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EVALUATION OF MARSHALL AND GYRATORY LABORATORY COMPACTION METHODS

by

Ivana Skabova

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of
Master of Engineering*

Department of Civil and Environmental Engineering
Carleton University
Ottawa, Canada

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"Evaluation of Marshall and Gyratory Laboratory compaction Methods"

Submitted by

IVANA SKABOVA, B.A.Sc., M.Sc.,

in partial fulfilment of the requirements for
the degree of Master of Engineering

Department of Civil and Environmental Engineering

Thesis Co-Supervisor

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Ottawa, Ontario, Canada
September 30, 1996

ABSTRACT

The last decade has been witness to dramatic increases in vehicular traffic on roads in North America. This has given rise to additional traffic, augmented axle loads and increased tire pressures on pavements designed for an earlier era. Budgetary cutbacks in road maintenance have exacerbated these conditions.

The recently-introduced "Superpave" design is performance-based, caters to the increased standards, but requires a gyratory compactor for design and quality control purposes. The Marshall design and its companion hammer has been in use since 1930. Marshall mix design cannot meet today's needs. However, the cost of a gyratory compactor is seven times that of the commonly-available Marshall hammer.

This thesis evaluates the two compaction methods, using the Marshall as a reference base line. Two types of asphalt mix with varying percentages of asphalt content were tested to simulate a post-construction environment. The salient mechanical properties of the Marshall specimens were found to be superior to that of the gyratory-compacted specimens. Future applicability of each of the two methods on current and emerging asphalt design was addressed.

ACKNOWLEDGEMENTS

I would like to express my grateful thanks to my thesis supervisor, Professor A.O. Abd. El Halim for his advice, guidance and encouragement during all phases of the thesis preparation, as well as for his financial support. I also wish to thank my co-supervisor, Dr. Otto J. Svec for his input, counsel, assistance and financial generosity. This research could not have been completed without their participation.

I would like to acknowledge the National Research Council (NRC) for giving me the opportunity to use their Pavement and Infrastructure laboratories and their equipment to realize my research work. Thanks are also in order to the Civil Engineering laboratories at Carleton University.

Special thanks to the following persons at NRC: Mario Gervais who provided continuing technical support and advice for the testing program, and Bill Bekking who provided technical support for the compaction exercises.

I also gratefully acknowledge H.J. McFarland construction Co., Nepean, Ontario and Husky Oil of Calgary, Alberta for their supplies of aggregates and asphalt binder, respectively.

I would like to express my gratitude to Aly Shariff for his critique and input in my thesis.

I would also like to thank to my friend Paul Marcinov for his critique, input and

encouragement along the way.

I am forever grateful to my parents Jaroslava and Rudolf in the Czech Republic who gave me the love, moral support, guidance and encouragement to go through so many years of studying. This thesis is dedicated to them. Rada bych poděkovala svým rodičům Jaroslavě a Rudolfovi za jejich lásku, podporu a porozumění v průběhu všech let mého studia. Tato diplomová práce je věnována jim.

Finally, I wish to express my deepest appreciation and gratitude to my husband Ladislav for his encouragement, support, patience, and understanding during the whole period of this thesis development. Thank you with all my love.

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LIST OF SYMBOLS AND ABBREVIATIONS

AASHTO	-	American Association of State Highway Transportation Officials
AC	-	Asphalt Cement
ASTM	-	American Society for Testing and Materials
BRD	-	Bulk Relative Density
C.O.V.	-	Coefficient of Variation
CBSF	-	Cycles Before Specimen Failure
CKE	-	Centrifuge-kerosene-equivalent
EMA	-	Ethylene Methacrylate Copolymer
ESAL	-	Equivalent Single Axle Load
EVA	-	Ethylene Vinyl Acetate Copolymer
FHWA-OTA	-	Federal Highway Administration - Office of Technology Applications
HMA	-	Hot Mix Asphalt
ITS	-	Indirect Tensile Strength
LCPC	-	Central Laboratory for Bridges and Roads
LVDT	-	Linear Variable Displacement Transducer
MTO	-	Ministry of Transportation of Ontario

MTS	-	Material Testing System
NRC	-	National Research Council
PEN	-	Penetration
QA	-	Quality Assurance
QC	-	Quality Control
RUCT	-	Repetitive Uniaxial Compression Test
SBS	-	Styrene Butadiene Bloc Copolymer
SGC	-	Superpave Gyratory Compactor
SHRP	-	Strategic Highway Research Program
STD	-	Standard Deviation
TMSG	-	Theoretical Maximum Specific Gravity
TSR	-	Tensile Strength Ratio
VMA	-	Voids in Mineral Aggregates
VTM	-	Voids in Total Mix

CHAPTER 1

INTRODUCTION

1.1 ASPHALT PAVEMENT

Asphalt pavements are made up of a mixture of mineral aggregates and asphalt binder. They are constructed in various thicknesses and for different types of end use. *Mineral aggregates* used in asphalt pavements may be made up of a combination of crushed stone, gravel, natural sand and gravel deposits, slag and mine refuse, rubble and refuse, artificial aggregates or other materials of mineral composition. They can be either natural or manufactured. The natural aggregates are obtained from natural sources and used without any changes in their nature during the production process (crushed stone, gravel, sand, shells, iron, etc.). The only alterations would be limited to washing, crushing, sizing and/or grading. The manufactured are usually obtained as a by-product (blast furnace slag, etc.) of industrial processes. Important aggregate properties in the preparation and the laying of a highly efficient asphalt pavement are their gradation, relative density and absorption, hardness, durability (resistance to weathering), shape and surface texture, deleterious substances, and crushing strength. *Asphalt binder* is "a dark to black cementitious material in which the predominating constituents are bitumens which occur in nature or are obtained in petroleum

processing" (Abd El Halim, 1994). Desired properties of asphalt are its consistency and purity. The consistency is determined by a viscosity or penetration test. The purity should be more than 99.9% soluble in carbon solution. Another desired property is that asphalt should be free of water. Traffic loads and stresses for any thickness and type of asphalt pavement are transmitted through the aggregate. The asphalt binder is employed as an adhesive instrument which binds the aggregates in a position that allows proper transmission of wheel loads to underlying layers where the load is finally dispersed

Asphalt pavement is a flexible pavement. Its function is to distribute the loads and stresses, and to provide a safe and smooth ride. The asphalt pavement is a multilayered elastic system in which the top layer is made of material with the best mechanical properties. The top layer is followed by a base course, sub-base course, and subgrade, respectively (Figure 1.1). The application of a load to the asphalt pavement produces two critical elastic strains: the horizontal tensile strain at the bottom of the asphalt layer and vertical compressive strain at the top of the layer. Such a layer will behave as a beam. It therefore follows that a successfully performing pavement is conditional on having layers with $E_1 > E_2 > E_3 > E_4$ and $t_1 < t_2 < t_3 < t_4$, where " E_i " is the modulus of elasticity of the layer of a thickness " t_i ".

Over the past decade, major changes have occurred in the loading conditions under which pavements have to perform. Legal axle loads and tire pressures have increased dramatically with the increases in the size of vehicles as has the percentage of heavy axle loads (expansion of the trucking industry) on most highways in Canada. Also, the load

Figure 1.1: Asphalt Pavement Layers

repetitions intensified with the growing number of vehicles. Changes in mixture properties and a growth in the use of asphalt modifiers have been occurring. The laboratory mix designs in current use do not simulate field conditions, because an asphalt mix prepared in a laboratory environment does not fully replicate that prepared at a production plant. Such findings have motivated the engineering community to pursue the development and evaluation of emerging trends in asphalt mix design.

1.2 ASPHALT CONCRETE MIX DESIGN

The fundamental objective of the laboratory mix design process for asphalt mixtures is to determine the combination of the aggregates and binder which will produce an asphalt mixture capable of withstanding loading and environmental distress throughout the intended design and performance period.

1.2.1 Historical Background

The first bituminous mixtures used in the United States (circa 1865) for sidewalks and cross-walks were mixtures of sand, gravel, broken stone, ashes, and similar materials with coal tar as the binder (Goetz, 1989). The first asphalt pavement was a sand mixture laid in 1870 in Newark, New Jersey. Similar pavements were then laid in New York City, Washington, D.C., and Philadelphia and usage of such pavement spread rapidly. These early sheet-asphalt mixtures were not scientifically designed in any real sense. However, their evolution and efforts to improve their performance in service resulted in the development of

certain principles and concepts. This was related to the properties of their primary materials as well as to their function in the mixture. It was recognized that the sand being used for mixtures had to be hard, adequately sharp, and with an appropriate gradation. It was also realized that the presence of dust in the mix could deter or prevent adhesion of asphalt to the surface of the sand grains and that such adhesion was necessary to resist water ingress. The ground limestone and Portland cement used as a filler had also been found to exhibit strong adhesive properties with asphalt.

In addition, attention was paid to the voids created in mixtures by grain shape, gradation, and quality of compaction. An early approach toward improving mix performance was to fill the air voids completely with asphalt. However, such a mixture became unstable and slippery under traffic. As a result, a more reliable design approach was to use an asphalt content sufficient to fill the voids to a degree that leaves some room for expansion in the asphalt volume at summer temperatures, and for a decrease in space available as the aggregate is further compacted in time by traffic.

With the use of binder courses as intermediate courses between the foundation and the wearing course of sheet-asphalt, larger aggregates were utilized following similar principles in the formulation of mixtures. The early evolution of asphalt pavements gave rise to certain concepts, principles, and relationships which are regarded today as fundamental. One concept is that a mixture must be stable in the sense that it does not rut or shove under traffic. Another is that the stability is related to the size of aggregates, size distribution, shape of aggregates, and surface texture. These concepts and principles resulted in developing mix design methods that have been evaluated and improved over time. The most common asphalt

mix design methods currently used in the United States and Canada are the Marshall, and the emerging gyratory methods, with the Hveem method used in certain parts of the U.S..

1.2.2 Mix Design Methods

Mix design methods are derived from the principle that mixtures must be stable and durable. The criteria were established by correlating of results obtained from laboratory specimens with performance of the same mixture in the field under traffic. Two requested conditions must be met in order to duplicate the field mixture in a laboratory environment: the same composition of the mixture, and the same production procedure. The major problem is the ability to produce a laboratory specimen of the mixture that truly replicates the production mixture to be used in the road construction. The compaction methods used in the laboratory vary from direct compression to hand tamping, impact hammer, kneading action, gyratory shear, vibration, and simulated rolling (Goetz, 1989). The most commonly used today are the Marshall, Hveem, and the gyratory methods.

The major difference between them is observed in the process of compacting the specimen. The specimens prepared by the Marshall method are compacted using hammer blows, while the specimens prepared by the Hveem method are compacted using a kneading action, and finally the specimens prepared using the gyratory method are compacted with gyrations under a given angle. Clearly, these methods are quite different from the roller compaction used in actual field conditions.

1.2.2.1 Marshall Mix Design

The Marshall mix design method was developed by the U.S. Army Corps of Engineers during World War II to be used for laboratory design and control of mixtures for airfield pavements. They chose a testing device conceived by Bruce Marshall of the Mississippi Highway Department, method of compaction using a hammer with a falling weight.

The Marshall testing apparatus applies a compressive load on the circumference of a cylindrical specimen through semi-circular heads. The maximum load and the deformation undergone by the specimen in reaching this maximum load are recorded. These values are denoted as Marshall stability and Marshall flow, respectively. The densities are measured before the specimens are tested for strength. The range of asphalt content for preparing the specimens is set at two values above and two values below the expected optimum asphalt content. The increments are normally one-half percent.

From the density and voids analyses, and the stability and flow tests, these values are plotted as follows:

- bulk density versus asphalt content,
- stability versus asphalt content,
- flow versus asphalt content,
- percent air voids in the total mixture versus asphalt content, and
- percent voids in the aggregate mass filled with asphalt versus asphalt content.

Proper mix design is achieved when the optimum asphalt content, which satisfies certain established criteria, is determined. In the Marshall design method, maximum density,

maximum stability, and specific voids ratios represent the main elements of the design criteria.

Some changes were introduced into this design method over the years to take into account a number of variables. For example, traffic volume has been categorized into light, medium, and heavy, and the compactive effort required for each specific volume of traffic has been determined. Mixing and compaction temperatures have been related to asphalt viscosity instead of being fixed numbers. There have also been fundamental changes from the Corps of Engineers original method such as dispensing with the criteria for percent voids in the aggregate mass filled with asphalt, and the substitution of criteria for percent voids in the mineral aggregate.

1.2.2.2 Hveem Mix Design

The Hveem or California method was developed and used by the California Division of Highways as of 1957 under its then director, F.N. Hveem. This method is based on a surface area concept and is primarily used for dense-graded mixtures. The optimum asphalt content in the mix is calculated by use of the centrifuge-kerosene-equivalent (CKE) method. Once the calculated surface area and the factors are obtained by the CKE method, the optimum asphalt content is determined by using nomographic charts. The mix is then tested for stability cohesion, void content, and water susceptibility. The test specimens are compacted with a kneading action to produce specimens similar to post-construction asphalt pavement. The stability of the mix is then measured by a Hveem Stabilometer under a temperature of 60°C and at a slow rate of loading. The cohesiometer value of this specimen is determined

by applying a direct tension in bending (at 60 °C). The air voids in the specimen are measured at this point. The last test is for water susceptibility and its purpose is to define the water resistance of the mixture. The test results are compared against benchmarks established by California Division of Highways for satisfactory mixtures. If the baseline criteria are not met, the gradation of the mix has to be adjusted.

1.2.2.3 Gyrotory Mix Design

With ever increasing loads and tire pressures the density of pavement in the field reached a point that could not be replicated in laboratory specimens through impact compaction. The U.S. Army Corps of Engineers resolved the issue by motorizing the Texas gyratory device, a 1930's invention. This device is based on gyratory compaction, a process during which a mold containing an asphalt mix is exposed to a vertical load while the mold is gyrated back and forth. The development of the gyratory testing machine resulted in the standardization of a test for compaction and shear properties of bituminous mixtures (ASTM Test Method for Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Corps of Engineers Gyratory Testing Machine, Designation: D 3387-83). This test includes the calculation of compaction properties such as unit mass total mix, unit mass aggregate only, gyratory compatibility index, and calculation of shear properties including gyratory stability index, gyratory shear, and gyratory shear factor (Goetz, 1989). Specimens with a range of asphalt contents are tested and the relationships between calculated compaction values versus asphalt content and shear properties versus asphalt content are plotted. An optimum mix is then selected from these plots.

In 1993, the Strategic Highway Research Program (SHRP) introduced and trademarked the Superpave (Superior Performing Asphalt Pavements) laboratory mix design procedure based on a gyratory compaction device. This system proposes mix design and analysis methods for Hot Mix Asphalt (HMA) materials related to performance and relies on volumetric principles for design purposes. The design number of gyrations, combined with the specific mixture gyratory densification curves which are developed for each mix under different asphalt contents, are used to determine the design asphalt content. This binder content depends upon traffic volume and environmental conditions (Hafez and Witzack, 1995).

1.3 OBJECTIVES OF THIS THESIS

The last decade has been witness to heavy increases in vehicular traffic on highways and roads in North America. This is attributed to increasing trade globalization, to a continuing shift of transport of goods from rail to road transport, to meet consumer needs for freshness and variety of produce throughout the year, to reduce transportation time, to a deregulation of the trucking industry, to cost-reduction initiatives such as "just in time" delivery of parts and to a reduction in inter-country tariff barriers.

This dramatic growth has given rise to additional traffic, augmented axle loads as well as increased tire pressure on pavements that were designed for an earlier era. Furthermore, all levels of governments have attempted to curtail deficit spending with cutbacks, including reductions in road maintenance programs, and this has again exacerbated the general conditions of our roads. To quote an old saying "the rubber hit the road", exceeding the

original design of our road network and resulting in the overstressed asphalt pavements that are common today.

To contend with these problems the Strategic Highway Research Program (SHRP) in Washington D.C. has developed a trademarked "Superpave" asphalt mix design predicated on performance-based and performance-related properties and the American Association of State Highway and Transportation Officials (AASHTO) is currently setting up the standards for this mix design. Superpave requires the use of a gyratory compactor to design the mix and for quality control purposes. This gyratory device also better simulates the actual stresses to which the pavement will be subjected during its service life.

Since the 1930's asphalt mixes have been mainly designed via the Marshall method. This design method attempts to achieve a stable and economical balance of asphalt binder and aggregate to provide the sufficient workability in the laying of the mix. Certain properties are tested in an attempt to gauge future performance, but there is no assurance that a trial mix design will meet specified performance criteria. The Marshall hammer compaction method is utilized in the mix design.

The Marshall mix design has long been adopted as the standard by highway agencies in North America. The Marshall hammer is also readily available to support the design of such mix. However, asphalt mixes designed via this system are unable to meet the performance standards of pavements required today. On the other hand, Superpave appears to cater to these increased standards but requires a gyratory compactor whose cost is seven times greater than that of the available Marshall hammer. There is also an ongoing debate in the scientific community in respect of the validity of the design method itself.

The objective of this thesis was to examine if any correlation between Marshall and gyratory laboratory compactions exist. In other words, it was important to identify under which conditions both laboratory compaction methods would give similar results. To accomplish this, two types of asphalt mixes (standard 85/100 Pen asphalt cement and polymer-modified asphalt cement) were utilized as well as various percentages of asphalt content (5.0%, 5.5%, 6.0%, 6.5%, and 7.0%). To conduct an unbiased comparison between these two compaction methods, the specimens would have to be prepared according to certain standards. However, no such standards currently exist. In order to select a baseline parameter to produce the targeted frame for comparison, a number of parameters were investigated. It is known that the control over the quality of compaction focuses on air voids and bulk relative density (BRD). Since current technology does not allow for proper investigation based on comparison of the air voids, it was decided to use BRD as the material property to control the adopted compaction quality. The gyratory compactor was then used to attain the same densities of the specimens as that achieved by the Marshall hammer and the numbers of requisite gyrational cycles were monitored. The resultant mechanical properties of each of the specimens of the asphalt mixes were measured by the following tests: tension, shear, compressive fatigue, temperature and permeability.

A subsidiary objective was the evaluation of two types of asphalt binders and to measure their effect on the mechanical properties of asphalt mixes.

1.4 SCOPE - ORGANIZATION OF THE THESIS

This section briefly outlines the organization of the thesis and describes the individual chapters and their purpose.

Chapter 1 outlines the problem definition, the evolution of asphalt mix design, and the objective of the research.

Chapter 2 presents the major results of a literature review characterizing compaction and asphalt mix design. The significance of compaction pavement mix design is introduced. The historical background is laid out as well as the current methods of compacting asphalt pavement. A brief study of results from laboratory and field research about asphalt concrete mixes using both types of compaction methods (Marshall and gyratory) is undertaken. A literature review of the influence of different types of asphalt binder is also presented.

Chapter 3 details the research plan and testing philosophy employed during this research. The gradation selection, asphalt cement binder selection, and the procedure of each compaction method are discussed. The relationship between blows and gyrations for obtaining equal densities of specimens compacted by Marshall hammer and by gyratory compactor are characterized. The testing conditions, testing equipment, materials, routine tests and testing program are described.

Chapter 4 focuses on the description of test results obtained from the experimental investigation. The effect of the compaction method, asphalt cement, and asphalt content on the mechanical properties of the mixes was measured by appropriate tests and documented.

Chapter 5 gives an analysis and discussion of the test results. The mechanical properties of Marshall-compacted specimens are compared to gyratory-compacted specimens and the influence of binder type on the asphalt mix is discussed.

Finally, Chapter 6 presents the summary and the conclusion of this study as well as recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION

increased traffic, axle loads and tire pressures, coupled with limited financial resources have resulted in a commonly-occurring overstressed asphalt pavements. These conditions have forced asphalt engineers and researchers to reconsider the current mix design approaches.

The proper selection of the aggregates and the asphalt binder can improve pavement performance, depending upon the environmental and traffic conditions to which the pavement is exposed. However, the asphalt concrete mix will not perform as required if the proper compaction procedure is not followed.

The most common mix design methods used in the United States are the Marshall, Hveem, and gyratory methods, and the Marshall and gyratory methods in Canada. The introduction of the Superpave laboratory mix design procedure, based on a gyratory compaction device, has given rise to calls for replacing the traditional Marshall mix design method by that of Superpave. Researchers and engineers have worked on identifying the best

properties of these mix design methods and have spent time validating the attributes of each method.

The validity of performance in the field and the cost of the equipment for the two mix design methods have to be taken into account in selecting whether a Marshall or a gyratory compaction device should be used in future asphalt concrete mix design.

The following three sections present a literature review of laboratory compaction, Marshall and gyratory mix design, and binder use.

2.2 LABORATORY COMPACTION

2.2.1 Definition

In general, compaction of an asphalt concrete mixture is defined as "...a stage of construction, which transforms the mix from its very loose state into a more coherent mass, thereby permitting it to carry traffic loads...the efficiency of the compactive effort will be a function of the internal resistance of the bituminous concrete. This resistance includes aggregate interlock, friction resistance, and viscous resistance" (Swanson et al., 1966). If the resistance of the mix to compactive effort is low then the pavement will be unable to carry traffic loads for any significant period of time.

Hughes (1989), defines compaction as ... "the process of reducing the air-void content of an asphalt concrete mixture. It involves the packing and orientation of the solid particles within a viscoelastic medium into a more dense and effective particle arrangement. Ideally, this process takes place under construction conditions rather than under traffic."

2.2.2 Importance of Compaction

Pavement compaction is critical for the development of internal strength and durability. Greater compaction results in higher density. However, there is a point of optimal density where the greatest strength is attained. Any further increase in density then degrades the performance of the asphalt pavement. Thus the optimum density that correlates with the best combination of strength and durability has to be established.

Another reason for compacting the asphalt pavement is to make it watertight and airtight (Smith, 1979). Compaction is the process of reducing the air-void content of an asphalt concrete mixture. Increasing density and reducing the percentage of air voids in asphalt concrete has a positive influence on the ability of the mix to perform as designed. Finn (1967), concluded that a high degree of compaction optimizes all desirable mix properties, as given in Table 2.1.

Compaction is the most important factor affecting pavement performance and influencing its strength, fatigue life, durability, resistance to deformation, and moisture damage. The *strength* of a pavement is inversely proportional to the void content. Any increase in air void content will reduce *fatigue life* and mixture stiffness. *Durability* of a paving mixture is not only defined as its resistance to the environmental elements, but also resistance to the casual effect of the abrasive action of traffic on aging (Finn, 1967). The lack of *resistance to deformation* (i.e. stability of the pavement mix) leads to rutting which had become one of the most common problems with ever-increasing traffic and axle loads. The second most common distress identified in contemporary pavement is *moisture damage*. Sufficient compaction of the pavement mix is necessary to reduce permeable voids.

**Table 2.1 Recommendable Characteristics to Enhance Mixture Properties
(Finn, 1967)**

Mix Property	Asphalt Content	Aggregate Gradation	Degree of Compaction
Stability	Low	Dense	Elevated
Durability	High	Dense	Elevated
Flexibility	High	Open	-
Fatigue resistance	High	Dense ¹	Elevated
Skid resistance	Low	Dense or open ²	Elevated ³
Imperviousness	High	Dense	Elevated
Fracture strength	High	Dense	Elevated

1 Assuming a heavy-duty, comparatively thick layer of asphaltic concrete.

2 Both types of gradations have exhibited good skid resistance characteristics. It would appear that the texture of the aggregate particles would be a major factor.

3 Although compaction is not normally called for in this property, it is certainly implied to ensure that aggregate particles not be dislodged under the tractive forces applied to the surface.

2.2.3 Factors Affecting Compaction

There are various factors affecting compaction. In the field this includes material properties, initial density of pavement, traffic volume, construction season and environment (Figure 2.1, Epps, 1969). Laboratory compaction is influenced by material properties (asphalt and aggregates), by mix design, and by the environment in which the compaction is effected. In other words, the properties of the asphalt, its temperature susceptibility and rheology, the surface texture of aggregates, their shape, maximum size, grading and absorption are all factors which can influence compaction. Temperature also plays a significant role in this compaction process.

2.2.4 Historical Background

Historically, three laboratory compaction methods have been used in asphalt concrete mix design (Blankenship et al., 1994). Those are:

- Impact compaction (Marshall).
- Kneading compaction (Hveem).
- Gyratory compaction (Texas and Superpave).

2.2.4.1 Compaction by Impact

This is the oldest technique in laboratory compaction. In the beginning of the 20th century, Hubbard and Field used a Proctor hammer to compact asphalt mixtures. This hammer was borrowed from the geotechnical field.

Figure 2.1: Factors Affecting Compaction (Epps, 1969)

In the 1930s, Bruce Marshall adopted the Hubbard-Field method and began developing the method which bears his name. The only difference was that he used a compactor face equal to the mold diameter. The number of blows applied to each face of the specimen was set to be 35, 50 or 75 depending upon the anticipated traffic volume. The higher the volume of traffic, the greater the number of blows. This is the most common mix design method used today. The Marshall mix design or a variation thereof has been adopted by 75 percent of the highway agencies in the U.S. However, Consuegra et al. (1989), concluded that the Marshall hammer least simulates the actual field conditions that will be encountered by pavement during its service life.

2.2.4.2 Kneading Compaction

In the 1930s and 1940s F.N. Hveem developed a mix design method referred to as kneading compaction. This method was different from the Marshall mix design method. The compacting force in this compactor is applied through a roughly triangular-shaped foot which partially covers the specimen face. To effect compaction, tamps are uniformly applied on the specimen face. The traffic volume is represented by the pressure of the tamps. More tamps and higher tamp pressure simulate mixtures subjected to high traffic volume.

This type of compaction is used primarily in parts of the Western United States, but used infrequently elsewhere.

2.2.4.3 Gyratory Compaction (Evolution)

Gyratory compaction was developed in the 1930s in Texas (Blankenship et al., 1994). This compaction produces a kneading action on the specimen by gyrating the specimen through a horizontal angle. The range of the angle varies from 1.00 to 6.00 degrees. During the process of compaction a vertical load is applied while gyrating the mold in a back-and-forth motion.

Development and use of compaction via gyratory action has continued by the U.S. Army Corps of Engineers and by the Central Laboratory for Bridges and Roads (LCPC) in France (Blankenship, 1994). Such development has focused on the application of the principle of gyratory movement and on the establishment of a new method of asphalt mix design to simulate service under extreme traffic conditions. The use of this compactor became commonplace in the early 1960s; however, the costly gyratory testing machine has achieved little acceptance as a routine mix design tool and is used mainly as a research tool. The LCPC had evaluated parameters affecting gyratory compaction and had finalized a gyratory protocol, where three major variables had been studied: angle of gyration, speed of rotation, and vertical pressure. Today, the gyratory compaction method is commonly used in the mix design process in France. A major difference between the French design process and North American design is that in the French design the compactor simulates density at the end of construction instead of during service.

In 1993, the SHRP introduced a trademarked "Superpave" laboratory mix design procedure based on a gyratory compaction device (Cominsky et al., 1994). This laboratory

design procedure was deemed to be appropriate for original and/or recycled hot mixtures and with and/or without modified binders.

The Superpave mix design method recommended three hierarchical levels of design, namely, Level 1, 2 and 3, based on anticipated traffic volume. Each design level also took into account the influence of the site climatic conditions. However, in 1995 the SHRP decided to employ the Level 1 design for all volumes of traffic (low, medium, and high). The sophisticated and complex analytical techniques and costly test equipment for levels 2 and 3 design did not lend themselves to usage in a Hot Mix Asphalt (HMA) production facility. The HMA industry concurred with this decision and was of the opinion that most pavements forming part of the National Highway System (NHS) would perform well if designed using the concepts of the Superpave Level 1 mix design (Decker, 1995).

2.2.4.4 Gyrotory Compaction (Superpave)

The Level 1 mix design necessitates gyrotory specimen compaction per SHRP Standard Method of Test M-002. The specimens have diameters of 100 mm and 150 mm with heights ranging from 60 mm to 100 mm, and 90 mm to 150 mm, respectively. They are compacted under a pressure of 600 kPa, with an angle of gyration of 1.25 degree and speed of gyration of 30.0 rpm. The gyrotory compactor continuously monitors the increase in specimen density and expresses this as a percentage of the theoretical maximum specific gravity (TMSG), as the compactive effort increases. Density is measured at three points on the densification curve (a plot of density values recorded during the compaction process). The appropriate design combination of aggregate structure and content of asphalt cement must produce a

densification curve which passes through 96% of theoretical maximum specific gravity at the design number of gyrations (N_{design}). Therefore, 4% air voids at N_{design} is the value at which the optimum design asphalt content is selected. The value of N_{design} used in a mix design is based on the forecasted traffic volume and the 7-day maximum air temperature at the pavement site. For the maximum number of gyrations (N_{max}), the mix must attain less than 98% of TMSG (voids content of more than 2%) and for the initial number of gyrations (N_{init}) the mix must reach 89% TMSG or less.

The density can be computed during any stage of the compaction process using the weight and height of the specimen. This density is named uncorrected (C_{ux}) density and is calculated from the following equation (Cominsky, 1994):

$$C_{ux} = \frac{w}{\left(\frac{\pi d^2}{4} \cdot H \right)} \cdot \frac{1}{G_{mm}} \quad (1)$$

where:

C_{ux} = the uncorrected density, (gm/cm^3).

w = the weight of the specimen. (gm).

d = the diameter of the specimen. (cm).

H = the height of the specimen at any number of gyration. (cm), and

G_{mm} = the theoretical maximum specific gravity of the tested specimen.

Using the final height recorded at the end of compaction (H_{eoc}) and the measured bulk specific gravity of the specimen at the end of compaction (G_{mb}), the uncorrected values of the theoretical maximum specific gravity are corrected and the final densification curve obtained. The corrected density for any number of gyrations (C_{cx}) is calculated by the following equation:

$$C_{cx} = C_{ux} * \frac{G_{mb}}{\left(\frac{\pi d^2 H_{eoc}}{w} \right)} \quad (2)$$

The densification curve is produced by plotting the corrected density against the logarithm of the number of gyrations.

The output of Superpave Level 1 mix design provides:

- a design aggregate structure, and
- a design asphalt content.

This compaction procedure is described in detail in the "Superpave Mix Design Manual for New Construction and Overlays" (Cominsky, 1994).

The SHRP protocol for gyratory compaction represents an amalgamation of the French LCPC, the U.S. Army Corps of Engineers, and the Texas gyratory methods (Blankenship, 1994). However, the high cost of the equipment necessary to realize the Superpave mix

design, the newness of this emergent design, and a lack of data to compare results with field trials has tended to reduce the widespread usage of this compaction method, at least for the present time.

The conclusion of this section is that compaction is one of the most important factors in designing and constructing asphalt pavements. Engineers working in the field of transportation should focus on evaluating and developing current compaction equipment from the point of view of cost and applicability based on post-construction performance.

2.3 MARSHALL AND GYRATORY MIX DESIGN

This section reviews the literature pertaining to the laboratory and field research, performed on asphalt concrete mixes in order to evaluate present asphalt mix design methods.

2.3.1 Marshall Mix Design vs Gyratory Mix Design

Button et al. (1994), compared four compaction devices (Texas gyratory compactor, Exxon rolling wheel compactor, Elf linear kneading compactor, and Marshall hammer) to determine which of them would most closely simulate actual field compaction. The study, limited to dense-graded mixtures, showed that specimens compacted via gyratory compactor most often simulated pavement cores. This occurred in 73% of the performed tests. The Marshall compactor gave the least probability of producing specimens simulating the pavement cores (in 50% of tests performed). However, the differences between field cores

and the specimens produced in the laboratory by the four compaction methods were relatively small when all the test results for each method are evaluated as a whole.

Similarly, Von Quintus et al. (1991), described the effect of five different laboratory compactors (Texas gyratory compactor, Rolling wheel compactor, Kneading compactor, Arizona vibratory/kneading compactor, and standard Marshall hammer) on the selected properties of the compacted mixtures. Field cores and specimens compacted in the laboratory were tested for indirect tensile strength (ITS), strain at failure, resilient modulus and creep and their aggregate particle orientation was evaluated. The authors compared the similarity between laboratory compaction and field compaction techniques. Their results are given in Table 2.2 (Von Quintus, 1991).

To facilitate the ranking of compaction devices, three procedures were used to define which compaction device more closely simulated the engineering properties of field cores. The ranking of the compactors by order of performance: the Texas Gyratory compactor followed by Rolling Wheel compactor, California Kneading compactor, Arizona Vibratory/Kneading compactor, and lastly, the standard Marshall hammer.

Another study to evaluate the ability of five compaction devices to simulate field compaction is described in Consuegra's et al. paper (1989). These devices are the mobile Steel wheel simulator, the Texas gyratory compactor, the California kneading compactor, the Marshall impact hammer, and the Arizona vibratory/kneading compactor. The ability of these compaction devices to simulate field compaction is based on the similarity between mechanical properties such as resilient moduli, indirect tensile strength and strains at failure, and tensile creep data of laboratory-compacted specimens and field cores.

Table 2.2: Summary of Engineering Property Comparisons (Von Quintus, 1991)

Compaction Device	Percentage of Indifference in Properties* between Laboratory-compacted Specimens and the Field Cores
Texas Gyratory	63
Rolling Wheel	49
Kneading	52
Arizona Vibratory/Kneading	41
Standard Marshall hammer	35

- * The mixture properties were evaluated based on ITS test at 5°C, 25°C and 40°C, creep load strains at 25°C and 40°C with a loading time of 300 sec. and slopes of creep curve at 25°C and 40°C.

While highest level of similar properties between laboratory-compacted specimens and field cores was demonstrated by the Texas gyratory compactor. The Marshall impact hammer ranked as the least effective. This was attributed to the lack of a kneading motion by the Marshall impact hammer. The authors concluded that the Marshall hammer is the least able to simulate any of the construction and traffic compaction methods.

Al-Sanad (1984), investigated the effect of various laboratory compaction methods on three different mixtures. The compaction methods were the Marshall hammer, the kneading compactor, and the gyratory compactor. The Marshall hammer produced a high impact stress energy and resulted in an excellent orientation of aggregates. Nevertheless, the specimens compacted with this compactor in the laboratory gave different stress-strain curves than pavement cores having the same density and asphalt content. He concluded that the compaction method affects the stability. The kneading compactor produced specimens with greater stability than the Marshall hammer and the gyratory compactor. The specimens compacted by the Marshall hammer and the gyratory compactor have approximately the same stability, but the level of air voids in cores compacted by the Marshall method was higher than that compacted by the gyratory method.

Murfee and Manzione (1991), analyzed the plastic behaviour of Marshall and gyratory mixes in order to determine if the asphalt mixtures are appropriate for fighter aircraft taxiways. The flexible and composite pavement test sections were prepared to study rutting of asphalt pavements under high tire inflation pressures. Late-model aircraft such as F-15s and F-16s which require tire inflation pressures in the order of 310 psi were considered for this study.

Asphalt specimens were sourced from the plant tank during the production process. The mixture contained an AC-20 asphalt with aggregates conforming to those recommended in air force manual AFM 88-6 for Highway pressure applications. Half of the asphalt mixture used for the sections was designed by the Marshall method and the remainder with gyratory.

The authors concluded that the Marshall mixture resulted in excess asphalt in the mix and subsequent premature rutting. This was attributed to insufficient laboratory compaction and to dust that was produced when fragments of aggregates were degraded in the dryer. The mix designed by the gyratory testing machine remained stable for F-15 aircraft traffic during the whole test period. Manufactured dust did not affect the mix. In the laboratory the Marshall compactor was unable to reproduce the high densities which would simulate those produced in the field by F-15 aircraft traffic on the sections designed by gyratory method.

Brown (1990), investigated the plastic behaviour of an asphalt mixture under traffic. When predicting the plastic behaviour in the laboratory, it is necessary, that the laboratory compaction effort be equal to the compaction effort caused by the expected traffic. As airport pavement traffic and load variations are dependent upon the function of the air bases, the laboratory compactive effort must therefore be adjustable to simulate the expected traffic. The rotational compaction pressure of the gyratory testing machine enables the achievement of customized densities that meets the desired compactive effort. If the fixed 75-blow Marshall compaction were increased, it would result in the degradation of the aggregate.

Rogue et al. (1995), address problems associated with the frictional resistance of asphalt pavement. They investigated 13 field test sections with different average daily auto and truck traffic levels and two mixture types, ID-2 versus ID-3 (dense-graded wearing courses with

12.5mm and 25mm maximum aggregate size, respectively). Three compaction methods were used to produce the mixtures in the laboratory: Marshall, Texas gyratory, and modified Texas gyratory. The modified Texas gyratory procedure was intended to emulate the SHRP gyratory procedure because at the time Rogue did his research, the SHRP gyratory procedure was as yet not standardized by ASTM, AASHTO, or the Asphalt Institute. As the Marshall compaction method cannot simulate field densification under traffic, high asphalt content mixes were selected. Since the effectiveness of the Marshall compaction was low when compacting the coarser mixtures, such a compaction became a primary problem for the ID-3 sections. The result was that the mixtures compacted in the laboratory had high air-void contents as compared to the mixtures in the field and the asphalt content chosen for these laboratory mixtures was too high.

The volume of air voids in both plant and laboratory Marshall asphalt mixtures was greater than the air voids measured in field cores obtained from the wheel paths of test sections that were prepared from the same mixture. On the other hand, air-void contents achieved with the modified Texas gyratory procedure were close to air voids measured in the wheel path core specimens. Laboratory tests produced per the production-mix formula pointed out that Texas gyratory shear compaction has over-compacted the mixtures on which the tests were performed when compared to the mixtures that were compacted by traffic in the field. In general, the Texas gyratory compactor surpassed the Marshall compactor in producing laboratory mixtures that most resembled actual field sections. However, the authors recommended that additional studies be undertaken to identify and validate the best laboratory compaction method.

Mauphin (1991), evaluated several test procedures that could be used for testing the susceptibility of asphalt mixes to rutting. Mixes were subjected to five tests: resilient modulus test, compression creep test, indirect tensile test, compaction resistance, and a test using the gyratory testing machine. Field performance of the Marshall-designed product was poor, and the use of the gyratory testing machine identified deficiencies in some Marshall-designed field mixes.

The report recommended further evaluation of the use of the gyratory testing machine as a tool to complement the Marshall design in developing heavy duty asphalt mixes.

Brennen et al. (1983), investigated the use of foamed asphalt for recycled bituminous pavements. Their objective was to evaluate the performance of three foamed asphalts as binders (AC-20, AP-4, and AC-2.5) for a recycled bituminous paving mixture using both the gyratory and the Marshall method, and the Marshall stability testing procedure. The penetration (0.1mm) and the kinematic viscosity at 135 °C (cSt) of these asphalts were 42, 69, 185, and 443, 261, 160 respectively. A ram pressure of 1.38 MPa and 20 revolutions of the gyratory compactor were used in order to simulate the initial compaction after construction. To obtain equivalent specimens, 75 blows with a Marshall compactor were used. All specimens were compacted at room temperature (22 to 24 °C). The specimens were 10 cm in diameter and approximately 6.4 cm high when compacted in the gyratory compactor and 6.9 cm high when compacted by the Marshall hammer. Three variables were measured for each specimen: Marshall stability, Marshall flow, and Marshall stiffness. The gyratory compactive effort resulted in densities of about 2.25 gm/cm^3 . However, the maximum density obtained with Marshall compaction was 2.0 gm/cm^3 . Again the 75-blow

determine a correlation between the number of gyrations in the gyratory compactor and anticipated traffic volumes; and 3) consideration of aggregate properties.

The primary concern of the Superpave aggregate consensus standard is the use of the "restricted" zone for the 0.45 maximum density curve. The rationale for this zone is to limit the amount of rounded, natural sand in the mix as such sand may cause mixture instability. However, the recommendations made for Superpave in aggregates are not based on research results of a broad range of materials, but rather on consensual guidelines. The feasibility of local materials must be evaluated at the local level from a historical performance perspective. Decker recommends the following actions as necessary to implement Superpave mixture analysis:

1. Establishment of a correlation between gyrations and specific traffic levels.
2. Development, testing and implementation of an easy and rapid method to evaluate the permanent deformation of the mix for medium to heavy traffic.
3. Necessity of evaluating the role and use of Superpave advanced mix testing devices.
4. Adoption of a gyratory compactor for mix design and field quality control/quality assurance (QC/QA).
5. An implementation plan should be developed within three to five years. The medium and high traffic volumes should be evaluated in the first phase. The next phase should include low traffic volume.

The HMA industry is of the opinion that the SHRP provided a repository of new information on HMA technology. The Superpave system lends itself to mix design and field

The goal of Terrel et al. (1994), was to evaluate new methods for controlling the quality of the asphalt concrete mixture in the top layer of pavement. The use of a gyratory compactor in the field laboratory to determine mix quality was evaluated. The standard tests such as density, voids, Marshall stability, and Hveem stability were utilized to test the properties of the mixtures.

They concluded that a gyratory compactor can operate effectively in a field laboratory setting. When comparing density and voids, the gyratory compactor was effective in compacting the representative specimens. The results obtained from gyratory-compacted specimens appeared to be more consistent than with Marshall-compacted specimens. The authors also concluded that it was valid to use the void content measured in gyratory-compacted field specimens as a field control parameter.

Pigois (1985), addressed the resistance of bituminous concrete to permanent deformation. The objective of his study was to compare five apparatuses and procedures. They were: Marshall hammer, gyratory compactor, creep test, static triaxial test, and wheel tracking test. The author opined that the mechanical properties of the test specimens are influenced by the mode of compaction. This study did not consider the influence of the aggregates nor the quality of asphalt binder. The specimens were compacted with the gyratory device to produce the same void content as specimens compacted by the Marshall compactor.

The findings were that there was no correlation between the Marshall stability and the rutting depth for Marshall-tested specimens and poor correlation between the Marshall flow and the Marshall stiffness. On the other hand, there was a very strong relationship between the level of compaction obtained after 1 and 80 gyrations with the gyratory compactor and

the rutting depth. For the creep test, the flow of the Marshall specimens after 60 minutes indicated a good correlation with the rutting depth which did not hold true for gyratory specimens. In the triaxial test, the relationship between the stiffness and the rutting depth was good in Marshall specimens.

The intent of Maupin's study (1995), was to determine the laboratory compactive effort required for a gyratory testing machine to produce the same void level as that reached in pavement being subjected to traffic. The study also evaluated the Marshall test method.

Specimens for this study were obtained from 10 resurfacing projects. The ages of the cored specimens varied from 28 to 44 months in order to determine void levels after varying traffic exposure. The specimens of mix from each resurfacing project were taken to a laboratory environment where six combinations of angle of gyration and vertical pressure were applied for gyratory shear test performance. The angle of gyration varied from 0.872 to 2.618×10^{-2} rad, and the vertical pressure was either 689 or 827 kPa. One aim was to develop a relationship between the voids obtained at each compaction level and the void levels in the pavement due to traffic.

During laboratory compaction, values of shear strength and shear strain were recorded at regular intervals until the rate of densification decreased to 16 kg/m^3 per 100 gyrations (revolutions). Compaction then ceased. For Marshall compaction, 75-blows were used to simulate a high traffic volume. Bulk specific gravities were measured and the voids in total mix (VTM) values were calculated.

Linear models were developed to predict post-construction pavement voids by measuring voids from gyratory shear tests. The voids of specimens using the gyratory shear test with an

angle of 0.872×10^{-2} rad and 827 kPa vertical pressure most closely replicated the final pavement voids. However, the cumulative stresses of additional traffic on the test sections could change these results. In conclusion, a close relationship was achieved between voids obtained by vehicular traffic in pavement and those obtained in the laboratory with the gyratory shear test. Such degree of correlation was contingent on the containment of post-construction voids. A slightly lesser degree of correlation was obtained between actual pavement voids and voids caused by the 75-blows of the Marshall compactor.

The above literature review suggests that the gyratory compactor better simulates field conditions and would, therefore, be preferable for asphalt mix design. While the Marshall compactor least emulates the field conditions amongst the five different compactors available on the market, the gyratory compactor does not fully replicate field conditions either. Such level of simulation is dependent upon the orientation of aggregates in the mix made during the compaction procedure in both the laboratory and the field. Based on these literature review results, the research plan was implemented to compare the Marshall and gyratory laboratory compactors in order to determine which of the two can prepare the laboratory specimens with the better mechanical properties.

2.3.2 Superpave Mix Design

In 1993, the Strategic Highway Research Program (SHRP) introduced a new procedure trademarked as "Superpave" laboratory mix design. This mix design is empirically performance-related and relies on volumetric principles. The procedure utilizes the gyratory

compaction device and the Superpave shear tester to predict the mixture performance during the post-construction stage.

In 1994, Cominsky et al. published "The Superpave Mix Design Manual for New Construction and Overlays". The Superpave mix design system contains three distinct levels of design, namely Level 1, Level 2, and Level 3.

Level 1 < 1 million ESALs (low traffic volume)

Level 2 1 - 10 million ESALs (medium traffic volume)

Level 3 > 10 million ESALs (high traffic volume).

An equivalent single axle load (ESAL) is the load which is applied by one pass of an 18,000 pound axle or 9,000 cars; i.e. one ESAL = one 18,000 pound axle load = 9,000 cars.

Together with the volumetric principles, all three design levels consider the effect of climate and traffic speed on pavement performance. Specimen paving mixes are evaluated for moisture sensitivity. Asphalt binders and paving mixes are aged under laboratory conditions to emulate the effect of aging on pavement service life. Both short- and long-term aging are included.

2.3.2.1 Level 1 Mix Design

The Superpave Level 1 mix design is based on empirical performance-related properties of aggregates and mixtures. Level 1 mix design employs principles of volumetric mix design to produce a paving mix with satisfactory performance without the need for performance-based testing. Asphalt content design selection is based on reaching pre-determined levels of air voids, voids in mineral aggregate, and voids filled with asphalt at three levels of compaction: initial, design, and maximum. An estimation of the pavement performance in terms of permanent deformation, fatigue cracking, or low-temperature cracking is not possible. For such estimation, the Level 2 or 3 performance-based tests are necessary with their attendant costly test equipment and complex test procedures. Successful Level 1 mix design can only be achieved through gyratory compaction. The detailed procedure of Superpave mix design is described in Cominsky's et al., 1994, manual.

In 1995, SHRP has decided to use the Level 1 design for all types of traffic - low, medium, and high. Because of the requirement for highly complex, sensitive equipment, and analysis techniques, Levels 2 and 3 analysis techniques are not expected to be used to mix design and process control at the production facility. The AASHTO is working on setting up the standards for Superpave mix design.

Decker's paper (1995), offers an industry perspective for an appropriate roll-out of the Superpave mix design. The author offers specific suggestions to resolve technical issues associated with the implementation process. The Hot Mix Asphalt (HMA) Industry believes that three principal issues require elaboration: 1) match design level to traffic volume; 2)

determine a correlation between the number of gyrations in the gyratory compactor and anticipated traffic volumes; and 3) consideration of aggregate properties.

The primary concern of the Superpave aggregate consensus standard is the use of the “restricted” zone for the 0.45 maximum density curve. The rationale for this zone is to limit the amount of rounded, natural sand in the mix as such sand may cause mixture instability. However, the recommendations made for Superpave in aggregates are not based on research results of a broad range of materials, but rather on consensual guidelines. The feasibility of local materials must be evaluated at the local level from a historical performance perspective. Decker recommends the following actions as necessary to implement Superpave mixture analysis:

1. Establishment of a correlation between gyrations and specific traffic levels.
2. Development, testing and implementation of an easy and rapid method to evaluate the permanent deformation of the mix for medium to heavy traffic.
3. Necessity of evaluating the role and use of Superpave advanced mix testing devices.
4. Adoption of a gyratory compactor for mix design and field quality control/quality assurance (QC/QA).
5. An implementation plan should be developed within three to five years. The medium and high traffic volumes should be evaluated in the first phase. The next phase should include low traffic volume.

The HMA industry is of the opinion that the SHRP provided a repository of new information on HMA technology. The Superpave system lends itself to mix design and field

QC/QA for most pavements. The primary element in the QC/QA processes must be the volumetric control of the field mixture. However, the HMA industry must implement and refine products and equipment for field production processes in order to facilitate the use of Superpave in paving projects.

2.3.3 Superpave Gyratory Compactor vs Marshall Compactor

Harman et al. (1995), investigated the applicability of the Superpave gyratory compactor (SGC) to field management of the production process. Based on production results, tolerance limits were established for SGC acceptance parameters. The Federal Highway Administration - Office of Technology Applications (FHWA-OTA) recommended that these parameters be asphalt binder content, voids in total mix, and voids in mineral aggregate. The volumetric properties of SGC specimens were compared to those of the Marshall specimens in Harman's paper.

As the cost of an SGC is approximately seven times that of a Marshall compactor and as there are relatively few units available for design and field quality control, an effective solution to this conundrum would be to utilize the Marshall hammer to field control the quality of Superpave mixes. The collected data indicated that there is no correlation between the SGC and the Marshall compactor. If the voids in specimens compacted with the SGC are compared to those compacted with the Marshall compactor, it is obvious that the SGC produces a compactive effort greater than that with Marshall. There is no fixed correction factor or constant which would permit the estimation of gyratory volumetrics based on Marshall specimens. In other words, the data from Marshall-compacted specimens is not

transformable for use in volumetric comparisons. In addition, the SGC and Marshall specimen volumetrics react differently to changes in asphalt cement content.

The authors emphasized the impracticality of adjusting a Superpave-designed mix based on Marshall field data. They are of the opinion that surrogate compactors should not be employed in the field management of Superpave mixes.

Hafez and Witeczak (1995), compared the design asphalt contents results obtained by the Marshall procedure to the Superpave gyratory Level 1 procedure. The Superpave designs were conducted to adequately sustain a traffic volume comparable to traffic represented by 75 blows in the Marshall procedure. Five mix groups and three climatic regions, from cool to warm, were evaluated. They concluded that the difference in asphalt content within any specific mix type was not sensitive to the air void level that was selected in developing the design value. The design range of the air voids was from 3.0% to 5.0%. The Superpave climatic regional changes dictated an increase of approximately 1.0% of additional asphalt required per climatic region in the Level 1 mix design as compared to a Marshall-designed mix. Furthermore, the design asphalt contents for the standard and wet process (manufacturer-preblended) asphalt rubber mixes were comparable in the Marshall and the Superpave specimens in warm climatic regions. Conversely, for wet process (plant-blended) asphalt rubber mixes, Marshall mixes required a 0.5% to 0.8% asphalt content less than the Superpave-designed mixes if polymer-modified asphalt cement was used, to meet equivalent traffic and climatic conditions.

Anderson et al. (1995), described the results of the quality control evaluation of asphalt mixtures with equipment developed in the SHRP. They focused on the feasibility of using

SGC for field quality assurance. The four asphalt contents used in the evaluation of the SGC were 4.0%, 4.5%, 5.0%, and 5.5 % in mixes. The Marshall mix design method was evaluated only at 4.5% design asphalt content. All specimens compacted with the SGC were prepared with approximately 5,000 gm of the mixture and subjected to 204 gyrations. The 4.5% specimens compacted with the Marshall compactor comprised approximately 1,200 gm of the mixture with the standard 75 blows. The research concentrated on the control of the mixture components (asphalt content, aggregate gradation) and the mixture volumetric and densification properties (percentage of air voids).

It was concluded that there was a close correlation between the percentage of voids in mineral aggregate (VMA) and the percent voids in filled asphalt (VFA) with the percentage of air voids established for both SGC and Marshall specimens. The percentage VFA was generally higher than the design values. Both the SGC and Marshall procedures were sensitive to changes in asphalt content and somewhat less significantly, to gradation. In the field specimens the average difference in air voids was 0.3% for the two SGC specimens, and 0.6% for the three Marshall specimens. For the specimens designed in the laboratory, the average difference in air voids was 0.1% for the three SGC specimens, and 0.6% for the three Marshall specimens. One may conclude that the SGC procedure produces specimens with less variance within the group. This could be attributed to the compaction process and might also be due to the larger specimen size in the SGC procedure.

The authors concluded that the SGC procedure appeared to be at least as good a tool for a field control as the Marshall procedure is. The lesser variability resulting from the SGC would instill greater confidence in the test results.

Harman et al. (1995), evaluated the use of the SGC in the field management process. They inspected four different paving projects. The designed mix was specimen directly from the delivery vehicles and sent to the FHWA-OTA mobile laboratory for compaction by a prototype SGC. The quality level of SGC and standard Marshall test results were statistically analysed. A volumetric property analysis was performed to compare the SGC specimens and the Marshall specimens.

The three control parameters utilized were asphalt binder content, VTM, and VMA. Study outputs dictated that production tolerances should be $\pm 0.4\%$ for asphalt cement (AC) content, $\pm 1.1\%$ for VTM, and $\pm 0.9\%$ for VMA. Thus the V_a (air voids) and VMA were set lower for SGC mixes than those for Marshall mixes ($\pm 1.5\%$ for V_a and VMA). The greater compactive effort by the SGC resulted in lesser VTA's and VMA's for all four study locations. The SGC specimens had on average a 1.7% lower V_a and a 1.6% lower VMA than the Marshall specimens. It became obvious that specimens with lower void levels would offer less variability and therefore lower standard deviations during production.

To come up with conclusions for compaction comparison (SGC versus a surrogate Marshall compactor) the authors considered the following facts: the cost of SGC's (7 times more than the Marshall compactor), the relatively few SGC's currently available for design and field quality control, and the widespread availability of the Marshall hammer. However, the data obtained from these four study locations indicated the following:

- no correlation of data between the SGC and Marshall compactor
- the SGC produces greater compactive effort
- the difference in SGC/Marshall compactive effort is not consistent among the four mixes

- it is not possible to establish a fixed correlation factor in order to estimate gyratory volumetrics through the use of Marshall compactor.

Based on these results, the authors indicated that the determination of appropriate tolerance limits based on local production which takes into account the regional differences should be within the purview of each U.S. state highway agency. They concluded that a Marshall compactor should not be used as a surrogate for field verification of Superpave-designed mixes. The primary reason is that the Marshall compactor compacts aggregate and asphalt differently from the SGC. As a result, Marshall compactors are not recommended for use in the field management of Superpave mixes.

D'Angelo et al. (1995), evaluated five different asphalt mixes which were produced at five different asphalt mix plants. Two of these mixes were designed using the Superpave Level 1 procedure and the remaining three were designed using the Marshall compactor. For each mix, specimens were obtained from the production facility, and prepared in an OEA mobile laboratory. The SGC and the Marshall compactors were used to compact paired specimens of a mix from each plant site. The performance of both compactors was evaluated through the volumetric properties of the paired specimens. The objective of the evaluation was to determine whether the SGC could be used for field Quality control, if the compaction devices could be interchangeable, and if the results were compactor-dependent.

The authors used VTM as a primary criterion in the volumetric design for hot mix asphalt specimens. The VTM values for both compactors were plotted against the asphalt content for all five mixes. The plots indicated that there was a relationship between the VTM and asphalt content with uniform results by the SGC and the Marshall hammer. The SGC

displayed slightly less dispersion than the Marshall. The VTM for both the Superpave Level 1 and the Marshall-compacted specimens was optimized by changing the asphalt binder content, after the VMA had been optimized via evaluation of the aggregate gradations. Another primary factor for evaluating the volumetric quality control is the VMA which is more inherent to the aggregate structure of the mix than the VTM. The VMA is defined as... "the volume of intergranular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective asphalt content, expressed as a percent of the total volume of the specimen" (D'Angelo et al., 1995). The VMA of the SGC and Marshall specimens in each of the five mixes was measured. The SGC specimen had a lower VMA than the Marshall specimen for each mix. This suggests that the aggregates are re-oriented during the SGC compaction to a much denser state. In addition, changes in asphalt content did not affect the VMA of the SGC specimens in the same manner as that of the Marshall specimens.

The authors concluded that the SGC yielded similar results to the Marshall compactor only when comparing the VTM. From this point of view the SGC and the Marshall were interchangeable for QC testing. However, when comparing the VMA results, the aggregate structures of the SGC specimens and the Marshall specimens differed significantly. In this instance, the SGC and the Marshall were not interchangeable for QC testing. Therefore, one must conclude that mixes designed with the SGC cannot be tested and controlled in the field with the Marshall compactor.

In reviewing this section, the new Superpave method and equipment for asphalt mix design appears to be an improvement over current methods for mix design. However, the

high cost of equipment coupled with an insufficiency of historical data has so far inhibited the usage of this compaction method.

2.4 BINDER

The use of asphalt cement in composite materials is based on its mechanical properties and its sensitivity to temperature changes. Hot bitumen is a fluid which adheres to other materials and therefore can be applied to, or mixed with, other substances. After cooling to the same temperature as the surrounding environment it becomes semi-solid and flexible. At very low temperature it becomes hard and brittle, which may limit its use. Jimenez, 1986, indicated that the binder affects the design requirement of asphalt mix for stability, durability, and fatigue resistance. The performance of asphalt concrete pavements is dependent upon such factors as penetration, viscosity, temperature susceptibility, stiffness, and the constituents of bitumen.

2.4.1 Bitumen Properties

There are varying manufacturing grades of bitumen, each exhibiting different mechanical properties. In order to characterize these grades, and to check if a given bitumen follows the specifications of a certain grade, the following technological test methods have been developed:

- Fraass breaking point or brittleness range.
- penetration or semi-solid range.
- softening point Ring and Ball or beginning of fluidity.

- viscosity or fluidity range, and
- stiffness modulus of all ranges.

The above properties were discussed in Heukelom's paper, 1973. He stated that effective asphalt mix design necessitates a better understanding of the conditions to which the binder is to be subjected. It is necessary to have data about the stress/strain conditions prevailing in bitumen depending upon its end use. The performance requirements are expressed in terms of penetration and/or viscosity and its relationship to the stiffness modulus.

Van der Poel (1954), discussed the direct relationship between the penetration and the stiffness modulus. He introduced the term "stiffness", $S_{t,T}$, to differentiate this parameter from the modulus E of elastic responses. The stiffness modulus is given by the following equation:

$$S_{t,T} = \left(\frac{\sigma}{E} \right)_{t,T} \quad (3)$$

where:

σ = refers to applied stress, N/m^2 ,

t = refers to the time of loading, sec. and

T = refers to the test temperature, $^{\circ}\text{C}$

Van der Poel stated that the stiffness modulus of bitumen (S_{bit}) depends upon variables such as temperature, the time of loading, the rheological characteristics of bitumen, and its

hardness. The hardness can be determined by the Ring-and-Ball temperature. The rheological performance of bitumen can be characterized by the Penetration Index (PI) given by the following equation:

$$\frac{\text{Log } 800 - \text{Log Penetration}}{T_{RB} - T} = \frac{1}{50} + \frac{20}{10} \cdot \frac{PI}{PI} \quad (4)$$

where:

T_{RB} = temperature of the Ring-and-Ball softening point, °C,

T = the temperature in °C of the penetration test, and

PI = Penetration Index of bitumen.

The value of the binder stiffness can be determined from the Van der Poel's nomograph. Figure 2.2. The binder stiffness is a function of time of loading, PI , and temperature difference (T_{dif}) representing the difference between the temperature at which penetration is determined and the temperature of Ring-and-Ball softening point.

In 1987, the Strategic Highway Research Program (SHRP) developed a performance based system for specifying asphalt materials (McGennis, 1994). The binders are specified according to operational climate and pavement temperature. Requirements for physical properties remain unchanged but the temperature is required to meet such properties changes. The binders are classified into grades in accordance to the SHRP binder specification and are shown in Table 2.3 (McGennis, 1994).

Figure 2.2: Van Der Pool's Nomograph (1954)

Table 2.3: Superpave Binder Grades (McGennis, 1994)

High Temperature grade (°C)	Low Temperature Grade (°C)
PG 46-	34, 40, 46
PG 52-	10, 16, 22, 28, 34, 40, 46
PG 58-	16, 22, 28, 34, 40
PG 64-	10, 16, 22, 28, 34, 40
PG 70-	10, 16, 22, 28, 34, 40
PG 76-	10, 16, 22, 28, 34
PG 82-	10, 16, 22, 28, 34

The asphalt binder can be selected using one of the following three Superpave criteria.

1. Geographic area (binder grade based on weather / policy decision),
2. Pavement temperature (design pavement temperature), or
3. Air temperature (design air temperature converted to design pavement temperature).

“Reliability, as used in Superpave, is the percent probability in a single year wherein the actual temperature will not exceed the design temperature” (McGennis, 1994). The flexibility of Superpave binder selection is that a different level of reliability can be assigned to high and low temperature grades. To select the binder grade, the user only has to enter minimum and maximum reliability and the Superpave program will calculate the proper asphalt binder

grade. However, Canadian researchers recommend the use of a conversion equation for calculating minimum design temperature, since an assumption that low air and a low temperature of pavement are equal is deemed to be too conservative. The conversion equation is as follows (McGennis, 1994):

$$T_{designmin} = 0.859 * T_{air} + 1.7 \quad (5)$$

where:

$T_{designmin}$ = minimum pavement design temperature in °C.

T_{air} = minimum air temperature in average year in °C.

Superpave binder selection is designed for a mixture that will be subjected to fast moving loads. Where the loads will be stationery, i.e. intersections, toll booths, etc. and where the binders have to offer higher stiffness to withstand a slower rate of loading, Superpave recommends an increase in the high temperature grade by at least one or two grades. Another Superpave recommendation is that the anticipated traffic volume has to be considered in binder selection. If the traffic volume is to be in excess of 10 million ESALs, a designer *can* increase the high temperature grade by one grade. Where the traffic volume exceeds 30 million ESALs, the designer *has* to increase the temperature by one grade.

Yet another evolutionary improvement in Superpave is the laboratory ageing of the binder to simulate field ageing and the subsequent testing of its physical properties. Such

properties are measured with dynamic shear rheometer, rotational viscometer, bending beam rheometer, and direct tension tester.

2.4.2 Pavement Performance

Bahia and Anderson (1995), defined four temperature zones wherein the asphalt binder influences the pavement performance. The first zone is that where the temperature is higher than 100°C. Most asphalt binders become totally viscous and behave like Newtonian fluids at temperatures above 100°C. The malleability or workability of asphalt during the mixing and construction of HMA can thus be adequately measured by its viscosity.

The second zone is that of temperatures between 45°C and 85 °C. This is the highest range of temperature for pavement in service. The main failure in this zone is rutting. The objective is to achieve a high resistance to permanent deformation and the low relative elasticity of asphalt reflecting a more elastic component of the total deformation.

Asphalts in the intermediate temperature zone between 0 °C and 45°C are commonly harder and more elastic than asphalts in higher temperature zones. The primary failure mode is fatigue damage and is caused by repeated loading cycles. A softer and more elastic material offers better resistance to fatigue damage. This is due to lower stress for a given deformation which results in an easy asphalt recovery from its preloading conditions.

The fourth temperature zone is the low-temperature zone, under 0 °C. The main failure mode here is thermal cracking brought about by thermal cooling and resultant shrinkage. During the cooling process, asphalt stiffness increases continuously with the corresponding greater stresses for a given shrinkage strain. There is also a coincident relaxation of the

thermal stresses caused by the viscoelastic flow of the binder. The higher rate of relaxation and a lower stiffness provides better resistance to thermal cracking.

2.4.3 Polymer-modified Asphalt Cement

Polymers are added to asphalt cement to improve its performance properties in the following areas: temperature susceptibility, cohesive strength, elastic recovery, and adhesive power (Hoban, 1990). The polymer-modified asphalt cement must be able to maintain its desirable characteristics during storage and service life, be chemically and physically stable and usable through all aspects of processing in addition to being cost-effective. Even though some polymer-modified binders bear a higher creep stiffness at low temperatures than the one which is desired, they do not have to crack. This is attributed to their ability to stretch without fracture at low temperatures (McGennis, 1994).

There have been numerous studies to determine the type and the amount of polymer required to improve the asphalt cement properties under certain conditions. The selection of modifiers has mainly been effected by conventional testing methods to meet the requirements associated with viscosity or with a penetration grading system. The SHRP has introduced a new set of testing techniques and a new grading system (Anderson, 1991). The testing and grading systems are premised on measuring fundamental properties having a closer relationship to pavement performance.

A binder is deemed to be successful when its usage is able to improve at least one of the basic properties of asphalt as it relates to pavement distress modes. These properties can be classified into four main types and are defined below (Bahia, 1995):

1. Rigidity.
2. Elasticity.
3. Brittleness.
4. Durability.

Rigidity is defined as the total resistance to deformation. High rigidity at high temperatures is desirable in order to withstand rutting. On the other hand, lower rigidity is preferable at intermediate and low temperatures to resist fatigue and thermal cracking. "Elasticity is the recovery of deformation by using the stored energy applied". Greater elasticity is desirable to improve resistance to rutting and fatigue damage. The low elasticity is preferable to resist thermal cracking. At the same time the ability to relax stress by flow has to be high. Brittleness is defined as failure at low strains. Strain tolerance must therefore be enhanced in order to improve the resistance to fatigue and thermal cracking. The properties that describe durability are oxidative aging, physical hardening, and volatilization. Binder resistance to all these changes is desirable.

Bahia describes the testing of asphalt binders that have been modified with three different types of additives: crumb rubber, polymeric additives, and mineral fillers. Polymer modifiers include styrene-butadiene-based modifiers and polyethylene-based modifiers. These were preblended during manufacture at concentrations of 3% to 6%. The testing included rheological and failure characterization at various temperatures. These temperatures were selected to cover climatic regions encountered in the United States and Canada. He found that rheological and failure properties can be improved by using polymer-modified paving-grade asphalts. Also the sensitivity of rheological properties to temperature and frequency

of loading can be reduced by using the polymer modifiers. Performance is greatly dependent on asphalt properties and polymer type and more noticeable at high temperatures where the polymers attain a higher stiffness. The effects are not so obvious at intermediate and low temperatures and can be negative in some cases.

Maccarone et al. (1995), presented findings in respect of the rheological properties of three types of polymer-modified binders (plastomeric and elastomeric types) used in Australia. They described laboratory testing of styrene butadiene block copolymer (SBS), ethylene vinyl acetate copolymer (EVA), and ethylene methacrylate copolymer (EMA) binders and the field performance of these binders. Their conclusion was that for optimum performance of asphalt pavement, a high degree of binder/polymer compatibility must be achieved. Elastomeric binders (SBS) offer improved recovery ability in terms of rut resistance and fatigue life. Plastomeric binders (EVA, EMA) also improved rut resistance without compromising fatigue properties. The susceptibility of SBS, EVA, and EMA-modified asphalt cements to temperature is similar and is significantly lower than that for standard binders without modification.

Lee et al. (1995), gave a detailed analysis of the mechanism of toughening in polyethylene-modified binders. Their paper demonstrated results of tests performed at low temperature on mixes with polyethylene-modified binders. The temperature fracture toughness and fracture energy increase if polyethylene and chlorinated polyethylene are used as additives to asphalt cements. This is due to enhanced shear-yielding mechanism giving plastic deformation at crack tips. The polymer modifier may also reduce damage from

thermal shrinkage through stress relaxation. However, the fine differences between polymer modifiers can make some binders perform better than others in the field.

The statement that polymer modification lowers the fracture temperature of the mix is proven in a paper written by King et al., 1988. Their research concludes that the addition of polymer modifiers causes the fracture temperature of the mix to be lowered by 2 °C to 5 °C.

Goodrich (1988), investigated whether polymer-modified asphalt mixes outperform conventional, unmodified asphalts in tests for low-temperature ductility, toughness-tenacity, temperature susceptibility, force ductility, and tilt oven durability. The performance behaviour of three conventional asphalts representing the extremes of temperature susceptibility and two polymer-modified asphalts were investigated in his project. He concluded that the improvement in low temperature performance depends upon the softness of the binder. The unexpected finding was that the conventional asphalt used consistently outperformed the polymer-modified asphalts. It was found that some asphalts naturally contain the appropriate balance of "viscous fluid-elastic sponge" properties. The author attributes this to the creation of an effective elastic network by molecular associations. As such, some asphalts do not require further alteration of their natural viscoelastic properties in order to improve their performance in asphalt concrete. It should be noted that binders alone will not improve the behaviour of an asphalt mix unless it is well designed and applied on a properly constructed road.

Abd El Halim et al. (1995), investigated the effect of the type of asphalt cement on the rutting resistance and mechanical properties of asphalt concrete mixes. Asphalt mixes with three different asphalt cements (Standard 85/100, 150/200, and a 85/100 polymer), three

different aggregate types (sand, gravel, and crushed stone), and four different gradations were tested. Density tests, static creep tests, static indirect tensile tests, and shear tests were performed. The test results allowed the authors to conclude that mixes with higher shear and indirect tensile strengths have better resistance to rutting and can be obtained through use of asphalt cements with high viscosity or high stiffness. The mixes with polymer binder (AC 85/100 Polymer) gave the best performance.

The review of the above literature has caused the author of this thesis to conclude that the primary factor in enhancing the mechanical properties is the selection of a proper asphalt binder for the environment in which it will be used. Such selection will result in a mix with high interlock and good friction between aggregates, with the ability to withstand climatic changes, with the resultant improvement in the mechanical properties of the asphalt mix.

2.5 CONCLUSIONS OF THE LITERATURE REVIEW

The preceding review of available literature leads the author of this thesis to make the following conclusions:

Marshall and Gyratory Compaction

- The orientation of the aggregates is important in order to develop mixture strength through stone-on-stone contact.
- The method of compaction affects the stability of specimens.
- Specimens compacted with the gyratory compactor exhibited similar properties to that of field core specimens.

- The Marshall compactor gives the least probability of producing specimens similar to pavement cores.
- Air voids are greater in specimens compacted by Marshall when compared to specimens compacted by a gyratory device.
- The rotational compaction pressure of the gyratory compactor permits the preparation of customized densities to meet the requested compactive effort.
- There is close correlation between pavement voids and voids obtained in the laboratory with the gyratory unit. A low degree of correlation characterizes the 75-blow Marshall compactive effort.
- Test equipment for Superpave mix design is approximately 7 times more costly than the standard Marshall compactor - a net inhibiting factor in terms of increasing the use of the Superpave design and associated test equipment.
- SGC and Marshall specimen volumetrics react differently to changes in asphalt binder content. There is no consistent correlation between these two compactors.
- Aggregates and asphalt contents are compacted differently in the Marshall compactor than in SGC. The re-orientation of aggregates during gyratory compaction results in specimens that are much denser and having a lower VMA than those compacted by Marshall. Therefore the Marshall resemble gyratory compactor should not be used as a surrogate for the gyratory compactor in the field management of Superpave mixes.
- Mixes designed with the SGC cannot be tested and controlled in the field using the Marshall because of differences in VMA (voids in mineral aggregates).

- Each locality or region has to evaluate material being used for mix design with an understanding of historical performance.
- Additional studies are necessary in order to identify and validate the best laboratory compaction method.
- Further evaluation of the gyratory compactor as a design tool for asphalt mixes is needed in order to supplement the Marshall design. The SGC method appears to be an effective field control tool, and at least as good as the Marshall method in one study.

Binder

- Asphalt binder affects the stability, durability, and the fatigue resistance of asphalt mixes.
- The addition of polymers improves the performance of asphalt cement with respect to temperature susceptibility, cohesive strength, elastic recovery, and adhesive power. Nevertheless, some asphalts already contain a natural balance and may not require modification of their natural viscoelastic properties to improve their performance in asphalt concrete.
- Polymer modification can lower the fracture temperature of the mix.
- The major effects are noticed at high temperatures where polymers obtain a high stiffness and low phase angle. The effects at intermediate and low temperatures are less pronounced and can be negative in some cases.

- The effects of a binder are highly dependent upon asphalt properties and polymer type.
- Improvement in low temperature performance depends upon the softness of the binder.

As a result of these conclusions, an experiment-based study was developed, and a performance-based testing plan was carried out. It was decided to use regular asphalt binder and polymer-modified asphalt binder in order to evaluate their influence on asphalt pavement performance and different mix design methods. A comparison of two the most common asphalt design methods (Marshall and gyratory), based on the densities of the specimens, was made on the bases of this testing. This comparison and evaluation should be useful in determining the optimum mix design.

CHAPTER 3

TESTING PROGRAM

3.1 RESEARCH PLAN

The research plan consisted of three phases. The first phase included in-depth a literature review of state-of-the-art pavement research and a definitions of the technical problems associated with current mix design methods. Also, the newly developed SHRP "Superpave" design method was presented. It has been shown that the main difference between both methods were the type of compactor used and the design criteria of each.

Based on the results of the literature review, the second phase of this research program was formulated. It involved the planning, design, and implementation of a comprehensive experimental investigation which included the selection of test parameters, test methods, and the actual testing. The main objective of the experimental investigation was to compare the performance results obtained from the laboratory testing of the specimens compacted by the Marshall and gyratory laboratory compactors, and to determine the effect of selection of the type of laboratory compaction method on the priordial important mechanical properties of each asphalt mix. A subsidiary objective was to evaluate the effect of asphalt binders on the

mechanical properties of asphalt mixes, whether designed by Marshall or gyratory compaction. Factors included in the experimental investigation were as follows:

1. Test specimens of 100 mm diameter and varying heights were compacted with either Marshall and gyratory laboratory compactors. In order to simulate heavy traffic conditions, the standard 75-blows were selected for the Marshall compaction.
2. To obtain comparable specimens from each compaction method, the density was taken as a control factor. Since it is not possible to regulate the density of Marshall-compacted specimens unlike that of gyratory-compacted specimens, the Marshall compaction was carried out first. The gyratory-compacted specimens were compacted to the same density as that achieved for the Marshall compacted-specimens.
3. Two different types of asphalt cement were employed to study the effect of viscosity on the mechanical properties of asphalt mixes: standard 85/100 Pen and 85/100 polymer-modified asphalt cements. For each mix five asphalt contents were applied, namely, 5.0%, 5.5%, 6.0%, 6.5%, and 7.0%.
4. Only one gradation was utilized in the test. The Ministry of Transportation of Ontario (MTO) has been using HL-3 on most of its highway projects.

The testing program was carried out in three stages. The first stage comprised the evaluation of the compaction methods using conventional industry criteria. Subsequently, tests to determine density, indirect tensile strength, and susceptibility to stripping or moisture induced damage were performed on test specimens under room temperature.

The second stage included the evaluation of the performance of the compacted specimens under extreme temperatures. Thus, vertical load cyclic tests were performed on test specimens under warm temperature of 40°C in order to evaluate the ability of the mix to rutting. While rutting is known to be associated with high temperatures, thermal cracking is identified with cold temperatures. Therefore, indirect tensile strength tests were performed at -35°C in order to assess the effect of the test parameters on pavement strength at cold temperature.

The third stage of this testing program used the shear testing capabilities at the Civil and Environmental Engineering Laboratory at Carleton University (Zawh, 1995). The main advantage of the shear strength test is that it provides a strength parameter that is directly related to the quality of compaction as well as the performance in the field.

Finally, the third and last phase of this research plan involved the data collection, test analysis, and utilization of the test results and analysis to achieve the prestated objectives of this research.

The mix preparation, specimens compaction, the testing program and the test method apparatus used for this investigation are described in the following sections. The compaction, indirect tensile strength, compressive fatigue, and moisture sensitivity tests were performed at the Pavement Laboratory and the Infrastructure Laboratory of the National Research Council (NRC) of Canada in Ottawa. The testing commenced on September, 1995 and completed on March, 1996. The shear strength tests were carried out at Carleton University during January and February, 1996. The research plan is outlined in Figure 3.1.

Figure 3.1: Research Plan Outline

3.2 MIX PREPARATION AND PROCEDURE

3.2.1 Aggregates

The coarse aggregates (crushed stone) and the fine aggregate (natural sand) used in designing the mix were obtained from the H.J.McFarland construction Co. in Nepean, Ontario. The aggregates were graded according to the specification limits gradation established by Canadian Specification MTO. Table 3.1 and Figure 3.2 give the selected aggregate gradation HL-3 within the specification limits. This selection was based on the availability of aggregates in the Ottawa region.

In order to achieve the proper gradation, the aggregates and the screenings were sieved and placed into separated containers. The requirement for fine aggregates was satisfied by the use of natural sand and limestone for filler.

3.2.2 Binder

The asphalt binder, 85/100 Pen asphalt and polymer-modified asphalt, were supplied by NRC of Canada courtesy of Husky Oil of Calgary, Alberta. The standard 85/100 asphalt cement is the most frequently used type of asphalt binder in the Ottawa region. Its physical properties are displayed in Table 3.2. The specifications for the polymer-modified asphalt binder were not obtained as the information is proprietary.

Table 3.1: Selected and Suggested Aggregate Gradation

Sieve Designation		% Passing by Dry Mass	
		HL-3 Gradation	
in	mm	Specification	Selected
3/4"	19	----	----
5/8"	16	100	100
1/2"	13.2	98 - 100	98
3/8"	9.5	75 - 90	83
No. 4	4.75	45 - 65	60
No. 8	2.36	36 - 64	45
No.16	1.18	25 - 58	30
No. 30	0.6	16 - 45	20
No. 50	0.3	7 - 26	10
No. 100	0.15	3 - 10	6
No. 200	0.075	0 - 5	3

Figure 3.2: Gradation Curve

Table 3.2 Physical Properties of Asphalt Cement 85/100 A Pen

<u>PROPERTY</u>	<u>ASTM NO.</u>	<u>SPECS.</u>		<u>TYPICAL ANALYSES</u>
		<u>MIN.</u>	<u>MAX.</u>	
Density @ 15°C, kg/L	D 70	-----	-----	1.0341
Pen. @ 25°C, 100g/5sec.	D 5	85	100	90
Flash Point, °C	D 92	230	-----	290
Ductility @ 25°C, cms	D 113	100	-----	150+
Solubility in C ₂ HCl ₃ , %mass	D 2042	99.5	-----	99.9
% Xylene for Negative Spot Test, AASHTO	T 102	-----	55	25
Viscosity @ 60°C, Pa.s (Absolute Viscosity) _a	D 2171	-----	-----	199
Viscosity @ 135°C, mm ² /s (Kinematic Viscosity)	D 2170	-----	-----	414
Thin-Film Oven Test, % loss	D 1754	-----	0.5	0.25
Test after T.F.O.T.:				
Pen. @ 25°C, 100g/5sec	D 5	-----	-----	55
% Retained Pen. @ 25°C		55	-----	61
Vis. @ 60°C, Pa.s	D 2171	-----	-----	484
Ratio of Absolute Viscosity		-----	-----	2.43

3.3 COMPACTION PROCESS

3.3.1 Compaction Apparatus

The purpose of this thesis was to compare the performance of pavement specimens compacted by two different compaction procedures. The first set was compacted with blows and the second set was compacted by employing gyrations. The compactors used to fabricate these specimens are described below.

3.3.1.1 Marshall Compactor

The Marshall compactor consisted of two compaction hammers with flat, circular tamping faces and a 4.536 ± 9 gm sliding weights, a concrete compaction pedestal, a specimen mold holder mounted on the compaction pedestal to center the compaction mold and hold it in the proper position during the compaction of the specimen, and a counter mechanism. During the compaction process the hammers were attached to a chain which was connected to the counter mechanism and adjusted for the pre-determined number of blows. A noise reduction cabinet surrounded the mechanical compactor apparatus. The Marshall compactor apparatus is shown in Figure 3.3.

3.3.1.2 Gyratory Compactor

The Rainhart Series 142 Gyratory Compactor with Self-Extraction Specimen was used to compact the specimens by gyration. The compactor consisted of a control panel, ram

Figure 3.3: Marshall Compactor Apparatus

pressure gauge, loading table, and accumulator. The control panel included the main power switch, a tilt toggle to actuate the angle of gyration of the mold, a ram toggle to control the location of the ram face by advancing the retraction of the ram into or out of the mold, and monitor switch to activate the specimen height display. The loading table was connected to the trolley, turntable, and to the counter turntable switch used for counting the specified number of gyrations. The gyratory compactor is presented in Figure 3.4 and Figure 3.5.

3.3.2 Marshall Compaction

The compaction procedure was performed according to MTO specification LS-261 (Method of Test for Preparation of Marshall Specimens).

3.3.2.1 Precompaction Conditions

The percentages of coarse and fine aggregates, filler, and asphalt cement were determined as shown in Table 3.3. The specific amount of aggregates required for each gradation size and sufficient to form a specimen of 1200 gm specimen, including the asphalt binder was calculated (Table 3.4). The aggregates were combined according to this calculation and conditioned in the oven for a period of three hours to achieve a temperature slightly higher than the mixing temperature. Bituminous material was placed in a 2000-ml beaker and heated, with occasional stirring, to a temperature which would achieve the proper viscosity. The mixing temperature described in MTO specification LS-261 and the temperature recommended by specialists at the Center for Surface Transportation Technology at NRC was used. The aggregates to be mixed with regular binder were preheated to 177°C and the

Figure 3.4: Rainhart Gyratory Compactor

Figure 3.5: Gyratory Compactor Apparatus

Table 3.3: types and Properties of Suggested Mixes

Mix		Aggregate				Weight % of Total Weight of Mix			
Asphalt Content	Asphalt Type	Type			Gradation	Asphalt Content	Aggregate		
		Coarse	Fine	Filler			Coarse	Fine	Filler
5.0%	85-100 Pen. AC	Crushed Stone	Sand	Lime- Stone	HL-3	5.00	38.00	54.15	2.85
5.5%						5.50	37.80	53.87	2.84
6.0%						6.00	37.60	53.58	2.82
6.5%						6.50	37.40	53.30	2.81
7.0%						7.00	37.20	53.01	2.79
5.0%	Polymer Modified AC	Crushed Stone	Sand	Lime- Stone	HL-3	5.00	38.00	54.15	2.85
5.5%						5.50	37.80	53.87	2.84
6.0%						6.00	37.60	53.58	2.82
6.5%						6.50	37.40	53.30	2.81
7.0%						7.00	37.20	53.01	2.79

2

**PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT**

PRECISIONSM RESOLUTION TARGETS

Table 3.4: Types and Properties of Suggested Mixes

Weight Weight of 1 Sample in Grams					
Mix	Asphalt	Aggregate			
85/100 AC or Polymer AC 5.0% asphalt content	66.00	Coarse		Fine	Filler
		456.00		649.80	34.20
		1.2	3.8	No. 4	Sand
		22.80	171.00	262.20	649.80
Mix	Asphalt	Aggregate			
85/100 AC or Polymer AC 5.5% asphalt content	66.00	Coarse		Fine	Filler
		453.60		646.44	34.08
		1.2	3.8	No. 4	Sand
		22.68	170.10	260.82	646.44
Mix	Asphalt	Aggregate			
85/100 AC or Polymer AC 6.0% asphalt content	72.00	Coarse		Fine	Filler
		451.20		642.96	33.72
		1.2	3.8	No. 4	Sand
		22.56	169.20	259.44	642.96
Mix	Asphalt	Aggregate			
85/100 AC or Polymer AC 6.5% asphalt content	78.00	Coarse		Fine	Filler
		448.80		639.60	33.72
		1.2	3.8	No. 4	Sand
		22.44	168.30	258.06	639.60
Mix	Asphalt	Aggregate			
85/100 AC or Polymer AC 7.0% asphalt content	84.00	Coarse		Fine	Filler
		446.40		636.12	33.48
		1.2	3.8	No. 4	Sand
		22.32	167.40	256.68	636.12

standard 85/100 asphalt cement to a temperature of 150 °C. The aggregates to be blended with the polymer-modified binder were heated to a temperature of 177 °C and the polymer-modified binder was heated to a temperature of 165 °C. The bowl for mixing was also heated to avoid temperature loss during the blending process.

The hot bituminous material was added to the hot aggregates in an amount according to the desired percent in the mix. The mixture was then rapidly mixed until the aggregate particles were completely and uniformly coated by the binder.

3.3.2.2 Compaction Conditions

The Marshall compactor allows compaction of two specimens at the same time. Specimen size was dictated by a mold diameter of 10 cm and molds were heated in advance to keep the compaction temperature during compaction process. A piece of filter paper having the same diameter as the mold was placed on the bottom of the mold before the batch was introduced and then on the top to prevent the mixture from sticking to the mold and to the hammer. The mixture was then compacted with 75 blows on each side, per the Asphalt Institute's guidelines for heavy traffic conditions. The compaction temperature for the mix with standard asphalt cement 85/100 was 140 °C and 155 °C for the mix with polymer-modified asphalt cement. The filter paper was then removed, the specimens were cooled to room temperature, extracted from the molds, and left to stand upright overnight on a flat surface at room temperature. The bulk relative density (BRD) for each specimen was then determined.

3.3.2.3 Bulk Relative Density (BRD)

Two days after compaction, the height of each specimen was recorded. Then the specimens were tested in accordance with M10 specification L.S-262 (Method of Test for Bulk Relative Density of Compacted Bituminous Mixtures). In the interest of accuracy all loose particles on the surface of specimens were carefully brushed off.

3.3.3 Gyrotory Compaction

The preparation of the aggregates and bituminous material for compaction was identical to the procedure outlined in Section 3.3.2.1.

The Rainhart series 142 gyrotory compactor with self-specimen extraction was used for specimen preparation. This compactor allows for the compaction of only one specimen at a time. To simulate heavy traffic conditions, a ram pressure of 600 kPa, representing the tire pressure, and an angle of gyration of one degree were used. Specimen diameter remained unchanged, as in Section 3.3.2.2, i.e. 10 cm.

3.3.3.1 Compaction Conditions

Before the mix was spooned into the mold, a filter paper with the same diameter as the mold was placed on the bottom plate of the mold. Another sheet of filter paper was put on the top of the mix inside the mold in order to prevent the mixture from sticking to the mold and loading head. The gyrotory compactor can continuously monitor the increase in specimen density as the compactive effort increases. For each equivalent asphalt cement mix, the number of gyrotory revolutions was based on the attained density of the paired specimens via

the Marshall method. The change in height was recorded after every fifth gyration during the process of compaction to calculate the corrected density and to draw the density curve.

After compaction the filter paper was removed, the specimens were placed on the flat desk, left to cool and then extracted from the molds. The height of each specimen was recorded and M10 specification I S-262 was used to obtain BRD.

3.4 TEST FACILITY

The test facility consisted of a shear apparatus, a hydraulic actuator and controller, monitoring devices, a data acquisition system, a temperature-controlled chamber, a temperature-controlled water bath, a cold room, and a vacuum-saturated apparatus. These apparatus are described bellow.

3.4.1 Shear Apparatus

The shear apparatus was used to test the shear strength of the specimens. The apparatus consisted of a Tinien Olsen Lo-Torg testing machine equipped with two jaws for fastening the specimen, a dial gauge for recording the maximum torque, a scale for recording the angle of twist, and two plates which were glued to the specimen to facilitate fastening the specimen to the jaws. The capacity of the dial gauge was 110 kNm with a sensitivity of 0.20 Nm. The torque testing machine is portrayed in Figure 3.6.

Figure 3.6: Torque Testing Machine

3.4.2 Hydraulic Actuator and Controller

All tests on the specimens at NRC were performed with an Material Testing System (MTS) hydraulic actuator coupled to an MTS 458.20 MicroConsole controller (Figure 3.7). The hydraulic actuator was equipped with an internal linear variable displacement transducer (LVDT) and a load cell. The actuator controller could be used for load or displacement control depending on test requirements.

ITS tests were executed using the internal function generator while two external generators were used to produce the required load pulse for the compressive fatigue test. The external generators were comprised of a Wavetek Model 182A 4-MHZ and a Hewlett Packard 8111A Pulse Function 20-MHZ. To ensure the production of the proper loading function, a Tektronix 2212 80 MHz Digital Storage Oscilloscope was employed. The function controller and the function generator are illustrated in Figure 3.8.

3.4.3 Monitoring Devices and Data Acquisition System

This testing apparatus was used to test the specimens in compressive fatigue, ITS, and moisture sensitivity tests. Load and displacement measurement characterizes the instrumentation part of the experimental investigation. The load measurements comprised the monitoring of the compressive loads by the built-in load cell of the hydraulic actuator. The internal LVDT was used to measure the stroke displacement of the hydraulic actuator.

Labtech Notebook software on a 486 microcomputer was used to monitor the load and displacement which were directly displayed on the computer screen. The hard disk was used to store data to allow further analysis.

Figure 3.7: Hydraulic Actuator with Temperature-controlled Chamber

Figure 3.8: Function Controller and Function Generator

3.4.4 Temperature Controlled Chamber

For testing specimens under climate control a small-scale chamber was constructed around the hydraulic actuator. This chamber was used to test the specimens at a cold temperature of -35°C (ITS tests) and at warm temperature of 40°C (compressive fatigue tests). The chamber was constructed out of metal with styrofoam insulation and had a window installed in the door in order to facilitate the viewing of the specimen during testing (Figure 3.7).

3.4.5 Temperature-controlled Water Bath

A SOILTEST Water Bath AP-152 with a temperature range from -20°C to $+100^{\circ}\text{C}$ was used to saturate and precondition the specimens at a temperature of 40°C in order to prepare the specimens for moisture sensitivity tests.

3.4.6 Cold Room

The cold room or controlled-temperature chamber fabricated by Tenney Engineering INC., Union N.J. was capable of conditioning specimens within a range of temperatures from -40°C to -50°C . This cold room was used for preconditioning specimens to be tested for ITS testing at a temperature of -35°C .

3.4.7 Vacuum-saturated Apparatus

The vacuum-saturated apparatus consisted of a vacuum pump, two 1000 ml Erlenmeyer flasks with rubber stoppers, one condenser vapour flask, a condenser in a beaker filled with

ice-water, where the condenser base was made of stainless steel, brass and or cooper, and a vacuum cell with a two-lead air shut-off valve fitted to the lid. The vacuum cell, the vacuum pump, the flasks, and the beaker were connected with rubber vacuum tubes. The Mercury manometer or vacuum gauge was used for measuring the specified vacuum. The apparatus was used in order to precondition specimens for moisture sensitivity tests.

3.5 DESCRIPTION OF THE TEST METHODS

Five different tests were effected, namely, a bulk relative density (BRD), a moisture sensitivity test, an indirect tensile strength (ITS), a compressive fatigue test or a repetitive uniaxial compression test (RUCT), and a shear strength test. Each test was performed on three specimens per compaction method, type of binder, and type of asphalt cement. These tests are described in bellow.

3.5.1 Bulk Relative Density

The BRD of each specimen was determined following the MTO specification LS-262. The BRD is defined as a ratio of the mass in gm of the specimen in air to the mass in gm of an equal volume of water, including the volume of air voids in the specimen.

The first step in the procedure of calculating BRD was to record the mass of the dry specimen in air (A_1). Then the specimen was placed in a container filled with 23 °C water and left to soak for four minutes. The specimen was then placed into a wired basket, submerged into the water and attached to the scale to record the mass of the submerged specimen. This mass was recorded as B_1 . Then the specimen was removed from water, its

surface was dried with a towel, and the mass in air was recorded (A_2). The BRD was calculated according to the equation below

$$BRD = \frac{A_1 - A_2}{B_1} \quad (6)$$

where:

A_1 = mass of specimen in air. (gm).

A_2 = surface dry mass of specimen in air after water immersion. (gm). and

B_1 = mass of specimen in water. (gm).

3.5.2 Indirect Tensile Strength Test

Since vertical traffic loads on in-service pavement induce indirect tensile strength in the asphalt layer, the mix should incorporate such mechanical property as well. Given its ease of application and comparison, the ITS test was employed to investigate the mechanical properties of the mix. Another reason for using this test is that the failure of a specimen is not significantly affected by surface conditions during ITS testing and is generated in an area of relatively uniform tensile stress (Kennedy et al., 1968).

The ITS test is effected by loading a cylindrical specimen with a single compressive vertical load which acts parallel to and along the vertical diametral plane. The load is applied by a steel curved loading strip developing relatively uniform tensile stress perpendicular to the direction of the load and along the diametral plane. The loading strip is used to achieve

an initial failure from the centre of the specimen instead of along the edge of the loading zone. Under these conditions, the specimen fails by splitting along the vertical diameter (Figure 3.9). The development of stresses within a cylindrical specimen which has been subjected to a vertical line load is described in detail by Kennedy and Hudson, 1968.

3.5.2.1 ITS at Room Temperature (23 °C)

The specimens were loaded at a rate of 51 mm per minute. The vertical displacement and corresponding load were recorded by the data acquisition system (computer attached to the testing machine). The output of each tested specimen was similar to that shown in Figure 3.10. The ITS was calculated as a function of the peak load and dimensions of the diametrical cross section of the specimen using the following equation (Kennedy and Hudson, 1968):

$$S_T = \frac{2 P_{ult}}{\pi h D} \quad (7)$$

where:

S_T = maximum tensile strength, MPa.

P_{ult} = ultimate applied load required to fail the specimen, N.

h = height of specimen, mm. and

D = diameter of specimen, mm.

Figure 3.9: Sample after ITS Test

Figure 3.10: Indirect Tensile Strength Output

Each specimen was loaded twice. The first loading was to achieve the ultimate load (Figure 3.11) and the second to cause complete failure of the specimen (Figure 3.12).

3.5.2.2 ITS Test at Temperature of -35 °C

The specimens were conditioned by placing them in a cold chamber at -35 °C temperature for 48 hours before testing. Since the material behaves more elastically and deformations associated with thermal cracking develop quickly under cold temperature, a slower loading rate of 2.54 mm per minute was applied. The procedure and the equation for testing at room temperature was followed. As most specimens were destroyed upon achieving the ultimate load, the second loading was never applied.

3.5.3 Moisture Sensitivity Test

The purpose of this test is to assess the effect of water on the tensile strength of the paving mixture. The testing procedure followed ASTM Standards, Designation: D 4867 - 88. Each specimen was placed into a beaker of warm water that had been heated to 40°C, with a 25.4 mm water cover. The specimen remained immersed in water after the vacuum saturation, to prevent surface stripping. The beaker containing the specimen was placed into the vacuum-saturated apparatus and the lid was tightly closed. The air shut-off valve was closed and the vacuum pump was turned on to reach an air pressure of 27 in. Hg. The water was brought to a boil in the weakened atmospheric pressure in the beaker, and boiling was continued for 10 min. After vacuum saturation each specimen was placed into the water chamber with warm 40°C water and left to soak for 72 hours. The specimens were then left

Figure 3.11: Sample Loaded to the Peak Load

Figure 3.12: Sample Loaded to the Failure Point

to return to room temperature over 24 hour period, prior to testing. The test on ITS was performed at a room temperature of 23°C, with a loading rate of 51 mm per minute. The program for recording the output, the test equipment, and the equation for calculating the tensile strength were the same as those of the testing of indirect tensile strength. Each specimen was loaded two times. First time the specimen was loaded until the ultimate load was reached, and the second time until the specimen completely failed. After reaching the maximum load values, the tensile strength ratio was calculated with the equation from ASTM Standards, Designation: D 4867 - 88:

$$TSR = \left(\frac{S_{tm}}{S_{td}} \right) 100 \quad (8)$$

where:

TSR = tensile strength ratio, %.

S_{tm} = tensile strength of the moisture-conditioned subset, MPa.

S_{td} = tensile strength of the dry subset, MPa.

3.5.4 Compressive Fatigue Test

The compressive fatigue test or repetitive uniaxial compression test is intended to be an index performance test. This index performance test is carried out to compare the resistance of the mix to permanent deformation on the vertical repeated load.

The permanent deformation curve as it relates to repeated loading is illustrated in Figure 3.13 (Guirguis, 1972). This curve represents the three stages associated with the repetitive loading process. During the first stage (densification) the deformation increases rapidly with the decrease in the air void content of the asphalt pavement. During the second stage (steady state flow) there is a direct linear relationship between pavement deformation and both the load and time. The last stage (damage) shows the increase in the rate of deformation and the resultant failure under repeated loading, that has been caused by cumulative pavement damage (Guirguis, 1972).

The repetitive uniaxial compression test (RUCT) has normally been used at the Centre for Surface Transportation Technology at NRC (El Hussein and Yue, 1994). The test was conducted at 40°C, a temperature at which rutting susceptibility is very high. The MTS hydraulic actuator at NRC was used for the testing.

A cylindrical plate was placed on the flat side of the specimen and a maximum load of 570 kg (690 kPa), which simulates the maximum tire pressure, was applied to the specimen (Figure 3.14). The rate of loading was selected to be 0.5 Hz. The loading function was a square wave load application derived from research work at Nottingham University that had for objective to simulate traffic loading (Brown and Bruton, 1984). The square wave lasted for two seconds and consisted of a loading period followed by a rest period. The loading

Figure 3.13: Typical Creep Curve

Figure 3.14: Compressive Fatigue test

period lasted for 0.2 seconds and the rest period for 1.8 seconds (Figure 3.15). A minimum load of 5 kg was applied during the rest cycle to maintain continuity between loading head and the specimen

The duration of the loading of each specimen was recorded by computer. The output for each specimen was similar to the specimen shown in Figure 3.16. The fatigue failure N_f (number of cycles at which the specimen failed) was represented by the point of intersection of the tangents to the duration of the loading curve.

3.5.5 Shear Test

The shear flow of the asphalt mix is a major contributor to rutting deformation. At the time when the asphalt layer is still soft, i.e. in the early stage of the pavement life, the lower vertical compressive stresses and higher tensile strains occur under the wheel load and cause the rutting (Gervais and Abd El Halim, 1990). To assess the shear strength flow of asphalt mixes, a new test method (shear test setup) was developed for this study (Zawh, 1995). The objective of this test was to find out the shear strength of the asphalt mixture by loading the specimen with a torque load along its axis. The test was performed at a temperature of 25°C. In that test each specimen was glued to two plates (one on each side), each plate having the same diameter as the specimen itself (101.6 mm) and a thickness of 10 mm. Then the specimens were left to dry in a vertical position for 24 hours before testing. The two arms of the glued plates were placed inside the opening of the two jaws on the torque machine and carefully fastened (Figure 3.17). The dial gauge of the torque moment was set to zero before testing. The torque was applied at a constant rate equal to three degrees of the twist angle

Figure 3.15: Compressive Fatigue Loading Function

Figure 3.16: Compressive Fatigue Test Output

Figure 3.17: Setup of Shear Strength Test

per second during the entire testing program. The maximum torque T and the time of testing in seconds were recorded for each test specimen at failure. The shear strength was calculated using the elastic torsion equation (Bowes, 1990):

$$\tau_{\max} = \frac{T D}{2 J} \quad (9)$$

and

$$J = \frac{\pi D^4}{32} \quad (10)$$

where:

$\tau_{\max}$ = maximum shear stress, N m^{-2} ,

T = Torque moment, Nm,

J = polar moment of inertia, m^4 , and

D = diameter, m.

3.6 TEST PROCEDURE SUMMARY

A summary of the testing program is given in Table 3.5. Two different mixes with two different asphalt cements, compacted by two different types of compactors were tested. To attain the objectives of this testing program, more than 500 specimens were prepared and used. Over three hundred specimens were tested to obtain the IIS, moisture damage, compressive fatigue, and shear strength test results. Fifteen specimens of each mix (standard 85 100 Pen AC and polymer-modified AC) were prepared. These were further divided into five groups of three specimens each which would allow three specimens to be used in each of the five tests. Such fifteen specimens were prepared for each category of asphalt content, i.e. 5.0%, 5.5%, 6.0%, 6.5%, and 7.0%. The selection of specimens was based on the ability to obtain same mean density for both compaction methods within the range of the allowed standard deviation (Appendix A).

The age of the specimens varied due to the availability of the test equipment, but since all of them were stored for longer than 21 days (the critical time for aging), the age neither influenced their physical properties, nor the results of their performance.

Table 3.5: Test Summary

Test Type	Temp.	Load Rate	# of Samples Tested per Asphalt Content	Aproximate Length of Test
ITS	+23 C	51 mm/min	3	5 min
	-35 C	2.5 mm/min	3	2.5 days
Compressive Fatigue	+40 C	0.5Hz	3	2.5 hrs
Moisture Sensitivity	+23 C	51 mm/min	3	4.5 days
Shear Strength	+25 C	----	3	1.5 days

CHAPTER 4

TEST RESULTS

This chapter presents the results of testing specimens manufactured by the Marshall and gyratory compaction methods using standard and polymer-modified 85/100 asphalt cements (AC). The Marshall method was taken as a benchmark for comparing the differences between the two compaction methods. A base line of 6.0% asphalt content was also used in providing detailed results. The test results of each specimen are given in Appendix B. The description of these test results is given in the next two sections, first discussing the test results obtained from Marshall-compacted specimens and the second discussing the test results obtained from gyratory-compacted specimens, in the followed order:

1. Conventional test results; the bulk relative density (BRD), the indirect tensile strength (ITS), and the moisture damage.
2. Test results obtained at extreme temperatures for ITS at -35°C and for compressive fatigue at 40°C .
3. Shear test results.

This chapter also discusses the variability of the test data and factors affecting the consistency of laboratory specimens. The analysis and recommendations from comparing the performance of the two laboratory compaction methods as well as the binder influence on the mix mechanical properties were based on these results.

4.1 TEST RESULTS - (MARSHALL-COMPACTED SPECIMENS)

One hundred and fifty specimens were compacted with 75-blows on each face by the Marshall compactor. Half of these specimens used a standard 85/100 asphalt cement (AC) and the other half used a polymer-modified asphalt cement. The results of testing these specimens are described below.

4.1.1 The Standard 85/100 Asphalt Cement

The mix using standard 85/100 AC was prepared with five asphalt contents. These were 5.0%, 5.5%, 6.0%, 6.5%, and 7.0%. Different types of tests were performed on these specimens. First, the conventional tests including the bulk relative density (BRD) test, the indirect tensile strength (ITS) test, and the moisture sensitivity test were performed. Secondly, the compressive fatigue and the ITS tests were performed at hot and cold temperatures, respectively. Finally, the shear strength test was performed.

4.1.1.1 Conventional Test Results

As mentioned above, three conventional tests were employed. These were the BRD test, the ITS test, and the moisture sensitivity test. The setup and results of these tests are discussed below.

Bulk Relative Density

Before the testing program could be started, the BRD of each specimen had to be obtained from the 15 specimens. Table 4.1 presents the calculated values of the BRD at 6.0% asphalt content. The mean value of the density was 2.335 gm/cm^3 with 0.5170% coefficient of variation (C.O.V.). The C.O.V. and the range of density values were very small indicating that there was a little variation in the values of densities. The range of density was between 2.312 gm/cm^3 and 2.355 gm/cm^3 . Table 4.2 shows the calculated averages of the BRD and their corresponding standard deviations for the five asphalt cement contents. It shows that the maximum density of 2.362 is achieved at 7.0% asphalt cement content.

The 15 specimens at each asphalt content were divided into five sets, each containing three specimens. The three specimens comprising each set were chosen such that their average density would be identical or close to the mean density of the 15 specimens, and their STD would be close to 0.0141 which is prespecified by ASTM for such specimens.

Indirect Tensile Strength Test Results

One set of three specimens at each asphalt content was used to perform this test. Each specimen was loaded until maximum load was achieved. Then the load was released and

Table 4.1: Average Density Test Results at 6.0% Asphalt Content

Marshall Compaction - 85/100 AC

SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
1	63.72	1198.2	1199.6	688.8	510.8	2.346			
2	63.65	1200.3	1201.2	691.5	509.7	2.355			
3	64.04	1194.5	1195.8	687.7	508.1	2.351			
4	62.37	1172.2	1172.7	671.9	500.8	2.341			
5	60.86	1146.8	1147.5	657.6	489.9	2.341			
6	62.40	1172.3	1173.0	671.8	501.2	2.339			
7	63.06	1180.1	1181.1	672.9	508.2	2.322			
8	63.60	1182.7	1183.8	672.3	511.5	2.312			
9	63.28	1191.4	1192.1	683.5	508.6	2.343			
10	63.38	1178.8	1180.6	671.6	509.0	2.316			
11	62.94	1180.5	1181.9	676.8	505.1	2.337			
12	63.25	1183.8	1184.9	677.6	507.3	2.334			
13	62.95	1179.0	1180.7	674.3	506.4	2.328			
14	63.18	1192.5	1193.4	684.0	509.4	2.341			
15	63.86	1190.3	1190.5	678.1	512.4	2.323			
16*	63.25	1195.5	1195.8	683.6	512.2		2.335	0.0121	0.5170

* Surplus sample - not included in formulaic calculations. The duplex nature of the Marshall hammers caused 16 specimens to be prepared. From a visual viewpoint the best 15 were chosen for these tests.

Table 4.2: Average Density Test Results

MIX Asphalt Content	DENSITY gm/cm³	STD	MIX Asphalt Content	DENSITY gm/cm³	STD
85/100 AC			85/100 AC		
M 5.0%	2.302	0.0123	G 5.0%	2.301	0.0072
M 5.5%	2.317	0.0086	G 5.5%	2.321	0.0119
M 6.0%	2.335	0.0121	G 6.0%	2.337	0.0111
M 6.5%	2.356	0.0135	G 6.5%	2.36	0.0124
M 7.0%	2.362	0.0167	G 7.0%	2.356	0.0128
Polymer			Polymer		
M 5.0%	2.286	0.0122	G 5.0%	2.285	0.0047
M 5.5%	2.302	0.0066	G 5.5%	2.305	0.0034
M 6.0%	2.308	0.0078	G 6.0%	2.305	0.0074
M 6.5%	2.322	0.0096	G 6.5%	2.324	0.0039
M 7.0%	2.314	0.0108	G 7.0%	2.321	0.0039

M: Marshall Compaction

G: Gyratory Compaction

AC: Asphalt Cement

reapplied again until the complete fracture of the specimen was obtained. The first load can be used to calculate the ITS and the second load measures the ability of the mix to resist crack propagation. The cracks are visible on the flat surface and the edge pieces of the specimen. Cracks started at the edges directly under the loading strip during the testing and then propagated to the center of the specimen. A photograph of a tested specimen is shown in Figure 3.9 (pp.87).

The result of testing one set of three specimens with 6.0% asphalt content is shown in Table 4.3. Table 4.4 gives the averages of the ITS for the five asphalt contents. It shows that the density increases as the asphalt content increases. As the asphalt content increases by 40%, from 5.0% to 7.0%, the density increases by 2.65%, from 2.301 gm/cm³ to 2.362 gm/cm³. One may argue that higher densities might be achieved if an asphalt cement content of greater than 7.0% were used. However, tests performed in this study and previous literature proved that this is not the case. While maximum density was obtained at the 7.0% asphalt content, the maximum ITS was obtained at 5.5% the asphalt content. An increase of 10% of asphalt cement in this mix (from 5.0% to 5.5% asphalt content) resulted in an increase of 27% in the ITS. On the other hand, the addition of 1.5% asphalt content or increasing the binder by 30% will result in a loss of strength by 18%. The largest variation within each three-specimen set was obtained at 5.0% asphalt content (Appendix B).

The test results of the second loading for three specimens with the same asphalt content of 6.0% are shown in Table 4.5, and the averages at the five asphalt contents are given in Table 4.6. The application of the second load on the specimens indicates that once the specimens are loaded with maximum load, their mechanical properties and resistance to

Table 4.3: Indirect Tensile Strength Test Results at 6.0% Asphalt Content

MIX Compaction	BINDER type	SAMPLE number	LOAD lb	LOAD N	HEIGHT mm	DENSITY gm/cm ³	TENSILE STRENGTH MPa	TENSILE STRENGTH MEAN
Marshall	85/100	2	2788.09	12404.21	63.65	2.355	1.2211	1.1445
		10	2424.32	10785.80	63.38	2.316	1.0663	
		12	2600.10	11567.84	63.25	2.334	1.1460	
Gyratory		6	2614.75	11633.02	65.96	2.333	1.1051	1.0493
		7	2397.46	10666.30	65.18	2.356	1.0254	
		12	2419.43	10764.04	66.29	2.325	1.0175	
Marshall	Polymer	10	1203.61	5354.86	64.14	2.306	0.5231	0.5569
		11	1291.50	5745.88	64.12	2.300	0.5615	
		12	1330.57	5919.71	63.30	2.321	0.5860	
Gyratory		1	1191.41	5300.58	66.20	2.312	0.5017	0.4633
		4	1015.63	4518.54	66.48	2.298	0.4259	
		7	1098.63	4887.80	66.24	2.309	0.4624	

Table 4.4: Average Indirect Tensile Strength Test Results

Asphalt Cement	Asphalt Content %	Marshall * M MPa	Density gm/cm³	Gyratory * G MPa	Density gm/cm³	Difference ** M - G MPa	Ratio G / M %
85/100	5.0	0.9298	2.301	0.8763	2.302	0.0535	94
	5.5	1.1763	2.317	1.0908	2.321	0.0855	93
	6.0	1.1445	2.335	1.0493	2.338	0.0952	92
	6.5	1.0390	2.357	0.9674	2.361	0.0716	93
	7.0	0.9679	2.362	0.8917	2.355	0.0762	92
Polymer	5.0	0.5428	2.287	0.4756	2.285	0.0672	88
	5.5	0.5656	2.303	0.4892	2.305	0.0764	86
	6.0	0.5569	2.309	0.4633	2.306	0.0936	83
	6.5	0.6001	2.322	0.5743	2.325	0.0258	96
	7.0	0.5088	2.312	0.4705	2.321	0.0383	92

* Indirect Tensile Strength (MPa)

** Difference between Marshall and Gyratory ITS

M: Marshall Compaction

G: Gyratory Compaction

Table 4.5: ITS Test Results at 6.0% Asphalt Content, Second Loading

MIX Compaction	BINDER type	SAMPLE number	HEIGHT mm	DENSITY gm/cm3	LOAD P2 MPa	LOAD P1 MPa	RATIO P2/P1 %	RATIO MEAN %
Marshall	85 100	2	63.65	2.355	4594.53	12404.21	37	39
		10	63.38	2.316	4551.10	10785.80	42	
		12	63.25	2.334	4355.57	11567.84	38	
Gyratory		6	65.96	2.333	5517.78	11633.02	47	43
		7	65.18	2.356	4149.23	10666.30	39	
		12	66.29	2.325	4540.25	10764.04	42	
Marshall	Polymer	10	64.14	2.306	2650.27	5354.86	49	46
		11	64.12	2.300	2367.89	5745.88	41	
		12	63.30	2.321	2737.16	5919.71	46	
Gyratory		1	66.20	2.312	2530.81	5300.58	48	48
		4	66.48	2.298	2063.76	4518.54	46	
		7	66.24	2.309	2519.96	4887.80	52	

P1: First Loading

P2: Second Loading

Table 4.6: Average ITS Test Results, Second Loading

MIN		MARSHALL (M)				GYRATORY (G)				RATIO
Asphalt Cement	Asphalt Content %	Density gm/cm ³	Load P1 MPa	Load P2 MPa	Ratio P2/P1 %	Density gm/cm ³	Load P1 MPa	Load P2 MPa	Ratio P2/P1 %	G / M %
85/100	5.0	2.301	9482.14	3979.33	42	2.302	9350.03	4479.09	48	114
	5.5	2.317	11969.72	5546.78	46	2.321	11564.21	6296.24	54	117
	6.0	2.335	11585.95	4500.40	39	2.338	11021.12	4735.75	43	111
	6.5	2.357	10438.20	3895.77	37	2.361	10036.34	4399.04	44	117
	7.0	2.362	9725.01	4145.59	43	2.355	9308.58	4149.23	45	105
Polymer	5.0	2.287	5546.78	3222.34	58	2.285	5072.48	1955.13	39	66
	5.5	2.303	5803.82	2219.44	38	2.305	5166.59	2147.01	42	109
	6.0	2.309	5673.48	2585.11	46	2.306	4902.31	2371.51	48	106
	6.5	2.322	6115.21	3349.07	55	2.325	6013.82	2787.86	46	85
	7.0	2.312	5123.16	2061.93	40	2.321	4945.75	2661.14	54	134

P1: First Loading

P2: Second Loading

cracking are decreased by more than 50%. The lowest resistance was shown at 6.5% asphalt content where the reloaded specimens withstood only 37% of the first load value, and the highest resistance was at 5.5% asphalt content where the specimens withstood 46% of the first load value. The increase and decrease in the values for the second loads are not proportional to the increase and decrease in the values for the first loads, respectively. Discrepancies within three-specimen groups are shown in Appendix B. They are slightly higher than those in other test which could be attributed to the structure of specimens being damaged during the first loading. In addition, there was some inaccuracy in the test data attributed to the time lag between the attainment of maximum loading and the manual switching-off of the loading unit.

Moisture Sensitivity Test Results

A second set of three specimens at each asphalt content was used to perform the moisture sensitivity test at room temperature (23°C) after the specimens were preconditioned in a water bath at 40°C. Since the test is based on a measurement of the ITS of each specimen, the specimens were loaded two times similar to the ITS test. The specimen was first loaded until the maximum load was achieved and then reloaded until total fracture. The obtained ITS of the each specimen was divided by the ITS of the specimen from the same mix (and the same asphalt content) recorded during testing at room temperature. Such a ratio is called the tensile strength ratio (TSR) which indicates the moisture susceptibility of the mix.

The test results for three specimens with 6.0% asphalt content are shown in Table 4.7. The average test results for the five asphalt contents are given in Table 4.8. Similar to

Table 4.7: Moisture Sensitivity, ITS Test Results at 6.0% Asphalt Content

MIX Compaction	BINDER type	SAMPLE number	LOAD lb	LOAD N	HEIGHT mm	DENSITY gm/cm ³	TENSILE STRENGTH MPa	TENSILE STRENGTH MEAN
Marshall	85-100	3	1616.21	7190.52	64.04	2.351	0.7036	0.7036
		6	1635.74	7277.41	62.40	2.339	0.7308	
		8	1540.43	6853.37	63.49	2.312	0.6764	
Gyratory		1	1933.11	8600.41	65.85	2.335	0.8184	0.8175
		11	1860.35	8276.70	66.07	2.326	0.7849	
		13	1994.63	8874.11	65.49	2.350	0.8491	
Marshall	Polymer	1	1163.48	5176.32	63.85	2.308	0.5080	0.5037
		5	1157.28	5148.74	64.22	2.292	0.5024	
		13	1147.46	5105.05	63.90	2.323	0.5006	
Gyratory		8	1079.10	4800.92	66.15	2.315	0.4548	0.4559
		12	1083.98	4822.63	66.47	2.293	0.4546	
		15	1088.87	4844.38	66.23	2.303	0.4583	

Table 4.8: Average Moisture Sensitivity Test Results

Asphalt Cement	Asphalt Content %	Marshall * M %	Density gm/cm ³	Gyratory * G %	Density gm/cm ³	Difference ** M - G %	Ratio G / M %
85/100	5.0	59	2.302	59	2.309	0	100
	5.5	48	2.318	65	2.320	-17	135
	6.0	62	2.334	78	2.337	-16	126
	6.5	79	2.355	83	2.361	-4	105
	7.0	76	2.363	89	2.359	-13	117
Polymer	5.0	70	2.287	88	2.285	-18	126
	5.5	79	2.304	89	2.305	-10	113
	6.0	91	2.308	99	2.304	-8	109
	6.5	93	2.322	94	2.324	-1	101
	7.0	103	2.314	108	2.321	-5	105

* Ratio: ITS under water / ITS under dry test (%)

** Difference between Marshall and Gyratory Ratios

M: Marshall Compaction

G: Gyratory Compaction

density, the TSR increases as the asphalt content increases up to 6.5%. However, unlike the density, the TSR decreases as the asphalt content continues to increase. Table 4.8 shows that for 30% increase of asphalt cement in the mix there was 34% increase in the TSR. The addition of another 8% asphalt cement in the mix resulted in a slight TSR decrease of 4%. The difference in the ITS among the three specimens of each set within one type of the mix is below 11% (Appendix B). These differences are shown for ITS of specimens preconditioned in the water because the TRSs are dependent upon the ITS test without preconditioning in the water.

The loads of the second loading test for the three specimens with the same asphalt content of 6.0% are shown in Table 4.9. The averages of those loads at the five asphalt contents are given in Table 4.10. The application of the second load on specimens shows that after loading the specimens to the maximum load their resistance to cracking decreases by about 35%. The greatest difference was achieved at 6.0% asphalt content where the specimens after reloading withstood 53% of the first load value, and the least at 6.5% asphalt content where the specimens withstood 66% of the first load value. The discrepancies within three-specimen groups are shown in Appendix B.

4.1.1.2 Test Results at Extreme Temperatures

Two types of tests were performed at extreme temperatures. These were the compressive fatigue tests effected at a warm temperature of 40°C and the ITS test performed at a temperature of -35°C.

**Table 4.9: Moisture Sensitivity Test Results at 6.0% Asphalt Content,
Second Loading**

MIX Compaction	BINDER type	SAMPLE number	HEIGHT mm	DENSITY gm/cm ³	LOAD P1 MPa	LOAD P2 MPa	RATIO P2/P1 "	RATIO MEAN "
Marshall	85/100	3	64.04	2.351	3858.51	7190.52	54	53
		6	62.40	2.339	3767.15	7177.41	52	
		8	63.49	2.312	3595.78	6853.37	57	
Gyratory		1	65.85	2.335	4434.19	8600.41	52	54
		11	66.07	2.326	4383.18	8276.70	53	
		13	65.49	2.350	5029.02	8874.11	57	
Marshall	Polymer	1	63.85	2.308	3345.43	5176.32	61	61
		5	64.22	2.292	3073.90	5145.74	61	
		13	63.90	2.323	2947.47	5105.05	59	
Gyratory		6	66.15	2.315	3106.47	4570.92	67	62
		12	66.47	2.293	2737.16	4821.63	57	
		15	66.23	2.303	3149.94	4844.38	54	

P1: First Loading

P2: Second Loading

Table 4.10: Average Moisture Sensitivity Test Results, Second Loading

MIX		MARSHALL (M)				GYRATORY (G)				RATIO
Asphalt Cement	Asphalt Content %	Density gm/cm ³	Load P1 MPa	Load P2 MPa	Ratio P2/P1 %	Density gm/cm ³	Load P1 MPa	Load P2 MPa	Ratio P2/P1 %	G/M %
85/100	5.0	2.302	5593.83	3298.92	59	2.309	5545.57	3667.52	66	112
	5.5	2.318	5720.64	3492.76	61	2.320	7552.58	4847.99	64	105
	6.0	2.334	7107.10	3758.65	53	2.337	8583.74	4617.13	54	102
	6.5	2.355	8265.84	5452.64	66	2.361	8349.13	5347.62	64	97
	7.0	2.363	7457.86	4866.09	65	2.359	8251.35	5344.02	65	99
Polymer	5.0	2.287	3895.01	1007.54	26	2.285	4526.81	1966.09	44	170
	5.5	2.304	4583.69	1135.71	25	2.305	4627.14	2433.77	53	212
	6.0	2.308	5143.37	3139.07	61	2.304	4822.64	2997.85	62	102
	6.5	2.322	5633.66	3417.86	61	2.324	5644.52	3577.14	63	104
	7.0	2.314	5277.45	3425.09	65	2.321	5338.86	3635.09	68	105

P1: First Loading

P2: Second Loading

Warm Temperature

The main distress of asphalt pavement in warm and/or hot environment is rutting. Under these conditions a traffic load repetition deteriorates the asphalt pavement. The traffic load is a major factor influencing rutting resistance. The compressive fatigue test (at 40°C), which simulates the traffic load in the field, was selected for this rutting resistance research.

Compressive Fatigue Test Results

A third set of three specimens at each asphalt content was used to perform the compressive fatigue test at 40°C to emulate the average temperature of asphalt pavement performance during the summer month in and about the 40^{ie}th parallel in Canada.

The average number of cycles before specimen failure (CBSF) was determined and given in Table 4.11. The results for each of the three specimens at 6.0% asphalt content are shown in Table 4.12. A photograph of the tested specimen is presented in Figure 4.1. The highest density was obtained at the 7.0% asphalt content as well as the maximum number of CBSF (388). However, while densities were increasing with the increase in asphalt content, the increase in CBSF was inconsistent. An increase of 20% asphalt binder resulted in a decrease of 20% of CBSF. However, the further increase of asphalt binder by 20% resulted in an increase of 14% in the number of CBSF.

The variation in the results within each three-specimen group are greater than in other tests (Appendix B). This was due to the effect of the high temperature on specimens under test. At this temperature the specimens were more susceptible to disintegration. The greatest variation was recorded at 7.0% asphalt content (44%).

Table 4.11: Compressive fatigue Test Results at 6.0% Asphalt Content

MIX Compaction	BINDER type	SAMPLE number	HEIGHT mm	DENSITY gm/cm ³	VERTICAL DISPLACEMENT mm	VERTICAL DISPLACEMENT %	CYCLES quantity	CYCLES MEAN
Marshall	85/100	5	60.86	2.341	5.745	9.44	360	341
		14	63.18	2.341	5.773	9.14	365	
		15	64.40	2.323	5.926	9.20	297	
Gyratory		8	65.37	2.351	5.646	8.64	305	273
		15	66.14	2.325	5.583	8.44	240	
		16	63.57	2.334	8.070	12.69	990	
Marshall	Polymer	7	63.35	2.304	5.314	8.03	444	471
		8	64.52	2.313	5.575	8.43	547	
		14	63.35	2.305	4.732	7.15	421	
Gyratory		5	66.15	2.314	4.176	6.59	235	250
		9	66.17	2.302	6.698	10.54	257	
		13	66.23	2.297	4.882	7.69	257	

Table 4.12: Average Compressive Fatigue Test Results

Asphalt Cement	Asphalt Content %	Marshall * M quantity	Density gm/cm³	Gyratory * G quantity	Density gm/cm³	Difference ** M - G number	Ratio G / M %
85/100	5.0	284	2.303	185	2.303	99	65
	5.5	258	2.317	190	2.322	68	74
	6.0	341	2.335	273	2.337	68	80
	6.5	373	2.356	368	2.361	5	99
	7.0	388	2.361	301	2.357	87	78
Polymer	5.0	299	2.287	216	2.285	83	72
	5.5	314	2.301	329	2.304	-15	105
	6.0	471	2.307	250	2.304	221	53
	6.5	558	2.322	391	2.324	167	70
	7.0	459	2.315	393	2.319	66	86

* Cycles before Specimen Failure (CBSF)

** Difference between Marshall and Gyratory CBSF

M: Marshall Compaction

G: Gyratory Compaction

Figure 4.1: Sample after Compressive Fatigue Test

Cold Temperature

The major distress occurring in asphalt pavement in a low-temperature environment is cracking. This cracking is attributed to the tensile stresses caused by a temperature decrease to very low temperature. The decrease in temperature results in shrinkage of pavement with a resultant development of tensile stresses. The ITS test at a temperature of -35°C was selected for this research.

ITS Test Results

Another three-specimen set at each asphalt content was used to perform this test. The specimens tested under this conditions were destroyed at the peak load, therefore the results of the ITS are presented for the first loading only.

The results of testing one set of three specimens at 6.0% asphalt content is given in Table 4.13. Table 4.14 presents the averages of the ITS of the sets used in this test at five asphalt contents together with their corresponding average densities. While the densities were increasing with the increase in the asphalt content, the ITS values were erratic. With an increase of 0.5% in asphalt content (from 5.0% to 5.5%) the ITS decreased by 10%. Further increases of 0.5% in asphalt content resulted in an increase in ITS of 10%, then a decrease of 2.5%, followed by an increase of 26%, respectively. The maximum ITS of value 3.2792 MPa was achieved at 7.0% asphalt content. The greatest discrepancy in the results within each three-specimen group was 13% and was recorded at 5.0% asphalt content (Appendix B).

Table 4.13: ITS Test Results at Temperature of -35C at 6.0% Asphalt Content

MIX Compaction	BINDER type	SAMPLE number	LOAD lb	LOAD N	HEIGHT mm	DENSITY gm/cm ³	TENSILE STRENGTH MPa	TENSILE STRENGTH MEAN
Marshall	85/100	1	6357.42	28284.16	63.62	2.346	2.7857	2.6517
		4	5639.65	25090.80	62.37	2.341	2.5207	
		7	5991.21	26654.89	63.06	2.322	2.6486	
Gyratory		2	7358.40	32737.52	65.33	2.332	3.1399	2.6944
		5	5161.13	22961.87	66.15	2.325	2.1750	
		10	6474.61	28805.54	65.20	2.357	2.7683	
Marshall	Polymer	2	10562.00	46990.34	63.45	2.310	4.6405	4.2648
		4	8134.77	36191.59	64.91	2.301	3.4937	
		6	10712.00	47657.69	64.08	2.314	4.6601	
Gyratory		6	10814.00	48111.49	66.27	2.314	4.5490	4.4431
		14	9960.94	44316.22	66.21	2.294	4.1940	
		16	10901.00	48498.55	66.26	2.303	4.5863	

Table 4.14: Average ITS Test Results at Temperature of -35C

Asphalt Cement	Asphalt Content %	Marshall * M MPa	Density gm/cm3	Gyratory * G MPa	Density gm/cm3	Difference ** M - G MPa	Ratio G / M %
85/100	5.0	2.6480	2.301	2.7328	2.301	-0.0848	103
	5.5	2.3853	2.316	2.1582	2.321	0.2271	90
	6.0	2.6517	2.336	2.6944	2.338	-0.0427	102
	6.5	2.5846	2.356	2.7135	2.360	-0.1289	105
	7.0	3.2792	2.362	3.1645	2.357	0.1147	97
Polymer	5.0	3.5583	2.286	3.7636	2.285	-0.2053	106
	5.5	4.1232	2.301	4.5416	2.305	-0.4184	110
	6.0	4.2648	2.308	4.4431	2.304	-0.1783	104
	6.5	4.5179	2.321	4.4545	2.324	0.0634	99
	7.0	4.4292	2.315	4.4989	2.321	-0.0697	102

* Indirect Tensile Strength (MPa)

** Difference between Marshall and Gyratory ITS

M: Marshall Compaction

G: Gyratory Compaction

4.1.1.3 Shear Strength Test Results

The last (fifth) set of specimens at each asphalt content was used for shear strength testing performed at 25°C.

The test results for each of the three specimens with 6.0% asphalt content are shown in Table 4.15. The average test results for all five asphalt contents are shown in Table 4.16. While the greatest density was obtained at 7.0% asphalt content, the maximum shear strength was recorded at 5.5% asphalt content. A 10% increase of asphalt cement (from 5.0% to 5.5% asphalt content) in the mix resulted in a 24% increase in the shear strength. However, the addition of 1.0% asphalt content (5.5% to 6.5%) decreased the shear strength of specimens by 35%. The addition of yet another 0.5% asphalt content (6.5% to 7.0%) slightly increased the shear strength by 2.0%. The greatest difference (12%) in results within each three-specimen group was obtained at 7% asphalt content. The differences between all the other specimens were negligible.

4.1.2 Polymer-modified Asphalt Cement

The mix was prepared with the same percentage (5.0%, 5.5%, 6.0%, 6.5%, and 7.0%) of asphalt content as the mix with standard 85/100 Pen binder. All the conditions for testing the Marshall-compacted specimens prepared from asphalt mix with polymer-modified AC were the same as for the specimens prepared from mix with 85/100 Pen AC. The test results of testing are described in the following sections.

Table 4.15: Shear Strength Test Results at 6.0% Asphalt Content

MIX	BINDER	SAMPLE	HEIGHT	DENSITY	TIME	TORQUE	SHEAR	SHEAR
Compaction	type	number	mm	gm/cm³	sec	Nm	STRENGTH MPa	STRENGTH MEAN
Marshall	85 100	9	63.28	2.343	7	210	1.0198	1.0182
		11	62.94	2.337	6	207	1.0052	
		13	62.95	2.328	7	212	1.0295	
Gyratory		3	65.98	2.327	8	202	0.9809	0.9939
		9	66.66	2.341	7	208	1.0101	
		14	65.74	2.341	8	204	0.9906	
Marshall	Polymer	9	63.44	1178.4	5	100	0.4856	0.4743
		15	64.38	1194.4	6	84	0.4079	
		16	64.17	1191.4	5	109	0.5293	
Gyratory		3	66.27	1195.8	6	102	0.4953	0.4694
		10	66.24	1195.1	6	92	0.4468	
		11	66.04	1193.9	7	96	0.4662	

Table 4.16: Average Shear Strength Test Results

Asphalt Cement	Asphalt Content %	Marshall * M MPa	Density gm/cm3	Gyratory * G MPa	Density gm/cm3	Difference ** M - G MPa	Ratio G / M %
85/100	5.0	1.0700	2.302	0.9631	2.300	0.1069	90
	5.5	1.3290	2.319	1.1444	2.321	0.1846	86
	6.0	1.0182	2.336	0.9939	2.336	0.0243	98
	6.5	0.8692	2.358	0.8417	2.359	0.0275	97
	7.0	0.8854	2.364	0.6523	2.354	0.2331	74
Polymer	5.0	0.4063	2.284	0.4565	2.285	-0.0502	112
	5.5	0.4969	2.303	0.4856	2.305	0.0113	98
	6.0	0.4743	2.309	0.4694	2.305	0.0049	99
	6.5	0.5309	2.322	0.4403	2.324	0.0906	83
	7.0	0.5390	2.314	0.4694	2.321	0.0696	87

* Shear Strength (MPa):

** Difference between Marshall and Gyratory Ratios

M: Marshall Compaction

G: Gyratory Compaction

4.1.2.1 Conventional Test Results

The Marshall-compacted specimens prepared from an asphalt mix with polymer-modified AC were tested under the same conditions as the specimens prepared from mix with standard 85/100 Pen AC.

Bulk Relative Density

The results of measured densities for each specimen at the 6.0% asphalt content level are shown in Table 4.17. These values were consistent (STD of 0.0078 and C.O.V. of 0.3396%). The values of densities are within the range from 2.292 gm/cm³ to 2.323 gm/cm³. The values shown in the table were rearranged (as in case of 85/100 AC) so that the average of each set of three test specimens would remain the same for all five sets. The calculated average densities for the five selected asphalt content mixes are shown in Table 4.2 (pp.107). The maximum BRD was obtained with the 6.5% asphalt content mix.

Indirect Tensile Strength Test Results

Table 4.3 (pp.109) presents the test results for the three specimens having the 6.0% asphalt content. The average test results for all five asphalt contents are shown in Table 4.4 (pp.110). Where the asphalt content increased from 5.0% to 6.5%, the density also increased from 2.287 gm/cm³ to 2.322 gm/cm³ i.e. for a 30% increase in asphalt content there was 1.53% increase in calculated density. On the other hand, with a further 10% increase in asphalt cement (from 6.5% to 7.0% asphalt content), the calculated density decreased to 2.312 gm/cm³ i.e. calculated density decreases by 0.43%. One could thus deduce that with

Table 4.17: Average Density Test Results at 6.0% Asphalt Content**Marshall Compaction - Polymer AC**

SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm³	DENSITY gm/cm³	MEAN density	STD	COV %
1	63.85	1186.9	1187.2	672.9	514.3	2.308			
2	63.45	1180.7	1181.1	670.0	511.1	2.310			
3*	64.90	1169.3	1170.0	663.0	507.0				
4	64.91	1204.6	1205.4	681.9	523.5	2.301			
5	64.22	1186.9	1187.3	669.4	517.9	2.292			
6	64.08	1196.5	1196.8	679.7	517.1	2.314			
7	63.35	1176.8	1177.0	666.2	510.8	2.304			
8	64.52	1203.3	1203.3	683.1	520.2	2.313			
9	63.44	1178.4	1178.9	669.5	509.4	2.313			
10	64.14	1192.1	1192.4	675.5	516.9	2.306			
11	64.12	1196.3	1196.7	676.5	520.2	2.300			
12	63.30	1184.5	1184.7	674.3	510.4	2.321			
13	63.90	1195.4	1195.6	681.1	514.5	2.323			
14	63.35	1176.5	1176.5	666.1	510.4	2.305			
15	64.38	1194.4	1194.7	676.3	518.4	2.304			
16	64.17	1191.4	1191.5	675.7	515.8	2.310	2.308	0.0078	0.3396

* Surplus sample - not included in formulaic calculations. The duplex nature of the Marshall hammers caused 16 specimens to be prepared. From a visual viewpoint the best 15 were chosen for these tests.

an increase of more than 30% of asphalt cement, the calculated density of specimens would decrease or remain at approximately the same value.

The maximum value of calculated density was obtained at 6.5% asphalt content as well as the maximum ITS value. However, the increase in asphalt content was not consistent with the ITS. With an increase in asphalt content from 5.0% to 6.5% (in 0.5% increments) the ITS increased by 4.0%, decreased by 2.0%, and finally increased by 8%, respectively. With a further increase of 10% of asphalt binder the ITS decreased to its minimum value of 15%. The greatest variation (23%) within the specimens in the same set (specimens made from the same mix with the same asphalt content) was obtained at 5% asphalt content (Appendix B).

The test results of the second loading for the three specimens at 6.0% asphalt content are shown in Table 4.5 (pp.111). Table 4.6 (pp.112) gives the average for all five asphalt contents. The application of the second load on specimens demonstrated that once the specimens were loaded with maximum load, their mechanical properties and resistance to cracking were decreased by about 48%. The greatest difference was achieved at 5.5% asphalt content where the specimens after reloading withstood only 38% of the first load value, and the least at 5.0% asphalt content where the specimens withstood 58% of the first load value. The increase and decrease in the values for the second load are not proportional to the increase and decrease in the values for the first load. The differences in results within each three-specimen set are slightly higher than in results in other tests (Appendix B). This could be attributed to the first loading when the structure of specimens was partially damaged. Again, as in the tests using standard 85/100 Pen binder mix, there was further inaccuracy in

the test data attributed to the time lag between the attainment of maximum loading and the manual switching-off of the loading unit.

Moisture Sensitivity Test Results

The test results for the three specimens in one set (asphalt content of 6.0%) are shown in Table 4.7 (pp.114). Table 4.8 (pp.115) shows the average test results for all five asphalt contents. While asphalt content increased from 5.0% to 7.0%, the TSR also increased from 70% to 103%, i.e. for a 40% increase in asphalt cement in the mix there was a 47% increase in the calculated TSR. On the other hand, the calculated densities of specimens increased up to the 6.5% asphalt content level and then with the addition of another 0.5% in asphalt content the density decreased by about 0.4%. The resultant discrepancies for all three-specimen sets were within a low range of up to 10% (Appendix B).

The test results of the second loading for the three specimens at 6.0% asphalt content are shown in Table 4.9 (pp.117). The average test results for all five asphalt contents are given in Table 4.10 (pp.118). The application of the second load on specimens demonstrated that once the specimens were loaded with maximum load, their mechanical properties and resistance to cracking decreased in the case of 5.0% and 5.5% asphalt content by about 75% and in the case of 6.0%, 6.5% and 7.0% asphalt content by about 48%. The increase in values for the second and first loads was proportional up to the 6.5% asphalt content levels. Beyond the 6.5% level the value of the first load increased with the addition of 7% of asphalt binder whereas the value of the second load decreased. Discrepancies within the three-specimen sets were again slightly higher than in other test results (Appendix B).

4.1.2.2 Test Results at Extreme Temperatures

Warm Temperature

The conditions for warm temperature testing of Marshall-compacted specimens made with polymer-modified AC were the same as for the specimens prepared from standard 85/100 Pen AC mix.

Compressive Fatigue Test Results

The test results for the three specimens at 6.0% asphalt content are given in Table 4.11 (pp.120). The summary of the obtained results is shown in Table 4.12 (pp.121). The number of cycles before specimen failure (CBSF) increased with an increase in the asphalt content up to 6.5% asphalt content i.e. with an increase of 30% in asphalt cement there was an increase of 87% in CBSF. On the other hand, the addition of a further 10% in asphalt cement resulted in a decrease of 18% of CBSF. However, the CBSF increased and decreased consistently with the calculated densities i.e. the maximum number of CBSF was achieved at 6.5% asphalt content, the same percent of asphalt content at which maximum calculated density was recorded. The variations in results within the three-specimen sets were again greater than in other tests. The greatest variations were 44%, 32%, and 31% and were recorded at 5.5%, 6.5% and 7.0% asphalt content, respectively.

Cold Temperature (-35°C)

The conditions for cold temperature testing of Marshall-compacted specimens made with polymer-modified AC mix were again the same as for the specimens prepared with standard 85/100 Pen AC mix.

Indirect Tensile Strength Test Results

The results of testing one set of three specimens at 6.0% asphalt content is given in Table 4.13 (pp.124). Table 4.14 (pp.125) presents the averages of the ITS of the sets used in this test at five asphalt contents together with their corresponding average densities. The ITS and densities of specimens increased consistently with the increase in asphalt content up to 6.5% asphalt content. In other words, with the addition of 30% of asphalt binder the ITS increases by 27% and the density by 1.5%. However, an additional 10% of binder caused a loss of strength by 2 %, and the density of specimens decreases as well. The greatest differences (23% and 25%) within the three-set specimens were recorded at 5.5% and 6.0% asphalt content, respectively.

4.1.2.3 Shear Strength Test Results

Table 4.15 (pp.127) gives the test results for three specimens at 6.0% asphalt content. The average test results of shear strength for all five asphalt contents are demonstrated in Table 4.16 (pp.128). While the asphalt content increased from 5.0% to 7.0%, the shear strength of the test specimens increases by 22% (from 5.0% to 5.5% asphalt content), decreased by 5% (at 6.0% asphalt content), and again increased by 14% (at 7.0% asphalt

content). In other words, the addition of 10% of binder increased the strength from minimum value, the next addition of 10% of binder resulted in loss of strength, and the last addition of 20% of binder resulted in the maximum strength. The greatest resultant difference (23%) within each three-specimen set was obtained at 6.0% asphalt content. The differences within other specimens were in the range up to 10% (Appendix B).

4.2 TEST RESULTS - (GYRATORY-COMPACTED SPECIMENS)

The remaining half of the test specimens (one hundred and fifty) prepared for this research was designed with a gyratory compactor. The densities of these specimens were determined from the results of measuring bulk specific densities of Marshall-compacted specimens. Each specimen from the specific asphalt mix and with a specific asphalt content was prepared to match a particular density of the Marshall-compacted specimen from the same asphalt mix and having the same asphalt content. One half of these specimens (seventy five) was prepared from mix with standard 85/100 Pen asphalt cement and the other half (seventy five) with polymer-modified asphalt cement. The results of the tests performed on these specimens are presented in the following sections.

4.2.1 85/100 Pen Asphalt Cement

This mix was prepared under the same conditions, and with the same percentage of asphalt content (5.0%, 5.5%, 6.0%, 6.5%, and 7.0%) as the Marshall-compacted mix.

4.2.1.1 Conventional Test Results

The same three tests as those performed on the Marshall-compacted specimens were effected to compare the performance of the test specimens made by the two different laboratory compactions. These were bulk relative density (BRD), indirect tensile strength test (ITS), and moisture damage test.

Bulk Relative Density

The aim of the gyratory compaction was to compact specimens prepared from mix with 85/100 Pen AC to the same densities as those prepared from the same mix and compacted with the Marshall hammer. Table 4.18 shows that the calculated values of the BRD at 6.0% asphalt content were again very consistent, with an STD value of 0.0111 (well within ASTM parameters) and a 0.4757% C.O.V. The values of densities were within a range from 2.325 gm/cm³ to 2.357 gm/cm³. Again, the fifteen specimens at each asphalt content were divided into five sets, each containing three specimens. The three specimens comprising each set were chosen such that their average density would be identical or close to the mean density of the fifteen specimens, and their STD would be close to 0.0141 which is prespecified by ASTM for such specimens. The calculated average densities for the selected asphalt contents are shown in Table 4.2 (pp.107). The maximum BRD was obtained at asphalt content of 6.5%.

Table 4.18: Average Density Test Results at 6.0% Asphalt Content**Gyratory Compaction - 85/100 AC**

SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm³	DENSITY gm/cm³	MEAN density	STD	COV %
1	65.85	1199.7	1200.0	686.2	513.8	2.335			
2	65.33	1201.0	1201.3	686.3	515.0	2.332			
3	65.98	1198.4	1198.7	683.6	515.1	2.327			
4*	65.27	1197.0	1197.1	690.1	507.0				
5	66.15	1198.6	1198.9	683.3	515.6	2.325			
6	65.96	1198.9	1199.1	685.2	513.9	2.333			
7	65.18	1197.0	1197.5	689.5	508.0	2.356			
8	65.37	1199.8	1200.3	689.9	510.4	2.351			
9	66.66	1200.0	1200.4	687.7	512.7	2.341			
10	65.20	1198.3	1198.5	690.0	508.5	2.357			
11	66.07	1200.1	1200.6	684.6	516.0	2.326			
12	66.29	1198.5	1198.8	683.3	515.5	2.325			
13	65.49	1199.8	1200.0	689.4	510.6	2.350			
14	65.74	1199.1	1199.4	687.2	512.2	2.341			
15	66.14	1200.6	1200.7	684.4	516.3	2.325			
16	63.57	1159.3	1159.4	662.8	496.6	2.334	2.337	0.0111	0.4757

* Surplus sample - not included in formulaic calculations. The duplex nature of the Marshall hammers caused 16 specimens to be prepared. From a visual viewpoint the best 15 were chosen for these tests.

Indirect Tensile Strength Test Results

The test was applied under the same condition as for test specimens compacted with Marshall compactor, i.e. each test specimen was loaded until maximum load was obtained. After that the load was released and reapplied again to cause complete fracture of the test specimen.

The test results for the three specimens at asphalt content of 6.0% are shown in Table 4.3 (pp.109). Table 4.4 (pp.110) gives the average test results for all five asphalt contents. For a 30% increase in asphalt binder there was an increase of 2.6% in the calculated density. With the addition of another 10% of asphalt binder the density value decreased by 0.25%. It may be assumed that with an increase in asphalt cement greater than 6.5%, the calculated density of specimens would decrease or stay at approximately the same value and one might assume that the mechanical properties would be increasing with the greater densities. However, the results will demonstrate that the increase in density values may not necessarily result in higher mechanical properties.

While densities were increasing with asphalt content up to 6.5%, the maximum ITS was recorded at 5.5% asphalt content. In other words, when the asphalt cements in the mix was increased by 10% (from 5.0% asphalt content to 5.5%), the strength increased by 24%. On the other hand the addition of 30% asphalt binder (from 5.5% to 7.0% asphalt content) resulted in the loss of strength by 18%. The greatest difference (16%) in the results within each three-specimen set was obtained at 6.5% asphalt content. The difference within results of the other specimens stayed within relatively small range (Appendix B).

The test results of the second load application for the three specimens at 6.0% asphalt content are shown in Table 4.5 (pp.111). Table 4.6 (pp.112) gives the average test results for all five asphalt contents. The application of the second load on specimens indicated that after the specimens were loaded with the maximum load their resistance to cracking decreased by an average of 53%. The difference between the two loadings was consistent for all five asphalt contents with an average value of 45% except at the 5.5% asphalt content level where the value of the second loading represented 54% of the first loading value. The increase and the decrease in loads were proportional. Differences within three-specimen sets are higher than in other test results (Appendix B). This can be attributed to the first loading when the structure of specimens was partially damaged and to the time lag between the attainment of maximum loading and the manual switching-off of the loading unit.

Moisture Sensitivity Test Results

The test results for the three specimens at 6.0% asphalt content are shown in Table 4.7 (pp.114). Table 4.8 (pp.115) gives the average results for all five asphalt contents. While asphalt content increased from 5.0% to 7.0%, the tensile strength ratio (TSR) also increased from 59% to 89%, i.e. for a 40% increase in asphalt cement in the mix there was a 51% increase in the calculated TSR. However, the calculated densities of specimens increased only up to the 6.5% asphalt content level and then with the addition of another 10% asphalt binder in the mix the density slightly decreased from 2.361 gm/cm^3 to 2.359 gm/cm^3 . The discrepancies in the test results between tested specimens were up to 10% for all asphalt contents (Appendix B).

The second loading test results for the three specimens at 6.0% asphalt content are shown in Table 4.9 (pp.117). The average test results for all five asphalt contents are given in Table 4.10 (pp.118). The application of the second load on the specimens indicated that once the specimens were loaded with maximum load, their mechanical properties and resistance to cracking were decreased by an average of 37%. These differences are relatively stable (by about 35%) except at 6.0% asphalt content, where the second load represents 54% of the first load value, i.e. after the first loading the resistance to cracking decreased by 46%. The increase and decrease in the values for the second load were not proportional to the increase and decrease in the values for the first load. Discrepancies within the three-specimen sets are given in Appendix B.

4.2.1.2 Test Results at Extreme Temperatures

Warm Temperature

Again, the same type of test for gyratory-compacted specimens was employed as for Marshall-compacted specimens.

Compressive Fatigue Test Results

The test results for the three specimens at 6.0% asphalt content are shown in Table 4.11 (pp.120). The average test results for all five asphalt contents are given in Table 4.12 (pp.121). The increase in asphalt cement of 30% (from 5.0% to 6.5% asphalt content) resulted in doubling the number of cycles before specimen failure (CBSF), i.e. the addition

of 2.0% of asphalt content increased the number of CBSF by 99%. On the other hand, the further addition of 0.5% asphalt content (from 6.5% to 7.0%) decreased the number of CBSF by about 18%. This is in direct relation to the densities of the test specimens. The discrepancies in the results within each three-specimen set were high comparing to the results of the other tests. The third specimen at 6.0% asphalt content withstood three times the number of CBSF that had been withstood by the other two specimens. Therefore, this anomalous specimen was rejected.

Cold Temperature

The same test under the same conditions was carried out for the group of gyratory-compacted specimens as had been carried out for the group of Marshall-compacted specimens.

Indirect Tensile Strength Test Results

The test results for the three specimens at 6.0% asphalt content are given in Table 4.13 (pp.124). Table 4.14 (pp.125) shows the average test results for all five asphalt contents. The highest densities were obtained at 6.5% asphalt content. The ITS initially decreased from 5.0% to 5.5% asphalt content. However, with the addition of 2.0% in asphalt content the strength increased by 47%. The maximum value of ITS was obtained at 7.0% asphalt content. It seems like that the addition of asphalt could result in an increase in ITS. However, one should consider the tradeoff between the cost of adding more asphalt cement and the associated improvement in mechanical properties. The greatest variations (31% and 21%)

in the results within each three-specimen set was recorded at 6.0% and 6.5% asphalt content, respectively (Appendix B). The variations within the specimens of three remaining asphalt contents were not significant (about 11%).

4.2.1.3 Shear Strength Test Results

The test results for the three specimens at 6.0% asphalt content are shown in Table 4.15 (pp.127). The average results of the shear strength tests are presented in Table 4.16 (pp.128). While densities increased with asphalt content (from 5.0% to 6.5%), the maximum shear strength was obtained at 5.5% asphalt content, i.e. with an increase of 0.5% in asphalt content there was an increase of 19% in strength. On the other hand, there was a loss of 43% in shear strength with a further addition of 30% in asphalt binder. The differences in the results within each three-specimen set were less than 6% (Appendix B).

4.2.2 Polymer-modified Asphalt Cement

The asphalt content for gyratory-compacted specimens was selected within the same range as for Marshall-compacted specimens, namely, 5.0%, 5.5%, 6.0%, 6.5%, and 7.0%.

4.2.2.1 Conventional Test Results

The bulk relative density (BRD), indirect tensile strength (ITS), and moisture sensitivity tests were performed on the specimens.

Bulk Relative Density

The aim of the gyratory compaction was to compact specimens made from the mix with polymer-modified AC to the same densities as those prepared from the same mix and compacted with Marshall hammer. As can be seen in Table 4.19, the calculated values of the BRD at 6.0% asphalt content were very consistent with a small STD value of 0.0074 and a C.O.V. of 0.3222%. The values of densities were within the range of 2.293 gm/cm^3 to 2.315 gm/cm^3 . These values were similarly rearranged as in the case of 85/100 AC in order to obtain five sets of three specimens each, wherein the average of each set of three test specimens remained the same. The calculated average densities for the five asphalt contents are shown in Table 4.2 (pp.107). The maximum BRD was obtained at 6.5% asphalt cement content. The increase and decrease in densities were not proportional to the increases and decreases in test results for all specimens.

Indirect Tensile Strength Test Results

The test results for a set of three specimens at 6.0% asphalt content are shown in Table 4.3 (pp.109). The average test results for all five asphalt contents are given in Table 4.4 (pp.110). While the increase in density is consistent with the increase in asphalt content from 5.0% to 6.5%, the ITS test results were not consistent with the increase of asphalt binder in the mix. This inconsistency occurred with the increase of asphalt content from 5.5% to 6.0%, i.e. with the addition of 9% asphalt binder there was a decrease in strength of 5%. As can be seen from Table 4.4 the values of calculated densities for both asphalt contents are

Table 4.19: Average Density Test Results at 6.0% Asphalt Content**Gyratory Compaction - Polymer AC**

SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm³	DENSITY gm/cm³	MEAN density	STD	COV %
1	66.20	1197.1	1197.4	679.7	517.7	2.312			
2*	66.32	1196.7	1197.0	678.1	518.9				
3	66.27	1195.8	1196.3	679.4	516.9	2.313			
4	66.48	1195.2	1196.0	675.8	520.2	2.298			
5	66.15	1194.5	1194.9	678.7	516.2	2.314			
6	66.27	1195.0	1196.1	679.7	516.4	2.314			
7	66.24	1195.1	1195.0	678.4	517.6	2.309			
8	66.15	1194.5	1194.9	679.0	515.9	2.315			
9	66.17	1193.3	1194.7	676.3	518.4	2.302			
10	66.24	1195.1	1195.9	676.8	519.1	2.302			
11	66.04	1193.9	1194.3	675.1	519.2	2.299			
12	66.47	1196.5	1197.0	675.3	521.7	2.293			
13	66.23	1194.4	1195.0	675.1	519.9	2.297			
14	66.21	1195.3	1195.5	674.5	521.0	2.294			
15	66.23	1194.8	1195.1	676.3	518.8	2.303			
16	66.26	1195.4	1196.0	677.0	519.0	2.303	2.305	0.0074	0.3222

* Surplus sample - not included in formulaic calculations. The duplex nature of the Marshall hammers caused 16 specimens to be prepared. From a visual viewpoint the best 15 were chosen for these tests.

quite close. One could thus state that the addition of only asphalt content can result in loss in strength. The maximum value of ITS was obtained at 6.5% asphalt content. Coincidentally the maximum value of density was also reached at 6.5% asphalt content. With a further addition of 10% of asphalt binder to the mix, the strength decreased by 18%. One could therefore assume that the use of more than 6.5% asphalt content could result in a loss in strength. The differences in the results within each three-specimen set were in a low range of up to 10% except for the specimens at 6.0% asphalt content where the variation in results was up to 15% (Appendix B).

The second loading test results for the three specimens at 6.0% asphalt content are shown in Table 4.5 (pp.111). The average test results for all five asphalt contents are given in Table 4.6 (pp.112). The application of the second load on specimens indicates that after loading the specimens with the maximum load, their mechanical properties and resistance to cracking are decreased by an average of 54%. The greatest variation was achieved at 5.0% asphalt content where the specimens after reloading withstood only 39% of the first load value, and the least variation was at 7.0% asphalt content where the specimens withstood 54% of the first load value. However, the increase and decrease in the values for the second load are not proportional to the increase and decrease in the values for the first load. Differences within three-specimen sets are higher than in other test results (Appendix B). This could be attributed to the first loading when the structure of specimens was partially damaged and to the time lag between the attainment of maximum loading and the manual switching-off of the loading unit.

Moisture Sensitivity Test Results

The test results for the three specimens at 6.0% asphalt content are given in Table 4.7 (pp.114). Table 4.8 (pp.115) shows the average test results for all five asphalt contents. The tensile strength ratio (TSR) increases from 88% to 99% with a 20% increase of asphalt binder (from 5.0% to 6.0% asphalt content) in the mix. With a further increase of 10% in asphalt cement (from 6.0% to 6.5% asphalt content) there was a slight decrease in TSR by about 5%. A final increase of 10% asphalt binder (from 6.5% to 7.0% asphalt content) increased the ratio by another 14%. The maximum TSR in the test program was obtained at 7% asphalt content. Nevertheless, the calculated densities of specimens increased only up to the 6.5% asphalt content level and a further addition of 10% asphalt binder in the mix resulted in a reduction of the density from 2.324 gm/cm^3 to 2.321 gm/cm^3 . The variations in test results within all three-specimen sets were very low. The maximum difference was 9% at 5.5% asphalt content (Appendix B).

The second loading test results for the three specimens at 6.0% asphalt content are shown in Table 4.9 (pp.117). The average test results for all five asphalt contents are given in Table 4.10 (pp.118). The application of the second load on specimens indicates that once the specimens are loaded with the maximum load, their mechanical properties and resistance to cracking are decreased by an average of 42%. The differences between the loads decrease with the addition of asphalt cement to the mix. The greatest difference was achieved at 5.0% asphalt content where the specimens after reloading withstood 43% of the first load value, and the least difference occurred at 7.0% asphalt content where the specimens withstood 68% of the first load value. The increases in the both first and second load values were

proportional. Discrepancies within three-specimen sets were higher than in the results of other tests (Appendix B).

4.2.2.2 Test Results at Extreme Temperatures

The conditions for testing the specimens in this test were the same as for all other specimens tested at 40°C temperature.

Compressive Fatigue Test Results

The test results for the three specimens at 6.0% asphalt content are shown in Table 4.11 (pp.120). Table 4.12 (pp.121) gives the average test results for all five asphalt contents. The number of cycles before specimen failure (CBSF) increased with the increase of asphalt content in the mix. The addition of 40% of asphalt binder (from 5.0% to 7.0% asphalt content) resulted in an increase of CBSF by 84%. However, the increase from 6.5% to 7.0% asphalt content resulted in an increase of only 0.5% in the number of CBSF and a decrease in the density. The greatest difference (40%) in the results within each three-specimen set was obtained for specimens within the set at 7.0% asphalt content, followed by a difference of 25% at 6.5% asphalt content. The differences in test results within the remaining sets of specimens were in the range of up to 18% (Appendix B).

Cold Temperature

The environment for the testing for these specimens was equal to that of all the earlier specimens tested at -40 °C temperature.

Indirect Tensile Strength Test Results

The test results for a set of three specimens at 6.0% asphalt content are shown in Table 4.13 (pp.124). The average test results for all five asphalt contents are given in Table 4.14 (pp.125). The ITS test results are not consistent with the increase in asphalt binder to the mix. This inconsistency occurs with an increase of asphalt content from 5.5% to 6.0%, i.e. with the addition of 9% asphalt binder there is a decrease in ITS of 2%. This is attributed to the values of calculated densities which remained quite close for both asphalt contents. One could state that the addition of only asphalt content will result in a loss of ITS. The maximum ITS value was obtained at 5.5% asphalt content. Greater densities may not necessarily result in higher ITS. The variation in test results within each three-specimen set was low, up to 10% for all tested specimens (Appendix B).

4.2.2.3 Shear Strength Test Results

The test results for the three specimens at 6.0% asphalt content are given in Table 4.15 (pp.127). Table 4.16 (pp.128) shows the average test results for all five asphalt contents. Again, it can be noted from these test results that higher densities not necessarily equate to greater mechanical performance. While densities increase with the increase in asphalt content, the maximum value of shear strength was recorded at 5.5% asphalt content. The increase of 10% in asphalt binder (from 5.0% to 5.5% asphalt content) in the mix results in an increase of 6% in the shear strength. The further addition of % asphalt cement to the mix did not increase the density and served to decrease the shear strength by 3%. The

discrepancies in the results within each three-specimen set did not exceed 10% (Appendix B).

All these test results are analyzed and discussed in the following chapter and give rise to detailed recommendations in the last chapter.

4.2.3 Direction of Torque Application

In addition, eight gyratory-compacted specimens were tested in a shear test to investigate if there is any influence on the direction in which a torque is applied. In other words, to determine the effect of the direction of torque that may be either concurrent to the rotational direction of gyrations in which the specimens were compacted or opposite to the rotational direction of compaction.

In case of the first four specimens the torque was applied in the same direction as the rotation of the specimens during the gyrational compaction, and the other four specimens were placed in the jaws in a way that the direction of the applied torque was opposite to the direction of the gyrations during the compaction. BRD test results are shown in Table 4.20 and shear strength test results are given in Table 4.21. The test results from specimens where the torque was applied concurrently to the direction of gyrations during compaction indicate lower shear strength by an average of 15% when compared to the specimens where the torque was applied in the direction opposite to the direction of gyration of the specimens during the compaction process. It may thus be deducted that the direction of asphalt

Table 4.20: Additional Shear Testing, Bulk Relative Density

Polymer AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
G 6.0%	1	66.29	1194.0	1194.4	675.2	519.2	2.300	2.305	0.0042	0.1812
	2	66.03	1196.1	1196.4	677.0	519.4	2.303			
	3	66.33	1196.0	1196.3	677.2	519.1	2.304			
	4	66.58	1199.1	1199.5	678.4	521.1	2.301			
	5	66.04	1196.7	1196.8	679.0	517.8	2.311			
	6	66.22	1196.8	1197.2	677.0	520.2	2.301			
	7	66.07	1197.6	1197.6	678.2	519.4	2.306			
	8	65.86	1198.7	1198.7	680.0	518.7	2.311			

Table 4.21: Shear Strength Test Results

Polymer AC

MIX type	DIRECTION OF TORQUE APPLIED	SAMPLE number	HEIGHT mm	DENSITY gm/cm ³	TIME sec	TORQUE Nm	SHEAR STRENGTH MPa	SHEAR STRENGTH MEAN
G 6.0%	with direction of gyrations	1	66.29	2.300	6	80	0.3885	0.3642
		2	66.03	2.303	7	74	0.3594	
		3	66.33	2.304	7	76	0.3691	
		4	66.58	2.301	7	70	0.3399	
	against direction of gyrations	5	66.04	2.311	7	80	0.3885	0.4176
		6	66.22	2.301	5	90	0.4370	
		7	66.07	2.306	7	96	0.4662	
		8	65.86	2.311	6	78	0.3788	

pavement compaction in the field vis-a-vis the direction of vehicular traffic during pavement service life can influence the mechanical properties of such pavement by at least 10%.

Finally, the results presented in this section suggest that further investigation should be carried out, employing other types of mixes and effecting shear tests under cold and warm temperatures.

4.3 VARIABILITY OF TEST RESULTS

It is evident that there is variability in the test results obtained within each three-specimen group (Appendix B). Even though specimens were prepared with care and attention to detail, it is not possible to produce exactly identical specimens. Some inaccuracies can also occur during specimen testing. This is influenced by a number of factors, some of which are described below:

- *aggregate orientation* - It is impossible to control the orientation of aggregates and this significantly influences the final performance of the specimens. This is due to the variability in aggregate shape and the location of aggregates within the specimens during the compaction process.
- *placement of specimen in testing machine* - The positioning of the specimen in the testing machine is essential for obtaining accurate test results. A small misalignment of the test specimen under the loading head can result in slightly skewed results in ITS tests, moisture damage tests, and compressive fatigue tests. However, it is not possible to ensure the placement of the specimen exactly in the centre under the loading head for every single test. The same holds true for specimens tested for shear

strength. How the specimens are glued to the metallic plates can significantly alter the final results. The least tilt of the assembly during the drying process can result in a shift of the specimen from the plate and affect the symmetry between the specimen and the axes of the two glued plates.

- *temperature* - The variability in test results can be influenced by either the oven temperature or the temperature of surrounding environment. There is no oven which can have the same temperature at any location within the oven. Each oven has its hot and cold spots. Furthermore, the temperature of the room in which the compaction was carried out, the temperature of molds and the mixing temperatures can vary slightly for every single specimen.
- *miscellaneous factors* - Factors such as daily changes in dust levels can influence the final results.
- *human factors* - These can affect test results. Care was taken to mitigate the influence of this.

4.4 SUMMARY OF RESULTS

This chapter presents the main results of the experimental investigation of the research plan. This investigation was carried out in three stages: the evaluation of test results obtained from conventional testing, the determination of test results obtained under extreme temperatures, and the evaluation of test results obtained from testing the specimens for the shear strength. Such an evaluation was done for Marshall-compacted specimens with both

types of asphalt cement and then for gyratory-compacted specimens, again with standard 85/100 Pen asphalt cement and polymer-modified asphalt cement.

The properties of the specimens compacted with the Marshall compactor and with the gyratory compactor and the influence of the asphalt binder type on each are summarized in Table 4.22. It is evident that the specimens prepared with the Marshall method demonstrated the superior performance-related behaviour to the specimens prepared with the gyratory method. The mix with standard 85/100 Pen AC performed better in a room temperature environment compared to the polymer-modified AC mix. However, the performance of the polymer-modified AC mix increased in cold and hot temperature environments.

Table 4.22 Results Summary

TEST type	MARSHALL compaction	GYRATORY compaction	BINDER performance for both
Compressive fatigue			
85/100 AC	1	0	0
Polymer AC	1	0	1
Moisture			
85/100 AC	0 - 1	1 - 0	0
Polymer AC	0	1	1
Shear			
85/100 AC	1	0	1
Polymer AC	1	0	0
ITS room temp			
85/100 AC	1	0	1
Polymer AC	1	0	0
-35C			
85/100 AC	0 - 1	1 - 0	0
Polymer AC	0	1	1

0 = weak performance

1 = good performance

0 - 1 = neutral

CHAPTER 5

ANALYSIS

The main purpose of this experimental investigation was to compare laboratory results of testing asphalt mixes by using the Marshall compactor to those using the gyratory compactor and to determine the effect of the compactor type on the asphalt mixes and their mechanical properties. The effect of two different types of asphalt binder on the properties of asphalt pavement was also investigated. The test results are evaluated together with the cost of designing an asphalt mix since in some cases the cost of the mix itself could overweight the good mechanical properties.

5.1 MARSHALL VS GYRATORY

This section analyzes and compares the performance of specimens compacted with the Marshall and gyratory compactors. The effect of compaction methods on test results was analyzed in terms of conventional tests, tests under extreme temperature conditions and shear strength tests.

5.1.1 Effect of Compaction Method on Conventional Test Results

This section analyzes results obtained from bulk relative density tests, indirect tensile strength tests, and moisture sensitivity tests.

5.1.1.1 Effect on Bulk Relative Density

The results showed that both compaction methods can achieve uniform and consistent laboratory densities. However, the Marshall compactor is limited by the maximum number of blows applied to the core specimen. Also, the gyratory compactor gave a more consistent density than those obtained by the Marshall method. The analysis of data from density test showed that in both types of asphalt cement, the calculated values of coefficient of variation (C.O.V.) for the Marshall compacted specimens were three to four times higher than the values of C.O.V. for the gyratory compacted specimens. Although the base line density was obtained by 75 blows of the Marshall compactor, the gyratory compactor can achieve higher densities and provides a much better quality control device than the Marshall.

5.1.1.2 Effect on Indirect Tensile Strength

The indirect tensile strength test results showed that for both types of asphalt cement, the Marshall-compacted asphalt mixes possessed higher strength. This was true at all asphalt contents. The maximum indirect tensile strength for both compaction methods occurred at asphalt contents of 5.5% and 6.5% for the standard 85/100 and polymer-modified asphalt cements, respectively. Furthermore, the ITS of the Marshall-compacted specimens was between 5% to 8% and 4% to 17% higher than that of the gyratory compaction method for

the standard 85/100 AC and polymer-modified, respectively (Figure 5.1 and 5.2). These results were influenced by the mode of compaction and by the different compaction procedures. The dynamically generated energy created during Marshall compaction influenced the final orientation of the aggregates in the compacted specimen. The IIS is very dependent upon the interface between the aggregates and the bond between the aggregates and asphalt cement.

5.1.1.3 Effect on Moisture Sensitivity

Moisture sensitivity test results indicate that gyratory-compacted mixes have little susceptibility to moisture damage (ratios were 59% to 89% for the 85/100 AC and 88% to 108% for the polymer-modified AC). On the other hand, the polymer-modified AC appears to improve the moisture resistance of the Marshall-compacted specimens. However, it should be noted that the moisture sensitivity performance is influenced more by the interaction between the compaction method and the amount of asphalt content in the mix. Also, the improvement observed in the mixes using polymer-modified AC has more to do with overall lower tensile strength values than with any real improvement in the strength itself. These results and analysis are of significance to both mix designers and contractors. Clearly, both compaction methods achieved higher densities with the Marshall providing mixes having an overall higher tensile strength (Figure 5.3 and 5.4). However, the kneading action of the gyratory compactor increases the impermeability of the kneaded surface of the specimen. The addition of asphalt cement serves to enhance the waterproof characteristics of the surface layer of the specimens. The gyrations result in closing the texture of the surface

**Figure 5.1: ITS Test Results at Temperature of 23°C, First Loading
85/100 AC**

**Figure 5.2: ITS Test Results at Temperature of 23°C, First Loading
Polymer-modified AC**

**Figure 5.3: ITS Test Results at Temperature of 23°C, First Loading
85/100 AC**

**Figure 5.4: ITS Test Results at Temperature of 23°C, First Loading
Polymer-modified AC**

and thus having a tighter surface than that resulting from the impact compaction of Marshall. Therefore, the effect of moisture on the mix is directly related to the degree of surface texture produced by the compaction method. Clearly, one must ask which of the two compaction methods better simulate the surface conditions of asphalt pavement in the field.

5.1.1.4 Effect on Second Loading

The specimens tested for ITS and moisture sensitivity tests were loaded twice. There was no significant influence of these two compaction methods on the properties of the specimens, i.e. there was no great difference in ratios between the first and second loading applied on specimens. In general, the gyratory-compacted specimens withstood a slightly higher second load. This is shown in Figure 5.5 and 5.6 for ITS and in Figure 5.7 and 5.8 for moisture sensitivity. It was by an average of 14% in case of 85/100 asphalt binder mix tested for ITS and by an average of 3% and 21% in the case of 85/100 and polymer-modified mix, respectively, when tested for moisture damage. However, in the case of the polymer-modified mix tested for ITS, the specimens compacted with the Marshall method withstood a higher second loading by an average of 4%.

5.1.2 Effect of Compaction Method on Extreme Temperature Results

This section analyzes the results of the tests performed at warm and cold temperatures, i.e. the compressive fatigue test performed at a temperature of 40°C and indirect tensile strength performed at a temperature of -35°C.

**Figure 5.5: Load Ratio Results for ITS Testing
85/100 AC**

**Figure 5.6: Load Ratio Results for ITS Testing
Polymer-modified AC**

**Figure 5.7: Load Ratio Results for Moisture Sensitivity Testing
85/100 AC**

**Figure 5.8: Load Ratio Results for Moisture Sensitivity Testing
Polymer-modified AC**

5.1.2.1 Effect on Rutting Resistance

The compressive fatigue test results showed that for both types of asphalt cement used in the experimental program, the test specimens compacted with Marshall compaction method withstood a higher number of cycles during which the load was applied (Figure 5.9 and 5.10). This is due to the orientation of the aggregates. The Marshall compaction results in preparing specimens with better stone-on-stone contact, resulting in greater friction between the individual particles of aggregate. For both compaction methods and both asphalt cements the number of cycles increased with addition of asphalt binder, because the addition of asphalt cement results in more compact (dense) mix that is then more resistant to load repetition. Clearly one could assume that an increase of the binder in the mix will increase the mechanical properties of asphalt pavement vis-a-vis traffic loading. However, cost of binder versus improvement in the mechanical properties must also be considered.

5.1.2.3 Effect on Indirect Tensile Strength (ITS)

The results of the ITS test under the cold temperature (-35 °C) showed a number of important trends. Firstly, specimens compacted with the gyratory compactor showed a slightly higher tensile strength than the Marshall-compacted ones (Figure 5.11 and 5.12). With the exception of the 5.5% and 7.0% asphalt content specimens, all other specimens showed an improvement of between 1.0% and 10% in the measured tensile strength. Secondly, and even more significant is the higher tensile strength achieved with the polymer-modified asphalt compared with the strength of the standard 85/100 binder. The cold

Figure 5.9: Compressive Fatigue Test Results at Temperature of 40°C
85/100 AC

Figure 5.10: Compressive Fatigue Test Results at Temperature of 40°C
Polymer-modified AC

Figure 5.11: ITS Test Results at Temperature of -35°C
85/100 AC

Figure 5.12: ITS Test Results at Temperature of -35°C
Polymer-modified AC

temperature results are reversed for the compaction methods compared to ITS test results obtained from tests carried out at room temperature. Clearly, these results suggested that tensile strength of asphalt mixes under extreme cold temperatures is not affected by the initial conditions of the mix, i.e. cold temperature cracking is more affected by the type of asphalt cement and asphalt content that are the main components of strength.

5.1.3 Effect of Compaction Method on Shear Strength

The shear tests gave results similar to those obtained from the ITS tests at room temperature, i.e. Marshall-compacted mixes possessed higher shear strength (Figure 5.13 and 5.14). It is interesting to note that while the Marshall-compacted asphalt specimens exhibited an overall higher shear strength (except for the 5.0% case with polymer-modified mix), the type of asphalt cement used appears to govern the optimum shear strength value. One could thus conclude that this is due to the vast differences between the Marshall and gyratory compaction process, the later having an influence on the orientation of aggregates. The rotational pressure on the mix during gyratory compaction results in smoother co-location of aggregate than when compacted with Marshall blows. Therefore, the stone-on-stone contact in Marshall-compacted specimens can better resist the distress caused by torsion. Comparing aggregates in tested specimens, the Marshall-compacted specimens contained more crushed aggregates in the shear plane than the gyratory-compacted specimens. In the Marshall-compacted specimens the aggregates were crushed throughout whole plane of failure, while the aggregates in the gyratory-compacted specimens were mostly crushed at the edges of the specimen.

Figure 5.13: Shear Strength Test Results at Temperature of 25°C
85/100 AC

Figure 5.14: Shear strength Test Results at Tempertaure of 25°C
Polymer-modified AC

5.2 85/100 PEN AC VS POLYMER-MODIFIED AC

This section analyzes the performance of specimens prepared from two different mixes, one with 85/100 Pen AC and the other with polymer-modified AC. The analysis and the comparison was carried out in three stages, i.e. under the same conditions as the analysis and the comparison between the two laboratory compaction methods.

5.2.1 Effect of Asphalt Cement on Conventional Test Results

5.2.1.1 Effect on Bulk Relative Density

The test results show that the use of the polymer-modified AC decreased the densities of test specimens by 0.7% and 2.0% at 5.0% asphalt content and 7.0% asphalt content, respectively, when Marshall compaction method was used, and by 0.7% and 1.5% at 5.0% asphalt content and 7.0% asphalt content, respectively, when gyratory compaction method was employed. Such a decrease is very much dependent on the softness of asphalt cement since the compaction energy is absorbed by the asphalt binder. The workability of a polymer-modified asphalt mix in laboratory becomes a significant element due to the changes in elasticity caused by temperature change in the mix and the inherent viscosity of the polymer itself.

5.2.1.2 Effect on Indirect Tensile Strength

The use of polymer-modified AC in the mix resulted in a loss of strength of about 50%. This is shown in Figure 5.15 for the Marshall compaction and in Figure 5.16 for the gyratory compaction.

Also, when the asphalt mix exceeded 6.5% asphalt content, the specimens proceeded to bleed asphalt binder during the compaction process. This scenario resulted in a slight decrease in the calculated density of the specimens prepared from mix with polymer-modified AC and in an achievement of the stable densities for the specimens prepared from mix with 85/100 Pen AC. Therefore, the 6.5% asphalt content should represent the upper limit of percent of asphalt binder used in these mixes.

5.2.1.3 Effect on Moisture Sensitivity Test

The polymer-modified AC appears to improve the moisture resistance of both the Marshall and gyratory-compacted specimens (Figure 5.17 and 5.18). However, it should be noted that the moisture sensitivity performance is influenced more by the interaction between the compaction method and amount of asphalt content in the mix. Also, the improvement observed in the mixes using polymer-modified AC has more to do with an overall lower tensile strength values than with strength improvement propel.

5.2.1.4 Effect on Second Loading

The specimens tested for ITS and moisture sensitivity tests were loaded two times. The mixes with 85/100 asphalt cement withstood a higher second load except for the

Figure 5.15: Binder Influence on ITS Results for Marshall-compacted specimens, First Loading

Figure 5.16: Binder Influence on ITS results for Gyratory-compacted specimens, First Loading

MOISTURE SENSITIVITY @ TEMP +23C
MARSHALL

Figure 5.17: Tensile Strength Ratio Results - 85/100 AC

MOISTURE SENSITIVITY @ TEMP +23C
GYRATORY

Figure 5.18: Tensile Strength Ratio Results - Polymer-modified AC

3

OF/DE

3

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

Marshall-compacted specimens tested for ITS where the polymer-modified mix withstood a higher second loading by an average of 17%. When testing the 85/100 asphalt cement (AC) mix the resistance of specimens to the second loading was increased by an average of 8% compared to polymer-modified mix (Figure 5.19 and 5.20). For gyratory-compacted specimens the 85/100 AC mix withstood higher second loading by an average of 2% for ITS and of an average of 9% for moisture sensitivity tests (Figures 5.21 and 5.22). Although it would appear that the 85/100 AC provides better resistance to crack propagation Figure 5.23 shows that the curve representing the loading as a function of time decreases in a much steeper way after specimen failure for the 85/100 AC mix than for polymer-modified AC mix. Therefore, asphalt pavement made from 85/100 AC mix may initially withstand higher loading after the application of maximum load, but this property decreases rapidly with time compared to asphalt pavement that is made from a polymer-modified mix.

5.2.2 Effect of Asphalt Cement on Extreme Temperature Results

This section analyzes the same type of tests results as did the Section 5.1.2, i.e. the results of tests performed at warm and cold temperatures.

5.2.2.1 Effect on Rutting Resistance

The test results indicate that the use of the polymer-modified AC in a warm environment improved the mix resistance to rutting. In case of the Marshall-compacted mix the

Figure 5.19: Binder Influence on Load Ratio for Marshall-compacted Specimens for ITS

Figure 5.20: Binder Influence on Load Ratio for Marshall-compacted Specimens for Moisture Damage

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY

Over the past decade, major changes have occurred in the loading conditions under which pavements have to perform. Legal axle loads and tire pressures have increased dramatically with the size of vehicles (expansion of the trucking industry) as has the percentage of heavy axle loads on most highways in Canada. Also, load repetitions have intensified with the growing number of vehicles. Changes in material behaviour, due to new mix design, and a growth in the use of asphalt modifiers have been occurring. The most important factor affecting pavement performance is compaction. Variables such as, homogeneity and density of materials, position of aggregates, potential surface or internal cracking due to compaction, etc. are all contributing factors influencing strength, fatigue durability, resistance to deformation and moisture damage of asphalt pavements. In addition, the compactibility of each individual mix is affected by binder viscosity, aggregate gradation, stone shapes, mix, road, and air temperature, etc.

The need for a stable and durable mix resulted in the development of new mix design methods. The criteria were established by a correlation of results obtained from laboratory

Figure 5.23: ITS Output for Loading up to the Specimen Failure

performance behaviour of the test specimens was improved by an average of 27%. The same holds true for the gyratory-compacted mix (the performance increases by an average of 32%) except for 6.0% asphalt cement where the performance of polymer-modified AC decreases by about 8%. Figure 5.24 and 5.25. This is attributed to the fact that polymer-modified asphalt binder is more flexible.

5.2.2.2 Effect on Indirect Tensile Strength

The polymer-modified binder mix produces a maximum ITS of 4.518 MPa and 4.542 MPa compared to the 85/100 binder mix which produces the maximum strength of 3.279 MPa and 3.165 MPa, for Marshall and gyratory compaction methods, respectively. These values represent improvements of 38% and 43% for the two compaction methods when the polymer is utilized instead of the standard 85/100 binder (Figure 5.26 and 5.27). The cold temperature results are reversed for the use of polymer-modified binder compared to indirect tensile strength test results obtained from tests carried out at room temperature. Since the differences in test results between the two compaction methods (Marshall and gyratory) are not as significant as the differences obtained between the 85/100 Pen AC and polymer-modified AC, it can be stated that the tensile strength of asphalt mixes under extreme cold temperatures is more affected by the type of asphalt cement and the percent of asphalt content in the mix than by the initial conditions of the mix, i.e. the compaction of the mix.

Figure 5.24: Binder Influence on Compressive Fatigue for Marshall-compact Specimens

Figure 5.25: Binder Influence on Compressive Fatigue for Gyratory-compact Specimens

Figure 5.26: Binder Influence on ITS Results for Marshall-compacted Specimens

Figure 5.27: Binder Influence on ITS Results for Gyratory-compacted Specimens

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

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The need for a stable and durable mix resulted in the development of new mix design methods. The criteria were established by a correlation of results obtained from laboratory

Figure 5.28: Binder Influence on Shear Strength Results for Marshall-compacted Specimens

Figure 5.29: Binder Influence on Shear Strength Results for Gyratory-compacted Specimens

in extreme temperature environments. The inherent flexibility of such binder is demonstrable only at such temperature extremes. At room temperature higher mechanical properties are offered from specimens made from 85/100 Pen asphalt cement mix. The influence of various concentrations of asphalt cement in the mix was analyzed and resulted in the conclusion that a higher percentage of asphalt content (7.0%) results in bleeding the excess asphalt binder during compaction and in decreasing the densities of specimens, especially in case of 85/100 Pen AC.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY

Over the past decade, major changes have occurred in the loading conditions under which pavements have to perform. Legal axle loads and tire pressures have increased dramatically with the size of vehicles (expansion of the trucking industry) as has the percentage of heavy axle loads on most highways in Canada. Also, load repetitions have intensified with the growing number of vehicles. Changes in material behaviour, due to new mix design, and a growth in the use of asphalt modifiers have been occurring. The most important factor affecting pavement performance is compaction. Variables such as, homogeneity and density of materials, position of aggregates, potential surface or internal cracking due to compaction, etc. are all contributing factors influencing strength, fatigue durability, resistance to deformation and moisture damage of asphalt pavements. In addition, the compactibility of each individual mix is affected by binder viscosity, aggregate gradation, stone shapes, mix, road, and air temperature, etc.

The need for a stable and durable mix resulted in the development of new mix design methods. The criteria were established by a correlation of results obtained from laboratory

specimens with performance of the same mixture in the field under traffic conditions. The most common asphalt mix design methods currently used in the United States are the Marshall, Hveem, and gyratory, and the Marshall and gyratory methods in Canada. The use of the new Superpave method is also gaining in prominence. The major difference between them is the process of compacting the specimen. The specimens prepared by the Marshall method are compacted using hammer blows, the specimens prepared by the Hveem and gyratory methods are compacted using a kneading action. The Superpave method is based on the use of a gyratory compactor. In 1993, the Strategic Highway Research Program (SHRP) introduced the Superpave (Superior Performing Asphalt Pavements) laboratory mix design procedure. This system is performance-related and relies on volumetric principles for design purposes. The designed asphalt content depends on traffic level and environmental conditions. Three hierarchical levels of Superpave design have been introduced: Level 1, 2, and 3, for low, medium, and high levels of traffic, respectively. However, due to the need for sophisticated and complex analytical techniques and costly test equipment for Level 2 and 3 design and control, the SHRP decided to use the Level 1 concept for all types of traffic. There is also some concern about the validity of the design method itself. Presently, only Level 1 Superpave is used. The intent is to introduce the remaining two levels at a later date.

The main objective of this thesis was the laboratory comparison of Marshall compaction with gyratory compaction and to determine the effect of the mix design method on the asphalt mix and its mechanical properties. The subsidiary objective was to evaluate the effect of asphalt binders to enhance the mechanical properties of asphalt mixes, again under the

Marshall and gyratory compaction methods, and to evaluate how those factors would interact and affect the selection of a given mix.

In order to achieve these objectives the following framework was developed and a laboratory investigation was carried out under room, cold and warm temperatures.

1. Two mixes consisting of HL3 gradation (specified by MTO), and two different types of asphalt cement (85 100 Pen and polymer-modified) were selected. Both mixes were based on 5.0%, 5.5%, 6.0%, 6.5%, and 7.0% asphalt contents in the mix.
2. Preparation of Marshall-compacted specimens with 75-blows and determining their densities.
3. Preparation of gyratory-compacted specimens having the equivalent densities as those prepared with Marshall compaction.
4. Investigating mechanical properties of each of the specimens of the asphalt mixes measured by the following tests: indirect tensile strength test, shear strength test, compressive fatigue test, and moisture damage test.
5. Comparing the two compaction methods, Marshall and gyratory, to evaluate which of the two would produce the specimens with the higher mechanical properties.
6. Evaluating the effect of asphalt binder on the mechanical properties of the Marshall and gyratory-compacted specimens.

6.2 CONCLUSIONS AND RECOMMENDATIONS

The results and analysis presented in this thesis support the following conclusions:

1. Results presented in this thesis are limited to the laboratory investigation. It is possible, that when these two design methods give similar results, the performance of the designed mix in the field can be predicted.
2. Marshall compaction of specimens in the laboratory environment provided higher results than gyratory compaction when specimens were tested for compressive fatigue test at 40°C, shear strength test and indirect tensile strength (ITS) test at room temperature. Gyratory compaction gave higher results if specimens were tested for moisture damage and slightly higher results if specimens were tested for ITS at -35°C.
3. The ITS test at -35°C was the only case where Marshall and gyratory compaction gave similar results. Cold temperature cracking appears to be independent of compaction method. In other words, the selection of compaction method effects insignificantly the capability of a design mix to resist thermal stresses at very low temperatures. The behaviour of mixes is influenced more by the type and amount of asphalt binder used.
4. Moisture damage or stripping is affected by the finish of the core surface of the specimens. The gyrations result in closing the texture of the surface and thus forming a membrane on the surface of the briquette. This is similar to the rotational compaction in the field. Such effect could not be replicated with the Marshall hammer.

5. The effective resistance to repeated traffic loads is more dependent on the type of asphalt binder used than on the compaction method. Nevertheless, the orientation of aggregates can influence the mechanical properties of the mix.
6. Shear strength test results showed that Marshall compaction provides higher resistance to the applied torque than gyratory compaction. This is due to the orientation of aggregates. The Marshall hammers compact the mix with a dynamic load which results in the dispersed orientation of the aggregates in all directions and the creation of a high friction index between them. Such a mix better resists the applied torque compared to the mix compacted with a gyratory compactor, resulting in a horizontally layered placement of aggregates and lesser friction.
7. The direction of torque load application relative to the direction of gyrational compaction should be considered. (There is a correlation between the direction of rotational compaction in the field and the direction of rotation of wheel loads).
8. The selection of an asphalt mix based solely on the optimum density as design criterion can result in either a mix that is not cost-effective, as in case of standard 85/100 asphalt cement mix, or one with inferior mechanical properties.
9. The use of engineered asphalt cements may require a closer review insofar as mix design is concerned. The results indicate that mixes utilizing polymer-modified binder would be affected by compaction method, type of test, and test temperature. Binder selection should be based on how it will be used and as a consequence, mix design methods must be specified before use.

The most important result of this study is that gyratory compaction considerably influences the internal geometric characteristics of the mix. Since all specimens used for comparing the two compaction methods were of the same density, the only major difference was the position of aggregates in the mix. Gyratory compaction is based on a uniaxial kneading process and application of a "static load" which leads to a more uniform, horizontal layered system. On the other hand, the Marshall compaction employs high impact dynamic loading that can eventually result in the degradation (cracking) of the aggregates.

Finally, the results presented in this thesis suggest that more research work is needed. It is recommended that this encompass other types of mixes and shear tests under extreme temperatures in order to expand upon the work reported in this thesis. Further research on torque load application relative to the direction of gyrational compaction should be undertaken.

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Samples Selection for Moisture Sensitivity Test @ Temperature of 23C

Polymer-modified AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm3	DENSITY gm/cm3	MEAN density	STD	COV %
M 5.0%	7	63.80	1190.5	1191.9	674.3	517.6	2.300	2.287	0.0117	0.5103
	9	64.42	1174.7	1175.5	658.4	517.1	2.272			
	14	64.59	1192.2	1193.5	672.7	520.8	2.289			
M 5.5%	1	64.10	1183.4	1183.5	673.2	510.3	2.319	2.304	0.0113	0.4857
	3	64.57	1187.9	1188.7	672.4	516.3	2.301			
	15	63.64	1173.5	1173.9	661.9	512.0	2.292			
M 6.0%	1	63.85	1186.9	1187.2	672.9	514.3	2.308	2.308	0.0129	0.5402
	5	64.22	1186.9	1187.3	669.4	517.9	2.292			
	13	63.90	1195.4	1195.6	681.1	514.5	2.323			
M 6.5%	7	63.30	1187.6	1188.1	677.4	510.7	2.325	2.322	0.0137	0.5885
	9	64.08	1186.8	1187.2	672.1	515.1	2.304			
	11	63.33	1187.9	1188.3	680.0	508.3	2.337			
M 7.0%	3	63.16	1172.9	1173.0	664.3	508.7	2.306	2.314	0.0067	0.2891
	8	63.57	1195.4	1195.7	680.9	514.8	2.322			
	12	63.39	1186.7	1186.7	673.8	512.9	2.314			
G 5.0%	4	67.12	1199.4	1200.7	677.3	523.4	2.292	2.285	0.0054	0.2366
	10	66.96	1195.4	1196.7	673.6	523.1	2.285			
	13	67.03	1196.8	1197.7	672.4	525.3	2.278			
G 5.5%	5	66.34	1198.1	1198.7	680.0	518.7	2.310	2.305	0.0045	0.1965
	12	66.49	1197.4	1198.2	678.8	519.4	2.305			
	13	66.32	1195.6	1196.9	676.8	520.1	2.299			
G 6.0%	8	66.15	1194.5	1194.9	679.0	515.9	2.315	2.304	0.0090	0.3893
	12	66.47	1196.5	1197.0	675.3	521.7	2.293			
	15	66.23	1194.8	1195.1	676.3	518.8	2.303			
G 6.5%	4	65.83	1194.4	1194.9	682.8	512.1	2.332	2.324	0.0062	0.2660
	6	65.82	1194.6	1194.8	680.5	514.3	2.323			
	11	65.84	1193.7	1193.9	678.8	515.1	2.317			
G 7.0%	4	65.63	1195.0	1195.3	682.0	513.3	2.328	2.321	0.0053	0.2293
	11	65.98	1194.4	1194.5	678.6	515.9	2.315			
	14	65.65	1192.0	1192.7	678.9	513.8	2.320			

M Marshall Compaction

G Gyrotory Compaction

**The Average Densities of Samples Selected for
ITS @ Temperature of 23C**

MIX	DENSITY gm cm³	STD	MIX	DENSITY gm cm³	STD
85/100 AC			85/100 AC		
M 5.0%	2.301	0.0139	G 5.0%	2.302	0.0076
M 5.5%	2.317	0.0105	G 5.5%	2.320	0.0104
M 6.0%	2.335	0.0159	G 6.0%	2.338	0.0133
M 6.5%	2.357	0.0166	G 6.5%	2.361	0.0136
M 7.0%	2.362	0.0189	G 7.0%	2.355	0.0077
Polymer			Polymer		
M 5.0%	2.287	0.0132	G 5.0%	0.0039	0.0028
M 5.5%	2.303	0.0065	G 5.5%	0.0043	0.0016
M 6.0%	2.309	0.0088	G 6.0%	0.008	0.0070
M 6.5%	2.322	0.0127	G 6.5%	0.0047	0.0017
M 7.0%	2.311	0.0138	G 7.0%	0.0052	0.0023

M: Marshall Compaction

G: Gyratory Compaction

Samples Selection for Indirect Tensile Strength Test @ Temperature of 23°C

85/100 AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
M 5.0%	3	63.46	1194.9	1196.4	681.3	514.9	2.321	2.301	0.0139	0.6043
	10	63.16	1169.3	1170.5	661.0	509.5	2.295			
	11	65.36	1202.1	1203.7	678.4	525.3	2.288			
M 5.5%	2	64.78	1210.3	1211.3	691.2	520.1	2.327	2.317	0.0105	0.4515
	3	63.58	1198.7	1199.6	683.0	516.6	2.320			
	16	63.34	1176.7	1177.5	666.4	511.1	2.302			
M 6.0%	2	63.62	1200.3	1201.2	691.5	509.7	2.355	2.335	0.0159	0.6830
	10	63.38	1178.8	1180.6	671.5	509.0	2.316			
	12	63.00	1183.8	1184.9	677.6	507.3	2.334			
M 6.5%	2	62.77	1195.9	1197.2	693.1	504.1	2.372	2.357	0.0166	0.7058
	6	62.55	1186.6	1186.9	685.1	503.8	2.365			
	16	63.56	1184.9	1185.2	677.5	507.7	2.334			
M 7.0%	1	62.79	1188.4	1188.8	688.7	500.1	2.376	2.362	0.0189	0.8018
	11	62.42	1186.6	1187.0	687.3	499.7	2.375			
	14	63.75	1173.5	1173.7	671.2	502.5	2.335			
G 5.0%	5	66.61	1200.0	1200.5	681.6	518.9	2.313	2.302	0.0076	0.3296
	15	67.45	1200.2	1201.6	678.5	523.1	2.294			
	16	66.51	1199.3	1200.0	678.6	521.4	2.306			
G 5.5%	3	66.35	1197.5	1197.9	682.4	515.5	2.323	2.320	0.0104	0.4436
	7	66.09	1199.5	1200.1	685.7	514.4	2.332			
	12	66.86	1199.0	1199.8	680.0	519.8	2.307			
G 6.0%	6	65.96	1198.9	1199.1	685.2	513.9	2.333	2.338	0.0133	0.5692
	7	65.18	1197.0	1197.5	689.5	508.0	2.356			
	12	66.29	1198.5	1198.8	683.3	515.5	2.325			
G 6.5%	2	64.44	1198.0	1198.3	694.1	504.2	2.376	2.361	0.0136	0.5740
	8	65.19	1199.3	1199.7	692.2	507.5	2.363			
	13	65.48	1198.5	1198.8	687.3	511.5	2.343			
G 7.0%	12	65.35	1197.9	1198.1	690.5	507.6	2.360	2.355	0.0077	0.3288
	14	65.19	1197.5	1197.8	690.4	507.4	2.360			
	15	65.72	1197.1	1197.3	686.5	510.8	2.344			

M - Marshall Compaction
G - Gyromatic Compaction

Samples Selection for Indirect Tensile Strength Test at Temperature of 23°C

Polymer-modified AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SURF gm	VOLUME cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
M 5.0%	2	63.69	1179.1	1179.6	664.1	515.5	2.287	2.287	0.0132	0.5767
	3	64.19	1187.9	1188.8	673.1	515.7	2.303			
	6	64.29	1175.1	1176.3	658.9	517.4	2.271			
M 5.5%	6	64.92	1180.3	1180.6	668.9	512.6	2.303	2.303	0.0065	0.2827
	7	64.71	1182.6	1183.0	667.8	515.2	2.295			
	8	63.98	1184.1	1184.6	672.3	512.3	2.311			
M 6.0%	10	64.14	1192.1	1192.4	675.5	516.9	2.306	2.309	0.0088	0.3807
	11	64.12	1196.3	1196.7	676.5	520.2	2.300			
	12	63.30	1184.5	1184.7	674.3	510.4	2.321			
M 6.5%	4	63.37	1194.4	1194.8	680.6	514.2	2.323	2.322	0.0127	0.5466
	5	64.96	1184.9	1185.0	671.1	513.9	2.306			
	6	63.37	1191.5	1191.9	682.0	509.9	2.337			
M 7.0%	7	63.32	1177.4	1177.9	664.5	513.4	2.293	2.311	0.0138	0.5950
	12	63.39	1186.7	1186.7	673.8	512.9	2.314			
	16	62.88	1179.2	1179.5	672.7	506.8	2.327			
G 5.0%	2	66.22	1187.1	1188.2	669.9	518.3	2.290	2.285	0.0039	0.1727
	12	67.16	1197.0	1198.4	674.2	524.2	2.283			
	15	67.08	1197.1	1198.0	673.2	524.8	2.281			
G 5.5%	2	66.23	1192.5	1193.1	675.9	517.2	2.306	2.305	0.0043	0.1873
	4	65.98	1191.9	1192.6	676.5	516.1	2.309			
	14	66.30	1194.1	1195.2	675.8	519.4	2.299			
G 6.0%	1	66.20	1197.1	1197.4	679.7	517.7	2.312	2.309	0.0080	0.3461
	4	66.48	1195.2	1196.0	675.8	520.2	2.298			
	7	66.24	1195.1	1196.0	678.4	516.0	2.316			
G 6.5%	12	65.92	1197.6	1197.7	681.4	516.3	2.320	2.326	0.0047	0.2031
	13	65.50	1191.2	1191.5	679.4	512.1	2.326			
	16	65.45	1192.6	1192.9	681.3	511.6	2.331			
G 7.0%	8	65.96	1194.2	1194.4	675.7	515.7	2.316	2.321	0.0052	0.2233
	9	65.85	1193.1	1193.2	675.7	514.5	2.319			
	12	65.77	1194.7	1194.9	681.7	513.2	2.378			

M Marshall Compaction

G Gyratory Compaction

**The Average Densities of Samples Selected for
Moisture Sensitivity Test @ Temperature of 23C**

MIX type	DENSITY gm/cm3	STD	MIX type	DENSITY gm/cm3	STD
85/100 AC			85/100 AC		
M 5.0%	2.302	0.0168	G 5.0%	2.309	0.0112
M 5.5%	2.318	0.0138	G 5.5%	2.320	0.0050
M 6.0%	2.334	0.0162	G 6.0%	2.337	0.0099
M 6.5%	2.355	0.0126	G 6.5%	2.361	0.0106
M 7.0%	2.363	0.0105	G 7.0%	2.359	0.0139
Polymer			Polymer		
M 5.0%	2.287	0.0117	G 5.0%	2.285	0.0054
M 5.5%	2.304	0.0113	G 5.5%	2.305	0.0045
M 6.0%	2.308	0.0129	G 6.0%	2.304	0.0090
M 6.5%	2.322	0.0137	G 6.5%	2.324	0.0062
M 7.0%	2.314	0.0067	G 7.0%	2.321	0.0053

M: Marshall Compaction

G: Gyratory Compaction

Samples Selection for Moisture Sensitivity Test @ Temperature of 23C

85/100 AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SIE gm	VOLUME cm ³	DENSITY gm/cm ³	MEAS density	STD	COV %
M 5.0%	2	63.76	1174.3	1175.3	661.6	513.7	2.286	2.302	0.0168	0.7301
	5	64.02	1194.6	1195.9	682.2	513.7	2.325			
	6	64.54	1197.9	1198.7	676.9	521.8	2.296			
M 5.5%	1	60.32	1134.4	1135.4	649.2	486.2	2.333	2.318	0.0138	0.5933
	11	64.21	1186.0	1186.7	671.0	515.7	2.300			
	12	64.10	1194.2	1195.0	680.3	514.7	2.320			
M 6.0%	3	64.04	1194.5	1195.8	687.7	508.1	2.351	2.334	0.0162	0.6932
	6	62.40	1172.3	1173.0	671.8	501.2	2.339			
	8	63.60	1182.7	1183.8	672.3	511.5	2.312			
M 6.5%	1	62.82	1191.2	1191.4	687.0	504.4	2.362	2.355	0.0126	0.5369
	3	62.65	1182.6	1183.1	683.3	499.8	2.366			
	8	63.69	1184.1	1184.3	677.7	506.6	2.337			
M 7.0%	4	62.80	1187.5	1188.1	688.6	499.5	2.377	2.363	0.0105	0.4438
	12	63.45	1189.2	1189.5	684.6	504.9	2.355			
	15	63.50	1186.9	1187.2	683.2	504.0	2.355			
G 5.0%	3	63.46	1194.9	1196.4	681.5	514.9	2.321	2.309	0.0112	0.4845
	4	66.50	1161.9	1163.1	660.6	502.5	2.312			
	8	65.95	1195.1	1195.9	674.9	521.0	2.294			
G 5.5%	1	66.08	1199.9	1201.0	683.4	517.6	2.318	2.320	0.0050	0.2153
	2	66.65	1199.8	1200.9	682.7	518.2	2.315			
	14	66.00	1199.6	1200.1	684.6	515.5	2.327			
G 6.0%	1	65.85	1199.7	1200.0	686.2	513.8	2.335	2.337	0.0099	0.4233
	11	66.07	1200.1	1200.6	684.6	516.0	2.326			
	13	65.49	1199.8	1200.0	689.4	510.6	2.350			
G 6.5%	9	65.55	1198.4	1198.6	687.8	510.8	2.346	2.361	0.0106	0.4479
	14	65.19	1199.0	1199.7	693.8	505.9	2.370			
	15	65.13	1195.9	1196.3	691.0	505.3	2.367			
G 7.0%	7	64.37	1194.6	1194.8	691.7	503.1	2.374	2.359	0.0139	0.5879
	10	65.23	1198.5	1198.7	691.0	507.7	2.361			
	11	65.68	1197.5	1197.6	686.0	511.6	2.341			

M Marshall Compaction

G Gyratory Compaction

Samples Selection for Moisture Sensitivity Test @ Temperature of 23°C

Polymer-modified AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
M 5.0%	7	63.80	1190.5	1191.9	674.3	517.6	2.300	2.287	0.0117	0.5103
	9	64.42	1174.7	1175.5	658.4	517.1	2.272			
	14	64.59	1192.2	1193.5	672.7	520.8	2.289			
M 5.5%	1	64.10	1183.4	1183.5	673.2	510.3	2.319	2.304	0.0113	0.4887
	3	64.57	1187.9	1188.7	672.4	516.3	2.301			
	15	63.64	1173.5	1173.9	661.9	512.0	2.292			
M 6.0%	1	63.85	1186.9	1187.2	672.9	514.3	2.308	2.308	0.0129	0.5602
	5	64.22	1186.9	1187.3	669.4	517.9	2.292			
	13	63.90	1195.4	1195.6	681.1	514.5	2.323			
M 6.5%	7	63.30	1187.6	1188.1	677.4	510.7	2.325	2.322	0.0137	0.5885
	9	64.08	1186.8	1187.2	672.1	515.1	2.304			
	11	63.33	1187.9	1188.3	680.0	508.3	2.337			
M 7.0%	3	63.16	1172.9	1173.0	664.3	508.7	2.306	2.314	0.0067	0.2891
	8	63.57	1195.4	1195.7	680.9	514.8	2.322			
	12	63.39	1186.7	1186.7	673.8	512.9	2.314			
G 5.0%	4	67.12	1199.4	1200.7	677.3	523.4	2.292	2.285	0.0054	0.2366
	10	66.96	1195.4	1196.7	673.6	523.1	2.285			
	13	67.03	1196.8	1197.7	672.4	525.3	2.278			
G 5.5%	5	66.34	1198.1	1198.7	680.0	518.7	2.310	2.305	0.0045	0.1965
	12	66.49	1197.4	1198.2	678.8	519.4	2.305			
	13	66.32	1195.6	1196.9	676.8	520.1	2.299			
G 6.0%	8	66.15	1194.5	1194.9	679.0	515.9	2.315	2.304	0.0090	0.3893
	12	66.47	1196.5	1197.0	675.3	521.7	2.293			
	15	66.23	1194.8	1195.1	676.3	518.8	2.303			
G 6.5%	4	65.83	1194.4	1194.9	682.8	512.1	2.332	2.324	0.0062	0.2660
	6	65.82	1194.6	1194.8	680.5	514.3	2.323			
	11	65.84	1193.7	1193.9	678.8	515.1	2.317			
G 7.0%	4	65.63	1195.0	1195.3	682.0	513.3	2.328	2.321	0.0053	0.2293
	11	65.98	1194.4	1194.5	678.6	515.9	2.315			
	14	65.65	1192.0	1192.7	678.9	513.8	2.320			

M Marshall Compaction

G Gyratory Compaction

**The Average Densities of Samples Selected for
Compressive Fatigue Test @ Temperature of 40C**

MIX type	DENSITY gm/cm³	STD	MIX type	DENSITY gm/cm³	STD
85/100 AC			85/100 AC		
M 5.0%	2.303	0.0080	G 5.0%	2.303	0.0032
M 5.5%	2.317	0.0043	G 5.5%	2.322	0.0146
M 6.0%	2.335	0.0085	G 6.0%	2.337	0.0105
M 6.5%	2.356	0.0146	G 6.5%	2.361	0.0125
M 7.0%	2.361	0.0193	G 7.0%	2.357	0.0129
Polymer			Polymer		
M 5.0%	2.287	0.0130	G 5.0%	2.285	0.0028
M 5.5%	2.301	0.0044	G 5.5%	2.304	0.0016
M 6.0%	2.307	0.0041	G 6.0%	2.304	0.0070
M 6.5%	2.322	0.0062	G 6.5%	2.324	0.0017
M 7.0%	2.315	0.0116	G 7.0%	2.319	0.0023

M: Marshall Compaction
G: Gyratory Compaction

Samples Selection for Compressive Fatigue Test @ Temperature of +40C

85/100 AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME gm/cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
M 5.0%	4	63.56	1161.9	1163.1	660.6	502.5	2.312	2.303	0.0080	0.3471
	9	64.20	1193.8	1194.5	676.4	518.1	2.304			
	13	63.94	1177.1	1177.6	664.2	513.4	2.293			
M 5.5%	6	62.14	1164.7	1165.5	664.1	501.4	2.323	2.317	0.0043	0.1836
	13	64.80	1204.3	1204.8	684.1	520.7	2.313			
	14	62.29	1162.6	1163.2	661.1	502.1	2.315			
M 6.0%	5	60.86	1146.8	1147.5	657.6	489.9	2.341	2.335	0.0085	0.3624
	14	63.18	1192.5	1193.4	684.0	509.4	2.341			
	15	63.86	1190.3	1190.5	678.1	512.4	2.323			
M 6.5%	11	62.62	1192.1	1192.4	690.8	501.6	2.377	2.356	0.0146	0.6205
	12	63.32	1192.7	1192.9	683.8	509.1	2.343			
	13	63.09	1191.2	1191.6	684.6	507.0	2.350			
M 7.0%	2	62.31	1191.6	1192.2	691.5	500.7	2.380	2.361	0.0193	0.8164
	3	62.88	1184.4	1185.1	685.2	499.9	2.369			
	8	63.88	1178.8	1179.1	674.2	504.9	2.335			
G 5.0%	6	67.69	1200.2	1201.0	680.3	520.7	2.305	2.303	0.0032	0.1388
	7	67.31	1201.9	1202.8	681.4	521.4	2.305			
	13	66.72	1199.7	1200.3	678.3	522.0	2.298			
G 5.5%	6	65.80	1198.0	1198.7	687.2	511.5	2.342	2.322	0.0146	0.6294
	10	66.70	1198.2	1198.5	679.2	519.3	2.307			
	11	66.72	1199.5	1200.5	682.9	517.6	2.317			
G 6.0%	8	65.37	1199.8	1200.3	689.9	510.4	2.351	2.337	0.0105	0.4481
	15	66.14	1200.6	1200.7	684.4	516.3	2.325			
	16	63.57	1159.3	1159.4	662.8	496.6	2.334			
G 6.5%	4	65.25	1198.3	1198.5	691.9	506.6	2.365	2.361	0.0125	0.5298
	11	64.73	1197.9	1198.2	693.7	504.5	2.374			
	16	63.39	1156.8	1157.1	663.7	493.4	2.345			
G 7.0%	1	64.64	1194.4	1194.7	691.8	502.9	2.375	2.357	0.0129	0.5464
	5	64.98	1193.1	1193.4	685.5	507.9	2.349			
	6	65.86	1199.3	1199.6	688.5	511.1	2.347			

M Marshall Compaction

G Gyrotory Compaction

Samples Selection for Compressive Fatigue Test @ Temperature of +40C

Polymer-modified AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME gm/cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
M 5.0%	4	64.96	1180.8	1181.5	663.2	518.3	2.278	2.287	0.0130	0.5694
	5	63.80	1192.1	1193.3	676.1	517.2	2.305			
	13	62.44	1151.2	1152.3	646.6	505.7	2.276			
M 5.5%	2	62.46	1156.5	1157.0	655.7	501.3	2.307	2.301	0.0044	0.1906
	11	64.29	1186.3	1187.0	670.5	516.5	2.297			
	14	64.31	1186.5	1187.2	671.1	516.1	2.299			
M 6.0%	7	63.35	1176.8	1177.0	666.2	510.8	2.304	2.307	0.0041	0.1791
	8	64.52	1203.3	1203.3	683.1	520.2	2.313			
	14	63.35	1176.5	1176.5	666.1	510.4	2.305			
M 6.5%	1	63.37	1182.2	1182.2	672.0	510.2	2.317	2.322	0.0062	0.2663
	3	63.55	1176.7	1177.0	669.3	507.7	2.318			
	13	63.46	1189.5	1189.9	679.5	510.4	2.331			
M 7.0%	5	63.67	1184.6	1184.9	670.4	514.5	2.302	2.315	0.0116	0.5018
	6	63.53	1189.6	1189.9	679.4	510.5	2.330			
	15	63.08	1186.6	1187.1	673.7	513.4	2.311			
G 5.0%	5	67.05	1195.5	1196.3	673.7	522.6	2.288	2.285	0.0028	0.1231
	9	66.81	1195.1	1196.2	673.7	522.5	2.287			
	16	67.27	1199.6	1200.4	674.6	525.8	2.281			
G 5.5%	3	66.64	1197.6	1198.5	678.5	520.0	2.303	2.304	0.0016	0.0707
	7	66.24	1194.8	1195.2	677.2	518.0	2.307			
	9	66.20	1195.1	1195.7	676.8	518.9	2.303			
G 6.0%	5	66.15	1194.5	1194.9	678.7	516.2	2.314	2.304	0.0070	0.3052
	9	66.17	1193.3	1194.7	676.3	518.4	2.302			
	13	66.23	1194.4	1195.0	675.1	519.9	2.297			
G 6.5%	3	65.83	1196.3	1196.6	681.6	515.0	2.323	2.324	0.0017	0.0749
	7	65.76	1192.4	1193.0	680.4	512.6	2.326			
	15	65.51	1192.9	1193.0	679.3	513.7	2.322			
G 7.0%	3	65.55	1194.9	1195.2	679.7	515.5	2.318	2.319	0.0023	0.0983
	10	65.93	1195.7	1195.9	681.1	514.8	2.323			
	13	65.94	1195.0	1195.3	679.7	515.6	2.318			

M. Marshall Compaction

G. Gyratory Compaction

**The Average Densities of Samples Selected for
ITS @ Temperature of -35C**

MIX type	DENSITY gm/cm3	STD	MIX type	DENSITY gm/cm3	STD
M 5.0%	2.301	0.0137	G 5.0%	2.301	0.0035
M 5.5%	2.316	0.0076	G 5.5%	2.321	0.0110
M 6.0%	2.336	0.0101	G 6.0%	2.338	0.0136
M 6.5%	2.356	0.0143	G 6.5%	2.360	0.0144
M 7.0%	2.362	0.0127	G 7.0%	2.357	0.0140
Polymer			Polymer		
M 5.0%	2.286	0.0137	G 5.0%	2.285	0.0032
M 5.5%	2.301	0.0048	G 5.5%	2.305	0.0038
M 6.0%	2.308	0.0054	G 6.0%	2.304	0.0081
M 6.5%	2.321	0.0090	G 6.5%	2.324	0.0033
M 7.0%	2.315	0.0133	G 7.0%	2.321	0.0039

M: Marshall Compaction
G: Gyratory Compaction

Samples Selection for Indirect Tensile Strength Test at Temperature of -35C

85/100 AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS S.B gm	VOLUME cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
M 5.0%	8	65.05	1195.1	1195.9	674.9	521.0	2.294	2.301	0.0137	0.5969
	14	64.79	1190.7	1191.9	671.8	520.1	2.289			
	16	64.35	1192.5	1193.3	679.4	513.9	2.320			
M 5.5%	4	63.54	1191.7	1193.1	680.6	512.5	2.325	2.316	0.0076	0.3283
	7	64.12	1191.4	1191.9	675.4	516.5	2.307			
	9	62.26	1159.6	1160.5	659.6	500.9	2.315			
M 6.0%	1	63.72	1198.2	1199.6	688.8	510.8	2.346	2.336	0.0101	0.4344
	4	62.37	1172.2	1172.7	671.9	500.8	2.341			
	7	63.06	1180.1	1181.1	672.9	508.2	2.322			
M 6.5%	5	63.35	1191.6	1191.9	686.5	505.4	2.358	2.356	0.0143	0.6088
	7	63.87	1190.9	1191.2	681.7	509.5	2.337			
	14	62.83	1193.3	1193.6	690.6	503.0	2.372			
M 7.0%	5	63.03	1182.7	1183.0	680.9	502.1	2.356	2.362	0.0127	0.5373
	6	62.47	1185.6	1186.0	687.7	498.3	2.379			
	9	63.29	1184.2	1184.4	680.5	503.9	2.350			
G 5.0%	1	67.06	1200.3	1201.5	679.4	522.1	2.299	2.301	0.0035	0.1530
	2	66.68	1200.3	1201.3	680.8	520.5	2.306			
	10	67.27	1200.6	1201.7	679.3	522.4	2.298			
G 5.5%	4	65.87	1196.5	1197.3	684.6	512.7	2.334	2.321	0.0110	0.4742
	8	66.59	1197.7	1198.3	679.1	519.2	2.307			
	9	66.42	1200.1	1200.8	683.9	516.9	2.322			
G 6.0%	2	65.33	1201.0	1201.3	686.3	515.0	2.332	2.338	0.0136	0.5827
	5	66.15	1198.6	1198.9	683.3	515.6	2.325			
	10	65.20	1198.3	1198.5	690.0	508.5	2.357			
G 6.5%	7	64.62	1198.0	1198.3	694.3	504.0	2.377	2.360	0.0144	0.6098
	10	65.49	1199.7	1199.9	691.6	508.3	2.360			
	12	66.24	1205.3	1205.6	690.9	514.7	2.342			
G 7.0%	2	65.35	1199.2	1199.4	688.0	511.4	2.345	2.357	0.0140	0.5922
	8	65.43	1197.4	1197.6	687.8	509.8	2.349			
	9	64.40	1195.5	1195.6	692.5	503.1	2.376			

M Marshall Compaction

G Gyratory Compaction

Samples Selection for Indirect Tensile Strength Test at Temperature of -35C

Polymer-modified AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
M 5.0%	8	63.66	1161.9	1162.1	650.7	511.4	2.270	2.286	0.0137	0.5989
	11	64.02	1190.5	1191.5	674.7	516.8	2.304			
	15	63.06	1163.9	1165.4	655.8	509.6	2.284			
M 5.5%	5	63.96	1183.5	1184.2	671.3	512.9	2.307	2.301	0.0048	0.2067
	13	64.49	1185.7	1189.1	671.4	517.7	2.296			
	16	64.30	1185.4	1185.9	670.4	515.5	2.300			
M 6.0%	2	63.45	1180.7	1181.1	670.0	511.1	2.310	2.308	0.0054	0.2331
	4	64.91	1204.6	1205.4	681.9	523.5	2.301			
	6	64.08	1196.5	1196.8	679.7	517.1	2.314			
M 6.5%	10	63.44	1187.8	1189.0	679.7	509.3	2.332	2.321	0.0090	0.3886
	12	63.38	1178.2	1178.2	668.2	510.0	2.310			
	16	62.75	1173.8	1173.8	667.8	506.0	2.320			
M 7.0%	4	63.29	1192.5	1192.8	681.4	511.4	2.332	2.315	0.0133	0.5761
	9	63.50	1185.6	1185.9	673.2	512.7	2.312			
	10	63.64	1180.5	1181.0	667.6	513.4	2.299			
G 5.0%	1	66.45	1188.6	1189.2	669.8	519.4	2.288	2.285	0.0032	0.1394
	11	67.21	1197.4	1198.4	673.4	525.0	2.281			
	14	67.10	1197.6	1198.4	674.5	523.9	2.286			
G 5.5%	6	66.22	1195.9	1196.6	678.3	518.3	2.307	2.305	0.0038	0.1662
	15	66.27	1197.0	1197.8	679.1	518.7	2.308			
	16	66.24	1195.0	1195.9	676.2	519.7	2.299			
G 6.0%	6	66.27	1195.0	1196.1	679.7	516.4	2.314	2.304	0.0081	0.3523
	14	66.21	1195.3	1195.5	674.5	521.0	2.294			
	16	66.26	1195.4	1196.0	677.0	519.0	2.303			
G 6.5%	8	65.81	1194.1	1194.4	679.6	514.8	2.320	2.324	0.0033	0.1422
	10	65.60	1190.9	1191.2	679.2	512.0	2.326			
	14	65.42	1190.5	1190.7	679.1	511.6	2.327			
G 7.0%	1	65.82	1197.6	1197.7	680.7	517.0	2.316	2.321	0.0039	0.1659
	5	65.70	1195.0	1195.0	681.2	513.8	2.326			
	6	65.73	1193.1	1193.3	679.5	513.8	2.322			

M Marshall Compaction

G Gyratory Compaction

**The Average Densities of Samples Selected for
Shear Strength Test at Temperature of 25C**

MIX type	DENSITY gm/cm³	STD	MIX type	DENSITY gm/cm³	STD
85/100 AC			85/100 AC		
M 5.0%	2.302	0.0079	G 5.0%	2.300	0.0035
M 5.5%	2.319	0.0033	G 5.5%	2.321	0.0154
M 6.0%	2.336	0.0059	G 6.0%	2.336	0.0067
M 6.5%	2.358	0.0075	G 6.5%	2.359	0.0102
M 7.0%	2.364	0.0198	G 7.0%	2.354	0.0139
Polymer			Polymer		
M 5.0%	2.284	0.0087	G 5.0%	2.285	0.0022
M 5.5%	2.303	0.0039	G 5.5%	2.305	0.0018
M 6.0%	2.309	0.0038	G 6.0%	2.305	0.0060
M 6.5%	2.322	0.0048	G 6.5%	2.324	0.0022
M 7.0%	2.314	0.0055	G 7.0%	2.321	0.0018

M: Marshall Compaction
G: Gyratory Compaction

Samples to be tested on SHEAR STRENGTH at temperature of 25C

85/100 AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
M 5.0%	1	64.90	1194.9	1197.5	679.1	518.4	2.305	2.302	0.0079	0.3427
	7	64.56	1185.8	1186.9	669.3	517.6	2.291			
	15	64.48	1197.7	1199.3	680.7	518.6	2.309			
M 5.5%	8	63.86	1191.9	1192.4	677.4	515.0	2.314	2.319	0.0033	0.1440
	10	64.24	1197.5	1198.2	682.5	515.7	2.322			
	15	61.66	1151.7	1152.5	656.2	496.3	2.321			
M 6.0%	9	63.28	1191.4	1192.1	683.5	508.6	2.343	2.336	0.0059	0.2527
	11	62.94	1180.5	1181.9	676.8	505.1	2.337			
	13	62.95	1179.0	1180.7	674.3	506.4	2.328			
M 6.5%	4	63.30	1182.1	1182.3	678.8	503.5	2.348	2.358	0.0075	0.3183
	9	62.66	1188.0	1188.3	684.9	503.4	2.360			
	10	62.58	1183.6	1183.8	683.5	500.3	2.366			
M 7.0%	10	62.83	1187.6	1188.1	688.6	499.5	2.378	2.364	0.0198	0.8364
	13	64.15	1190.0	1190.1	680.7	509.4	2.336			
	16	63.11	1192.8	1193.2	691.7	501.5	2.378			
G 5.0%	9	66.87	1200.1	1201.4	679.1	522.3	2.298	2.300	0.0035	0.1532
	11	67.37	1200.3	1201.6	680.9	520.7	2.305			
	12	66.76	1200.3	1201.6	679.2	522.4	2.298			
G 5.5%	5	65.44	1198.4	1198.8	687.3	511.5	2.343	2.321	0.0154	0.6653
	13	66.83	1199.6	1200.2	680.5	519.7	2.308			
	15	66.47	1200.4	1200.9	681.8	519.1	2.312			
G 6.0%	3	65.98	1198.4	1198.7	683.6	515.1	2.327	2.336	0.0067	0.2882
	9	66.66	1200.0	1200.4	687.7	512.7	2.341			
	14	65.74	1199.1	1199.4	687.2	512.2	2.341			
G 6.5%	3	65.40	1199.0	1199.3	689.1	510.2	2.350	2.359	0.0102	0.4317
	5	64.91	1197.3	1197.5	693.0	504.5	2.373			
	6	60.46	1107.4	1107.7	637.2	470.5	2.354			
G 7.0%	3	65.82	1199.3	1199.5	687.4	512.1	2.342	2.354	0.0139	0.5913
	4	64.88	1194.2	1194.7	691.6	503.1	2.374			
	13	65.43	1197.7	1198.0	687.7	510.3	2.347			

M: Marshall Compaction

G: Gyration Compaction

Samples to be tested on SHEAR STRENGTH at temperature of 25C

Polymer-modified AC

MIX type	SAMPLE number	HEIGHT mm	MASS DRY gm	MASS SSD gm	MASS SUB gm	VOLUME cm ³	DENSITY gm/cm ³	MEAN density	STD	COV %
M 5.0%	10	64.45	1190.1	1191.6	671.9	519.7	2.290	2.284	0.0087	0.3826
	12	62.02	1134.5	1135.5	636.1	499.4	2.272			
	16	64.06	1186.5	1188.0	670.0	518.0	2.291			
M 5.5%	4	63.48	1173.5	1174.2	665.3	508.9	2.306	2.303	0.0039	0.1712
	9	64.45	1188.7	1189.1	671.7	517.4	2.297			
	10	64.78	1180.5	1181.1	669.1	512.0	2.306			
M 6.0%	9	63.44	1178.4	1178.9	669.5	509.4	2.313	2.309	0.0038	0.1660
	15	64.38	1194.4	1194.7	676.3	518.4	2.304			
	16	64.17	1191.4	1191.5	675.7	515.8	2.310			
M 6.5%	2	63.31	1180.9	1181.4	671.7	509.7	2.317	2.322	0.0048	0.2055
	14	64.44	1184.9	1185.2	674.5	510.7	2.320			
	15	63.58	1197.4	1197.6	683.3	514.3	2.328			
M 7.0%	2	62.33	1167.2	1167.5	664.2	503.3	2.319	2.314	0.0055	0.2398
	13	63.33	1186.9	1187.3	675.0	512.3	2.317			
	14	62.72	1173.7	1174.3	665.4	508.9	2.306			
G 5.0%	3	67.11	1198.2	1199.1	674.3	524.8	2.283	2.285	0.0022	0.0952
	6	66.85	1194.4	1195.9	673.8	522.1	2.288			
	7	67.18	1197.2	1198.9	674.5	524.4	2.283			
G 5.5%	8	66.32	1197.0	1197.7	678.9	518.8	2.307	2.305	0.0018	0.0802
	10	66.33	1196.8	1197.5	677.8	519.7	2.303			
	11	66.41	1196.5	1197.0	677.7	519.3	2.304			
G 6.0%	3	66.27	1195.8	1196.3	679.4	516.9	2.313	2.305	0.0060	0.2609
	10	66.24	1195.1	1195.9	676.8	519.1	2.302			
	11	66.04	1193.9	1194.3	675.1	519.2	2.299			
G 6.5%	1	66.16	1196.6	1196.9	682.4	514.5	2.326	2.324	0.0022	0.0935
	5	65.77	1192.4	1193.0	680.3	512.7	2.326			
	9	65.65	1191.9	1192.2	678.7	513.5	2.321			
G 7.0%	2	65.85	1197.6	1197.9	682.1	515.8	2.322	2.321	0.0018	0.0797
	7	65.84	1194.8	1195.0	680.5	514.5	2.322			
	15	65.90	1195.0	1195.1	679.6	515.5	2.318			

M Marshall Compaction

G Gyratory Compaction

APPENDIX B

ITS Test Results @ temperature of +23C

85/100 Pen AC

MIX Comp-Asp.Content	SAMPLE number	LOAD lb	LOAD N	HEIGHT mm	DENSITY gm/cm ³	TENSILE STRENGTH MPa	TENSILE STRENGTH MEAN
M-5.0%	10	2236.33	9949.43	63.16	2.295	0.9871	0.9298
	11	1872.56	8331.02	65.36	2.288	0.7987	
	12	2285.00	10165.97	63.46	2.321	1.0038	
G-5.0%	5	2246.09	9992.85	66.61	2.313	0.9400	0.8763
	15	2120.24	9432.95	67.45	2.294	0.8763	
	16	1938.48	8624.30	66.51	2.300	0.8125	
M-5.5%	2	2763.67	12295.57	64.78	2.327	1.1893	1.1736
	3	2727.05	12132.65	63.58	2.320	1.1957	
	16	2580.57	11480.96	63.34	2.302	1.1358	
G-5.5%	3	2546.39	11328.89	66.35	2.323	1.0699	1.0908
	7	2680.66	11926.26	66.09	2.332	1.1307	
	12	2570.80	11437.49	66.86	2.307	1.0719	
M-6.0%	2	2788.09	12404.21	63.65	2.355	1.2211	1.1445
	10	2424.32	10785.80	63.38	2.316	1.0663	
	12	2600.10	11567.84	63.25	2.334	1.1460	
G-6.0%	6	2614.75	11633.02	65.96	2.333	1.1051	1.0493
	7	2397.46	10666.30	65.18	2.356	1.0254	
	12	2419.43	10764.04	66.29	2.325	1.0175	
M-6.5%	2	2556.15	11372.31	62.77	2.372	1.1352	1.0390
	6	2224.12	9895.11	62.55	2.365	0.9912	
	16	2258.30	10047.18	63.56	2.334	0.9905	
G-6.5%	2	2460.94	10948.72	64.44	2.376	1.0646	0.9674
	8	2214.36	9851.69	65.19	2.363	0.9469	
	13	2092.29	9308.60	65.48	2.343	0.8908	
M-7.0%	1	2348.68	10449.28	62.79	2.376	1.0428	0.9679
	11	2204.59	9808.22	62.42	2.375	0.9846	
	14	2004.39	8917.53	63.75	2.335	0.8765	
G-7.0%	12	2009.28	8939.29	65.35	2.360	0.8571	0.8917
	14	2224.12	9895.11	65.19	2.360	0.9511	
	15	2043.46	9091.35	65.72	2.344	0.8668	

M: Marshall Compaction

G: Gyrotory Compaction

ITS Test Results @ temperature of +23C - Differences within Mix

85/100 Pen AC

MIX Comp-Asp.Content	SAMPLE number	TENSILE STRENGTH MPa	PERCENT max=100%	DIFFERENCE % max=100%	PERCENT min=100%	DIFFERENCE % min=100%
M-5.0%	11	0.7987	79.57	20.43	100.00	0.00
	10	0.9871	98.33	1.67	123.59	23.59
	12	1.0038	100.00	0.00	125.68	25.68
G-5.0%	16	0.8125	86.43	13.57	100.00	0.00
	15	0.8763	93.22	6.78	107.85	7.85
	5	0.9400	100.00	0.00	115.69	15.69
M-5.5%	16	1.1358	94.99	5.01	100.00	0.00
	2	1.1893	99.47	0.53	104.71	4.71
	3	1.1957	100.00	0.00	105.28	5.28
G-5.5%	3	1.0699	94.62	5.38	100.00	0.00
	12	1.0719	94.80	5.20	100.19	0.19
	7	1.1307	100.00	0.00	105.69	5.69
M-6.0%	10	1.0663	87.32	12.68	100.00	0.00
	12	1.1460	93.85	6.15	107.47	7.47
	2	1.2211	100.00	0.00	114.52	14.52
G-6.0%	12	1.0175	92.07	7.93	100.00	0.00
	7	1.0254	92.79	7.21	100.78	0.78
	6	1.1051	100.00	0.00	108.61	8.61
M-6.5%	16	0.9905	87.25	12.75	100.00	0.00
	6	0.9912	87.32	12.68	100.08	0.08
	2	1.1352	100.00	0.00	114.61	14.61
G-6.5%	13	0.8908	83.67	16.33	100.00	0.00
	8	0.9469	88.95	11.05	106.31	6.31
	2	1.0646	100.00	0.00	119.52	19.52
M-7.0%	14	0.8765	84.06	15.94	100.00	0.00
	11	0.9846	94.42	5.58	112.33	12.33
	1	1.0428	100.00	0.00	118.97	18.97
G-7.0%	12	0.8571	90.12	9.88	100.00	0.00
	15	0.8668	91.14	8.86	101.13	1.13
	14	0.9511	100.00	0.00	110.96	10.96

M: Marshall Compaction

G: Gyratory Compaction

ITS Test Results @ temperature of +23C

Polymer

MIX Comp-Asp.Content	SAMPLE number	LOAD lb	LOAD N	HEIGHT mm	DENSITY gm/cm ³	TENSILE STRENGTH MPa	TENSILE STRENGTH MEAN
M-5.0%	2	1381.84	6147.81	63.69	2.287	0.6048	0.5428
	3	1289.06	5735.03	64.19	2.303	0.5598	
	6	1069.34	4757.49	64.29	2.271	0.4637	
G-5.0%	2	1069.34	4757.49	66.22	2.290	0.4502	0.4756
	12	1159.67	5159.37	67.16	2.283	0.4814	
	15	1191.41	5300.58	67.08	2.281	0.4951	
M-5.5%	6	1252.44	5572.11	64.92	2.303	0.5378	0.5656
	7	1335.45	5941.42	64.03	2.295	0.5814	
	8	1325.68	5897.95	63.98	2.311	0.5776	
G-5.5%	2	1164.55	5181.08	66.23	2.306	0.4902	0.4892
	4	1113.28	4952.98	65.98	2.309	0.4704	
	14	1206.05	5365.72	66.30	2.299	0.5071	
M-6.0%	10	1203.61	5354.86	64.14	2.306	0.5231	0.5569
	11	1291.50	5745.88	64.12	2.300	0.5615	
	12	1330.57	5919.71	63.30	2.321	0.5860	
G-6.0%	1	1191.41	5300.58	66.20	2.312	0.5017	0.4633
	4	1015.63	4518.54	66.48	2.298	0.4259	
	7	1098.63	4887.80	66.24	2.309	0.4624	
M-6.5%	4	1420.90	6321.58	63.37	2.323	0.6251	0.6001
	5	1259.77	5604.72	64.96	2.306	0.5406	
	6	1442.87	6419.33	63.37	2.337	0.6347	
G-6.5%	12	1315.92	5854.53	65.92	2.320	0.5565	0.5743
	13	1394.04	6202.08	65.50	2.326	0.5933	
	16	1345.21	5984.84	65.45	2.331	0.5730	
M-7.0%	7	1098.63	4887.80	63.32	2.293	0.4837	0.5088
	11	1164.55	5181.08	63.09	2.316	0.5146	
	16	1191.41	5300.58	62.88	2.327	0.5282	
G-7.0%	8	1083.98	4822.63	65.96	2.316	0.4581	0.4705
	9	1127.93	5018.16	65.85	2.319	0.4775	
	12	1123.05	4996.45	65.77	2.328	0.4760	

M: Marshall Compaction

G: Gyratory Compaction

ITS Test Results @ temperature of +23C - Differences within Mix

Polymer

MIX Comp-Asp.Content	SAMPLE number	TENSILE STRENGTH MPa	PERCENT max=100%	DIFFERENCE % max=100%	PERCENT min=100%	DIFFERENCE % min=100%
M-5.0%	6	0.4637	76.66	23.34	100.00	0.00
	3	0.5598	92.56	7.44	120.74	20.74
	2	0.6048	100.00	0.00	130.44	30.44
G-5.0%	2	0.4502	90.92	9.08	100.00	0.00
	12	0.4814	97.22	2.78	106.93	6.93
	15	0.4951	100.00	0.00	109.99	9.99
M-5.5%	6	0.5378	92.50	7.50	100.00	0.00
	8	0.5776	99.35	0.65	107.40	7.40
	7	0.5814	100.00	0.00	108.11	8.11
G-5.5%	1	0.4704	92.76	7.24	100.00	0.00
	2	0.4902	96.66	3.34	104.21	4.21
	14	0.5071	100.00	0.00	107.81	7.81
M-6.0%	10	0.5231	89.27	10.73	100.00	0.00
	11	0.5615	95.82	4.18	107.34	7.34
	12	0.5860	100.00	0.00	112.02	12.02
G-6.0%	4	0.4259	84.89	15.11	100.00	0.00
	7	0.4624	92.16	7.84	108.56	8.56
	1	0.5017	100.00	0.00	117.80	17.80
M-6.5%	5	0.5406	85.17	14.83	100.00	0.00
	4	0.6251	98.48	1.52	115.62	15.62
	6	0.6347	100.00	0.00	117.41	17.41
G-6.5%	12	0.5565	93.79	6.21	100.00	0.00
	16	0.5730	96.57	3.43	102.96	2.96
	13	0.5933	100.00	0.00	106.62	6.62
M-7.0%	7	0.4837	91.57	8.43	100.00	0.00
	11	0.5146	97.42	2.58	106.39	6.39
	16	0.5282	100.00	0.00	109.20	9.20
G-7.0%	8	0.4581	95.94	4.06	100.00	0.00
	12	0.4760	99.69	0.31	103.90	3.90
	9	0.4775	100.00	0.00	104.23	4.23

M: Marshall Compaction

G: Gyratory Compaction

ITS Test Results, Second loading @ temperature of +23C

85/100 Pen AC

MIX Comp-Asp.Content	SAMPLE number	LOAD P2 N	LOAD P1 N	HEIGHT mm	DENSITY gm/cm ³	RATIO P2/P1 %	RATIO MEAN
M-5.0%	10	4130.05	9949.43	63.16	2.295	42	42
	11	3614.50	8331.02	65.36	2.288	43	
	12	4193.45	10165.97	63.46	2.321	41	
G-5.0%	5	4544.30	9992.85	66.61	2.313	45	48
	15	4296.44	9432.95	67.45	2.294	46	
	16	4596.53	8624.30	66.51	2.300	53	
M-5.5%	2	5235.41	12295.57	64.78	2.327	43	46
	3	5485.22	12132.65	63.58	2.320	45	
	16	5919.71	11480.96	63.34	2.302	52	
G-5.5%	3	6234.70	11328.89	66.35	2.323	55	54
	7	6766.93	11926.26	66.09	2.332	57	
	12	5887.09	11437.49	66.86	2.307	51	
M-6.0%	2	4594.53	12404.21	63.65	2.355	37	39
	10	4551.10	10785.80	63.38	2.316	42	
	12	4355.57	11567.84	63.25	2.334	38	
G-6.0%	6	5517.78	11633.02	65.96	2.333	47	43
	7	4149.23	10666.30	65.18	2.356	39	
	12	4540.25	10764.04	66.29	2.325	42	
M-6.5%	2	4127.47	11372.31	62.77	2.372	36	37
	6	3410.60	9895.11	62.55	2.365	34	
	16	4149.23	10047.18	63.56	2.334	41	
G-6.5%	2	4496.78	10948.72	64.44	2.376	41	44
	8	4073.19	9851.69	65.19	2.363	41	
	13	4627.14	9308.60	65.48	2.343	50	
M-7.0%	1	4388.18	10449.28	62.79	2.376	42	43
	11	3975.40	9808.22	62.42	2.375	41	
	14	4073.19	8917.53	63.75	2.335	46	
G-7.0%	12	4214.40	8939.29	65.35	2.360	47	45
	14	3084.76	9895.11	65.19	2.360	31	
	15	5148.52	9091.35	65.72	2.344	57	

P1: First Loading
 P2: Second Loading
 M: Marshall Compaction
 G: Gyratory Compaction

ITS Test Results, Second loading @ temperature of +23C - Differences within mix

85/100 Pen AC

MIX Comp-Asp.Content	SAMPLE number	LOAD P2 N	PERCENT max=100%	DIFFERENCE % max=100%	PERCENT min=100%	DIFFERENCE % min=100%
M-5.0%	11	3614.50	86.19	13.81	100.00	0.00
	10	4130.05	98.49	1.51	114.26	14.26
	12	4193.45	100.00	0.00	116.02	16.02
G-5.0%	15	4296.44	93.47	6.53	100.00	0.00
	5	4544.30	98.86	1.14	105.77	5.77
	16	4596.53	100.00	0.00	106.98	6.98
M-5.5%	2	5235.41	88.44	11.56	100.00	0.00
	3	5485.22	92.66	7.34	104.77	4.77
	16	5919.71	100.00	0.00	113.07	13.07
G-5.5%	12	5887.09	87.00	13.00	100.00	0.00
	3	6234.70	92.13	7.87	105.90	5.90
	7	6766.93	100.00	0.00	114.95	14.95
M-6.0%	12	4355.57	94.80	5.20	100.00	0.00
	10	4551.10	99.05	0.95	104.49	4.49
	2	4594.53	100.00	0.00	105.49	5.49
G-6.0%	7	4149.23	75.20	24.80	100.00	0.00
	12	4540.25	82.28	17.72	109.42	9.42
	6	5517.78	100.00	0.00	132.98	32.98
M-6.5%	6	3410.60	82.20	17.80	100.00	0.00
	2	4127.47	99.48	0.52	121.02	21.02
	16	4149.23	100.00	0.00	121.66	21.66
G-6.5%	8	4073.19	88.03	11.97	100.00	0.00
	2	4496.78	97.18	2.82	110.40	10.40
	13	4627.14	100.00	0.00	113.60	13.60
M-7.0%	11	3975.40	90.59	9.41	100.00	0.00
	14	4073.19	92.82	7.18	102.46	2.46
	1	4388.18	100.00	0.00	110.38	10.38
G-7.0%	14	3084.76	59.92	40.08	100.00	0.00
	12	4214.40	81.86	18.14	136.62	36.62
	15	5148.52	100.00	0.00	166.90	66.90

P2: Second Loading

M: Marshall Compaction

G: Gyratory Compaction

ITS Test Results, Second loading @ temperature of +23C

Polymer

MIX Comp-Asp.Content	SAMPLE number	LOAD N	LOAD N	HEIGHT mm	DENSITY gm/cm ³	RATIO P2/P1 %	RATIO MEAN
M-5.0%	2	4127.47	6147.81	63.69	2.287	67	58
	3	3312.86	5735.03	64.19	2.303	58	
	6	2226.68	4757.49	64.29	2.271	47	
G-5.0%	2	1843.27	4757.49	66.22	2.290	39	39
	12	2074.61	5159.37	67.16	2.283	40	
	15	1947.51	5300.58	67.08	2.281	37	
M-5.5%	6	2128.94	5572.11	64.92	2.303	38	38
	7	2172.36	5941.42	64.03	2.295	37	
	12	2357.04	5897.95	63.98	2.311	40	
G-5.5%	2	2150.65	5181.08	66.23	2.306	42	42
	4	2020.29	4952.98	65.98	2.309	41	
	14	2270.10	5365.72	66.30	2.299	42	
M-6.0%	10	2650.27	5354.86	64.14	2.306	49	46
	11	2367.89	5745.88	64.12	2.300	41	
	12	2737.16	5919.71	63.30	2.321	46	
G-6.0%	1	2530.81	5300.58	66.20	2.312	48	48
	4	2063.76	4518.54	66.48	2.298	46	
	7	2519.96	4887.80	66.24	2.309	52	
M-6.5%	4	3215.11	6321.58	63.37	2.323	51	55
	5	3225.97	5604.72	64.96	2.306	58	
	6	3606.14	6419.33	63.37	2.337	56	
G-6.5%	12	2509.06	5854.53	65.92	2.320	43	46
	13	3160.79	6212.08	65.50	2.326	51	
	16	2693.74	5984.84	65.45	2.331	45	
M-7.0%	7	2139.79	4887.80	63.32	2.293	44	40
	11	1721.59	5181.08	63.09	2.316	33	
	16	2324.42	5300.58	62.88	2.327	44	
G-7.0%	8	2465.64	4822.63	65.96	2.316	51	54
	9	2954.40	5018.16	65.85	2.319	59	
	12	2563.38	4996.45	65.77	2.329	51	

P1: First Loading

P2: Second Loading

M: Marshall Compaction

G: Gyratory Compaction

ITS Test Results, Second loading @ temperature of +23C - Differences within mix

Polymer

MIX Comp-Asp.Content	SAMPLE number	LOAD P2 N	PERCENT max=100%	DIFFERENCE % max=100%	PERCENT min=100%	DIFFERENCE % min=100%
M-5.0%	6	2226.68	53.95	46.05	100.00	0.00
	3	3312.86	80.26	19.74	148.78	48.78
	2	4127.47	100.00	0.00	185.36	85.36
G-5.0%	2	1843.27	88.85	11.15	100.00	0.00
	15	1947.51	93.87	6.13	105.66	5.66
	12	2074.61	100.00	0.00	112.55	12.55
M-5.5%	6	2128.94	90.32	9.68	100.00	0.00
	7	2172.36	92.16	7.84	102.04	2.04
	12	2357.04	100.00	0.00	110.71	10.71
G-5.5%	4	2020.29	89.00	11.00	100.00	0.00
	2	2150.65	94.74	5.26	106.45	6.45
	14	2270.10	100.00	0.00	112.37	12.37
M-6.0%	11	2367.89	86.51	13.49	100.00	0.00
	10	2650.27	96.83	3.17	111.93	11.93
	12	2737.16	100.00	0.00	115.59	15.59
G-6.0%	4	2063.76	81.55	18.45	100.00	0.00
	7	2519.96	99.57	0.43	122.11	22.11
	1	2530.81	100.00	0.00	122.63	22.63
M-6.5%	4	3215.11	89.16	10.84	100.00	0.00
	5	3225.97	89.46	10.54	100.34	0.34
	6	3606.14	100.00	0.00	112.16	12.16
G-6.5%	12	2509.06	79.38	20.62	100.00	0.00
	16	2693.74	85.22	14.78	107.36	7.36
	13	3160.79	100.00	0.00	125.98	25.98
M-7.0%	11	1721.59	74.07	25.93	100.00	0.00
	7	2139.79	92.06	7.94	124.29	24.29
	16	2324.42	100.00	0.00	135.02	35.02
G-7.0%	8	2465.64	83.46	16.54	100.00	0.00
	12	2563.38	86.76	13.24	103.96	3.96
	9	2954.40	100.00	0.00	119.82	19.82

P2: Second Loading

M: Marshall Compaction

G: Gyrotory Compaction

MOISTURE SENSITIVITY. ITS Test Results @ temperature of +23C

85/100 Pen AC

MIX Comp-Asp.Content	SAMPLE number	LOAD lb	LOAD N	HEIGHT mm	DENSITY gm cm ³	TENSILE STRENGTH MPa	TENSILE STRENGTH MEAN
M-5.0%	2	1345.21	5984.84	63.76	2.286	0.5882	0.5469
	5	1213.38	5398.33	64.02	2.325	0.5284	
	6	1213.38	5398.33	64.54	2.296	0.5241	
G-5.0%	3	1269.53	5648.14	66.94	2.321	0.5287	0.5174
	4	1199.90	5338.36	67.62	2.312	0.4947	
	8	1270.00	5650.23	66.95	2.294	0.5288	
M-5.5%	1	1181.64	5257.12	60.32	2.333	0.5461	0.5696
	11	1298.88	5778.72	64.21	2.300	0.5640	
	12	1376.96	6126.10	64.10	2.320	0.5988	
G-5.5%	1	1604.00	7136.20	66.08	2.318	0.6767	0.7144
	2	1721.19	7657.57	66.65	2.315	0.7199	
	14	1767.58	7863.96	66.00	2.327	0.7466	
M-6.0%	3	1616.21	7190.52	64.04	2.351	0.7036	0.7036
	6	1635.74	7277.41	62.40	2.339	0.7308	
	8	1540.43	6853.37	63.49	2.312	0.6764	
G-6.0%	1	1933.11	8600.41	65.85	2.335	0.8184	0.8175
	11	1860.35	8276.70	66.07	2.326	0.7849	
	13	1994.63	8874.11	65.49	2.350	0.8491	
M-6.5%	1	1906.74	8483.09	62.82	2.362	0.8461	0.8217
	3	1916.50	8526.51	62.65	2.366	0.8528	
	8	1750.49	7787.93	63.69	2.337	0.7663	
G-6.5%	9	1872.56	8331.02	65.55	2.346	0.7964	0.8013
	14	1940.92	8635.15	65.19	2.370	0.8301	
	15	1816.41	8081.21	65.13	2.367	0.7775	
M-7.0%	4	1738.92	7736.46	62.80	2.377	0.7719	0.7390
	12	1602.97	7131.61	63.45	2.355	0.7043	
	15	1687.01	7505.51	63.50	2.355	0.7406	
G-7.0%	7	1927.30	8574.56	64.37	2.374	0.8347	0.7945
	10	1835.94	8168.10	65.23	2.361	0.7847	
	11	1800.72	8011.40	65.68	2.341	0.7643	

M: Marshall Compaction

G: Gyrotory Compaction

MOISTURE SENSITIVITY, ITS Test Results @ temperature of +23C - Differences within mix

85/100 Pen AC

MIX	SAMPLE	TENSILE	PERCENT	DIFFERENCE	PERCENT	DIFFERENCE
Comp-Asp.Content	number	STRENGTH MPa	max=100%	% max=100%	min=100%	% min=100%
M-5.0%	6	0.5241	89.12	10.88	100.00	0.00
	5	0.5284	89.83	10.17	100.80	0.80
	2	0.5882	100.00	0.00	112.21	12.21
G-5.0%	4	0.4947	93.55	6.45	100.00	0.00
	3	0.5287	99.98	0.02	106.87	6.87
	8	0.5288	100.00	0.00	106.89	6.89
M-5.5%	1	0.5461	91.19	8.81	100.00	0.00
	11	0.5640	94.18	5.82	103.27	3.27
	12	0.5988	100.00	0.00	109.66	9.66
G-5.5%	1	0.6767	90.63	9.37	100.00	0.00
	2	0.7199	96.42	3.58	106.39	6.39
	14	0.7466	100.00	0.00	110.34	10.34
M-6.0%	8	0.6764	92.56	7.44	100.00	0.00
	3	0.7036	96.28	3.72	104.02	4.02
	6	0.7308	100.00	0.00	108.04	8.04
G-6.0%	11	0.7849	92.45	7.55	100.00	0.00
	1	0.8184	96.39	3.61	104.26	4.26
	13	0.8491	100.00	0.00	108.17	8.17
M-6.5%	8	0.7663	89.85	10.15	100.00	0.00
	1	0.8461	99.22	0.78	110.43	10.43
	3	0.8528	100.00	0.00	111.29	11.29
G-6.5%	15	0.7775	93.67	6.33	100.00	0.00
	9	0.7964	95.94	4.06	102.42	2.42
	14	0.8301	100.00	0.00	106.76	6.76
M-7.0%	12	0.7043	91.24	8.76	100.00	0.00
	15	0.7406	95.95	4.05	105.16	5.16
	4	0.7719	100.00	0.00	109.60	9.60
G-7.0%	11	0.7643	91.57	8.43	100.00	0.00
	10	0.7847	94.01	5.99	102.67	2.67
	7	0.8347	100.00	0.00	109.21	9.21

M: Marshall Compaction

G: Gyratory Compaction

MOISTURE SENSITIVITY. ITS Test Results @ temperature of +23C

Polymer

MIX Comp-Asp Content	SAMPLE number	LOAD lb	LOAD N	HEIGHT mm	DENSITY gm cm ³	TENSILE STRENGTH MPa	TENSILE STRENGTH MEAN
M-5.0%	7	929.80	4136.68	63.80	2.300	0.4063	0.3798
	9	845.57	3761.94	64.42	2.272	0.3659	
	14	851.07	3786.41	64.59	2.289	0.3673	
G-5.0%	4	1035.16	4605.43	67.12	2.292	0.4299	0.4231
	10	1054.69	4692.32	66.96	2.285	0.4391	
	13	962.62	4282.70	67.03	2.278	0.4004	
M-5.5%	1	1074.22	4779.20	64.10	2.319	0.4672	0.4480
	3	1040.04	4627.14	64.57	2.301	0.4491	
	15	976.56	4344.72	63.64	2.292	0.4278	
G-5.5%	5	1093.76	4866.14	66.34	2.310	0.4596	0.4368
	12	1030.27	4583.67	66.49	2.305	0.4320	
	13	996.09	4431.60	66.32	2.299	0.4187	
M-6.0%	1	1163.48	5176.32	63.85	2.308	0.5080	0.5037
	5	1157.28	5148.74	64.22	2.292	0.5024	
	13	1147.46	5105.05	63.90	2.323	0.5006	
G-6.0%	8	1079.10	4800.92	66.15	2.315	0.4548	0.4559
	12	1083.98	4822.63	66.47	2.293	0.4546	
	15	1088.87	4844.38	66.23	2.303	0.4583	
M-6.5%	7	1254.88	5582.96	63.30	2.325	0.5527	0.5553
	9	1264.65	5626.43	64.08	2.304	0.5502	
	11	1279.30	5691.61	63.33	2.337	0.5631	
G-6.5%	4	1308.59	5821.92	65.83	2.332	0.5542	0.5373
	6	1235.35	5496.07	65.82	2.323	0.5232	
	11	1262.21	5615.57	65.84	2.317	0.5344	
M-7.0%	3	1138.63	5065.76	63.16	2.306	0.5026	0.5218
	8	1265.21	5628.92	63.57	2.322	0.5548	
	12	1154.79	5137.66	63.39	2.314	0.5079	
G-7.0%	4	1220.70	5430.89	65.63	2.328	0.5185	0.5088
	11	1151.31	5122.18	65.98	2.315	0.4864	
	14	1228.03	5463.51	65.65	2.320	0.5215	

M: Marshall Compaction

G: Gyratory Compaction

MOISTURE SENSITIVITY, ITS Test Results @ temperature of +23C - Differences within mix

Polymer

MIX Comp-Asp.Content	SAMPLE number	TENSILE STRENGTH MPa	PERCENT max=100%	DIFFERENCE % max=100%	PERCENT min=100%	DIFFERENCE % min=100%
M-5%	9	0.3659	90.06	9.94	100.00	0.00
	14	0.3673	90.41	9.59	100.39	0.39
	7	0.4063	100.00	0.00	111.04	11.04
G-5%	13	0.4004	91.19	8.81	100.00	0.00
	4	0.4299	97.91	2.09	107.38	7.38
	10	0.4391	100.00	0.00	109.66	9.66
M-5.5%	15	0.4278	91.57	8.43	100.00	0.00
	3	0.4491	96.12	3.88	104.97	4.97
	1	0.4672	100.00	0.00	109.21	9.21
G-5.5%	13	0.4187	91.10	8.90	100.00	0.00
	12	0.4320	93.98	6.02	103.17	3.17
	5	0.4596	100.00	0.00	109.77	9.77
M-6%	13	0.5006	98.55	1.45	100.00	0.00
	5	0.5024	98.90	1.10	100.35	0.35
	1	0.5080	100.00	0.00	101.47	1.47
G-6%	12	0.4546	99.19	0.81	100.00	0.00
	8	0.4548	99.22	0.78	100.03	0.03
	15	0.4773	100.00	0.00	100.82	0.82
M-6.5%	9	0.5502	97.70	2.30	100.00	0.00
	7	0.5527	98.15	1.85	100.46	0.46
	11	0.5631	100.00	0.00	102.36	2.36
G-6.5%	6	0.5232	94.42	5.58	100.00	0.00
	11	0.5344	96.44	3.56	102.14	2.14
	4	0.5542	100.00	0.00	105.91	5.91
M-7%	3	0.5026	90.59	9.41	100.00	0.00
	12	0.5079	91.54	8.46	101.05	1.05
	8	0.5548	100.00	0.00	110.39	10.39
G-7%	11	0.4864	93.28	6.72	100.00	0.00
	4	0.5185	99.44	0.56	106.61	6.61
	14	0.5215	100.00	0.00	107.21	7.21

M: Marshall Compaction

G: Gyratory Compaction

MOISTURE SENSITIVITY Test Results @ temperature of 23C

85/100 Pen AC

MIX Comp-Asp.Content	SAMPLE number	HEIGHT mm	DENSITY gm cm ³	ITS Submerged MPa	ITS Dry MPa	RATIO Sub/Dry %	RATIO MEAN %
M-5.0%	2	63.76	2.286	0.5882	0.9871	60	59
	5	64.02	2.325	0.5284	0.7987	66	
	6	64.54	2.296	0.5241	1.0038	52	
G-5.0%	3	66.94	2.321	0.5287	0.9400	56	59
	4	67.62	2.312	0.4947	0.8763	56	
	8	66.95	2.294	0.5288	0.8125	65	
M-5.5%	1	60.32	2.333	0.5461	1.1893	46	48
	11	64.21	2.300	0.5640	1.1957	47	
	12	64.10	2.320	0.5988	1.1358	53	
G-5.5%	1	66.08	2.318	0.6767	1.0699	63	65
	2	66.65	2.315	0.7199	1.1307	64	
	14	66.00	2.327	0.7466	1.0719	70	
M-6.0%	3	64.04	2.351	0.7036	1.2211	58	62
	6	62.40	2.339	0.7308	1.0663	69	
	8	63.49	2.312	0.6764	1.1460	59	
G-6.0%	1	65.85	2.335	0.8184	1.1051	74	78
	11	66.07	2.326	0.7849	1.0254	77	
	13	65.49	2.350	0.8491	1.0175	83	
M-6.5%	1	62.82	2.362	0.8461	1.1352	75	79
	3	62.65	2.366	0.8528	0.9912	86	
	8	63.69	2.337	0.7663	0.9905	77	
G-6.5%	9	65.55	2.346	0.7964	1.0646	75	83
	14	65.19	2.370	0.8301	0.9469	88	
	15	65.13	2.367	0.7775	0.8908	87	
M-7.0%	4	62.80	2.377	0.7719	1.0428	74	76
	12	63.45	2.355	0.7043	0.9846	72	
	15	63.50	2.355	0.7406	0.8765	84	
G-7.0%	7	64.37	2.374	0.8347	0.8571	97	89
	10	65.23	2.361	0.7847	0.9511	83	
	11	65.68	2.341	0.7643	0.8668	88	

M: Marshall Compaction

G: Gyratory Compaction

MOISTURE SENSITIVITY Test Results @ temperature of 23C

Polymer

MIX Comp-Asp Content	SAMPLE number	HEIGHT mm	DENSITY gm cm ³	ITS Submerged MPa	ITS Dry MPa	RATIO Sub/Dry %	RATIO MEAN %
M-5.0%	7	63.80	2.300	0.4063	0.6048	67	70
	9	64.42	2.272	0.3659	0.5598	65	
	14	64.59	2.289	0.3673	0.4637	79	
G-5.0%	4	67.12	2.292	0.4299	0.4502	96	88
	10	66.96	2.285	0.4391	0.4814	91	
	13	67.03	2.278	0.4004	0.4951	81	
M-5.5%	1	64.10	2.319	0.4672	0.5378	87	79
	3	64.57	2.301	0.4491	0.5814	77	
	15	63.64	2.292	0.4278	0.5776	74	
G-5.5%	5	66.34	2.310	0.4596	0.4902	94	89
	12	66.49	2.305	0.4320	0.4704	92	
	13	66.32	2.299	0.4187	0.5071	83	
M-6.0%	1	63.85	2.308	0.5080	0.5231	97	91
	5	64.22	2.292	0.5024	0.5615	89	
	13	63.90	2.323	0.5006	0.5860	85	
G-6.0%	8	66.15	2.315	0.4548	0.5017	91	99
	12	66.47	2.293	0.4546	0.4259	107	
	15	66.23	2.303	0.4583	0.4624	99	
M-6.5%	7	63.30	2.325	0.5527	0.6251	88	93
	9	64.08	2.304	0.5502	0.5406	102	
	11	63.33	2.337	0.5631	0.6347	89	
G-6.5%	4	65.83	2.332	0.5542	0.5565	100	94
	6	65.82	2.323	0.5232	0.5933	88	
	11	65.84	2.317	0.5344	0.5730	93	
M-7.0%	3	63.16	2.306	0.5026	0.4837	104	103
	8	63.57	2.322	0.5548	0.5146	108	
	12	63.39	2.314	0.5079	0.5282	96	
G-7.0%	4	65.63	2.328	0.5185	0.4581	113	108
	11	65.98	2.315	0.4864	0.4775	102	
	14	65.65	2.320	0.5215	0.4760	110	

M: Marshall Compaction

G: Gyratory Compaction

MOISTURE SENSITIVITY Test Results, Second loading**85/100 Pen AC**

MIX Comp-Asp.Content	SAMPLE number	Load P2 N	Load P1 N	HEIGHT mm	DENSITY gm/cm ³	RATIO P2/P1 %	RATIO MEAN %
M-5.0%	2	3388.89	5984.84	63.76	2.286	57	59
	5	3336.22	5398.33	64.02	2.325	62	
	6	3171.65	5398.33	64.54	2.296	59	
G-5.0%	3	3584.38	5648.14	66.94	2.321	63	66
	4	3453.63	5338.36	67.62	2.312	65	
	8	3964.55	5650.23	66.95	2.294	70	
M-5.5%	1	3149.94	5257.12	60.32	2.333	60	61
	11	3627.85	5778.72	64.21	2.300	63	
	12	3700.50	6126.10	64.10	2.320	60	
G-5.5%	1	4898.66	7136.20	66.08	2.318	69	64
	2	4876.95	7657.57	66.65	2.315	64	
	14	4768.35	7863.96	66.00	2.327	61	
M-6.0%	3	3888.51	7190.52	64.04	2.351	54	53
	6	3792.15	7277.41	62.40	2.339	52	
	8	3595.28	6853.37	63.49	2.312	52	
G-6.0%	1	4434.18	8600.41	65.85	2.335	52	54
	11	4388.18	8276.70	66.07	2.326	53	
	13	5029.02	8874.11	65.49	2.350	57	
M-6.5%	1	5463.51	8483.09	62.82	2.362	64	66
	3	5800.21	8526.51	62.65	2.366	68	
	8	5094.19	7787.93	63.69	2.337	65	
G-6.5%	9	5658.99	8331.02	65.55	2.346	68	64
	14	5430.89	8635.15	65.19	2.370	63	
	15	4952.98	8081.21	65.13	2.367	61	
M-7.0%	4	5278.83	7736.46	62.80	2.377	68	65
	12	4551.10	7131.61	63.45	2.355	64	
	15	4768.35	7505.51	63.50	2.355	64	
G-7.0%	7	5680.75	8574.56	64.37	2.374	66	65
	10	5300.58	8168.10	65.23	2.361	65	
	11	5050.73	8011.40	65.68	2.341	63	

P1: First Loading

P2: Second Loading

M: Marshall Compaction

G: Gyratory Compaction

MOISTURE SENSITIVITY Test Results, Second loading @ temperature of +23C**85/100 Pen AC - Differences within mix**

MIX Comp-Asp.Content	SAMPLE number	LOAD P2 N	PERCENT max=100%	DIFFERENCE %	PERCENT min=100%	DIFFERENCE %
M-5.0%	6	3171.65	93.59	6.41	100.00	0.00
	5	3336.22	98.45	1.55	105.19	5.19
	2	3388.89	100.00	0.00	106.85	6.85
G-5.0%	4	3453.63	87.11	12.89	100.00	0.00
	3	3584.38	90.41	9.59	103.79	3.79
	8	3964.55	100.00	0.00	114.79	14.79
M-5.5%	1	3149.94	85.12	14.88	100.00	0.00
	11	3627.85	98.04	1.96	115.17	15.17
	12	3700.50	100.00	0.00	117.48	17.48
G-5.5%	14	4768.35	97.34	2.66	100.00	0.00
	2	4876.95	99.56	0.44	102.28	2.28
	1	4898.66	100.00	0.00	102.73	2.73
M-6.0%	8	3595.28	92.46	7.54	100.00	0.00
	6	3792.15	97.52	2.48	105.48	5.48
	3	3888.51	100.00	0.00	108.16	8.16
G-6.0%	11	4388.18	87.26	12.74	100.00	0.00
	1	4434.18	88.17	11.83	101.05	1.05
	13	5029.02	100.00	0.00	114.60	14.60
M-6.5%	8	5094.19	87.83	12.17	100.00	0.00
	1	5463.51	94.20	5.80	107.25	7.25
	3	5800.21	100.00	0.00	113.86	13.86
G-6.5%	15	4952.98	87.52	12.48	100.00	0.00
	14	5430.89	95.97	4.03	109.65	9.65
	9	5658.99	100.00	0.00	114.25	14.25
M-7.0%	12	4551.10	86.21	13.79	100.00	0.00
	15	4768.35	90.33	9.67	104.77	4.77
	4	5278.83	100.00	0.00	115.99	15.99
G-7.0%	11	5050.73	88.91	11.09	100.00	0.00
	10	5300.58	93.31	6.69	104.95	4.95
	7	5680.75	100.00	0.00	112.47	12.47

P2: Second Loading

M: Marshall compaction

G: Gyratory compaction

MOISTURE SENSITIVITY Test Results, Second loading**Polymer**

MIX Comp-Asp.Content	SAMPLE number	Load P2 N	Load P1 N	HEIGHT mm	DENSITY gm/cm ³	RATIO P2/P1 %	RATIO MEAN %
M-5.0%	7	1025.36	4136.68	63.80	2.300	25	26
	9	878.50	3761.94	64.42	2.272	23	
	14	1118.75	3786.41	64.59	2.289	30	
G-5.0%	4	1690.40	4605.43	67.12	2.292	37	44
	10	2176.72	4692.32	66.96	2.285	46	
	13	2031.15	4282.70	67.03	2.278	47	
M-5.5%	1	1326.02	4779.20	64.10	2.319	28	25
	3	1214.35	4627.14	64.57	2.301	26	
	15	866.75	4344.72	63.64	2.292	20	
G-5.5%	5	2333.10	4866.14	66.34	2.310	48	53
	12	2294.04	4583.67	66.49	2.305	50	
	13	2674.16	4431.00	66.32	2.299	60	
M-6.0%	1	3345.43	5176.32	63.85	2.308	65	61
	5	3073.90	5148.74	64.22	2.292	60	
	13	2997.87	5105.05	63.90	2.323	59	
G-6.0%	8	3106.47	4800.92	66.15	2.315	65	62
	12	2737.16	4822.63	66.47	2.293	57	
	15	3149.94	4844.38	66.23	2.303	65	
M-6.5%	7	3573.53	5582.96	63.30	2.325	64	61
	9	3084.76	5626.43	64.08	2.304	55	
	11	3595.28	5691.61	63.33	2.337	63	
G-6.5%	4	3356.28	5821.92	65.83	2.332	58	63
	6	3736.45	5496.07	65.82	2.323	68	
	11	3638.70	5615.57	65.84	2.317	65	
M-7.0%	3	3399.75	5065.76	63.16	2.306	67	65
	8	3551.81	5628.92	63.57	2.322	63	
	12	3323.71	5137.66	63.39	2.314	65	
G-7.0%	4	3725.59	5430.89	65.63	2.328	69	68
	11	3399.75	5122.18	65.98	2.315	66	
	14	3779.91	5463.51	65.65	2.320	69	

P1: First Loading

P2: Second Loading

M: Marshall Compaction

G: Gyratory Compaction

MOISTURE SENSITIVITY Test Results, Second loading @ temperature of +23C**Polymer - Differences within mix**

MIX Comp-Asp.Content	SAMPLE number	LOAD P2 N	PERCENT max=100%	DIFFERENCE %max=100%	PERCENT min=100%	DIFFERENCE %min=100%
M-5.0%	9	878.50	78.53	21.47	100.00	0.00
	7	1025.36	91.65	8.35	116.72	16.72
	14	1118.75	100.00	0.00	127.35	27.35
G-5.0%	4	1690.40	77.66	22.34	100.00	0.00
	13	2031.15	93.31	6.69	120.16	20.16
	10	2176.72	100.00	0.00	128.77	28.77
M-5.5%	15	866.75	65.36	34.64	100.00	0.00
	3	1214.35	91.58	8.42	140.10	40.10
	1	1326.02	100.00	0.00	152.99	52.99
G-5.5%	12	2294.04	85.79	14.21	100.00	0.00
	5	2333.10	87.25	12.75	101.70	1.70
	13	2674.16	100.00	0.00	116.57	16.57
M-6.0%	13	2997.87	89.61	10.39	100.00	0.00
	5	3073.90	91.88	8.12	102.54	2.54
	1	3345.43	100.00	0.00	111.59	11.59
G-6.0%	12	2737.16	86.90	13.10	100.00	0.00
	8	3106.47	98.62	1.38	113.49	13.49
	15	3149.94	100.00	0.00	115.08	15.08
M-6.5%	9	3084.76	85.80	14.20	100.00	0.00
	7	3573.53	99.39	0.61	115.84	15.84
	11	3595.28	100.00	0.00	116.55	16.55
G-6.5%	4	3356.28	89.83	10.17	100.00	0.00
	11	3638.70	97.38	2.62	108.41	8.41
	6	3736.45	100.00	0.00	111.33	11.33
M-7.0%	12	3323.71	93.58	6.42	100.00	0.00
	3	3399.75	95.72	4.28	102.29	2.29
	8	3551.81	100.00	0.00	106.86	6.86
G-7.0%	11	3399.75	89.94	10.06	100.00	0.00
	4	3725.59	98.56	1.44	109.58	9.58
	14	3779.91	100.00	0.00	111.18	11.18

P2: Second Loading

M: Marshall compaction

G: Gyratory compaction

COMPRESSIVE FATIGUE Test Results @ temperature of +40C

85/100 Pen AC

MIX Comp-Asp.Content	SAMPLE number	HEIGHT mm	DENSITY gm/cm ³	VERTICAL DISPLACEMENT mm	VERTICAL DISPLACEMENT %	CYCLES quantity	CYCLES MEAN
M-5.0%	4	63.56	2.312	4.694	7.39	297	284
	9	64.20	2.304	2.855	4.45	313	
	19	63.94	2.293	4.262	6.67	242	
G-5.0%	6	67.69	2.305	4.681	6.92	180	185
	7	67.31	2.305	5.436	8.08	173	
	13	66.72	2.298	4.437	6.65	201	
M-5.5%	6	62.14	2.323	5.418	8.72	240	258
	13	64.80	2.313	4.953	7.64	275	
	14	62.29	2.315	3.980	6.39	260	
G-5.5%	6	65.80	2.342	6.182	9.40	252	190
	10	66.70	2.307	5.207	7.81	162	
	11	66.72	2.317	4.120	6.18	157	
M-6.0%	5	60.86	2.341	5.745	9.44	360	341
	14	63.18	2.341	5.773	9.14	365	
	15	64.40	2.323	5.926	9.20	297	
G-6.0%	8	65.37	2.351	5.646	8.64	305	273
	15	66.14	2.325	5.583	8.44	240	
	16	63.57	2.334	8.070	12.69	990	
M-6.5%	11	62.62	2.377	5.857	9.35	437	373
	12	63.32	2.343	6.251	9.87	342	
	13	63.09	2.350	5.375	8.52	339	
G-6.5%	4	65.25	2.365	4.854	7.44	362	368
	11	64.73	2.374	6.312	9.75	387	
	16	63.39	2.345	5.527	8.72	355	
M-7.0%	2	62.31	2.380	8.458	13.57	542	388
	3	62.88	2.369	7.023	11.17	303	
	8	63.88	2.335	7.607	11.91	320	
G-7.0%	1	64.64	2.375	7.043	10.90	339	301
	5	64.98	2.349	6.172	9.50	255	
	6	65.86	2.347	5.860	8.90	310	

M: Marshall Compaction

G: Gyratory Compaction

COMPRESSIVE FATIGUE Test Results @ temperature of +40C - Differences within Mix

85/100 Pen AC

MIX	SAMPLE	CYCLES	PERCENT	DIFFERENCE	PERCENT	DIFFERENCE
Comp-Asp.Content	number	number	max=100%	% max=100%	min=100%	% min=100%
M-5.0%	19	242	77.32	22.68	100.00	0.00
	4	297	94.89	5.11	122.73	22.73
	9	313	100.00	0.00	129.34	29.34
G-5.0%	7	173	86.07	13.93	100.00	0.00
	6	180	89.55	10.45	104.05	4.05
	13	201	100.00	0.00	116.18	16.18
M-5.5%	6	240	87.27	12.73	100.00	0.00
	13	260	94.55	5.45	108.33	8.33
	14	275	100.00	0.00	114.58	14.58
G-5.5%	11	157	62.30	37.70	100.00	0.00
	10	162	64.29	35.71	103.18	3.18
	6	252	100.00	0.00	160.51	60.51
M-6.0%	15	297	81.37	18.63	100.00	0.00
	5	360	98.63	1.37	121.21	21.21
	14	365	100.00	0.00	122.90	22.90
G-6.0%	8	305	30.81	69.19	100.00	0.00
	15	240	24.24	75.76	78.69	-21.31
	16	990	100.00	0.00	324.59	224.59
M-6.5%	13	339	77.57	22.43	100.00	0.00
	12	342	78.26	21.74	100.88	0.88
	11	437	100.00	0.00	128.91	28.91
G-6.5%	16	355	91.73	8.27	100.00	0.00
	4	362	93.54	6.46	101.97	1.97
	11	387	100.00	0.00	109.01	9.01
M-7.0%	3	303	55.90	44.10	100.00	0.00
	8	320	59.04	40.96	105.61	5.61
	2	542	100.00	0.00	178.88	78.88
G-7.0%	5	255	75.22	24.78	100.00	0.00
	6	310	91.45	8.55	121.57	21.57
	1	339	100.00	0.00	132.94	32.94

M: Marshall Compaction

G: Gyrotory Compaction

COMPRESSIVE FATIGUE Test Results @ temperature of +40C**Polymer**

MIX Comp-Asp.Content	SAMPLE number	HEIGHT mm	DENSITY gm cm ³	VERTICAL DISPLACEMENT mm	VERTICAL DISPLACEMENT %	CYCLES quantity	CYCLES MEAN
M-5.0%	4	64.96	2.278	5.212	8.02	302	299
	5	63.80	2.305	5.372	8.42	273	
	13	62.44	2.276	4.638	7.43	322	
G-5.0%	5	67.05	2.288	5.395	8.05	195	216
	9	66.81	2.287	3.157	4.73	229	
	16	67.27	2.281	5.578	8.29	225	
M-5.5%	2	62.46	2.307	3.795	6.08	218	314
	11	64.29	2.297	5.159	8.02	390	
	14	64.31	2.299	4.503	7.00	335	
G-5.5%	3	66.64	2.303	4.989	7.49	295	329
	7	66.24	2.307	4.470	6.75	359	
	9	66.20	2.303	5.527	8.35	332	
M-6.0%	7	63.35	2.304	5.598	8.84	444	471
	8	64.52	2.313	4.564	7.07	547	
	14	63.35	2.305	6.787	10.71	421	
G-6.0%	5	66.15	2.314	5.314	8.03	235	250
	9	66.17	2.302	5.575	8.43	257	
	13	66.23	2.297	4.732	7.15	257	
M-6.5%	1	63.37	2.317	4.176	6.59	550	558
	3	63.55	2.318	6.698	10.54	455	
	13	63.46	2.331	4.882	7.69	670	
G-6.5%	3	65.83	2.323	6.220	9.45	345	391
	7	65.76	2.326	5.954	9.05	458	
	15	65.51	2.322	6.007	9.17	370	
M-7.0%	5	63.67	2.302	5.403	8.49	377	459
	6	63.53	2.330	4.925	7.75	543	
	15	63.08	2.311	5.321	8.44	457	
G-7.0%	3	65.55	2.318	5.408	8.25	465	393
	10	65.93	2.323	4.890	7.42	435	
	13	65.94	2.318	4.869	7.38	280	

M: Marshall Compaction

G: Gyratory Compaction

COMPRESSIVE FATIGUE Test Results @ temperature of +40C - Differences within Mix

Polymer

MIX	SAMPLE	CYCLES	PERCENT	DIFFERENCE	PERCENT	DIFFERENCE
Comp-Asp.Content	number	number	max=100%	% max=100%	min=100%	% min=100%
M-5%	5	273	84.78	15.22	100.00	0.00
	4	302	93.79	6.21	110.62	10.62
	13	322	100.00	0.00	117.95	17.95
G-5%	5	195	85.15	14.85	100.00	0.00
	16	225	98.25	1.75	115.38	15.38
	9	229	100.00	0.00	117.44	17.44
M-5.5%	2	218	55.90	44.10	100.00	0.00
	14	335	85.90	14.10	153.67	53.67
	11	390	100.00	0.00	178.90	78.90
G-5.5%	3	295	82.17	17.83	100.00	0.00
	9	332	92.48	7.52	112.54	12.54
	7	359	100.00	0.00	121.69	21.69
M-6%	14	421	76.97	23.03	100.00	0.00
	7	444	81.17	18.83	105.46	5.46
	8	547	100.00	0.00	129.93	29.93
G-6%	5	235	91.44	8.56	100.00	0.00
	9	257	100.00	0.00	109.36	9.36
	13	257	100.00	0.00	109.36	9.36
M-6.5%	3	455	67.91	32.09	100.00	0.00
	1	550	82.09	17.91	120.88	20.88
	13	670	100.00	0.00	147.25	47.25
G-6.5%	3	345	75.33	24.67	100.00	0.00
	15	370	80.79	19.21	107.25	7.25
	7	458	100.00	0.00	132.75	32.75
M-7%	5	377	69.43	30.57	100.00	0.00
	15	457	84.16	15.84	121.22	21.22
	6	543	100.00	0.00	144.03	44.03
G-7%	13	280	60.22	39.78	100.00	0.00
	10	435	93.55	6.45	155.36	55.36
	3	465	100.00	0.00	166.07	66.07

M: Marshall Compaction

G: Gyrotory Compaction

ITS Test Results @ temperature of -35C

85/100 Pen AC

MIX Comp-Asp.Content	SAMPLE number	LOAD lb	LOAD N	HEIGHT mm	DENSITY gm/cm ³	TENSILE STRENGTH MPa	TENSILE STRENGTH MEAN
M-5.0%	8	6640.63	29544.16	64.85	2.294	2.8546	2.6480
	14	5771.48	25677.31	64.79	2.289	2.4833	
	16	6015.63	26763.54	64.35	2.320	2.6060	
G-5.0%	1	6464.84	28762.07	67.06	2.299	2.6875	2.7328
	2	6904.30	30717.23	66.68	2.306	2.8865	
	10	6333.01	28175.56	67.27	2.298	2.6244	
M-5.5%	4	5366.21	23874.27	63.54	2.325	2.3543	2.3853
	7	5830.08	25938.03	64.12	2.307	2.5347	
	9	5062.50	22523.06	62.26	2.315	2.2668	
G-5.5%	4	5312.50	23635.31	65.87	2.334	2.2483	2.1582
	8	5278.32	23483.25	66.59	2.307	2.2097	
	9	4804.69	21376.07	66.42	2.322	2.0166	
M-6.0%	1	6357.42	28284.16	63.62	2.346	2.7857	2.6517
	4	5639.65	25090.80	62.37	2.341	2.5207	
	7	5991.21	26654.89	63.06	2.322	2.6486	
G-6.0%	2	7358.40	32737.52	65.33	2.332	3.1399	2.6944
	5	5161.13	22961.87	66.15	2.325	2.1750	
	10	6474.61	28805.54	65.20	2.357	2.7683	
M-6.5%	5	5722.66	25460.11	63.35	2.358	2.5183	2.5846
	7	6064.45	26980.74	63.87	2.337	2.6469	
	14	5854.49	26046.63	63.05	2.372	2.5885	
G-6.5%	7	5454.10	24265.29	64.62	2.377	2.3529	2.7135
	10	7021.48	31238.56	65.49	2.360	2.9888	
	12	6650.39	29587.59	66.24	2.342	2.7988	
M-7.0%	5	7548.83	33584.74	63.08	2.356	3.3361	3.2792
	6	6928.71	30825.83	62.37	2.379	3.0969	
	9	7729.49	34388.50	63.29	2.350	3.4046	
G-7.0%	2	6889.65	30652.05	65.35	2.345	2.9390	3.1645
	8	7739.26	34431.97	65.43	2.349	3.2974	
	9	7524.41	33476.10	64.40	2.376	3.2571	

M: Marshall Compaction

G: Gyratory Compaction

ITS Test Results @ temperature of -35C - Differences within Mix

85/100 Pen AC

MIX Comp-Asp.Content	SAMPLE number	TENSILE STRENGTH MPa	PERCENT max=100%	DIFFERENCE % max=100%	PERCENT min=100%	DIFFERENCE % min=100%
M-5.0%	14	2.4833	86.99	13.01	100.00	0.00
	16	2.6060	91.29	8.71	104.94	4.94
	8	2.8546	100.00	0.00	114.95	14.95
G-5.0%	10	2.6244	90.92	9.08	100.00	0.00
	1	2.6875	93.10	6.90	102.40	2.40
	2	2.8865	100.00	0.00	109.99	9.99
M-5.5%	9	2.2668	89.43	10.57	100.00	0.00
	4	2.3543	92.88	7.12	103.86	3.86
	7	2.5347	100.00	0.00	111.82	11.82
G-5.5%	9	2.0166	89.69	10.31	100.00	0.00
	8	2.2097	98.28	1.72	109.58	9.58
	4	2.2483	100.00	0.00	111.49	11.49
M-6.0%	4	2.5207	90.49	9.51	100.00	0.00
	~	2.6486	95.08	4.92	105.07	5.07
	1	2.7857	100.00	0.00	110.51	10.51
G-6.0%	5	2.1750	69.27	30.73	100.00	0.00
	10	2.7683	88.16	11.84	127.28	27.28
	2	3.1399	100.00	0.00	144.36	44.36
M-6.5%	5	2.5183	95.14	4.86	100.00	0.00
	14	2.5885	97.79	2.21	102.79	2.79
	7	2.6469	100.00	0.00	105.11	5.11
G-6.5%	7	2.3529	78.72	21.28	100.00	0.00
	12	2.7988	93.64	6.36	118.95	18.95
	10	2.9888	100.00	0.00	127.03	27.03
M-7.0%	6	3.0969	90.96	9.04	100.00	0.00
	5	3.3361	97.99	2.01	107.72	7.72
	9	3.4046	100.00	0.00	109.94	9.94
G-7.0%	2	2.9390	89.13	10.87	100.00	0.00
	9	3.2571	98.78	1.22	110.82	10.82
	8	3.2974	100.00	0.00	112.19	12.19

M: Marshall Compaction

G: Gyratory Compaction

ITS Test Results @ temperature of -35C

Polymer

MIX Comp-Asp.Content	SAMPLE number	LOAD lb	LOAD N	HEIGHT mm	DENSITY gm cm ³	TENSILE STRENGTH MPa	TENSILE STRENGTH MEAN
M-5%	8	8706.05	38733.22	63.66	2.270	3.8124	3.5583
	11	8369.14	37234.30	64.02	2.304	3.6443	
	15	7280.00	32388.72	63.06	2.284	3.2183	
G-5%	1	8955.08	39841.15	66.45	2.288	3.7568	3.7636
	11	9526.37	42382.82	67.21	2.281	3.9513	
	14	8623.05	38363.95	67.10	2.286	3.5825	
M-5.5%	5	10589.00	47110.46	63.96	2.307	4.6153	4.1232
	13	8178.71	36387.08	64.49	2.296	3.5354	
	16	9731.45	43295.22	64.30	2.300	4.2191	
G-5.5%	6	10712.00	47657.69	66.22	2.307	4.5095	4.5416
	15	10775.00	47937.98	66.27	2.308	4.5326	
	16	10889.00	48445.16	66.24	2.299	4.5826	
M-6%	2	10562.00	46990.34	63.45	2.310	4.6405	4.2648
	4	8134.77	36191.59	64.91	2.301	3.4937	
	6	10712.00	47657.69	64.08	2.314	4.6601	
G-6%	6	10814.00	48111.49	66.27	2.314	4.5490	4.4431
	14	9960.94	44316.22	66.21	2.294	4.1940	
	16	10901.00	48498.55	66.26	2.303	4.5863	
M-6.5%	10	10432.00	46411.97	63.44	2.332	4.5841	4.5179
	12	10322.00	45922.58	63.38	2.310	4.5400	
	16	9970.70	44359.64	62.75	2.320	4.4296	
G-6.5%	8	10567.00	47012.58	65.81	2.320	4.4762	4.4545
	10	10982.00	48858.92	65.50	2.326	4.6740	
	14	9887.70	43990.38	65.42	2.327	4.2134	
M-7%	4	10774.00	47933.53	63.29	2.332	4.7456	4.4292
	9	9438.48	41991.80	63.50	2.312	4.1436	
	10	10041.00	44672.41	63.64	2.299	4.3984	
G-7%	1	10231.00	45517.72	65.82	2.316	4.3332	4.4989
	5	10829.00	48178.22	65.70	2.326	4.5949	
	6	10772.00	47924.63	65.73	2.322	4.5686	

M: Marshall Compaction

G: Gyratory Compaction

ITS Test Results @ temperature of -35C - Differences within Mix

Polymer

MIX Comp-Asp.Content	SAMPLE number	TENSILE STRENGTH MPa	PERCENT max=100%	DIFFERENCE % max=100%	PERCENT min=100%	DIFFERENCE % min=100%
M-5.0%	15	3.2183	84.42	15.58	100.00	0.00
	11	3.6443	95.59	4.41	113.24	13.24
	8	3.8124	100.00	0.00	118.46	18.46
G-5.0%	14	3.5825	90.67	9.33	100.00	0.00
	1	3.7568	95.08	4.92	104.87	4.87
	11	3.9513	100.00	0.00	110.29	10.29
M-5.5%	13	3.5354	76.60	23.40	100.00	0.00
	16	4.2191	91.42	8.58	119.34	19.34
	5	4.6153	100.00	0.00	130.54	30.54
G-5.5%	6	4.5095	98.40	1.60	100.00	0.00
	15	4.5326	98.91	1.09	100.51	0.51
	16	4.5826	100.00	0.00	101.62	1.62
M-6.0%	4	3.4937	74.97	25.03	100.00	0.00
	2	4.6405	99.58	0.42	132.83	32.83
	6	4.6601	100.00	0.00	133.39	33.39
G-6.0%	14	4.1940	91.45	8.55	100.00	0.00
	6	4.5490	99.19	0.81	108.47	8.47
	16	4.5863	100.00	0.00	109.35	9.35
M-6.5%	16	4.4296	96.63	3.37	100.00	0.00
	12	4.5400	99.04	0.96	102.49	2.49
	10	4.5841	100.00	0.00	103.49	3.49
G-6.5%	14	4.2134	90.15	9.85	100.00	0.00
	8	4.4762	95.77	4.23	106.24	6.24
	10	4.6740	100.00	0.00	110.93	10.93
M-7.0%	9	4.1436	87.31	12.69	100.00	0.00
	10	4.3984	92.68	7.32	106.15	6.15
	4	4.7456	100.00	0.00	114.53	14.53
G-7.0%	1	4.3332	94.31	5.69	100.00	0.00
	6	4.5686	99.43	0.57	105.43	5.43
	5	4.5949	100.00	0.00	106.04	6.04

M: Marshall Compaction

G: Gyratory Compaction

SHEAR STRENGTH Test Results @ temperature of +25C**85/100 Pen AC**

MIX Comp-Asp.Content	SAMPLE number	HEIGHT mm	DENSITY gm/cm ³	TIME sec	TORQUE Nm	SHEAR STRENGTH MPa	SHEAR STRENGTH MEAN
M-5.0%	1	64.99	2.305	7	222	1.0781	1.0700
	7	64.56	2.291	7	221	1.0732	
	15	64.48	2.309	8	218	1.0586	
G-5.0%	9	66.87	2.298	7	200	0.9712	0.9631
	11	67.37	2.305	6	204	0.9906	
	12	66.76	2.298	7	191	0.9275	
M-5.5%	8	63.86	2.314	8	286	1.3888	1.3290
	10	64.24	2.322	7	266	1.2917	
	15	61.66	2.321	7	269	1.3063	
G-5.5%	5	65.44	2.343	8	230	1.1169	1.1444
	13	66.83	2.308	7	235	1.1412	
	15	66.47	2.312	6	242	1.1752	
M-6.0%	9	63.28	2.343	7	210	1.0198	1.0182
	11	62.94	2.337	6	207	1.0052	
	13	62.95	2.328	7	212	1.0295	
G-6.0%	3	65.98	2.327	8	202	0.9809	0.9939
	9	66.66	2.341	7	208	1.0101	
	14	65.74	2.341	8	204	0.9906	
M-6.5%	4	63.30	2.348	8	179	0.8692	0.8692
	9	62.66	2.360	7	179	0.8692	
	10	62.58	2.366	6	179	0.8692	
G-6.5%	3	65.40	2.350	6	175	0.8498	0.8417
	5	64.91	2.373	6	173	0.8401	
	6	60.46	2.354	5	172	0.8352	
M-7.0%	10	62.83	2.378	5	190	0.9227	0.8854
	13	64.15	2.336	6	189	0.9178	
	16	63.11	2.378	5	168	0.8158	
G-7.0%	3	65.82	2.342	6	137	0.6653	0.6523
	4	64.88	2.374	6	134	0.6507	
	13	65.43	2.347	6	132	0.6410	

M: Marshall Compaction

G: Gyratory Compaction

SHEAR STRENGTH Test Results @ temperature of +25C - Differences within Mix

85/100 Pen AC

MIX Comp-Asp.Content	SAMPLE number	SHEAR STRENGTH MPa	PERCENT max=100%	DIFFERENCE % max-100%	PERCENT min=100%	DIFFERENCE % min=100%
M-5.0%	15	1.0586	98.20	1.80	100.00	0.00
	7	1.0732	99.55	0.45	101.38	1.38
	1	1.0781	100.00	0.00	101.83	1.83
G-5.0%	12	0.9275	93.63	6.37	100.00	0.00
	9	0.9712	98.04	1.96	104.71	4.71
	11	0.9906	100.00	0.00	106.81	6.81
M-5.5%	10	1.2917	93.01	6.99	100.00	0.00
	15	1.3063	94.06	5.94	101.13	1.13
	8	1.3888	100.00	0.00	107.52	7.52
G-5.5%	5	1.1169	95.04	4.96	100.00	0.00
	13	1.1412	97.11	2.89	102.17	2.17
	15	1.1752	100.00	0.00	105.22	5.22
M-6.0%	11	1.0052	97.64	2.36	100.00	0.00
	9	1.0198	99.06	0.94	101.45	1.45
	13	1.0295	100.00	0.00	102.42	2.42
G-6.0%	3	0.9809	97.12	2.88	100.00	0.00
	14	0.9906	98.08	1.92	100.99	0.99
	9	1.0101	100.00	0.00	102.97	2.97
M-6.5%	4	0.8692	100.00	0.00	100.00	0.00
	9	0.8692	100.00	0.00	100.00	0.00
	10	0.8692	100.00	0.00	100.00	0.00
G-6.5%	6	0.8352	98.29	1.71	100.00	0.00
	5	0.8401	98.86	1.14	100.58	0.58
	3	0.8498	100.00	0.00	101.74	1.74
M-7.0%	16	0.8158	88.42	11.58	100.00	0.00
	13	0.9178	99.47	0.53	112.50	12.50
	10	0.9227	100.00	0.00	113.10	13.10
G-7.0%	13	0.6410	96.35	3.65	100.00	0.00
	4	0.6507	97.81	2.19	101.52	1.52
	3	0.6653	100.00	0.00	103.79	3.79

M: Marshall Compaction

G: Gyratory Compaction

SHEAR STRENGTH Test Results at temperature of +25C**Polymer**

MIX Comp-Asp.Content	SAMPLE number	HEIGHT mm	DENSITY gm/cm ³	TIME sec	TORQUE Nm	SHEAR STRENGTH MPa	SHEAR STRENGTH MEAN
M-5.0%	10	64.45	1190.1	5	80	0.3885	0.4063
	12	62.02	1134.5	6	88	0.4273	
	16	64.06	1186.5	6	83	0.4031	
G-5.0%	3	67.11	1198.2	6	94	0.4565	0.4565
	6	66.85	1194.4	5	96	0.4662	
	7	67.18	1197.2	7	92	0.4468	
M-5.5%	4	63.48	1173.5	5	106	0.5147	0.4969
	9	64.45	1188.7	6	103	0.5002	
	10	64.78	1180.5	5	98	0.4759	
G-5.5%	8	66.32	1197.0	6	103	0.5002	0.4856
	10	66.33	1196.8	7	98	0.4759	
	11	66.41	1196.5	7	99	0.4808	
M-6.0%	9	63.44	1178.4	5	100	0.4856	0.4743
	15	64.38	1194.4	6	84	0.4079	
	16	64.17	1191.1	5	109	0.5293	
G-6.0%	3	66.27	1195.8	6	102	0.4953	0.4694
	10	66.24	1195.1	6	92	0.4468	
	11	66.04	1193.9	7	96	0.4662	
M-6.5%	2	63.31	1180.9	6	115	0.5585	0.5309
	14	64.44	1184.9	6	105	0.5099	
	15	63.58	1197.4	7	108	0.5245	
G-6.5%	1	66.16	1196.6	6	94	0.4565	0.4403
	5	65.77	1192.4	7	91	0.4419	
	9	65.65	1191.9	8	87	0.4225	
M-7.0%	2	62.33	1167.2	6	110	0.5342	0.5390
	13	63.33	1186.9	6	111	0.5390	
	14	62.72	1173.7	5	112	0.5439	
G-7.0%	2	65.85	1197.6	6	101	0.4905	0.4856
	7	65.84	1194.8	7	98	0.4759	
	15	65.90	1195.0	6	101	0.4905	

M - Marshall Compaction

G - Gyratory Compaction

SHEAR STRENGTH Test Results @ temperature of +25C - Differences within Mix

Polymer

MIX	SAMPLE	TENSILE	PERCENT	DIFFERENCE	PERCENT	DIFFERENCE
Comp-Asp.Content	number	STRENGTH MPa	max=100%	% max=100%	min=100%	% min=100%
M-5.0%	10	0.3885	90.91	9.09	100.00	0.00
	16	0.4031	94.33	5.67	103.76	3.76
	12	0.4273	100.00	0.00	110.00	10.00
G-5.0%		0.4468	95.83	4.17	100.00	0.00
	3	0.4565	97.92	2.08	102.17	2.17
	6	0.4662	100.00	0.00	104.35	4.35
M-5.5%	10	0.4759	92.45	7.55	100.00	0.00
	9	0.5002	97.17	2.83	105.10	5.10
	4	0.5147	100.00	0.00	108.16	8.16
G-5.5%	10	0.4759	95.15	4.85	100.00	0.00
	11	0.4808	96.12	3.88	101.02	1.02
	8	0.5002	100.00	0.00	105.10	5.10
M-6.0%	15	0.4079	77.06	22.94	100.00	0.00
	9	0.4856	91.74	8.26	119.05	19.05
	16	0.5293	100.00	0.00	129.76	29.76
G-6.0%	10	0.4468	90.20	9.80	100.00	0.00
	11	0.4662	94.12	5.88	104.35	4.35
	3	0.4953	100.00	0.00	110.87	10.87
M-6.5%	14	0.5099	91.30	8.70	100.00	0.00
	15	0.5245	93.91	6.09	102.86	2.86
	2	0.5585	100.00	0.00	109.52	9.52
G-6.5%	9	0.4225	92.55	7.45	100.00	0.00
	5	0.4419	96.81	3.19	104.60	4.60
	1	0.4565	100.00	0.00	108.05	8.05
M-7.0%	2	0.5342	98.21	1.79	100.00	0.00
	13	0.5390	99.11	0.89	100.91	0.91
	14	0.5439	100.00	0.00	101.82	1.82
G-7.0%	7	0.4759	97.03	2.97	100.00	0.00
	2	0.4905	100.00	0.00	103.06	3.06
	15	0.4905	100.00	0.00	103.06	3.06

M: Marshall Compaction

G: Gyratory Compaction

END

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