics of asphalt for engineering and construction purposes, a) Consistency (viscosity) b) Purity c) safety (Asphalt Institute, 1989, p. 33).

a) Consistency

Asphalts are thermoplastic materials because they are finally liquefied when exposed to heat. Asphalt cements are specified by their consistency or resistance to flow at different temperature. Consistency is used for describing the viscosity which is the degree of fluidity of asphalt at various temperatures. It is necessary to use a standard temperature when viscosity of different asphalts is compared with each other because viscosity (consistency) of asphalt cement varies with temperature. Asphalt cements are graded according to their consistency at a standard temperature. Changing in consistency or viscosity of asphalt cement can be seen when its exposed to air in thin film at elevated temperature, for example during mixing with aggregate when it gets harden. Viscosity test and penetration test are two common tests used for measuring consistency of asphalt cement.

b) Purity

Asphalt cement is almost entirely made up of bitumen which is entirely soluble by carbon disulfide. Refined asphalts are almost pure bitumen and are usually more than 99.5 percent soluble in carbon disulfide. Normally, when asphalt cement leaves refinery it's free of water, but however transport loading asphalt may have some moisture in their truck, if there is any moisture inadvertently with asphalt, it will cause the asphalt to foam when it is heated above 100 °C (212 °F).

c) Safety

Asphalt foam is dangerous for health and specifications usually require that asphalt not foam up to 175 °C (347 °F). If asphalt cement heated to a high temperature it gives enough vapors to flash in the presence of open flame (spark). The temperature at which this happens is called flash point. Flash point indicates the maximum temperature that asphalt can be heated without the danger of instantaneous flame and its well above the temperature normally used in paving operation.

2.2.4Specifications and Tests for Asphalt Cement

Asphalt cement is available in different range of consistency (grades), according to the asphalt handbook 1989 edition, page 34 asphalt cements categorized base on their penetration in 5 standard grades: 40-50, 60-70, 85-100, 120-150, and 200-300, that the numerical grade shows the allowable range of penetration for each standard grade. In which the asphalt cement with (40-50) is the hardest asphalt and asphalt cement with (200-300) is the softest asphalt cement. Grading asphalt cement on the basis of the penetration is empirical and approximately inadequate whit the advent of new technology. The modern method is to classified asphalt cements according to their viscosity grades in poise at 60 °C (140 °F), according to American Society for Testing and Materials (ASTM) D 3381 – 05 asphalt cements are divided into 6 grades base on their viscosity, AC-2.5, AC-5, AC-10, AC-20, AC-30, AC-40. There are also other specifications to determine specific properties for asphalt like flash point, ductility, etc, that we will go through them in the following.

According to the *asphalt handbook manual* series No.4 (MS-4) 1989 edition and *hot mix asphalt materials….* Roberts et al in 1991 here are explanations about some important tests for asphalt cement which are specified in Table 1:

Table 1: ASTM Tests for Asphalt Cement.

Test	**Test method (ASTM)**
1. Viscosity at 60 °C (140 °F)	D 2171
2. Viscosity at 135 °C (2475 °F)	D 2170
3. Penetration	D 5
4. Softening Point	D 36
5. Thin Film Oven	D 1754
6. Rolling Thin Film Oven	D 2872
7. Ductility	D 113

2.2.4.1 Viscosity Tests

Viscosity can be defined as a resistance to flow of a fluid and it's measured at two different temperatures:

1. Absolute viscosity at 60 °C (140 °F)
2. Kinematic viscosity at 135 °C (275 °F)

"The viscosity at 60 °C (140 °F) is the viscosity used to grade asphalt cement"(Asphalt Institute, 1982, p. 21).But "A minimum viscosity at 135 °C (275°F) also is usually specified"(Asphalt Institute, 1989, p. 35).

2.2.4.2 Penetration Test

Penetration test is an empirical test used for measuring consistency (viscosity) of asphalt cement. A container of asphalt cement is heated to the 25 °C (77 °F) by placed in the thermostatically-controlled water bath, test is usually done at this temperature because its approximately average service temperature of the HMA pavement. Sample is placed under a needle of prescribed dimension which is loaded with 100 g weight and can penetrate the sample for 5 seconds. The depth of penetration is measured in tenth of millimeter (0.1 mm) and is called as penetration unit. As an example if the penetration depth is 7 mm, the penetration of asphalt cement is 70. This test also can be done in other temperatures like 32, 39, and 105 °F. But with changing in temperature the weight and time of penetration of needle is also changed. At low temperature like 39.2 °F the weight of needle is jump to200 g and the time of penetration is increased to 60 seconds, this increment in weight and time is because of viscoelastic characterization of asphalt cement, which in this temperature is stiffer than in 77 °F.

2.2.4.3 Softening Point

Softening point is measured by ring and ball (R&B) method and it describes the temperature at which asphalt cement can't support the weight of steel ball and starts to flow. The reason of doing this test is to measure the temperature at which change phase occurs in the asphalt cement. First a brass ring filled with asphalt cement should be placed in a beaker which is filled with water or ethylene glycol. Then a steel ball with specific dimension and weight is placed in the center of brass ring and the bath is heated at a controlled rate of 5 °C per minute. Because of the temperature, asphalt cement starts to be softened, and the ball and the asphalt cement moves to the bottom of the beaker. The temperature is recorded when softened asphalt cement touches the bottom plate. The test is done with duplicate specimens to measure the difference in temperature between these two. If the difference exceeds 2 °F, the test must be repeated.

2.2.4.4 Thin Film Oven

The Thin film oven (TFO) test it's not actually a test, it's just a procedure to approximate simulate of the hardening conditions (aging) for HMA that occur in normal hot mix facility operations. The TFO test is carried out by placing 50 g of asphalt cement in a cylindrical flat-bottom pan which has 5.5 inches inside diameter and 3/8 inch deep. The depth of asphalt cement in the pan is approximately 1/8 inch. Then the asphalt cement sample is placed on a shelf in ventilated oven at 325 °F. The operation of this oven is to rotate the sample in about 5 to 6 revolutions per minute for about 5 hours. And then the sample is transferred to appropriate container for measuring penetration or viscosity of the aged asphalt cement.

2.2.4.5 Rolling Thin Film Oven

The rolling thin film oven (RTFO) is the same in purpose with TFO but with some difference in procedure. In RTFO first a prescribed amount of asphalt cement is poured into a bottle which is used as a container. Then the bottle is placed in a rack which is rotates around horizontal axis in the oven that is held at a constant temperature at 163 °C (325 °F). The rotating bottle continuously exposes fresh film of asphalt cement. There is an air jet that orifice of asphalt bottle passes in front of it during each rotation. The result of both TFO and RTFO is the same but the difference is in the:

1. Time, which is less in RTFO, which is only 75 minutes, in comparison with 5 hours for TFO.
2. Number of Samples, which higher in RTFO. It can accommodate a large number of samples than the TFO.

2.2.4.6 Ductility

Among all the asphalt cement's tests, ductility is recognized as one of the most important tests by many of asphalt paving technologists. In this test the briquette of asphalt cement is molded under standard conditions and dimensions, and then it's put in the ductility test equipment at the standard temperature which is normally 25°C (77 °F). One part of the briquette is pulled away from the other one at the rate of 5 cm/minute until rapture. Ductility is measured as a distance in centimeter that standard briquette of asphalt cement will stretch before breaking, this test can also be done at 39.2 °F, but the pulling rate usually at this temperature is 1 cm/minute.

2.3 Aggregates

Aggregates are referred to rocks, granular materials, and mineral aggregates. Typical aggregates are included of sand, gravel, crushed stone, slag, and rock dust. “Aggregates make up 90-95 percent by weight and 75-85 percent by volume of most pavement structures”(Asphalt Institute, 1982, p. 36). The main load-bearing characteristic of pavements is provided by aggregates and the performance of pavement is heavily influenced by select of proper aggregates.

2.3.1 Aggregate classification

In continuous and on the same page Asphalt Institute explains about the rocks that are divided into three general types:

1. **Sedimentary** rocks are formed either by “deposition of insoluble residue from the disintegration of existing rocks or from deposition of the inorganic remains of marine animals”.(Roberts, F.L., Kandhal, P. S., 1991, p. 85) Sedimentary rocks are categorized as calcareous (lime stones, chalks, etc), siliceous (chert, sandstone, etc.) and argillaceous (shale. etc).
2. **Igneous** rocks are formed by cooled and solidified of molten material (magma) and have two types: extrusive and intrusive. The difference between these two types is in the place that they are formed. The first type (extrusive) is formed on the surfacing of the earth, and the second type (intrusive) is formed magma trapped within the earth’s crust. Classification of igneous rocks:

Table 2: Classification of Igneous Rocks Based on Composition (Roberts, F.L., Kandhal,P. S., 1991, p. 85).

	Acidic	**Intermediate**	**Basic**
Silica, %	>66	55-66	< 55
Specific gravity	< 2.75	-	>2.75
color	Light	-	Dark
Presence of free quartz	Yes	-	No

3. **Metamorphic** rocks are igneous or sedimentary rocks that have been under pressure and heat within the earth, which is changed their mineral structure so they're different from the original rocks. Grain size of metamorphic rocks is changed from fine to coarse.

Roberts & Kandhal in *Hot Mix Asphalt Materials, Mixture Design, and Construction*, 1991, added three groups to above classification:

1. **Gravels:** gravels are formed by breaking down of any type of natural rocks and are found in existing or ancient waterways, as their obvious characteristics, roundness and smoothness can be mentioned, because of moving by the action of water along the water way. Gravels most often should be crushed before being used in the HMA.
2. **Sands:** sands consist of the most resistance final residue of the deterioration of natural rocks and mostly made of quartz, the size normally ranges from No. 8 sieve to dust size (No. 200 sieve). Because of containing silt and/or clay particle they should be washed prior to use in HMA.
3. **Slags:** this kind of aggregate is a byproduct of metallurgical processing and is typically produced from processing of steel, tin, and copper. Blast furnace slag produced during the processing of steel is the most widely used of the slag for pavement because of producing high quality asphalt mix and having good skid resistance. The main problem of using slag is absorption of this

kind of aggregate which need higher percent of asphalt compare with conventional asphalt mixture.

2.3.2Aggregate sources

Aggregates are classified base on their sources into three sections:

1. **Natural aggregates** as it can be concluded by their names these kinds of aggregates are used in their natural form without processing or with a little process. These aggregates are made up by natural erosion and degradation process, like effect of water, wind, moving ice, and chemicals. The two major kinds of natural rocks are gravel and sand. Aggregates which are equal or larger than 6.35 mm (1/4 inch) are called as gravel and the particle smaller than 6.35 mm (1/4 inch) but larger than 0.075 mm (No.200) are called sand, there is a third group by name of mineral filler which is called to aggregates smaller than 0.075 mm (No.200).
2. **Processed Aggregates** are the aggregates which have been processed, e.g. crushed and screened, as a preparation on them. Two basic sources for processed aggregate are natural gravels which are crushed to be more suitable in asphalt pavements and fragments of bedrock and large stone. This type should be reduced in size till can be used in pavement.
3. **Synthetic Aggregates** These kinds of aggregate don't exist in nature and are produced by chemical or physical processing that why they're called synthetic or artificial aggregates. Slag is the most by-product aggregate. Synthetic aggregates have been used in bridge-deck and roof-deck paving and also pavement surface which need maximum skid resistance (Asphalt Institute, 1982, pp. 37-39). Table 3 shows different aggregate classification.

2.3.3 Aggregate Properties

As Roberts & Kandhal in *Hot Mix Asphalt Materials, Mixture Design, and Construction*, in 1991 mentioned suitability of aggregates which is included of cost, quality of the materials, etc to use in asphalt pavement (not only for pavement surface) is determined by evaluating these aggregates:

1. Size and Grading

The maximum size of aggregates is specified by the smallest sieve that all (100%) the aggregates pass through it. The nominal maximum size is specified by the largest sieve size that retains some of the aggregate particles, but generally not more than 10 percent. Maximum aggregate size is normally limited to one-half of lift thickness from a construction standpoint. Size and grading is also related to the amount of asphalt and strength, larger aggregate size is concluded on lower amount of asphalt cement and also more resistance to rutting.

2. Cleanliness

Cleanliness refers to aggregates without foreign or deleterious materials which are undesirable for HMA. Typical objectionable materials as an example are vegetation, shale, soft particles, clay lumps. Usually these foreign materials can be reduced by washing.

3. Toughness and Abrasion Resistance

Aggregates are subject to abrasion both in placing, and compaction of asphalt paving mixes and also later under traffic loads. They must have an ability to resist crushing, degradation, and disintegration. Aggregates on the surface of the HMA or near to it should be tougher and more resistant than aggregate in the lower layers.

Table 3: Different Aggregate Classification (Asphalt Institute, 1982, p. 38)

Class	Type	Family
Sedimentary	**Calcareous**	**Limestone** Dolomite
	Siliceous	Shale Sandstone Chert Conglomerate Breccia
Metamorphic	Foliated	Gneiss Schist Amphibolite Slate
	Nonfoliated	Quartize Marble Serpentinte
Igneous	Intrusive (Coarse-Grained)	Granite Syenite Diorite Gabbro Periodotite Pyroxenite Hornblendite
	Extrusive (Fine-Grained)	Obsidian Pumice Tuff Rhyolite Trachyte Andesite Basalt Diabase

4.Durability and Soundness

Aggregate must be resistant to crack or breakdown or disintegration under cyclic wetting and drying (changes in moisture content). Increasing and decreasing of moisture content of an aggregate produce internal stress which cause cracking in aggregate. Aggregates more prone to water showing this phenomenon shouldn't be used in applications where water can gain access to them (Barksdale, p. 11).

5. Particle Shape and Surface Texture

In HMA aggregate particles should be cubic rather than flat or elongate. Because in compacted mixture angular particles have greater interlock and internal fiction, and the result is in higher stability, thin, elongated aggregate particles reduce strength when load is applied to the flat side of the particle and also they are prone to size segregation under handling and to breakdown during compaction. Like particle shape surface texture is also effective on workability and strength. Smooth surface aggregates are easier to be coated by asphalt but asphalt cement adhere to rough surface better (Barksdale, p. 25).

6. Absorption and Affinity for Asphalt

Hydrophilic aggregates are the aggregates that tend to water instead of asphalt like quartz and granite. These kinds of aggregates have stripping (separation of asphalt film from the aggregate because of the water) problem which is a disadvantage for the aggregates. On the other hand some aggregates like limestone, dolomite, and traprock are hydrophobic and it means that they are more attracted to asphalt than the water. This fact has direct effect on aggregates strength.

2.3.4 Specific Gravity

Definitions, equations, and explanation of tests are from *The Asphalt Handbook*, manual series No.4 (MS-4), 1989 edition.

The specific gravity of aggregates is the ratio of the weight of unit volume of aggregate to the weight of water in an equal volume at 20 to 25 °C (68 to 75 °F). General specific gravity for aggregates:

- **Apparent Specific Gravity** which includes only the volume of the aggregate particles not the volume any pores or capillary filled with water after 24-hour soaking.
- **Bulk Specific Gravity** that considers volume of the aggregates plus pores filled with water after a 24-hour soaking.

- **Effective Specific Gravity** which considers volume of the aggregates plus pores filled with water after 24-hour soaking minus the volume of the larger pores that absorbs asphalt (it's approximately the average of the apparent and bulk specific gravity). Figure 2 demonstrates different specific gravities of aggregate particles.

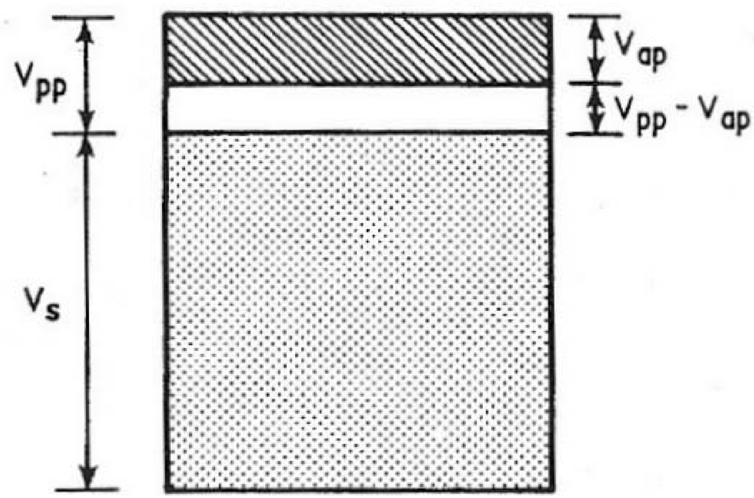

Figure 2: Relationship among the Different Specific Gravities of an Aggregate Particle (Roberts, F.L., Kandhal, P. S., 1991, p. 112)

- V_s= Volume of solids
- V_{pp}= Volume of water permeable pores
- V_{ap}= Volume of pores absorbing asphalt
- $V_{pp} – V_{ap}$= Volume of water permeable pores not absorbing asphalt
- W_s = Oven-dried weight of aggregate
- γ_w = Unit weight of aggregate = 1 g/cm^3

Apparent specific gravity = $G_{sa} = \frac{W_s}{V_s \gamma_w}$ (2.2)

Bulk specific gravity = $G_{sb} = \frac{W_s}{(V_s+V_{pp})\gamma_w}$ (2.3)

Effective specific gravity = $G_{se} = \frac{W_s}{(V_s+V_{pp}-V_{ap})\gamma_W}$ (2.4)

Table 4 shows standards for different tests on aggregates:

Table 4: ASTM Codes

Test	Test Method (ASTM)
1. Specific Gravity of Coarse Aggregate	C 127
2. Specific Gravity of Fine Aggregate	C 128
3. Los Angles Abrasion Test	C 131

2.3.4.1 Specific for Coarse Aggregate

About 5 kg of washed aggregate retained on sieve N0.4 (4.75 mm) is oven dried. The dried sample is then immersed in water for 24-hour. The aggregates is removed from water and drained, and saturated surface dried until all visible films of water are removed but the surface is still damp. Then sample in this condition (saturated surface-dry) is weighted. After weight the sample, it's placed in wire basket, and the weight of submerged aggregate in the water at the room temperature (for 24 ± 4hours) is determined. Finally the sample is put in the oven-dried to a constant weight and the weight of aggregate in this condition (oven-dried) is determined.

A = Oven-dried weight of aggregate. g.

B = Saturated surface-dry weight of aggregate, g. and

C = Submerged weight of aggregate in water, g.

then

$$\text{Apparent specific gravity} = G_{sa} = \frac{A}{A-C} \quad (2.5)$$

$$\text{Bulk specific gravity} = G_{sb} = \frac{A}{B-C} \quad (2.6)$$

$$\text{Absorption} = G_{se} = \frac{(B-A)\,100}{A} \quad (2.7)$$

2.3.4.2 Specific for Fine Aggregate

In this test first the aggregate should be immersed in the water for 24-hour after that sample is placed on a flat surface and exposed to a current of warm air. Current of warm air continued until the saturated surface-dry condition and it's the time when an inverted cone is removed a sample of material is slightly compacted (slump). A 500 g saturated surface-dry aggregates is placed in a flask and then filled with the water and weighted. Finally fine aggregates are removed from the flask, oven dried to a constant weight, and then the weight of it is measured.

A = Weight of oven-dry sample. g.

B = Weight of pycnometer filled with water, g. and

C = weight of pycnometer with specimen and water to calibration mark, g.

then

Apparent specific gravity $= G_{sa} = \frac{A}{B+A-C}$ (2.8)

Bulk specific gravity $= G_{sb} = \frac{A}{B+500-C}$ (2.9)

Absorption $= G_{se} = [\frac{500-A}{A}]\ 100$ (2.10)

2.3.5 Los Angeles Abrasion Test

Aggregates transmit the wheel load to the underlying layers, they should be resistant to polishing and abrasion under this load and also be tough enough to resist crushing, degradation and disintegration. One of the most widely used specific test for this matter is Los Angles Abrasion (Degradation) Test. This test was originally developed in the Municipal Testing Laboratory of the Los Angeles City in the mid-1920s. A 5000 gm is placed in a steel drum with 6 to 12 steel balls. The drum is rotated for 500 revolutions and a steel shelf within the drum lift and drops aggregates about 27 in. This test is performed with washed and oven dried aggregate. After the 5000 revolutions aggregates are removed from machine and sieved dry with No. 12 sieve. The percent passing the sieve is termed as a percent of loss of aggregate in Los Angeles Abrasion value.

2.3.6 Size and Gradation

Aggregate gradation is a distribution of aggregates on their particle sizes, (by passing through the sieves) and it's in two approaches, weight distribution and volume distribution, in which distribution of the total volume is the important approach. But the weight distribution is much easier and also is standard practice. The weight distribution and volume distribution are approximately equal when specific gravities of aggregates are approximately equal. If there is a difference in specific gravity, aggregate gradation should be plot in volume distribution. As it was mentioned before aggregates form 90-95 percent of asphalt cement by weight (and 75-85 percent by volume) which shows how much the existence and decoration of aggregates is important. By gradation main properties such as stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance and resistance to moisture damage can be estimated(Roberts, F.L., Kandhal, P. S., 1991, pp. 117-118).

2.3.6.1 Maximum Aggregate Size

Maximum aggregate size affect on HMA, if it is to small the mix will be unstable and if it is too large, HMA can have workability and segregation problem(harsh mix) in the future(Roberts, F.L., Kandhal, P. S., 1991, p. 120)

According to ASTM C125 there are two approaches for maximum particle size:

1. Maximum size, defined as the smallest sieve size which passes all (100 percent) the aggregates.

2. Nominal maximum size, defined as the maximum sieve size on which some percent (normally lower than 10 percent) of aggregates remain (Roberts, F.L., Kandhal, P. S., 1991, p. 120).

- **Procedure of finding Best Gradation for HMA Mix Design**

Different studies have been carried out to find the best gradation for maximum density. One of the best attempts is for Fuller and Thompson by Fuller's curve.

$P = 100\ (d/D)^n$

Where

d is the diameter of the sieve size in question;

P is the total percentage passing or finer than the sieve;

D is the maximum size of the aggregate.

Studies by Fuller and Thompson indicated that the n should be 5 for maximum density but in the early of 1960s, the Federal Highway Administration (FHWA) introduced the formula for maximum density based on Fuller gradation whit little difference in exponent. They concluded that n should be equal to 0.45 in the equation. Theoretically, it would be good to use the maximum density curve for gradation because it provides increased stability, increased interparticle contacts, it also reduces voids in the mineral aggregate. But this trait can also be negative because there must be adequate air void for asphalt cement to ensure sufficient durability, and also in hot weather lack of voids can result in bleeding/flushing in the pavement (Roberts, F.L., Kandhal, P. S., 1991, p. 118).

There is a different classification of aggregate gradation:

1. Dense (well) Graded Mixes: dense graded HMA consists of continuously graded aggregate. dense graded HMA is divided into three type of gradation:

a) Conventional HMA with nominal aggregate size from 12.5 mm (0.5 in.) to 19 mm (0.75 in.). This gradation is the most common gradation for HMA in U.S.A.

b) Large-stone mixes with nominal maximum size larger than 25 mm (1 in.). This mix has the highest percentage of coarse (larger than 4.75 mm (NO. 4)) aggregate in dense graded.

c) Sand asphalt consists of aggregates pass through 9.5 mm (0.375 in.) sieve. In comparison with conventional mix it has higher amount of binder because of the increased voids in the mineral aggregate (US Army Corps of engineers, 2000, p. 3). Figure 3 shows different gradation for dense-graded mix.

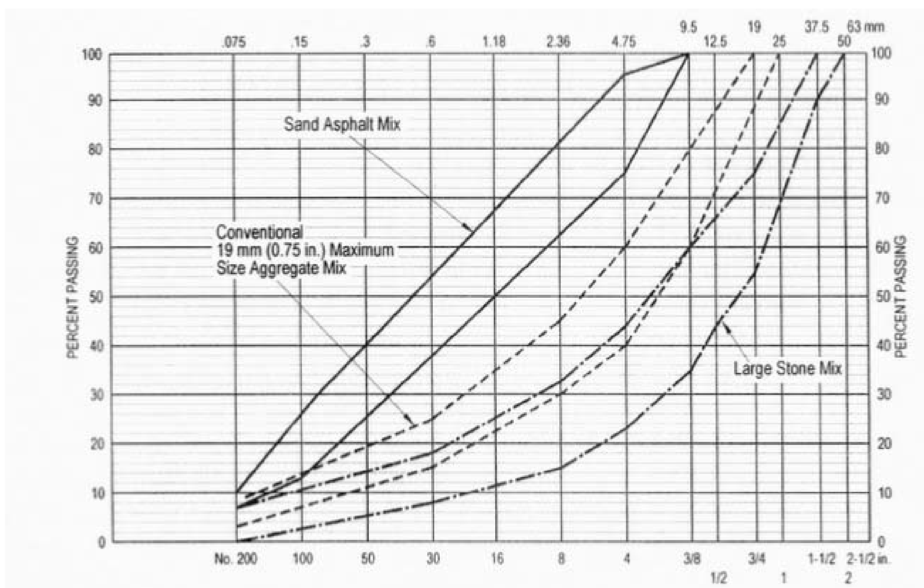

Figure 3: Dense-Graded Mix (US Army Corps of Engineers, 2000, p. 5)

2. Open (uniformly) Graded Mixes: This kind of mixes consists of an aggregate with approximately uniform grading. The reason of using open grade mixes is to drain water that go through the pavement. There two types of open-graded mixes, open-graded friction course which is used as a surface course to provide a free-draining surface and asphalt-treated permeable base, used to drain water which goes through the structural pavement. Open graded mixes

contain only a small percentage of aggregate in the small range (which result in not enough small particle to fill the empty space between large particles), and that is the reason why it has high air void. This type of gradation needs lower temperature for mixing to prevent draindown during storage and delivery to the paver by haul vehicle and also less compactive effort compare with dense-graded mixture (US Army Corps of engineers, 2000, p. 4). In Figure 4 two kinds of open-graded mix for base and surface is plotted.

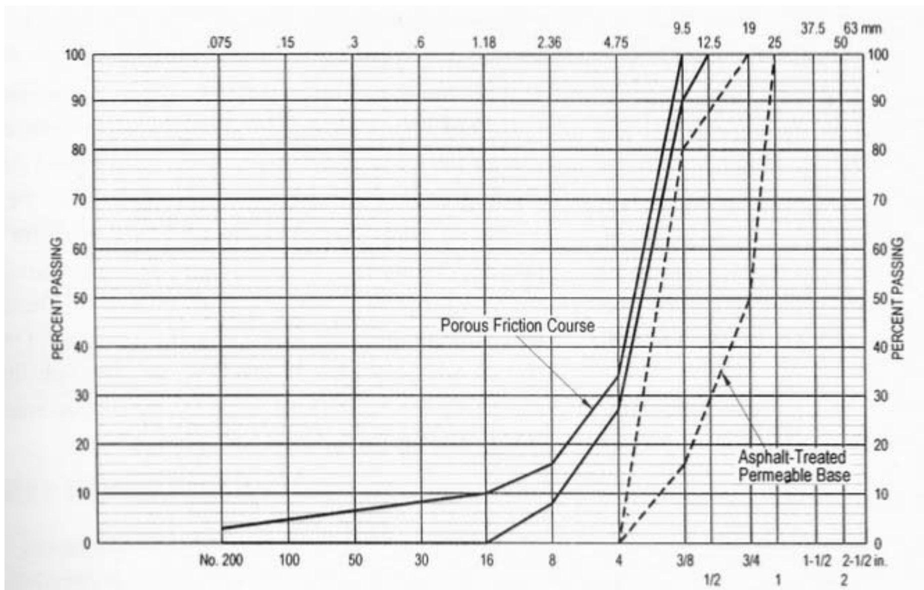

Figure 4: Open-Graded Mix (US Army Corps of Engineers, 2000, p. 5)

3. Gap-Graded Mixes: Like dens-graded mixes gap-graded also provide impervious layer when compacted properly. Gap-graded are divided into two approaches: conventional gap-graded mixes and stone-matrix asphalt (SMA), which, conventional gap-graded aggregates range are from coarse to fine with missing in intermediate size and present in small amounts, and the second approach (SMA), designed to maximize rutting resistance and durability by using of stone-on-stone contact structure. SMA require significant amount of mineral filler in about 8 to 10 percent passing 0.075mm (No.200), (US Army Corps of engineers, 2000, p. 5). Figure 2.7 indicates

different between conventional gap gradation and stone matrix asphalt gradation.

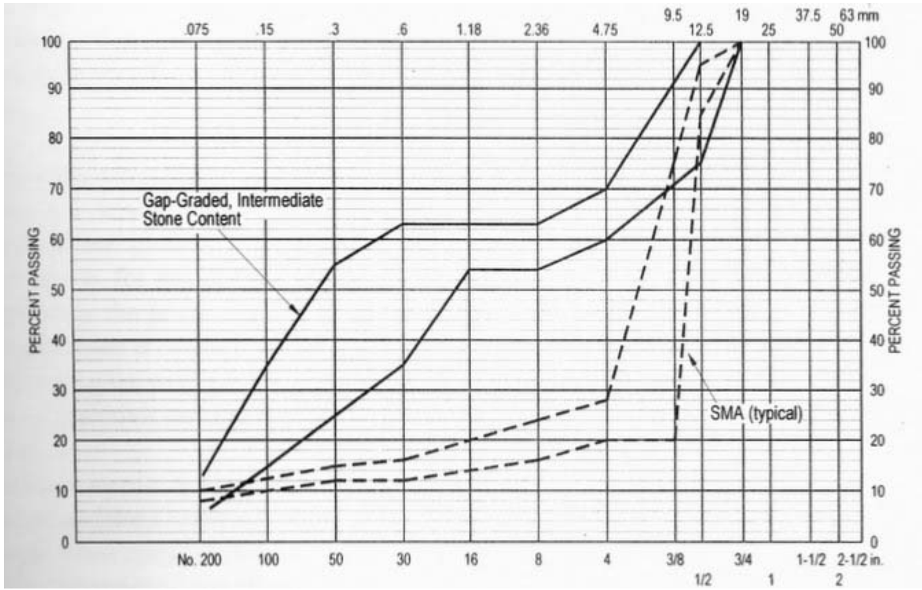

Figure 5: Gap-Graded Mix (US Army Corps of Engineers, 2000, p. 5)

As a summary Table 5 demonstrates common type of hot mix asphalt,

Table 5: Types of Hot-Mix asphalt (US Army Corps of Engineers, 2000, p. 4)

Dense-Graded	**Open-Graded**	**Gap-Graded**
Conventional Nominal maximum aggregate size usually 12.5 to 19 mm (0.5 to 0.75 in)	Porous friction course	Conventional gap-graded
Large-Stone Nominal maximum aggregate size usually between 25 and 37.5 mm (1 to 1.5 in)	Asphalt-treated permeable base	Stone-matrix asphalt (SMA)
Sand asphalt Nominal maximum aggregate size less than 9.5 mm (0.375 in)		

2.3.6.2 Restricted Zone

There are different criterions for specifying Superpave hot-mix asphalt (HMA), one of them is restricted zone that lies along the maximum density gradation line between intermediate sieve sizes [4.75 or 2.36 mm depends on nominal maximum aggregate size] and the 0.3 mm sieve size. It is recommended for Superpave not to pass through this zone because of the rutting problem. But after different studies in this area it is indicated that this zone should be removed from Superpave procedure.

According to Transportation Research Board, *Significance of Restricted Zone in Superpave Aggregates Gradation Specification*, E-C043 in September 2002, it is distinctly indicated that:

> Independent results from the literature clearly indicate that no relationship exists between the Superpave restricted zone and HMA rutting or fatigue performance. Mixes meeting Superpave and fine aggregate angularity (FAA) requirements with gradations that violated the restricted zone performed similarly to or better than the mixes having gradations passing outside the restricted zone. Results from numerous studies show that the restricted zone is redundant in all conditions (such as nominal maximum aggregate size (NMAS) and traffic levels) when all other relevant Superpave volumetric mix and FAA requirements are satisfied.

And also there is a same result in other studies like REPORT 464 of National Cooperative Highway Research Program (NCHRP), *The Restricted Zone in the Superpave Aggregate Gradation Specification* in 2001, and the study that have been done with Kandhal and Cooley, *Effect of Restricted Zone on Performance Deformation of Dense-Graded Superpave Mixtures*, which specify that mixes pass through the restricted zone don't necessary have more prone to rutting compare to mixes pass outside of the restricted zone. These results show that the restricted zone is "redundant" for mixes meeting all Superpave volumetric parameters and the required FAA.

2.4 Distresses in HMA Pavements

HMA like other paving materials is subject to the different kinds of the distresses. In a simple explanation distress is a condition in which pavement starts to lose its performance or encounter with reduction in serviceability (Roberts, F.L., Kandhal, P. S., 1991, p. 403).

An admirable reference to recognize and classified distresses in HMA is the *Highway Pavement Distress Identification Manual* published by Federal Highway Administration (Huang, 2004, p. 368). According to this manual there are four basic types of pavements: 1.Asphalt concrete surfaced. 2. Jointed plain concrete. 3. Jointed reinforcement concrete. 4. Continuously reinforced concrete. In this section we are going to look over some of the most important asphalt cement surface distresses with an explanation depend on their significance.

2.4.1 Alligator or Fatigue Cracking:

Fatigue cracking occurs because of inadequate structural support for the applied load that can be initiated as, first because of poor drainage or stripping at the bottom of HMA layers which caused decrease in pavement-load-supporting, second encounter with level of load higher than that is anticipated, third poor construction like inadequate compaction. Fatigue cracking is different in demonstrate in two type of thin and thick pavement. In thin pavement (usually pavements with thickness lower than 2 in) fatigue cracking is propagate from the bottom of HMA layer due to high tensile strain upward to the top of the HMA, whereas in thick pavement (usually pavements with thickness higher than 6 in) fatigue cracking initiate from the HMA layer because of the tensile stress at the surface mitigated down to the bottom. With not considering this type of fatigue in appropriate time, pavement faces with the secondary distress which is infiltration of water into the pavement. The first type of crack is also called bottom-up cracking and second type is top-down cracking in literature. Potholes (we'll go through it later) are separated piece of HMA which are caused by action of traffic and also from fatigue cracking.

There are two type of control loading in fatigue test, controlled-stress (force) and controlled-strain (displacement). The difference between these two categories is, in the first one stress is remain constant and strain increases with the number of repetition and in the second test strains are held constant and stress decreases with the cycle strain application. After different studies it is suggested that controlled-stress represents the behavior of thick HMA pavements and controlled-strain is suitable to show the performance of the thin HMA pavements (Francisco Thiago S. AragBo, Yong-Rak Kim, Junghun Lee, 2008, pp. 18-19). Alligator crack is happened because of high tensile stress or strain under the bottom of asphalt layer (higher than that asphalt layer can bear) under an overweight wheel load. Beside of the weight of trucks or any kinds of vehicle another important reason for alligator cracking is exist of inadequate pavement thickness. These formed cracks propagate to the surface layer initially as one or more longitudinal parallel cracks, which in appearance are like alligator's back. The feature of alligator is that it occurs only under the wheel load not over an entire area unless the entire area was subjected to the traffic loading (Roger E. Smith, Michael I. Darter, Stanley M. Herrin, 1986, p. 3). Severity levels of alligator are divided into 3 parts, low, moderate and high which are related to the connection and spalls of cracks (U.S. Department of Transportation: Federal Highway Administration, 2009). Figure 6 shows Low Severity Alligator Cracking which can be specified according to:

- An area of cracks has no or very few interconnecting cracks,
- Cracks are not spalled, and
- Cracks are <= 0.25 in (6 mm) in mean width.

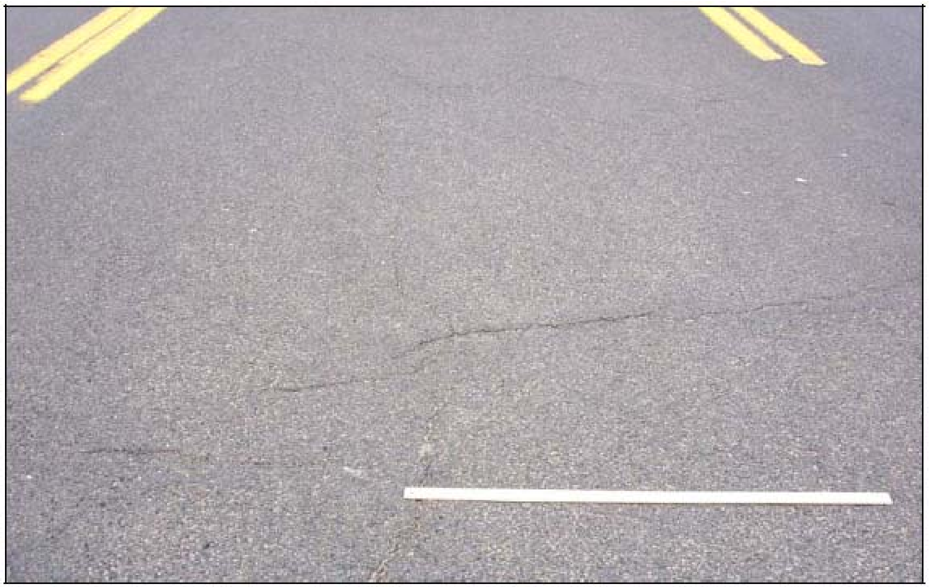

Figure 6: Low Severity Alligator Cracking (Federal Highway Administration, 2006-2009, p. 6)

Figure 7 shows Medium Severity Alligator Cracking which has these signs:

- An area has an interconnected cracks which form a complete model,
- Cracks maybe slightly spalled, and
- Cracks are >0.25 in. (6 mm) and <= 0.75 in. (19 mm) or any crack with a mean width equal or lower than 19 mm and adjacent low severity cracking.

Figure 7: Medium Severity Alligator Cracking (Federal Highway Administration, 2006-2009, p. 6)

And the last category which is shown with Figure 8 is High Severity Alligator Cracking:

- An area has an interconnected cracks forming a complete model,
- Cracks are moderately or severely spalled, and
- Cracks are >0.75 in (19mm) or any crack with a mean width >= 0.75 in (19mm) and adjacent medium to high severity random cracking. (Federal Highway Administration, 2006-2009)

Figure 8: High Severity Alligator Cracking (Federal Highway Administration, 2006-2009, p. 5)

2.4.2 Longitudinal and Transverse Cracking:

Longitudinal cracks are individual that initially run parallel to the pavement's centerline. The reasons are 1) Poor constructed paving. 2) Shrinkage of the asphalt cement because of hardening or low temperature. 3) The last reason is caused by cracks under the surface course. Transverse cracks extend across the centerline of the pavement and usually caused by the second and third named reason. Longitudinal and transverse cracking are usually non-wheel cracks. Severity levels depend on width of cracks (Smith *et al*., 1986, p. 26). Figure 9 to 14 indicates different cracks in their level of severity which are divided into three levels; Low, Medium and High severity for both longitudinal and transverse cracking. For both kind of distress level of severity is distinguished by the width of the crack. If the width of the crack is lower than 0.25 in (6 mm), category is low, for cracks with thickness between 0.25in (6 mm) and 0.75 in (19 mm) the category is known as medium and for the last type, cracks with opening higher than 0.75 in (19 mm) are identified as high severity

Figure 9: Low Severity Longitudinal Cracking (Federal Highway Administration, 2006-2009, p. 8)

Figure 10: Medium Severity Longitudinal Cracking (Federal Highway Administration, 2006-2009, p. 8)

Figure 11: High Severity Longitudinal Cracking (Federal Highway Administration, 2006-2009, p. 7)

Figure 12: Low Severity Transverse Cracking (Federal Highway Administration, 2006-2009, p. 10)

Figure 13: Medium Severity Transverse Cracking (Federal Highway Administration, 2006-2009, p. 10)


Figure 14: High Severity Transverse Cracking (Federal Highway Administration, 2006-2009, p. 9)

2.4.3 Potholes:

Potholes are relatively small holes of various sizes in the pavements. As it was mentioned before they're caused by alligator cracking and also by localized disintegration of the mixture (Smith *et al*., 1986, p. 38). The severity levels are classified on the depth of potholes in three levels:

1. Low: Depth lower than 1.0 in (25 mm) deep, as it shown in Figure 15


Figure 15: Low Severity Pothole (Opus Consultants International (Canada) Limited, 2009, p. 49)

2. Moderate: Depth between 1.0 in (25 mm) to 2.0 in (50 mm) deep, Figure 16 shows moderate type of pothole distress.

Figure 16: Moderate Severity Pothole (Opus Consultants International (Canada) Limited, 2009, p. 49)

3. High: In this type (Figure 17), depth is higher than 2.0 in (50 mm) deep (Miller, J. S., & Bellinger, W. Y., 2003, p. 18).

Figure 17: High Severity Pothole (Opus Consultants International (Canada) Limited, 2009, p. 50)

2.4.4 Raveling and Weathering

Raveling and weathering are wearing away of the Asphalt cement surface because of either dislodging of aggregate particles which called raveling or loss of asphalt cement binder which is called weathering. In general this phenomenon is happened because of excessive hardening of asphalt cement. Severity levels are based on the percent of dislodging of aggregate or asphalt (Smith et al. 1986, p. 45). Raveling range is from loss of fines to loss of some coarse aggregate. Figures 18 to 20 show different losing of aggregate in raveling distress (Miller, J. S., & Bellinger, W. Y., 2003, p. 28).

Figure 18: Loss of Fine Aggregate (Miller, J. S., & Bellinger, W. Y., 2003, p. 28)

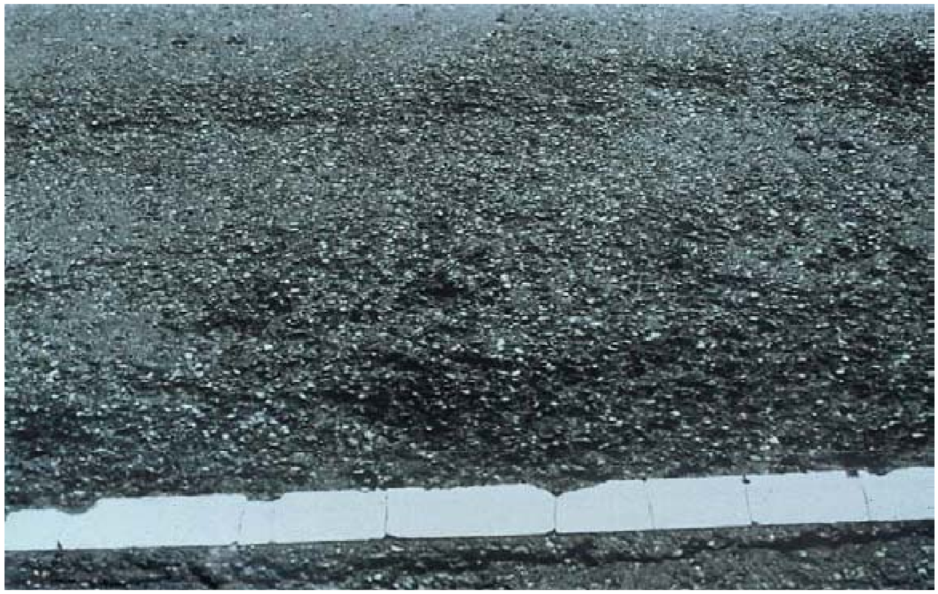

Figure 19: Loss of Fine and Some Coarse Aggregate (Miller, J. S., & Bellinger, W. Y., 2003, p. 28)

Figure 20: Loss of Coarse Aggregate (Miller, J. S., & Bellinger, W. Y., 2003, p. 28)

2.4.5 Permanent Deformation (Rutting)

Permanent deformation or rutting is one the main problems in HMA pavements and is usually defined as: developing of longitudinal deformation (depression) under the action of repeated wheel path (Kandhal, P.S., Mallick, R.B., Brown, E.R., 1998, p. 3) & (Sebaaly, P. E., McNamara, W. M., Epps, J.A., 2000, p. 2), or it can be defined as when a cross section of surface of the pavement is no longer in its design position, it is called by "Permanent" deformation name because it shows an accumulation of small amount of depression (deformation, strain) which occurs under the repeated load of vehicles wheel path (Druta, 2006, p. 116). Different studies in this area has shown that rutting is usually confined to the top 7 to 10 cm (surface and binder courses), (Kandhal *et al.,* 1998, p. ii) & (Frazier Parker, E. Ray Brown, 1992, p. 68). When a wheel load is applied to a flexible pavement two kind of different stresses are transmitted to the HMA: one of them is vertical compressive stress within the pavement layers which has its most affection on the top of the subgrade and the other stress is horizontal tensile stress on the bottom of the surface layer (Druta, 2006, p. 115) & (Huang, 2004, p. 58). These stresses as shown in Figure 21, Compressive stresses are labeled with (1), (3), and (4), (in which (4) enters to the subgrade) whilst tensile stresses with (2).

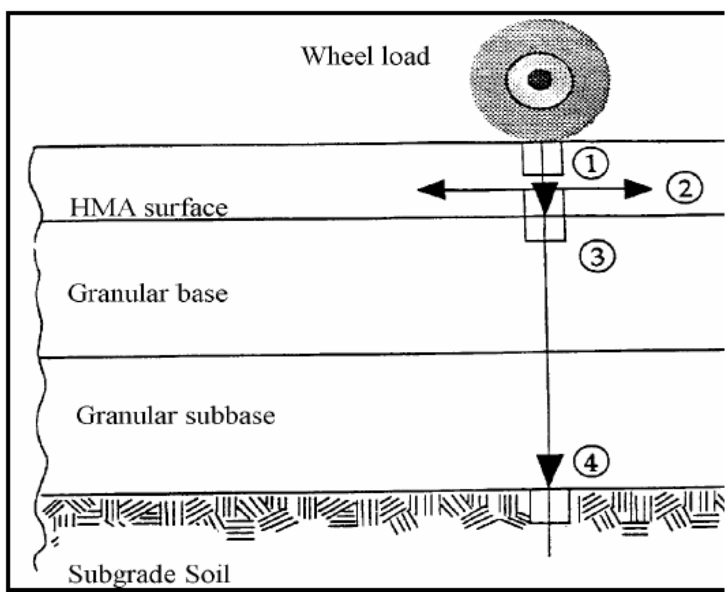

Figure 21: Critical stresses transmitted in flexible pavement (Druta, 2006, p. 115)

Usually rutting shows itself in two distinct phases, the first phase, rutting is happened because of applying too much stress on the subgrade (or subbase or base) directly below the tires, with very little upheaval zones (Figure 22), the second phase, is referred to load cycles after initial densification, deformation is below the tires but in this case with upheaval zone (Figure 23). Hydroplaning and steering problem are happened when ruts depths reach greater than 0.2 inch, with result in a reduction in the service of the section and safety concern (Druta, 2006, pp. 116-117)&(Sebaaly*et al.,* 2000, p. 3).

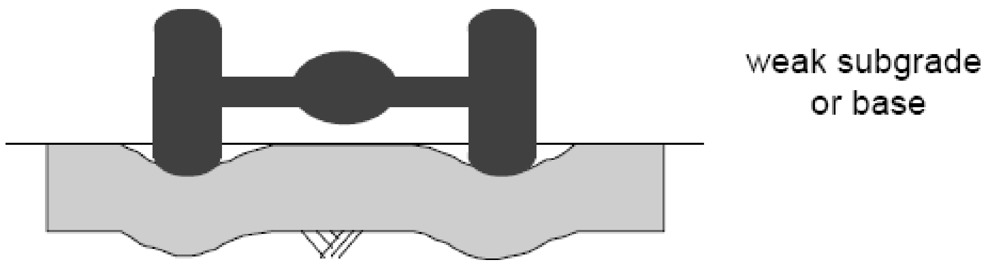

Figure 22: Deformation of the flexible pavement due to weak structure
(Druta, 2006, p. 116)

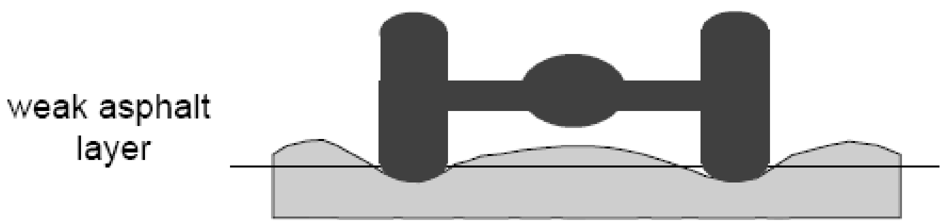

Figure 23: Deformation of the flexible pavement due to poor HMA design
(Druta, 2006, p. 117)

Regardless to the reason, rutting is categorized in tree level of severity:

1. Low: Ruts with a measured depth ≥ 0.20 in. and ≤ 0.49 in. which is indicated in Figure 24,
2. Medium: Ruts with a measured depth ≥ 0.50 in. and ≤ 0.99 in. as it can be seen in Figure 25 and,
3. High: Ruts with a measured depth ≥ 1.00 in. as shown in Figure 26 (Federal Highway Administration, 2006-2009, p. 14).

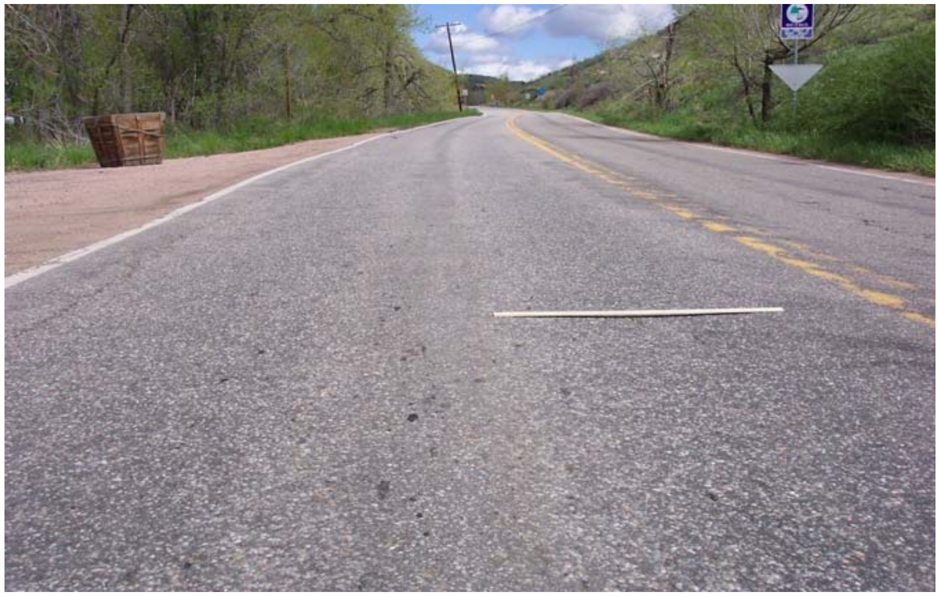

Figure 24: Low Severity Rutting (Federal Highway Administration, 2006-2009, p. 16)

Figure 25: Medium Severity Rutting (Federal Highway Administration, 2006-2009, p. 15)

Figure 26: High Severity Rutting (Federal Highway Administration, 2006-2009, p. 15)

2.4.5.1 Causes of Permanent deformation

Permanent deformation or rutting development in flexible pavements can be result of three mechanisms, Consolidation, Mechanical Deformation, and Plastic Flow.

1. ***Consolidation*** is defined as a compaction of pavement under traffic load immediately after its initial construction, it occurs because of lack of compaction, which is shown in high percent of air voids (greater than 10%) on the layer like subgrade or untreated base or even asphalt mix itself, this type of rutting is in the category of phase one (without upheaval zones).
2. ***Mechanical Deformation*** can also arise from traffic compaction and bearing compaction type of failure, in other word when layers under pavement surface (base, subbase, subgrade) loses its stability for any reason, and is displaced under the load.
3. ***Plastic Flow*** occurs in pavements with excessive amount of asphalt binder and insufficient air voids. In this kind of mixtures, asphalt binders work as a

lubricant and reduce the internal friction in the pavement result in development of unrecoverable strain under load concentration. Plastic movement (flow) is in second phase category with upheaval zone in rut are.

In addition severity of permanent deformation is directly correlated with high temperature, which is by different studies that in high temperature region susceptibility of pavement for rutting is higher. There are some other topics in the asphalt mixes that are important in developing of permanent deformation:

- Increased traffic loads,
- Increased tire pressure,
- Selection of excessive high asphalt contents,
- Excessive minus 200 material (fines),
- High pavement service temperature,
- Soft asphalt,
- etc.

Asphalt concrete pavement rutting can be minimized by taking some measures including the following:

- Lower asphalt content,
- Coarser gradation,
- Angular and rough textured aggregate,
- Improved bond between pavement layers,

(Kandhal, P.S., Mallick, R.B., Brown, E.R., 1998, pp. 3-4) & (Sebaaly *et al.,* 2000, pp. 3-4), another important reason in rut distress is “shear stress” which we will go through it in Superpave section.

2.5 Mix Design

There are the most three popular approaches in HMA mix design:

1. Superpave Method
2. Marshall Method
3. Hveem Method

2.5.1 Hveem Method

This method which is detailed in ASTM D 1561 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, p. 21). The Hveem device has a kneading compaction and a stabilometer (an empirical measurement) to prepare specimens according to their range of asphalt and test them upon their internal friction. In this method vertical axial load is applied to a Hot Mix Asphalt (HMA) mixture which has 4 inches diameter and 2.5 inches high. And displacement is measured, the temperature in which HMA specimens should cure is 140 °F (60 °C) (Roberts, F.L., Kandhal, P. S., 1991, p. 226).

2.5.2 Marshall Method

The earliest version of Marshall mix design was developed by Bruce Marshall at the Mississippi Highway Department around 1939 and the U.S Army Corps of Engineering (USACE) developed it during World War II, and it's primarily because of increment in aircraft wheel load (US Army Corps of engineers, 2000, p. 20) & (Roberts, F.L., Kandhal, P. S., 1991, p. 141). This test explained in ASTM D 1559 includes of a 10-pound hammer with $3^{7/8}$-inch diameter, the laboratory compactive effort is include of different drop hammer weights, different combinations of number of blows per side and different mold base shapes and materials. The design procedure includes a density-voids analysis of the compacted specimens to determine air voids, voids in mineral aggregates (VMA) and voids filled with asphalt (VFA), and the last step before testing the compacted sample in the Marshall Stability device is putting the specimen in the hot water bath at 60 °C (140 °F) for 30 to 40 minutes.

2.5.3 Superpave Method

Asphalt Institute in Superpave Mix Design manual, Superpave Series No. 2 (SP – 2) gives details about Superpave method. In this section all the information is borrowed from named book. In 1987, the Strategic Highway Research Program (SHRP) began developing a new system for asphalt cement in the lab to simulate field condition in a better way (like obtaining performance grade for asphalt which is known as PG) which asphalt cement will meet in its service life. The final product of the SHRP is a new system called Superpave, short for Superior Performing Asphalt Pavements.

2.5.3.1 Mineral Aggregate Behavior

One of the important factor in Hot Mix Asphalt (HMA) is the role of aggregates in the mix, a wide variety of mineral aggregates are used in HMA such as natural aggregates which are simply mined from river or glacial deposits, with or without crushing process. Regardless of the source, aggregates must provide enough shear strength to resist traffic load. When aggregates are overloaded a shear plane develops and aggregate particles start to slide or shear on each other's surface as it can be seen in Figure 27, resulting in permanent deformation. This fact happened because of excess shear stress on shear strength.

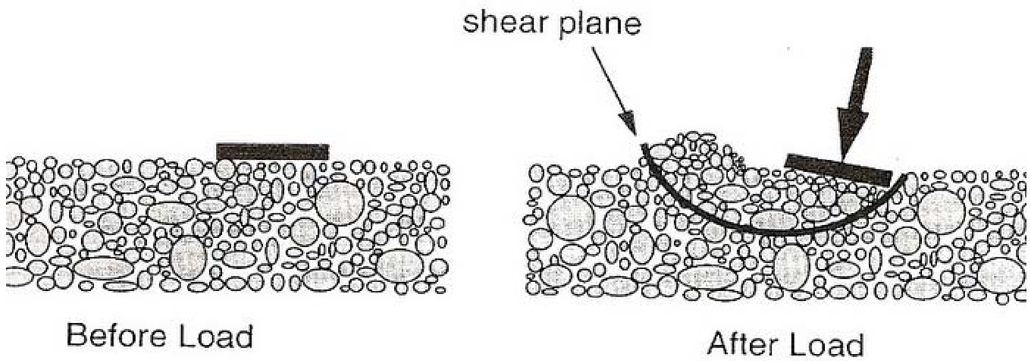

Figure 27: Shear Loading Behavior of Aggregate (Asphalt Institute, 1996)

Because aggregates have relatively little cohesion, the internal friction between them is very important to provide adequate shear strength, that's the reason of using high amount of cubical, rough-textured aggregates instead of rounded, smooth-textured aggregates (Figure 28).

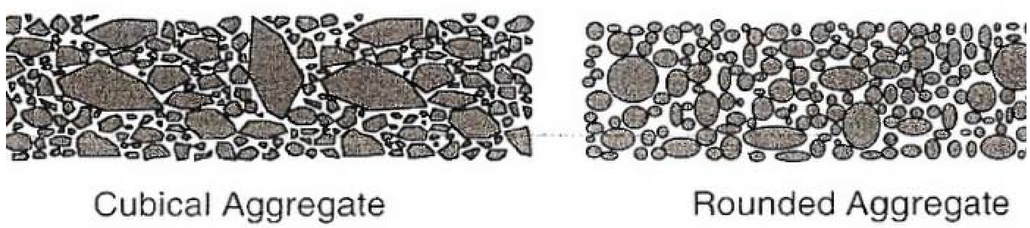

Figure 28: Aggregate Stone Skeleton (Asphalt Institute, 1996)

2.5.3.2 Asphalt Mixture Behavior

When a wheel load is applied to a pavement, two primary stresses are transmitted to the HMA:

1. Vertical compressive stress through the HMA which result in rutting distress, to face this problem asphalt mixture should be internally strong and resilient, and at the same time,
2. Horizontal tensile stress at the bottom of the asphalt layer which is the reason of the fatigue distress, high tensile strength asphalt is needed to withstand the tensile stress to carry load applications without damage (Figure 21).

2.5.3.3 Test Equipment

The device which is used in Superpave Mix Design for making sample is Superpave Gyratory Compactor (SGC).SHRP had different goals in developing the Superpave Gyratory Compactor, the main reason was to have equipment which compact mix specimen in realistic condition with more and more closeness to field condition that compacted specimen will meet. They also wanted the compactor to be able to measure compactability so that potential tender mix behavior and similar compaction problems could be identified and another important priority for SHRP was to have a portable device that can be carried to the mixing facility for quality control operation and because of not having any equipment to have all these capability the SGC was developed. The reference of SGC was Texas gyratory compactor produced to have realistic specimen densification and it was reasonably portable. The changes which has been done in Texas Gyratory Compactor by SGC are, first of all angle and speed of gyration were moderated by lowering them to 1.25 and 30 respectively and also adding real time specimen height recording capability. The sample diameter is 6-inch can accommodate mixtures containing maximum aggregate size, 50 mm (37.5 mm nominal).

The SGC consists of these components:

- Reaction frame, rotation base, and motor
- Loading system, loading ram, and pressure gauge
- Height measuring and recording system
- Mold and base plate

Figure 29 is a schematic figure which indicates different part of SGC.

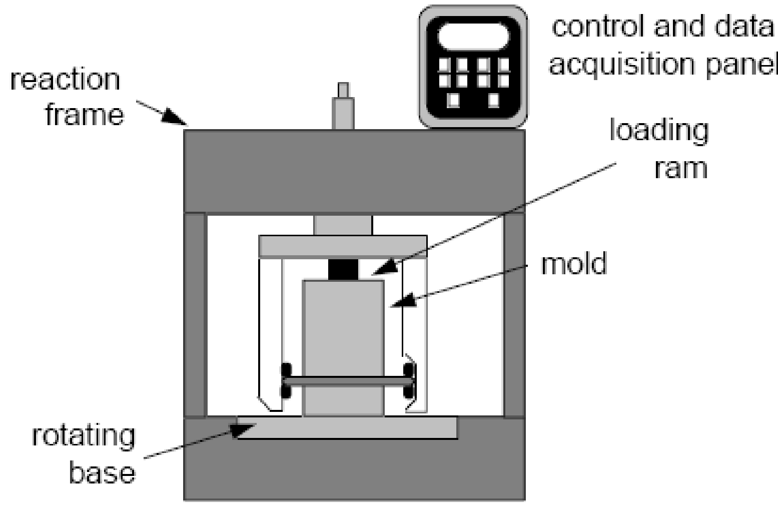

Figure 29: Superpave Gyratory Compactor (Asphalt Institute, 1996, p. 48)

The pressure applied with loading mechanism is 600 kPa in form of compaction pressure, and a pressure gauge measures the ram loading to maintain constant pressure during compaction. The SGC mold has an inside diameter of 150 mm (and also 100 mm) and a base plate in the bottom of the mold provide confinement during compaction. The rotation of the SGC base is fixed at a constant 30 revolution per minute during compaction with the mold positioned at a compaction angle of 1.25 degrees (Figure 30).

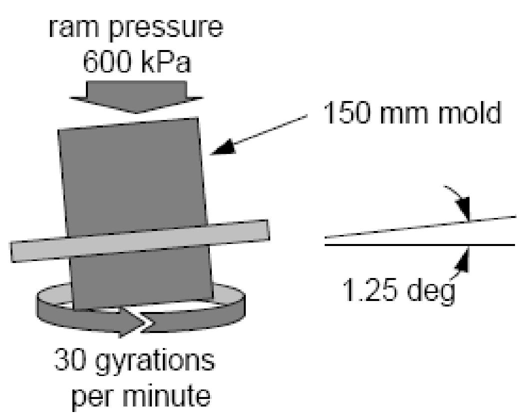

Figure 30: SGC Mold Configuration (Asphalt Institute, 1996, p. 49)

The specimen height is an important function because with having height and also the mass of compacted mixture, density can be easily calculated. Height is measured by recording the position of the ram throughout the test. Like other mix design procedures asphalt mixtures are compacted at the specific level of compactive effort which in Superpave is N_{des}, which is function of climate and traffic level as it can be seen in details in Table 6. Climate is characterized by the average of temperature for seven-day maximum air temperature for project conditions and traffic is represented by the design ESALs. Beside of N_{des} there are two other gyration levels: N_{ini} which is the initial number of gyrations used for estimation of the compactability of the mixture and N_{max} which is the maximum number of gyration used for compaction level. N_{ini} and $N_{max}$are calculated from N_{des}, with these relationships:

Log N_{max}= 1.10 Log N_{des}

Log N_{ini} = 0.45 log N_{des}

The maximum allowable mixture density at N_{ini} is 89 percent and at N_{max} is 98 percent (Asphalt Institute, 1996).

Table 6: Superpave Design Gyratory Compactive Effort (Asphalt Institute, 1996, p. 50)

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	78121		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

2.6 Polypropylene

To solve different distresses explained in this chapter, besides change the aggregate gradation and the type of the asphalt binder, scientists have developed some techniques called asphalt modification by adding different kind of polymer to the asphalt. The polymers which are added to asphalt (or aggregate), are divided into two categories mainly known as plastomers and elastomers. Plastomer additives, modify asphalt by forming a tough and rigid network within the binder to resist deformation and elastomer additives, increase elastic response of the asphalt and therefore resister it against permanent deformation by stretching and recovering its initial shape. The most commonly used polymer for bitumen modification is the elastomer, styrene butadiene styrene (SBS) and as a plastomer modifier one of the popular additives is polypropylene which is investigated in detail through this study. The application of polymer modification began in early 1990s (Tapkin *et al.,* 2009, p.p 240-241).Polypropylene fibers are widely used as a reinforcing agent in concrete (Abtahi *et al.,* 2009). The polypropylene fibers provide three-dimensional reinforcement of the concrete and cause increment in toughness and durability in concrete pavements, but they can’t be used as a wire mesh reinforcement and work as a secondary reinforcement which can also be economical by partially replacing steel fibers. Polypropylene fibers were also used as a modifier in asphalt concrete in the United States, Ohio State Department of Transportation (ODOT), (Tapkin, 2008) based on Ohio State Department of Transportation standard the polypropylene fibers should be added to the asphalt mix in the ratio of about 2.7 Kg/ton (ITEM 400HS, 1998). However the ratio can be changed in order to satisfy the desire mechanical properties of asphalt pavement. For adding polypropylene to asphalt pavement there are two common approaches:

- Dry base
- Wet base

In Dry basis polypropylene is added first to the aggregate and after adequate mixing, asphalt is introduced to the aggregate and polypropylene like (Tapkin, 2008, p. 1065) or (Abtahi *et al.,* 2009) Which in these studies fiber was first added to the aggregate for about 10 seconds (time can be increased if needed) and then mixed with the asphalt binder.

In Wet basis polypropylene is premixed with asphalt in the first step, and then the mixture of fiber and asphalt will blend with aggregate like (Tapkin *et al.,* 2009, p.242) or (Al-hadidy, A. I., & Yi-qiu, T., 2008, p. 1135). In the two last studies the fibers were premixed with asphalt binder for about 2 h, then aggregate was added to the modified asphalt.

Polypropylene has different advantage in asphalt pavement, Tapkin (2008) conducted study by using polypropylene in 0.3%, 0.5% and 1.0% by weight of mixture in dry basis, test procedures was included Marshall Stability and Indirect Tensile Test, and the results showed, improvement in stability by increasing 58% and decreasing flow value by 142% reduction and 27% increment in fatigue life. In another study Al-Hadidy and Yi-qiu (2008) used polypropylene in pyrolisis form (PP was subjected to thermal degradation) in wet basis and was mixed with the asphalt by 1, 3, 5 and 7% by weight of asphalt binder for 5min at temperature 160 ± 5 °C. They concluded that the tensile strength ratio for different mixtures containing PP were greater than 85%, shows it won't be any problem for mixture when exposed to moisture, penetration index values in this test indicates that PP reduced the temperature susceptibility of asphalt, also there was increase in Marshall Stability and decrease in flow. The optimum amount for PP was 5%, beyond this ratio, stability decrease and flow increase because of reduction in interlocking offered by PP-asphalt binder and aggregate particle.

Tapkin *et al.,* (2009) stated that the best type of polypropylene fiber for wet basis is M-03 type fibers (fiber length is equal to 3mm) and the optimal amount is 0.3% by weight of aggregate, the mixing temperature was around 165-170 °C with standard mixer at 500 rpm for 2 h. In this study M-03 in 0.3%, 0.45% and 0.6%, and M-09 in 0.3% was utilized. There was 20% increased in Marshall Stability and also "The results from the analysis of the tested specimens show that the additional of polypropylene fibers improves the behavior of the specimens by increasing the life of samples under repeated creep test". Abdul-Rahim I and Al-Hadidy have found out that Marshall Stability, Marshall Stiffness, V.F.B and density values increase by adding polypropylene while Marshall Flow, air voids and V.M.A tend to decrease. They performed their study in wet basis, the combined aggregate and filler were heated to 160°C, the modified binder was heated up to 150 °C and the combination were mixed at temperature 150±5 °C for 1.5 min. polypropylene was mixed with asphalt in 1,2,3,4,6& 8 % by weight of asphalt for seven min at temperature of 150±5 °C, the addition of polypropylene increased stability and decreased flow up to 2%, beyond this percent the stability decreases and flow increases and this happens for V.F.B and V.M.A and air voids as well, (V.F.B increase up to 2% and then decrease, V.M.A and air voids vice versa). And they also concluded that temperature susceptibility decrease by adding polypropylene. Abtahi *et al.,* (2009) were carried out a test by using both polypropylene fibers and Styrene-Butadiene-Styrene Polymers (SBS) to reinforce Asphalt Concrete samples. In their study polypropylene was added in dry procedure, blended with aggregate prior to adding asphalt in 0.0625%, 0.125% and 0.25% by weight of mixture, and SBS was added in wet procedure, blended with asphalt in the first step and then mixed with the aggregate in 2%, 3%, 4% and 5% by the total weight of bitumen mixture. Aggregates were kept at 170 °C for 16 h, later they were blended with fibers and bitumen at 132 °C for Fiber Reinforced Asphalt Concrete (FRAC) or with Polymer Modified Asphalt (PMA) at 132 °C. They concluded that both fibers (0.125% and 0.25%) and SBS (4% and 5%) are effective in Stability at 95% confidence but the Resilience Modulus improvement was statistically satisfied by 0.125% and 0.25% of PP fibers.

Also there are lots of other studies which have been done by different researchers like Simpson and Kamyar, 1994, they concluded that mixtures containing polypropylene fibers have higher tensile strength and resistance to cracking, and also they deduced polypropylene mixture will not have thermal cracking at low temperature. Jenq, Chwen-jang, & Pei, 1993 carried out study with polypropylene and polyester fibers, they figured out that the fracture energy in the modified samples was increased by 50 to 100% which means toughness value increased but tensile strength and elasticity values were not changed considerably (Tapkin, S., Cevik, A., & Usar, U., 2009, pp. 11187-11188).

Chapter 3

METHODOLOGY

3.1 Introduction

This chapter will discuss about different tests that was performed in this study on aggregate, asphalt and compacted specimens. Information about physical features of polypropylene fiber used for increasing capability of asphalt mixture is also derived. Data are classified in appropriate tables depend on their categories. This chapter is divided into five parts:

- Aggregate,
- Asphalt,
- Polypropylene,
- Mix Design, and
- Analysis of Compacted Mixture.

The last part, Analysis of Compacted Mixture, was calculated in both Marshall and Superpave Mix Design Method.

3.2 Aggregate

3.2.1 Type

All the aggregates in this study are 100% crushed. The aggregates are limestone obtained from North Cyprus Highway Department quarries in Besparmak Mountains in TRNC (Tawfiq, 2002, p. 16).

3.2.2 Gradation

The gradation of the aggregates is according to Turkish Highway Standard for binder course, Type 1. Table 7 shows the gradation.(Tawfiq, 2002, p. 16)

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

3.2.3 Specific Gravity of the Aggregate

The specific gravities for coarse and fine aggregates were determined separately according to their Standard.

3.2.3.1 Specific Gravity and Absorption of the Coarse Aggregate

The coarse aggregates (the aggregates retained on sieve No.4) are tested according to American Society for Testing and Materials (ASTM) C 127-07, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate. According to the standard, test sample which is minimum 3 Kg (mass of test sample is depend on the nominal maximum size of the aggregate gradation) should be dried in the oven to constant mass at a temperature of 110 ± 5 °C, after it gets dried it is cooled in air temperature for 1 to 3 h till can be handled easily. Subsequently immersed in water at room temperature for 24 ± 4 h, and then the test sample is removed from water to be dried by cloth to Saturated Surface-Dry (SSD) condition. The mass of the test sample in SSD condition is determined to the nearest 0.5 g or 0.05% of the sample mass whichever is greater.

After determining the mass in air, the saturated surface-dry test sample is placed in the sample container for determining the apparent mass in water at 23 ± 2.0 °C. At the last step the test sample is dried in the oven to constant mass at a temperature of 110 ± 5 °C, cooled in air temperature 1 to 3 h for determining the mass. Table 8 shows the result of specific gravity and absorption of coarse aggregates.

Table 8: Specific Gravity and Absorption of the Coarse Aggregate

Items		**Size**			
		19 mm	**12.5 mm**	**9.5 mm**	**4.75 mm**
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)	2.79	2.78	2.79	2.81
Bulk specific gravity (SSD)	B/(B-C)	2.81	2.80	2.81	2.83
Apparent Specific gravity	A/(A-C)	2.84	2.82	2.84	2.87
Absorption	[(B-A)/A]*100	0.60	0.51	0.58	0.76

3.2.3.2 Specific Gravity and Absorption of Fine Aggregate

The specific gravity and absorption of fine aggregate (aggregates passing sieve No.4) is tested according to American Society for Testing and Materials (ASTM) C 128-07, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of fine Aggregate. According to the test approximately 800 g of fine aggregate should be placed in a pan with water cover it for 24 h. Then the sample spread on a flat surface exposed to a warm air and stirred to get to the Saturated Surface-dry (SSD) condition. SSD dry sample shall be divided into two equal sections; one of them is weighted and dried to constant weight at a temperature 100 – 110 °C, then it should be cooled in air and weighted. The other section is introduced into the flask which is filled almost to 1000 ml. after one hour in a constant temperature at 20 °C, flask is weighted. In Table 9 result of specific gravity and absorption of fine aggregate is illustrated.

Table 9: 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)	2.73
Bulk specific gravity (SSD)	S/(B+S-C)	2.77
Apparent specific gravity	A/(B+A-C)	2.85
Absorption %	[(S-A)/A]*100	1.57

The average specific gravity and absorption according to ASTM C 127 – 07 are calculated by the following equation:

$$G = \frac{1}{\frac{P_1}{100G_1} + \frac{P_2}{100G_2} + \dots \frac{P_n}{100G_n}} \tag{3.1}$$

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:

$$A = (P_1A_1/100) + (P_2A_2/100) + \dots (P_nA_n/100) \tag{3.2}$$

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.

According to the equations the value for specific gravities and absorption is brought in the following table;

Table 10: Overall Average Values for Specific Gravity and Absorption

Average bulk specific gravity (Dry)	2.76
Average bulk specific gravity (SSD)	2.82
Average Apparent specific gravity	2.85
Average Absorption, %	1.15

3.2.4 Los Angeles Abrasion Test

ASTM C 131 – 06 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine, is carried out to satisfy the hardness and toughness of the crushing aggregate specification. According to the standard aggregate should be washed and placed in the oven at 110 ± 5 °C (230 ± 9 °C) to substantially constant mass. Then sample is placed in the Los Angles testing machine. After 500 revolutions at a speed of 30 to 33 r/min aggregates are taken out from machine and the aggregates coarser than 1.70–mm (No. 12) are oven dried at 110 ± 5 °C (230 ± 9 °F) to substantially constant mass and weighted to the nearest 1 g. At the end the percent loss of aggregates is calculated, according to the code for nominal 19.0 mm (3/4 – in) the percent loss of aggregate should be in the range of 10 to 45%. See Table 11.

Table 11: Los Angeles Abrasion Value

No. of Test	**Original Mass** (Input)	**Final Mass** (Output)	**Percent Loss**
1	4996.2	3315.5	33.65
2	5006.3	3324.7	33.59
3	5003.9	3316.6	33.72
		Average	33.65

3.3 Asphalt

3.3.1 Type

The type of asphalt in this study is 50-70 penetration which is obtained from Highway Department of North Cyprus.

3.3.2 Penetration

According to the ASTM D 5 – 06, Standard Test Method for Penetration of Bituminous Materials, a container of asphalt cement is brought to the standard test temperature, 25 °C in a thermostatically controlled water bath, and then the sample is placed under the standard needle with 100 g weight, which is allowed to penetrate the asphalt cement sample for 5 seconds. At least three determinations at points on the surface of the asphalt sample not less than 10 mm from the side of the container and not less than 10 mm apart are conducted as it is shown in Table 12. Penetration test can be performed at different temperature 0, 4, 45, 46.1 °C, the difference in performance among these temperature is weight of needle and time of penetrating, for example for 4 °C, weight of needle is 200 g and time is 60 seconds and so on. The depth of penetration is measured in units of tenth (0.1) of millimeter and reports as penetration units.

Table 12: Penetration test Result

Sample No.	Reading No.	Initial Reading	Final Reading	Penetration (0.1 mm)
1	1	0	96	96
	2	0	92	92
	3	0	88	88
			Average	92
2	1	0	85	85
	2	0	89	89
	3	0	93	93
			Average	89

3.3.3 Softening Point

According to ASTM D 36 – 06 Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus), the softening point is the temperature at which asphalt can’t support the weight of steel ball and starts flowing. Test is performed by immersing ring–and–ball apparatus in the distilled water (30 to 80 °C), USP glycerin (80 to 157 °C) or ethylene glycol (30 to 110 °C). Steel ball has 9.5 mm (3/8 inch) diameter and 3.50 ± 0.05 g weight. This test was conducted in distilled water and results are brought in table 13.

Table 13: Softening point Test Result

Reading No.	Temperature
1	40.5
2	42.6
3	41.9
Average	41.7

3.3.4 Ductility

The ductility test is conducted according to ASTM D 113 – 07, Standard Test Method for Ductility of Bitumen Materials. Aim of ductility test is to measure the distance asphalt can stretch before breaking. Test is made at a temperature of 25 ± 5 °C and with a speed of 5 cm/min. Test specimen is placed in the water at a specified temperature for 90 ± 5 min to be brought to the test temperature. See Table 14 for results.

Table 14: Ductility Test Result

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

3.4 Polypropylene

3.4.1 Physical Properties

The physical properties of polypropylene fibers used in this study are summarized in Table 15

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	6 mm, 12 mm

3.4.2 Procedure

In this study dry basis approach was selected, in this method first polypropylene and aggregate are mixed together for appropriate time (about 30 sec), and then they are introduced to asphalt. Polypropylene is applied in two length 6 and 12 mm. 6mm polypropylene was added in 0.1, 0.2, 0.3 & 0.5% by weight of total mix. Among these length 0.1, 0.2 & 0.3% were added in 3.5, 4.0, 4.5, 5.0 & 5.5% of asphalt by weight of total mix, and the optimum asphalt was calculated, and 0.5% polypropylene by weight of total mix was only added at optimum percent of asphalt. 12mm polypropylene was added in 0.3 & 0.5% by weight of asphalt and only at the optimum percent of asphalt.

3.5 Mix Design Method

The mix design procedure is according to ASTM D 1559 – 89, Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus. In this study the aggregates are heated to 170 °C and mixed with 3.5, 4.0, 4.5, 5.0, and 5.5% of asphalt by weight of mix, then according to Superpave Mix Design, Superpave Series No. 2 (SP – 2), mixtures are left in the oven at 135 °C for 4 hours for short term aging which simulates the delays that can occur in the actual construction. After short term aging mixtures are placed in another oven to get to the compaction temperature which is 150 – 160 °C no longer than 30 min. the compaction molds and base/top plates are also placed in the same temperature for 45 – 60 minutes before compaction. Because mixtures are supposed to be tested with Marshall Stability the mold with 100 mm (4 inch) diameter is used. In this study the design ESALs is 1 – 3 millions and average design high air temperature is 39 – 40 °C. After 24 h, prepared specimens are brought to the specified temperature at 60 ± 1 °C (140 ± 1.8 °F) by placing in the water bath for 30 to 40 min for test with Marshall Stability.

3.6 Maximum Specific Gravity of Loose Mixture

ASTM D 2041 – 03a, Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Mixtures is used to measure maximum specific gravity of loose bituminous mixture which leads us determining air voids. Test is done by bowls in two situations, under water determination, and in air determination. The weight of sample for the test is specified according to the Nominal Maximum Aggregate Size, which in this study nominal size is ¾ inch (19 mm) and the weight will be 2500 g. The sample is weighted in air, in dry condition and is placed in the bowel with sufficient water at a temperature of approximately 25 °C (77 °F) covers it. For the next step vacuum is applied to the sample gradually until the residual pressure manometer reads 3.7 ± 0.3 kPa (27.5 ± 2.5 mm) of Hg. This required vacuum should be achieved within 2 min and continues for 15 ± 2 min. after requisite time vacuum is released and the sample and container are submerged in the

25 ± 1 °C (77 ± 1.8 °F) water where the lid is also placed there for 10 ± 1 min. At the end weight of sample, bowel, lid and water are designated for two times and shouldn't be difference more than 1.0 g between them. Table 16 shows the maximum specific gravity for 5.0% asphalt binder by weight of mix.

Table 16: Theoretical Maximum Specific Gravity 5% Percent Asphalt

Weight of empty bowel (g)	B	4210
Weight of bowel and sample (g)	C	6747
Weight of sample (g)	A	2537
Weight of bowel and water (g)	D	19138
Weight of bowel 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 this section needed formula and equations are prepared, according to two approaches

- Superpave Mix Design
- Marshall Mix Design

The measurements and calculation for analyzing a compacted paving mixture for Superpave Gyratory Compactor (SGC) are from Superpave Mix Design, Asphalt Institute No. 2 (SP – 2), and for Marshall from (American Society for Testing and Materials, 1989) and (Roberts, F.L., Kandhal, P. S., 1991).

3.7.1 Effective Specific Gravity of Aggregate

Based on a maximum specific gravity of a paving mixture, G_{mm}, which is used for determining percent of air voids in mixture, the effective specific gravity of the aggregate, G_{se}, include all void spaces in the aggregate particle except those that absorb asphalt is calculated as:

$$G_{se} = \frac{P_{mm} - P_b}{\frac{P_{mm}}{G_{mm}} - \frac{P_b}{G_b}} \quad (3.3)$$

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.

Note that because the volume of asphalt absorbed by aggregate is almost invariably less than the volume of absorbed water, the value for G_{se} should always be between bulk and apparent specific gravities, otherwise if the value of G_{se} falls outside these limits, the value must be assumed to be incorrect.

3.7.2 Maximum Specific Gravity of Mixtures with Different Asphalt Contents

In designing a paving mixture with a given aggregate, the maximum specific gravity, G_{mm}, at each asphalt content is needed to calculate the percentage of air voids for each asphalt content and because the effective specific gravity of the aggregate is approximately constant after calculating the effective specific gravity of the aggregate from maximum specific gravity at any amount of asphalt (which is more precisely if this amount is close to the design asphalt content), maximum specific gravity can be calculated for other amount of asphalt from:

$$G_{mm} = \frac{P_{mm}}{\frac{P_s}{G_{se}} + \frac{P_b}{G_b}} \tag{3.4}$$

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

Absorption is expressed as a percentage by mass of aggregate rather than as a percentage by total mass of mixture. Asphalt absorption, P_{ba}, is calculated:

$$P_{ba} = 100 \times \frac{G_{se} - G_{sb}}{G_{se} G_{sb}} \times G_b \quad (3.5)$$

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

The effective asphalt content, P_{be}, of a paving mixture is the total asphalt content minus the amount of asphalt lost by absorption into the aggregate:

$$P_{be} = P_b - \frac{P_{ba}}{100} \times P_s \quad (3.6)$$

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

According to ASTM D 2726 – 08, Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Bituminous Mixtures, for laboratory-prepared thoroughly dry specimens, the mass is determined by weighing the specimen in air at room temperature (A). Then the sample is completely submerged in water bath at 25 ± 1 °C (77 ± 1.8 °F) for 3 to 5 min for determining the mass (C), and at the end the mass of Saturated Surface-Dry is determined in air (A). The bulk specific gravity is:

$$\text{Bulk sp gr} = \frac{A}{B-C} \tag{3.7}$$

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; and

C = mass of the specimen in water, g.

After computing bulk specific gravity, estimated bulk specific gravity, corrected bulk specific gravity, and corrected percentage of maximum theoretical specific gravity is calculated for each desired gyration, as it was mentioned before G_{mb} is for compacted specimen and G_{mm} for loose mixture. G_{mb} is made by dividing the mass of the mixture by the volume of the compaction mold:

$$G_{mb}(estimated) = \frac{W_m/V_{mx}}{\gamma_w} \tag{3.8}$$

Where,

G_{mb}(estimated) = estimated bulk specific gravity of specimen during compaction

W_m = mass of specimen, grams,

γ_w = density of water = 1 g/cm^3

V_{mx} = volume of compaction mold (cm^3), calculated using this equation:

$$V_{mx} = \frac{\pi d^2 h_x}{4} \times 0.001 \text{ cm}^3/\text{mm}^3 \tag{3.9}$$

Where,

d = diameter of mold,

h_x = height of specimen in mold during compaction (mm), The assumption in this equation is that the specimen is a smooth-sided cylinder, which is not. Surface irregularities cause the volume of the specimen to be slightly less than the volume of a smooth-sided cylinder. Because of this fact the final estimated G_{mb} at N_{max} is different from the measured G_{mb} at N_{max} and correction factor is used for estimated G_{mb}:

$$C = \frac{G_{mb}(measured)}{G_{mb}(estimated)} \tag{3.10}$$

Where,

C = correction factor,

G_{mb}(measured) = measured bulk specific gravity after N_{max},

G_{mb}(estimated) = estimated bulk specific gravity at N_{max}.

The estimated G_{mb} at any other gyration level is then determined using:

$$G_{mb}(corrected) = C \times G_{mb}(estimated) \tag{3.11}$$

Where,

G_{mb}(corrected) = corrected bulk specific gravity of the specimen at any gyration,

C = correction factor, and

G_{mb}(estimated) = estimated bulk specific gravity at any gyration.

Percent of G_{mm} is then calculated as the ratio of G_{mb} (corrected) to G_{mm} (measured), at any gyration and then average percent G_{mm} values are calculated.

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

The definition of VMA is, the volume of intergranular void space between the aggregate particles in the compacted mixtures which includes the air voids and volume of the asphalt not absorbed into the aggregates (Roberts, F.L., Kandhal, P. S., 1991, p. 156). In SGC the percent of voids in mineral aggregate is calculated using:

$$\%VMA = 100 - \left(\frac{\%G_{mm}@\,N_{des} \times G_{mm} \times P_S}{G_{sb}}\right) \tag{3.12}$$

Where,

VMA= voids in mineral aggregate, percent of bulk volume

$\%G_{mm}@\,N_{des}$ = maximum theoretical specific gravity @ N_{des},

G_{mm} = maximum theoretical specific gravity,

G_{sb} = bulk specific gravity of total aggregate

P_s = aggregate content, cm^3/cm^3, by total mass of mixture.

In Marshall Mix Design the VMA is calculated as:

$$VMA = 100\left(1 - \frac{G_{mb}(1-P_b)}{G_{sb}}\right) \tag{3.13}$$

Where,

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

G_{sb} = bulk specific gravity of aggregate,

G_{mb} = bulk specific gravity of compacted mixture,

P_b = asphalt content.

3.7.7 Calculating the Percent Air Voids in the Compacted Paving Mixtures (VTM, V_a):

The percentage of air voids at N_{des} is determined from the:

$$V_a = 100 - \%\,G_{mm}\,@\,N_{des} \tag{3.14}$$

Where,

V_a = air voids@ N_{des}, percent of total volume,

$\%\,G_{mm}\,@\,N_{des}$ = maximum theoretical specific gravity@ N_{des}, percent.

In Marshall Mix Design the VTM is calculated as:

$$VTM = \left(1 - \frac{G_{mb}}{G_{mm}}\right)100 \tag{3.15}$$

Where,

VTM = voids in total mix (air voids),

G_{mb} = bulk specific gravity of compacted specimen,

G_{mm} = maximum theoretical specific gravity of mixture.

3.7.7 Calculating the Percent of Voids Filled with Asphalt in the Compacted Mixture

For VFA:

$$VFA = \frac{VMA - VTM}{VMA} \times 100 \qquad (3.16)$$

Where,

VFA= voids filled with asphalt, percent of VMA

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

VTM = air voids in compacted mixture, percent of total volume.

Chapter 4

ANALYSIS AND RESULTS

4.1 Introduction

In this chapter results of two kinds of asphalt specimens which were tested are brought into appropriate tables. Control group (no modification) specimens made of 3.5, 4.0, 4.5, 5.0 & 5.5% of asphalt by weight of mix, each percent of asphalt was made in three samples, and asphalt specimens modified with polypropylene. Two type of polypropylene in length were added to asphalt mixture, 6mm polypropylene in 0.1, 0.2, 0.3& 0.5% by weight of mix, and 12mm polypropylene in 0.3 & 0.5% by weight of mix. Polypropylene with 6mm length (except 0.5% which is only added at optimum percent of asphalt) was added to all percentage of asphalt mixture and 12mm polypropylene was added only at optimum percent of asphalt cement. Different tables are allocated for variant results. First tables are specified for Marshall Analysis which compound of Air Voids, VMA, VFA, Marshall Stability, Flow and Unit Weight and after that, results for Superpave Gyratory Compactor (SGC) is shown in detail.

4.2 Marshall Analysis

This section is about Marshall Analysis on compacted specimens. In Table 17 to Table 20 four groups of asphalt combinations were tested for 3.5, 4.0, 4.5, 5.0 and 5.5% of asphalt by weight of total mix. In Table 17 information for control group mixture (no polypropylene was used), are shown, for control group with increasing asphalt Flow was also increased, 3.99 mm was the best value for Flow, the best Stability is for 4.0% asphalt cement by weight of mix which is 1676 kg. Like Flow, VFA also increased with increasing percent of asphalt unlike air void, which was decreased with increasing percentage of asphalt, VMA was decreased, up to 5.0% asphalt then increase at 5.5% percent asphalt.

Table 18, 19 and 20 show data for 0.1%, 0.2% and 0.3% of 6 mm long polypropylene, as it can be seen with increasing percentage of polypropylene air void increase in noticeable amount like Marshall Stability, VMA is also increased, VFA and unit weight are decreased. Flow is decreased in noticeable amount. Except 0.1% PP, which in this percent Marshall Stability, Air Voids and VMA are decreased and VFA is increased, but Flow and Unit Weight played like the other percents of PP.

Table 21 is about 0.5% by weight of total mix of 6mm long polypropylene and two different percentages (0.3% and 0.5%) of 12mm long polypropylene added only to the optimum percentage (4.20%) of the asphalt mixture. As it can be seen for 0.5% of 6 mm PP, Marshall Stability increased to 1780 Kg (14.1% increase), flow with 26.4% reduction was dropped to 3.9 mm, air void jumped to 5.9% and VMA to 14.95%, VFA and unit weight fell off to 61% and 2432 Kg/m^3.

For 0.3% and 0.5% of 12 mm polypropylene Marshall Stability was increased to 1902 Kg (22.0% increase) and 1971 Kg (26.3% increase), flow reduced to 3.8 (28.3% reduction) and 3.3 (37.7% reduction). Air void jumped to 5.1% (27.5% increase) and 6.7% (67.5% increase), VMA was increased to 14.27% (8.1% increase) and 15.74% (19.2% increase), VFA was decreased to 64% (8.6% decrease) and 57% (18.6% decrease) and unit weight was decreased to 2451 Kg/m^3 (0.9% reduction) and 2413 Kg/m^3 (2.4% reduction) respectively.

Table 17: Marshall Test Results (Control Group (No Modification))

			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	3.5	64.21	1229.4	731.6	1231.3	499.7	2.460		2437.8	6.71	14.05	52.24	1670	1579	3.07
2	3.5	64.63	1232.9	734.8	1233.8	499.0	2.471		2428.9	6.29	13.67	53.99	1679	1578	5.13
3	3.5	64.39	1236.9	738.0	1238.2	500.2	2.473		2445.8	6.22	13.60	54.26	1724	1629	3.78
	Average						**2.468**	**2.637**	**2437.5**	**6.41**	**13.77**	**53.50**		**1595**	**3.99**
1	4.0	64.38	1242.0	744.5	1243.4	498.9	2.489		2456.3	4.85	13.49	64.05	1774	1702	4.99
2	4.0	64.24	1242.9	744.6	1244.1	499.5	2.488		2463.4	4.89	13.52	63.83	1745	1658	5.60
3	4.0	64.50	1242.1	744.5	1243.3	498.8	2.490		2451.9	4.82	13.45	64.16	1755	1668	5.18
	Average						**2.489**	**2.616**	**2457.2**	**4.85**	**13.49**	**64.01**		**1676**	**5.26**
1	4.5	63.85	1252.1	753.2	1252.8	496.6	2.521		2496.8	2.89	12.83	77.47	1487	1443	4.39
2	4.5	64.11	1249.8	752.0	1250.4	498.4	2.507		2482.1	3.43	13.32	74.25	1526	1450	6.10
3	4.5	64.08	1249.2	752.6	1250.2	497.6	2.511		2482.1	3.27	13.18	75.42	1541	1464	5.60
	Average						**2.513**	**2.596**	**2487.0**	**3.20**	**13.11**	**75.71**		**1453**	**5.36**
1	5.0	64.31	1261.0	763.1	1261.5	498.4	2.530		2496.6	1.79	12.98	86.21	1335	1268	7.04
2	5.0	64.45	1256.1	758.8	1256.6	497.8	2.524		2481.5	2.02	13.19	84.68	1270	1206	5.55
3	5.0	63.65	1254.4	759.6	1254.9	495.3	2.533		2509.3	1.67	12.88	87.03	1310	1284	5.27
	Average						**2.529**	**2.576**	**2495.8**	**1.83**	**13.02**	**85.97**		**1253**	**5.95**
1	5.5	64.12	1252.7	756.2	1253.1	496.9	2.521		2487.5	1.33	13.74	90.32	1000	960	5.54
2	5.5	64.58	1261.3	761.0	1261.8	500.8	2.518		2486.7	1.45	13.85	89.53	1047	990	7.78
3	5.5	64.54	1262.3	761.8	1263.1	501.3	2.518		2490.3	1.45	13.85	89.53	1066	1008	6.35
	Average						**2.519**	**2.555**	**2488.2**	**1.41**	**13.81**	**89.79**		**986**	**6.56**

Table 18: Marshall Test Results (0.1% Polypropylene-6mm)

			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	3.5	64.63	1228.6	727.9	1229.5	501.6	2.449		2420.4	7.13	14.43	50.59	1632	1542	3.19
2	3.5	65.57	1235.8	732.4	1236.7	504.3	2.451		2399.7	7.05	14.37	50.94	1593	1497	3.82
3	3.5	65.47	1237.7	733.9	1238.8	504.9	2.451		2407.1	7.05	14.37	50.94	1612	1516	3.27
	Average						**2.450**	**2.637**	**2409.1**	**7.08**	**14.39**	**50.82**		**1519**	**3.86**
1	4.0	64.35	1240.9	745.9	1242.9	497.0	2.497		2455.5	4.55	13.21	65.56	1702	1617	4.13
2	4.0	64.38	1244.8	748.2	1246.7	498.5	2.497		2461.8	4.55	13.21	65.56	1665	1584	4.09
3	4.0	64.29	1243.3	747.1	1244.4	497.3	2.500		2462.3	4.43	13.11	66.21	1608	1554	4.12
	Average						**2.498**	**2.616**	**2459.9**	**4.51**	**13.18**	**65.78**		**1585**	**4.11**
1	4.5	63.98	1251.4	758.2	1252.3	494.1	2.533		2490.4	2.43	12.42	80.43	1633	1568	5.22
2	4.5	63.70	1241.3	747.4	1242.0	494.6	2.510		2481.1	3.31	13.21	74.94	1559	1528	4.06
3	4.5	64.43	1248.1	753.1	1248.6	495.5	2.519		2466.4	2.97	12.90	76.98	1537	1446	5.15
	Average						**2.521**	**2.596**	**2479.3**	**2.90**	**12.84**	**77.45**		**1514**	**4.81**
1	5.0	64.13	1257.7	757.0	1258.5	501.5	2.508		2497.0	2.64	13.74	80.79	1264	1201	5.50
2	5.0	63.41	1246.1	752.9	1246.6	493.7	2.524		2502.1	2.02	13.19	84.68	1258	1271	5.13
3	5.0	64.46	1253.9	755.9	1254.3	498.4	2.516		2476.7	2.33	13.46	82.69	1278	1208	4.60
	Average						**2.516**	**2.576**	**2491.9**	**2.33**	**13.46**	**82.72**		**1227**	**5.07**
1	5.5	64.76	1265.8	761.8	1266.2	504.4	2.510		2488.7	1.76	14.12	87.53	1052	994	5.39
2	5.5	64.36	1258.1	757.7	1258.6	500.9	2.512		2488.9	1.68	14.05	88.04	1109	1054	5.58
3	5.5	64.60	1260.8	755.9	1261.4	505.5	2.494		2485.0	2.39	14.67	83.71	1117	1061	5.63
	Average						**2.505**	2.555	**2487.5**	**1.94**	**14.28**	**86.43**		**1036**	**5.53**

Table 19: Marshall Test Results (0.2% Polypropylene-6mm)

			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	3.5	65.70	1241.5	733.9	1243.5	509.6	2.436		2405.9	7.62	14.89	48.82	1745	1588	3.92
2	3.5	65.44	1229.5	723.9	1230.9	507.0	2.425		2399.2	8.04	15.27	47.35	1756	1598	3.67
3	3.5	65.99	1235.8	728.5	1237.5	509.0	2.429		2384.4	7.89	15.13	47.85	1767	1608	3.89
	Average						**2.430**	**2.637**	**2396.2**	**7.85**	**15.10**	**48.01**		**1598**	**3.83**
1	4.0	64.78	1247.8	745.9	1249.5	503.6	2.478		2452.5	5.27	13.87	62.00	1875	1762	4.82
2	4.0	64.35	1238.3	740.9	1239.9	499.0	2.481		2450.1	5.16	13.77	62.53	1866	1773	3.00
3	4.0	64.87	1243.2	743.7	1244.3	500.6	2.483		2440.1	5.08	13.70	62.92	1833	1733	4.35
	Average						**2.481**	**2.616**	**2447.6**	**5.17**	**13.78**	**62.48**		**1756**	**4.06**
1	4.5	64.92	1252.8	754.5	1253.8	499.3	2.509		2457.1	3.35	13.25	74.72	1630	1532	4.45
2	4.5	64.25	1248.2	750.8	1248.9	498.1	2.506		2473.6	3.47	13.35	74.01	1601	1521	4.46
3	4.5	64.37	1248.9	750.2	1250.3	500.1	2.500		2470.3	3.70	13.56	72.71	1599	1519	5.57
	Average						**2.505**	**2.596**	**2467.0**	**3.51**	**13.39**	**73.81**		**1522**	**4.83**
1	5.0	65.08	1260.2	759.7	1261.2	501.5	2.513		2465.5	2.45	13.56	81.93	1393	1296	5.59
2	5.0	65.25	1259.9	759.0	1260.9	501.9	2.510		2458.7	2.56	13.67	81.27	1409	1311	5.41
3	5.0	64.83	1257.5	760.5	1260.2	499.7	2.516		2469.7	2.33	13.46	82.69	1424	1346	3.85
	Average						**2.513**	**2.576**	**2464.6**	**2.45**	**13.56**	**81.96**		**1318**	**4.95**
1	5.5	65.82	1260.9	755.9	1261.7	505.8	2.493		2440.6	2.43	14.70	83.47	1060	965	4.68
2	5.5	65.65	1262.3	762.7	1262.9	500.2	2.523		2449.3	1.25	13.68	90.86	1139	1036	5.12
3	5.5	65.11	1266.2	760.2	1266.9	506.7	2.499		2476.1	2.19	14.50	84.90	1116	1038	5.82
	Average						**2.505**	**2.555**	**2455.3**	**1.96**	**14.29**	**86.41**		**1014**	**5.21**

Table 20: Marshall Test Results (0.3% Polypropylene-6mm)

			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	3.5	65.74	1239.8	732.6	1241.6	509.0	2.436		2401.2	7.62	14.89	48.82	1817	1663	3.06
2	3.5	65.22	1239.8	733.8	1240.5	506.7	2.447		2420.4	7.20	14.51	50.38	1702	1566	4.27
3	3.5	65.49	1242.6	735.1	1243.7	508.6	2.443		2415.8	7.36	14.64	49.73	1743	1604	3.55
	Average						**2.442**	**2.637**	**2412.5**	**7.39**	**14.68**	**49.64**		**1612**	**3.63**
1	4.0	65.63	1247.5	743.6	1249.3	505.7	2.467		2420.2	5.69	14.25	60.07	2014	1864	4.02
2	4.0	65.45	1246.4	740.5	1247.7	507.2	2.457		2424.7	6.08	14.60	58.36	1985	1836	4.11
3	4.0	65.41	1250.2	742.6	1251.3	508.7	2.458		2433.6	6.04	14.57	58.54	2022	1871	4.08
	Average						**2.461**	**2.616**	**2426.2**	**5.96**	**14.47**	**58.99**		**1857**	**4.07**
1	4.5	65.04	1251.7	748.1	1253.1	505.0	2.479		2450.3	4.51	14.28	68.42	1708	1605	4.82
2	4.5	64.80	1251.0	747.7	1252.2	504.5	2.480		2458.1	4.47	14.29	68.72	1735	1648	4.23
3	4.5	64.71	1254.3	749.1	1255.2	506.1	2.478		2468.0	4.54	14.25	68.14	1678	1594	4.47
	Average						**2.479**	**2.596**	**2458.8**	**4.51**	**14.27**	**68.43**		**1616**	**4.50**
1	5.0	65.31	1263.1	758.3	1264.1	505.8	2.497		2462.5	3.07	14.11	78.24	1587	1476	4.43
2	5.0	65.31	1260.8	754.8	1261.5	506.7	2.488		2458.0	3.42	14.42	76.28	1496	1391	5.05
3	5.0	64.92	1260.4	753.7	1260.9	507.2	2.485		2471.9	3.53	14.53	75.70	1604	1508	5.38
	Average						**2.490**	**2.576**	**2464.1**	**3.34**	**14.35**	**76.74**		**1459**	**4.95**
1	5.5	65.46	1262.0	757.0	1262.8	505.8	2.495		2454.7	2.35	14.63	83.94	1166	1072	4.83
2	5.5	65.46	1264.1	758.0	1264.8	506.8	2.495		2458.7	2.39	14.67	83.71	1246	1146	5.32
3	5.5	65.68	1265.6	758.2	1266.3	508.1	2.491		2453.4	2.50	14.77	83.07	1186	1085	5.24
	Average						**2.493**	**2.555**	**2455.6**	**2.41**	**14.69**	**83.57**		**1102**	**5.13**

Table 21: Marshall Test Results (4.20% (Optimum) 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)
0.5% PP 6mm															
1	4.20	65.39	1251.2	744.3	1253.2	508.9	2.459		2436.3	5.64	14.75	61.76	1946	1790	4.50
2	4.20	65.37	1253.1	745.5	1255.1	509.6	2.459		2440.7	5.64	14.75	61.76	1914	1761	3.74
3	4.20	65.89	1251.2	740.1	1252.5	512.4	2.442		2417.8	6.29	15.34	59.00	1943	1788	3.48
						Average	**2.453**	**2.606**	**2431.6**	**5.86**	**14.95**	**60.84**		**1780**	**3.91**
0.5% PP 12mm															
1	4.20	66.61	1257.5	742.6	1258.8	516.2	2.436		2403.7	6.52	15.55	58.07	2188	1980	3.47
2	4.20	66.06	1254.9	739.7	1256.0	516.3	2.430		2418.7	6.75	15.76	57.17	2151	1957	3.19
3	4.20	66.09	1253.8	738.9	1255.7	516.8	2.426		2415.5	6.91	15.90	56.54	2171	1976	3.37
						Average	**2.431**	**2.606**	**2412.6**	**6.73**	**15.74**	**57.26**		**1971**	**3.34**
0.3% PP 12mm															
1	4.20	64.93	1250.6	746.1	1252.0	505.9	2.472		2452.3	5.14	14.30	64.05	2045	1913	3.86
2	4.20	64.96	1252.0	747.1	1253.7	506.6	2.471		2454.0	5.18	14.34	63.88	2016	1886	3.62
3	4.20	65.19	1253.1	749.5	1255.6	506.1	2.476		2447.4	5.00	14.16	64.69	2049	1905	3.95
						Average	**2.473**	**2.606**	**2451.2**	**5.11**	**14.27**	**64.21**		**1902**	**3.81**

Figure 31 is about control group specimens without polypropylene, the optimum percent of asphalt is 4.20% by the weight of total mix for 4.0% air void, Marshall Stability at optimum asphalt is 1560 kg and Flow, VMA, VFA and Unit Weight are, 5.3 mm, 13.2%, 70% and 2473 Kg/m^3 respectively.

Figure 32 indicates results for specimens with 0.1% of 6 mm long polypropylene additive by weight of total mix. Marshall Stability at 4.20% asphalt is 1540 kg and Flow 4.4mm, as it can be seen 0.1% PP decrease the Stability for about 1.3% but increase in flow is observed for about 17%, in this percent of PP. Air void was decreased to 3.8% (5.0% reduction), VMA to 13.0% (1.5% reduction) and unit weight to 2468 Kg/m^3 (0.2% reduction), VFA was increased to 71% (1.4% increase).

Figure 33 shows the data for 0.2% of 6 mm long polypropylene by weight of total mix, in this percent of polypropylene Marshall Stability jumps up to 1640 Kg which improved Stability for about 5.1%, Flow is 4.4 mm (it didn't change in compare with 0.1% PP). Air void was increased for 10% and changed to 4.4%, VMA increased to 13.6% (3.0% increases). VFA decreased for 2.9% and dropped to 68% and finally unit weight which is decreased for about 0.7% and became 2456 Kg/m^3.

Figure 34 shows 12.2% increase for 0.3% of 6 mm long polypropylene by weight of total mix in Marshall Stability, the value was increased it to 1750Kg, flow decreased to 4.3 mm and showed about 19% reduction, air void and VMA were increased to 5.3% (32.5% increase) and 14.32% (8.5% increase) respectively, and VFA and unit weight were decreased to 63% and 2444 Kg/m^3 (10% and 1.2% reduction respectively).These information are illustrated in Figure 35 to 40 in graphical form, data for 0.5% of 6 mm long and 0.3, 0.5% of 12 mm long polypropylene were taken directly from Table 21.

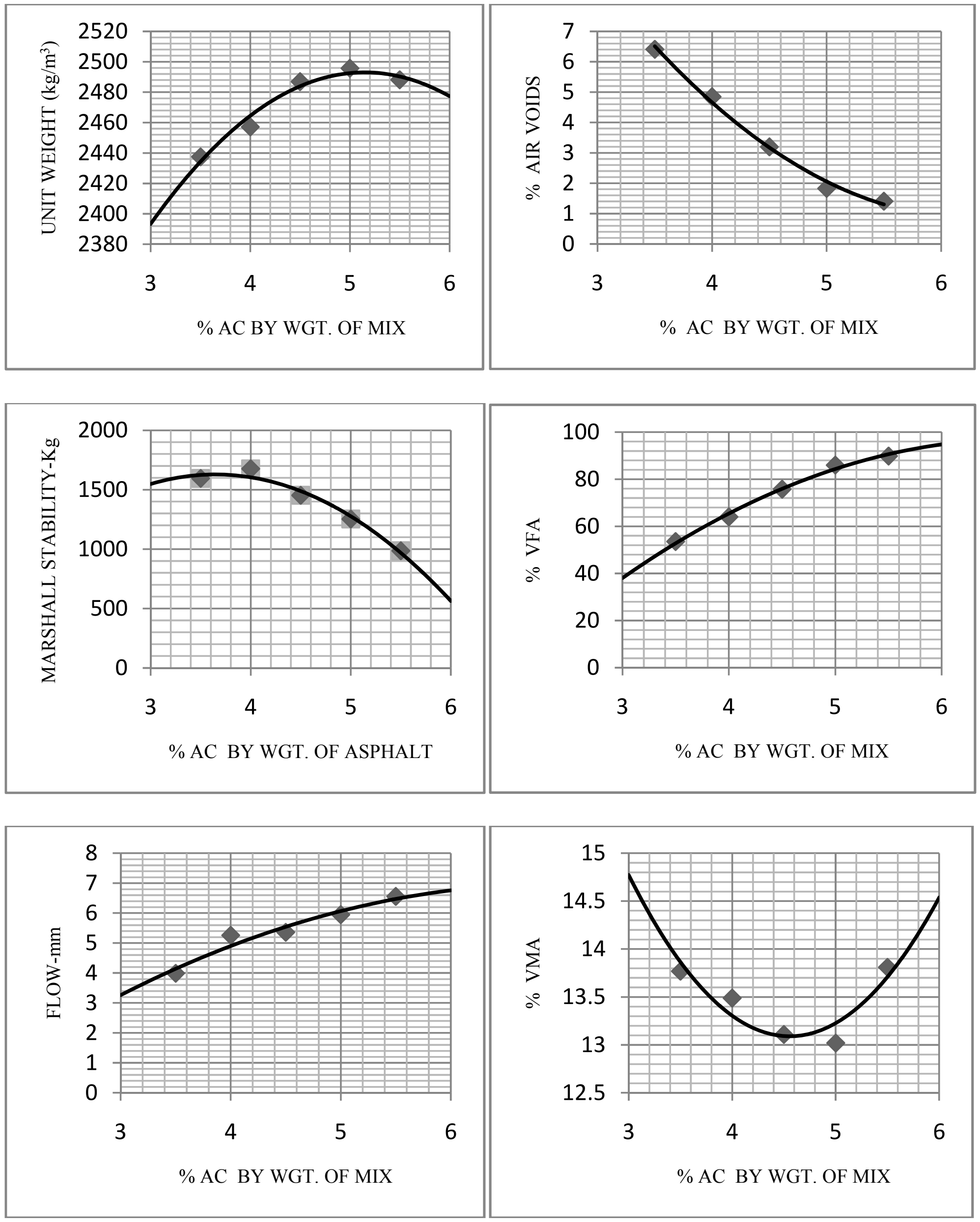

Figure 31: Graphical Illustration of HMA Design data by Marshall Method (Control Group)

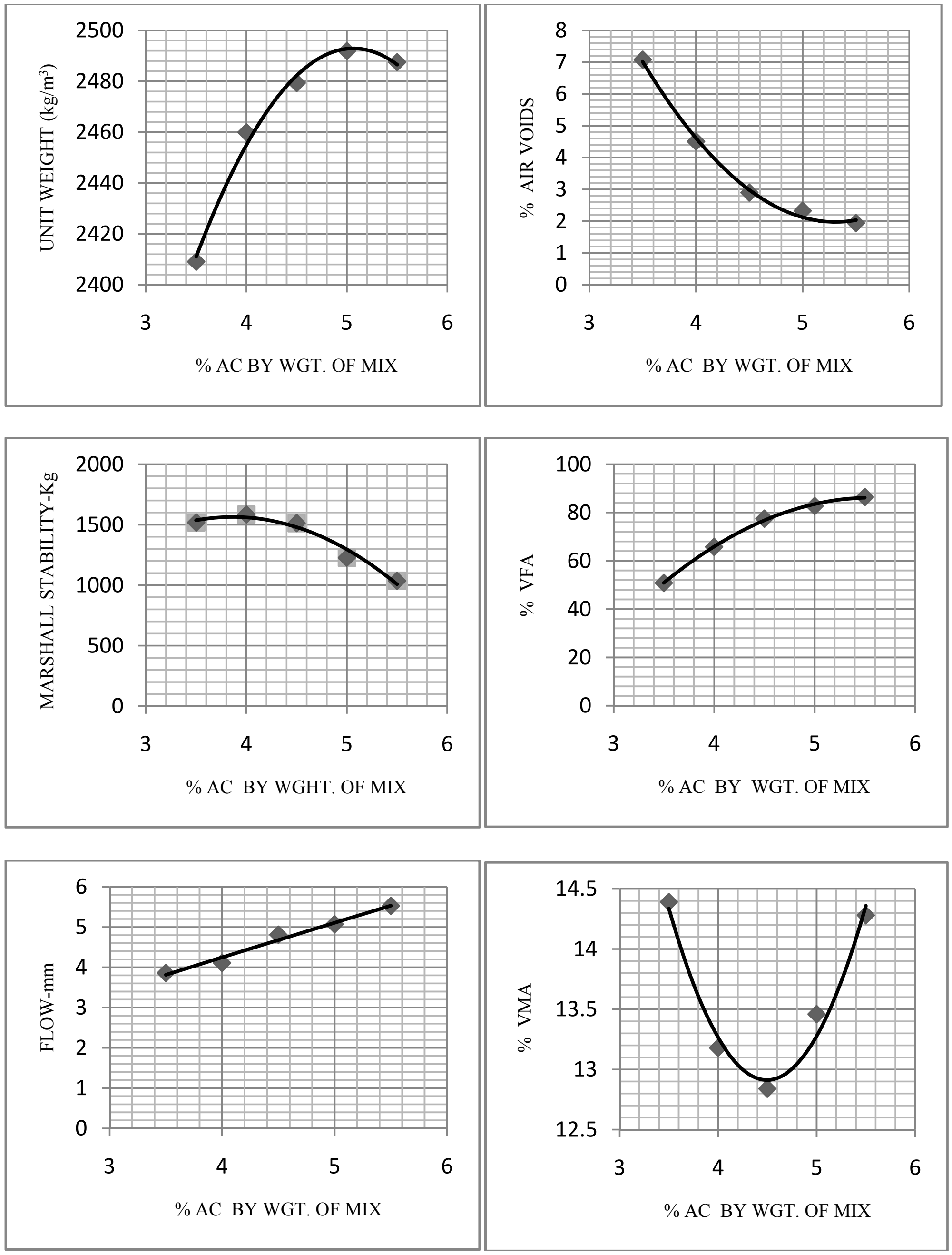

Figure 32: Graphical Illustration of HMA Design data by Marshall Method (0.1% Polypropylene-6mm)

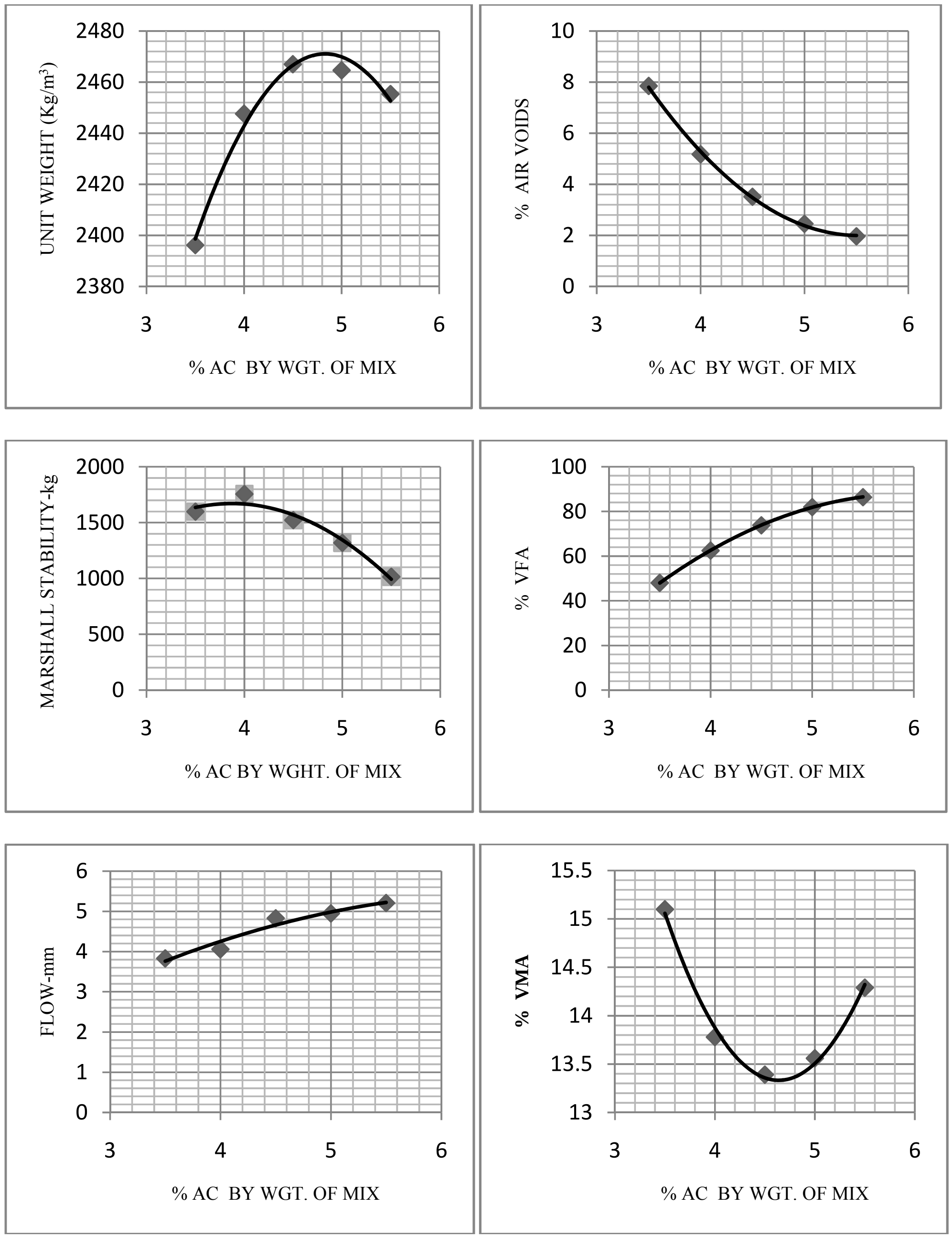

Figure 33: Graphical Illustration of HMA Design data by Marshall Method (0.2% Polypropylene-6mm)

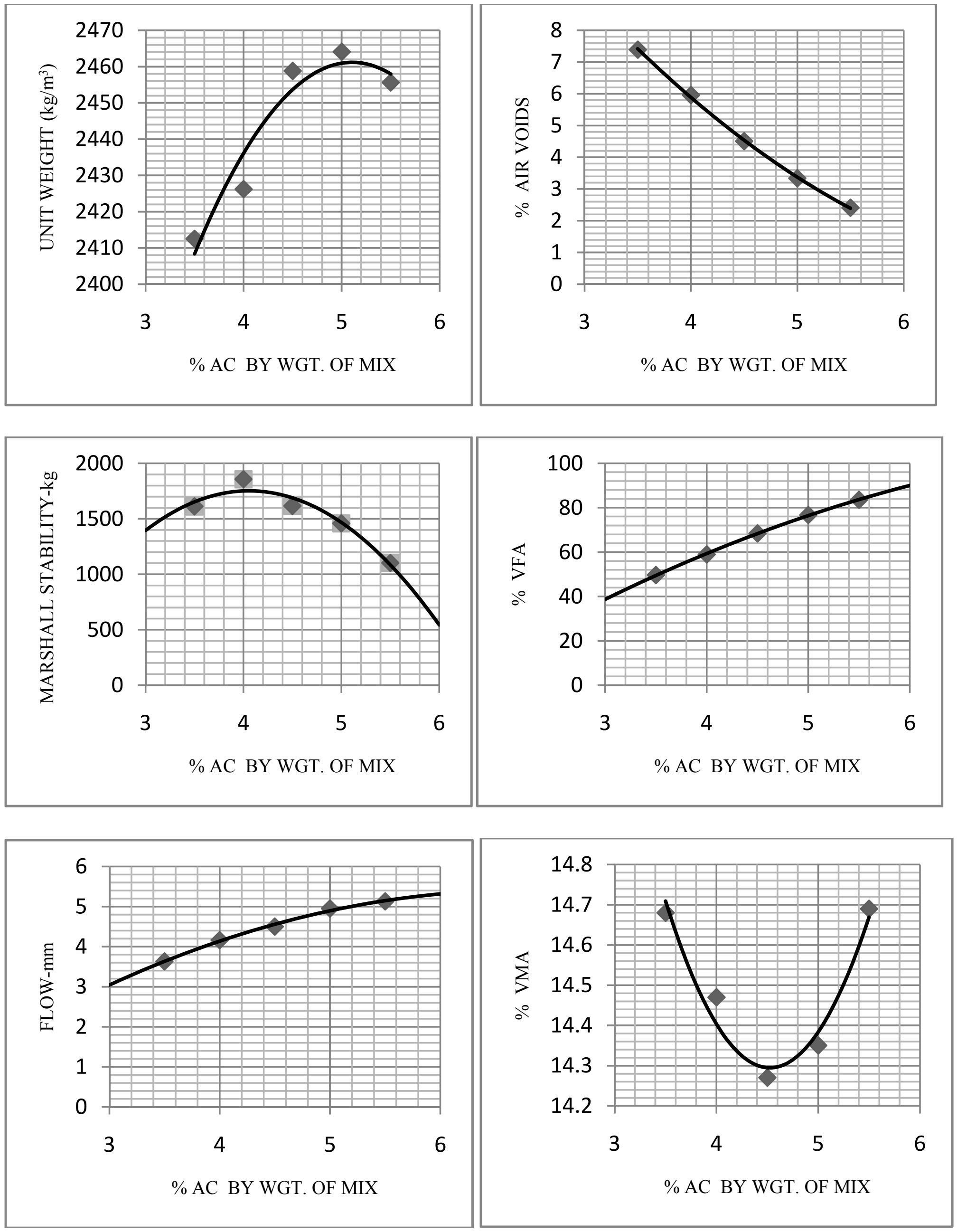

Figure 34: Graphical Illustration of HMA Design data by Marshall Method (0.3% Polypropylene-6mm)

As it can be seen in Figure 35 by increasing percentage of polypropylene Marshall Stability goes high (except 0.1% of 6 mm long) and also providing higher stability with longer polypropylene is observed. Flow is also developed (got lower) by adding higher percentage of polypropylene in percentage and length (Figure 36). Percent of air void increases like stability as polypropylene is increased in percentage and length but with two exceptions, 0.1% of 6 mm long and 0.3% of 12mm long (Figure 37). VMA also deals with increasing polypropylene as air void does (Figure 38). Applying more polypropylene causes decreasing VFA (with the same exceptions at 0.1% of 6 mm long and 0.3% of 12 mm long as it is shown in Figure 39) and finally unit weight which is decreased by increasing polypropylene, with one exception at 0.3% of 12 mm long (Figure 40).

After reviewing results author's opinion is 0.3% of 12 mm polypropylene is better than the rest of percentages and lengths, because at the higher percentage, air void is increased to a high percent (6.7%), which in this value, amount of optimum asphalt will become disadvantage.

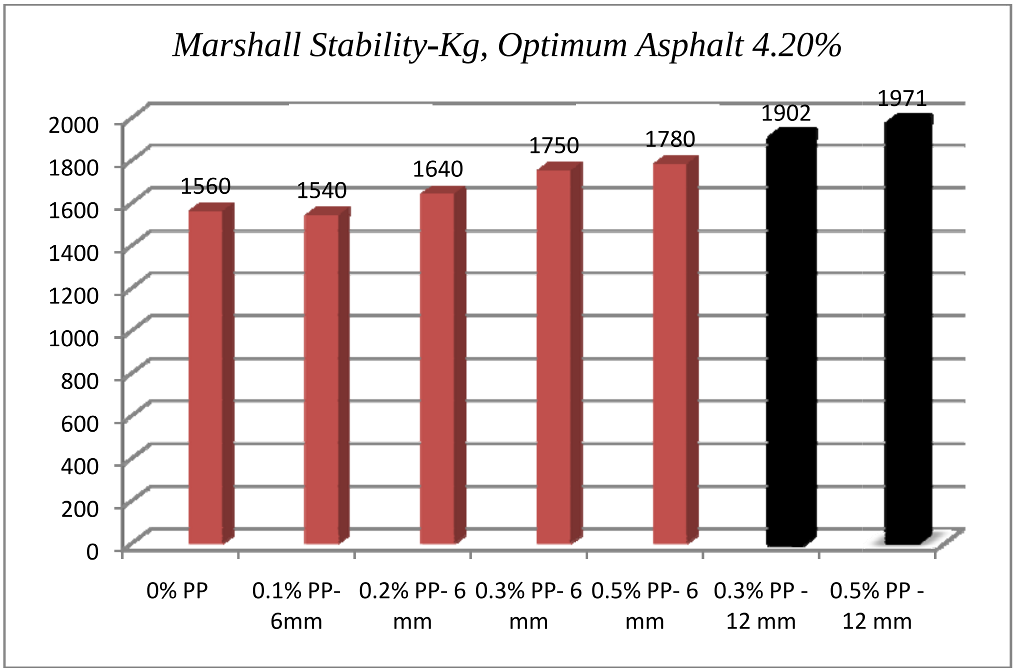

Figure 35: Marshall Stability Results at Optimum Asphalt Content

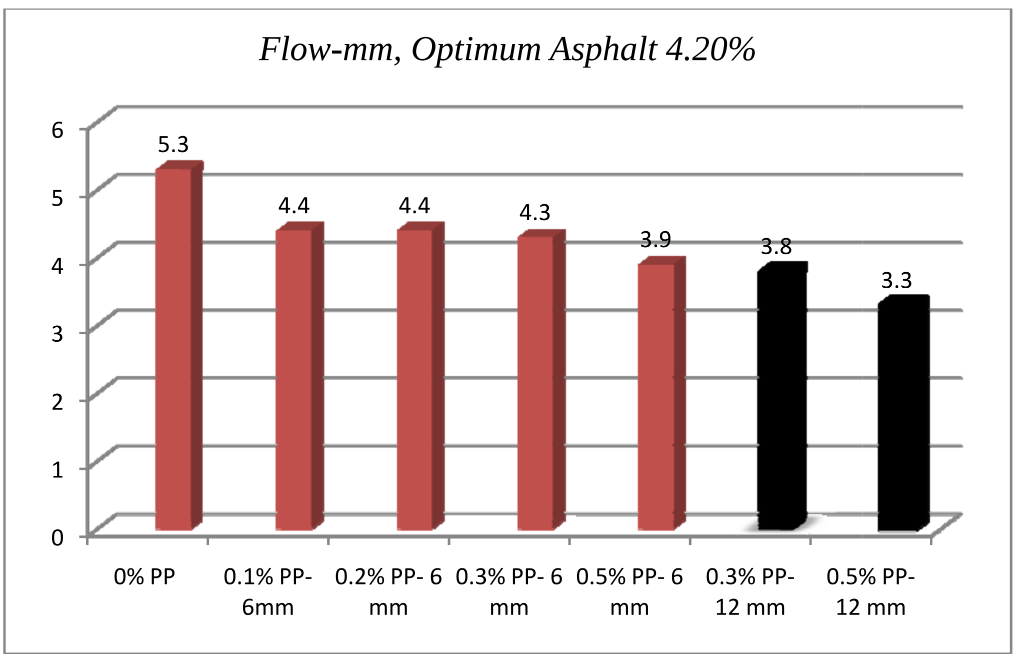

Figure 36: Flow Result at Optimum Asphalt Content

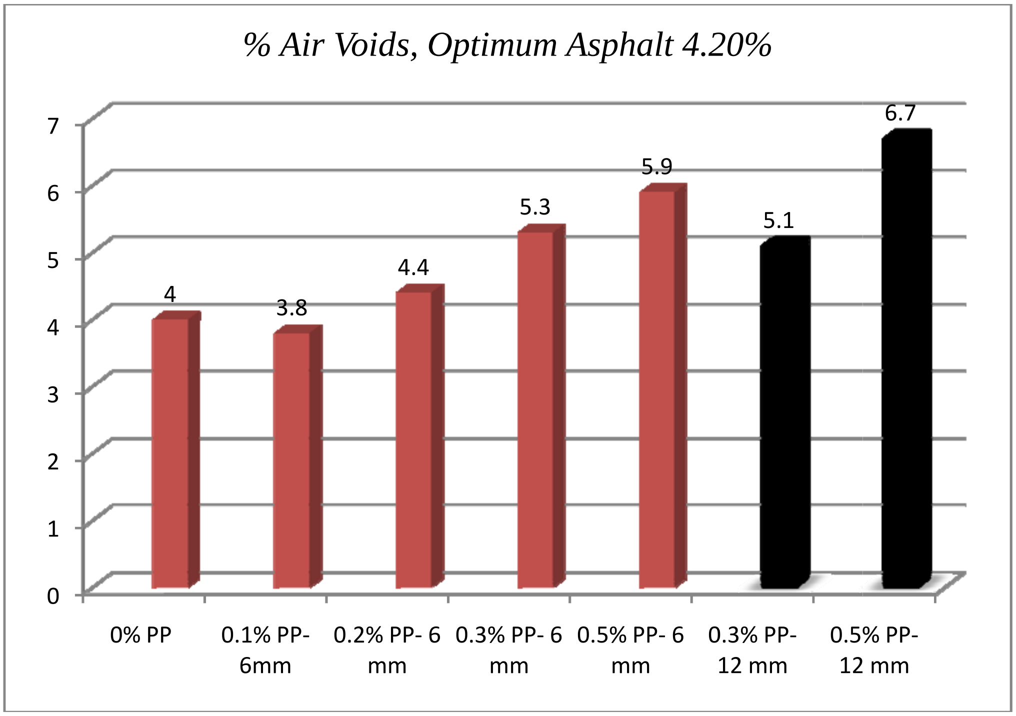

Figure 37: Air Voids Results at Optimum Asphalt Content

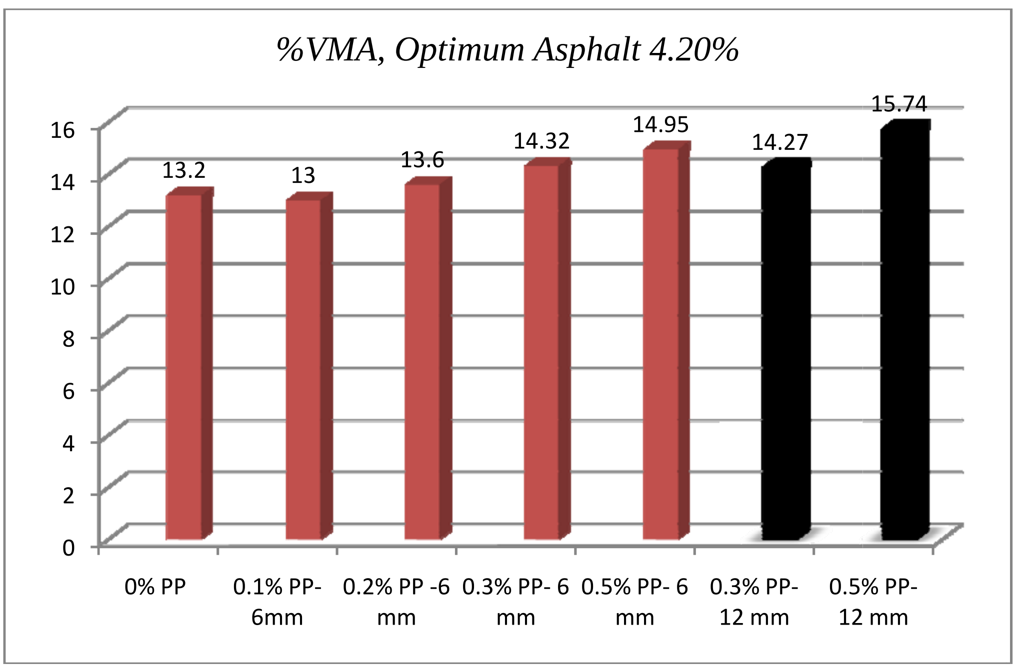

Figure 38: VMA Result at Optimum Asphalt Content

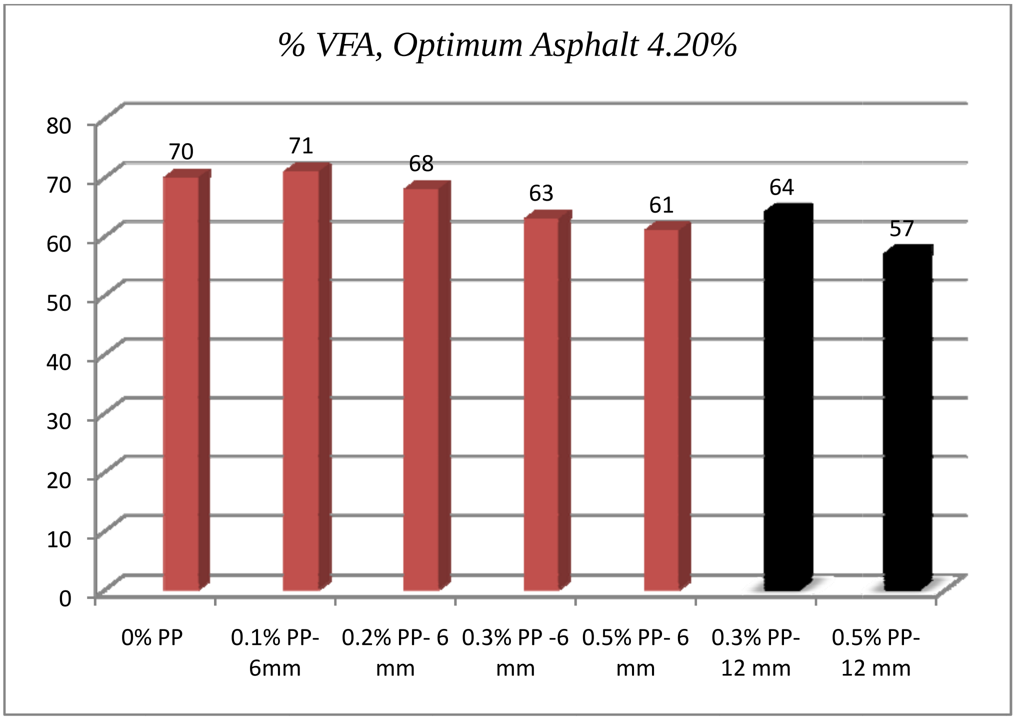

Figure 39: VFA Result at Optimum Asphalt Content

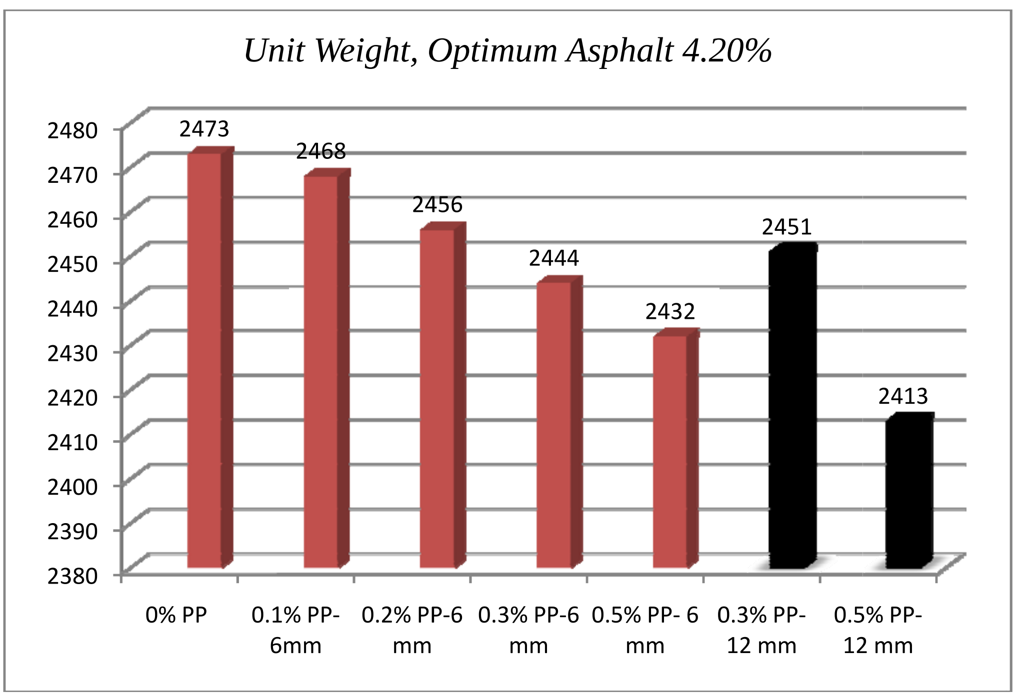

Figure 40: Unit Weight Result at Optimum Asphalt Content

4.3 Superpave Analysis

This section is about analysis on compacted mixture based on Superpave Analysis, divided into three parts, densification data, percentage of air void and detailed data (%G_{mm}, VMA, etc.) about asphalt specimens.

Table 22 and 23show densification data of Superpave Gyratory Compactor, first table is about control group specimens with 3.5% asphalt by weight of total mix, as it can be seen %G_{mm} increased with increasing number of gyration which shows reduction of air void. Second table is the same data for 0.1% of 6 mm polypropylene, in these tables %G_{mm} is the most important variable for us because at next step with this factor percent of air void will become calculated. These two tables are brought as an example the rest of the tables are in APPENDIX A.

Table 24 and 25show average air void in different gyrations, gyration #8, #95 and #150 are important, because these are N_{ini}, N_{des} and N_{max} for North Cyprus traffic and temperature. The important point in these gyrations is:

First, for N_{ini}, the maximum allowable mixture density should be 89 percent, which means percent of air void in N_{ini} must be at least 11.0%,

Second, for N_{des}, all the calculations (percent of Air Voids, %VMA, %VFA, etc.) are calculated by percent of G_{mm} in this gyration, and

Third, for N_{max}, the maximum allowable mixture density should be 98 percent, which means percent of air void in N_{max} must be at least 2.0%. These conditions are important for optimum percent of asphalt. The rest of the tables are in APPENDIX A.

Figure 41 to 44 shows graphical illustration of %G_{mm} at N_{ini}, %G_{mm} at N_{des}, %G_{mm} at N_{max}, percent of Air Voids, %VMA, %VFA for conventional asphalt (no polypropylene), 0.1, 0.2 and 0.3% of 6 mm long polypropylene.

Table 22: Gyratory Compactor Test Results (3.5% Asphalt, No Polypropylene)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.14	2.056	2.222	84.2	76.6	2.049	2.221	84.2	75.33	2.077	2.231	84.6	84.3
8	74.8	2.093	2.261	85.8	75.27	2.086	2.260	85.7	74.03	2.114	2.270	86.1	85.9
10	74.22	2.109	2.279	86.4	74.68	2.102	2.278	86.4	73.46	2.130	2.288	86.8	86.5
20	72.54	2.158	2.332	88.4	72.89	2.154	2.334	88.5	71.79	2.180	2.341	88.8	88.6
30	71.62	2.186	2.362	89.6	71.89	2.184	2.367	89.7	70.88	2.208	2.371	89.9	89.7
40	71.00	2.205	2.382	90.3	71.26	2.203	2.387	90.5	70.28	2.227	2.391	90.7	90.5
50	70.55	2.219	2.398	90.9	70.77	2.218	2.404	91.2	69.84	2.241	2.406	91.3	91.1
60	70.2	2.230	2.410	91.4	70.44	2.229	2.415	91.6	69.46	2.253	2.420	91.8	91.6
80	69.72	2.245	2.426	92.0	69.89	2.246	2.434	92.3	68.98	2.268	2.436	92.4	92.2
95	69.44	2.254	2.436	92.4	69.55	2.257	2.446	92.8	68.7	2.278	2.446	92.8	92.7
100	69.36	2.257	2.439	92.5	69.45	2.260	2.450	92.9	68.59	2.281	2.450	92.9	92.8
125	69.00	2.269	2.451	93.0	69.12	2.271	2.461	93.3	68.26	2.292	2.462	93.4	93.2
150	68.76	2.276	2.460	93.3	68.85	2.280	2.471	93.7	67.96	2.303	2.473	93.8	93.6

	Specimen 1	Specimen 2	Specimen 3
	C = 1.081	C = 1.084	C = 1.074
	Gmb = 2.460	Gmb = 2.471	Gmb = 2.473
	Gmm = 2.637	Gmm = 2.637	Gmm = 2.637

Table 23: Gyratory Compactor Test Results (3.5% Asphalt, 0.1% Polypropylene-6mm)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.29	2.050	2.217	84.1	77.79	2.023	2.205	83.6	77.97	2.023	2.199	83.4	83.7
8	75.04	2.085	2.254	85.5	76.43	2.059	2.244	85.1	76.61	2.059	2.238	84.9	85.2
10	74.5	2.100	2.270	86.1	75.81	2.076	2.263	85.8	75.96	2.076	2.257	85.6	85.8
20	72.84	2.148	2.322	88.1	73.96	2.127	2.319	87.9	74.09	2.129	2.314	87.8	87.9
30	71.95	2.174	2.351	89.1	72.99	2.156	2.350	89.1	73.13	2.157	2.345	88.9	89.0
40	71.35	2.192	2.370	89.9	72.35	2.175	2.371	89.9	72.46	2.177	2.366	89.7	89.8
50	70.91	2.206	2.385	90.4	71.87	2.189	2.387	90.5	71.99	2.191	2.382	90.3	90.4
60	70.58	2.216	2.396	90.9	71.52	2.200	2.398	90.9	71.59	2.203	2.395	90.8	90.9
80	70.07	2.232	2.414	91.5	70.97	2.217	2.417	91.6	71.04	2.220	2.414	91.5	91.5
95	69.77	2.242	2.424	91.9	70.68	2.226	2.427	92.0	70.73	2.230	2.424	91.9	91.9
100	69.68	2.245	2.427	92.0	70.6	2.229	2.429	92.1	70.62	2.233	2.428	92.1	92.1
125	69.31	2.257	2.440	92.5	70.22	2.241	2.443	92.6	70.27	2.245	2.440	92.5	92.5
150	69.06	2.265	2.449	92.9	69.98	2.248	2.451	92.9	69.96	2.255	2.451	92.9	92.9

Specimen 1	Specimen 2	Specimen 3
C = 1.081	C = 1.090	C = 1.087
Gmb = 2.449	Gmb = 2.451	Gmb = 2.451
Gmm = 2.637	Gmm = 2.637	Gmm = 2.63

Table 24: Calculation of Air Voids by SGC (3.5% Asphalt, No Polypropylene)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	84.2	15.8	84.2	15.8	84.6	15.4	84.3	15.7
8	85.8	14.2	85.7	14.3	86.1	13.9	85.9	14.1
10	86.4	13.6	86.4	13.6	86.8	13.2	86.5	13.5
20	88.4	11.6	88.5	11.5	88.8	11.2	88.6	11.4
30	89.6	10.4	89.7	10.3	89.9	10.1	89.7	10.3
40	90.3	9.7	90.5	9.5	90.7	9.3	90.5	9.5
50	90.9	9.1	91.2	8.8	91.3	8.7	91.1	8.9
60	91.4	8.6	91.6	8.4	91.8	8.3	91.6	8.4
80	92.0	8.0	92.3	7.7	92.4	7.6	92.2	7.8
95	92.4	7.6	92.8	7.2	92.8	7.2	92.7	7.3
100	92.5	7.5	92.9	7.1	92.9	7.1	92.8	7.2
125	93.0	7.0	93.3	6.7	93.4	6.6	93.2	6.8
150	93.3	6.7	93.7	6.3	93.8	6.2	93.6	6.4

Table 25: Calculation of Air Voids by SGC (3.5% Asphalt, 0.1% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	84.1	15.9	83.6	16.4	83.4	16.6	83.7	16.3
8	85.5	14.5	85.1	14.9	84.9	15.1	85.2	14.8
10	86.1	13.9	85.8	14.2	85.6	14.4	85.8	14.2
20	88.1	11.9	87.9	12.1	87.8	12.2	87.9	12.1
30	89.1	10.9	89.1	10.9	88.9	11.1	89.0	11.0
40	89.9	10.1	89.9	10.1	89.7	10.3	89.8	10.2
50	90.4	9.6	90.5	9.5	90.3	9.7	90.4	9.6
60	90.9	9.1	90.9	9.1	90.8	9.2	90.9	9.1
80	91.5	8.5	91.6	8.4	91.5	8.5	91.5	8.5
95	91.9	8.1	92.0	8	91.9	8.1	91.9	8.1
100	92.0	8.0	92.1	7.9	92.1	7.9	92.1	7.9
125	92.5	7.5	92.6	7.4	92.5	7.5	92.5	7.5
150	92.9	7.1	92.9	7.1	92.9	7.1	92.9	7.1

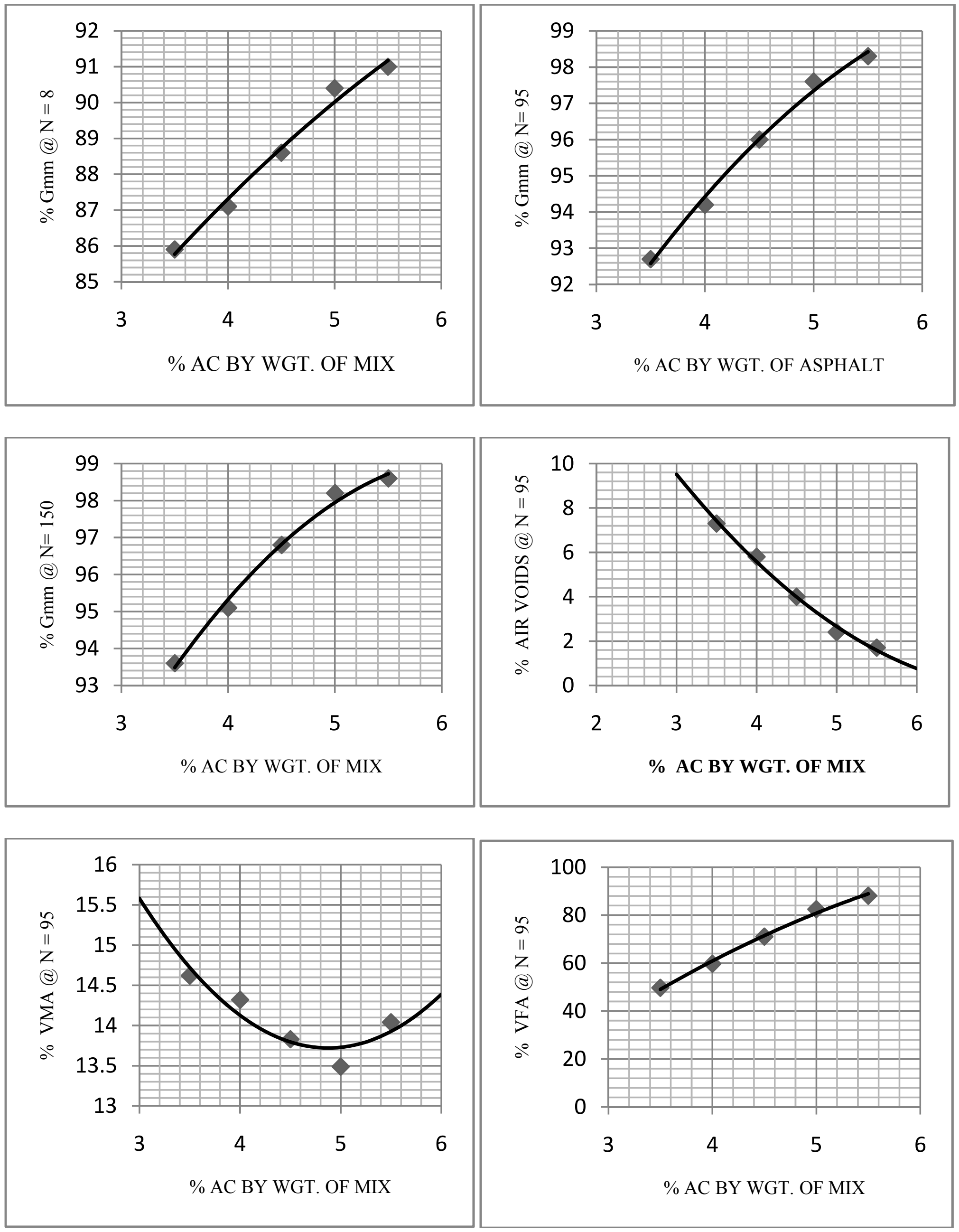

Figure 41: Graphical Illustration of HMA Design data by Superpave Method (No Polypropylene)

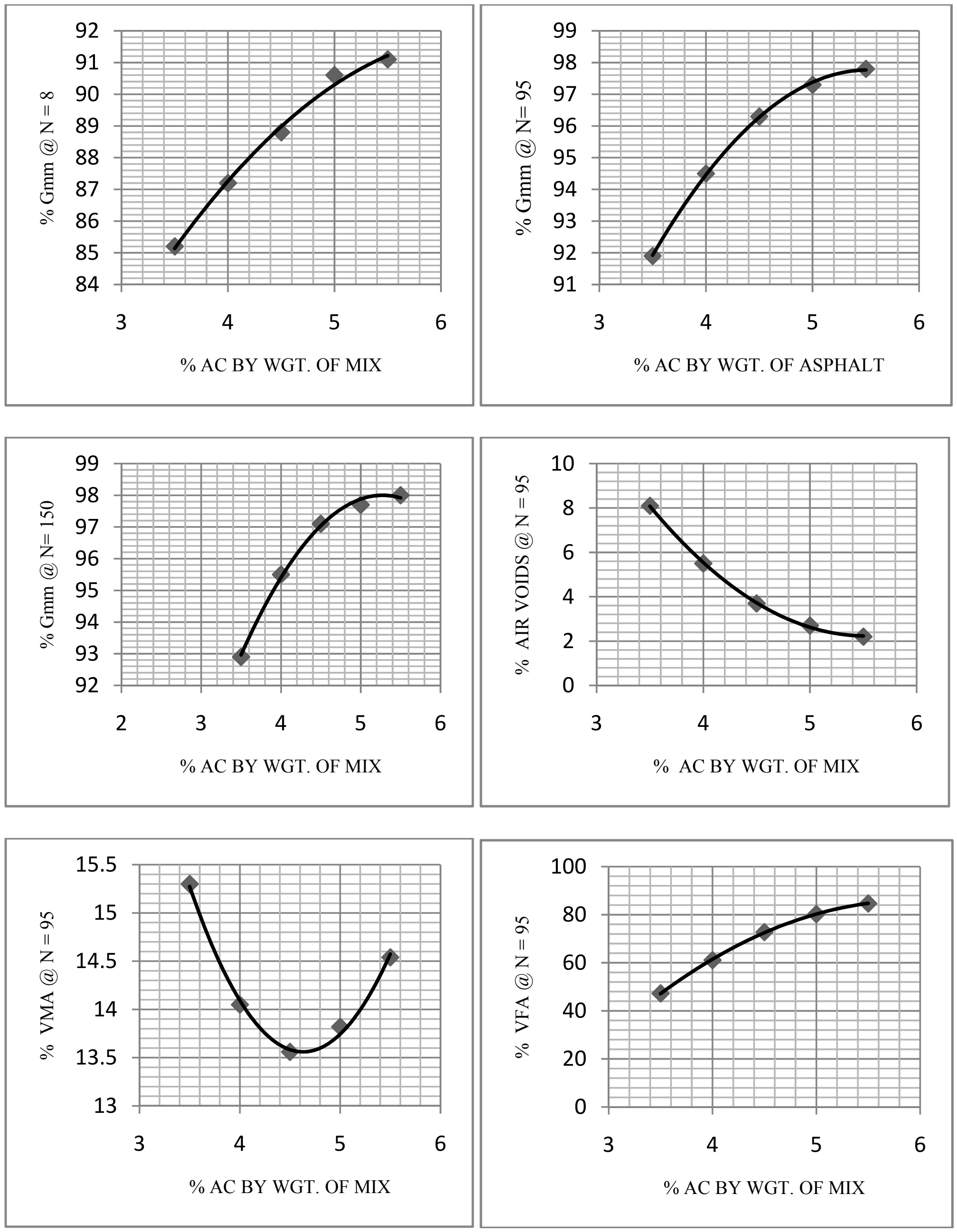

Figure 42: Graphical Illustration of HMA Design data by Superpave Method (0.1% Polypropylene)

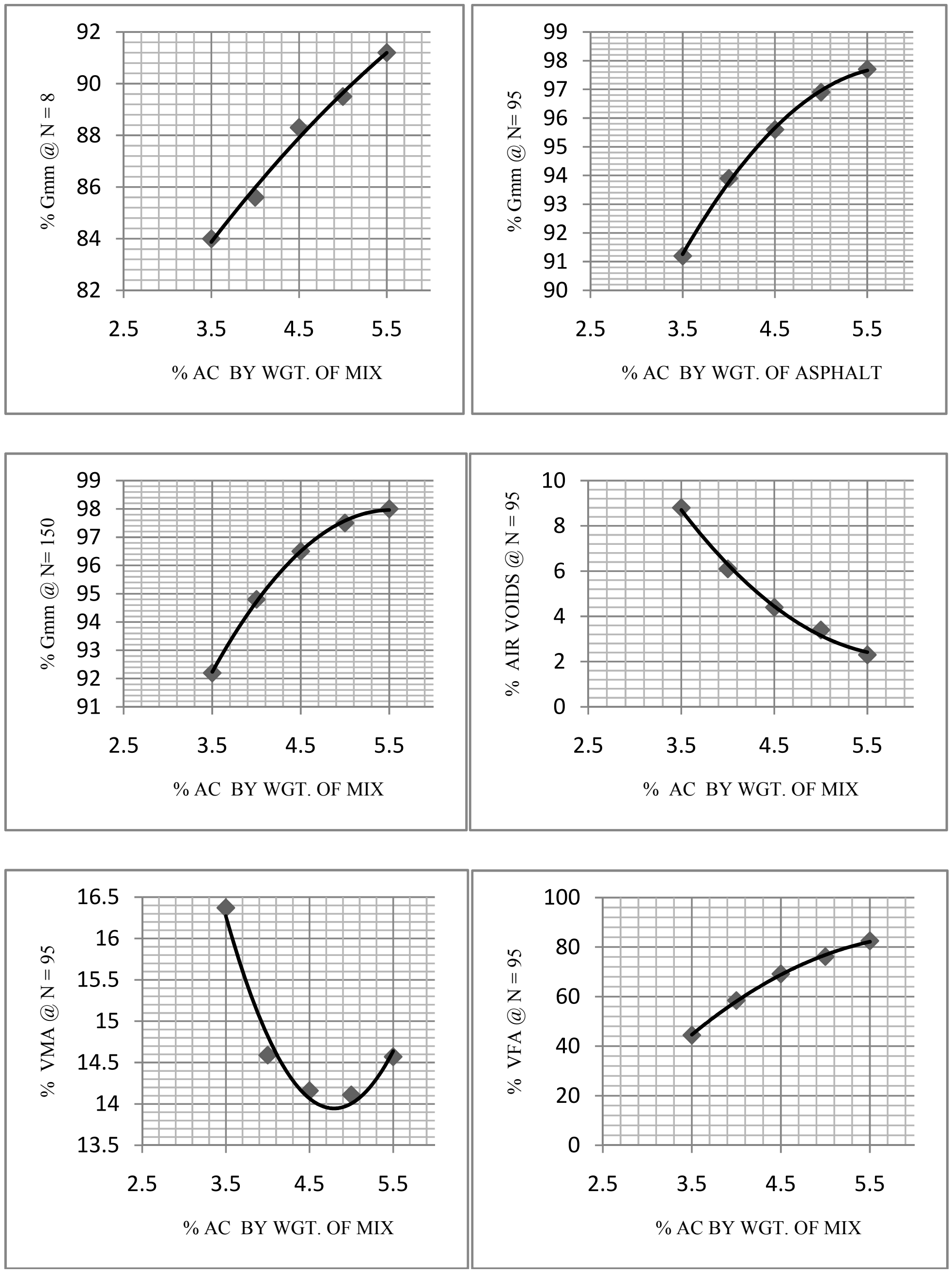

Figure 43: Graphical Illustration of HMA Design data by Superpave Method (0.2% Polypropylene)

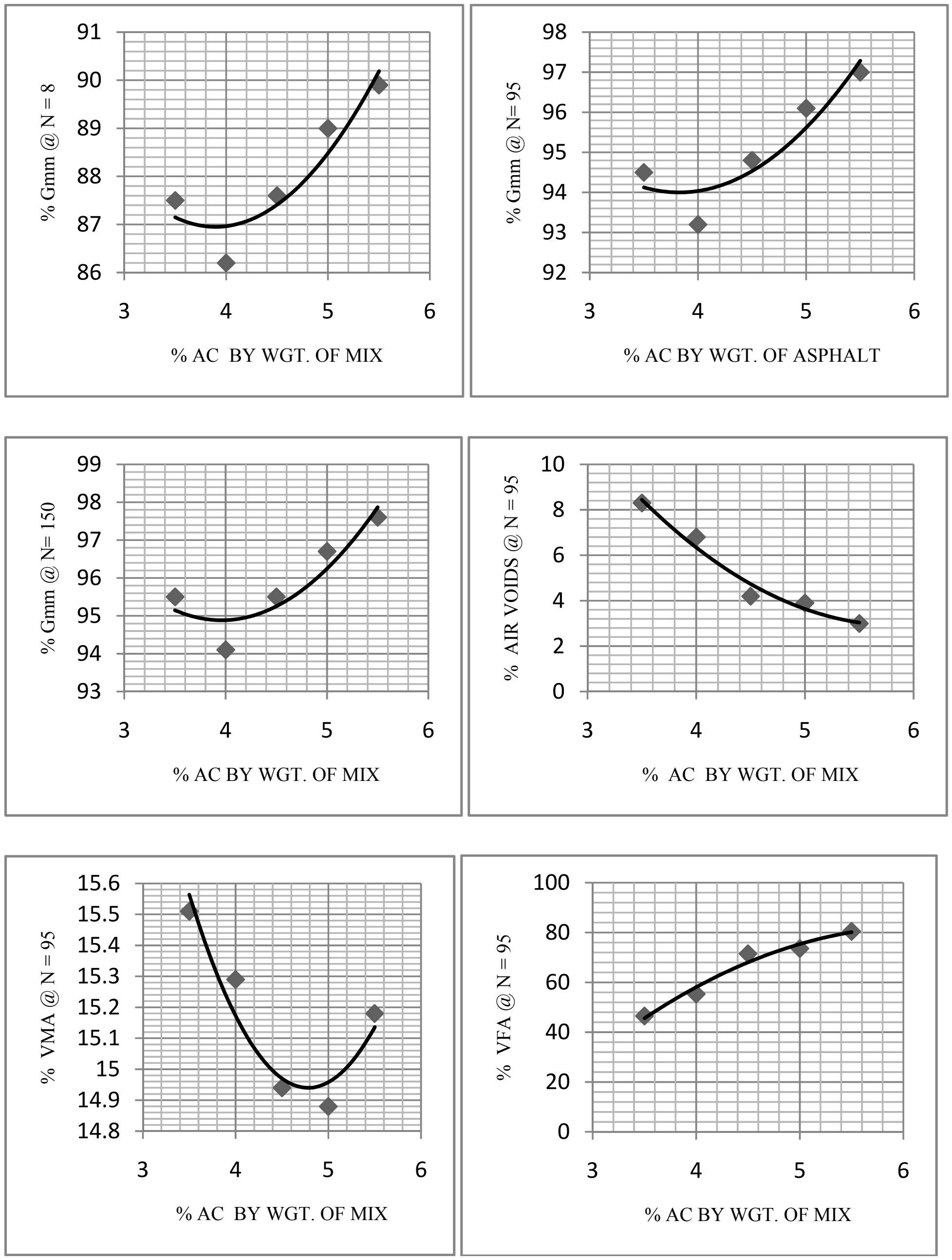

Figure 44: Graphical Illustration of HMA Design data by Superpave Method (0.3% Polypropylene)

Figure 45 to 50 shows $\%G_{mm}$ at N_{ini}, $\%G_{mm}$ at N_{des}, $\%G_{mm}$ at N_{max}, percent of air void, %VMA and %VFA at optimum percent of asphalt (4.20% by weight of total mix). For 0.5% of 12 mm long polypropylene $\%G_{mm}$ at N_{ini} was decreased about 2.8% and $\%G_{mm}$ at N_{des} and $\%G_{mm}$ at N_{max} for about 3.0%. Percent of air void was increased 61.7% and %VMA about 20%, and finally %VFA was decreased about 17%. These data show susceptibility of Marshall Analysis and Superpave Analysis are approximately same for percent air voids, %VMA and %VFA.

In all the different percentage of polypropylene $\%G_{mm}$ for initial number of gyration and maximum number of gyration was behind the criteria and %VMA was higher than 13% which is minimum VMA percent for 19.0mm Nominal Maximum Aggregate (NMA), size according to Superpave criteria.

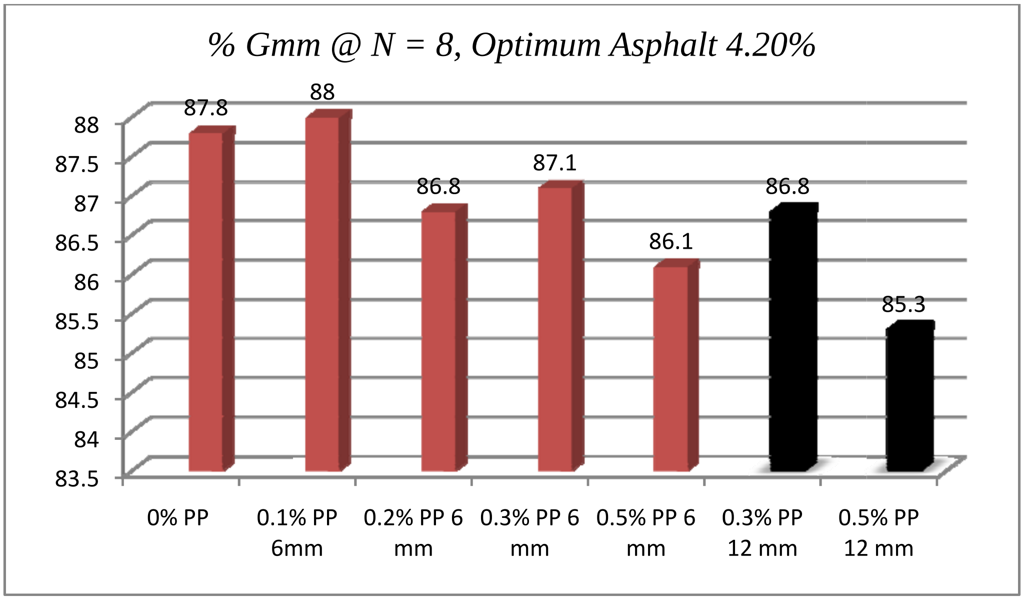

Figure 45: % Gmm @ N = 8 Results at Optimum Asphalt Content

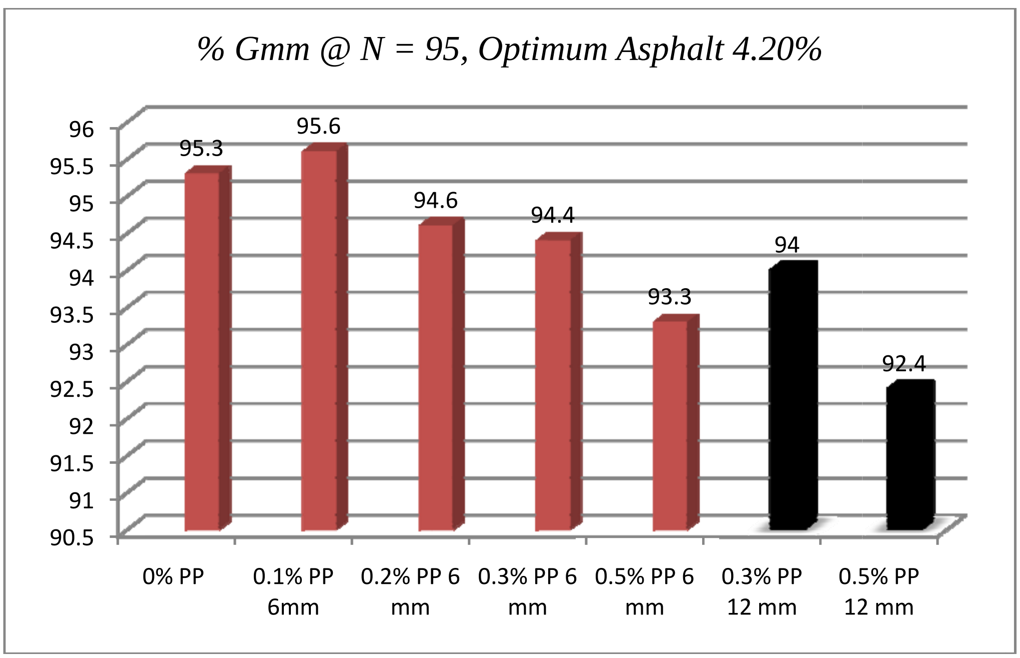

Figure 46: % Gmm @ N = 95 Result at Optimum Asphalt Content

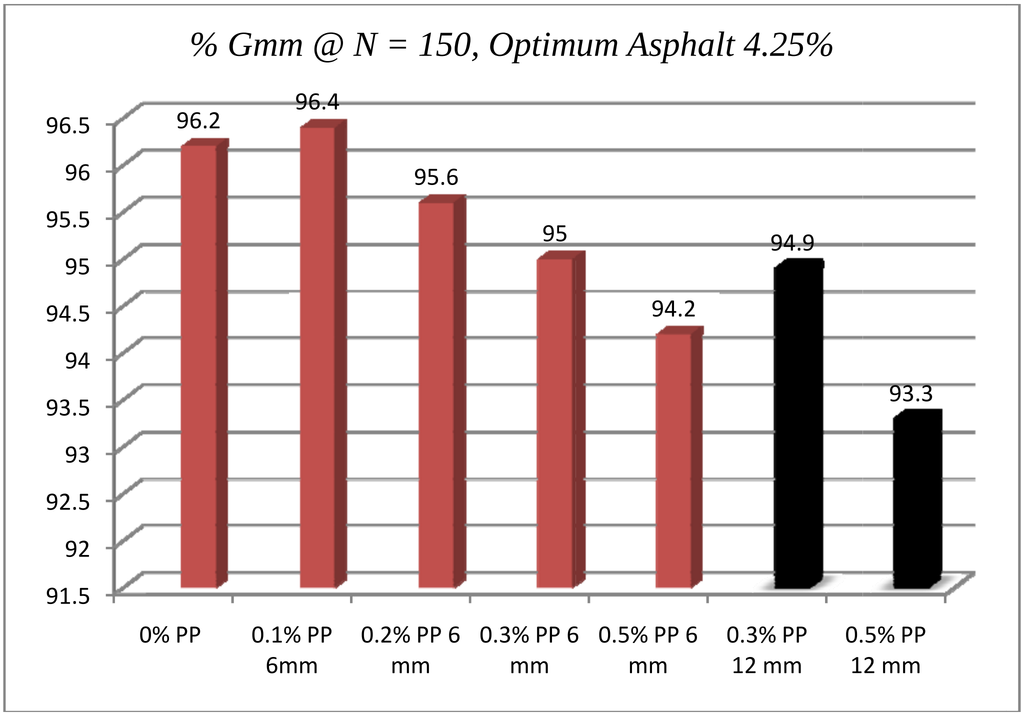

Figure 47: % Gmm @ N = 150 Results at Optimum Asphalt Content

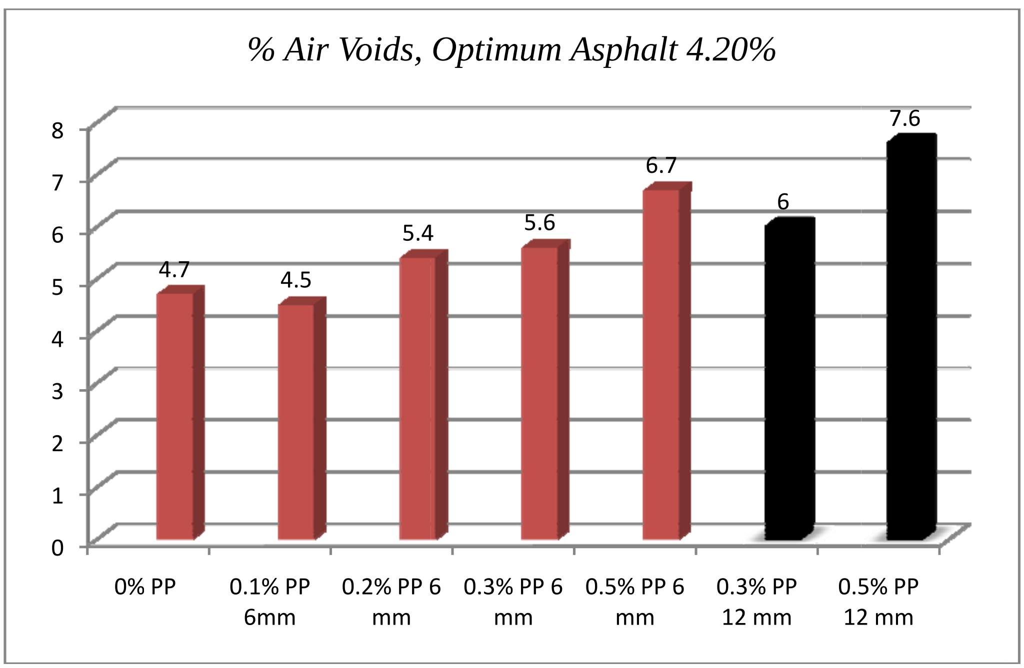

Figure 48: Air Voids Result at Optimum Asphalt Content

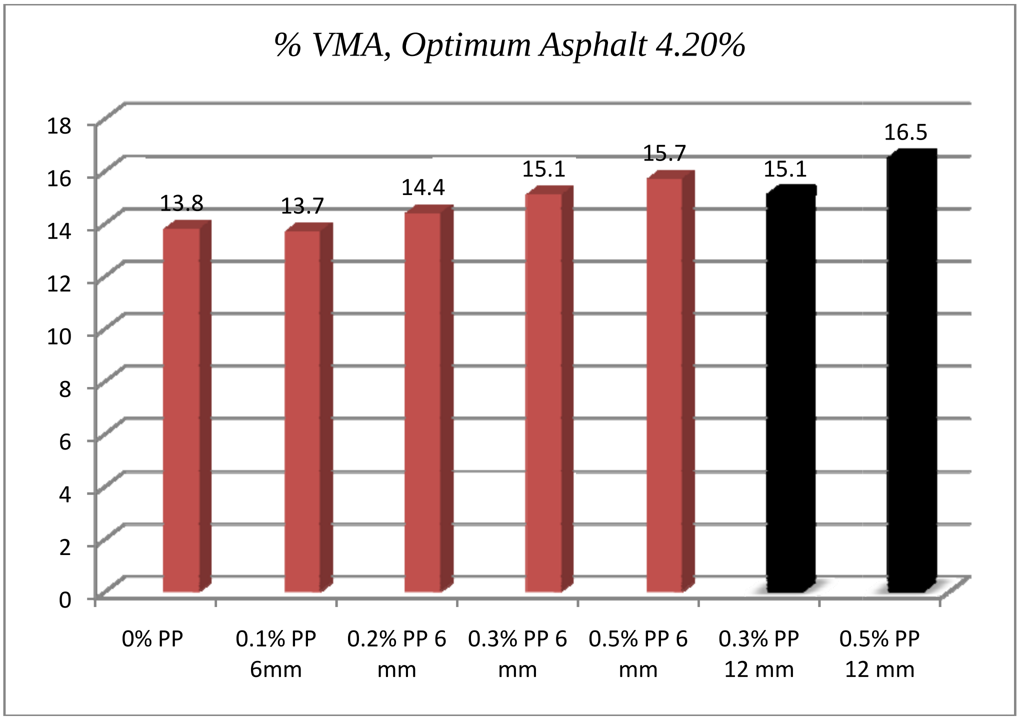

Figure 49: VMA Result at Optimum Asphalt Content

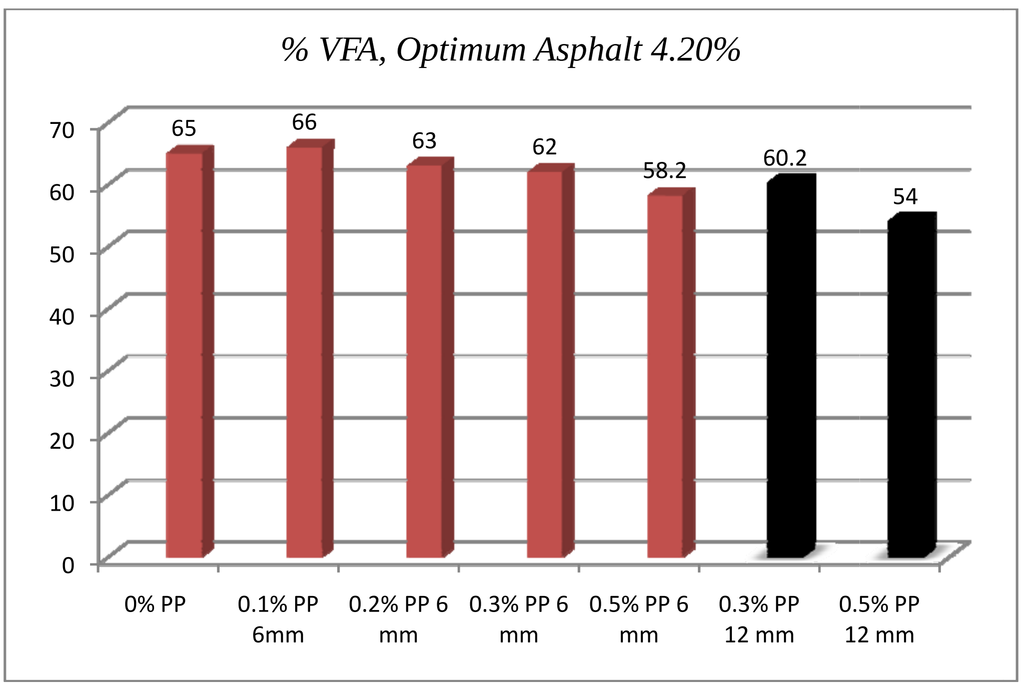

Figure 50: VFA Result at Optimum Asphalt Content

4.4 Results and Discussion

As it was explained before in Marshall Analysis, optimum amount of asphalt for 4.0% air voids was calculated 4.20% by weight of total mix. For control group specimens without polypropylene, Marshall Stability at optimum asphalt is 1560kg and Flow, VMA, VFA and Unit Weight are, 5.3 mm, 13.2%, 70% and 2473 Kg/m^3 respectively.

Results for modified asphalt with 0.1% of 6 mm long polypropylene additive by weight of total mix are: Marshall Stability 1540 kg and Flow 4.4 mm, as it can be seen 0.1% PP decrease the Stability for about 1.3% but increase in flow is observed for about 17%, in this percent of PP. Air void 3.8% (5.0% reduction), VMA 13.0% (1.5% reduction) and unit weight 2468 Kg/m^3 (0.2% reduction), VFA was increased to 71% (1.4% increase).

For 0.2% of 6 mm long polypropylene by weight of total mix, in this percent of polypropylene Marshall Stability jumped up to 1640 Kg which improved Stability for about 5.1%, Flow was 4.4mm (it didn't change in compare with 0.1% PP). Air void was increased for 10% and changed to 4.4%, VMA increased to 13.6% (3.0% increases). VFA decreased for 2.9% and dropped to 68% and finally unit weight which is decreased for about 0.7% and became 2456 Kg/m^3.

12.2% increase for 0.3% of 6 mm long polypropylene by weight of total mix for Marshall Stability was observed, the value was increased it to 1750 Kg, flow decreased to 4.3mm and showed about 19% reduction, air void and VMA were increased to 5.3% (32.5% increase) and 14.32% (8.5% increase) respectively, and VFA and unit weight were decreased to 63% and 2444 Kg/m^3 (10% and 1.2% reduction respectively).

0.5% of 6 mm PP was added only at optimum percent of asphalt cement which is 4.2% by weight of total mix, for this ratio Marshall Stability increased to 1780 Kg (14.1% increase), flow with 26.4% reduction was dropped to 3.9 mm, air void jumped to 5.9% and VMA to 14.95%, VFA and unit weight fell off to 61% and 2432 Kg/m^3.

0.3% and 0.5% of 12 mm polypropylene were also added at optimum percent of asphalt, for these percents of polypropylene; Marshall Stability was increased to 1902 Kg (22.0% increase) and 1971 Kg (26.3% increase), flow reduced to 3.8 mm (28.3% reduction) and 3.3 mm (37.7% reduction). Air void jumped to 5.1% (27.5% increase) and 6.7% (67.5% increase), VMA was increased to 14.27% (8.1% increase) and 15.74% (19.2% increase), VFA was decreased to 64% (8.6% decrease) and 57% (18.6% decrease) and unit weight was decreased to 2451 Kg/m^3 (0.9% reduction) and 2413 Kg/m^3 (2.4% reduction) respectively.

These results show that polypropylene can be helpful for increasing pavements life as other studies are also show this improvement, More on, increasing air void is important for the pavements designed to serve in hot regions where flashing and bleeding are one of the main problems which can be solved by increasing air void.

Using Superpave Method showed increase in percent of Air Voids in compare with Marshall, optimum amount of asphalt jumped to 4.5% by weight of total mix, but again same results was observed in VMA (20% increase), VFA (17% decrease) and Air Voids (61.7% increase), G_{mm} at N_{ini} was decreased 2.8% and in N_{des} an N_{max} 3.0% reduction was observed.

Chapter 5

CONCLUSIONAND RECOMMENDATION

5.1 Conclusion

The base reason of this study was to increase flexible pavement life by improving Hot Mix Asphalt (HMA) characteristics. To solve this problem, Polypropylene (PP) additive was selected because of locally available situation, being as a low-cost additive (~5 T.L/Kg), initial price of HMA with considering 110 T.L/Ton will increase 13.6% for 0.3% of 12 mm PP, but duration of maintenance will decrease (according to different studies PP increase pavement life to 27%), and having good correlation with HMA according to different studies. Different percentages (0.1%, 0.2%, and 0.3%) of 6 mm long PP were added to asphalt mixture in 3.5, 4.0, 4.5, 5.0 and 5.5% percent of asphalt by weight of total mix and 0.5% of 6 mm long PP and 0.3, 0.5% of 12 mm long PP were added to optimum percent of asphalt (4.20% by weight of total mix), to see the difference in asphalt characteristics.

Asphalt specimens were made by Superpave Gyratory Compactor (SGC), and analyzed by both Marshall Analysis and Superpave Analysis and finally tested by Marshall Stability. Adding PP showed increasing in Marshall Stability (26.3%), percent of air void (67.5%), and also decreasing Flow (38%). These results show increase pavement life service, also increasing percent of air void is useful for hot regions which bleeding and flushing are important distresses. Analyzing on compacted specimens made by Superpave Gyratory Compactor with Superpave showed more air void than Marshall.

Author concluded that 0.3% of 12 mm polypropylene is better than the other percentages and lengths, because higher than this percentage, air void is increased to a high percent (6.7%), which in this percentage, amount of asphalt will become disadvantage and there isn't a lot difference in stability (3.6%).

5.2 Recommendation

Because of lack of studies in North Cyprus there is a lots of area to work on in these field, it can be tested with Stone Mastic Asphalt (SMA), to both increase stability and decrease drain down, it can be implemented for Open Graded Fracture Course (OGFC) for again increasing stability, decreasing flow, drain down, and because of increasing air void, polypropylene can really be useful for providing enough air void For OGFC. Different studies show increase in fatigue life and elastic which be tested in this region by North Cyprus gradation and traffic.

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APPENDICES

Appendix A: Superpave Test Result

A.1 Densification Data

Table 26 : Gyratory Compactor Test Results (3.5% Asphalt, No Polypropylene)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.14	2.056	2.222	84.2	76.6	2.049	2.221	84.2	75.33	2.077	2.231	84.6	84.3
8	74.8	2.093	2.261	85.8	75.27	2.086	2.260	85.7	74.03	2.114	2.270	86.1	85.9
10	74.22	2.109	2.279	86.4	74.68	2.102	2.278	86.4	73.46	2.130	2.288	86.8	86.5
20	72.54	2.158	2.332	88.4	72.89	2.154	2.334	88.5	71.79	2.180	2.341	88.8	88.6
30	71.62	2.186	2.362	89.6	71.89	2.184	2.367	89.7	70.88	2.208	2.371	89.9	89.7
40	71.00	2.205	2.382	90.3	71.26	2.203	2.387	90.5	70.28	2.227	2.391	90.7	90.5
50	70.55	2.219	2.398	90.9	70.77	2.218	2.404	91.2	69.84	2.241	2.406	91.3	91.1
60	70.2	2.230	2.410	91.4	70.44	2.229	2.415	91.6	69.46	2.253	2.420	91.8	91.6
80	69.72	2.245	2.426	92.0	69.89	2.246	2.434	92.3	68.98	2.268	2.436	92.4	92.2
95	69.44	2.254	2.436	92.4	69.55	2.257	2.446	92.8	68.7	2.278	2.446	92.8	92.7
100	69.36	2.257	2.439	92.5	69.45	2.260	2.450	92.9	68.59	2.281	2.450	92.9	92.8
125	69.00	2.269	2.451	93.0	69.12	2.271	2.461	93.3	68.26	2.292	2.462	93.4	93.2
150	68.76	2.276	2.460	93.3	68.85	2.280	2.471	93.7	67.96	2.303	2.473	93.8	93.6

Specimen 1	Specimen 2	Specimen 3
C = 1.081	C = 1.084	C = 1.074
Gmb = 2.460	Gmb = 2.471	Gmb = 2.473
Gmm = 2.637	Gmm = 2.637	Gmm = 2.637

Table 27: Gyratory Compactor Test Results (4.0% Asphalt, No Polypropylene)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	75.93	2.083	2.244	85.8	76.15	2.078	2.238	85.5	75.91	2.082	2.245	85.8	85.7
8	74.61	2.120	2.284	87.3	74.75	2.117	2.280	87.1	74.95	2.109	2.273	86.9	87.1
10	74	2.137	2.303	88.0	74.12	2.135	2.299	87.9	73.99	2.136	2.303	88.0	88.0
20	72.3	2.187	2.357	90.1	72.33	2.188	2.356	90.1	72.23	2.188	2.359	90.2	90.1
30	71.36	2.216	2.388	91.3	71.38	2.217	2.387	91.3	71.32	2.216	2.389	91.3	91.3
40	70.76	2.235	2.408	92.1	70.76	2.237	2.408	92.1	70.73	2.235	2.409	92.1	92.1
50	70.3	2.249	2.424	92.7	70.32	2.251	2.423	92.6	70.3	2.248	2.424	92.7	92.7
60	69.96	2.260	2.436	93.1	69.97	2.262	2.435	93.1	69.96	2.259	2.436	93.1	93.1
80	69.42	2.278	2.455	93.8	69.42	2.280	2.455	93.8	69.42	2.277	2.454	93.8	93.8
95	69.12	2.288	2.466	94.3	69.18	2.288	2.463	94.2	69.15	2.286	2.464	94.2	94.2
100	69.06	2.290	2.468	94.3	69.09	2.291	2.466	94.3	69.07	2.288	2.467	94.3	94.3
125	68.73	2.301	2.480	94.8	68.74	2.302	2.479	94.8	68.71	2.300	2.480	94.8	94.8
150	68.47	2.310	2.489	95.1	68.49	2.311	2.488	95.1	68.43	2.310	2.490	95.2	95.1

Specimen 1	Specimen 2	Specimen 3
C = 1.077	C = 1.077	C = 1.078
Gmb = 2.489	Gmb = 2.488	Gmb = 2.490
Gmm = 2.616	Gmm = 2.616	Gmm = 2.616

Table 28: Gyratory Compactor Test Results (4.5% Asphalt, No Polypropylene)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.96	2.071	2.231	85.9	76.26	2.086	2.247	86.6	75.72	2.102	2.259	87.0	86.5
8	74.5	2.140	2.304	88.8	74.74	2.128	2.293	88.3	74.27	2.143	2.303	88.7	88.6
10	73.84	2.159	2.325	89.6	74.08	2.147	2.313	89.1	73.61	2.162	2.323	89.5	89.4
20	71.96	2.215	2.386	91.9	72.18	2.204	2.374	91.4	71.71	2.219	2.385	91.9	91.7
30	70.98	2.246	2.419	93.2	71.19	2.234	2.407	92.7	70.69	2.251	2.419	93.2	93.0
40	70.36	2.266	2.440	94.0	70.55	2.254	2.429	93.6	70.05	2.272	2.441	94.0	93.9
50	69.94	2.279	2.455	94.6	70.1	2.269	2.444	94.2	69.6	2.286	2.457	94.7	94.5
60	69.54	2.293	2.469	95.1	69.77	2.280	2.456	94.6	69.25	2.298	2.470	95.1	94.9
80	69.04	2.309	2.487	95.8	69.25	2.297	2.474	95.3	68.79	2.313	2.486	95.8	95.6
95	68.76	2.319	2.497	96.2	68.97	2.306	2.484	95.7	68.57	2.321	2.494	96.1	96.0
100	68.66	2.322	2.500	96.3	68.88	2.309	2.488	95.8	68.5	2.323	2.497	96.2	96.1
125	68.34	2.333	2.512	96.8	68.56	2.320	2.499	96.3	68.26	2.331	2.505	96.5	96.5
150	68.1	2.341	2.521	97.1	68.35	2.327	2.507	96.6	68.11	2.336	2.511	96.7	96.8

Specimen 1	Specimen 2	Specimen 3
C = 1.077	C = 1.077	C = 1.075
Gmb = 2.521	Gmb = 2.507	Gmb = 2.511
Gmm = 2.596	Gmm = 2.596	Gmm = 2.596

Table 29: Gyratory Compactor Test Results (5.0% Asphalt, No Polypropylene)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	75.89	2.116	2.282	88.6	76.27	2.097	2.269	88.1	75.1	2.127	2.299	89.2	88.6
8	74.41	2.158	2.327	90.3	74.81	2.138	2.313	89.8	73.66	2.168	2.344	91.0	90.4
10	73.76	2.177	2.348	91.1	74.43	2.149	2.325	90.3	73.06	2.186	2.363	91.7	91.0
20	71.84	2.235	2.410	93.6	72.2	2.215	2.397	93.1	71.17	2.244	2.426	94.2	93.6
30	70.84	2.266	2.444	94.9	71.22	2.246	2.430	94.3	70.19	2.276	2.459	95.5	94.9
40	70.21	2.287	2.466	95.7	70.6	2.265	2.451	95.2	69.62	2.294	2.480	96.3	95.7
50	69.77	2.301	2.482	96.3	70.15	2.280	2.467	95.8	69.23	2.307	2.493	96.8	96.3
60	69.42	2.313	2.494	96.8	69.8	2.291	2.480	96.3	68.93	2.317	2.504	97.2	96.8
80	69.01	2.327	2.509	97.4	69.33	2.307	2.496	96.9	68.59	2.329	2.517	97.7	97.3
95	68.81	2.333	2.516	97.7	69.1	2.314	2.505	97.2	68.41	2.335	2.523	98.0	97.6
100	68.76	2.335	2.518	97.8	69.01	2.318	2.508	97.4	68.39	2.336	2.524	98.0	97.7
125	68.54	2.343	2.526	98.1	68.75	2.326	2.517	97.7	68.25	2.340	2.529	98.2	98.0
150	68.44	2.346	2.530	98.2	68.57	2.332	2.524	98.0	68.15	2.344	2.533	98.3	98.2

Specimen 1: C = 1.078, Gmb = 2.530, Gmm = 2.576

Specimen 2: C = 1.082, Gmb = 2.524, Gmm = 2.576

Specimen 3: C = 1.081, Gmb = 2.533, Gmm = 2.576

Table 30: Gyratory Compactor Test Results (5.5% Asphalt, No Polypropylene)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	78.55	2.045	2.211	86.5	75.37	2.116	2.279	89.2	75.05	2.142	2.300	90.0	88.6
8	75.63	2.124	2.296	89.9	73.79	2.162	2.328	91.1	73.54	2.185	2.347	91.9	91.0
10	74.47	2.157	2.332	91.3	73.08	2.183	2.351	92.0	72.9	2.205	2.368	92.7	92.0
20	71.74	2.239	2.420	94.7	71.15	2.242	2.415	94.5	71.03	2.263	2.430	95.1	94.8
30	70.61	2.275	2.459	96.3	70.2	2.272	2.447	95.8	70.14	2.291	2.461	96.3	96.1
40	69.96	2.296	2.482	97.1	69.61	2.291	2.468	96.6	69.6	2.309	2.480	97.1	96.9
50	69.6	2.308	2.495	97.6	69.24	2.304	2.481	97.1	69.25	2.321	2.493	97.6	97.4
60	69.44	2.313	2.501	97.9	68.95	2.313	2.492	97.5	69.04	2.328	2.500	97.9	97.8
80	69.16	2.323	2.511	98.3	68.62	2.324	2.504	98.0	68.84	2.335	2.507	98.1	98.1
95	69.03	2.327	2.516	98.5	68.47	2.329	2.509	98.2	68.73	2.338	2.511	98.3	98.3
100	69.01	2.328	2.516	98.5	68.43	2.331	2.511	98.3	68.7	2.339	2.513	98.3	98.4
125	68.94	2.330	2.519	98.6	68.29	2.336	2.516	98.5	68.61	2.343	2.516	98.5	98.5
150	68.88	2.332	2.521	98.7	68.23	2.338	2.518	98.6	68.55	2.345	2.518	98.6	98.6

Specimen 1	Specimen 2	Specimen 3
C = 1.081	C = 1.077	C = 1.074
Gmb = 2.521	Gmb = 2.518	Gmb = 2.518
Gmm = 2.555	Gmm = 2.555	Gmm = 2.555

Table 31: Gyratory Compactor Test Results (3.5% Asphalt, 0.1% Polypropylene-6mm)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.29	2.050	2.217	84.1	77.79	2.023	2.205	83.6	77.97	2.023	2.199	83.4	83.7
8	75.04	2.085	2.254	85.5	76.43	2.059	2.244	85.1	76.61	2.059	2.238	84.9	85.2
10	74.5	2.100	2.270	86.1	75.81	2.076	2.263	85.8	75.96	2.076	2.257	85.6	85.8
20	72.84	2.148	2.322	88.1	73.96	2.127	2.319	87.9	74.09	2.129	2.314	87.8	87.9
30	71.95	2.174	2.351	89.1	72.99	2.156	2.350	89.1	73.13	2.157	2.345	88.9	89.0
40	71.35	2.192	2.370	89.9	72.35	2.175	2.371	89.9	72.46	2.177	2.366	89.7	89.8
50	70.91	2.206	2.385	90.4	71.87	2.189	2.387	90.5	71.99	2.191	2.382	90.3	90.4
60	70.58	2.216	2.396	90.9	71.52	2.200	2.398	90.9	71.59	2.203	2.395	90.8	90.9
80	70.07	2.232	2.414	91.5	70.97	2.217	2.417	91.6	71.04	2.220	2.414	91.5	91.5
95	69.77	2.242	2.424	91.9	70.68	2.226	2.427	92.0	70.73	2.230	2.424	91.9	91.9
100	69.68	2.245	2.427	92.0	70.6	2.229	2.429	92.1	70.62	2.233	2.428	92.1	92.1
125	69.31	2.257	2.440	92.5	70.22	2.241	2.443	92.6	70.27	2.245	2.440	92.5	92.5
150	69.06	2.265	2.449	92.9	69.98	2.248	2.451	92.9	69.96	2.255	2.451	92.9	92.9

Specimen 1	Specimen 2	Specimen 3
C = 1.081	C = 1.090	C = 1.087
Gmb = 2.449	Gmb = 2.451	Gmb = 2.451
Gmm = 2.637	Gmm = 2.637	Gmm = 2.637

Table 32: Gyratory Compactor Test Results (4.0% Asphalt, 0.1% Polypropylene-6mm)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.5	2.065	2.235	85.4	76.56	2.070	2.233	85.4	76.25	2.076	2.246	85.9	85.6
8	75.07	2.105	2.277	87.0	75.1	2.110	2.277	87.0	74.85	2.115	2.288	87.5	87.2
10	74.4	2.124	2.298	87.8	74.4	2.130	2.298	87.9	74.21	2.133	2.308	88.2	88.0
20	72.47	2.180	2.359	90.2	72.47	2.187	2.360	90.2	74.42	2.127	2.301	88.0	89.5
30	71.45	2.211	2.393	91.5	71.49	2.217	2.392	91.4	71.46	2.215	2.397	91.6	91.5
40	70.79	2.232	2.415	92.3	70.83	2.238	2.414	92.3	70.81	2.236	2.419	92.5	92.4
50	70.32	2.247	2.431	92.9	70.38	2.252	2.430	92.9	70.37	2.250	2.434	93.0	92.9
60	69.96	2.258	2.443	93.4	70.01	2.264	2.442	93.4	70	2.261	2.447	93.5	93.4
80	69.42	2.276	2.462	94.1	69.47	2.281	2.461	94.1	69.47	2.279	2.465	94.2	94.1
95	69.13	2.285	2.473	94.5	69.19	2.291	2.471	94.5	69.2	2.288	2.475	94.6	94.5
100	69.03	2.289	2.476	94.7	69.12	2.293	2.474	94.6	69.12	2.290	2.478	94.7	94.7
125	68.7	2.300	2.488	95.1	68.76	2.305	2.487	95.1	68.77	2.302	2.491	95.2	95.1
150	68.46	2.308	2.497	95.5	68.48	2.314	2.497	95.5	68.51	2.311	2.500	95.6	95.5

Specimen 1	Specimen 2	Specimen 3
C = 1.082	C = 1.079	C = 1.082
Gmb = 2.497	Gmb = 2.497	Gmb = 2.500
Gmm = 2.616	Gmm = 2.616	Gmm = 2.616

Table 33: Gyratory Compactor Test Results (4.5% Asphalt, 0.1% Polypropylene-6mm)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.38	2.086	2.270	87.4	75.24	2.101	2.258	87.0	76.73	2.071	2.261	87.1	87.2
8	74.88	2.128	2.315	89.2	73.85	2.140	2.300	88.6	75.32	2.110	2.304	88.7	88.8
10	74.2	2.147	2.336	90.0	73.23	2.158	2.320	89.4	74.68	2.128	2.323	89.5	89.6
20	72.21	2.207	2.401	92.5	71.39	2.214	2.380	91.7	72.78	2.183	2.384	91.8	92.0
30	71.17	2.239	2.436	93.8	70.41	2.245	2.413	92.9	71.75	2.215	2.418	93.2	93.3
40	70.51	2.260	2.459	94.7	69.77	2.265	2.435	93.8	71.1	2.235	2.440	94.0	94.2
50	70.04	2.275	2.475	95.3	69.31	2.280	2.451	94.4	70.62	2.250	2.457	94.6	94.8
60	69.72	2.285	2.486	95.8	68.97	2.292	2.463	94.9	70.26	2.262	2.470	95.1	95.3
80	69.23	2.301	2.504	96.5	68.47	2.308	2.481	95.6	69.73	2.279	2.488	95.9	96.0
95	69.00	2.309	2.512	96.8	68.21	2.317	2.490	95.9	69.48	2.287	2.497	96.2	96.3
100	68.91	2.312	2.516	96.9	68.15	2.319	2.493	96.0	69.37	2.291	2.501	96.3	96.4
125	68.61	2.322	2.527	97.3	67.86	2.329	2.503	96.4	69.11	2.299	2.511	96.7	96.8
150	68.44	2.328	2.533	97.6	67.68	2.335	2.510	96.7	68.88	2.307	2.519	97.0	97.1

Specimen 1	Specimen 2	Specimen 3
C = 1.088	C = 1.075	C = 1.092
Gmb = 2.533	Gmb = 2.510	Gmb = 2.519
Gmm = 2.596	Gmm = 2.596	Gmm = 2.596

Table 34: Gyratory Compactor Test Results (5.0% Asphalt, 0.1% Polypropylene-6mm)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	75.52	2.120	2.274	88.3	74.36	2.134	2.296	89.1	75.12	2.125	2.289	88.9	88.8
8	73.96	2.165	2.322	90.1	72.83	2.178	2.344	91.0	73.7	2.166	2.333	90.6	90.6
10	73.28	2.185	2.343	91.0	72.15	2.199	2.366	91.8	73.06	2.185	2.353	91.4	91.4
20	71.33	2.245	2.407	93.5	70.2	2.260	2.432	94.4	71.29	2.239	2.412	93.6	93.8
30	70.39	2.275	2.440	94.7	69.27	2.290	2.464	95.7	70.37	2.269	2.443	94.9	95.1
40	69.83	2.293	2.459	95.5	68.77	2.307	2.482	96.4	69.85	2.286	2.462	95.6	95.8
50	69.48	2.305	2.472	95.9	68.43	2.319	2.494	96.8	69.48	2.298	2.475	96.1	96.3
60	69.23	2.313	2.480	96.3	68.23	2.325	2.502	97.1	69.21	2.307	2.484	96.4	96.6
80	68.89	2.325	2.493	96.8	67.93	2.336	2.513	97.5	68.86	2.318	2.497	96.9	97.1
95	68.76	2.329	2.497	96.9	67.82	2.339	2.517	97.7	68.67	2.325	2.504	97.2	97.3
100	68.71	2.331	2.499	97.0	67.81	2.340	2.517	97.7	68.64	2.326	2.505	97.2	97.3
125	68.53	2.337	2.506	97.3	67.68	2.344	2.522	97.9	68.47	2.332	2.511	97.5	97.6
150	68.47	2.339	2.508	97.4	67.63	2.346	2.524	98.0	68.34	2.336	2.516	97.7	97.7

Specimen 1	Specimen 2	Specimen 3
C = 1.072	C = 1.076	C = 1.077
Gmb = 2.508	Gmb = 2.524	Gmb = 2.516
Gmm = 2.576	Gmm = 2.576	Gmm = 2.576

Table 35: Gyratory Compactor Test Results (5.5% Asphalt, 0.1% Polypropylene-6mm)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.53	2.106	2.269	88.8	75.84	2.112	2.281	89.3	75.78	2.118	2.275	89.1	89.1
8	74.89	2.152	2.319	90.8	74.27	2.157	2.329	91.2	74.2	2.163	2.324	91.0	91.0
10	74.15	2.174	2.342	91.7	73.57	2.177	2.351	92.0	73.52	2.183	2.345	91.8	91.8
20	72.11	2.235	2.408	94.3	71.51	2.240	2.419	94.7	71.58	2.243	2.409	94.3	94.4
30	71.15	2.265	2.441	95.5	70.6	2.269	2.450	95.9	70.64	2.273	2.441	95.5	95.6
40	70.55	2.284	2.462	96.3	70.02	2.288	2.470	96.7	70.1	2.290	2.460	96.3	96.4
50	70.19	2.296	2.474	96.8	69.66	2.300	2.483	97.2	69.79	2.300	2.471	96.7	96.9
60	69.94	2.304	2.483	97.2	69.42	2.307	2.492	97.5	69.57	2.307	2.479	97.0	97.2
80	69.6	2.316	2.495	97.7	69.15	2.316	2.501	97.9	69.37	2.314	2.486	97.3	97.6
95	69.48	2.320	2.500	97.8	69.03	2.321	2.506	98.1	69.29	2.317	2.489	97.4	97.8
100	69.44	2.321	2.501	97.9	69.01	2.321	2.507	98.1	69.26	2.318	2.490	97.4	97.8
125	69.28	2.326	2.507	98.1	68.9	2.325	2.511	98.3	69.21	2.319	2.491	97.5	98.0
150	69.19	2.329	2.510	98.2	68.86	2.326	2.512	98.3	69.14	2.322	2.494	97.6	98.0

Specimen 1	Specimen 2	Specimen 3
C = 1.078	C = 1.080	C = 1.074
Gmb = 2.510	Gmb = 2.512	Gmb = 2.494
Gmm = 2.555	Gmm = 2.555	Gmm = 2.555

Table 36: Gyratory Compactor Test Results (3.5% Asphalt, 0.2% Polypropylene-6mm)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	78.13	2.023	2.185	82.9	78.06	2.005	2.172	82.4	78.78	2.000	2.169	82.3	82.5
8	76.73	2.060	2.225	84.4	76.66	2.042	2.211	83.9	77.33	2.038	2.210	83.8	84.0
10	76.08	2.078	2.244	85.1	76.05	2.058	2.229	84.5	76.68	2.055	2.228	84.5	84.7
20	74.18	2.131	2.301	87.3	74.17	2.111	2.286	86.7	74.73	2.108	2.287	86.7	86.9
30	73.17	2.160	2.333	88.5	73.17	2.139	2.317	87.9	73.65	2.139	2.320	88.0	88.1
40	72.51	2.180	2.354	89.3	72.47	2.160	2.339	88.7	73.00	2.158	2.341	88.8	88.9
50	72.01	2.195	2.371	89.9	72.01	2.174	2.354	89.3	72.48	2.174	2.358	89.4	89.5
60	71.65	2.206	2.383	90.4	71.59	2.187	2.368	89.8	72.08	2.186	2.371	89.9	90.0
80	71.1	2.223	2.401	91.1	70.99	2.205	2.388	90.6	71.51	2.203	2.390	90.6	90.8
95	70.8	2.233	2.411	91.4	70.65	2.216	2.400	91.0	71.15	2.215	2.402	91.1	91.2
100	70.73	2.235	2.414	91.5	70.57	2.218	2.402	91.1	71.06	2.217	2.405	91.2	91.3
125	70.36	2.247	2.426	92.0	70.19	2.230	2.415	91.6	70.64	2.231	2.419	91.7	91.8
150	70.08	2.256	2.436	92.4	69.91	2.239	2.425	92.0	70.35	2.240	2.429	92.1	92.2

Specimen 1	Specimen 2	Specimen 3
C = 1.080	C = 1.083	C = 1.085
G_{mb} = 2.436	G_{mb} = 2.425	G_{mb} = 2.429
G_{mm} = 2.637	G_{mm} = 2.637	G_{mm} = 2.637

Table 37: Gyratory Compactor Test Results (4.0% Asphalt, 0.2% Polypropylene-6mm)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.74	2.070	2.224	85.0	79.06	1.994	2.151	82.2	76.62	2.066	2.233	85.4	84.2
8	75.35	2.108	2.265	86.6	77.98	2.022	2.181	83.4	75.23	2.104	2.274	86.9	85.6
10	74.69	2.127	2.285	87.4	77.29	2.040	2.200	84.1	74.62	2.121	2.293	87.7	86.4
20	72.83	2.181	2.344	89.6	73.45	2.147	2.315	88.5	72.8	2.174	2.350	89.8	89.3
30	71.8	2.213	2.377	90.9	72.03	2.189	2.361	90.3	71.84	2.203	2.382	91.0	90.7
40	71.12	2.234	2.400	91.7	71.18	2.215	2.389	91.3	71.21	2.223	2.403	91.9	91.6
50	70.64	2.249	2.416	92.4	70.62	2.233	2.408	92.1	70.75	2.237	2.418	92.4	92.3
60	70.3	2.260	2.428	92.8	70.2	2.246	2.423	92.6	70.43	2.247	2.429	92.9	92.8
80	69.77	2.277	2.446	93.5	69.57	2.266	2.445	93.4	69.9	2.265	2.448	93.6	93.5
95	69.47	2.287	2.457	93.9	69.25	2.277	2.456	93.9	69.6	2.274	2.458	94.0	93.9
100	69.42	2.289	2.459	94.0	69.16	2.280	2.459	94.0	69.51	2.277	2.462	94.1	94.0
125	69.1	2.299	2.470	94.4	68.82	2.291	2.471	94.5	69.18	2.288	2.473	94.5	94.5
150	68.88	2.307	2.478	94.7	68.55	2.300	2.481	94.8	68.91	2.297	2.483	94.9	94.8

C = 1.074
G_{mb} = 2.478
G_{mm} = 2.616

C = 1.079
G_{mb} = 2.481
G_{mm} = 2.616

C = 1.081
G_{mb} = 2.483
G_{mm} = 2.616

Table 38: Gyratory Compactor Test Results (4.5% Asphalt, 0.2% Polypropylene-6mm)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	77.04	2.070	2.254	86.8	76.19	2.085	2.252	86.7	76.67	2.074	2.240	86.3	86.6
8	75.55	2.111	2.298	88.5	74.71	2.127	2.296	88.5	75.22	2.113	2.283	87.9	88.3
10	74.87	2.130	2.319	89.3	74.09	2.145	2.315	89.2	74.52	2.133	2.304	88.8	89.1
20	72.96	2.186	2.380	91.7	72.21	2.200	2.376	91.5	72.6	2.190	2.365	91.1	91.4
30	72.00	2.215	2.412	92.9	71.26	2.230	2.407	92.7	71.57	2.221	2.399	92.4	92.7
40	71.39	2.234	2.432	93.7	70.6	2.251	2.430	93.6	70.93	2.241	2.421	93.3	93.5
50	70.96	2.247	2.447	94.3	70.15	2.265	2.445	94.2	70.46	2.256	2.437	93.9	94.1
60	70.64	2.258	2.458	94.7	69.8	2.276	2.458	94.7	70.12	2.267	2.449	94.3	94.6
80	70.10	2.275	2.477	95.4	69.3	2.293	2.475	95.4	69.6	2.284	2.467	95.1	95.3
95	69.84	2.283	2.486	95.8	69.06	2.301	2.484	95.7	69.33	2.293	2.477	95.4	95.6
100	69.76	2.286	2.489	95.9	69.0	2.303	2.48	95.8	69.24	2.296	2.48	95.5	95.7
125	69.43	2.297	2.501	96.3	68.7	2.313	2.497	96.2	68.91	2.307	2.492	96.0	96.2
150	69.22	2.304	2.509	96.6	68.47	2.321	2.506	96.5	68.7	2.315	2.500	96.3	96.5

Specimen 1: C = 1.089, G_{mb} = 2.509, G_{mm} = 2.596

Specimen 2: C = 1.080, G_{mb} = 2.506, G_{mm} = 2.596

Specimen 3: C = 1.080, G_{mb} = 2.500, G_{mm} = 2.596

Table 39: Gyratory Compactor Test Results (5.0% Asphalt, 0.2% Polypropylene-6mm)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.97	2.085	2.250	87.4	76.42	2.099	2.261	87.8	76.22	2.101	2.264	87.9	87.7
8	75.37	2.129	2.298	89.2	74.93	2.141	2.306	89.5	74.68	2.144	2.311	89.7	89.5
10	74.63	2.150	2.321	90.1	74.24	2.161	2.328	90.4	74.01	2.163	2.332	90.5	90.3
20	72.54	2.212	2.388	92.7	72.26	2.220	2.392	92.8	72.11	2.220	2.394	92.9	92.8
30	71.43	2.246	2.425	94.1	71.25	2.251	2.425	94.2	71.15	2.250	2.426	94.2	94.2
40	70.76	2.268	2.448	95.0	70.61	2.272	2.447	95.0	70.55	2.269	2.446	95.0	95.0
50	70.31	2.282	2.463	95.6	70.19	2.285	2.462	95.6	70.11	2.284	2.462	95.6	95.6
60	69.95	2.294	2.476	96.1	69.87	2.296	2.473	96.0	69.81	2.294	2.472	96.0	96.0
80	69.51	2.308	2.492	96.7	69.43	2.310	2.489	96.6	69.36	2.308	2.488	96.6	96.6
95	69.32	2.315	2.498	97.0	69.24	2.317	2.496	96.9	69.12	2.316	2.497	96.9	96.9
100	69.25	2.317	2.501	97.1	69.18	2.319	2.498	97.0	69.07	2.318	2.499	97.0	97.0
125	69.06	2.323	2.508	97.4	68.97	2.326	2.506	97.3	68.8	2.327	2.509	97.4	97.4
150	68.92	2.328	2.513	97.6	68.85	2.330	2.510	97.4	68.6	2.334	2.516	97.7	97.6

Specimen 1	Specimen 2	Specimen 3
C = 1.079	C = 1.077	C = 1.078
G_{mb} = 2.513	G_{mb} = 2.510	G_{mb} = 2.516
G_{mm} = 2.576	G_{mm} = 2.576	G_{mm} = 2.576

Table 40: Gyratory Compactor Test Results (5.5% Asphalt, 0.2% Polypropylene-6mm)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	75.24	2.134	2.289	89.6	76.55	2.100	2.282	89.3	76.47	2.108	2.274	89.0	89.3
8	73.67	2.179	2.338	91.5	74.92	2.145	2.332	91.3	74.89	2.153	2.322	90.9	91.2
10	72.98	2.200	2.360	92.4	74.2	2.166	2.354	92.1	74.21	2.172	2.344	91.7	92.1
20	71.17	2.256	2.420	94.7	72.19	2.226	2.420	94.7	72.21	2.233	2.409	94.3	94.6
30	70.4	2.280	2.447	95.8	71.23	2.256	2.453	96.0	71.33	2.260	2.438	95.4	95.7
40	69.97	2.294	2.462	96.3	70.64	2.275	2.473	96.8	70.79	2.277	2.457	96.2	96.4
50	69.66	2.305	2.473	96.8	70.26	2.288	2.486	97.3	70.49	2.287	2.467	96.6	96.9
60	69.49	2.310	2.479	97.0	69.95	2.298	2.497	97.7	70.25	2.295	2.476	96.9	97.2
80	69.3	2.317	2.485	97.3	69.63	2.308	2.509	98.2	69.95	2.305	2.486	97.3	97.6
95	69.21	2.320	2.489	97.4	69.48	2.313	2.514	98.4	69.86	2.308	2.490	97.4	97.7
100	69.19	2.320	2.489	97.4	69.42	2.315	2.516	98.5	69.82	2.309	2.491	97.5	97.8
125	69.13	2.322	2.492	97.5	69.30	2.319	2.521	98.7	69.7	2.313	2.495	97.7	98.0
150	69.09	2.324	2.493	97.6	69.24	2.321	2.523	98.7	69.6	2.316	2.499	97.8	98.0

Specimen 1	Specimen 2	Specimen 3
C = 1.073	C = 1.087	C = 1.079
G_{mb} = 2.493	G_{mb} = 2.523	G_{mb} = 2.499
G_{mm} = 2.555	G_{mm} = 2.555	G_{mm} = 2.555

Table 41: Gyratory Compactor Test Results (3.5% Asphalt, 0.3% Polypropylene-6mm)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	77.34	2.041	2.204	83.6	77.09	2.048	2.204	83.6	78.46	2.016	2.196	83.3	83.5
8	76.01	2.077	2.243	85.0	75.72	2.085	2.244	85.1	77.11	2.052	2.234	84.7	84.9
10	75.4	2.094	2.261	85.7	75.1	2.102	2.262	85.8	76.46	2.069	2.253	85.4	85.6
20	73.67	2.143	2.314	87.8	73.28	2.154	2.318	87.9	74.63	2.120	2.308	87.5	87.7
30	72.77	2.169	2.343	88.8	72.35	2.182	2.348	89.0	73.76	2.145	2.336	88.6	88.8
40	72.16	2.188	2.362	89.6	71.75	2.200	2.368	89.8	72.99	2.168	2.360	89.5	89.6
50	71.72	2.201	2.377	90.1	71.28	2.215	2.383	90.4	72.54	2.181	2.375	90.1	90.2
60	71.38	2.211	2.388	90.6	70.91	2.226	2.396	90.9	72.13	2.193	2.388	90.6	90.7
80	70.88	2.227	2.405	91.2	70.42	2.242	2.413	91.5	71.58	2.210	2.407	91.3	91.3
95	70.62	2.235	2.414	91.5	70.12	2.251	2.423	91.9	71.27	2.220	2.417	91.7	91.7
100	70.56	2.237	2.416	91.6	70.03	2.254	2.426	92.0	71.17	2.223	2.421	91.8	91.8
125	70.23	2.248	2.427	92.0	69.72	2.264	2.437	92.4	70.8	2.235	2.433	92.3	92.2
150	69.98	2.256	2.436	92.4	69.43	2.274	2.447	92.8	70.52	2.244	2.443	92.6	92.6

Specimen 1	Specimen 2	Specimen 3
C = 1.080	C = 1.076	C = 1.089
Gmb = 2.436	Gmb = 2.447	Gmb = 2.443
Gmm = 2.637	Gmm = 2.637	Gmm = 2.637

Table 42: Gyratory Compactor Test Results (4.0% Asphalt, 0.3% Polypropylene-6mm)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	77.49	2.050	2.215	84.7	77.04	2.060	2.220	84.9	77.36	2.058	2.213	84.6	84.7
8	76.12	2.087	2.255	86.2	75.71	2.096	2.259	86.3	75.93	2.096	2.255	86.2	86.2
10	75.47	2.105	2.274	86.9	75.06	2.114	2.278	87.1	75.28	2.115	2.274	86.9	87.0
20	73.67	2.156	2.330	89.1	73.31	2.165	2.333	89.2	73.4	2.169	2.333	89.2	89.2
30	72.72	2.184	2.360	90.2	72.35	2.193	2.364	90.4	72.45	2.197	2.363	90.3	90.3
40	72.06	2.204	2.382	91.0	71.76	2.211	2.383	91.1	71.82	2.216	2.384	91.1	91.1
50	71.57	2.219	2.398	91.7	71.32	2.225	2.398	91.7	71.37	2.230	2.399	91.7	91.7
60	71.23	2.230	2.410	92.1	70.98	2.236	2.409	92.1	71.03	2.241	2.411	92.1	92.1
80	70.62	2.249	2.430	92.9	70.52	2.250	2.425	92.7	70.53	2.257	2.428	92.8	92.8
95	70.33	2.259	2.440	93.3	70.23	2.260	2.435	93.1	70.28	2.265	2.436	93.1	93.2
100	70.22	2.262	2.444	93.4	70.16	2.262	2.437	93.2	70.19	2.268	2.439	93.3	93.3
125	69.86	2.274	2.457	93.9	69.84	2.272	2.449	93.6	69.89	2.278	2.450	93.7	93.7
150	69.57	2.283	2.467	94.3	69.6	2.280	2.457	93.9	69.66	2.285	2.458	94.0	94.1

Specimen 1	Specimen 2	Specimen 3
C = 1.080	C = 1.077	C = 1.076
Gmb = 2.467	Gmb = 2.457	Gmb = 2.458
Gmm = 2.616	Gmm = 2.616	Gmm = 2.616

Table 43: Gyratory Compactor Test Results (4.5% Asphalt, 0.3% Polypropylene-6mm)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	77.36	2.060	2.225	85.7	76.65	2.078	2.228	85.8	76.2	2.096	2.234	86.0	85.8
8	75.81	2.102	2.270	87.4	75.22	2.118	2.270	87.5	74.72	2.137	2.278	87.8	87.6
10	75.11	2.122	2.291	88.3	74.56	2.136	2.290	88.2	74.09	2.156	2.297	88.5	88.3
20	73.14	2.179	2.353	90.6	72.69	2.191	2.349	90.5	72.22	2.211	2.357	90.8	90.6
30	72.12	2.210	2.386	91.9	71.7	2.222	2.382	91.7	71.27	2.241	2.388	92.0	91.9
40	71.5	2.229	2.407	92.7	71.04	2.242	2.404	92.6	70.69	2.259	2.408	92.8	92.7
50	71.05	2.243	2.422	93.3	70.57	2.257	2.420	93.2	70.26	2.273	2.423	93.3	93.3
60	70.7	2.254	2.434	93.8	70.21	2.269	2.432	93.7	69.96	2.283	2.433	93.7	93.7
80	70.24	2.269	2.450	94.4	69.69	2.286	2.450	94.4	69.47	2.299	2.450	94.4	94.4
95	69.96	2.278	2.460	94.8	69.42	2.294	2.460	94.8	69.21	2.307	2.459	94.7	94.8
100	69.92	2.279	2.461	94.8	69.36	2.296	2.462	94.8	69.16	2.309	2.461	94.8	94.8
125	69.6	2.290	2.473	95.2	69.06	2.306	2.473	95.3	68.87	2.319	2.472	95.2	95.2
150	69.42	2.296	2.479	95.5	68.86	2.313	2.480	95.5	68.69	2.325	2.478	95.5	95.5

Specimen 1	Specimen 2	Specimen 3
C = 1.080	C = 1.072	C = 1.066
Gmb = 2.479	Gmb = 2.480	Gmb = 2.478
Gmm = 2.596	Gmm = 2.596	Gmm = 2.596

Table 44: Gyratory Compactor Test Results (5.0% Asphalt, 0.3% Polypropylene-6mm)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	76.85	2.093	2.259	87.7	75.96	2.113	2.267	88.0	77.82	2.062	2.217	86.1	87.3
8	75.34	2.135	2.305	89.5	74.47	2.156	2.313	89.8	76.27	2.104	2.262	87.8	89.0
10	74.64	2.155	2.326	90.3	73.83	2.174	2.333	90.6	75.55	2.124	2.284	88.7	89.9
20	72.75	2.211	2.387	92.7	72.07	2.227	2.390	92.8	73.43	2.185	2.350	91.2	92.2
30	71.8	2.240	2.418	93.9	71.22	2.254	2.418	93.9	72.36	2.218	2.384	92.6	93.5
40	71.21	2.258	2.438	94.7	70.68	2.271	2.437	94.6	71.66	2.239	2.408	93.5	94.3
50	70.81	2.271	2.452	95.2	70.31	2.283	2.449	95.1	71.16	2.255	2.425	94.1	94.8
60	70.52	2.281	2.462	95.6	70.07	2.291	2.458	95.4	70.79	2.267	2.437	94.6	95.2
80	70.15	2.293	2.475	96.1	69.72	2.302	2.470	95.9	70.28	2.283	2.455	95.3	95.8
95	69.96	2.299	2.482	96.4	69.54	2.308	2.477	96.1	69.98	2.293	2.465	95.7	96.1
100	69.9	2.301	2.484	96.4	69.48	2.310	2.479	96.2	69.95	2.294	2.467	95.8	96.1
125	69.69	2.308	2.492	96.7	69.33	2.315	2.484	96.4	69.61	2.305	2.479	96.2	96.4
150	69.54	2.313	2.497	96.9	69.22	2.319	2.488	96.6	69.43	2.311	2.485	96.5	96.7

Specimen 1	Specimen 2	Specimen 3
C = 1.080	C = 1.073	C = 1.075
Gmb = 2.497	Gmb = 2.488	Gmb = 2.485
Gmm = 2.576	Gmm = 2.576	Gmm = 2.576

Table 45: Gyratory Compactor Test Results (5.5% Asphalt, 0.3% Polypropylene-6mm)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	77.68	2.069	2.241	87.7	77.36	2.081	2.247	87.9	76.85	2.097	2.262	88.6	88.1
8	76.05	2.113	2.289	89.6	75.83	2.123	2.292	89.7	75.28	2.141	2.310	90.4	89.9
10	75.34	2.133	2.310	90.4	75.10	2.143	2.314	90.6	74.59	2.160	2.331	91.2	90.7
20	73.24	2.194	2.376	93.0	73.14	2.201	2.376	93.0	72.68	2.217	2.392	93.6	93.2
30	72.2	2.226	2.411	94.4	72.09	2.233	2.411	94.4	71.81	2.244	2.421	94.8	94.5
40	71.54	2.246	2.433	95.2	71.48	2.252	2.431	95.2	71.3	2.260	2.439	95.4	95.3
50	71.1	2.260	2.448	95.8	71.05	2.265	2.446	95.7	70.97	2.271	2.450	95.9	95.8
60	70.77	2.270	2.459	96.3	70.73	2.276	2.457	96.2	70.37	2.290	2.471	96.7	96.4
80	70.34	2.284	2.474	96.8	70.28	2.290	2.473	96.8	70.4	2.289	2.470	96.7	96.8
95	70.14	2.291	2.481	97.1	70.07	2.297	2.480	97.1	70.2	2.295	2.477	96.9	97.0
100	70.07	2.293	2.484	97.2	70.02	2.299	2.482	97.1	70.16	2.297	2.478	97.0	97.1
125	69.9	2.299	2.490	97.5	69.81	2.306	2.490	97.4	69.95	2.304	2.486	97.3	97.4
150	69.76	2.303	2.495	97.7	69.66	2.311	2.495	97.7	69.8	2.309	2.491	97.5	97.6
	C = 1.083 Gmb = 2.495 Gmm = 2.555				C = 1.080 Gmb = 2.495 Gmm = 2.555				C = 1.079 Gmb = 2.491 Gmm = 2.555				

Table 46: Gyratory Compactor Test Results (4.20% Asphalt (Optimum), 0.5% Polypropylene-6mm)

	Specimen 1				**Specimen 2**				**Specimen 3**				**Average**
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	77.82	2.047	2.200	84.4	78.04	2.044	2.204	84.6	77.96	2.043	2.198	84.3	84.4
8	76.31	2.088	2.243	86.1	76.61	2.083	2.246	86.2	76.54	2.081	2.238	85.9	86.1
10	75.59	2.108	2.265	86.9	75.95	2.101	2.265	86.9	75.94	2.098	2.256	86.6	86.8
20	73.59	2.165	2.326	89.3	74	2.156	2.325	89.2	74.01	2.153	2.315	88.8	89.1
30	72.55	2.196	2.360	90.5	72.99	2.186	2.357	90.4	73.05	2.181	2.345	90.0	90.3
40	71.88	2.216	2.382	91.4	72.33	2.206	2.378	91.3	72.39	2.201	2.367	90.8	91.2
50	71.39	2.232	2.398	92.0	71.83	2.221	2.395	91.9	71.9	2.216	2.383	91.4	91.8
60	71.05	2.242	2.410	92.5	71.48	2.232	2.407	92.4	71.57	2.226	2.394	91.9	92.3
80	70.56	2.258	2.426	93.1	70.97	2.248	2.424	93.0	71.06	2.242	2.411	92.5	92.9
95	70.28	2.267	2.436	93.5	70.66	2.258	2.435	93.4	70.79	2.250	2.420	92.9	93.3
100	70.19	2.270	2.439	93.6	70.57	2.261	2.438	93.5	70.73	2.252	2.422	93.0	93.4
125	69.9	2.279	2.449	94.0	70.24	2.271	2.449	94.0	70.4	2.263	2.434	93.4	93.8
150	69.62	2.288	2.459	94.4	69.96	2.281	2.459	94.4	70.16	2.271	2.442	93.7	94.2

Specimen 1	Specimen 2	Specimen 3
C = 1.075	C = 1.078	C = 1.075
Gmb = 2.459	Gmb = 2.459	Gmb = 2.442
Gmm = 2.606	Gmm = 2.606	Gmm = 2.606

Table 47: Gyratory Compactor Test Results (4.20% Asphalt (Optimum), 0.3% Polypropylene-12mm)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	77.24	2.062	2.220	85.2	77.01	2.070	2.221	85.2	77.45	2.060	2.221	85.2	85.2
8	75.77	2.102	2.263	86.8	75.64	2.107	2.261	86.8	76.04	2.098	2.262	86.8	86.8
10	75.08	2.121	2.284	87.6	74.99	2.126	2.281	87.5	75.37	2.117	2.283	87.6	87.6
20	73.25	2.174	2.341	89.8	73.14	2.180	2.339	89.7	73.44	2.173	2.342	89.9	89.8
30	72.29	2.203	2.372	91.0	72.18	2.208	2.370	90.9	72.46	2.202	2.374	91.1	91.0
40	71.64	2.223	2.393	91.8	71.51	2.229	2.392	91.8	71.78	2.223	2.397	92.0	91.9
50	71.15	2.238	2.410	92.5	71.05	2.244	2.407	92.4	71.32	2.237	2.412	92.6	92.5
60	70.77	2.250	2.423	93.0	70.71	2.254	2.419	92.8	70.96	2.248	2.424	93.0	92.9
80	70.27	2.266	2.440	93.6	70.18	2.271	2.437	93.5	70.42	2.266	2.443	93.7	93.6
95	69.99	2.275	2.450	94.0	69.91	2.280	2.447	93.9	70.14	2.275	2.453	94.1	94.0
100	69.92	2.277	2.452	94.1	69.8	2.284	2.450	94.0	70.04	2.278	2.456	94.3	94.1
125	69.58	2.288	2.464	94.6	69.46	2.295	2.462	94.5	69.72	2.288	2.467	94.7	94.6
150	69.36	2.296	2.472	94.9	69.22	2.303	2.471	94.8	69.48	2.296	2.476	95.0	94.9

C = 1.077
Gmb = 2.472
Gmm = 2.606

C = 1.073
Gmb = 2.471
Gmm = 2.606

C = 1.078
Gmb = 2.476
Gmm = 2.606

Table 48: Gyratory Compactor Test Results (4.20% Asphalt (Optimum), 0.5% Polypropylene-12mm)

	Specimen 1				Specimen 2				Specimen 3				Average
Gyrations	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	Ht, mm	Gmb(eas)	Gmb(Corr)	%Gmm	%Gmm
5	78.89	2.030	2.186	83.9	78.17	2.044	2.189	84.0	78.46	2.035	2.180	83.6	83.8
8	77.44	2.068	2.227	85.4	76.77	2.081	2.229	85.5	77.1	2.071	2.218	85.1	85.3
10	76.79	2.085	2.246	86.2	76.14	2.098	2.248	86.3	76.42	2.089	2.238	85.9	86.1
20	74.83	2.140	2.304	88.4	74.27	2.151	2.304	88.4	74.53	2.142	2.295	88.1	88.3
30	73.82	2.169	2.336	89.6	73.31	2.179	2.335	89.6	73.55	2.170	2.325	89.2	89.5
40	73.15	2.189	2.357	90.5	72.7	2.198	2.354	90.3	72.93	2.189	2.345	90.0	90.3
50	72.67	2.203	2.373	91.1	72.23	2.212	2.369	90.9	72.46	2.203	2.360	90.6	90.9
60	72.32	2.214	2.384	91.5	71.87	2.223	2.381	91.4	72.07	2.215	2.373	91.1	91.3
80	71.76	2.231	2.403	92.2	71.37	2.239	2.398	92.0	71.5	2.233	2.392	91.8	92.0
95	71.49	2.240	2.412	92.6	71.1	2.247	2.407	92.4	71.2	2.242	2.402	92.2	92.4
100	71.38	2.243	2.416	92.7	71.03	2.249	2.409	92.5	71.1	2.245	2.406	92.3	92.5
125	71.05	2.253	2.427	93.1	70.67	2.261	2.422	92.9	70.77	2.256	2.417	92.7	92.9
150	70.79	2.262	2.436	93.5	70.43	2.269	2.430	93.2	70.5	2.264	2.426	93.1	93.3

Specimen 1	Specimen 2	Specimen 3
C = 1.077	C = 1.071	C = 1.071
Gmb = 2.436	Gmb = 2.430	Gmb = 2.426
Gmm = 2.606	Gmm = 2.606	Gmm = 2.606

A.2 Calculation of Air Voids

Table 49: Calculation of Air Voids by SGC (3.5% Asphalt, No Polypropylene)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	84.2	15.8	84.2	15.8	84.6	15.4	84.3	15.7
8	85.8	14.2	85.7	14.3	86.1	13.9	85.9	14.1
10	86.4	13.6	86.4	13.6	86.8	13.2	86.5	13.5
20	88.4	11.6	88.5	11.5	88.8	11.2	88.6	11.4
30	89.6	10.4	89.7	10.3	89.9	10.1	89.7	10.3
40	90.3	9.7	90.5	9.5	90.7	9.3	90.5	9.5
50	90.9	9.1	91.2	8.8	91.3	8.7	91.1	8.9
60	91.4	8.6	91.6	8.4	91.8	8.3	91.6	8.4
80	92.0	8.0	92.3	7.7	92.4	7.6	92.2	7.8
95	92.4	7.6	92.8	7.2	92.8	7.2	92.7	7.3
100	92.5	7.5	92.9	7.1	92.9	7.1	92.8	7.2
125	93.0	7.0	93.3	6.7	93.4	6.6	93.2	6.8
150	93.3	6.7	93.7	6.3	93.8	6.2	93.6	6.4

Table 50: Calculation of Air Voids by SGC (4.0% Asphalt, No Polypropylene)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	85.8	14.2	85.5	14.5	85.8	14.2	85.7	14.3
8	87.3	12.7	87.1	12.9	86.9	13.1	87.1	12.9
10	88.0	12	87.9	12.1	88.0	12	88.0	12
20	90.1	9.9	90.1	9.9	90.2	9.8	90.1	9.9
30	91.3	8.7	91.3	8.7	91.3	8.7	91.3	8.7
40	92.1	7.9	92.1	7.9	92.1	7.9	92.1	7.9
50	92.7	7.3	92.6	7.4	92.7	7.3	92.7	7.3
60	93.1	6.9	93.1	6.9	93.1	6.9	93.1	6.9
80	93.8	6.2	93.8	6.2	93.8	6.2	93.8	6.2
95	94.3	5.7	94.2	5.8	94.2	5.8	94.2	5.8
100	94.3	5.7	94.3	5.7	94.3	5.7	94.3	5.7
125	94.8	5.2	94.8	5.2	94.8	5.2	94.8	5.2
150	95.1	4.9	95.1	4.9	95.2	4.8	95.1	4.9

Table 51: Calculation of Air Voids by SGC (4.5% Asphalt, No Polypropylene)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	85.9	14.1	86.6	13.4	87.0	13	86.5	13.5
8	88.8	11.2	88.3	11.7	88.7	11.3	88.6	11.4
10	89.6	10.4	89.1	10.9	89.5	10.5	89.4	10.6
20	91.9	8.1	91.4	8.6	91.9	8.1	91.7	8.3
30	93.2	6.8	92.7	7.3	93.2	6.8	93.0	7.0
40	94.0	6	93.6	6.4	94.0	6	93.9	6.1
50	94.6	5.4	94.2	5.8	94.7	5.3	94.5	5.5
60	95.1	4.9	94.6	5.4	95.1	4.9	94.9	5.1
80	95.8	4.2	95.3	4.7	95.8	4.2	95.6	4.4
95	96.2	3.8	95.7	4.3	96.1	3.9	96.0	4.0
100	96.3	3.7	95.8	4.2	96.2	3.8	96.1	3.9
125	96.8	3.2	96.3	3.7	96.5	3.5	96.5	3.5
150	97.1	2.9	96.6	3.4	96.7	3.3	96.8	3.2

Table 52: Calculation of Air Voids by SGC (5.0% Asphalt, No Polypropylene)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	88.6	11.4	88.1	11.9	89.2	10.8	88.6	11.4
8	90.3	9.7	89.8	10.2	91.0	9	90.4	9.6
10	91.1	8.9	90.3	9.7	91.7	8.3	91.0	9.0
20	93.6	6.4	93.1	6.9	94.2	5.8	93.6	6.4
30	94.9	5.1	94.3	5.7	95.5	4.5	94.9	5.1
40	95.7	4.3	95.2	4.8	96.3	3.7	95.7	4.3
50	96.3	3.7	95.8	4.2	96.8	3.2	96.3	3.7
60	96.8	3.2	96.3	3.7	97.2	2.8	96.8	3.2
80	97.4	2.6	96.9	3.1	97.7	2.3	97.3	2.7
95	97.7	2.3	97.2	2.8	98.0	2	97.6	2.4
100	97.8	2.2	97.4	2.6	98.0	2	97.7	2.3
125	98.1	1.9	97.7	2.3	98.2	1.8	98.0	2.0
150	98.2	1.8	98.0	2	98.3	1.7	98.2	1.8

Table 53: Calculation of Air Voids by SGC (5.5% Asphalt, No Polypropylene)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	86.5	13.5	89.2	10.8	90.0	10	88.6	11.4
8	89.9	10.1	91.1	8.9	91.9	8.1	91.0	9.0
10	91.3	8.7	92.0	8.0	92.7	7.3	92.0	8.0
20	94.7	5.3	94.5	5.5	95.1	4.9	94.8	5.2
30	96.3	3.7	95.8	4.2	96.3	3.7	96.1	3.9
40	97.1	2.9	96.6	3.4	97.1	2.9	96.9	3.1
50	97.6	2.4	97.1	2.9	97.6	2.4	97.4	2.6
60	97.9	2.1	97.5	2.5	97.9	2.1	97.8	2.2
80	98.3	1.7	98.0	2	98.1	1.9	98.1	1.9
95	98.5	1.5	98.2	1.8	98.3	1.7	98.3	1.7
100	98.5	1.5	98.3	1.7	98.3	1.7	98.4	1.6
125	98.6	1.4	98.5	1.5	98.5	1.5	98.5	1.5
150	98.7	1.3	98.6	1.4	98.6	1.4	98.6	1.4

Table 54: Calculation of Air Voids by SGC (3.5% Asphalt, 0.1% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	84.1	15.9	83.6	16.4	83.4	16.6	83.7	16.3
8	85.5	14.5	85.1	14.9	84.9	15.1	85.2	14.8
10	86.1	13.9	85.8	14.2	85.6	14.4	85.8	14.2
20	88.1	11.9	87.9	12.1	87.8	12.2	87.9	12.1
30	89.1	10.9	89.1	10.9	88.9	11.1	89.0	11.0
40	89.9	10.1	89.9	10.1	89.7	10.3	89.8	10.2
50	90.4	9.6	90.5	9.5	90.3	9.7	90.4	9.6
60	90.9	9.1	90.9	9.1	90.8	9.2	90.9	9.1
80	91.5	8.5	91.6	8.4	91.5	8.5	91.5	8.5
95	91.9	8.1	92.0	8	91.9	8.1	91.9	8.1
100	92.0	8.0	92.1	7.9	92.1	7.9	92.1	7.9
125	92.5	7.5	92.6	7.4	92.5	7.5	92.5	7.5
150	92.9	7.1	92.9	7.1	92.9	7.1	92.9	7.1

Table 55: Calculation of Air Voids by SGC (4.0% Asphalt, 0.1% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	85.4	14.6	85.4	14.6	85.9	14.1	85.6	14.4
8	87.0	13	87.0	13	87.5	12.5	87.2	12.8
10	87.8	12.2	87.9	12.1	88.2	11.8	88.0	12.0
20	90.2	9.8	90.2	9.8	88.0	12	89.5	10.5
30	91.5	8.5	91.4	8.6	91.6	8.4	91.5	8.5
40	92.3	7.7	92.3	7.7	92.5	7.5	92.4	7.6
50	92.9	7.1	92.9	7.1	93.0	7.0	92.9	7.1
60	93.4	6.6	93.4	6.6	93.5	6.5	93.4	6.6
80	94.1	5.9	94.1	5.9	94.2	5.8	94.1	5.9
95	94.5	5.5	94.5	5.5	94.6	5.4	94.5	5.5
100	94.7	5.3	94.6	5.4	94.7	5.3	94.7	5.3
125	95.1	4.9	95.1	4.9	95.2	4.8	95.1	4.9
150	95.4	4.6	95.4	4.6	95.6	4.4	95.5	4.5

Table 56: Calculation of Air Voids by SGC (4.5% Asphalt, 0.1% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	87.4	12.6	87.0	13	87.1	12.9	87.2	12.8
8	89.2	10.8	88.6	11.4	88.7	11.3	88.8	11.2
10	90.0	10	89.4	10.6	89.5	10.5	89.6	10.4
20	92.5	7.5	91.7	8.3	91.8	8.2	92.0	8.0
30	93.8	6.2	92.9	7.1	93.2	6.8	93.3	6.7
40	94.7	5.3	93.8	6.2	94.0	6	94.2	5.8
50	95.3	4.7	94.4	5.6	94.6	5.4	94.8	5.2
60	95.8	4.2	94.9	5.1	95.1	4.9	95.3	4.7
80	96.5	3.5	95.6	4.4	95.9	4.1	96.0	4.0
95	96.8	3.2	95.9	4.1	96.2	3.8	96.3	3.7
100	96.9	3.1	96.0	4	96.3	3.7	96.4	3.6
125	97.3	2.7	96.4	3.6	96.7	3.3	96.8	3.2
150	97.6	2.4	96.7	3.3	97.0	3	97.1	2.9

Table 57: Calculation of Air Voids by SGC (5.0% Asphalt, 0.1% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	88.3	11.7	89.1	10.9	88.8	11.2	88.7	11.3
8	90.1	9.9	91.0	9.0	90.6	9.4	90.6	9.4
10	91.0	9.0	91.8	8.2	91.4	8.6	91.4	8.6
20	93.5	6.5	94.4	5.6	93.6	6.4	93.8	6.2
30	94.7	5.3	95.7	4.3	94.8	5.2	95.1	4.9
40	95.5	4.5	96.3	3.7	95.6	4.4	95.8	4.2
50	95.9	4.1	96.8	3.2	96.1	3.9	96.3	3.7
60	96.3	3.7	97.1	2.9	96.4	3.6	96.6	3.4
80	96.8	3.2	97.5	2.5	96.9	3.1	97.1	2.9
95	96.9	3.1	97.7	2.3	97.2	2.8	97.3	2.7
100	97.0	3.0	97.7	2.3	97.2	2.8	97.3	2.7
125	97.3	2.7	97.9	2.1	97.5	2.5	97.6	2.4
150	97.4	11.7	98.0	2.0	97.7	2.3	97.7	2.3

Table 58: Calculation of Air Voids by SGC (5.5% Asphalt, 0.1% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	88.8	11.2	89.3	10.7	89.1	10.9	89.1	10.9
8	90.8	9.2	91.5	8.5	91.0	9.0	91.1	8.9
10	91.7	8.3	92.0	8.0	91.8	8.2	91.8	8.2
20	94.3	5.7	94.7	5.3	94.3	5.7	94.4	5.6
30	95.5	4.5	95.9	4.1	95.5	4.5	95.6	4.4
40	96.3	3.7	96.7	3.3	96.3	3.7	96.4	3.6
50	96.8	3.2	97.2	2.8	96.7	3.3	96.9	3.1
60	97.2	2.8	97.5	2.5	97.0	3.0	97.2	2.8
80	97.7	2.3	97.9	2.1	97.3	2.7	97.6	2.4
95	97.8	2.2	98.1	1.9	97.4	2.6	97.8	2.2
100	97.9	2.1	98.1	1.9	97.4	2.6	97.8	2.2
125	98.1	1.9	98.3	1.7	97.5	2.5	98.0	2.0
150	98.2	1.8	98.3	1.7	97.6	2.4	98.0	2.0

Table 59: Calculation of Air Voids by SGC (3.5% Asphalt, 0.2% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	82.9	17.1	82.4	17.6	82.3	17.7	82.5	17.5
8	84.4	15.6	83.9	16.1	83.8	16.2	84.0	16.0
10	85.1	14.9	84.5	15.5	84.5	15.5	84.7	15.3
20	87.3	12.7	86.7	13.3	86.7	13.3	86.9	13.1
30	88.5	11.5	87.9	12.1	88.0	12.0	88.1	11.9
40	89.3	10.7	88.7	11.3	88.8	11.2	88.9	11.1
50	89.9	10.1	89.3	10.7	89.4	10.6	89.5	10.5
60	90.4	9.6	89.8	10.2	89.9	10.1	90.0	10.0
80	91.1	8.9	90.6	9.4	90.6	9.4	90.8	9.2
95	91.4	8.6	91.0	9.0	91.1	8.9	91.2	8.8
100	91.5	8.5	91.1	8.9	91.2	8.8	91.3	8.7
125	92.0	8.0	91.6	8.4	91.7	8.3	91.8	8.2
150	92.4	7.6	92.0	8.0	92.1	7.9	92.2	7.8

Table 60: Calculation of Air Voids by SGC (4.0% Asphalt, 0.2% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	85.0	15	82.2	17.8	85.4	14.6	84.2	15.8
8	86.6	13.4	83.4	16.6	86.9	13.1	85.6	14.4
10	87.4	12.6	84.1	15.9	87.7	12.3	86.4	13.6
20	89.6	10.4	88.5	11.5	89.8	10.2	89.3	10.7
30	90.9	9.1	90.3	9.7	91.0	9.0	90.7	9.3
40	91.7	8.3	91.3	8.7	91.9	8.1	91.6	8.4
50	92.4	7.6	92.1	7.9	92.4	7.6	92.3	7.7
60	92.8	7.2	92.6	7.4	92.9	7.1	92.8	7.2
80	93.5	6.5	93.4	6.6	93.6	6.4	93.5	6.5
95	93.9	6.1	93.9	6.1	94.0	6	93.9	6.1
100	94.0	6	94.0	6	94.1	5.9	94.0	6
125	94.4	5.6	94.5	5.5	94.5	5.5	94.5	5.5
150	94.7	5.3	94.8	5.2	94.9	5.1	94.8	5.2

Table 61: Calculation of Air Voids by SGC (4.5% Asphalt, 0.2% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	86.8	13.2	86.7	13.3	86.3	13.7	86.6	13.4
8	88.5	11.5	88.5	11.5	87.9	12.1	88.3	11.7
10	89.3	10.7	89.2	10.8	88.8	11.2	89.1	10.9
20	91.7	8.3	91.5	8.5	91.1	8.9	91.4	8.6
30	92.9	7.1	92.7	7.3	92.4	7.6	92.7	7.3
40	93.7	6.3	93.6	6.4	93.3	6.7	93.5	6.5
50	94.3	5.7	94.2	5.8	93.9	6.1	94.1	5.9
60	94.7	5.3	94.7	5.3	94.3	5.7	94.6	5.4
80	95.4	4.6	95.4	4.6	95.1	4.9	95.3	4.7
95	95.8	4.2	95.7	4.3	95.4	4.6	95.6	4.4
100	95.9	4.1	95.8	4.2	95.5	4.5	95.7	4.3
125	96.4	3.6	96.2	3.8	96.0	4.0	96.2	3.8
150	96.6	3.4	96.5	3.5	96.3	3.7	96.5	3.5

Table 62: Calculation of Air Voids by SGC (5.0% Asphalt, 0.2% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	87.3	12.7	87.8	12.2	87.9	12.1	87.7	12.3
8	89.2	10.8	89.5	10.5	89.7	10.3	89.5	10.5
10	90.1	9.9	90.4	9.6	90.5	9.5	90.3	9.7
20	92.7	7.3	92.8	7.2	92.9	7.1	92.8	7.2
30	94.1	5.9	94.1	5.9	94.2	5.8	94.1	5.9
40	95.0	5.0	95.0	5.0	95.0	5.0	95	5
50	95.6	4.4	95.6	4.4	95.6	4.4	95.6	4.4
60	96.1	3.9	96.0	4.0	96.0	4.0	96.0	4.0
80	96.7	3.3	96.6	3.4	96.6	3.4	96.6	3.4
95	97.0	3.0	96.9	3.1	96.9	3.1	96.9	3.1
100	97.1	2.9	97.0	3.0	97.0	3.0	97.0	3.0
125	97.3	2.7	97.3	2.7	97.4	2.6	97.3	2.7
150	97.5	2.5	97.4	2.6	97.7	2.3	97.5	2.5

Table 63: Calculation of Air Voids by SGC (5.5% Asphalt, 0.2% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	89.6	10.4	89.3	10.7	89.2	10.8	89.4	10.6
8	91.5	8.5	91.3	8.7	90.9	9.1	91.2	8.8
10	92.4	7.6	92.2	7.8	91.7	8.3	92.1	7.9
20	94.7	5.3	94.7	5.3	94.3	5.7	94.6	5.4
30	95.8	4.2	96.0	4.2	95.4	4.6	95.7	4.3
40	96.3	3.7	96.8	3.2	96.2	3.8	96.4	3.6
50	96.8	3.2	97.3	2.7	96.6	3.4	96.9	3.1
60	97.0	3.0	97.7	2.3	96.9	3.1	97.2	2.8
80	97.3	2.7	98.2	1.8	97.3	2.7	97.6	2.4
95	97.4	2.6	98.4	1.6	97.4	2.6	97.7	2.3
100	97.4	2.6	98.5	1.5	97.5	2.5	97.8	2.2
125	97.5	2.5	98.7	1.3	97.7	2.3	98.0	2.0
150	97.6	2.4	98.7	1.3	97.8	2.2	98.0	2.0

Table 64: Calculation of Air Voids by SGC (3.5% Asphalt, 0.3% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	83.6	16.4	83.6	16.4	83.3	16.7	83.5	16.5
8	85.4	14.6	85.1	14.9	84.7	15.3	85.1	14.9
10	85.7	14.3	85.8	14.2	85.4	14.6	85.6	14.4
20	87.7	12.3	87.9	12.1	87.5	12.5	87.7	12.3
30	88.8	11.2	89.0	11.0	88.6	11.4	88.8	11.2
40	89.6	10.4	89.8	10.2	89.5	10.5	89.6	10.4
50	90.1	9.9	90.4	9.6	90.1	9.9	90.2	9.8
60	90.6	9.4	90.9	9.1	90.6	9.4	90.7	9.3
80	91.2	8.8	91.4	8.6	91.3	8.7	91.3	8.7
95	91.5	8.5	91.9	8.1	91.7	8.3	91.7	8.3
100	91.6	8.4	92.0	8.0	91.8	8.2	91.8	8.2
125	92.0	8.0	92.4	7.6	92.3	7.7	92.2	7.8
150	92.4	7.6	92.8	7.2	92.6	7.4	92.6	7.4

Table 65: Calculation of Air Voids by SGC (4.0% Asphalt, 0.3% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	84.7	15.3	84.8	15.2	84.6	15.4	84.7	15.3
8	86.2	13.8	86.3	13.7	86.2	13.8	86.2	13.8
10	86.9	13.1	87.1	12.9	86.9	13.1	87.0	13
20	89.1	10.9	89.2	10.8	89.2	10.8	89.2	10.8
30	90.2	9.8	90.3	9.7	90.3	9.7	90.3	9.7
40	91.0	9.0	91.1	8.9	91.1	8.9	91.1	8.9
50	91.7	8.3	91.7	8.3	91.7	8.3	91.7	8.3
60	92.1	7.9	92.1	7.9	92.1	7.9	92.1	7.9
80	92.9	7.1	92.7	7.3	92.8	7.2	92.8	7.2
95	93.3	6.7	93.1	6.9	93.1	6.9	93.2	6.8
100	93.4	6.6	93.2	6.8	93.5	6.5	93.4	6.6
125	93.9	6.1	93.6	6.4	93.6	6.4	93.7	6.3
150	94.3	5.7	93.9	6.1	94.0	6	94.1	5.9

Table 66: Calculation of Air Voids by SGC (4.5% Asphalt, 0.3% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	85.7	14.3	85.8	14.2	86.0	14	85.8	14.2
8	87.4	12.6	87.5	12.5	87.8	12.2	87.6	12.4
10	88.3	11.7	88.2	11.8	88.5	11.5	88.3	11.7
20	90.6	9.4	90.5	9.5	90.8	9.2	90.6	9.4
30	91.9	8.1	91.7	8.3	92.0	8	91.9	8.1
40	92.7	7.3	92.6	7.4	92.8	7.2	92.7	7.3
50	93.3	6.7	93.2	6.8	93.3	6.7	93.3	6.7
60	93.8	6.2	93.7	6.3	93.7	6.3	93.7	6.3
80	94.4	5.6	94.4	5.6	94.4	5.6	94.4	5.6
95	94.8	5.2	94.8	5.2	94.7	5.3	94.8	5.2
100	94.8	5.2	94.8	5.2	94.8	5.2	94.8	5.2
125	95.2	4.8	95.3	4.7	95.2	4.8	95.2	4.8
150	95.5	4.5	95.5	4.5	95.5	4.5	95.5	4.5

Table 67: Calculation of Air Voids by SGC (5.0% Asphalt, 0.3% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	87.7	12.3	88.0	12.0	86.1	13.9	87.3	12.7
8	89.5	10.5	89.8	10.2	87.8	12.2	89.0	11.0
10	90.3	9.7	90.5	9.5	88.6	11.4	89.8	10.2
20	92.7	7.3	92.8	7.2	91.2	8.8	92.2	7.8
30	93.9	6.1	93.9	6.1	92.6	7.4	93.5	6.5
40	94.7	5.3	94.6	5.4	93.5	6.5	94.3	5.7
50	95.2	4.8	95.1	4.9	94.1	5.9	94.8	5.2
60	95.6	4.4	95.4	4.6	94.6	5.4	95.2	4.8
80	96.1	3.9	95.9	4.1	95.3	4.7	95.8	4.2
95	96.4	3.6	96.1	3.9	95.7	4.3	96.1	3.9
100	96.4	3.6	96.2	3.8	95.7	4.3	96.1	3.9
125	96.7	3.3	96.4	3.6	96.2	3.8	96.4	3.6
150	96.9	3.1	96.6	3.4	96.5	3.5	96.7	3.3

Table 68: Calculation of Air Voids by SGC (5.5% Asphalt, 0.3% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	87.7	12.3	87.9	12.1	88.5	11.5	88.0	12.0
8	89.6	10.4	89.7	10.3	90.4	9.6	89.9	10.1
10	90.4	9.6	90.6	9.4	91.2	8.8	90.7	9.3
20	93.0	7.0	93.0	7.0	93.6	6.4	93.2	6.8
30	94.3	5.7	94.3	5.7	94.8	5.2	94.5	5.5
40	95.2	4.8	95.2	4.8	95.4	4.6	95.3	4.7
50	95.8	4.2	95.7	4.3	95.9	4.1	95.8	4.2
60	96.2	3.8	96.2	3.8	96.7	3.3	96.4	3.6
80	96.8	3.2	96.8	3.2	96.7	3.3	96.8	3.2
95	97.1	2.9	97.1	2.9	96.9	3.1	97.0	3.0
100	97.2	2.8	97.1	2.9	97.0	3.0	97.1	2.9
125	97.5	2.5	97.4	2.6	97.3	2.7	97.4	2.6
150	97.6	2.4	97.6	2.4	97.5	2.5	97.6	2.4

Table 69: Calculation of Air Voids by SGC (4.20% Asphalt, 0.5% PP – 6mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	84.4	15.6	84.6	15.4	84.3	15.7	84.4	15.6
8	86.1	13.9	86.2	13.8	85.9	14.1	86.1	13.9
10	86.9	13.1	86.9	13.1	86.6	13.4	86.8	13.2
20	89.3	10.7	89.2	10.8	88.8	11.2	89.1	10.9
30	90.5	9.5	90.4	9.6	90.0	10.0	90.3	9.7
40	91.4	8.6	91.3	8.7	90.8	9.2	91.2	8.8
50	92.0	8.0	91.9	8.1	91.4	8.6	91.8	8.2
60	92.5	7.5	92.3	7.7	91.9	8.1	92.2	7.8
80	93.1	6.9	93.0	7.0	92.5	7.5	92.9	7.1
95	93.5	6.5	93.4	6.6	92.9	7.1	93.3	6.7
100	93.6	6.4	93.5	6.5	93.0	7.1	93.4	6.6
125	94.0	6.0	94.0	6.0	93.4	6.6	93.8	6.2
150	94.4	5.6	94.4	5.6	93.7	6.3	94.2	5.8

Table 70: Calculation of Air Voids by SGC (4.20% Asphalt, 0.3% PP – 12mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	85.2	14.8	85.2	14.8	85.2	14.8	85.2	14.8
8	86.8	13.2	86.8	13.2	86.8	13.2	86.8	13.2
10	87.6	12.4	87.5	12.5	87.6	12.4	87.6	12.4
20	89.8	10.2	89.7	10.3	89.9	10.1	89.8	10.2
30	91.0	9.0	90.9	9.1	91.1	8.9	91.0	9.0
40	91.8	8.2	91.8	8.2	92.0	8.0	91.9	8.1
50	92.5	7.5	92.4	7.6	92.6	7.4	92.5	7.5
60	93.0	7.0	92.8	7.2	93.0	7.0	92.9	7.1
80	93.6	6.4	93.5	6.5	93.7	6.3	93.6	6.4
95	94.0	6.0	93.9	6.1	94.1	5.9	94.0	6.0
100	94.1	5.9	94.0	6.0	94.3	5.7	94.1	5.9
125	94.6	5.4	94.5	5.5	94.7	5.3	94.6	5.4
150	94.9	5.1	94.8	5.2	95.0	5.0	94.9	5.1

Table 71: Calculation of Air Voids by SGC (4.20% Asphalt, 0.5% PP – 12mm)

Gyration 150	**Specimen No.1**		**Specimen No.2**		**Specimen No.3**		**Average**	
Gyrations	%Gmm	Va	%Gmm	Va	%Gmm	Va	%Gmm	Va
5	83.9	16.1	84.0	16	83.6	16.4	83.8	16.2
8	85.4	14.6	85.5	14.5	85.1	14.9	85.3	14.7
10	86.2	13.8	86.3	13.7	85.9	14.1	86.1	13.9
20	88.4	11.6	88.4	11.6	88.1	11.9	88.3	11.7
30	89.6	10.4	89.6	10.4	89.2	10.8	89.5	10.5
40	90.5	9.5	90.3	9.7	90.0	10	90.3	9.7
50	91.1	8.9	90.9	9.1	90.6	9.4	90.9	9.1
60	91.5	8.5	91.4	8.6	91.1	8.9	91.3	8.7
80	92.2	7.8	92.0	8	91.8	8.2	92.0	8
95	92.6	7.4	92.4	7.6	92.2	7.8	92.4	7.6
100	92.7	7.3	92.5	7.5	92.3	7.7	92.5	7.5
125	93.1	6.9	92.9	7.1	92.7	7.3	92.9	7.1
150	93.5	6.5	93.2	6.8	93.1	6.9	93.3	6.7

Appendix B: Mix Design Criteria for the Two Compaction Method

B.1 Marshall Mix Design Criteria

Table 72: Marshall Mixture 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	---

B.2 Superpave Mix Design Criteria

Table 73: Superpave VMA Criteria

Nominal Maximum Aggregate Size, (mm)	**Minimum VMA, percent**
9.5	15.0
12.5	14.0
19.0	13.0
25.0	12.0
37.5	11.0

Table 74: Superpave VFA Criteria

Traffic, million EASLs	**Design VFA, percent**
< .3	70-80
< 1	65-78
< 3	65-78
< 10	65-75
< 30	65-75
< 100	65-75
>= 100	65-75

Table 75: Superepave Control Points

	Control Points		**Restricted Zone Boundary**	
Sieve, mm	Minimum	Maximum	Minimum	Maximum
25		100.0		
19	90.0	100.0		
12.5		90.0		
9.5				
4.75				
2.36	23.0	49.0	34.6	34.6
1.18			22.3	28.3
0.600			16.7	20.7
0.300			13.7	13.7
0.150				
0.075	2.0	8.0		

Appendix C: Distresses in North Cyprus

C.1 Longitudinal Cracking

Figure 51: Longitudinal, High Severity

Figure 52: Longitudinal, Medium Severity


Figure 53: Longitudinal, Low Severity

C.2 Transverse cracking


Figure 54: Transverse, High Severity

Figure 55: Transverse, Medium Severity

Figure 56: Transverse, Low Severity

C.3 Potholes

Figure 57: Potholes, High Severity

Figure 58: Potholes, Medium Severity

C.4 Fatigue Cracking (Alligator)

Figure 59: Alligator Cracking, High Severity

Figure 60: Alligator Cracking, Medium Severity


Figure 61: Alligator Cracking, Low Severity