AN ABSTRACT OF THE DISSERTATION OF

Jesús A. Sandoval Gil for the degree of Doctor of Philosophy in Civil Engineering presented on November 16, 2004.

Title: Permanent Deformation Characteristics of Dense-Graded Mixes using the Asphalt Pavement Analyzer

Abstract approved:

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James R. Lundy

The Asphalt Pavement Analyzer (APA) device was used to characterize the impact of various mix factors on the development of permanent deformation in dense-graded mixes given a standard compactive effort. Factors included two aggregate sizes, three VMA levels, two fines contents, three binder contents and four binder types. All specimens received the same compactive effort (100 gyrations) using the Superpave Gyratory Compactor (SGC). For some tests, testing temperatures followed the standard APA test protocol (64C) and for some others, the test temperature was set at the high temperature of standard performance asphalt binder grade (e.g. 70C for a PG 70-22 asphalt binder).

Statistical results showed that increased binder content increased permanent deformation in the 19.0 mm dense graded mixes prepared with the PG 64-22 binder irrespective of the other mix parameters. These effects were not noted in the mixes prepared with PG 70-22 and PG 76-22 binders, when tested at 64C. However, the

same effect was noted when mixes prepared with PG 70-22, PG 70-22 Modified and PG 76-22 binders were tested at the high temperature of standard performance asphalt binder grade. All mixes prepared with the stiffer binders showed very low permanent deformation when tested at the standard 64C regardless of the value of the other mix parameters. The statistical analysis of permanent deformation provides evidence that the mixes prepared with the PG 76-22 and PG 70-22 Modified binders perform better than mixes prepared with the PG 70-22 and the PG 64-22 binders. The effect of VMA on permanent deformation depends on the maximum aggregate size used, test temperature, binder type and the fines content. It was not possible to separate these interaction effects. The results of this study suggest that the APA is relatively insensitive to changes in mix properties within the range of variables studied, when using the standard APA test temperature (64C). However, the APA device is sensitive when the test temperature matches the high temperature of the standard performance binder grade (e.g. 70C for a PG 70-22 binder).

Based on the results of this study, it appears that the APA can be used to indicate the rut resistance of a mixture. Although some of the mix factors have an interactive effect in the mixes, the APA has a potential to predict the relative rutting of the hot mix asphalt mixes even when polymer modified mixes are used, provided that testing is conducted at the appropriate test temperature.

Permanent Deformation Characteristics of Dense-Graded Mixes Using Asphalt Pavement Analyzer

by

Jesús A. Sandoval Gil

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Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Jesús A. Sandoval Gil, Author

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To my father

J. JESUS SANDOVAL RODRIGUEZ (†).

Permanent Deformation Characteristics of Dense-Graded Mixes Using the Asphalt Pavement Analyzer

CHAPTER 1. Introduction

1.1. Background

Highways are a major component of the world's infrastructure. The first use of asphalt roads in the United States was in Battery Park in 1872. Today, of the 2.3 million miles of paved roads in the United States, 96 percent of roads and streets - almost two million miles - are surfaced with asphalt (http://inventors.about.com). Since those first roads were constructed, pavement engineers have been concerned about distress (e.g. stripping, raveling, cracking), including permanent deformation.

Permanent deformation, commonly termed rutting, is a surface depression in the wheel paths sometimes accompanied by lateral displacement of material to the sides. Figure 1.1 shows an example of permanent deformation. Permanent deformation is typically caused by a combination of densification (decrease in volume and, hence, increase in density) and shear deformation (lateral movement) and can occur in any one or more of the hot mix asphalt (HMA) layers, as well as in the unbound materials underneath the HMA (Brown et al., 2001). Shear failure in a HMA pavement generally occurs in the top 100 mm of the HMA structure (Brown and Cross, 1992).

Permanent deformation may also be defined as the accumulation of small amounts of unrecoverable strain resulting from applied wheel loads to HMA pavement (Cooley et al., 2000). It is a very complex problem, and to date most modeling attempts have had only limited success (Bhasin et al., 2003; Stuart et al., 2000; King et al., 1993; Brown and Cross, 1992; Leahy and Witczak, 1991; and Brown and Cross, 1989). Permanent deformation can be easily seen after a rainfall, when the wheel paths are filled with water. As a result, it has been considered as a serious safety issue for road users because of the potential for hydroplaning.

Figure 1.1 Permanent deformation

The factors that influence the permanent deformation characteristics of HMA pavements are aggregate size and type, binder type and mixture properties (Sousa et al., 1991). Other factors that may also contribute to the development of permanent deformation are combinations of an increase of traffic loads and higher tire pressures, the use of studded tires, the effect of high temperatures, etc. Table 1.1 summarizes the effect that each of these factors may have in the mixture.

Table 1.1 Factors affecting rutting of asphalt-concrete mixtures (after Sousa et al., 1991)

	Factor	**Change in Factor**	**Effect of Change in Factor on Rutting Resistance**
Aggregate	Surface Texture	Smooth to rough	Increase
	Gradation	Gap to continuous	Increase
	Shape	Rounded to angular	Increase
	Size	Increase in maximum size	Increase
Binder	Stiffness [a]	Increase	Increase
Mixture	Binder content	Increase	Decrease
	Air void content [b]	Increase	Decrease
	VMA	Increase	Decrease[c]
	Method of compaction	-[d]	-[d]
Test field conditons	Temperature	Increase	Decrease
	State of stress/strain	Increase in tire contact pressure	Decrease
	Load repetitions	Increase	Decrease
	Water	Dry to wet	Decrease if mix is water sensitive

[a]Refers to stiffness at temperature at which rutting propensity is being determined. Modifiers may be utilized to increase stiffness at critical temperatures, thereby reducing rutting potential.

[b]When air void contents are less than 3 percent, the rutting potential of mixes increases.

[c]It is argued that very low VMA's (e.g., less than 10 percent) should be avoided.

[d]The method of compaction, either laboratory or field, may influence the structure of the system and therefore the propensity for rutting.

Asphalt is a viscoelastic material. Viscoelastic materials are materials that exhibit both viscous and elastic properties. Most of the time asphalt exhibits a combination of both properties with the propensity for one or the other depending on the duration of loading and temperature. At high temperatures or under long loading periods, the asphalt behaves more like a viscous liquid. This behavior results in plastic deformation meaning that once the asphalt flows and deforms it never recovers its original shape (see Figure 1). At low temperatures or under rapid loading, the asphalt behavior is more elastic. When loaded, the asphalt deforms; and when unloaded, the asphalt recovers its original shape (Asphalt Institute, MS-22, 2001).

Permanent deformation may result when the binder softens during periods of high temperatures, long loading times or when heavier loads are applied. In order to mitigate this problem, the use of polymers has become a common practice in the United States. A 1997 survey of state highway agencies found that 35 of 52 agencies reported they will be using greater quantities of modified binders, and 47 of 52 reported using the same or more of modified binders (Bahia, 1998). The purpose of adding polymers to the asphalt binder is to improve the asphalt mix characteristics (e.g. durability, service life) and resist permanent deformation with minimal effects on the properties of the asphalt binder at lower temperatures (Lavin, 2003).

Because of the complexity of the asphalt material behavior (temperature and time dependency), it has been difficult to predict permanent deformation of HMA by means of fundamental test procedures (Monismith et al., 1994). Some authors (Brûlé 1996; Rogge et al., 1990) have used single binder test results to estimate permanent deformation without complete success, particularly when attempting to connect laboratory results and field performance when using modified binders.

Superpave (Superior Performing Asphalt Pavements) is the result of the Strategic Highway Research Program (SHRP). This research was conducted from October 1987 through March 1993 to develop new ways to specify, test, and design asphalt materials. The three major components of Superpave are the asphalt binder specification, the mixture design and analysis system, and a computer software system.

Historically, asphalt binder was categorized according to its viscosity at specific temperatures. Superpave system classifies asphalt binders based on their performance in the field. The asphalt binder grading system in Superpave is called performance grading (PG) system. The system is a radical departure from the previous viscosity or penetration based systems. All PG binders are characterized based upon fundamental engineering parameters (Huang, 2004). Grade identifiers start with the PG followed by two numbers representing the maximum and minimum pavement design temperatures in Celsius. For example, an asphalt binder PG 52-28 would meet the specification for a design high pavement temperature up to 52C and a design low temperature warmer than -28C. The high temperature is calculated 20 mm below the pavement surface, and the lowest temperature is calculated at the pavement surface (Mamlouk and Zaniewski, 1999). The binder selection process is intended to minimize permanent deformation during high temperature and thermal cracking during low temperature.

The Superpave asphalt binder specification differs from other asphalt specifications (e.g. penetration, viscosity) in that the tests used measure physical properties that can be directly related to field performance by engineering principles. An unique feature of the Superpave binder specification is that instead of performing a test at a constant temperature and varying the specified value, the specified value is constant and the test temperature at which this value must be achieved is varied. The Superpave binder specification and its test methods with a brief description of its use are listed in Table 1.2 (Roberts et al., 1996).

Table 1.2 Superpave Asphalt Testing Equipment and Purpose (after Roberts et al., 1996)

Equipment	Purpose	Performance Parameter
*Rolling Thin Film Oven (RTFO)	Simulate binder aging (hardening) during HMA production and construction	Resistance to aging (durability) during construction
*Pressure Aging Vessel (PAV)	Simulates binder aging (hardening) during HMA service life	Resistance to aging (durability) during service life
*Dynamic Shear Rheometer (DSR)	Measure binder properties at high and intermediate service temperatures	Resistance to permanent deformation (rutting) and fatigue cracking
*Rotational Viscometer (RV)	Measure binder properties at high construction temperatures	Handling and pumping
*Bending Beam Rheometer (BBR)	Measure binders properties at low service temperatures	Resistance to thermal cracking
*Direct Tension Tester (DTT)	Measure binders properties at low service temperatures	Resistance to thermal cracking

The Superpave mix design procedure involves selecting asphalt and aggregate materials. The asphalt selection is based on the project's climate and the design traffic. The aggregate material is chosen from some Superpave consensus and source properties (e.g. coarse aggregate angularity and toughness, respectively). Once the asphalt and the aggregate materials are chosen, several aggregate trial blends at different asphalt contents are compacted to determine the best (design) aggregate structure. Finally, by using this aggregate structure, the design asphalt content is determined. One of the weaknesses of the Superpave mix design and analysis system is that is does not presently specify a proof test to assess the relative permanent deformation susceptibility of HMA.

Assessment of rutting potential of HMA can play a critical role in producing high performance asphalt pavements. There are a variety of procedures that have been used to evaluate rutting potential of hot mix asphalt mixtures, but sometimes they don’t provide consistent results when assessing permanent deformation (Brown and Cross, 1992).

There is still the need to assure that any mix in the field will perform without rutting for the design life of the road. Loaded wheel testers (LWT) have been used by several countries for quite some time (Ksaibati et al., 1994). They were first used in Europe, and currently several LWT are being used in the United States.

The basic principle of these devices is to simulate the stress conditions resulting from repeated, moving-wheel loads as they actually occur on in-service pavements. The common feature of these wheel tracking devices is the utilization of a moving wheel to apply the load on the compacted asphalt concrete samples (Choubane et al., 1998).

The LWTs include the Georgia Loaded Wheel Tester (GLWT), Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking Device (HWTD), LCPC (French) Wheel Tracker, Purdue University Laboratory Wheel Tracking Device (PURWheel), and one-third scale Model Mobile Load Simulator (MMSL3) (Cooley et al., 2000). Among the currently available equipment, the Asphalt Pavement Analyzer (APA), a multifunctional loaded wheel tester, is probably the most widely used laboratory equipment to test asphalt concrete mixes for permanent deformation susceptibility in the United States. In a recent study conducted by Brown et al. (2001), the APA was ranked as the number one choice to assess permanent deformation.

This study assesses the suitability of the APA device as a tool for evaluating mixtures and judges the effects of varying mix properties on APA results. A total of 540 asphalt cylinders are compacted using the Superpave Gyratory Compactor (SGC). The asphalt cylinders are then tested using the APA device. Some of the mix properties, e.g., aggregate size, voids in the mineral aggregate (VMA), binder and fines content, among others, are varied to assess their effect on permanent deformation. A standard (fixed) compactive effort using the SGC is applied. The goal behind the fixed compactive effort is to mimic what is done in the field (i.e. a fixed number of passes by the rollers over the mat). Modified binders are used to assess their effect in HMA specimens. APA test temperature is set, in some cases, to the high temperature rating of the binder and in other cases, the standard APA testing protocol is followed (i.e., test temperature of 64C). The specific objectives of this study are presented in the following section.

1.2. Objectives

As noted in the preceding section, the primary goal of this study is to assess the suitability of the APA device and judge the effects of varying mix properties on APA results. To accomplish this goal, the project focuses on the following factors to assess permanent deformation characteristics of different asphalt mixes when using the APA device:

- maximum aggregate size
- gradation as reflected in Voids in Mineral Aggregate (VMA)
- binder type
- binder content
- fines content

1.3. Scope

Permanent deformation is influenced by a variety of factors beyond those identified above (e.g., the use of studded tires, failure to achieve adequate field density). These factors are not considered in this research. The type of permanent deformation addressed in this study relates to instability within the asphalt mix. The study was divided in three phases. The first phase consisted of preparing a total of 378 asphalt cylinders (150 mm diameter x 115 mm height) using the SGC. A fractional factorial, which involved two aggregate sizes, three binder content, three VMA levels, three binder types, and two fines contents, was created. The fractional factorial consisted of 63 cells with six cylinders by cell. Using this fractional factorial a two-way interaction of the factors was investigated. A standard (fixed) compactive effort using the SGC was applied. In this phase the standard APA testing protocol (i.e., test temperature of 64C) was followed.

In the second phase, a fractional factorial involving 54 cells with a total of 324 asphalt cylinders was used. The fractional factorial in this phase consisted of one aggregate size, three binder content, three VMA levels, and two binder types. Also, a standard (fixed) compactive effort using the SGC was applied. In this phase, the APA test temperature was modified. The test temperature used was set at the high temperature rating of the binder (e.g. 70C for a PG 70-22 asphalt binder).

In the third phase, a fractional factorial involving 18 cells with a total of 108 asphalt cylinders was used. The fractional factorial on this phase consisted of one aggregate size, three binder contents, three VMA levels, and two binder types. This phase used one modified binder. The modified binder met the specification from the

Oregon Department of Transportation (ODOT) for the elastic recovery test (ODOT TM 429). A standard (fixed) compactive effort using the SGC was also applied. In this phase, the test temperature was also modified. The test temperature used was set at the high temperature rating of the binder (e.g. 70C for a PG 70-22 asphalt binder).

After compaction, the Bulk Specific Gravity (Gmb) of each cylinder was determined following the AASHTO Procedure T166 (Method A). All cylinders were finally tested with the APA device to assess their permanent deformation susceptibility. No efforts were made to vary any testing procedure in the APA device (i.e., tube pressure, wheel load, etc) except for test temperature in the second and third phase. Finally, the results were compared and conclusions and recommendations were made based on the analysis of the test results.

CHAPTER 2. Literature Review

2.1. Permanent Deformation Characterization

Properly designed and constructed asphalt mixtures result in a road surface that is smooth and will remain smooth for its design life. Permanent deformation is an accumulation of small deformations in the asphalt surface caused by repeated heavy loads at high temperatures. This can occur either through consolidation or through plastic flow, or some combination of the two. Consolidation is basically the result of further compaction of the asphalt pavement by traffic after construction. Plastic flow may result from excessive asphalt binder in the mix which leads to a loss of internal friction between aggregate particles (Roberts et al., 1996).

Dawley et al. (1990) stated that there are three basic types of permanent deformation which can occur in the HMA pavements. These three types are depicted in Figure 2.1 and include wear rutting, structural rutting and instability rutting. Wear rutting (a) is due to the progressive loss of coated aggregate particles from the pavement surface, and is caused by combined environmental and traffic influences or in some states, studded tires. It also may be caused by inadequate compaction during construction. Structural rutting (b) is due to the permanent vertical deformation of the pavement structure under repeated traffic loads and is essentially a reflection of permanent deformation within the subgrade. Rutting stems from the permanent deformation in any of the pavement layers or the subgrade usually caused by consolidation or lateral movement of the materials due to traffic loads. Instability rutting (c) is due to lateral displacement of material within the pavement layer, and occurs within the wheelpaths. It occurs when structural properties of the compacted pavement are inadequate to resist the stresses imposed upon it, particularly by frequent repetitions of high axle load.

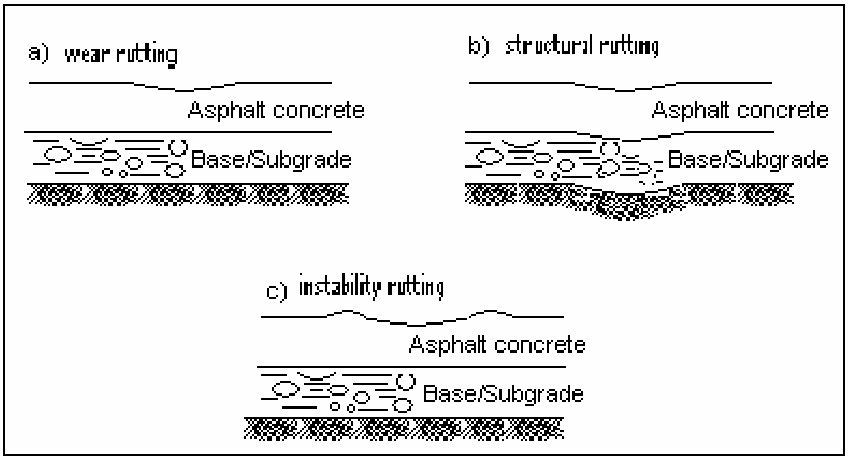


Figure 2.1 Types of permanent deformation (after Dawley et al., 1990)

The components of a HMA are air voids, mineral aggregates, and asphalt cement. In production, the latter two materials are proportioned by mass (weight). The effect that these three components may have in the permanent deformation of HMA is always interrelated. For many years three volumetric parameters have been widely used, and at various times, have formed critical thresholds. These are the percent Air

Voids (Va), the Voids in the Mineral Aggregate (VMA), and the Voids Filled with Asphalt (Vfa) (Coree, 1999).

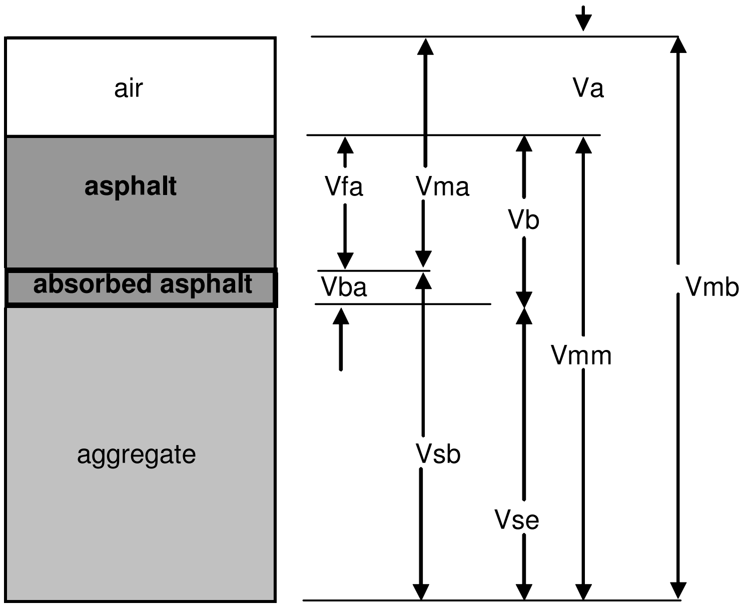
- Percent Air Voids (Va) – the volume of Air Voids (Va) expressed as a percentage of the total volume of the mixture. Air voids is the volume concentration of air within the compacted sample.

- Voids in the Mineral Aggregate (Vma) – the sum of Air Voids (Va), and the Voids Filled with Asphalt (Vfa) expressed as a percentage of the total volume of the mixture. This parameter is directly analogous to "porosity" in soil mechanics. Effective binder is the mass concentration of asphalt binder that is not lost to absorption.

- Voids Filled with Asphalt (Vfa) – the degree to which the Vma are filled with the bituminous binder, expressed as a percentage. Once again, this is directly analogous to the "degree of saturation" in soil mechanics.

These three parameters are represented in Figure 2.2 in a "phase diagram" (Asphalt Institute SP-2, 2001).

Permanent deformation is affected by the properties and proportions in which air voids, asphalt content and aggregates are mixed. Aggregates make up 90-95 percent by weight of HMA. Aggregates are the skeleton of the asphalt mixes. Ideally, the aggregate skeleton for the mixture is able to carry the traffic load, especially in the summer, when the temperatures are relatively high, because the viscosity of the binder is low at high temperatures. If the aggregate has a poor structure, then permanent deformation is likely to occur.



Vma = Volume of voids in mineral aggregate
Vmb = Bulk volume of compacted mix
Vmm = Voidless volume of paving mix
Vfa = Volume of voids filled with asphalt
Va = Volume of air voids
Vb = Volume of asphalt
Vba = Volume of absorbed asphalt
Vsb = Volume of mineral aggregate (by bulk spec. gravity)
Vse = Volume of mineral aggregate (by effective spec. gravity)

Figure 2.2 Component Diagram of Compacted Sample of HMA

When the contribution of the aggregates is considered, selecting aggregates of rough surface texture and cubical shape, which should be graded in such a manner so that there is a better contact between each particle, would help to prevent permanent deformation (Button et al., 1990; Asam, 2001). Aggregate properties, such as surface texture, angularity, nominal maximum size, and gradation, have been shown to affect a mixture resistance to permanent deformation (McGennis at al., 1995).

Aggregate gradation (i.e. particle size distribution) will influence hot mix asphalt properties (Geller 1988, and Ruth et al., 1992). Dense graded mixtures with the same nominal maximum size can have a fine gradation, a coarse gradation, or anything in between. Brown (1988) stated that mixtures composed mostly of fines particles are susceptible to permanent deformation. Maximum aggregate size is defined as one sieve larger than the nominal maximum size, which is one sieve larger than the first sieve to retain more than 10 percent. The increase in maximum aggregate size mixes minimizes the potential to permanent deformation (Kandhal 1999; Mahboub and Allen, 1999). Brown and Bassett (1990) concluded that mixes with larger maximum aggregate size are generally stronger and require significantly less asphalt content than mixes with smaller maximum aggregate size.

The asphalt cement acts as glue or bonding material. It covers and keeps the aggregate skeleton together in the mixture. However, the asphalt binder must be sufficiently strong to resist excessive shear loads generated between the aggregate particles. If the binder is not strong enough, especially in hot weather, rolling tires can dislodge aggregate particles and shear deformation may easily occur (Huber, 1999).

Air voids may be influenced by aggregate gradation, aggregate properties and binder content in HMA. Wedding and Gaynor (1961), evaluating the effect of particle shape in dense graded asphalt concrete mixtures, concluded that an increase in the amount of crushed particles caused an increase in mineral aggregate voids. The amount of air voids in asphalt concrete mixtures affects the stability and durability of the mix. A minimum air void content is desirable to allow the pavement to expand and contract under loading and temperature changes (Lavin, 2003). As noted before, air voids in the mixture are related to the asphalt content in the mixture. Pavements that have very low air void contents tend to have asphalt binder bleeding or flushing on the surface and tend to deform under traffic. For better performance of asphalt concrete mixtures, an air void content of approximately four percent of the asphalt mixture is suggested and a minimum of three percent is recommended to avoid instability and excessive permanent deformation of the mixes (Monismith et al., 1985). The reduction in air voids as a result of increases in asphalt content shows that the air void space is becoming filled with asphalt. This additional asphalt content acts as a "lubricant" between aggregate particles, making the mix unstable and increasing its susceptibility to deform permanently (Mahboub and Little, 1988).

The effect of VMA in the mix properties has been associated with mix durability since the early part of this century, yet only 40 years ago was it recognized as a critical mix design parameter, principally through the efforts of Dr. Norman MacLeod. Today in the Superpave volumetric mix design process, it indirectly defines what is an acceptable aggregate gradation (Coree and Hislop, 1999; Button et al., 1990). VMA is important in that it allows room for enough asphalt binder to make a durable mixture plus enough room for mixture air voids to ensure a stable mixture. A durable asphalt mixture requires an adequate film thickness. VMA is an indirect way to specify the amount of the asphalt binder film thickness in a mixture (Lavin, 2003). Without adequate film thickness, the asphalt cement can be oxidized faster, the films are more easily penetrated by water, and the tensile strength of the mixture is adversely affected. As the nominal maximum particle size of the aggregate increases, the minimum VMA required decreases. This occurs because the total void space between large aggregate particles is smaller than the voids space between small aggregate particles (Roberts et al., 1996).

Mineral fillers, or dust, for asphalt paving mixtures consist of fine mineral particles that are added to or are naturally present in the mineral aggregate, and that predominantly pass the U.S. Standard Sieve No. 200. As such, they may normally be viewed as a continuation or extension of the mineral aggregate which usually is well-graded and larger than the opening sieve of No. 200. In this sense, mineral fillers are part of the aggregate skeleton on the pavement. They provide contact points between individual particles and, therefore, are generally considered to perform the same function as the coarser particles in resisting stresses imposed on the pavement (Kallas et al., 1962).

Kallas et al. (1962) stated that all mineral fillers regardless of type and concentration increase stability or strength properties of compacted asphalt paving mixes. They also stated that fillers also increase compactive efforts required to compact specimens to the same volume or air void content.

Brown et al. (1989) stated that additional minus No. 200 (filler) material produced a lower optimum asphalt content (filler material fills the voids in an asphalt mixture and lowers the optimum asphalt content), a higher stability, and a more sensitive asphalt mixture to changes in asphalt content. The authors stated that some filler is needed to obtain the required stability, but excessive filler can result in unsatisfactory mixes.

Mineral fillers have a significant effect on VMA. A one percent decrease in the amount of minus 0.075 mm in the mixture will increase VMA around one percent (Murphy and Bentsen, 2001).

When asphalt pavement is exposed to high temperature, the binder becomes less stiff and permanent deformation may result. When exposed to low temperatures, the binder becomes too brittle to resist cracking caused by some combination of thermal stresses, repeated loading, low temperature physical hardening or oxidative (King et al., 1992). In order to overcome these failures, the practice of modifying the asphalt binder became common, and polymers, in particular, have received widespread attention as the performance improvers of unmodified asphalt binder (Lenoble and

Nahas, 1994; Bahia et al., 1998; King et al., 1992 and 1993, and Brule and Maze, 1995).

A polymer is a chain of units called monomers. Polymers commonly used in flexible pavement construction can be separated into one of two general categories of polymers: plastomers and elastomers (Stroup-Gardiner and Newcomb, 1995). Plastomers are materials that exhibit a quick early strength under load, but tend to exhibit little ability to strain without brittle failure. Elastomers resist permanent deformation by an ability to stretch and recover their original shape once the load is removed (Stroup-Gardiner and Newcomb, 1995). Styrene-butadiene-styrene (SBS) is an elastomer that has been used most frequently to reduce the rutting problem on the pavement surface because it can be stretched and recover its initial shape (Chen and Huang, 2000; Khattak and Baladi, 1998; and Brûlé, 1995).

Even though the physical properties of conventional asphalt cements have been characterized for a long time, carrying out the same procedures on modified asphalt has proven to lead to unreliable results as these procedures do not accurately describe the mechanical behavior of modified asphalt cements. Several test methods have been proposed to specify each type of modified asphalt (force ductility, elastic recovery, toughness and tenacity), but these are material-oriented procedures which may reflect the amount and type of polymer, but do not necessarily guarantee resistance to permanent deformation or cracking. Therefore, the performance of modified asphalt cements cannot be described based solely on the material-oriented procedures, but it must also be defined in terms of performance physical properties, related to pavement life (King et al., 1993; Brule and Maze, 1995; King et al., 1992, and Lenoble and Nahas, 1994).

A wide variety of test methods and procedures have been developed over the years to characterize asphalt mixes, many of which are still being used today. These test methods can be classified into different categories. These categories are in-place versus laboratory tests, empirical versus fundamental tests, and those tests grouped according to the mode of test (e.g., indirect tension, compression shear, flexural, or torsion). Tests which yield these fundamental properties directly are desirable. Laboratory tests that are currently used to characterize asphalt mixes include evaluation of the individual asphalt cement (binder) and aggregate materials followed by evaluation of the hot mix asphalt mixture (Roberts, Kandhal, Brown, Lee, and Kennedy, 1996).

The Superpave asphalt binder tests (evaluation) measure physical properties of the binders that can be directly related to field performance in terms of rutting, fatigue cracking, and low temperature cracking. The Dynamic Shear Test (DSR) is used to characterize the viscous and elastic behavior of the asphalt binders. The DSR measures the complex modulus G* and phase angle (δ) of asphalt binders at the desired temperature and frequency of loading. Complex modulus consists of two components: (a) storage modulus G' or the elastic part and (b) loss modulus G" or the viscous (non-recoverable) part. These viscous and elastic properties of the binder are measured on a thin binder sample sandwiched between an oscillating plate and a base plate. The relationship between these two properties is used to measure the ability of the binder to resist permanent deformation and fatigue cracking. For rutting resistance, a high complex modulus G* value and low phase angle δ are both desirable. In other words, to resist rutting, a binder needs to be stiff and elastic; to resist fatigue cracking, the binder needs to be flexible and elastic (Roberts et al., 1996; and Asphalt Institute, 2001).

In addition to the asphalt binder evaluation tests to predict rutting (e.g. DST), researchers have made use of a variety of laboratory procedures to also evaluate permanent deformation potential of unmodified and modified hot mix asphalt mixtures. In the study by Zhang et al. (2002), these were classified into three groups, as listed below.

Fundamental tests:

- unconfined and confined cylindrical specimens in creep,
- repeated dynamic loading,
- cylindrical specimens in diametral creep or repeated loading,
- Superpave Shear Test (SST),
- repeated shear at constant height test,

- shear modulus test,
- quasi-direct shear test and shear strength test.

Empirical mix design related tests:

- Marshall Stability and Flow
- Hveem Stabilometer and Cohesionometer.

Simulative Tests

- Georgia Loaded Wheel Tester,
- Hamburg Wheel Tracking Device,
- LCPC Wheel Tracker,
- Purdue University Laboratory Wheel Tracking Device,
- Nottingham pavement tester
- Accelerated Pavement Tester (e.g., ALF)
- Asphalt Pavement Analyzer

Each of the test devices and procedures has advantages and disadvantages. A recent study by Brown et al. (2001) includes the advantages and disadvantages of the devices and procedures in the three categories. Table 2.1 summarizes these advantages and disadvantages.

Among the simulative tests currently available, Brown et al. (2001) ranked the Asphalt Pavement Analyzer (APA) as the number one choice. In a recent study by Kandhal and Colley (2003), it was indicated that the APA could be used to determine the permanent deformation susceptibility of HMA mixes in the field. In the same study, a tentative standard method of the APA test procedure in AASHTO format was developed and recommended. The focus herein is on the Asphalt Pavement Analyzer.

The APA, as shown in Figure 2.3, is the latest version of the Georgia Loaded Wheel Tester (GLWT). The GLWT was developed by C.R. Benedict. It was originally used for evaluating certain properties of slurry seals. This original prototype was then modified with the objective of making it more applicable for evaluating the rutting behavior of asphalt mixes under a laboratory environment. This modification was done by the Georgia Institute of Technology under a contract with the Georgia Department of Transportation (GDOT) (Lai and Lee, 1990; Collins et al., 1995). In 1986, the GDOT started using the GLWT to assess permanent deformation on asphalt mixtures under laboratory environment (Miller et al., 1995).

Table 2.1 Comparative assessment of test methods (after Brown, Kandhal and Zhan, 2001)

Test Type	Advantages	Disadvantages
Fundamental Diametral Test	*Tests are easy to perform *The equipment is usually available in most of the labs and the specimens are easy to fabricate (4 in. in dameter x 2.3 inches in height) *These tests are considered non-destructive.	*These tests are maybe inapropiate for estimating permanent deformation *These tests have been found to overestimate permanent deformation *For the dynamic test, the equipment is complex.
Fundamental Triaxial Test	*Relative simple test and equipment *Sample dimensions are 4 in. diameter x 8 in. in height (others may be used) *These tests are considered non-destructive. *Potentially inexpensive.	*Requires triaxial chamber *Equipment is relatively complex and expensive *Ability to predict permanent deformation is questionable.
Fundamental Shear Test	*AASHTO standardized procedure available *Sample available from SGC samples (6 in. diameter x 8 in. in height) *These tests are considered non-destructive.	*Equipment extremely expensive and rarely available *SGC samples need to be cut and glued before testing *Test is complex and difficult to run, usually need special training.
Empirical Test	*Tests wide spread and well known *Sample dimensions are 4 in. diameter x 2.5 in. in height *Equipment available in all labs *Developed with a good basic philosophy.	*Not able to correctly rank mixes for permanent deformation *Not much data available.
Simulative Test	*Simulate field traffic and temperature conditions *Specimens can be from the field as well as lab prepared *Most of them use SGC samples.	*Relative expensive *Not widely available in U.S. *Very little data available.

Initially, beam samples were tested in the GLWT machine, but later, in 1992, a new GLWT was developed (Collins et al., 1996). By 1996, after several improvements, the modified GLWT or APA device was developed to promote its usage along with the Superpave volumetric design in evaluating the permanent deformation susceptibility of asphalt mixtures (Collins et al., 1996).

2.2. The Asphalt Pavement Analyzer

The APA is a wheel tracking device that has gained credibility in the Asphalt Industry and with several state DOTs. The APA is considered a multi-functional loaded wheel device as a result of its ability to measure permanent deformation susceptibility, fatigue cracking and moisture susceptibility of HMA mixes.

HMA specimens may be prepared using a gyratory compactor, a vibratory compactor, or a Marshall Hammer (152.4 mm diameter by 76.2 mm thick). The device is also capable of testing beams (76.2 x 76.2 x 381 mm) or cores extracted from the roadway. Permanent deformation tendencies can be determined on three beam specimens, six cylindrical specimens, or a combination of both.

Figure 2.3 The Asphalt Pavement Analyzer

Permanent deformation tests are conducted in a controlled temperature environment, from 30C to 70C, either dry or submerged. Each sample is loaded independently with up to 113 kg. Tire pressures of up to 827 kPa can be simulated, with optional pressures up to 1379 kPa available. During the test, the samples are subjected to repeated stresses applied through a loading wheel riding back-and-forth on a pressurized hose placed lengthwise on top of the samples (Choubane et al., 1998; Lai and Lee, 1990).

An automated rut-depth measuring system is available, and capable of plotting the deformation with respect to cycles or time. The system obtains rutting measurements and displays those measurements in a numeric and a graphical format, as shown in Figure 2.4. Five measurements can be taken during a single pass over a beam specimen, and two measurements can be taken during a single pass over a cylindrical specimen.

The APA can also determine fatigue resistance of a mixture by using a steel wheel, in place of the rubber hose and concave wheel used in the permanent deformation test. The test is conducted in a controlled environment of 5C to 30C. Each sample can be loaded independently with up to 113 kg and with a contact pressure in excess of 827 kPa. Moisture susceptibility of a mix can also be determined by conducting the test for permanent deformation susceptibility on both dry and pre-conditioned wet specimens.

The pre-conditioned specimens are submerged in water during testing (2 h 15 min). This method compares favorably with AASHTO T 283; the widely accepted standard procedure for evaluating moisture susceptibility (Lynn, 2000).

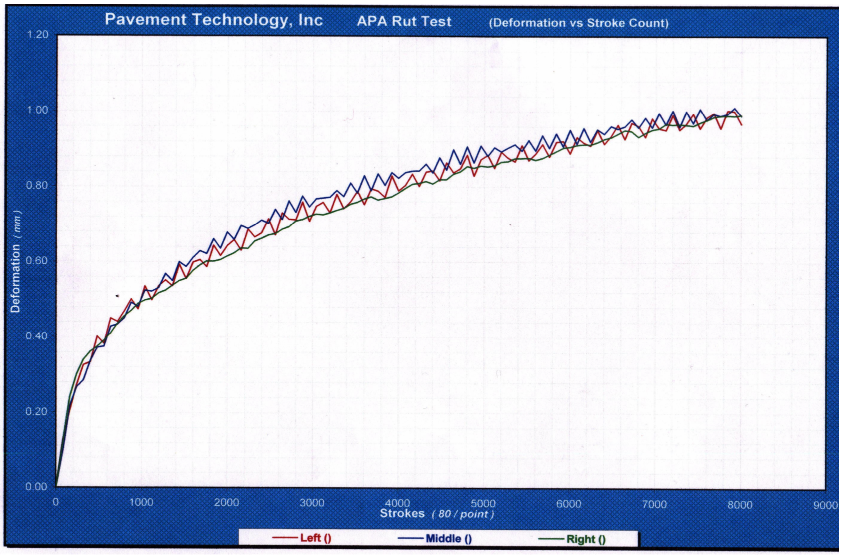


Figure 2.4 Rut Typical results

2.3. Current Research

2.3.1. APA and Permanent Deformation

Some studies have shown that the APA can provide valuable data on permanent deformation (e.g. Hooper et al., 2004; Zhang et al., 2004; Bashin, Button, and Chowdhury, 2003; Skok et al., 2003; Kandhal and Cooley, 2003; Bennert and Maher, 2003; Cooley and Brown, 2003; Kandhal and Cooley, 2002; Jackson and Baldwin, 1999).

"The SHRP program formed an Aggregate Expert Task Group (ETG) to develop recommendations for aggregate properties and gradations for HMA. The final recommendations for aggregate gradations included a restricted zone that lies along the maximum density line (MDL) between an intermediate sieve size (2.36 or 4.75

mm depending on the maximum aggregate size) and the 0.3 mm size. The restricted zone was recommended to reduce the incidence of tender or permanent deformation prone mixes. A further gradation recommendation from the Aggregate ETG was that mixes designed for high and very high traffic levels should utilize gradations passing below the restricted zone (BRZ). The ETG suggested mixes having gradations passing below the restricted zones have higher shear strength to resist permanent deformation because of high inter-particle contact" (Zhang et al., 2004).

In a recent study by Zhang et al. (2004), the APA device was used to evaluate the impact that the restricted zone has on permanent deformation. For this study, four contractor mix designs that met the requirements and recommendations (i.e. aggregate type, gradation, maximum aggregate size, and design compactive effort) for the Alabama Department of Transportation (ALDOT) were identified. Of the four selected mixes two were wearing/surface course mixes, one upper binder mix, and one base/binder mix. Maximum aggregate sizes (MAS) included two 19.0 mm, one 12.5 mm and one 25.0 mm. Initially, the four mixes had gradations passing below the restricted zone (BRZ). Gradations were then modified to obtain mixes with gradation passing above the restricted zone (ARZ) and through the restricted zone (TRZ). After developing these gradations, asphalt contents were selected to provide 4 percent air voids using respective design number of gyrations. The asphalt binder used in the study was PG 64-22, meeting high temperature requirement above 67C. The original properties of the four mixes were: Mix one (wearing course) was granite with MAS of

19.0 mm and a design gyrations of 100. Mix two (base/binder course) was limestone with MAS of 25.0 mm and a design gyrations of 50. Mix three (upper binder course) was gravel with MAS of 12.5 mm and a design gyrations of 100. Mix four (wearing course) was gravel with MAS of 19.0 mm and a design gyrations of 75.

All of the mixes were subjected to three different performance tests: APA, Rotary Loaded Wheel Tester (RutMeter), and Marshall Stability and flow. The APA tests were conducted at 64C to 8,000 cycles. Wheel load and hose pressure were 445 N and 690 kpa. RutMeter tests were conducted at 64C, applying 16,000 individual wheel loadings of 125 N with a contact pressure of 690 kpa. The RutMeter uses gyratory samples compacted at the design number of gyrations. Marshall Stability and flow testing were conducted on 150 mm diameter gyratory compacted samples at 60C. All specimens for Marshall testing were prepared at 4.0 ± 0.5 percent air voids.

Results from the APA device indicated that two from the total of twelve mixes exceeded the maximum rut depth of 8.2 mm. (critical value used for this study). The BRZ had slightly higher rut depths than the ARZ and TRZ gradations. On average, mixes having gradations BRZ rutted about 2.4 mm and 1.3 mm more than did mixes having TRZ and ARZ gradations, respectively. Results from APA device suggested that the aggregate properties have a great impact for mixes BRZ. Results from RutMeter device also suggested that aggregate sources and properties become important for mixes having gradations BRZ. The results from the RutMeter indicated that mixes having gradations TRZ performed better than did mixes having gradations BRZ and ARZ. The Marshall stability and stiffness index appeared to confirm the APA and the RutMeter conclusions. In general, the authors indicated that mixes having gradations violating the restricted zone performed similarly to or better than mixes with gradations passing outside the restricted zone.

In another study by Kandhal and Cooley (2002), the APA device was also used to compare coarse-graded and fine-graded Superpave mixtures in terms of resistance to permanent deformation. In this case, two coarse aggregates (coming from different mineralogical types, with different particle shape and texture), crushed granite and crushed gravel were used. Four fine aggregates (having different mineralogical compositions, particle shape and surface texture), sandstone, limestone, granite, and diabase, were used. The asphalt binder used was PG 64-22.

Eight 9.5 mm nominal maximum aggregate size (NMAS) mixtures were designed using a combination of granite or crushed gravel coarse aggregate and the three fine aggregates: limestone, sandstone, and diabase (traprock). Sandstone fine aggregate was used with both granite and crushed gravel coarse aggregate. Two gradations, coarse gradation BRZ and fine gradation ARZ were used for each coarse/fine aggregate combination. A common material (limestone filler) passing 0.075 mm (No. 200) sieve (P200) was used in al HMA mixtures to eliminate P200 as a variable. All eight 9.5 mm NMAS mixtures, including BRZ and ARZ gradations were, designed with the Superpave volumetric mix design method. Compaction was carried out to N_{design} (100 gyrations, representing a traffic level of 3-30 million ESAL's) to determine the optimum asphalt content (4 percent air voids). Three 19.0 mm NMAS mixtures were also designed using a combination of granite or crushed gravel coarse aggregate and the three fines aggregates: granite, sandstone and diabase. Two compactive efforts (N_{design} = 75 and 100 gyrations) were used for the 19.0 mm NMAS mixes. All 14 mixes evaluated permanent deformation susceptibility on the bases of performance-related mechanical tests. This was accomplished by one empirical test, the APA and two fundamental tests, the Superpave Shear Tester (SST) and the Repeated Load Confined Creep (RLCC).

The APA test was conducted at 64C and permanent deformation was evaluated after 8000 cycles. APA testing was conducted on three pairs of gyratory compacted samples of 75 mm height. The air void content of the different mixtures was 6.0 ± 0.5 percent. Hose pressure and wheel load were 690 kPa and 445 N, respectively. The specimens for the SST testing were prepared at 3.0 ± 0.5 percent air voids and tested at 50C. For the RLCC test the target air voids for the specimens used was 4.0 ± 0.5 percent. The test temperature was 60C. The loadings consisted of a 138 kPa confining pressure and an 827 kPa normal pressure.

Results of the statistical procedures for all three performance tests indicated that the BRZ and ARZ gradations performed similarly. However, the authors indicated that disregarding the statistics and looking purely at the magnitudes of the different permanent deformation parameters, for some NMAS/coarse aggregate/fine aggregate combinations, the BRZ had lower permanent deformation potential while for other combinations the ARZ had lower permanent deformation potential.

Purcell and Cross (2001), used the APA device to assess the effect of the fine aggregate angularity (FAA) and flaky aggregates (chat sand) on VMA and permanent deformation. More specifically, researchers wanted to investigate how much fine aggregate angularity was needed to meet minimum VMA requirements while maintaining stability. Five aggregate sources were used for the production of samples. These consisted of three crushed limestones, one coarse (plus 4.75 mm) and two fines (minus 4.75 mm), a natural river sand, and chat sand. Two 12.5 mm nominal gradations, one coarse and one fine, were established, containing 100 percent crushed limestone. Two mixes based on Kansas Department of Transportation (KDOT) designation, SM-1B and SM-2A were used. The SM-2A mix stayed above the maximum density line, and the SM-1B mix gradation was an S shaped curve that started above and ended below the maximum density line. APA samples were made using the SGC with a normal force of 600 kPa. The samples were compacted to a N_{design} of 75 gyrations (corresponding to a traffic level of 0.3 to 3 million Equivalent Single axle Loads (ESAL's)). Samples were compacted at estimated asphalt contents at 4 ± 1 percent air voids. A single PG 58-22 asphalt binder was used for the mixture. APA testing was conducted at the high temperature rating of the asphalt binders, 58C.

The wheel load was 440 N and the hose pressure was 690 kPa. The samples were tested to 8,000 cycles.

Based on the APA results researchers indicated that when using rounded natural sands, both gradations showed that until a minimum FAA was reached, the effect of FAA on VMA was negligible. For the samples made with crushed limestone and natural sand, permanent deformation susceptibility decreased as the FAA was increased. They also observed that VMA was boosted with the introduction of chat sand into the mix. Both mixes indicated that increasing chat sand content increased VMA. Researchers concluded that increasing the FAA increases VMA for typical mixes, those that contained natural sand and crushed limestone. For mixes containing chat sand, VMA was not a function of FAA.

Researchers also found that when chat screenings were used to replace natural sand, permanent deformation of a mix stayed the same, indicating that chat screenings and natural sand had an equal susceptibility to permanent deformation. In general, researchers concluded that gradation greatly affects the stability of a mix. They also emphasized that increase in natural sand content increases permanent deformation. Increasing the FAA resulted in less permanent deformation for these mixes made with natural sand and limestone.

Researchers finally concluded that meeting the minimum Superpave mix volumetric design was not adequate assurance that a mix will perform satisfactorily.

Also, it was indicated that meeting the minimum FAA requirement also was not an adequate assurance for a mix to perform satisfactorily.

Kandhal and Mallick (1999) used the APA and the Superpave Shear Tester (SST) test to predict permanent deformation potential on HMA mixes. Two SST tests were selected for their usefulness and simplicity: the repeated shear at constant height (RSCH) and repeated shear at constant stress ratio (RSCSR). The RSCH can give an estimate of rut depth, whereas the RSCSR is capable of identifying mixes susceptible to permanent deformation at low air voids content.

This study included mixes with different aggregates (granite, limestone, gravel) and similar gradations except, near the restricted zone. Therefore, gradations passing above, through, and below the restricted zone (ARZ, TRZ, and BRZ respectively), were used. Two different asphalt binders (PG 64-22 and PG 58-22) were compared. Mixes with PG 64-22 and PG 58-22 asphalt binders were tested at 64C and 58C, respectively. For this study, the wearing (nominal size 12.5 mm) and binder courses (nominal size 19.5 mm) were tested separately. All test samples were prepared at 4 percent air voids with the Superpave gyratory compactor (SGC). The samples were compacted at N_{design}= 76 (corresponding to 0.3-1 million ESALS). Additional work included testing three sections on I-85 (south of Georgia/Alabama border) which were showing good, fair, and poor performance in terms of permanent deformation. Cores were obtained from each section from the travel lane, about 300 mm away from the pavement edge. In the laboratory, the wearing courses were sawed off from the cores. The cores were heated and ten gyratory samples were then compacted with each type of mix, at 4 percent air voids. The samples were then tested in the APA.

Statistical analyses of data from the APA device showed significant effects of aggregate type, asphalt binder type, gradation, course type and the interaction of aggregate and gradation on permanent deformation. Mixes with gravel and limestone aggregates showed higher rutting than granite mixes. Mixes with asphalt PG 58-22 showed higher rutting compared with PG 64-22 asphalt mixes. For the granite and limestone mixes, with gradation passing below the restricted zone (BRZ), they generally showed the highest amount of rutting. Whereas, gradations through the restricted zone (TRZ) showed the lowest rut depth and, ARZ gradations showed intermediate rutting. For gravel mixes, the BRZ gradations showed the least amount of rutting; whereas mixes with ARZ gradation showed highest amount of rutting. Mixes with gradations TRZ showed either higher or similar rutting, as mixes with gradations BRZ. The authors indicated that APA was sensitive to mix gradation.

It was also noticed that while granite and limestone tended to have more permanent deformation with an increase in film thickness (for wearing courses), for gravel, the rutting decreased with an increase in film thickness. In the case of granite and limestone mixes, there was an increase in rut depth with an increase in VMA. The trend was reversed for gravel mixes, as there was a decrease in rut depth with an increase in VMA, but the researcher didn't explain this behavior. An ANOVA test was done to try to determine correlations between mix rut depths and density at $N_{initial}$ and at N_{max}. It was concluded that mixes meeting $N_{initial}$ and N_{max} criteria did not necessarily show less rutting potential than mixes that did not meet the criteria. The SST test results indicated that, for the wearing course, the TRZ mixes showed the lowest permanent deformation potential. Finally, researchers mentioned a fair correlation (R^2 = 0.62) between the results from the APA and the RSCH devices, indicating that both tests characterized the mixes in the same way.

Cross, et al. (1999), used the APA device to evaluate the laboratory performance of two Kansas DOT bituminous mixtures. The first mixture, from US-183 (12.5 mm nominal size), was an S-shaped gradation that stayed below the maximum density line and passed below the restricted zone. This mixture was referred to as the coarse mix. The second mixture, from US-281 (12.5 mm nominal size), had a finer gradation that stayed above the maximum density line and above the restricted zone. This mixture was referred to as the fine mix. These two mixtures were part of a mixture performance study previously conducted by the authors. As a part of that study, four pavements were sampled and cores from the pavements were obtained. The gradations were coarsened to simulate the effects of production variability and segregation. The binder used in that study was a coastal AC-20.

Samples were batched to the gradations of the coarse and fine mixes and to 5 to 20 percent coarser, as measured on the 4.75 mm sieve. Samples were compacted to the density of the respective mixtures in the field. The air voids of the mixtures in the field ranged from 6.1 to 15.5 percent. Samples with 101.6 mm in diameter were compacted in the U.S. Army Corps of Engineers Gyratory Testing Machine (GTM). Also, samples with 150 mm in diameter were compacted on the SGC device. The 101.6 mm samples were tested for indirect tensile strength (ASTM D4123), voids analysis (ASTM D3202) and air permeability (ASTM D3637). The 150 mm diameter samples were tested in the APA device for permanent deformation resistance (Georgia Test Method GDT-115, Method A), moisture damage (GDT-115, Method B), and fatigue life. The APA test was performed using a 440 N load on a 690 kpa pressurized hose pressure at a test temperature of 50C. Researchers didn't specify the kind of asphalt used in this study.

Results from the indirect tensile tests indicated that the fine mix had a higher indirect tensile strength than the coarse mix, being 6 percent larger. The coarse mix showed a slightly greater loss in indirect tensile strength with a coarsening in gradation. Results from the APA test at 8000 cycles indicated that the fine mix had less permanent deformation (5.0 mm) than the coarse mix (8.9 mm). APA results also indicated that the coarse mixture was more sensitive to a coarsening in gradation than the fine mixture. Coarsening the gradation caused an increase in permanent deformation for the coarse mixture. However, the permanent deformation went down slightly for the fine mixtures. It appeared that fine mixtures, above the maximum density line, developed their strength from the fine aggregate and didn't rely on a coarse aggregate skeleton for their stability. With respect to APA results in the moisture sensitivity test, the samples were tested in the same manner as in the permanent deformation test, except that the samples are submerged in 40C water. The results showed that the coarse mixture had higher wet permanent deformation and could be more sensitive to moisture damage.

2.3.2. APA and Different HMA Mixes

Cooley and Brown (2003), used the APA device to evaluate fine and conventional Stone Mastic Asphalt (SMA). Researchers defined fine SMA as mixes with a Nominal Aggregate Maximum Size (NMAS) of either 4.75 mm or 9.5 mm. Conventional SMAs have NMAS of 12.5 mm and 19.0 mm. Researchers pointed out that one of the benefits of fine SMA is that it can be placed in thinner lifts, it could be used as a part of a preventive maintenance program, and should be more workable.

In this study, four NMASs were used: 4.75, 9.5, 12.5, and 19.0 mm. For each NMAS, two gradations were investigated. Materials utilized in this study included a coarse aggregate, fine aggregate, mineral filler, asphalt binder, and stabilizing additive. An unmodified PG 64-22 asphalt binder was used for all mixes. Cellulose fiber was used as the stabilizing additive. Samples having a range of air voids contents were prepared by varying the number of gyrations with the SGC. Gyrations of 10, 30, and 50 were used. These gyration levels provided approximately 5 to 10 percent air voids, which were above and below the desired density level in the field (6 percent air voids). The APA testing was conducted at two test temperatures 50C and 64C. All APA testing was conducted in a dry condition utilizing a wheel load of 445 N and hose pressure of 689 kPa.

For each NMAS (except the 19.0 mm NMAS), two break point sieves were used. The significance of the break point (BP) sieve is that this sieve identifies the point at which the gap in the SMA gradation begins. For the 4.75 mm NMAS, the two BP sieves were the 2.36 and 1.18 mm, while the 9.5 mm NMAS gradations utilized BP sieves of 4.75 and 2.36 mm. Similar to the fine gradations, the two 12.5 mm NMAS gradations utilized different BP sieves, 9.5 and 4.75 mm. The BP for the 19.0 SMAS gradation was the 4.75 mm sieve. Optimum asphalt contents for the eight mixes ranged from a low of 5.5 percent to a high of 8.3 percent. Within the mix design system for SMA, optimum asphalt content is defined as the asphalt content that provides 3.5 to 4 percent air voids.

Results from the APA device showed that at 50C, all of the mix combinations had permanent deformation less than 5.0 mm. This was significant because the Georgia Department of Transportation (GDOT) has set a permanent deformation criterion of 5.0 mm maximum for mixes to be placed in high traffic areas. Two of the mix combinations on this study had the highest asphalt contents (8.0 and 8.3 percent).

Of importance, these two mixes had also a permanent deformation of less than 5.0 mm. From these limited data, researchers concluded that it seemed to confirm that these mixes had stone-on-stone contact and thus were rut resistance. Mixes tested at 64C, as expected by the researchers, had higher permanent deformation (higher test temperature). However, researchers mentioned that the magnitude of the permanent deformation was still relatively low. The highest permanent deformation was 5.4 mm, which barely failed the GDOT criteria for testing at 50C. Therefore, based upon the APA testing, the authors concluded that the fine SMA mixture having both 4.75 and 9.5 mm NMAS can be designed and utilized as rut resistance overlays.

Xie et al. (2003) also used the APA device to evaluate and refine the design of SMA mixes having a 4.75 mm NMAS, compared with conventional NMAS SMA mixes. Researchers were interested in assessing the effect of the fraction passing the 0.075 mm sieve; also the requirements for the draindown basket were evaluated. Four different SMA mixes having a 4.75 mm NMAS were used. Two aggregates were included: granite and limestone. A single gradation was used, except that two fractions passing the 0.075 mm sieve were investigated: 9 and 12 percent. The 9 percent was evaluated to determine the potential for lower dust contents in 4.75 mm NMAS SMA mixes. The BP for this 4.75 SMA mixture was the 1.18 mm sieve. Marble dust was used as mineral filler. No fibers were used for this study.

A PG 64-22 asphalt binder meeting Superpave high temperature requirements above 67C was used for all the mixes. No polymer modified asphalts were used because they tend to mask the effect of the aggregate structure. A constant compactive effort was used for all designs. The design compactive effort (N_{design}) was 75 gyrations. Two air void levels 4 and 6 percent were used. There were a total of 8 designed mixes (2 aggregate types * 2 dust contents * 2 design air void levels).

The APA test temperature was set at 64C; a wheel load of 534 N and a hose pressure of 827 kPa were used. Samples used in the test were SGC specimens (height 115 ± 5 mm). A test temperature of 175C was used during the draindown test.

Initial observations showed that all mixes met the criteria for stone-on-stone contact required for SMA. Also, it was observed that none of the four limestone mixes met the VMA requirements for an SMA (17 percent minimum). Researchers reported that as the percent passing the 0.075 mm sieve ($P_{0.075}$) increased, optimum asphalt content decreased for mixes using both aggregates types. For granite mixes, increasing the $P_{0.075}$ by 3 percent (from 9 to 12 percent) generally reduced optimum asphalt content by 0.5 percent; however, for limestone mixes, increasing the $P_{0.075}$ by 3 percent, from 9 to 12 percent, decreased optimum asphalt content by two percent.

It was also found that mixes designed at 4.0 percent air voids had higher average optimum asphalt contents (5.9 percent) than the mixes designed at 6.0 percent air voids (5.1 percent). The 2.0 percent range in design air voids resulted in about 0.8

percent difference in optimum asphalt content. VMA values for the individual mixes ranged from a high of 18.1 percent to a low of 14.0 percent. VMA at optimum asphalt content was affected by the aggregate type and $P_{0.075}$. On average, the granite mixes had higher VMA (average 17.5 percent) than limestone mixes (average 14.3 percent). It was observed that when the $P_{0.075}$ increased, the average VMA of granite mixes decreased (from 18.1 to 17.1 percent); the average VMA of limestone mixes also slightly decreased (from 14.4 to 14.1 percent).

An ANOVA test was used to evaluate the effect of the main factors (aggregate type, dust content, and design air voids) and their respective interactions. Based on this analysis the researchers found that permanent deformation results from the APA device for a 4.75 mm SMA were relatively high compared to the conventional NMAS SMA (5 mm maximum, based on 689 kPa hose pressure and a load of 445 N). Authors suggested that two possible factors affected these high results, the result of using non-modified asphalt and the high ratio of sample height and NMAS used for the APA testing. It was also concluded that aggregate shape, angularity and texture played an important role in achieving the required design volumetric criteria for 4.75 mm NMAS SMA mixes. Based on the draindown test results, durability consideration, and relative comparison of APA testing results, researcher indicated that SMA mixes having a 4.75 mm NMAS can sometimes be successfully designed having gradations with aggregate fractions having the 0.075 mm sieve less than 12 percent. Gradations with aggregate fractions passing the 0.075 mm sieve of 9 percent can be utilized as long as all other requirements are met.

Open Graded Friction Courses (OGFC) are special mixes used to improve surface frictional resistance, minimize hydroplaning, reduce splash and spray, improve high visibility, and lower pavement noise level (Watson, Johnson, and Jared, 1988).

In a study by Cooley et al. (2000), the APA device, among other tests, was used to evaluate the use of cellulose fibers within OGFC mixtures. This study was accomplished by comparing cellulose and mineral fibers, both in the field and laboratory. The field portion of this study entailed a visual distress survey performed on six experimental OGFC sections located on I-75 in Georgia. The mixes were: D (Coarse OGFC), D16R (Coarse OGFC with 16 percent crumb rubber), DM (Coarse OGFC with mineral fibers), DC (Coarse OGFC with cellulose fibers), DP (Coarse OGFC with styrene-butadiene (SB) polymer), and DCP (Coarse OGFC with SB and cellulose fibers). These test sections were constructed in 1992, and a visual distress was done in 1998 to evaluate the performance of each section with respect to surface texture, permanent deformation, cracking and raveling.

The laboratory entailed testing specimens prepared with the Marshall hammer using a total of 25 blows per face. Four mix designs were conducted and included one aggregate source, one asphalt binder, and four forms of fibers. The gradation for these mixtures was identical and met a Georgia Department of Transportation (GDOT) 12.5

mm OGFC gradation. A granite aggregate was selected for this study. Of the four types of fibers used, three of them were cellulose, while the fourth was slag wool (mineral fiber). For all of the mixtures a PG 76-22 asphalt binder was used. This binder was modified with a styrene butadiene styrene (SBS) polymer.

Four types of laboratory tests were conducted. First, a test was used to quantify the amount of water absorbed into the OGFC mixtures containing the four fiber types. The second laboratory test conducted was the GDT-66, “Method of Test for Evaluating the Moisture Susceptibility of Bituminous Mixtures by Diametral Tensile Splitting”. The third laboratory test also evaluated the sensitivity of the different mixtures to moisture induced damage. The final laboratory test was conducted with the APA device. Three beam samples of OGFC were prepared using the loose cellulose and mineral fibers. Mixes with the loose cellulose had 17.1 percent of air voids, and the mixes with mineral fibers had 17.5 percent of air voids. These beams were prepared and tested in accordance with GDT-115, “Method of Test for Determining Rutting Susceptibility Using the Loaded Wheel Tester”, while submerged in water at 60C.

From the visual distress survey, researchers concluded that section DC performed well, if no better than the other five sections. The DC section had a relatively low amount of coarse aggregate pop-out, the lowest amount of reflective cracking and a very minor raveling. However, the DC section did have the highest permanent deformation at 4.1 mm. Permeability testing of the cores obtained indicated that the DC section also had the highest amount of permeability.

From the laboratory results, it was observed that all four mixes had similar volumetric properties at optimum asphalt content. However, the loose cellulose fiber mix did have slightly lower optimum asphalt content. Results of water absorption testing indicated that all four mixes had approximately the same rate of water loss. The TSR test and the boil test indicated that the cellulose fibers were comparable to the mineral fibers with respect to resisting moisture damage. TSR tests after three freeze-thaw cycles were satisfactory (above 70 percent retained strength) for all four mixes. The APA test was conducted for only the loose cellulose and mineral fiber mixtures at optimum asphalt content. Based on the permanent deformation results from the APA device, researchers indicated that the loose cellulose mixture had a lower permanent deformation after 8,000 cycles than did the mineral fiber mix. Finally, researchers concluded that the field and the laboratory data appeared to provided the same indications.

One possible use for the fine aggregate stockpiles (or sometimes called screenings) is for the thin-lift HMA applications. The thin-lift HMA layers have been used for most maintenance and rehabilitation applications.

In a recent study by Cooley et al. (2003), the APA device was used to determine: a) if permanent deformation resistance HMA mixtures could be attained with the aggregate portion of the mixture consisting solely of manufactured aggregate screenings; and b) to determine what effects, both a modified asphalt binder and a fiber modified additive might have on permanent deformation performance when screenings are applied.

To accomplish these objectives, two aggregate screenings (granite and limestone), two grades of asphalt binder (PG 64-22 and PG 76-22 (SBS modified)), and a fiber additive (cellulose) were selected. The material variables were combined to produce eight test mixtures. Each of these mixtures was designed at three different air void contents (4, 5, and 6 percent) and then tested in the APA device. The APA test was conducted at 64C. The samples were loaded with a 2.54 cm diameter linear hose inflated at 690 kPa with a steel wheel applying a 445 N load to the hose. The steel wheel made 16,000 passes (8,000 cycles).

Based upon the analysis of the permanent deformation data of this study, it was concluded that mixes having screenings as the sole aggregate portion can be successfully designed in the laboratory to be rut resistance. It was observed that screenings type, the existence of cellulose fiber, and design air void content significantly affected optimum binder content. Of these three factors, screenings type had the largest impact on optimum binder content followed by the existence of cellulose fiber and design air void content, respectively. It was also concluded that screenings type and the existence of cellulose fiber significantly affected air voids in mineral aggregate.

Researchers pointed out that if the screenings mix is intended for a low volume roadway where long-term durability is most important, then mixes should be designed at 4 percent air voids. On the other hand, when a designed mix is intended for a roadway that will contain either heavy or slow/standing traffic, design air void contents above 4 percent may be required. Based on the preliminary results, researchers concluded that VMA alone may not be a good indicator of rut resistance. It was suggested that a maximum VFA criterion of 80 percent may be used to help identify mixes with a high potential for permanent deformation.

Finally, researchers concluded that screenings material, design air void contents, and binder type significantly affected laboratory permanent deformation. Of these, binder type had the largest impact followed by screening material and design air voids content, respectively. Mixes containing a PG 76-22 binder had significantly lower permanent deformation than mixes containing a PG 64-22. Mixes designed at 4 percent air voids had significantly higher permanent deformation than mixes designed at 5 or 6 percent air voids.

In another recent study by Mohammad et al. (2003), the APA device was used to assess the fatigue and permanent deformation properties of Superpave mixtures when using recycled polymer modified asphalt mixes. A SBS elastomeric polymer modified asphalt cement (PMAC) meeting Louisiana DOTD specification for PG 70-22M was selected. The PMAC was formulated from an AC-30 binder and 3 percent SBS by weight. An eight year old polymer modified asphalt binder (referred as US61 binder) was recovered from a wearing course mixture located on route US61 in Livingston Parish, Louisiana. A 19.0 mm Superpave mixture was selected for this study. This mixture was evaluated with a blend of asphalt cement that included 0, 20, 40, and 60 percent of recovered binder (previously mentioned) from the field aged mixtures and using original aggregates. Specimens were prepared using the SGC at 4 percent air voids and using an N_{design} = 125 gyrations. The optimum binder content was 4.2 percent. A Bohlin CVO dynamic shear rheometer, DSR, was used to investigate the rheological behavior of the virgin PMAC and field recovered binder. The Bending Beam Rheometer was used to measure the low temperature creep response of PAV aged binders. The indirect tensile stress (ITS) and strain were used to determine the tensile strength and strain of the mixtures. This test was incorporated in the study to ensure the durability of the mixtures would not be compromised while the permanent deformation resistance of the mixtures was being improved. The repeated shear at constant height test (RSCH), the indirect tensile creep test, and the beam fatigue test were also used. The APA test was conducted at 64C, using a vertical load of 444.4 N, 700 kPa hose pressure and a total of 8000 cycles.

From the ITS results, it was observed that as the percentages of the US61 binder was increased, the IT strength was increased and the IT strain at failure was decreased. It appeared that the potential of fatigue cracking of asphalt mixtures increased as the content of the US61 binder increased. From the beam fatigue test it was observed that mixtures containing 0 percent of US61 binder showed the best fatigue cracking resistance in terms of longer fatigue life than the other mixes. From the indirect tensile creep test it was observed that the steeper the creep slope, the higher permanent deformation susceptible the asphalt binder became. From the RSCH test, it was observed that high permanent shear strain values presented high rut susceptibility of mixtures. There was no significant difference between the mean permanent shear strains of mixtures containing 0 and 20 percent US61 binders. However, the mean permanent shear strain decreased gradually with an increase in the US61 binder from 20 to 60 percent in the mixtures. Researchers also observed that as the percentage of US61 binder mixed with virgin PMAC binder increased, higher oxidation was obtained.

Finally, from the APA results, similar to the indirect tensile creep test results, it was observed that mixtures containing higher US61 binder percentages presented lower APA rut depths than those mixtures with lower US61 binder percentages. It was also observed that as the binder permanent deformation factor, $G^*/\sin(\delta)$, increased, the rut resistance of the mixtures tended to increase resulting in a lower APA rut depth.

In a different study conducted by Zaniewski, and Nallamothu (2003), the APA device was used to evaluate the performance of the asphalt concrete using three different asphalt binder grades. The research included mix designs for the base and wearing courses. The base course was a 37.5 mm mix with a 100 percent of limestone aggregates and the wearing course was a 12.5 mm mix with 95 percent slag and 5 percent of crushed limestone (the crushed limestone was finer than 4.75 mm). HMA samples were obtained from the field (from a recent rehabilitated project using the PG 76-22 binder) to compare their permanent deformation with specimens made in the laboratory when using the APA device.

The binders used were PG 64-22, PG 70-22, and PG 76-22. The PG 76-22 was a modified binder using Styrene Butadiene Styrene (SBS) copolymer. APA samples were prepared using the SGC to a 7 ± 0.5 percent air voids. All samples were compacted to a height of 75 mm. Twelve specimens were made using the HMA from the field for each mix design (12.5 mm and 37.5 mm). Six specimens were mixed in the laboratory and compacted for each mix design using the three different binders. All the specimens were tested at 60C with a hose pressure of 690 ± 34 kPa and a wheel load of 445 ± 22 N. Permanent deformation measurements were taken after 8000 cycles.

From the APA results it was demonstrated that the mixes containing polymer-modified PG 76-22 asphalt performed better than the mixes with unmodified binders.

Comparison of the mixes with the unmodified binders produced mixed results. According to researchers, the expectation was that PG 70-22 mixes should have performed better than PG 64-22 mixes and this was the case for 12.5 mm mix. However, the 37.5 mm mix did not show a statistically different performance with the unmodified binders. The 12.5 mm mix predominately contained slag aggregates, which had very high surface texture. All the 12.5 mixes showed lower rutting potential than the 37.5 mm mixes, which had 100 percent limestone aggregates. Therefore, researchers assumed that this difference in performance was attributed to the texture of the aggregate.

Researchers compared the results from the rehabilitated project (using modified binders) with mixes that have been used on other projects with similar material characteristics (using unmodified binders). They found that the 37.5 mm mix with the PG 76-22 binder had an average rut depth of less than 3 mm. The average rut depth for the other projects in the state had rut depths of approximately 4.5 mm.

One concern they had about the APA device (for this study) was that the APA samples were limited to 75 mm tall, and when using the 37.5 mm NMAS a specimen of 150 mm height was needed. They pointed out, that generally in asphalt testing the sample dimensions should be four times the nominal-maximum aggregate size diameter (APA sample size is only appropriate for mixes with a nominal-maximum aggregate size of 19.0 mm).

In one study conducted by Bennert et al. (2003), the APA was used to try to develop a pass/fail criterion for the mixtures used by the New Jersey Department of Transportation (NJDOT). The gradations used for this study consisted of two coarse and two fine gradations both with a two NMAS (19.0 mm and 12.5 mm). The 12.5 mm fine gradation passed through the restricted zone. Eleven different mix designs were developed. Six of them were designed for very heavy traffic (ESAL's > 30 million), four were designed for heavy traffic (3 to 30 million ESAL's), and one was designed for medium to low traffic (0.3 to 3 million ESAL's). Three different asphalt binders (PG 64-22, PG 70-22, and PG 76-22) were used. APA samples with a height of 77 mm and a target air void content of 7 ± 0.5 percent were compacted using the SGC. The APA test was conducted at 64C with a hose pressure of 690 kPa and a wheel load of 445 N.

Results from the APA device indicated that the mixes designed for the very heavy traffic (12.5 mm both coarse and fine graded) sustained the lowest amount of rutting, with the modified asphalts (PG 76-22) having the least. The mean permanent deformation was 3.0 mm. It was also observed that as the design traffic levels went down, the APA permanent deformation increased. For the mixes designed for the medium traffic level (12.5 mm and 19.0 mm, both coarse and fine graded), it was concluded that the mean permanent deformation obtained was 5.01 mm. Finally, for the mixes designed for the medium to low traffic level (12.5 mm), it was concluded that the mean permanent deformation obtained was 8.75 mm.

Based on these APA results, researchers proposed a maximum permanent deformation (pass/fail) criterion for use in mixtures for future projects. The criteria was to use a maximum permanent deformation of 8.0 mm for mixes designed for medium traffic level, a maximum permanent deformation of 5.0 mm for mixes designed for heavy traffic level, and a maximum permanent deformation of 3.0 mm for mixes designed for very heavy traffic level.

In another study conducted by Prowell (2001), the Virginia Department of Transportation used the APA and the Georgia Loaded Wheel Tester (GLWT) to evaluate their special provisions, for the use of stabilized and modified mixes. The study evaluated three modifiers and two types of fibers (stabilizers) for hot mix asphalt (HMA) commonly available in Virginia. Ten sections were constructed in the eastbound lane of I-66 just west of Manassas, Virginia. Approximately 25 mm of pavement was milled over the entire project and replaced with 38 mm of new HMA. In the test section three mixes were used, two VDOT dense-graded mixes, SM-2A and SM-2C, and a Superpave 12.5 mm nominal maximum size (NMS) referred as SM-12.5 mix. The "A" denoted a 50-blow Marshall design with a viscosity-graded AC-20 (PG 64-22), and the "C" denoted 75-blow Marshall Design with AC-30 (PG 70-22). The "M" suffix in SM-2A referred to a mix containing modified asphalt, and the "S" referred to a mix containing a stabilizer (fiber). Both SM-2 mixes contained recycled asphalt pavements, whereas the Superpave SM-12.5 mix did not. The Superpave SM-12.5 mix was designed for 10 million equivalent single axle loads (ESAL) over 12-

year design life. The design asphalt content chosen for all mixes was 4.5 percent air voids.

The modified asphalts used complied with the specifications for performance grade (PG) 76-22. The methods of modification used to produce PG 76-22 were to use styrene-butadiene-styrene (SBS), an air-blowing process (AB), and a chemical gelling agent supplemented with a small dose of styrene-butadiene-rubber. All three modifiers were included in the SM-A and SM-12.5 mixes. The stabilizers used were polypropylene fibers and polyester fibers. The two stabilizing agents were included only in the SM-2A mix.

Beam specimens, 75 mm x 125 mm x 300 mm, were compacted with a kneading action in a rolling wheel compaction machine. The target for air voids was 7 percent. The beams were tested at 49C, with a vertical load of 553 N, and the hose inflation pressure of 830 kpa. In the field, rut measurements were taken on the road surface with a Face Dipstick 2000 after 45 months of use. No consistent differences were observed between the rutting performance of the sections using the SM-2 gradation, which passed through the restricted zone, and the sections with the SM-12.5 gradation, which passed below the restricted zone.

Both the GLWT and the APA indicated that the mixes would be rut resistant, but neither device accurately predicted rut depths in the field. However, according to the author, both devices can be used to indicate the rut resistance of a mix. The Author also concluded that a PG 76-22 can be used to produce rut-resistant mixes at low Superpave gyratory compactor (SGC) air voids using the original (1994) Superpave compaction levels. Finally, it was concluded that the SBS, AB, and gelled modifiers provided equal rut resistances in the field.

Sargand and Kim (2001) conducted a research with the objective of determining the effect of the aggregate characteristics and gradations and polymer modifier on pavement permanent deformation and fatigue performance. It was also intended to determine the correlation of predicted performance of pavement system by laboratory methods with accelerated load test. Seven laboratory test methods, the APA, a triaxial repeated load test, a uniaxial static creep test, a flexural beam fatigue test, the indirect tensile resilient modulus test, the indirect tensile strength test, and a moisture susceptibility test, were employed to evaluate permanent deformation resistance. Two types of aggregates (limestone and gravel), four aggregates gradations with a NMAS of 12.5 mm, and three types of asphalt binder were used to prepare test specimens. Limestone gradations were adjusted to pass above, below and through the restricted zone. The gravel blend was kept on the coarse side of the density line, passing below the restricted zone. Two of the binders used for this study were polymer modified (SBS, and SBR modified PG 70-22), and one unmodified PG 70-22 (used as a control). The actual continuous PG grades of the unmodified, SBS, and SBR modified binders were estimated to be PG 72-25, PG 77-23, and PG 76-26, respectively.

Cylindrical and beam tests specimens were prepared using the SGC and a static compression machine, respectively. All mix designs (unmodified and modified) followed the Superpave procedure. The optimum asphalt contents for the unmodified asphalt mixes were 6.4 percent, 5.7 percent, and 5.7 percent for the coarse, intermediate, and fine gradation samples, respectively. For the case of the polymer modifiers mixes, the optimum asphalt content was reduced, because the absorption of the aggregates with modified asphalt was lower. Optimum asphalt contents of the SBS mixes were 6.4 percent, 5.4 percent, and 5.4 percent for the coarse, intermediate, and fine gradation samples, respectively. Optimum asphalt contents of the SBR mixes were 6.0 percent, 5.1 percent, and 5.1 percent for the coarse, intermediate, and fine gradation samples, respectively.

APA test specimens 150 mm diameter x 76.2 mm in height with 7 ± 0.5 air void contents were prepared using the SGC. For the triaxial repeated load test, the uniaxial static creep test, the Diametral resilient modulus test, and the indirect tensile strength test, specimens 150 mm in diameter x 115 mm in height with a $N_{design} = 109$ to have 4 ± 0.5 air voids content were also prepared using the SGC. For the flexural fatigue test, a set of beam specimens (381 mm x 63 mm x 50 mm) were compacted to 8 ± 0.5 air void contents using a static press with a load of 534 kN. APA testing was conducted at 60C in both, dry and wet conditions, with a 511.5 N wheel load and 689.4 kPa hose pressure. Permanent deformation was measured at 5, 500, 1000, and 8000 cycles. For the triaxial repeated load test, the specimens were subjected to an 827 kPa deviator stress for 10,000 cycles and a confining pressure of 138 kPa. The deviator stress was applied 0.1 seconds in a haversine form and had a rest period of 0.9 seconds. For the uniaxial static creep test, a static creep stress of 414 kPa was applied for 3,600 seconds, followed by 3,600 second of recovery. In this test, duplicate samples were tested at 60C and 40C. For the flexural beam fatigue test, the strain applied on the samples was 275 microstrains at a frequency of 5 Hz. The indirect tensile resilient modulus test was performed at three temperatures (5, 25, and 40C) with a repeated haversine wave form (0.1 second loading time and 0.9 seconds rest period). The total loads applied to the samples at 5, 25, and 40C were 7,000 N, 4,000 N, and 2,000 N, respectively. For the indirect tensile strength test, compressive loads were applied on the asphalt specimen along the diametral axis at a deformation rate of 50 mm per minute until failure. Finally, in the case of the moisture susceptibility test, two aggregates (limestone coarse gradation and gravel blend) and two asphalt binders (unmodified and SBS) were used. The specimens of about 63.5 mm height were prepared with the SGC with 100 mm diameter mold. TSRs were determined after 1, 2, and 3 cycles of freeze/thaw conditioning for limestone mixes and only after 3 cycles of freeze/thaw conditioning for gravel mixes.

From the analysis of the results, researchers concluded that aggregate angularity was the most significant factor influencing permanent deformation, Mixes with crushed limestone exhibited much less permanent deformation than mixes with rounded gravel. The APA, the triaxial repeated load, and the uniaxial static creep tests indicated that aggregate type, gradation, and binder type were all statistically significant factors in permanent deformation development. Researchers observed that an intermediate gradation passing through the restricted zone performed as well as the other gradations. A coarse gradation passing below the restricted zone showed the most rutting potential, while a fine gradation passing above the restricted zone exhibited the least rutting potential. Researchers indicated that these conclusions just mentioned, regarding the effect of aggregate gradation on permanent deformation, were influenced by the different asphalt binder film thickness associated with each mix with similar air void content. It was also indicated that polymer modified mixes showed significantly reduced temperature dependency, improved strain recovery, and reduced permanent deformation susceptibility when compared to unmodified mixes.

These differences were most noticeable in dynamic testing and in gravel mixes with less aggregate interlock. For many mixes, it was mentioned that the permanent deformation measured by the wet APA test was lower than the rut depths measured by the dry APA test.

Based on the laboratory test results, three mixes were chosen for further evaluation at the Ohio Accelerated Pavement Loading Facility (APLF). The three mixes were placed in the APLF using materials from the same sources as was in the laboratory tests. From this research, the researchers observed that when the nominal air temperature was increased from 40C to 50C, permanent deformation increased more in the mix with an unmodified binder than in a similar mix with SBS modified binder. They also observed that when wheel speed was increased from 3 to 8 km/h, permanent deformation resistance of the SBS modified mix was significantly improved in comparison with permanent deformation resistance of the unmodified binder. Finally, researchers indicated that for the three mixes tested, APA test results (at 60C) correlated well with the APLF test results at 3 km/h and 40C. The speed of the APA wheel was closer to 3 km/h than 8 km/h.

In Tennessee, the APA device was used to determine if it is readily distinguished between differing properties of HMA (Jackson and Baldwin, 1999). Mixes designed by both Marshall and Superpave mix design methods were evaluated. Both modified and unmodified binders including AC-20, PG 76-22, PM AC-20, PG 64-22, and MG 20-40, were tested.

Specimens were compacted in the SGC to achieve 7 ± 1 percent air voids (typical value for Tennessee). The compacted samples were subjected to a total of 8000 cycles in the APA. Rut depth measurements were obtained at a seating load of 10 cycles, and intermediate loadings of 500, 1000, 4000, and 8000 cycles. The wheel loading conditions were held constant at 445 N, and a hose pressure of 690 kPa was used. The chamber temperature was set at 49C.

Data indicated that there was a higher occurrence of excessive rutting (greater than 5 mm) in the conventional Marshall surface mixes, as opposed to the other type of mixes. Every mix tested that exhibited excessive rutting in the APA (> 5 mm), whether designed by the Marshall or Superpave mix design methods, contained a PG64-22 or AC-20 binder.

It was also found that there was a slight (weak) tendency for increased rutting, with an increase in binder content, especially above about 6.5 percent. The dust content (percent passing the # 200 sieve) was also analyzed. It showed that, within reasonable limits, it didn't correlate well with performance of HMA in the APA. The dust-to-asphalt ratio analysis suggested that the APA was more sensitive to its effect than either, the binder content or dust content alone. Finally, it was illustrated that the APA results at 500 cycles correlate well with the results at 8000 cycles (R^2=0.93). After 500 cycles, any mix with a rut depth greater than 1.5 mm (0.058 in) experienced excessive rutting (> 5 mm) at the end of the 8000 cycle test.

In a different study conducted by Albritton et al. (1999), the APA device was used to evaluate permanent deformation of polymer modified HMA mixtures. The experimental design called for the use of nine different modifiers, each to be used in sections approximately 0.84 km long in the 38.1 mm top binder and 38.1 mm surface courses. The nine polymers used were: Kraton (SBS Block Copolymer), Ultrapave (SB Latex), Novophalt (LDPE), Styrelf (SB Block), GF-80 rubber (-80 Mesh Tire Rubber), Seal-O-Flex (SBS), Vestoplast-S (Ethylene, Butylene, Terpolymer), Multi-grade (Gelled asphalt), and Cryo-80 Mesh (Cryogenic Ground Rubber).

Transition sections, also approximately 0.84 km long, separated the test sections. All test sections as well as the control section were in the northbound lanes of I-55 and had essentially the same type and amount of traffic loading. The control section with no modifier comprised the remainder of the northbound lanes outside the test sections and transitions and contained at least 2 miles having generally the same topography as in the rest of the sections. The polymer modified binders were used in the HMA for the top two pavement layers.

Asphalt cement grade AC-20 was the base asphalt for all the modified asphalt cement binders. The control section utilized AC-30 asphalt cement. The NMAS of the mixtures was 19.0 mm. Both designs (binder course and surface course) included reclaimed asphalt pavement (RAP) and the addition of 1 percent hydrated lime to reduce stripping. For the modified mixes, the base petroleum asphalt cement was grade AC-20. The binder course had 4.8 percent and the surface course had 5.2 percent of it by weight of the total mix. The RAP used in both had an AC content of 5.15 percent. The RAP contributed 21 percent of the total AC used in the binder mix and 10 percent of the total AC used in the surface mix.

During the placement of the modified hot mix pavement sections, samples of the mix were taken to conduct asphalt acceptance tests in the field laboratory. For the binder course, the laboratory air voids were in the range of 3-5 percent with the field air voids ranging from 4-8 percent. In all the cases for the binder course, the air voids from the cores were higher than those from the laboratory. All laboratory specimens where prepared by using the Marshall test (75 blows). The SGC was also used to determine densities of 6 in diameter pills at 7 percent air voids. Twenty-four samples were made for each modifier for the right lane pavement and these samples were to be tested later in the APA device.

The APA was used to test cores and pills of the various modifiers. All APA tests were conducted at 49C and at 64C in a dry condition. Permanent deformation measurements were registered after 8,000 cycles. For the pills, researchers found that the control mix experienced the greatest amount of permanent deformation and the Styrelf modifier experienced the least amount of permanent deformation. For the cores, the permanent deformation observed in both the Cryopolymer Rubber and Ultrapave modifiers exceeded the Control mix, and the Seal-O-Flex modified experienced the least amount of rutting. At 64C, the Control mix experienced the greatest amount of permanent deformation and the Styrelf modifier experienced the least amount of permanent deformation. At 49C, the permanent deformation experienced by the Cryopolymer Rubber and Novophalt modifiers exceeded the Control mix, and the Stryrelf modified experienced the least amount of permanent deformation.

Researchers concluded that the comparison of laboratory acceptance tests conducted during construction and cores taken from the pavement the next morning showed that the laboratory air voids were closer to the design air voids than the field results. They also indicated that results to date indicate all the modifiers are out-performing the control section, both in terms of roadway permanent deformation and permanent deformation in the APA. It was also indicated that the selection of a modified asphalt binder grade based on the high temperature component of the PG designation could be quite inappropriate for a given project, especially when rubber modifiers are considered for use in HMA. Finally, researchers mentioned that the APA test results correlated well with the field permanent deformation measurements for the polymer modifiers, indicating the potential for using the APA to predict the relative permanent deformation performance of this type of modifier.

2.3.3. Variability of the APA

Some researchers have been interested in testing the variability of the APA (Sholar and Page, 1999). The objective of this study was to analyze the variability of the APA in terms of rutting potential of four Superpave mixes: two 12.5 mm mixes, one coarse graded and one fine graded, each of the same aggregate type; and two 9.5 mm mixes, one coarse graded and one fine graded, containing an unmodified binder, AC-30. A comparison between the automated data recording system and the manual method of recording was also included in the research.

The two coarse graded mixes had gradations that passed below the restricted zone. The two fine graded mixes had gradations that passed above the restricted zone.

The N_{design} = 96 gyrations for coarse graded mix and 86 gyrations for fine graded mix. In this study, 36 beams were made with a target air void content of 7 ± 0.5.

The test temperature was 64C, the hose pressure was set to 689.5 kPa, and the vertical load was set to 450 N. A 25 cycle seating load was applied, and initial rut depths were manually recorded. Manual measurements were also recorded at 500, 2000, 4000, and 8000 cycles.

Sholar and Page tried to find a relationship between air voids and rut depth in this study. The results indicated that there was no significant relationship between the air void content and the rut depth (R^2=0.29) within the range of air voids tested (7 ± 0.5).

The research concluded that the variability between tests and the locations was high; but using the average rut depth for the three beams, it was possible to get fairly consistent results from test to test. It was also found that the center position on this particular APA device consistently resulted in higher rut depths than the left or right positions. Results also indicated that the 12.5 mm mixes rutted less than 9.5 mm mixes and that the coarse graded mixes rutted less than the fine graded mixes for a given nominal maximum size aggregate.

The automated data acquisition system used by Scholar and Page (1999) for this study was very accurate when compared to the manual method of measuring rut depth, and was much less time consuming. Therefore, the automated data acquisition system was chosen to be used on all mixes in the future, with occasional manual measurements taken to verify the accuracy of the automated system.

2.3.4. APA and other ways to evaluate permanent deformation

One study conducted by Bashin et al. (2003), used a wide variety of HMA materials and mixture designs from six states in the central region of the United States. These mixtures were selected to be evaluated in the laboratory by the simple performance test procedures (STP) (dynamic modulus, flow number, and flow time), the Superpave shear test using frequency sweep at constant height (SST-FSCH), and the APA device as a torture test. The STP tests were used as an indicator of permanent deformation (limited to plastic deformation of the HMA layer alone and not deep layer rutting). The main objective was to evaluate the ability of the STPs to properly characterize highly polymer-modified HMA mixtures (designed to exhibit low dynamic modulus but high recovery strains) and to compare the results from the dynamic modulus test with the rest of the tests.

Twelve HMA mixtures were obtained from different state DOTs. One mixture (NMAS of 9.5 mm), which was intended to be rut susceptible, was designed using rounded gravel and sand with an PG 64-22 asphalt binder. Two additional mixtures (NMAS of 9.5 mm) were designed using highly polymer-modified asphalt, PG 64-40, to evaluate the tests using mixes with low modulus but high recovery. One of the mixtures containing PG 64-40 asphalt was designed using crushed river gravel aggregate and the other using rhyolite aggregate. Four mixtures were designed using a PG 64-22 binder. Two of them (Basalt and limestone) had NMASs of 19.0 mm and the other two (Twin Lakes gravel and granite mountain) had a NMAS of 9.5 mm. One mixture (monzonite, vado) was designed using a PG 82-16 with a NMAS of 19.0 mm. One mixture (granite + limestone) was designed using a PG 70-28 with a NMAS of 12.5 mm. One mixture (limestone) was designed using a PG 76-22 with a NMAS of 12.5. Finally, two of the mixtures (Nova-Scotia granite, and Hard rock crushed gravel, respectively) were designed using a PG 70-22M and PG 70-22 binders, both with a NMAS of 12.5 mm.

All test specimens were molded using the mixture design developed by individual agencies (DOTs). For the dynamic modulus, flow time, and flow number tests, the specimens were 100 mm in diameter and 150 mm in height with a gauge length of 100 mm. These specimens were prepared by compacting a 150 mm diameter and 175 mm height specimen using the SGC, coring it, and sawing the ends. It was ensured that the air voids in the cored and finished specimens were between 6 and 8 percent. The APA and SST test samples were prepared using the SGC. Two replicates were used for the SST test, and three replicates were used for the APA device. The samples were 150 mm in diameter and 50 mm in height.

The APA test was conducted in a dry condition at 60C with a pressure of 689 kpa in the hose and a vertical load of 440 N. The relevant parameters from the APA device results used for evaluation were the final rut depth at 8000 cycles and the creep slope of the linear portion of the permanent deformation versus the number of cycles curve.

The HWTD consisted of oscillating a 200-mm diameter and 47-mm wide steel wheel loaded with 705 N over a SGC compacted specimen 63 mm in height submerged in water at 50C. Permanent deformation of each specimen was recorded with reference to the number of passes of the loaded wheel.

The SST-FSCH test was performed at frequencies of 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz. A constant and controlled shear strain (100 microstrains) was applied. The parameters related to permanent deformation evaluated in this test were G^* and $G^*/\sin\delta$ at 10 Hz and 40 C, and G^* and $G^*/\sin\delta$ at 1Hz at 40C.

The dynamic modulus test was conducted at 25, 10, 5, 1, 0.5, 0.5, and 0.1 Hz and -10, 4, 20, 38, and 54.4C in an unconfined condition. The parameters related to permanent deformation evaluated in this test were E^* and $E^*/\sin\Phi$ at 10 Hz and 54.4C, and E^* and $E^*/\sin\Phi$ at 1 Hz at 54.4C.

The Flow time (static creep) test was conducted at 54.4C in an unconfined condition. A stress level of 0.207 MPa was selected. The parameters related to permanent deformation evaluated in this test were the flow time value, the slope parameter (m) and the intercept parameter (a). The Flow number (dynamic creep) test was conducted at 54.4C. The stress was applied using a haversine waveform with a wavelength of 0.1 seconds followed by a rest or dwell period of 0.9 seconds. The parameters related to permanent deformation evaluated in this test were the flow number and the slope parameter (b).

Three different approaches were used to perform the analysis. The first method was to rank the mixtures in terms of permanent deformation resistance based on various parameters for different tests. The second approach analysis was to group the mixtures based on the comparison of their means at a significance level of $\alpha = 0.05$. The higher the total number of groups the more sensitive the test parameter was to differentiate between the mixes. The third approach was to determine direct correlation between the APA and Hamburg results to the other test parameters.

Based on the tests conducted and the analysis of the results, researchers made the following conclusions: flow time slope and flow number provided the best correlations with the APA and HWTD permanent deformation results. It was pointed out that the correlation between the APA rut depth and the flow time value was better than that between the APA rut depth and flow number. It was also concluded that the APA rut depth correlated with the flow number and flow time parameters better than the APA creep slope correlated with these values.

Correlations of the APA tests parameters with dynamic modulus and FSCH tests were not as good as correlation of the APA tests parameters with the flow time and flow number test parameters. It was noticed that the correlations of E*/sin Φ or G*/sin δ with the APA test parameters were better than the correlations of E* or G* alone with these parameters. Correlations of the Hamburg permanent deformation results with the other tests parameters were similar to the correlations between the APA rut depth and those same parameters. Flow number value, flow time slope, E*/sin Φ at 1 Hz, flow number slope, and flow time value were among the best five correlations both with the HWDT and the APA rut depths.

Using the Duncan multiple range test, flow time slope and flow number slope separated the mixes into six groups of statistically equivalent values, which indicated they offered more sensitivity than the flow time or flow number values. Duncan groupings for |E*| placed the PG 64-40 mixtures in the worst performing mixtures regarding permanent deformation. These groupings were quite contrary to those for the APA parameters. Flow time slope and flow number slope categorized the PG 64-40 mixes in groups similar to the APA rut depth. Based on this finding and assuming that APA related well to pavement permanent deformation, flow number and flow time slope appeared to relate well to predicted permanent deformation in a pavement.

Finally, the researchers concluded that the APA can be used, at best, only as an indicator of permanent deformation susceptibility and not as a valid tool for predicting pavement rutting performance of the mixes. They also emphasized that dynamic modulus is a stiffness test related to thickness design of asphalt pavement layers subjected to vehicular loads at highway speeds and may not always relate to HMA permanent deformation resistance, particularly when polymer modified asphalts are to be used. Researchers suggested that other tests in addition to dynamic modulus should be considered to assess permanent deformation of HMA paving mixtures accurately.

In another study conducted by Chowdhury et al. (2001), the APA and the Superpave Shear Tester (SST) devices were used to evaluate the effect of the restricted zone on permanent deformation of HMA while the shape and texture of the aggregates remained constant. The concept was to compare properties of HMA containing the same aggregate type with three different gradations: passing through, above and below the restricted zone. The aggregates tested were crushed limestone, crushed granite, partially siliceous river gravel, and a combination of partially crushed river gravel (for the coarse fraction) and natural sub-rounded sand (for the fine fraction). The nominal maximum size of aggregate was 19.0 mm for each case. The asphalt used for this study was a PG 64-22 binder. Twelve HMA mixtures (three gradations for each of four aggregate types) were designed for performance testing the SST and APA device. The tests performed using the SST were the simple shear at constant height (SSCH), frequency sweep at constant height (FSCH), repeated shear at constant stress ratio (RSCSR), and repeated shear at constant height (RSCH).

The FSCH test was used for the river gravel mixtures and was performed at three different temperatures (4, 20, and 46C) with three different asphalt contents (low, design, and high). The same tests with limestone, granite and natural sand mixtures were performed using one asphalt content and at only one temperature (46C). The RSCH test was performed only with river gravel mixtures using three gradations with 5000 load cycles. The RSCSR test was performed with 3 percent air voids and high asphalt content at 46C. All twelve mixtures were tested in the APA device in a dry condition. Four cylindrical specimens for each mixture were prepared using the SGC. Specimen size was with 150-mm diameter and 75-mm height. Only two pairs of specimens were prepared for each mixture. Specimens were prepared with 4 percent air voids and the test was conducted at 64C. Each set of specimens were subjected to 8,000 load cycles.

From the SST results, researchers observed that the gradations passing through restricted zone didn’t have a significant impact on permanent deformation. It was also observed that consistent permanent deformation rankings for HMA were obtained with the different tests performed. From the APA results, there was no indication that mixtures passing through the restricted zone produced the highest permanent deformation. In most of the cases, below the restricted zone mixtures produced highest permanent deformation. Finally, it was observed that at high temperatures, HMA mixture rheology was predominately affected by the aggregate, but at low temperatures, it was predominately affected by asphalt content.

Zhang et al. (2002), made comparisons of two fundamental and one simulative test for determining the permanent deformation of hot mix asphalt mixtures. The fundamental tests used were the repeated shear at constant height (RSCH) and the repeated load confined creep (RLCC). The simulative test was the APA device. The material used for this study consisted of two coarse aggregates, seven fines aggregates, and a single PG 64-22 binder. The seven fine aggregates were numbered as follows: FA-2 (natural quartz, no processing), FA-3 (natural quartz, uncrushed), FA-4 (mined stone, cone crushed), FA-6 (mined limestone, crushed by impact crusher), FA-7 (mined granite, cone crusher), FA-9 (mined diabase, impact crusher), and FA-10 (natural sand). Five 9.5 mm NMAS gradations were used. The gradations followed the same trend from the 12.5 mm sieve down to the 4.75 mm sieve. From the 4.75 mm sieve to the 0.15 mm sieve, they varied the rest of the material passing the sieves. The difference was the way they passed or avoided the restricted zone. For this study, these gradations were: above the restricted zone (ARZ), below the restricted zone (BRZ), through the restricted zone (TRZ), humped the restricted zone (HRZ), and cross the restricted zone (CRZ). All the gradations used the same passing the 0.075 mm sieve (No. 200 sieve)-P200 material to eliminate P200 as a variable. The compactive efforts used in the mixes were N_{design} = 75, 100, 125 for 0.3-3 million ESALs, 3-30 million ESALs, and ≥ 30 million ESALs, respectively.

All test specimens for the RSCH testing were prepared at 0.3 ± 0.5 percent air voids to the required dimensions and tested at 50C. The test was performed to 5000 load cycles. The RLCC test was conducted at 60C with a test loading of 138 kPa confining pressure and an 827 kPa normal pressure. The target void for the specimens tested was 4.0 ± 0.5 percent. A deviator stress along with a confining stress (3600 load cycles) was applied for 1 hour with 0.1 second load duration and 0.9 second rest period intervals.

From the comparison and analysis of the results, researchers concluded that the three test methods used to evaluate permanent deformation had good correlations with each other. They observed that the initial shear deformation and the deformation in the RSCH test for various mixes were different, and they were correlated with the plastic shear strain in RSCH test. Mixes with higher initial shear strain and higher deformation rate had permanent shear strain.

Researchers also indicated that the good correlation between slopes from the RSCH and APA, as well as the significant correlation between respective intercepts, showed similar behavior for HMA mixtures under RSCH and APA test loading conditions. Finally, a critical rut depth for using in the APA test methodology (at a test temperature corresponding to the high temperature of PG grading system and after 8000 cycles) of 8.2 mm was recommended.

2.3.5. Field Results Correlated to APA Results

In a recent study by, Kandhal and Cooley (2003), attempts were also made to correlate field rut depth measurements to APA results. For this study, 10 HMA mixes from three different full-scale pavement research projects of known field rutting performance were used. The three projects were: WesTrack (Nevada) with 3 mixes, the Minnesota Road Research Project (MnRoad) with 3 mixes, and the FHWA Accelerated Loading Facility (ALF) at Turner-Fairbank Highway Research Center (Virginia) with 4 mixes. The asphalt binder originally used on the projects were: PG 64-22 for the WesTrack project, AC-20 and 120/150 penetration-graded binder for the MnRoad project, and a AC-10, AC-20 and a polymer modified binder for the ALF project. For the MnRoad project, it was mentioned that the AC-20 and the 120/150 have performance grades of the PG 64-22 and PG 58-28 binders, respectively. For the ALF project it was mentioned that the AC-10, AC-20 and SBS polymer modified binder had performance grades of PG 58-22, PG 64-22 and PG 82-22, respectively.

The factors considered for the projects were: specimen type (beams and cylinders); hose diameter (standard 25 mm and 38 mm); test temperature (high temperature of standard performance grade based on climate and 6C higher than high temperature of standard performance grade); and air void content (4.0 ± 0.5 percent and 7.0 ± 0.5 percent). Three different gradations were used for the projects; Westrack project used one gradation, 19.00 mm; MnRoad project used two gradations, 12.5 mm and 19.0 mm; and AFL project used one gradation, 37.5 mm. The specimens prepared for this study closely matched the gradations and the original asphalt contents. Field rut measurements from all the projects were obtained.

Results reported that the cylindrical samples compacted to 4 percent air voids and beam samples compacted to 5 percent air voids resulted in APA test results that were more closely related to field rutting performance than were cylindrical and beam specimens compacted to 7 percent air voids.

Results also indicated that the samples tested in the APA at a test temperature corresponding to the high temperature of the standard performance grade (e.g. test temperature of 70C for a PG 70-22 binder grade) for a project location, better predicted field rutting performance than did samples tested at 6C higher than the high temperature of standard performance grade. Researchers concluded that the test temperature significantly affects measured rut depths in the APA. As the test temperature increased, APA rut depths increased.

Samples with both standard and large-diameter hoses predicted field rutting performance about equally. During the study, researchers observed that beam samples produced collective higher rut depths than did cylindrical samples. However, at low APA rut depths (< 4 mm), the two sample types provided similar rut depths and above 4 mm, the beam samples provided higher rut depths. Finally, researchers indicated that beam and cylindrical samples predicted field rutting performance about equally well.

However, they didn't establish a preference for any of them for future used. Based on the results previously mentioned, it was also concluded that the APA can be used to determine the rutting potential of HMA mixes in the field.

In one study conducted by Williams (2003), the APA and the Evaluator of Rutting and Stripping in Asphalt (ERSA) devices were also used in an attempt to develop relationships between laboratory and field measurements.

Two analyses involving regression procedures were performed. In the first analysis, seven Arkansas mixtures from five locations were identified by the Arkansas Highway and Transportation Department (AHTD). These mixes were placed in the field during 1997 and 1998. Five of the mixes were 12.5 mm surface mixes and two of the mixes were 25.0 mm binder mixes that corresponded with two of the surface mixes.

The mixes were: AR22 (NMAS of 12.5 mm), AR45 (NMAS of 12.5 mm), US71B (NMAS of 12.5 mm), I30S (NMAS of 12.5 mm), I30B (NMAS of 25.0 mm), I40S (NMAS of 12.5 mm), and I40B (NMAS of 25.0 mm). The mixes on interstate routes (I30S, I30B, I40S, and I40B) contained a PG 76-22 binder, the mixes with moderated traffic level (US71B) contained a PG 70-22 binder, and the mixes used on low traffic routes (AR22 and AR45) contained PG 64-22 binders. All seven mixes were coarse-graded (i.e. below the restricted zone). Approximately twenty-five samples were tested from each of the seven mixes.

Laboratory samples were compacted from the field mix sampled at the asphalt plant. The specimens were compacted to a target of 7 percent air voids, which was recommended for testing in both ERSA and the APA. APA samples were tested at the typical wheel load of 445 N and hose pressure of 690 kpa. The only exceptions to common testing procedures were that the samples were tested submerged at a temperature of 50C. ERSA samples were tested at 50C and with a load of 591 N while submerged in water.

Regression analysis was employed to determine which HMA characteristics played significant roles in laboratory rutting performance. For the first analysis (using field data, ERSA and APA results) researchers summarized the factors and their individual effects on permanent deformation as follows:

As VMA increased, rut depth increased; as PG grade increased, rut depth decreased; as binder content increased, rut depth increased; and as the film thickness increased, rut depth increased. The overall conclusion of this analysis was that while many factors played a role in the permanent deformation characteristics of HMA, none was able to predict permanent deformation behavior adequately according to laboratory wheel tracking tests.

In the second analysis, information from a database compiled by AHDT was used. These data included permanent deformation measurements as determined by the APA for over 340 mixtures designed for use on a wide variety of Arkansas highways.

No field performance data were available for comparison with the laboratory data. For this analysis, all samples were tested in the APA device in the dry state at 64C. Regression analysis was also used to determine which volumetric mixture design properties were most influential in permanent deformation performance of HMA. Nine mixture characteristics were known for each mix. These characteristics (predictor variables) included: nominal maximum aggregate size (NMAS), maximum number of gyrations (N_{max}), optimum binder content, high temperature performance grade of the binder (PG grade), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), fines to asphalt ratio, surface area of the aggregate blend, and film thickness.

From this analysis researchers found these trends: VMA seemed to be the most influential property such that as the VMA increased, permanent deformation also increased. Relative to the PG grade, as the binder grade increased, permanent deformation decreased; and as the NMAs increased, permanent deformation decreased.

Researchers pointed out that in both analyses, it was evident that many factors possess a significant relationship to permanent deformation, but not in such a way that a combination of properties would reliably predict permanent deformation.

In another study by, Choubane et al. (2000), attempts were also made to correlate field rut depth measurements to APA results. The main objective of this study was to evaluate the APA device for assessing the permanent deformation susceptibility of asphalt mixes previously tested with the Georgia Loaded Wheel Tester (GLWT) device. The evaluation process also consisted of correlating the APA's predicted permanent deformation with known field performance of asphalt concrete pavements in Florida.

Three sections with different types of mix from the Florida interstate pavement system were considered in this study (Mix B, Mix C, and Mix D). The sections were selected because of their varied performance (good, severely rutted, and light to moderate rutting). Core samples were obtained from the three sections to determine the in-place aggregate gradations and asphalt contents. The specimens prepared for this study closely matched the gradations and the original asphalt contents. The original asphalt cements used for these sections were not available, so a standard grade AC–20 was used for all three mixes. The air void contents of the original and reproduced designs were between 2.8 percent and 4.3 percent, and the VMA was between 13.7 and 15.9.

All samples were compacted to a target air void content of 7 percent to simulate the typical initial density achieved in the field. A total of 90 samples were prepared, 72 beams by using the AVC and 18 specimens by using the SGC. Testing in both the APA and the Georgia Loaded Wheel Tester (GLWT) was performed at 41C with the sample sides in full confinement. The wheel load and the hose pressure were set at 540 N and 690 kPa, respectively. Permanent deformation measurements were collected at 0, 1000, 4000, and 8000 loading cycles.

Researchers reported that the gyratory samples had greater permanent deformation than beam samples when the ruts were less than 10 mm. Above the 10 mm mark, the beam deformed more regardless of the mixture type. They also reported that the APA testing variability may differ from test to test and, within each test, from location to location, for both gyratory and beam samples.

The beam and gyratory samples did not result in statistically similar results, regardless of the mix type. Thus, they concluded that it may not be appropriate to use the same pass/fail test criteria for both. Researchers suggested that average values within the ranges of 7 to 8 mm and of 8 to 9 mm may be used as a performance limiting criteria at 8000 cycles for beam and gyratory samples, respectively. Finally, they found that under similar testing conditions, independently of the mix type and loading cycle number, a good correlation between the APA and Georgia Loaded Wheel Tester (GLWT) test results was obtained. However, the magnitudes of the respective rut depths were not comparable. The APA deformations were approximately twice as large as those of the GLWT.

Finally, in another study conducted by Williams and Prowell (1999), the French Pavement rutting Tester (FPRT), the Hamburg Wheel-Tracking Device (HWTD) and the APA device were used to evaluate their abilities to predict permanent deformation performance of a full-scale pavement and, to present a rational approach for establishing mixture design specification limits for these LWDTs. The results were compared to WesTrack performance data. WesTrack is a 2.9-km oval test track with each tangent consisting of thirteen 70-m sections. The track was constructed in 1995. Because of failure, some premature, 10 sections were replaced during a June 1997 rehabilitation of the track. These ten sections were the focus of this study. Eight sections, called FHWAS sections, used a neat PG 64-18 and the other two sections (43 and 51), called NDOT sections, used a modified PG 64-22 binder. Section 43 used the same coarse aggregate as the FHWA sections. Section 51 used crushed gravel and was a 76-mm overlay of the previous failed section. All sections were milled prior to placement, theoretically maintaining a uniform thickness of 152 mm for all test sections. Samples for the APA and FPRT were removed from the left wheel path and the HWDT samples were removed from the right path. Three replicates were tested in each device from each section. The air void contents in the test sections varied from a low 1.7 percent to a high 12 percent. No information about the air void contents for the specimens tested in the laboratory was provided.

The APA test used beam samples: 300 mm x 125 mm x 75 mm; a test temperature of 60C; a load of 533 N and an aluminum wheel on a pressurized hose at 830 kpa. The FPRT test used beam samples: 500 mm x 180 mm x 100 mm; a test temperature of 60C; a load of 5000 N and a pneumatic pressure of 600 kpa. The HWDT test also used beam samples: 320 mm x 260 mm x 80 mm; a test temperature of 50C in a wet state; a load of 683 N and a steel wheel with a 204 mm in diameter and 47 mm wide.

Based on the data analyses in this study, researchers concluded that three devices showed a reasonable level of correlation with WesTrack performance. The correlations were 89.9 percent, 83.4 percent, and 90.4 percent for the APA, FPRT, and HWDT, respectively. However, the advantages of the APA over the permanent deformation testing devices as the Hamburg Wheel tracking device and the French rutting tester PUR wheel are: APA can test cylindrical or beam samples and it simulates field traffic and temperatures. The APA test is simple; and three to six samples can be tested together (Skok, Johnson, and Turk 2003).

2.4. Conclusions from Literature Research

Many investigators have attempted to evaluate the effects that a variety of mix factors has on permanent deformation. However, as can be seen from previous research, often there are interactions among the factors that affect permanent deformation and therefore, it is difficult to accomplish this evaluation.

Some studies suggest that the APA is capable of distinguishing mixes that are susceptible to permanent deformation. Some other research has shown that the APA device distinguishes well between different binder grades, binder contents and other mix properties. Sometimes, when using the APA device, researchers have found good correlations between permanent deformation and any of the mix factors that directly affect permanent deformation (e.g. VMA, air voids), but as mentioned before, often the results don't show consistent trends, and occasionally results are counter-intuitive. Nevertheless, most past research indicates that the APA is still able to identify mixes that have a tendency to rut. The focus of this study is to assess the suitability of the APA device as a tool for evaluating mixtures and judge the effects of varying mix properties (factors) on APA results.

The Superpave procedure, in its mix design phase, requires a certain number of gyrations (compactive effort) by the SGC on the mix, which is a function of climate and traffic level. This number is represented by N_{design}. The volumetric properties of the mixture (e.g. air voids, VMA, VFA) are calculated at the N_{design} value at a specified asphalt content. As observed, from the literature review, some researchers have used different air void contents (4 and 7 percent) for the mixtures designed in the laboratory. Sometimes, it is difficult to maintain these percentages while placing the mix in the field. Contractors basically place the mix and then apply a fixed compactive effort with the rollers until the required density is achieved. However, normal mix variability results in changes in mix properties frequently without significant change in compactive effort. Therefore, a fixed compactive effort (number of gyrations) will be applied to the specimens using the SGC to try to mimic the compactive effort developed by the equipment in the field (i.e. a fixed number of passes by the rollers over the mat).

The asphalt binder content and air voids in the mixture affect the VMA. These three parameters are related. Asphalt content affects VMA only to the extent that the asphalt binder acts as lubricant and has an effect on how well the aggregate particles are compacted together (Lavin, 2003). Higher air voids mean lower asphalt contents and vice versa. For this study, the amount of VMA and the asphalt binder content will be varied to assess their effects on permanent deformation while maintaining a fixed compactive effort by the SGC in the specimens.

Contractors and/or mix producers are required by the environmental regulations to capture the dust (bag houses). As a result, this creates a disposal problem for them. The most obvious way to avoid this problem is by recycling the dust into the mix. The process of running the aggregate to the plant is also another dust problem. It tends to make some additional fines, and so even though the design of dust content (P200) is fixed during the mix design, it is quite possible that the actual produced mix may increase this value, resulting in with higher dust contents. The increase of the dust content in the mix may result in an increase in the surface area in the mix, and second it creates a mastic combination of very fine dust along with the asphalt cement. Theoretically, this mastic effect tends to reduce the tendency to permanent deformation of the mix because it is a denser, more viscous material. To try to assess this effect and to observe the consequences of the increase in dust content, the mix design in this study will include two P200 values, design and design with a 3 percent increment.

The effect of stiffer asphalt binders has been demonstrated to improve the rut resistance of HMA. The study herein will include the use of unmodified and modified asphalt binders. Their effect in the asphalt mixture, in terms of permanent deformation, will be assessed when testing them on the APA device.

CHAPTER 3. "Effect of Fines Content on Permanent Deformation Characteristics of Dense-Graded Mixes Using Asphalt Pavement Analyzer"

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To Be Submitted to:

Transportation Research Board

3.1. Abstract

Pavement deformation, also termed rutting, has been a primary concern for pavement engineers for decades. Permanent deformation is the result of lack of shear strength in the asphalt mixtures, mainly influenced by a variety of its material properties. The Asphalt Pavement Analyzer (APA) device was used to characterize the impacts of various mix factors on the development of permanent deformation of dense-graded mixes. Factors investigated included two aggregate sizes (12.5 and 19.0 mm), three VMA levels (high, design, and low), two fines contents (design and high), three binder contents (low, design, and high) and three binder types (PG 64-22, PG 70-22, and PG 76-22). A single aggregate source (basaltic material) was used for all mixes. All specimens received the same compactive effort (100 gyrations) and were tested at 64C.

Based on the information from this study, it was observed that the increase in binder content increased permanent deformation in the 19.0 mm mixes prepared with the PG 64-22 binder irrespective of the other mix parameters. These effects were not noted in the mixes prepared with PG 70-22 and PG 76-22 binders, perhaps due to the use of standard temperature with stiffer binders. The statistical analysis of the rut depths provides evidence that all mixes prepared with stiffer binders showed very low permanent deformation when tested at the standard 64C regardless of the value of the other mix parameters. There was no statistical evidence that the mean APA rut depths

change when the fines content is increased by three percent over the design value. Finally, the results indicate that the APA device can identify mixes susceptible to permanent deformation.

Key Words: Asphalt Pavement Analyzer, permanent deformation, VMA, fines.

3.2. Introduction

Rutting is defined as the load-induced permanent deformation along the wheel path of flexible pavements due to repeated movement of traffic (Roberts et al., 1996). Changes in permanent deformation have long been associated with changes in mix properties including binder type and content, voids in mineral aggregates (VMA) and air voids to name a few.

Because of the influence of binder stiffness, mixes with same aggregate gradation, but different asphalt binders, should exhibit different rutting potential when tested at the same temperature. However, Kandhal and Mallick (1999) suggested that when mixes with the same aggregate structure are prepared with different binders, they will exhibit the same rutting potential if tested at the same high temperature of the PG binder.

Currently, it is widely accepted that the conventional mix design procedures, Marshall and Hveem, are inadequate to address the present in-service performance problems (Choubane et al., 2000). The Superpave mix design and analysis system does not presently specify a proof test to assess the relative rutting susceptibility of hot mix asphalt (HMA). Such a test would assure that the proposed mix would resist permanent deformation for the design life of the road. One such device, the Asphalt Pavement Analyzer (APA), was developed to test asphalt concrete mixes for rutting susceptibility.

3.3. Objective

Permanent deformation is influenced by a variety of factors (e.g. VMA, asphalt content, aggregate size). It is difficult to separate them due to their confounding effects. However, the APA can be used to assess the influence each of these factors produce in the HMA mixes. Therefore, it has been hypothesized that permanent deformation can be assessed by using the APA device (Kandhal and Cooley 2003; and Jackson and Baldwin 1999).

The objective of this study is to assess the suitability of the APA device as a tool for evaluating mixtures and judge the effects of varying the mix properties on APA results. The factors (mix properties) to be investigated are:

- Binder Types – PG 64-22, PG 70-22, and PG 76-22
- Voids in Mineral Aggregate (VMA) – Low, Design and High
- Asphalt Content- Low, Optimum, and High
- Aggregate Source – Single Source, basaltic material
- Aggregate Maximum Size – 12.5 mm and 19.0 mm
- Fines Content – Design and Design+3%
- Constant SGC compaction level for all the mixes.

There are a total of 108 ($2^2 3^3$) cells in the full factorial, but testing of all the combinations exceeded the available resources for this study. Therefore, a fractional factorial was proposed, and is displayed in Table 3.1. This ½ factorial requires only 54 of the cells be filled, yet allows the main factors (as listed above) and the two-way interactions to be investigated. A total of 189 asphalt cylinders is prepared using the Superpave Gyratory Compactor (SGC).

In Table 3.2, a modification of the matrix shown in Table 3.1 was done to further establish the effect of the fines content. Nine extra combinations were tested to avoid the confounding effect of aggregate size with the fines content (shaded areas of Table 3.2).

Table 3.1 Fractional factorial experimental design

			Binder Grade and Content								
			PG 64-22			**PG 70-22**			**PG 76-22**		
Max. Agg. Size	**VMA**	Fines Content	Low	Optimum	High	Low	Optimum	High	Low	Optimum	High
19.0 mm	Low VMA	Design	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
		Design + 3%									
	Design VMA	Design	**X**	**X***	**X**	**X**	**X**	**X**	**X**	**X**	**X**
		Design + 3%									
	High VMA	Design	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
		Design + 3%									
12.5 mm	Low VMA	Design									
		Design + 3%	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
	Design VMA	Design		*							
		Design + 3%	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
	High VMA	Design									
		Design + 3%	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**

Note:*indicates control mixes; all tests were conducted at 64C

Table 3.2 Modified fractional factorial for the experimental design

Max. Agg. Size	VMA	Fines Content	Binder Grade and Content								
			PG 64-22			PG 70-22			PG 76-22		
			Low	Optimum	High	Low	Optimum	High	Low	Optimum	High
19.0 mm	Low VMA	Design	X	X	X	X	X	X	X	X	X
		Design + 3%	X	X	X						
	Design VMA	Design	X	X*	X	X	X	X	X	X	X
		Design + 3%	X	X	X						
	High VMA	Design	X	X	X	X	X	X	X	X	X
		Design + 3%	X	X	X						
12.5 mm	Low VMA	Design									
		Design + 3%	X	X	X	X	X	X	X	X	X
	Design VMA	Design		*							
		Design + 3%	X	X	X	X	X	X	X	X	X
	High VMA	Design									
		Design + 3%	X	X	X	X	X	X	X	X	X

3.4. Materials and Procedures

3.4.1. Aggregate tests

Aggregate property tests were performed and summary results for the 19.0 mm and 12.5 mm aggregates size are listed in Tables 3.3 and 3.4, respectively. All the aggregates used in this study met the ODOT specifications. ODOT requires the Soundness Loss Test, ODOT TM 206, for both coarse and fine aggregates, with a weighted loss not exceeding 12 percent when subjected to five cycles. This test estimates the resistance of aggregate to in-service weathering. The Abrasion Loss Test (AASHTO T96, 1993) provides durability testing of coarse aggregate. ODOT specification limit is 30 percent.

The Fracture Faces test, ODOT TM 213, was conducted in this study. ODOT specifications require a minimum of 75 percent for materials retained on 2.36 mm sieve (#8) sieve (one fractured face) and a minimum of 75 percent for materials retained on 37.5, 25.0, 19.0, 12.5 and 4.75 mm sieves (two fractured faces), (ODOT, 2003).

Table 3.3 Summary of aggregate test results for 19.0 mm maximum aggregate size

COARSE AGGREGATE		**FINE AGGREGATE**		
Size, mm	19.0-4.75	Size, mm	4.75-2.36	2.36-0
Soundness Loss %	1.0	Soundness Loss %	6.0	7.0
Abrasion loss % (LAR)	12.7			
Sediment Height, mm	16.0	Sediment Height, mm	17.0	17.0
% passing 0.85mm (No. 20)	13.1	% passing 0.85mm (No. 20)	9.7	9.7
Bulk Specific Gravity (Gsb)	2.629	Bulk Specific Gravity (Gsb)	2.587	2.591
Absorption, %	1.7	Absorption, %	2.3	2.3
Fracture Faces, %	minimum met	Fracture Faces, %	minimum met	minimum met
Lightweight Pieces, %	0.0	Lightweight Pieces, %	0.0	

Table 3.4 Summary of aggregate test results for 12.5 mm maximum aggregate size

COARSE AGGREGATE		**FINE AGGREGATE**		
Size, mm	12.5-4.75	Size, mm	4.75-2.36	2.36-0
Soundness Loss %	1.0	Soundness Loss %	6.0	7.0
Abrasion loss % (LAR)	12.0			
Sediment Height, mm	9.0	Sediment Height, mm	17.0	17.0
% passing 0.85mm (No. 20)	12.7	% passing 0.85mm (No. 20)	9.7	9.7
Bulk Specific Gravity (Gsb)	2.638	Bulk Specific Gravity (Gsb)	2.587	2.591
Absorption, %	1.7	Absorption, %	2.3	2.3
Fracture Faces, %	minimum met	Fracture Faces, %	minimum met	minimum met
Lightweight Pieces, %	0.0	Lightweight Pieces, %	0.0	

ODOT also requires the aggregate degradation test, ODOT TM 208. The degradation test is used to measure the quantity and quality of the material produced by attrition similar to that produced in the roadway under repeated traffic loading and unloading. The quantity is indicated by a percentage (by weight) of fine material produced. The quality is measured by means of a modified sand equivalent test. The fine material is made by the rubbing action of one particle against another in the presence of water by mean of air jets. These results are shown in Tables 3.3 and 3.4 under “sediment height” and “percent passing 0.85 mm (No. 20)”. The maximum limit for sediment height for coarse and fine aggregate is 75 mm and 100 mm, respectively. The maximum value in the percent passing 0.850 mm (No. 20) sieve test, for coarse and fine aggregate, corresponds to 30 percent. The lightweight pieces test was done according to AASHTO T113 (1993) procedure. ODOT allows a maximum value of 1.0 percent for coarse aggregates.

3.5. Mix Design

The Job Mix Formula (JMF) for this project was developed based on a Level 3 mix design from ODOT specifications (ODOT, 2003). In the State of Oregon Hot Mixed Asphalt Concrete (HMAC) Level 3 designs are assigned to road applications exposed to moderated truck traffic (1 to 10 million ESAL’s) during the design life. A summary of the mix design values obtained are shown in Tables 3.5 and 3.6.

The optimum binder content for the control mix was determined for a 100 gyration mix using a PG 64-22 binder (commonly used in Oregon). The design (optimum) asphalt content was 6.2 and 6.6 percent for the 19.0 mm and the 12.5 mm, respectively. The high and low binder contents were selected at 0.5 percent above and below the optimum binder content. In summary, this approach yielded, low, design and high binder contents of 5.7, 6.2 and 6.7 percent for the 19.0 mm and 6.1, 6.6 and 7.1 percent binder contents for the 12.5 mm mixes. The same binder contents were used for the mixes using the PG 70-22 and PG 76-22 binders at the design fines content and design VMA.

Table 3.5 Summary of mix design results for 19.0 mm mix (PG 64-22)

MIXTURE PROPERTIES		JOB MIX FORMULA	Percent Passing
Maximum Specific Gravity (Gmm)	2.454	25.0mm	100
Gyro. Bulk Specific Gravity (Gmb)	2.357	19.0mm	94
Air Voids, % (Va)	4.0	12.5mm	81
VMA, %	15.5	9.5mm	71
VFA, %	74	6.3mm	66
Effective Asphalt Content (Pbe), %	4.9	4.75mm	59
P0.075/Asphalt Content Ratio	1.0	2.36mm	42
P0.075/Pbe Ratio	1.3	0.600mm	19
Target Maximum Density, Kg/m^3	2454	0.075mm	6.3
Combined Aggregate Gsb	2.606		
		Asphalt Content, %	6.2
		Asphalt Grade	64-22
		Mix Temperature Range, C	156-161
		Compaction Temperature Range, C	142-147
		Asphalt Sp. Gr. (Gb) at 15.6C	1.033

Table 3.6 Summary of mix design for 12.5 mm mix (PG 64-22)

MIXTURE PROPERTIES		JOB MIX FORMULA	Percent Passing
Maximum Specific Gravity (Gmm)	2.439	25.0mm	100
Gyro. Bulk Specific Gravity (Gmb)	2.338	19.0mm	100
Air Voids, % (Va)	4.0	12.5mm	96
VMA, %	16.2	9.5mm	83
VFA, %	74	6.3mm	70
Effective Asphalt Content (Pbe), %	5.3	4.75mm	62
P0.075/Asphalt Content Ratio	1.0	2.36mm	43
P0.075/Pbe Ratio	1.2	0.600mm	20
Target Maximum Density, Kg/m^3	2439	0.075mm	6.4
Combined Aggregate Gsb	2.605		
		Asphalt Content, %	6.6
		Asphalt Grade	64-22
		Mix Temperature Range, C	156-161
		Compaction Temperature Range, C	142-147
		Asphalt Sp. Gr. (Gb) at 15.6C	1.033

The voids in mineral aggregate (VMA) was adjusted by modifying the aggregate gradations as shown in Tables 3.7 and 3.8. These same gradations are shown in graphical format in Figures 3.1 and 3.2 for the 19.0 mm mixes, and in Figures 3.3 and 3.4 for the 12.5 mm mixes.

Table 3.7 Aggregate gradation for the 19.0 mm mixes

Sieve Size (mm)	Target P200 Content			Target P200 Contet +3%		
	Low VMA	Design VMA	High VMA	Low VMA	Design VMA	High VMA
25.0	100	100	100	100	100	100
19.0	92	94	98	92	94	98
12.5	79	81	85	79	81	85
9.5	69	71	73	69	71	73
6.3	66	66	54	66	66	54
4.75	60	59	46	60	59	46
2.36	44	42	30	44	42	30
0.600	21	19	12	21	19	12
0.075	6.5	6.3	3.5	9.5	9.3	6.5
Expected VMA, %	14.1	15.5	18.1	12.7	13.1	17.5

Table 3.8 Aggregate gradation for the 12.5 mm mixes

SieveSize (mm)	Target P200 Content			Target P200 Contet +3%		
	Low VMA	Design VMA	High VMA	Low VMA	Design VMA	High VMA
19.0	100	100	100	100	100	100
12.5	90	96	98	90	96	98
9.5	80	83	84	80	83	84
6.3	75	70	60	75	70	60
4.75	69	62	51	69	62	51
2.36	50	43	32	50	43	32
0.600	22	20	15	22	20	15
0.075	7.4	6.4	4.4	10.4	9.4	7.4
Expected VMA, %	15.5	16.2	18.0	14.6	14.6	17.9

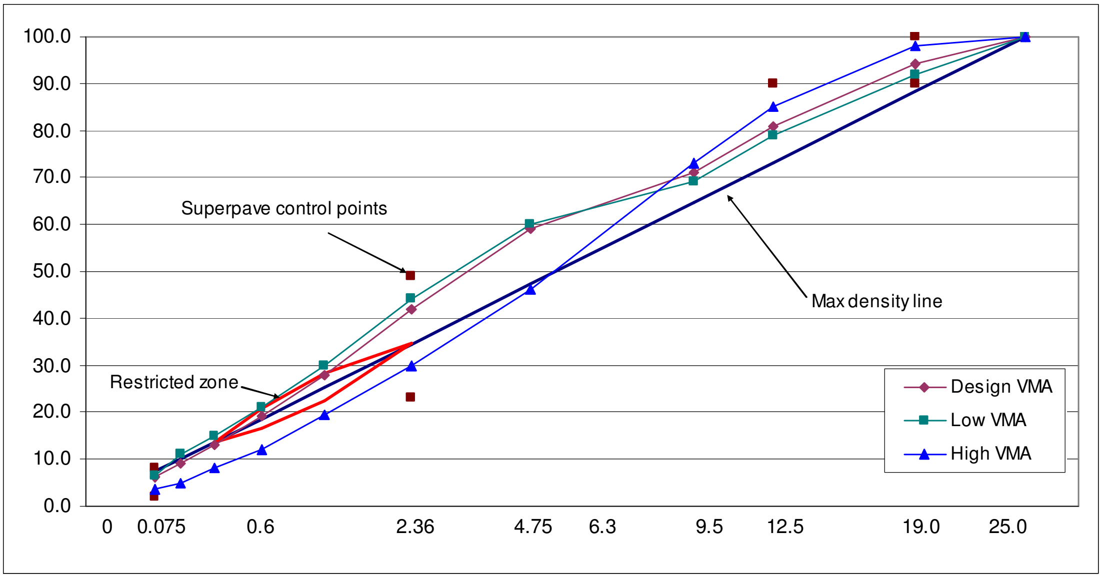

Figure 3.1 Aggregate gradation for the 19.0 mm mixes (Target P200)

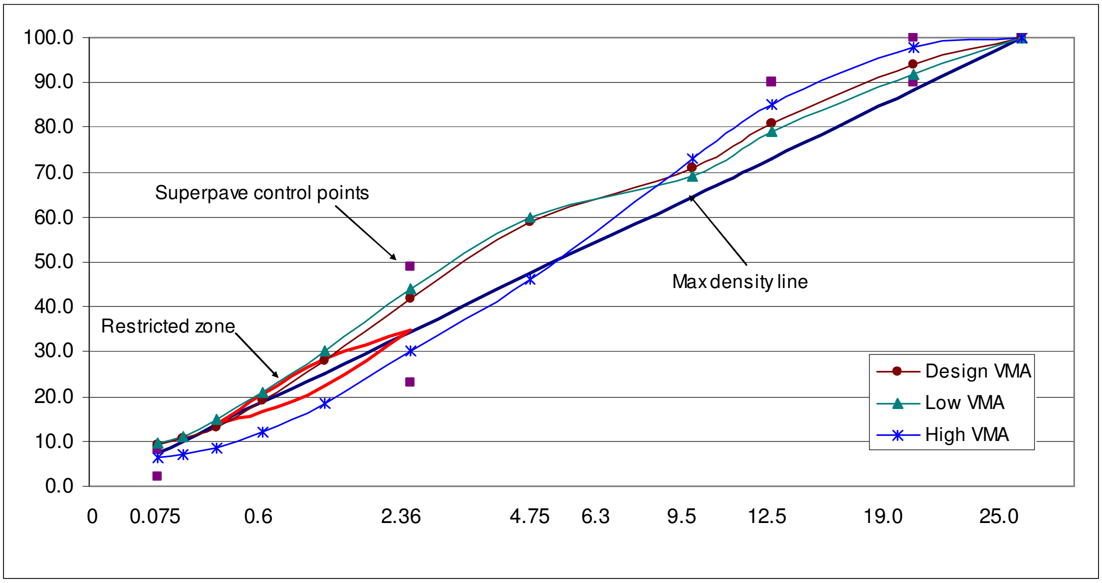

Figure 3.2 Aggregate gradation for the 19.0 mm mixes (Target P200 + 3%)

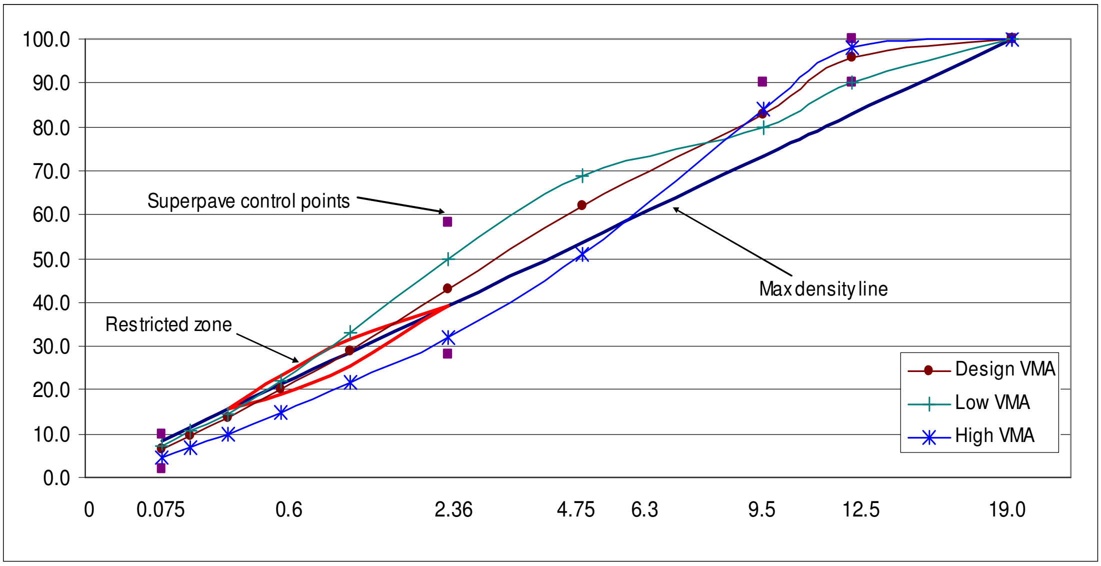

Figure 3.3 Aggregate gradation for the 12.5 mm mixes (Target P200)

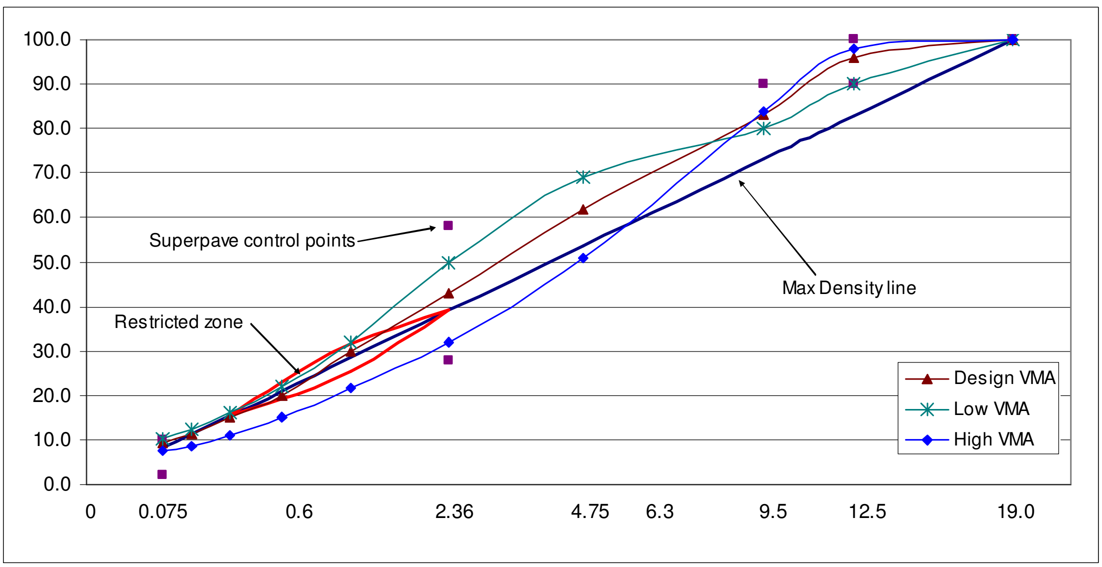

Figure 3.4 Aggregate gradation for the 12.5 mm mixes (Target P200 + 3%)

3.5.1. Superpave Gyratory Compactor (SGC)

The Superpave Gyratory Compactor (SGC), as shown in Figure 3.5, was used to prepare the asphalt cylinders. The SGC produces asphalt mix specimens to densities approximating those achieved under actual construction conditions. The SGC consists of a rigid reaction frame, a loading system, a specimen height measurement and recording system.

Figure 3.5 Superpave Gyratory Compactor

The SGC compacts the asphalt mixture specimen at a constant pressure of 600 kPa. The mixture is compacted by a gyratory kneading action using a compaction angle of 1.25 degrees and operating at 30 rpm.

As observed, from the literature review, some researchers have used different air void contents (4 and 7 percent) for the mixtures designed in the laboratory. Sometimes, it is difficult to maintain these percentages while placing the mix in the field. Contractors basically place the mix, and then apply a fixed compactive effort with the rollers until the required density is achieved. However, normal mix variability results in changes in mix properties frequently without significant change in compactive effort. Therefore, following ODOT standards (ODOT, 2003), a fixed compactive effort (N_{design}) of 100 gyrations will be applied to the specimens using the SGC, to try to mimic the compactive effort developed by the equipment in the field (i.e. a fixed number of passes by the rollers over the mat), By doing so, it is important to note that air voids content in the cylinders will not be maintained at seven percent.

3.5.2. APA Testing

Testing was conducted with a tube pressure of 690 kPa and an applied mass of 450 N. Each test in the APA device consisted of six cylinders for each combination of the factor levels. Permanent deformation measurements were automatically recorded and sent to a computer. It is particularly important to note that all testing was conducted at 64C, regardless of the binder grade used in the mix.

3.6. Results and Analysis

The rut depths, air voids and the VMA values are shown in Tables 3.9 for the 12.5 mm aggregate size and in Table 3.10 for the 19.0 mm maximum aggregate size. Also, these results are shown in Table 3.11 for the cells containing the extra three percent dust content. Only the mean values per cell (six specimens) of the measured permanent deformation, air voids, and the calculated VMA results are shown. Complete results are included in Appendix A.

Table 3.9 Summary Results for 12.5 mm mixes

		Binder Grade								
		PG 64-22			**PG 70-22**			**PG 76-22**		
12.5 mm	**Averages**	*6.1*	*6.6*	*7.1*	*6.1*	*6.6*	*7.1*	*6.1*	*6.6*	*7.1*
Design VMA, P200	Rut Depth (mm)		3.63							
	Air content (%)		3.50							
	VMA		15.4							
Low VMA, P200+3%	Rut Depth (mm)	2.16	2.65	2.34	1.57	2.07	2.29	0.85	0.84	1.00
	Air content (%)	2.60	2.00	0.60	3.10	2.10	0.90	3.10	1.60	0.90
	VMA	13.5	14.1	13.8	14.4	14.5	14.6	14.0	13.8	14.3
Des VMA, P200+3%	Rut Depth (mm)	3.47	3.11	1.76	2.22	2.30	2.06	1.00	0.77	1.12
	Air content (%)	3.80	2.50	1.40	3.70	2.00	1.10	4.10	2.80	1.30
	VMA	14.6	14.6	14.7	14.9	14.5	14.9	15.0	14.9	14.8
High VMA, P200+3%	Rut Depth (mm)	3.73	4.82	4.71	3.01	3.54	3.70	1.84	1.76	2.33
	Air content (%)	5.80	5.60	4.00	5.80	4.10	3.40	5.30	5.10	3.40
	VMA	16.3	17.2	16.5	16.7	16.3	16.6	16.0	16.8	16.4

Table 3.10 Summary Data for 19.0 mm mixes

		Binder Grade								
		PG 64-22			**PG 70-22**			**PG 76-22**		
19.0 mm	**Averages**	*5.7*	*6.2*	*6.7*	*5.7*	*6.2*	*6.7*	*5.7*	*6.2*	*6.7*
Low VMA, P200	Rut Depth (mm)	2.39	3.05	3.56	2.03	1.83	1.78	1.11	1.05	1.39
	Air content (%)	3.90	2.50	1.60	4.10	2.50	1.30	3.80	2.30	1.50
	VMA	14.2	14.0	14.2	14.2	13.8	13.8	14.1	13.8	14.3
Des VMA, P200	Rut Depth (mm)	3.13	4.18	5.05	2.11	2.78	1.98	1.31	1.45	1.33
	Air content (%)	4.80	3.00	1.90	4.60	3.50	1.90	4.20	3.40	1.80
	VMA	14.9	14.4	14.5	14.7	14.7	14.4	14.5	14.9	14.5
High VMA, P200	Rut Depth (mm)	3.75	3.76	3.16	3.52	3.26	3.41	1.78	1.69	1.83
	Air content (%)	8.70	7.20	5.30	9.00	7.30	5.30	8.00	7.10	5.00
	VMA	18.4	18.0	17.4	18.5	18.1	17.3	17.8	18.1	17.3

Table 3.11 Summary Data for 19.0 mm mixes (P200+3%)

		Binder Grade		
		PG 64-22		
19.0 mm	**Averages**	5.7	6.2	6.7
Low VMA, P200+3%	Rut Depth (mm)	2.30	3.39	3.13
	Air content (%)	1.10	0.40	0.10
	VMA	12.0	12.5	13.4
Des VMA, P200+3%	Rut Depth (mm)	2.35	2.26	2.94
	Air content (%)	2.20	0.80	0.70
	VMA	13.2	13.0	14.0
High VMA, P200+3%	Rut Depth (mm)	4.29	4.65	5.42
	Air content (%)	6.60	5.60	4.40
	VMA	17.2	17.4	17.5

3.6.1. Discussion of Results

The discussion of permanent deformation refers to APA results not to field performance. A brief discussion of the raw data is covered before including any statistical analysis. The 19.0 mm mixes containing the PG 64-22 binder show some interesting trends. As shown in Figure 3.6, the air voids content tends to decrease when the binder content is increased, for a given VMA level. This is an expected and logical result. The increased binder in the mix fills the air void and as a consequence the air void content is reduced.

Within VMA levels, it is observed that the increase in binder content generates more permanent deformation. These results were expected, as mentioned in the literature review (Mahboub and Little, 1988), the increase in binder content in the mix may reduce the stone-to-stone contact and as a result it creates higher permanent deformation.

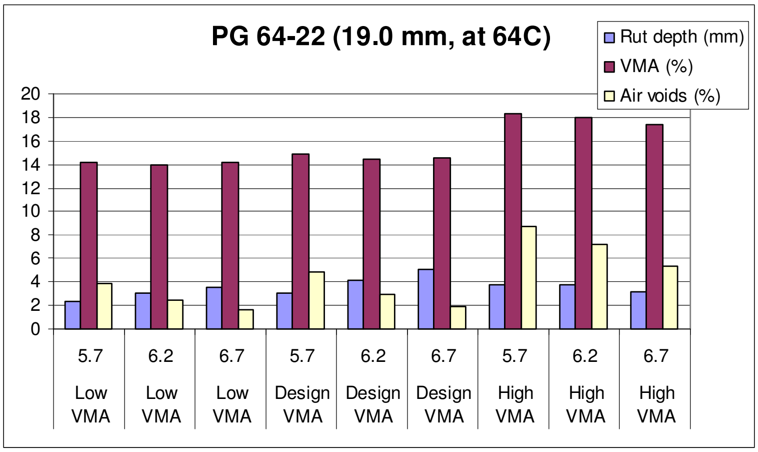

Figure 3.6 Effect of VMA and air voids on permanent deformation

However, in this case this effect was marked for the low and design VMA level, while for the high VMA level the permanent deformation was reversed, giving less rutting at higher binder contents. An interesting feature is that no marked effect was found between the air voids and the permanent deformation. As shown in Figure 3.7, a weak relationship (R^2 = 0.083) was found. Air voids in the mixture ranged from

1.60 to 8.70. As observed, extremely high and low air voids tended to increase permanent deformation as previously noted by Monismith et al. (1985).

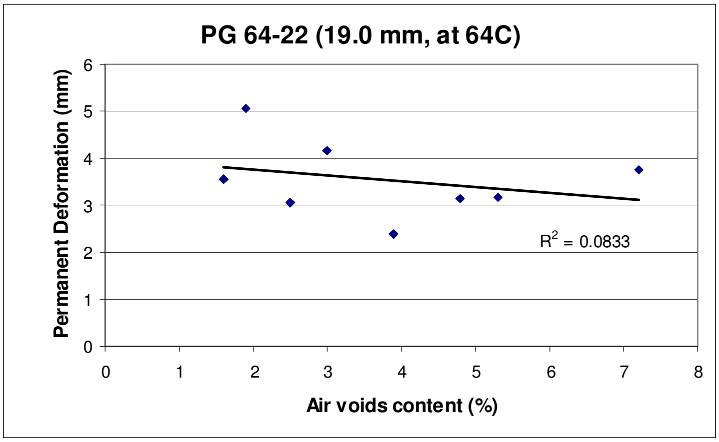

Figure 3.7 Effect of air voids on permanent deformation

For the case of the mixes using the PG 70-22 asphalt binder (Figure 3.8), the air voids content also decreases when the binder content was increased, regardless of the VMA level.

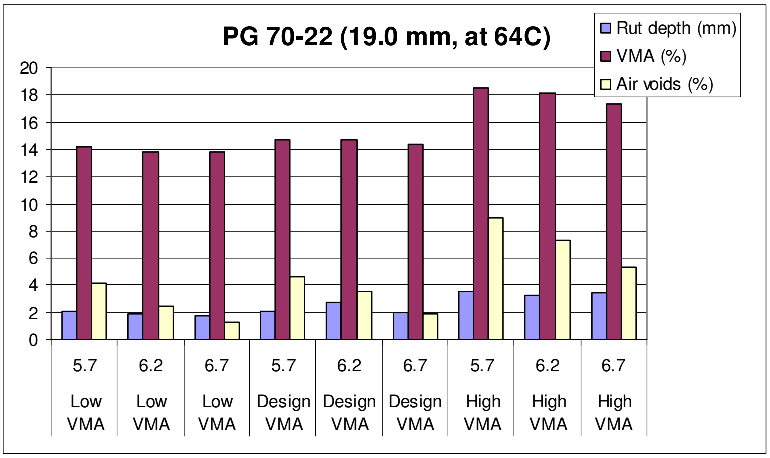

Figure 3.8 Effect of VMA and air voids on permanent deformation

In this case, there is a strong correlation (R^2 = 0.725) between the air void contents and the permanent deformation on the mixes using the PG 70-22 binder. As shown in Figure 3.9, higher air voids created more permanent deformation. The air voids in the mixture ranged from 1.30 to 9.0. It is important to notice that for the low and design VMA levels, there was less permanent deformation in the mixes using the PG 70-22 asphalt binder. This is an expected result because a stiffer binder is used.

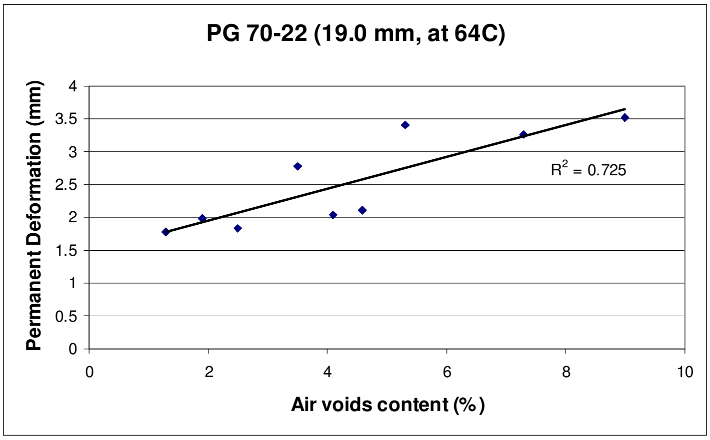

Figure 3.9 Effect of air voids on permanent deformation

In the case of the mixes using the PG 76-22 asphalt binder, as shown in Figure 3.10, the air voids content was also decreased when the binder content was increased, regardless of the VMA level. There is a reverse effect created by the binder content among the VMA levels. For the low VMA level, the increase in binder content creates a reduction in the VMA, when going from low to design, and then there is an increase in the VMA when moving the binder content from design to high. However, this effect was totally reversed for design and high VMA levels.

In general, the effect of the binder content on the VMA levels in the mix is similar to the effect seen in the mixes using the PG 64-22 and PG 70-22 binders.

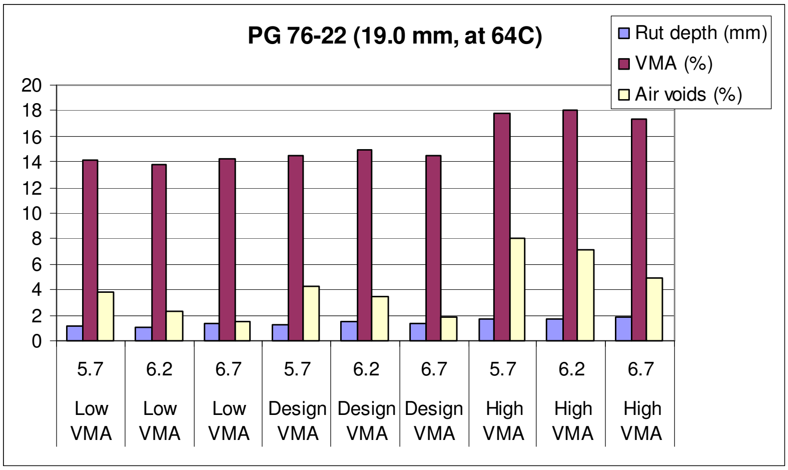

Figure 3.10 Effect of VMA and air voids on permanent deformation

For these mixes (using the PG 76-22 binders), there is a fair correlation (R^2 = 0.506) between the air void contents and the permanent deformation. As shown in Figure 3.11, higher air voids creates more permanent deformation. The air voids in the mixture ranged from 1.50 to 8.0 percent.

Figures 3.12 and 3.13 show the percent reduction in APA-measured rut depth obtained by using stiffer asphalt binders in the mixes and tested at the standard test temperature of 64C. As shown in these figures, in mixes using the PG 70-22 binder, there is approximately a 40 percent reduction in rut depths, compared to mixes using the PG 64-22 asphalt binder. In the case of mixes using the PG 76-22 asphalt binder, there is approximately a 60 percent reduction in rut depth, compared to mixes using the PG 64-22 binder.

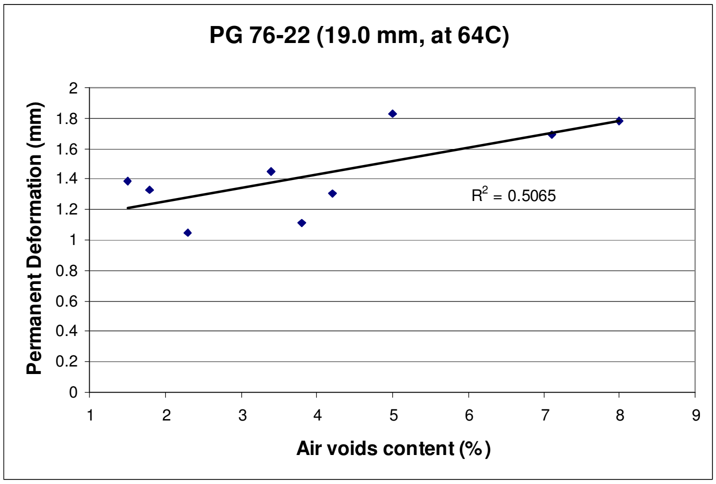

Figure 3.11 Effect of air voids on permanent deformation

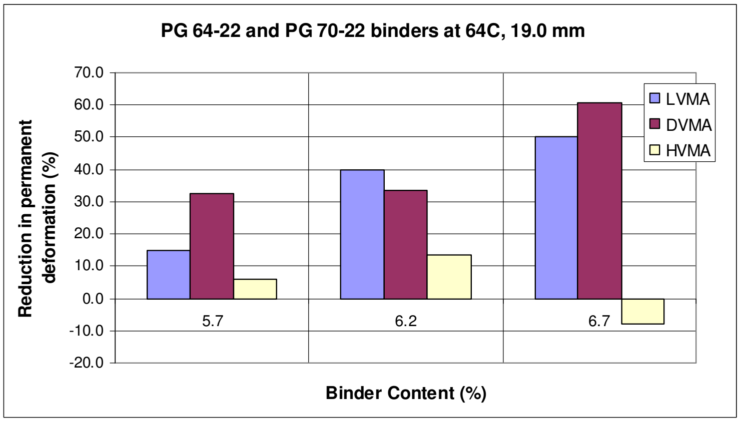

Figure 3.12 Effect of binder type in mixes

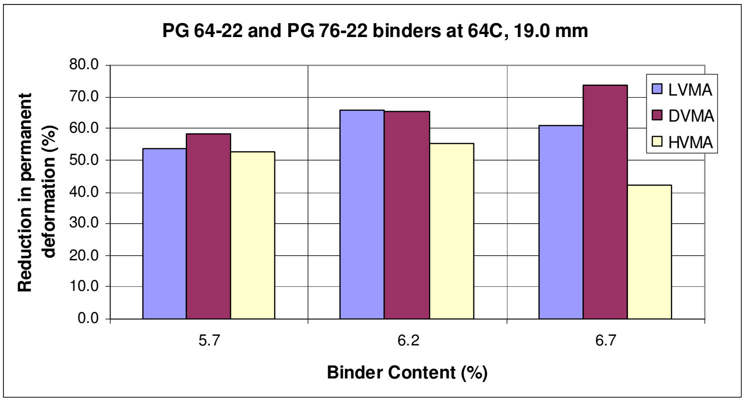

Figure 3.13 Effect of binder type in mixes

A similar assessment was done for the 12.5 mm mixtures. In this case (Figure 3.14), the air voids content tends to decrease when the binder content is increased, regardless of the VMA level.

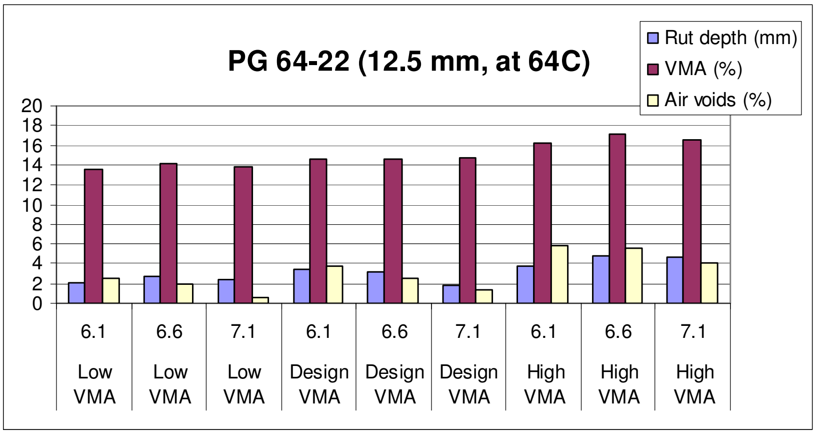

Figure 3.14 Effect of VMA and air voids on permanent deformation

There is no significant impact of the binder content on the VMA in the mix. As shown in Figure 3.15, there is a marked relationship (R^2 = 0.672) between the air voids and the permanent deformation. The air voids in the mixture ranged from 0.6 to 5.8.

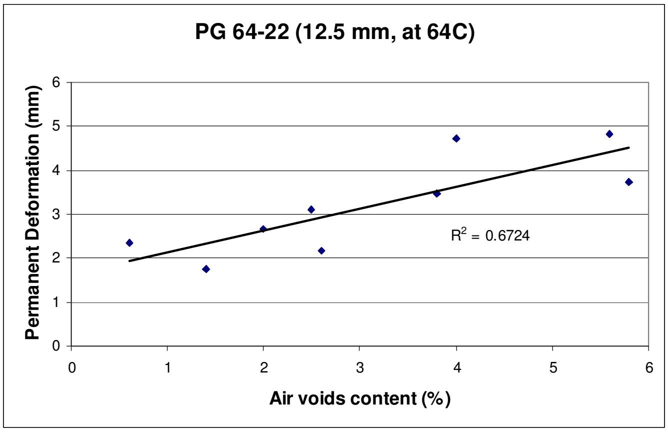

Figure 3.15 Effect of air voids on permanent deformation

For mixture using the PG 70-22 binder, as shown in Figure 3.16, the air voids content also tended to decrease when the binder content was increased, regardless of the VMA level.

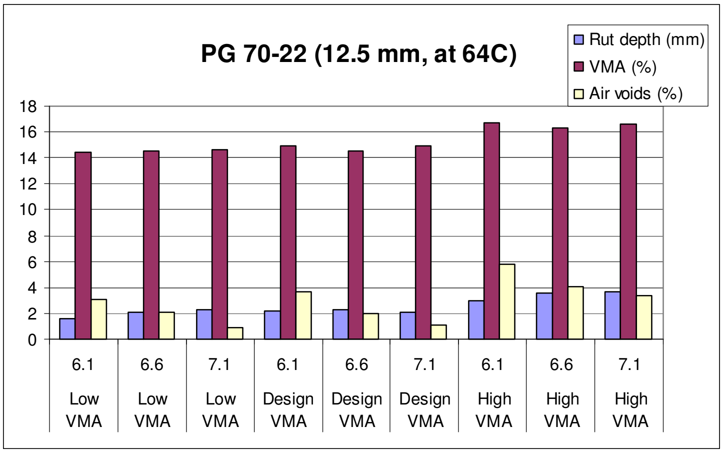

Figure 3.16 Effect of VMA and air voids on permanent deformation

Like mixes using the PG 64-22 binder, a small change is observed for the high VMA values when compared to low and design results. Figure 3.17 shows the weak relationship (R^2 = 0.265) between the air voids and the permanent deformation in this mix. Low permanent deformation values were obtained for air voids contents close to 3 percent. The air voids in the mixture ranged from 0.9 to 5.8.

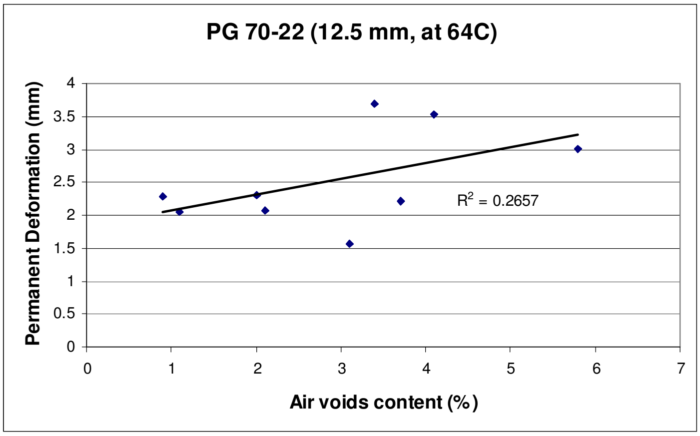

Figure 3.17 Effect of air voids on permanent deformation

In the case of mixes using the PG 76-22 binder, as shown in Figure 3.18, the air voids content also decreased when the binder content was increased, regardless of the VMA level.

For these mixes as shown in Figure 3.19, there is a weak relationship (R^2 = 0.309) between the air voids and the permanent deformation. In this case, the air voids in the mixture ranged from 0.9 to 5.3

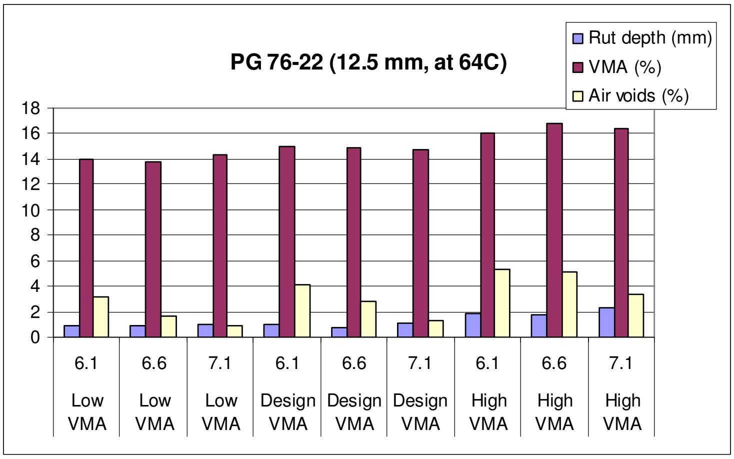

Figure 3.18 Effect of VMA and air voids on permanent deformation

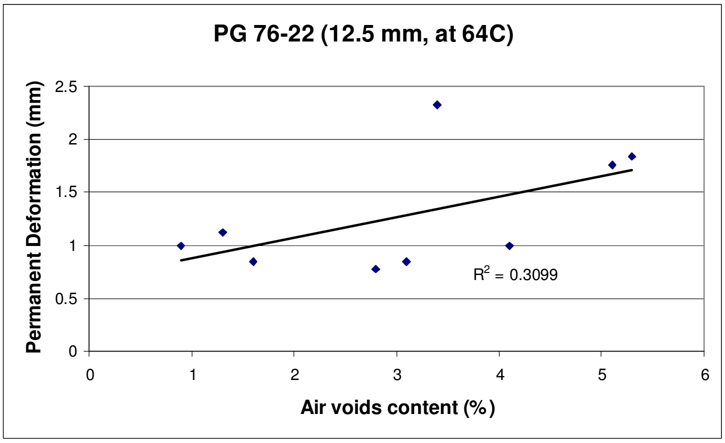

Figure 3.19 Effect of air voids on permanent deformation

Figures 3.20 and 3.21 show the percent reduction in APA-measured rut depth obtained by using stiffer asphalt binders in the mixes and tested at the standard test temperature of 64C. As shown in these figures, in mixes using the PG 70-22 binder, there is approximately a 30 percent reduction in rut depths, compared to mixes using the PG 64-22 asphalt binder. However, there is marked increase in permanent deformation, at the design VMA with 7.1 binder content, of approximately 17 percent.

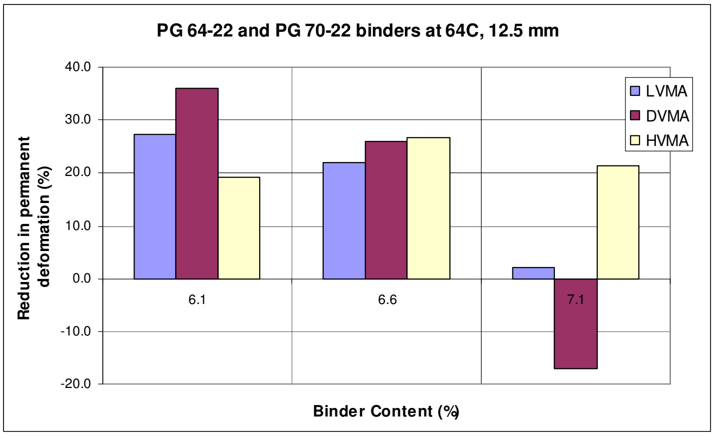

Figure 3.20 Effect of the PG 70-22 asphalt binder

In the case of mixes using the PG 76-22 asphalt binder, there is approximately a 60 percent reduction in rut depth, compared to mixes using the PG 64-22 binder.

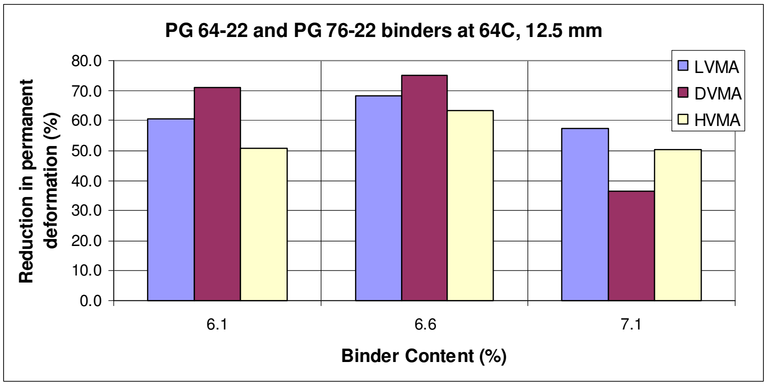

Figure 3.21 Effect of the PG 76-22 asphalt binder

In the case of mixes using the PG 64-22 binder with the increase on P200 content by 3 percent, as shown in Figure 3.22, the air voids content decreased when the binder content was increased, regardless of the VMA level.

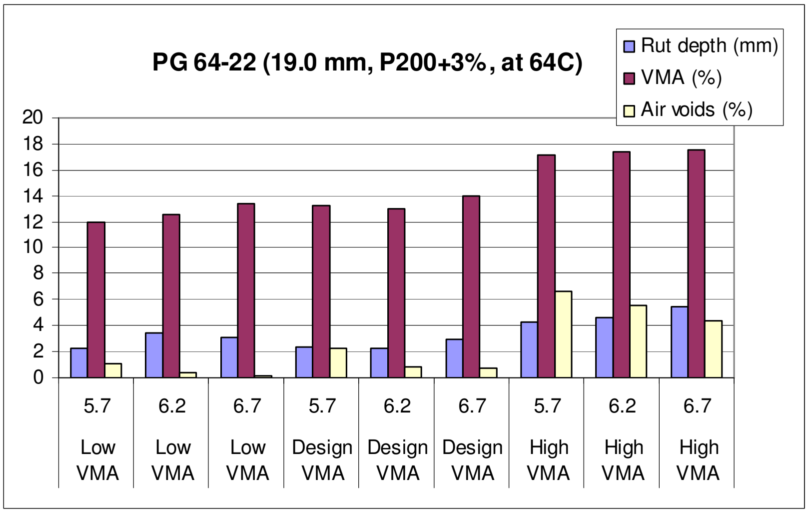

Figure 3.22 Effect of VMA and air voids on permanent deformation

As seen in this plot, the air voids content was low in the low VMA level. However, the permanent deformation didn't vary significantly. In this case, there was also detected a small trend within the VMA values. The increase in binder content created a small increase in the VMA in the mix. Among VMA levels, as seen on the rest of the mixtures, a small change was observed for the high VMA values compared to low and design VMA results.

As shown in Figure 3.23, there is also a modest relationship (R^2 = 0.556) between the air voids and the permanent deformation of the mix. In this case, the air voids in the mixture ranged from 0.1 to 6.6.

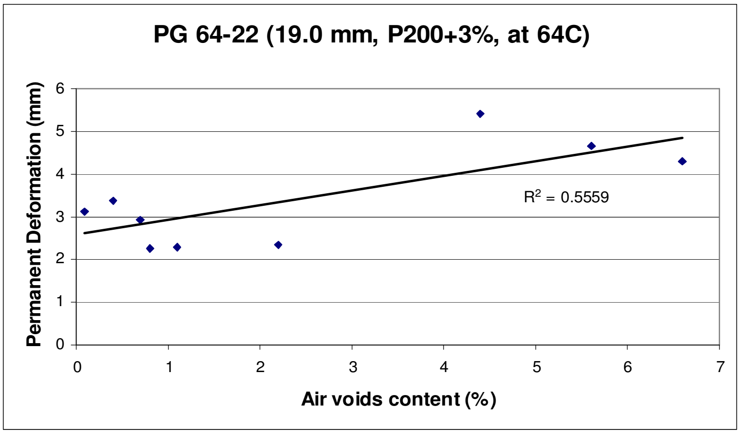

Figure 3.23 Effect of air voids on permanent deformation

Figure 3.24 shows the percent increase and/or reduction in APA-measured rut depths obtained by adding an extra three percent P200 to the mixes. As shown in this figure, the design VMA level is the one with approximately 35 percent reduction in permanent deformation as a result of adding extra dust to the mix. Conversely, as shown in this figure, there is an increase in permanent deformation up to 40 percent for the High VMA level.

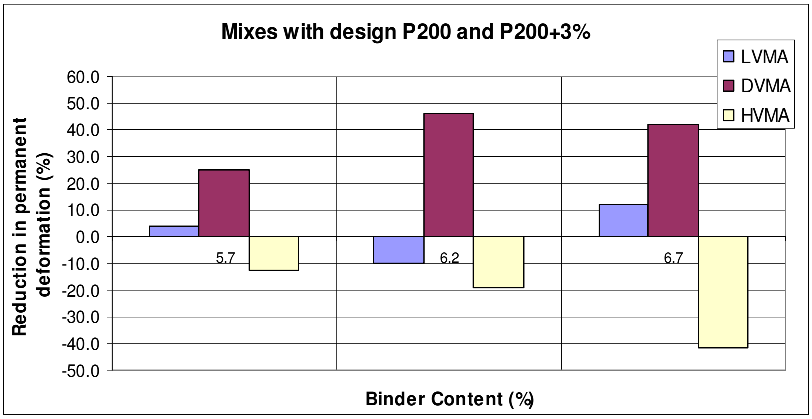

Figure 3.24 Effect of extra P200 on permanent deformation

In summary, it was noticed that the air voids were varied for all mixes when applying a fixed compactive effort. The average air voids for the 19.0 mm mixes was 4.28 percent, for the 12.5 mm was 3.04 percent, and for the 19.0 mm using an extra 3 percent of P200 was 2.4 percent. The average VMA for the 19.0 mm mixes was 15.5 percent, for the 12.5 mm was 15.1 percent, and for the 19.0 mm using an extra 3 percent of P200 was 14.4 percent. Mixes using the 12.5 mm aggregate size have the lowest permanent deformation. The average permanent deformation for the 19.0 mm mixes was 2.51 mm, for the 12.5 mm was 2.33 mm, and for the 19.0 mm using an extra 3 percent of P200 was 3.41 mm.

It was observed that rut depth mean values decreased as the high temperature grade of the binder increased. A similar trend was found by Kandhal and Mallick, (1999). This pattern was easily observed in the previous graphs. There is no remarkable effect of the changes in binder content on permanent deformation. Finally, mixes with an extra three percent of dust tended to be less rut resistance than mixes without it. The relative difference (0.9 mm) in the mean values is small.

However, it is necessary to mention that, although the raw analysis indicated some good relationships between the mix factors and permanent deformation, these trends were the result of single factors and does not take into account the interaction of factors. As mentioned in the previous chapter, permanent deformation is really affected by the combination of all the factors. To try to assess the effect of each factor after taking into account the rest of the other mix factors, it is necessary to apply statistical tools that can give a closer look of all mix factors on permanent deformation. In the next section the ANOVA procedure is used to accomplish this task.

3.6.2. Statistical Approach

The results of this study were analyzed by conducting an ANOVA test, using SAS software (SAS, 2001; Little et al., 2002; Kuehl, 2000). Following ANOVA, the levels of significance and two-way interactions were assessed using multiple comparisons with a Tukey-Kramer adjustment. There are a total of 63 cells with permanent deformation values; each cell containing 6 rut values.

The model considered for this study contained rut depth as the "dependent variable". The independent variables were: aggregate size (two levels), binder type (three levels), binder content (three levels), VMA (three levels), fines content P-200 (two levels), and the covariate air content.

After taking into account all other factors, the questions to be addressed in this study were:

- Does VMA affect permanent deformation results as measured by the APA device?

- Does aggregate size affect permanent deformation results as measured by the APA device?
- Does binder content affect permanent deformation results as measured by the APA device?
- Does the increase in fines content by three percent affect permanent deformation results as measured by the APA device?
- Does binder type affect permanent deformation results as measured by the APA device?

3.6.3. Statistical Analysis

A Type III ANOVA was used because the experiment was unbalanced as a result of including the extra nine cells used to investigate the effects of fines content on rut depth (ANOVA tables are shown in Appendix B).

Initially the statistical analysis was conducted with air content included as a covariate. This analysis showed that the only factor of significance was binder type. The two-way interaction of fines content and VMA was identified as significant. However, further analysis showed that this interaction was confounded with air content and therefore not statistically significant. The statistical consultant for this project recommended that subsequent analysis exclude the covariate air content ("personal communication", February 2004). The ANOVA results described below do not include the covariate air content.

It has been established that the rut depths tend to decrease as the high temperature grade of the binder increases (Cooley et al., 2003; Zaniewski and Nallamothu, 2003; Bennert and Maher, 2003; Williams, 2003; and Kandhal and Mallick, 1999). The effect of binder type on rut depth is shown in Figure 3.25. Statistical analysis showed that there is strong evidence that the rut depth mean values decrease as the high temperature grade of the binder increases (p-value = 0.0001). This reflects the increasing high temperature stiffness of the binder. Since all mixes were tested at the same temperature 64C following standard procedure, it is not surprising that the higher stiffness binders demonstrated less permanent deformation. The estimated rut mean value for the mixes using the PG 64-22 binder was 3.3 mm (95% confidence interval: 3.1 to 3.6). The estimated rut mean value for the mixes using the PG 70-22 binder was 2.5 mm (95% confidence interval: 2.2 to 2.7). The estimated rut mean value for the mixes using the PG 76-22 binder is 1.3 mm (95% confidence interval: 1.1 to 1.5). There is no statistical evidence that changes in binder content, within the range investigated here, affects rutting potential (p-value = 0.3245). In summary, there is a 26 and 60 percent reduction in APA-measured rut depths in the mix (with PG 64-22 binder) at 64C, when using the PG 70-22 and PG 76-22 binders, respectively.

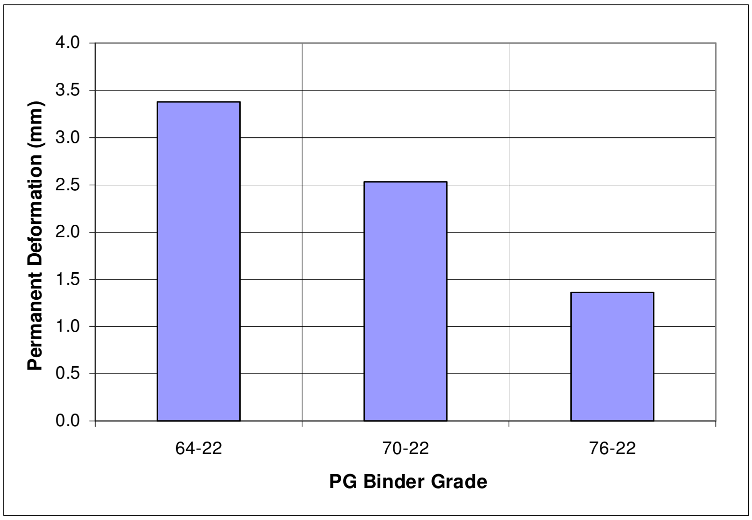

Figure 3.25 Effect of Binder type on permanent deformation

Figures 3.26 and 3.27 show the effects of binder content for the 19.0 mm and 12.5 mm mixes, respectively. As shown in these figures, as the binder content increases, the permanent deformation also increases for the mixes using the PG 64-22 binder (19.0 mm mix), but not for the other binder grades. Again, when the standardized test temperature of 64C is used for all mixes, regardless of binder grade, the effect of increasing binder content is masked. Conversely, it can be argued that for a given environment, small variations in binder content will not result in increased rutting if a higher stiffness binder is used. This assumes that the APA results are indicative of field performance.

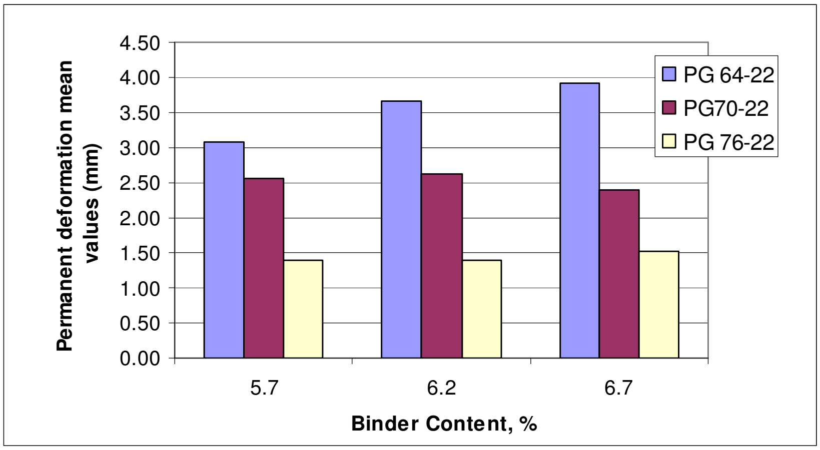

Figure 3.26 Effect of Binder content in permanent deformation for 19.0 mm mixes

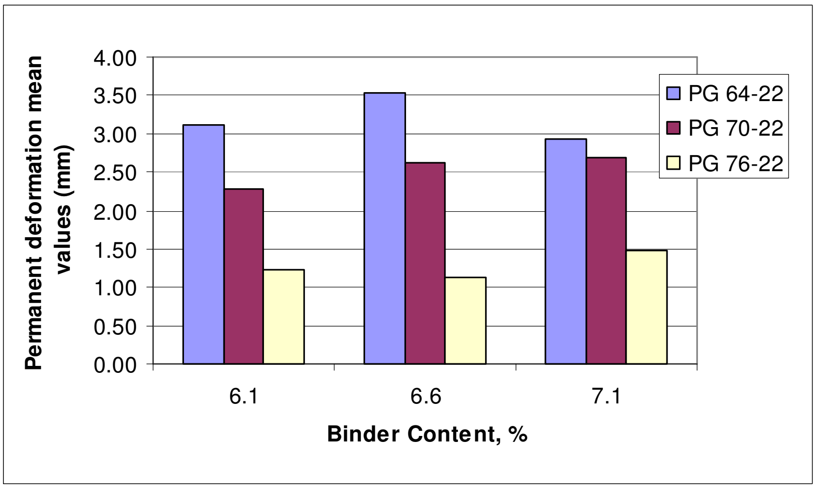

Figure 3.27 Effect of Binder content in permanent deformation for 12.5 mm

A special contrast analysis was done to assess the effect of the extra three percent fines content in the 19.0 mm, PG 64-22 mixes. There was no statistical evidence that the mean rut depths change when the fines content is increased by three percent over the design value (p-value = 0.5349). Figure 3.28, shows the relationship between rut depths, VMA, and binder content for the two fines levels investigated.

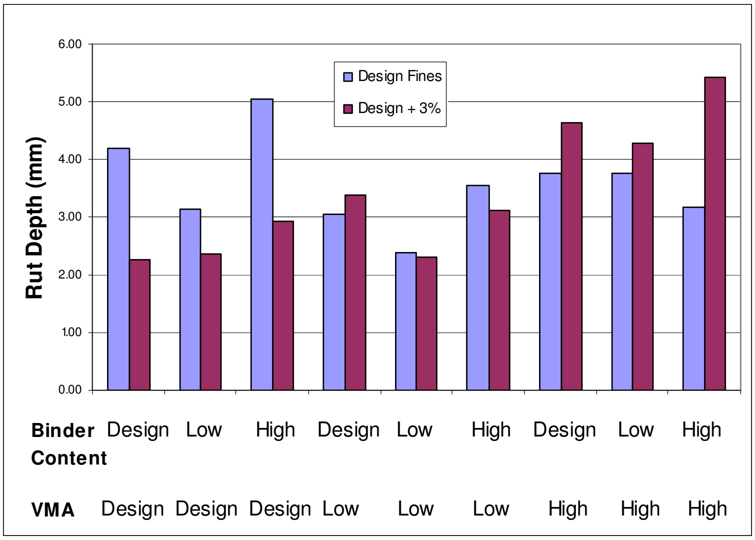

Figure 3.28 Effect of fines content on mean APA rut depths in 19.0 mm mixes

The statistical analysis showed that there was a significant interaction effect (p-value = 0.0006) between P200 and VMA on the measured APA rut depths. A summary of the ANOVA Table is shown in Appendix B. From that summary, it is clear that the degree of significance depends entirely on the different levels of VMA and P200 in the mixture.

Figure 3.29, shows the effect of the extra three percent fines on the air voids in the 19.0 mm mixes. As shown in the figure, the air voids followed the same trend in the design and high fines mixes. As expected, there was a reduction of air voids in the mix as the fines content increased. The air voids dropped an average of 1.9 percent when the fines content was increased by three percent.

Figure 3.30, shows the effect of the interaction of VMA and aggregate size on permanent deformation across all mix combinations. Statistically, there is a modest relationship (p-value = 0.05) between VMA and aggregate size on the measured APA rut depths. There are statistically significant differences between the mean values shown (i.e., 19.0 mm high VMA versus 19.0 mm design VMA), but there is no consistent trend across the range of VMA levels and aggregate size investigated.

A summary of these least squares means analysis (Tukey-Kramer) is shown in Appendix B.

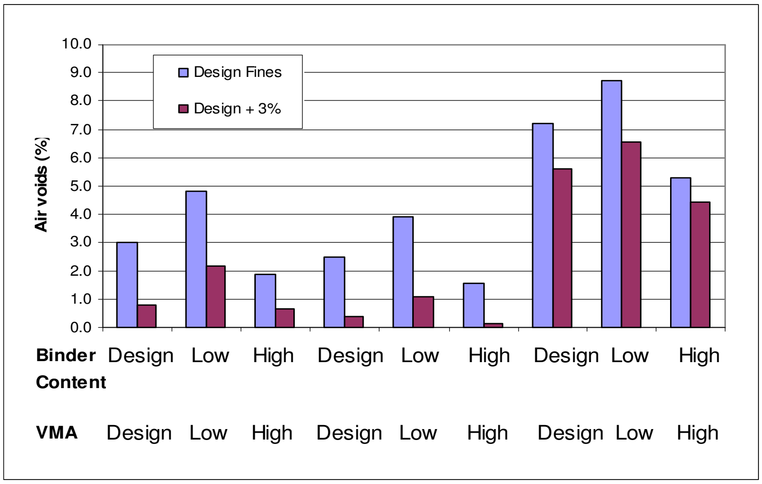

Figure 3.29 Effect of fines content on mean air voids in 19.0 mm mixes

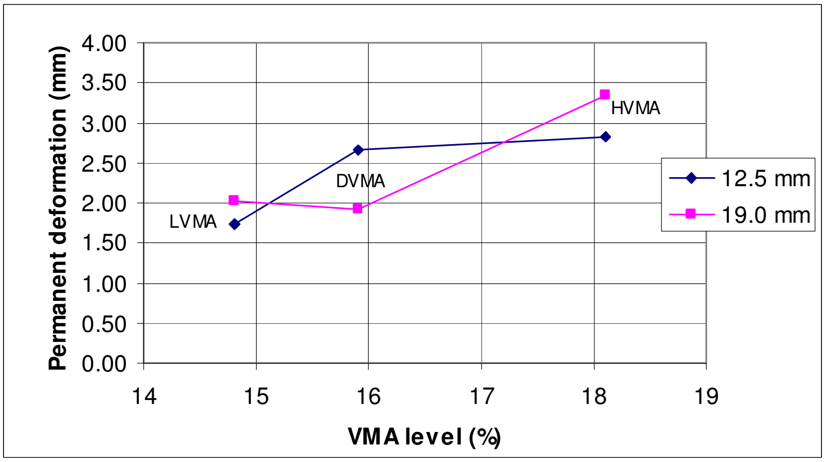

Figure 3.30 Effect of VMA and aggregate size on permanent deformation

The effects are separated further in Figures 3.31 and 3.32 to show the effects of binder type.

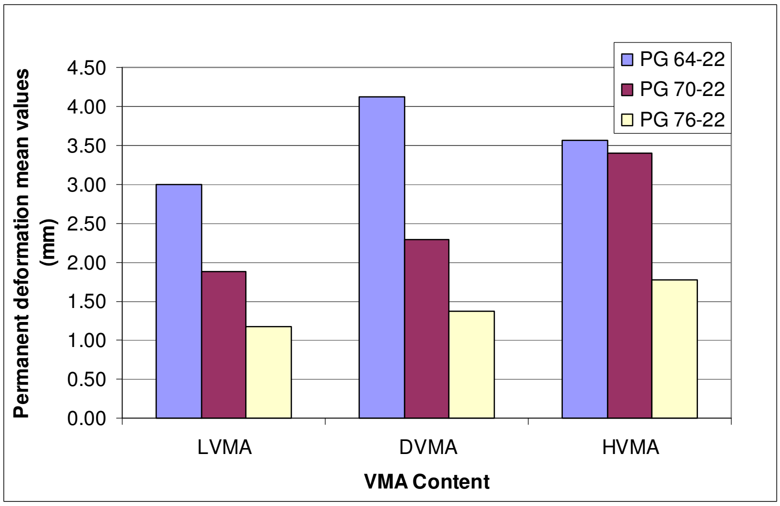

Figure 3.31 Effect of VMA in permanent deformation for 19.0 mm

As shown in these figures, there is no a similar trend for the different PG binder types used in the 19.0 mm mixes, specially the PG 64-22 binder. However, in the 12.5 mm mixes there is an increase in permanent deformation for the different VMA levels going from low to high.

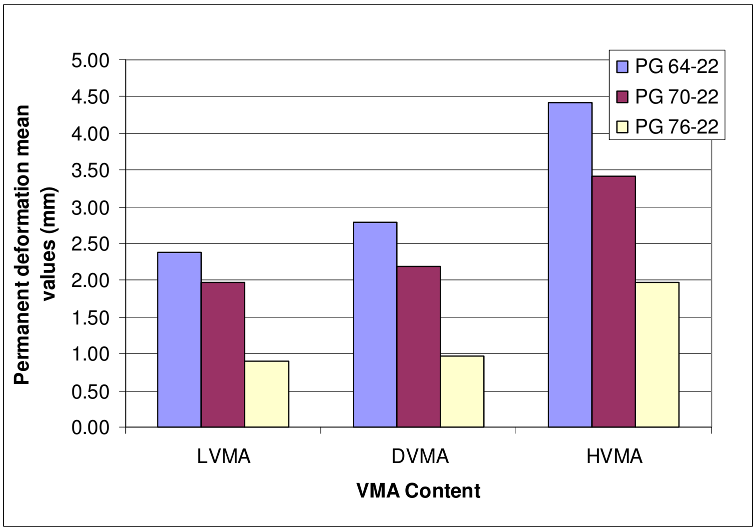

Figure 3.32 Effect of VMA in permanent deformation for 12.5 mm.

3.7. Summary and Recommendations

The APA device was used to characterize the impacts of various mix factors on the measured permanent deformation in dense-graded mixes. Current practice tests all mixes at 64C and limits the maximum acceptable permanent deformation to 8 mm after 8000 cycles when air voids in the compacted mixes is seven percent.

The research reported herein focused on the effects of voids in mineral aggregate (VMA), binder type, binder content, maximum aggregate size, and fines content. Each of the factors was considered at three levels, except that only two maximum aggregate sizes were included from single crushed basaltic source in western Oregon. For the variables investigated in this study, the following conclusions and recommendations appeared herein are warranted:

- The effect of VMA results depend on the aggregate size used and the fines content. It was not possible to separate these interaction effects.

- Permanent deformation increased with increasing binder content for the PG 64-22 mixes, but this trend was not evident in the stiffer binders. One would expect that the trend exhibited in the mixes using the PG 64-22 binder would also be present in the stiffer binders if they were tested at higher temperatures.

- There was no statistical evidence that the mean rut depths change when the fines content is increased by three percent over the design value. However, it was observed a reduction of air voids in the mix as the fines content increased. The air voids dropped an average of 1.9 percent when the fines content was increased by three percent.

- Mixes using stiffer binders (PG 70-22 and PG 76-22) had lower measured permanent deformation compared to the mixes using the PG 64-22 binder grade. This is not surprising since all mixes were tested at 64C.

- The use of a stiffer binder than required by the test temperature (e.g., PG 70-22 rather than a PG 64-22) appears to limit APA-measured permanent deformation, even when variation in mix properties occurs.

In general, it appears that the APA has a potential to predict the relative rutting potential of the hot mix asphalt mixes. However, this research suggests that the APA device is relatively insensitive to changes in mix properties when the test temperature does not match the high temperature rating of the binder. It is possible, that when tested at the high temperature PG rating, similar trends will emerge. Further testing is recommended to confirm this hypothesis.

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CHAPTER 4. "Effect of Test Temperatures on Permanent Deformation Characteristics of Dense-Graded Mixes Using Asphalt Pavement Analyzer"

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To Be Submitted to:

The American Society of Civil Engineers

4.1. Abstract

Pavement deformation has been an important concern for pavement engineers for decades. Permanent deformation is caused by the progressive movement of materials under repeated loads, either in the asphalt pavement layers or the underlying base. It may also be the result of lack of shear strength in the asphalt mixtures, mainly influenced by a variety of its material properties. The Asphalt Pavement Analyzer (APA) device was used to characterize the impacts of various mix factors on the development of permanent deformation of dense-graded mixes. Factors investigated included three VMA levels (high, design, and low), three binder contents (low, design, and high), two binder types (PG 70-22 and PG 76-22), and three test temperatures (64C, 70C and 76C). A 19.0 mm maximum aggregate size from a single quarry was used for this study. All specimens received the same compactive effort (100 gyrations). Different test temperatures were used in this study; one temperature was set at the standard APA testing protocol (64C), and the others were set at the high temperature of standard performance binder grade (i.e. 70C for the PG 70-22 and 76 for the PG 76-22 binder).

Based on the statistical analysis, there was no evidence that changes in binder content affected permanent deformation for the mixes using the PG 70-22 binder. On the other hand, in the case of the mixes using the PG 76-22 binder, there was modest evidence that changes in binder content affected permanent deformation of the mixes.

The use of higher test temperature (i.e. 70C instead of 64C) has a moderate impact in permanent deformation measurements for the mixes using the PG 70-22 asphalt binder. In the case of the mixtures using the PG 76-22 asphalt binder, it was found that the use of higher test temperature had a big impact in permanent deformation measurements. Permanent deformation results are affected by the interaction effect of VMA and the test temperature. It is difficult to separate this interaction effect due to the limited data of this study

Key Words: Asphalt Pavement Analyzer, permanent deformation, VMA, test temperature.

4.2. Introduction

Permanent deformation is defined as the load-induced permanent deformation along the wheel path of flexible pavements due to repeated movement of traffic (Roberts et al., 1996). Premature deformation may be attributed to softer binders resulting from higher temperatures, which increases the likelihood of permanent deformation. Permanent deformation may be caused by an asphalt mixture that is too low in shear strength to resist the repeated heavy loads to which it is subjected (McGennis et al., 1995).

The appropriate test temperature of the APA device is the subject of research. Some researchers have followed the existing standard test temperature of 64C when using the APA device. However, others have been using the high temperature of standard performance binder grade (i.e. 70C for the PG 70-22 binder). In the previous chapter, it was observed that APA device was relatively insensitive to changes in mix properties when the test temperature does not match the high temperature rating of the binder. In a recent study by Kandhal and Cooley (2003), the APA device was used and a revised APA testing protocol has been proposed and recommended in AASHTO format for future research. This revised test protocol proposes the use of the temperature corresponding to the high temperature of the standard performance grade for a project location for future tests using the APA device.

Currently, it is widely accepted that the conventional mix design procedures, Marshall and Hveem, are inadequate to address the present in-service performance problems (Choubane et al., 2000). The current Superpave mix design and analysis system does not presently specify a proof test to assess the rutting susceptibility of hot mix asphalt (HMA). Therefore, there is a need for a test to evaluate the performance of the modified asphalt mixes. Such a test would assure that the propose mix would resist permanent deformation for the design life of the road. One such device, the Asphalt Pavement Analyzer (APA), was developed to test asphalt concrete mixes for rutting susceptibility.

4.3. Objective

Permanent deformation is influenced by a variety of factors (e.g. VMA, asphalt content, temperature). It is difficult to separate them due to their confounding effects. However, the APA can be used to assess the influence that each of these factors produces in the HMA mixes. Therefore, it can be hypothesized that permanent deformation can be better assessed by using the APA device. The objective of this study is to assess the suitability of the APA device as a tool for evaluating asphalt mixes and judge the effects of varying mix properties on APA results.

In this study two test temperatures are used. One of them is the test temperature matching the temperature that corresponds to the high temperature of the standard performance binder grade. The other temperature is the standard test temperature currently used in the APA device (64C). The factors (mix properties) to be investigated are:

- Binder Types – PG 70-22 and PG 76-22
- Test temperature, 70C and 76C, which correspond to the high temperature of the standard performance binder grade, and the current used 64C
- Voids in Mineral Aggregate (VMA) – Low, Design and High
- Asphalt Content- Low, Optimum, and High
- Analysis of mixes tested at 64C, 70C, and 76C.

There are a total of 36 cells, as shown in Table 4.1. The main factors (as listed above) and the two-way interactions are investigated. A total of 216 asphalt cylinders are prepared using the SGC.

Table 4.1 Fractional factorial experimental design

VMA	***Binder Grade and Content***					
	PG 70-22 at 64C			**PG 76-22 at 64C**		
	Low	Optimum	High	Low	Optimum	High
Low VMA	**X**	**X**	**X**	**X**	**X**	**X**
Design VMA	**X**	**X**	**X**	**X**	**X**	**X**
High VMA	**X**	**X**	**X**	**X**	**X**	**X**
VMA	***Binder Grade and Content***					
	PG 70-22 at 70C			**PG 76-22 at 76C**		
	Low	Optimum	High	Low	Optimum	High
Low VMA	**X**	**X**	**X**	**X**	**X**	**X**
Design VMA	**X**	**X**	**X**	**X**	**X**	**X**
High VMA	**X**	**X**	**X**	**X**	**X**	**X**

4.4. Materials and Procedures

Half of the specimens were compacted using a SGC located at Oregon State University (OSU) in Corvallis, Oregon and the other half using a SHRP gyratory compactor located at the Asphalt Pavement Association of Oregon (APAO) in Salem, Oregon (from a simultaneous project conducted using the same material). Following the approach taken by ODOT mix design procedures (ODOT, 2003), all specimens received a compactive effort of 100 gyrations.

4.4.1. Aggregate Tests

Aggregate property tests were performed and summary results are listed in Table 4.2. All the aggregates used in this study met the ODOT specifications. ODOT requires the Soundness Loss Test, ODOT TM 206, for both coarse and fine aggregates, with a weighted loss not exceeding 12 percent when subjected to five cycles. This test estimates the resistance of aggregate to in-service weathering. The Abrasion Loss Test (AASHTO T96, 1993) provides durability testing of coarse aggregate. ODOT specification limit is 30 percent.

The Fracture Faces test, ODOT TM 213, was conducted in this study. ODOT specifications require a minimum of 75 percent for materials retained on 2.36 mm sieve (#8) sieve (one fractured face) and a minimum of 75 percent for materials retained on 37.5, 25.0, 19.0, 12.5 and 4.75 mm sieves (two fractured faces), (ODOT, 2003).

Table 4.2 Summary of aggregate test results

COARSE AGGREGATE		FINE AGGREGATE		
Size, mm	19.0-4.75	Size, mm	4.75-2.36	2.36-0
Soundness Loss %	1.0	Soundness Loss %	6.0	7.0
Abrasion loss % (LAR)	12.7			
Sediment Height, mm	16.0	Sediment Height, mm	17.0	17.0
% passing 0.85mm (No. 20)	13.1	% passing 0.85mm (No. 20)	9.7	9.7
Bulk Specific Gravity (Gsb)	2.629	Bulk Specific Gravity (Gsb)	2.587	2.591
Absorption, %	1.7	Absorption, %	2.3	2.3
Fracture Faces, %	minimum met	Fracture Faces, %	minimum met	minimum met
Lightweight Pieces, %	0.0	Lightweight Pieces, %	0.0	

ODOT also requires the aggregate degradation test, ODOT TM 208. The degradation test is used to measure the quantity and quality of the material produced by attrition similar to that produced in the roadway under repeated traffic loading and unloading. The quantity is indicated by a percentage (by weight) of fine material produced. The quality is measured by means of a modified sand equivalent test. The fine material is made by the rubbing action of one particle against another in the presence of water by mean of air jets. These results are shown in Table 4.2 under “sediment height” and “percent passing 0.85 mm (No. 20)”. The maximum limit for sediment height for coarse and fine aggregate is 75 mm and 100 mm, respectively.

The maximum value in the percent passing 0.850 mm (No. 20) sieve test, for coarse and fine aggregate, corresponds to 30 percent. The lightweight pieces test was done according to AASHTO T113 (1993) procedure. ODOT allows a maximum value of 1.0 percent for coarse aggregates.

4.5. Mix Design

The Job Mix Formula (JMF) for this project was developed based on a Level 3 mix design from ODOT specifications (ODOT, 2003). In the State of Oregon, Hot Mixed Asphalt Concrete (HMAC) Level 3 designs are assigned to road applications exposed to moderated truck traffic (1 to 10 million ESAL's) during the design life. A summary of the mix design values obtained is shown in Table 4.3.

The optimum binder content for the control mix was determined for a 100 gyration mix using a PG 64-22 binder (commonly used in Oregon). The design (optimum) asphalt content was 6.2. The high and low binder contents were selected at 0.5 percent above and below the optimum binder content. This approach yielded, low, design and high binder contents of 5.7, 6.2 and 6.7 percent, respectively.

The same binder contents (5.7, 6.2, and 6.7) were used for the mixes using the PG 70-22 and PG 76-22 binders.

Table 4.3 Summary of mix design results for the mix with the PG 64-22 binder

MIXTURE PROPERTIES		JOB MIX FORMULA	Percent Passing
Maximum Specific Gravity (Gmm)	2.454	25.0mm	100
Gyro. Bulk Specific Gravity (Gmb)	2.357	19.0mm	94
Air Voids, % (Va)	4.0	12.5mm	81
VMA, %	15.5	9.5mm	71
VFA, %	74	6.3mm	66
Effective Asphalt Content (Pbe), %	4.9	4.75mm	59
P0.075/Asphalt Content Ratio	1.0	2.36mm	42
P0.075/Pbe Ratio	1.3	0.600mm	19
Target Maximum Density, Kg/m^3	2454	0.075mm	6.3
Combined Aggregate Gsb	2.606		
		Asphalt Content, %	6.2
		Asphalt Grade	64-22
		Mix Temperature Range, C	156-161
		Compaction Temperature Range, C	142-147
		Asphalt Sp. Gr. (Gb) at 15.6C	1.033

The voids in mineral aggregate (VMA) was adjusted by modifying the aggregate gradations as shown in Table 4.4.

Table 4.4 Aggregate gradation for the 19.0 mm mix

Sieve Size (mm)	Low VMA	Design VMA	High VMA
25.0	100	100	100
19.0	92	94	98
12.5	79	81	85
9.5	69	71	73
6.3	66	66	54
4.75	60	59	46
2.36	44	42	30
0.600	21	19	12
0.075	6.5	6.3	3.5
Expected VMA, %	14.1	15.5	18.1

4.5.1. Asphalt Binder Characteristics

For this study two asphalt binders, PG 70-22 and PG 76-22, were used. Table 4.5 shows a summary of the binder characteristics.

Table 4.5 Asphalt binder characteristics

Original properties	**PG 70-22**	**PG 76-22**	**Specification**
Specific Gravity @ 15.6C (60F)	1.0419	1.0430	
Rotational Viscosity, 135C, Pas	0.688	1.056	3.00 -
Dynamic Shear, G*/sin δ, 70C, kPa	1.28	1.09	1.0+
RTFO Residue Properties			
Dynamic Shear, G*/sin δ, 70C, kPa	3.61	2.50	2.20+
PAV Residue Properties			
m-value, -12 C	0.330	0.319	0.300+
Creep Stiffness, -12C, MPa	162	192	300 -

Note: "-" denotes a maximum value of, and "+" denotes a minimum value of.

4.5.2. Superpave Gyratory Compactor (SGC)

The Superpave Gyratory Compactor (SGC), as shown in Figure 4.1, was used to prepare half of the asphalt cylinders. The SGC produces asphalt mix specimens to densities approximating those achieved under actual construction conditions.

The SGC consists of a rigid reaction frame, a loading system, a specimen height measurement and recording system. It compacts the asphalt mixture specimen at a constant pressure of 600 kPa. The mixture is compacted by a gyratory kneading action using a compaction angle of 1.25 degrees and operating at 30 rpm. The SGC used for this study was equipped with an automated system, which sent all the information to a PC.

Figure 4.1 Superpave Gyratory Compactor

4.5.3. APA Testing

Testing was conducted with a tube pressure of 690 kPa and an applied mass of 450 N. Each test in the APA device consisted of six cylinders for each combination of the factor levels. Permanent deformation measurements were automatically recorded and sent to a computer.

It is particularly important to note that some testing was conducted at 70C for the mixes using the PG 70-22 binder and at 76C for the mixes using the PG 76-22 binder (that is, using the high temperature of standard performance binder grade), as suggested by in a recent study by Kandhal and Cooley (2003). This was done with the purpose of assessing the effects of test temperature on permanent deformation.

As previously mentioned, specimens were prepared with a standard compactive effort of 100 gyrations, rather than attempting to adjust the compactive effort to achieve constant air voids of 4 or 7 percent. As a consequence, there was no control for the air voids in the specimens.

4.6. Results and Analysis

The rut depths, air voids and the VMA values are shown in Table 4.6. Only the mean values of the six specimens of the measured permanent deformation, air voids, and the calculated VMA results are shown. Complete results are included in Appendix A.

Table 4.6 Summary Data for mixes

		Binder Grade					
		PG 70-22 (64C)			PG 76-22 (64C)		
VMA Level	**Averages**	*5.7*	*6.2*	*6.7*	*5.7*	*6.2*	*6.7*
Low VMA	Rut Depth (mm)	2.03	1.83	1.78	1.11	1.05	1.39
	Air content (%)	4.10	2.50	1.30	3.80	2.30	1.50
	VMA	14.2	13.8	13.8	14.1	13.8	14.3
Des VMA	Rut Depth (mm)	2.11	2.78	1.98	1.31	1.45	1.33
	Air content (%)	4.60	3.50	1.90	4.20	3.40	1.80
	VMA	14.7	14.7	14.4	14.5	14.9	14.5
High VMA	Rut Depth (mm)	3.52	3.26	3.41	1.78	1.69	1.83
	Air content (%)	9.00	7.30	5.30	8.00	7.10	5.00
	VMA	18.5	18.1	17.3	17.8	18.1	17.3
		PG 70-22 (70C)			PG 76-22 (76C)		
	Averages	*5.7*	*6.2*	*6.7*	*5.7*	*6.2*	*6.7*
Low VMA	Rut Depth (mm)	1.54	1.50	2.14	1.23	1.30	1.53
	Air content (%)	2.90	1.20	0.60	2.20	1.30	0.80
	VMA	13.9	12.6	13.2	13.3	12.8	13.4
Des VMA	Rut Depth (mm)	1.38	1.50	1.93	1.26	1.25	1.72
	Air content (%)	2.90	1.40	0.90	2.50	1.70	0.80
	VMA	13.9	12.9	13.5	13.8	13.3	13.5
High VMA	Rut Depth (mm)	3.57	4.07	3.76	2.69	2.91	2.78
	Air content (%)	6.30	4.90	3.70	6.00	4.40	3.10
	VMA	17.2	16.3	16.3	17.1	15.9	15.9

4.6.1. Discussion of the results

The discussion of permanent deformation refers to APA results not to field performance. A brief discussion of the raw data is included before the statistical analysis. For the case of the mixes using the PG 70-22 binder and tested at 64C, as shown in Figure 4.2, the air voids content decreased when the binder content is increased, regardless of the VMA level. There is a marked difference among the VMA levels, especially the high VMA compared to the other two levels. This is an expected and logical result. The increase of binder in the mix fills the air voids and as a consequence the air void content is reduced.

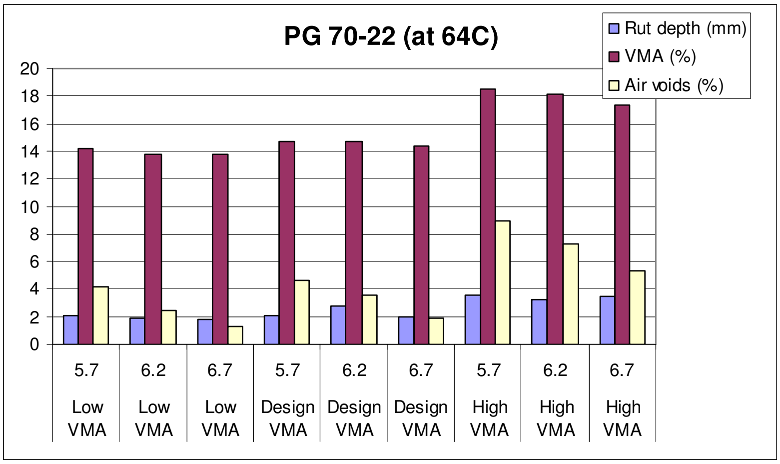

Figure 4.2 Effect of VMA and air voids on permanent deformation

In this case, within VMA levels it is observed that the increase in binder content doesn't generate more permanent deformation. There is a strong correlation (R^2 = 0.725) between the air void contents and the permanent deformation on these mixes. As shown in Figure 4.3, higher air voids creates more permanent deformation. The air voids in the mixture ranged from 1.30 to 9.0.

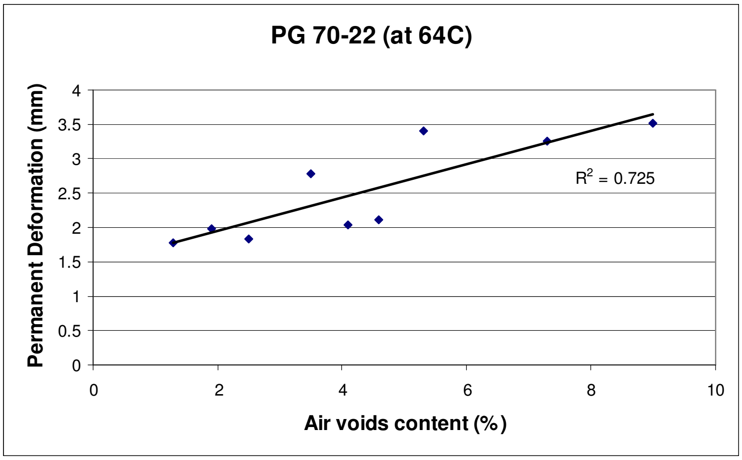

Figure 4.3 Effect of air voids on permanent deformation

In the case of the mixes using the PG 70-22 binder and tested at 70C, as shown in Figure 4.4, the air voids content also decreased when the binder content was increased, regardless of the VMA level (similar trend as previous mixes tested at 64C).

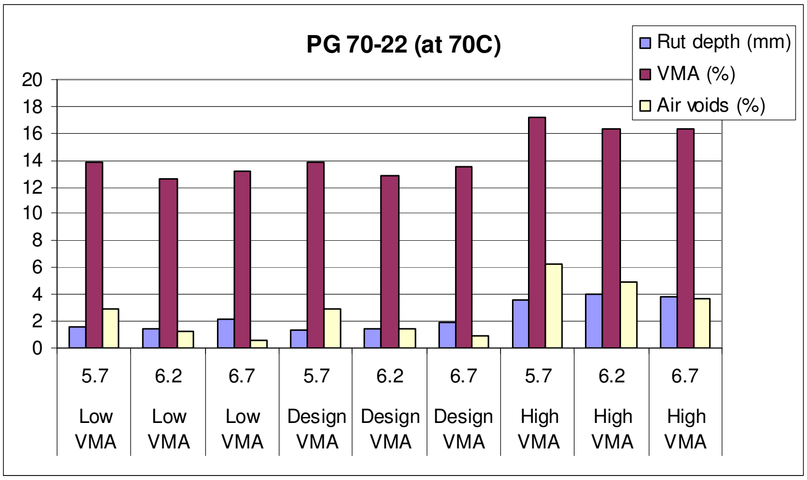

Figure 4.4 Effect of VMA and air voids on permanent deformation

There is a fair correlation ($R^2 = 0.5548$) between the air void contents and the permanent deformation on these mixes. As shown in Figure 4.5, higher air voids creates more permanent deformation. However, it was noticed that most of the permanent deformation values were around 2.0 mm. The air voids in the mixture ranged from 0.6 to 6.3.

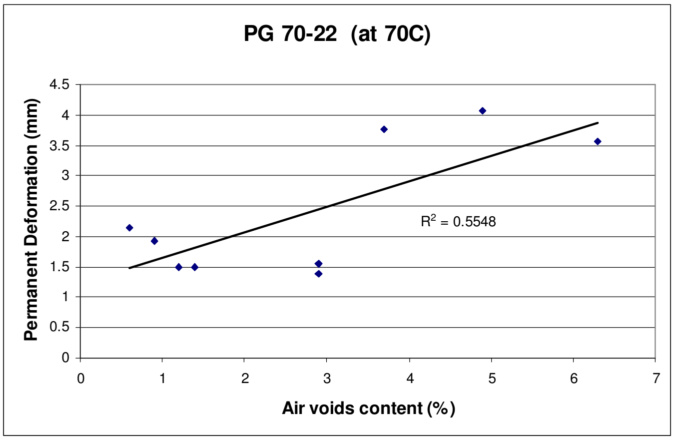

Figure 4.5 Effect of air voids on permanent deformation

A similar assessment was done for the mixes using PG 76-22 binders, tested at 64C and 76C. In this case, as shown in Figure 4.6, in the mixes tested at 64C the air voids content also decreased when the binder content was increased, regardless of the VMA level.

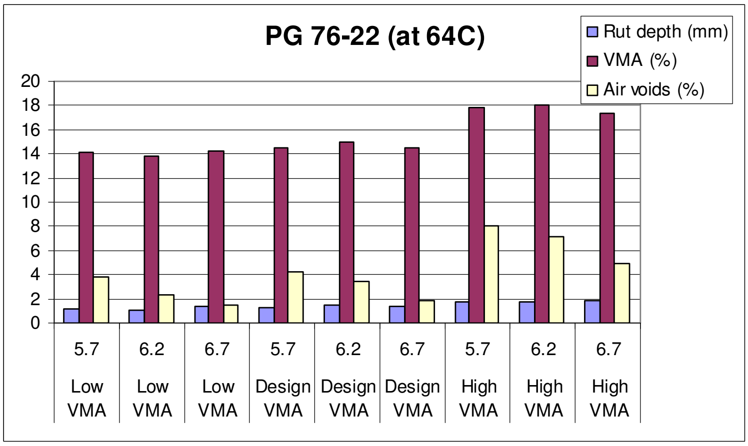

Figure 4.6 Effect of VMA and air voids on permanent deformation

The permanent deformation was low. Permanent deformation values varied from 1.05 mm to 1.83 mm. Current practice limits the maximum acceptable permanent deformation to 8 mm.

There was found a fair correlation (R^2 = 0.5065) between the air void contents and the permanent deformation on these mixes. As shown in Figure 4.7, higher air voids created more permanent deformation. The air voids in the mixture ranged from 1.50 to 8.0.

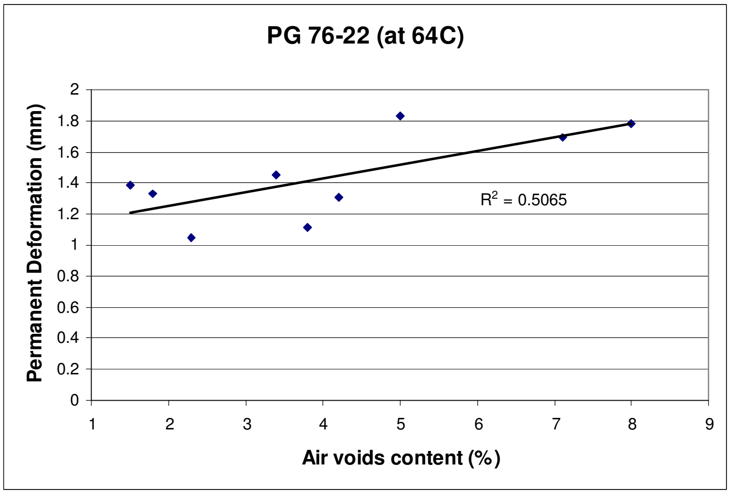

Figure 4.7 Effect of air voids on permanent deformation

In the case of the mixes tested at 70C, as shown in Figure 4.8, the air voids content also decreased when the binder content was increased, regardless of the VMA level. The permanent deformation in this case was also low, especially for the low and design VMA levels. Permanent deformation values varied from 1.25 mm to 2.91 mm.

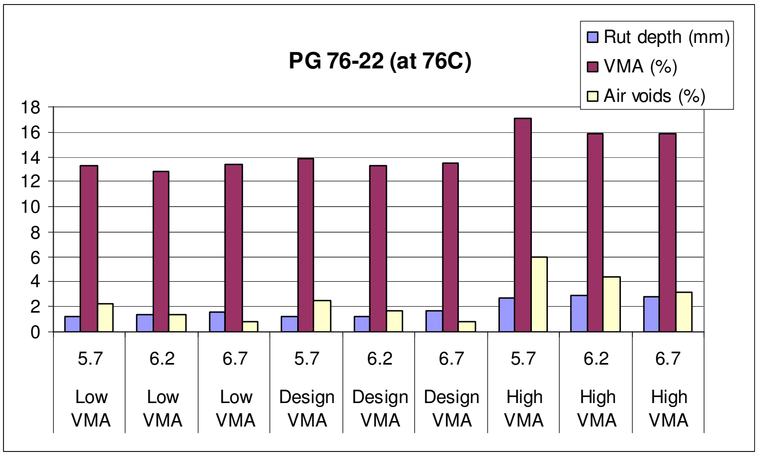

Figure 4.8 Effect of VMA and air voids on permanent deformation

In this case, there is also a fair correlation (R^2 = 0.5684) between the air void contents and the permanent deformation on these mixes, as shown in Figure 4.9. Higher air voids created more permanent deformation. The air voids in the mixture ranged from 0.8 to 6.0.

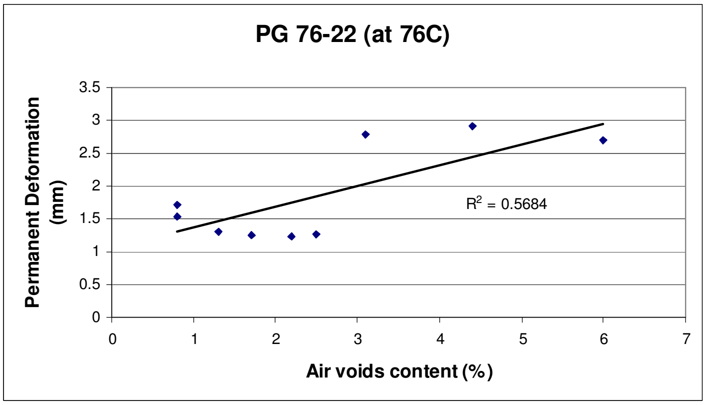

Figure 4.9 Effect of air voids on permanent deformation

In summary, it was noticed that the air voids were varied for all mixes when applying a fixed compactive effort, giving less permanent deformation around three and four percent air voids in the mix. Similar trends have been found by others (e.g. Tarefder and Zaman, 2002; Prowell, 2001; Kandhal and Mallick, 1999; West et al., 1991; and Ford, 1988). The average air voids for the mixes using the PG 70-22 binder and tested at 64C was 4.39 percent, and for mixes using the PG 70-22 binder and tested at 70C was 2.76 percent. The VMA value for the mixes using the PG 70-22 binder and tested at 64C was 15.5 percent, and for mixes using the PG 70-22 binder and tested at 70C was 14.4 percent. Mixes using the PG 70-22 binder and tested at 70C have lower permanent deformation. The average permanent deformation for the mixes using the PG 70-22 binder and tested at 64C was 2.52 mm, and for mixes using the PG 70-22 binder and tested at 70C was 2.38 mm.

In the case of mixes using the PG 76-22 binders, the average air voids for the mixes 64C was 4.12 percent, and for mixes tested at 76C was 2.53 percent. The VMA value for the mixes tested at 64C was 15.4 percent, and for mixes tested at 76C was 14.3 percent. Finally, in this case the mixes tested at 64C have lower permanent deformation. The average permanent deformation for the mixes tested at 64C was 1.44 mm, and for mixes tested at 76C was 1.85 mm.

In the previous chapter it was observed that rut depth mean values decreased as the high temperature grade of the binder increased. However, as shown in this case, when stiffer binders were used, and the mixes were tested at the high temperature of the standard performance grade, the permanent deformation was increased compared to the mixtures tested at the standard temperature of 64C using the same PG binder grade.

Furthermore, it was observed that rut depth mean values decreased as the high temperature grade of the binder increased, as expected. This pattern can be observed in the previous graphs. In this case, there is no a remarkable effect of the changes in binder content on permanent deformation.

It is necessary to mention again that, although the raw analysis indicated some relationships between the mix factors and permanent deformation, these trends are the result of single factors and not the effect of them as a group. As mentioned before, permanent deformation results from a combination of factors. To try to assess the effect of each factor after taking into account the rest of the other mix factors, it is necessary to apply statistical tools that can give a closer look of all mix factors on permanent deformation. In the next section the ANOVA procedure is used to accomplish this task.

4.6.2. Statistical Approach

The results of this study were analyzed by conducting an ANOVA test, using SAS software (SAS, 2001; Little et al., 2002; Kuehl, 2000). Following ANOVA, the levels of significance and two-way interactions were assessed using multiple comparisons with a Tukey-Kramer adjustment. There were a total of 36 cells with permanent deformation values; each cell containing 6 rut values.

The model considered for this study contained rut depth as the "dependent variable". The independent variables were: binder content (3 levels), test temperature (2 levels), and VMA (3 levels).

After taking into account all other factors, the questions to be addressed in this study were:

- Does the test temperature affect permanent deformation results as measured by the APA device?
- Does VMA affect permanent deformation results as measured by the APA device?
- Does binder content affect permanent deformation results as measured by the APA device?

4.6.3. Statistical Analysis

A Type I ANOVA was used because the experiment was balanced. Two different statistical analyses were used for this study, one including mixes with the PG 70-22 asphalt binder, tested at two temperatures, 64C and 70C and the second analysis which included mixes with the PG 76-22 asphalt binders also tested at two temperatures, 64C and 76C, (ANOVA tables are shown in Appendix B).

Similar to the data analysis from previous chapter, first the statistical analysis was conducted with air content included as a covariate. Based on the results from this analysis, once again, the statistical consultant for this project recommended that subsequent analyses exclude the covariate, air content ("personal communication", March 2004). The ANOVA results described below do not include the covariate, air content.

From previous research, it has been established that when testing asphalt mixes, at the same test temperature and using different binder grades, the rut depths in the mixes will tend to decrease as the high temperature grade of the binder used increases (Cooley et al., 2003; Zaniewski and Nallamothu, 2003; Bennert and Maher, 2003; Williams, 2003; and Kandhal and Mallick, 1999). Kandhal and Mallick (1999), also established that mixes with the same aggregate gradation, but different asphalt binders, should exhibit similar rutting potential, when the test temperature matches the high temperature of the standard performance binder grade (i.e. 70C for the PG 70-22 binder).

In this study, it was observed that the measured rut depth for the mixes with the PG 70-22 asphalt binder was affected by the interaction of VMA and test temperature. Statistical analysis showed that the interaction between the VMA and the test temperature have a modest influence on the measured APA rut depths for the mixes with the PG 70-22 asphalt binders (p-value = 0.0333). As a consequence, as shown in Figure 4.10, the rut depth mean values varied for the different VMA levels in the mix.

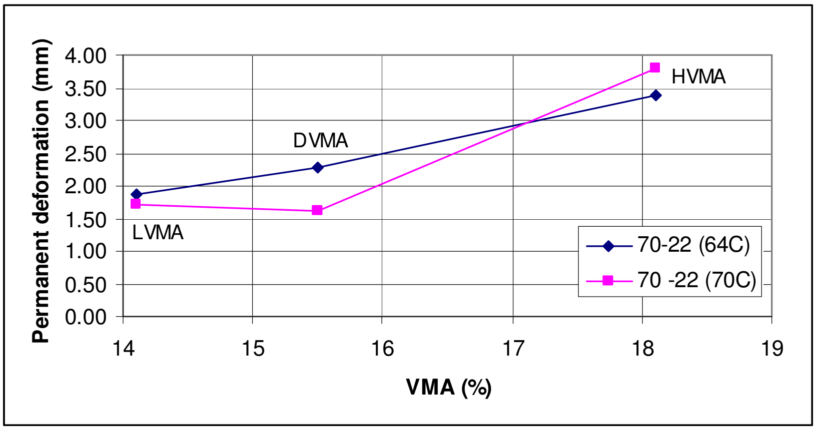

Figure 4.10 Effect of VMA and Test temperature on permanent deformation

However, both mixes showed the same trend; with an increase in the VMA levels, there was a tendency for the mix to rut more. It can be also observed, as shown in Figure 4.11, that the mixes tested at higher temperature have approximately the same permanent deformation. Statistical analysis didn't show a significant difference between the two estimated rut mean values of the mixes (p-value = 0.3313). The estimated rut mean value for mixes with the PG 70-22 asphalt binder tested at 64C was 2.52 mm (95% confidence interval: 2.30 to 2.75). The estimated rut mean value for mixes with the PG 70-22 asphalt binder tested at 70C was 2.38 mm (95% confidence interval: 2.15 to 2.60).

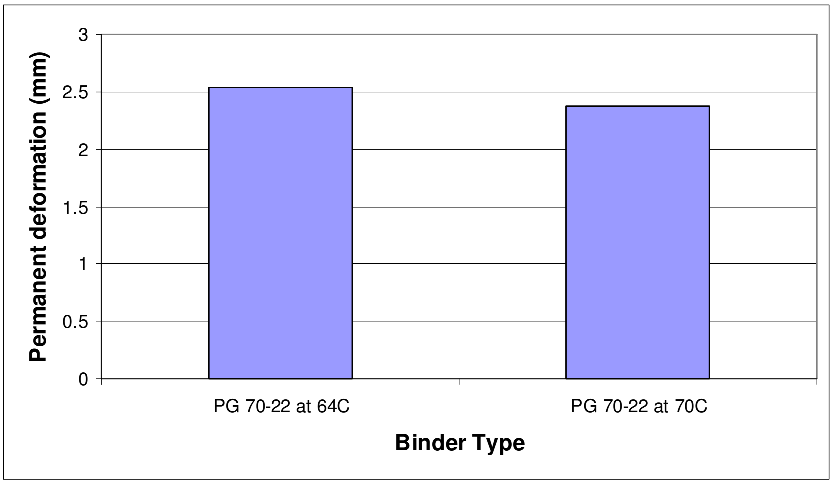

Figure 4.11 Effect of Test temperature on permanent deformation

There was no statistical evidence that changes in binder content, within the range investigated here, affects rutting potential (p-value = 0.6742). Figure 4.12 shows the effects of binder content for the mixes at the different test temperature. As shown in this figure, as the binder content increases, the permanent deformation tends to increase for the mixes with the PG 70-22 asphalt binder tested at 70C, but not for the mixes tested at 64C, in which there is a small variation in rut depths for the different binder contents. A permanent deformation difference of 0.2 mm was found between the low and high binder contents for the mixes tested at 64C and a difference of 0.5 mm was found between the low and high binder contents for the mixes tested at 70C.

This suggests that for a given test temperature, small variations in binder content will not result in a large increase in APA-measured permanent deformation, assuming that the APA results correlate to the permanent deformation measured in the field.

There was no statistical evidence of interaction effect on permanent deformation between binder content and VMA (p-value = 0.7766). A summary of these least squares means analysis (Tukey-Kramer) is shown in Appendix B.

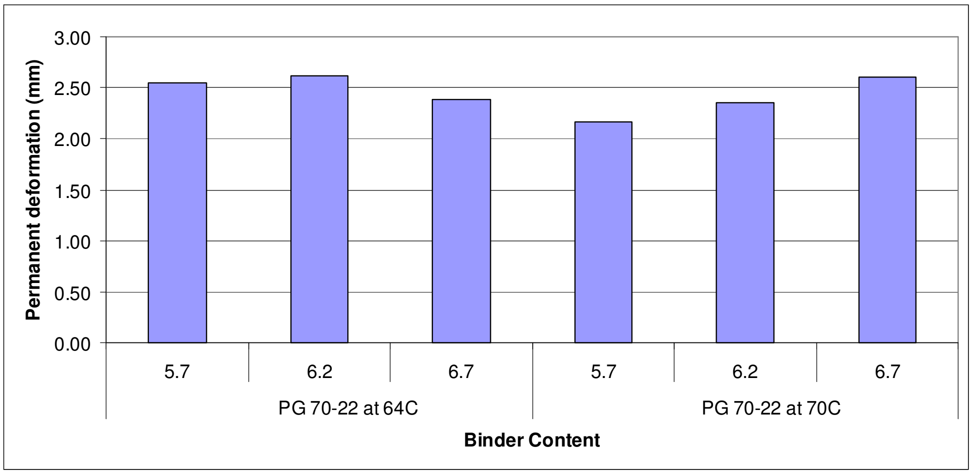

Figure 4.12 Effect of Binder content in permanent deformation

The effect of VMA and binder content is shown in Figure 4.13. As shown in this figure, permanent deformation results are different; especially the high VMA level compared to the low and design VMA levels.

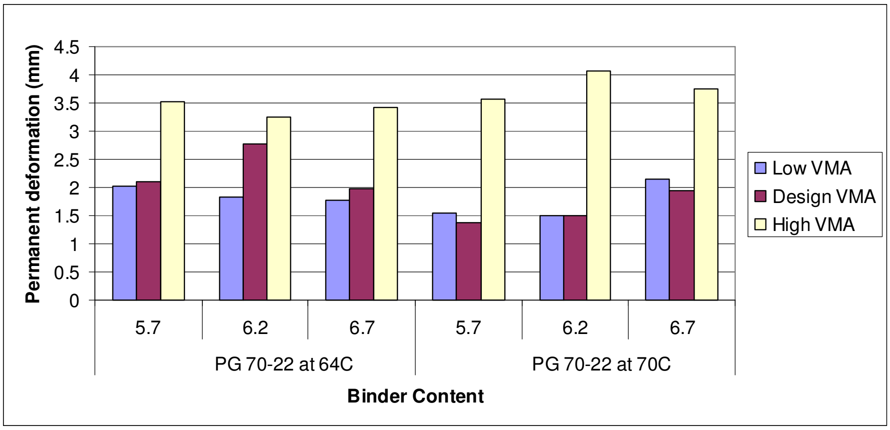

Figure 4.13 Effect of Binder content and VMA in permanent deformation

In the second analysis, the measured rut depth for mixes with the PG 76-22 asphalt binder was also affected by the interaction of VMA and test temperature. Statistical analysis showed that the interaction between the VMA content and the test temperature have a strong influence on the measured APA rut depths for the mixes with the PG 76-22 asphalt binders (p-value = 0.0001). As a consequence, as shown in Figure 4.14, the rut depth mean values varied for the different levels of VMA in the mix. However, both mixes showed the same trend; with an increase in the VMA contents, there was a tendency for the mix to rut more. Figure 4.14 shows that for the low and design VMA levels, the APA-measured rut values are relatively the same; however, in the case of high VMA level, the test temperature makes a difference in the rut depths. As shown in this figure, when testing at the high temperature of the binder grade, it may be possible to get approximately a 58% increment on the APA-measured rut depth values compared to results measured when testing at 64C.

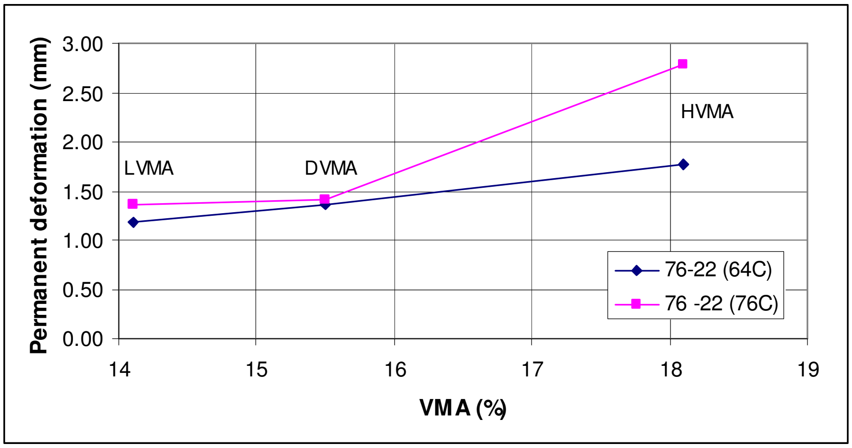

Figure 4.14 Effect of VMA and Test temperature on permanent deformation

In this case it can be also seen, as shown in Figure 4.15, that the mixes tested at higher temperature, demonstrated higher permanent deformation. There was a statistically significant difference between the two estimated rut mean values of the mixes tested (p-value < 0.0001). The estimated rut mean value for mixes with the PG 70-22 binder tested at 64C was 1.44 mm (95% confidence interval: 1.34 to 1.56). The estimated rut mean value for mixes with PG 70-22 binder tested at 76C was 1.85 mm (95% confidence interval: 1.75 to 1.95).

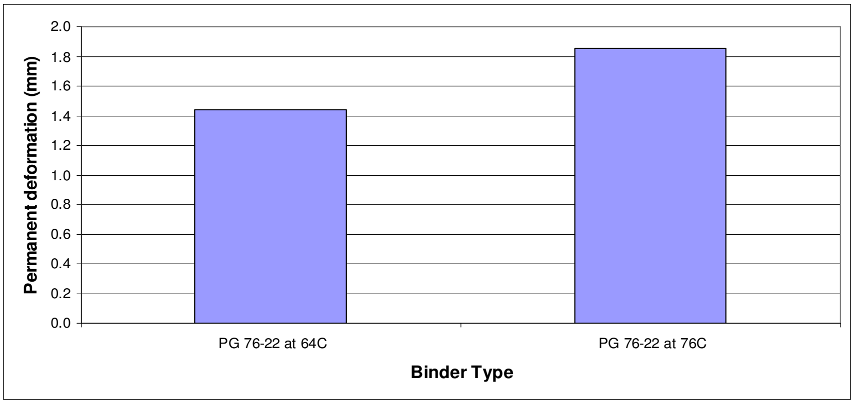

Figure 4.15 Effect of Test temperature on permanent deformation

There is a modest statistical evidence that changes in binder content, within the range investigated here, affects rutting potential (p-value = 0.0588). Figure 4.16 shows the effects of binder content for the PG 76-22 mixes at the different test temperature. As shown in this figure, as the binder content increases, the rutting tends to increase for both PG 76-22 asphalt binder mixes. It can be seen, that mixes tested at 76C rutted more than mixes tested at 64C.

However, both mixes have the same trend, that is, permanent deformation increases with an increase of binder content. As mentioned before, it can also be suggested that for a given environment, small variations in binder content will not result in significant increases in rutting.

There was no statistical evidence of interaction effects on permanent deformation between binder content and VMA (p-value = 0.7823) as shown in Figure 4.17.

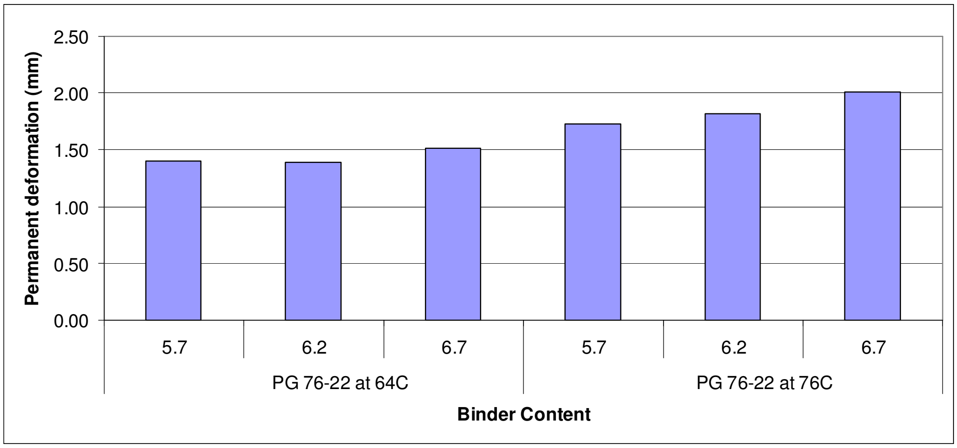

Figure 4.16 Effect of Binder content in permanent deformation

A summary of these least squares means analysis (Tukey-Kramer) is shown in Appendix B.

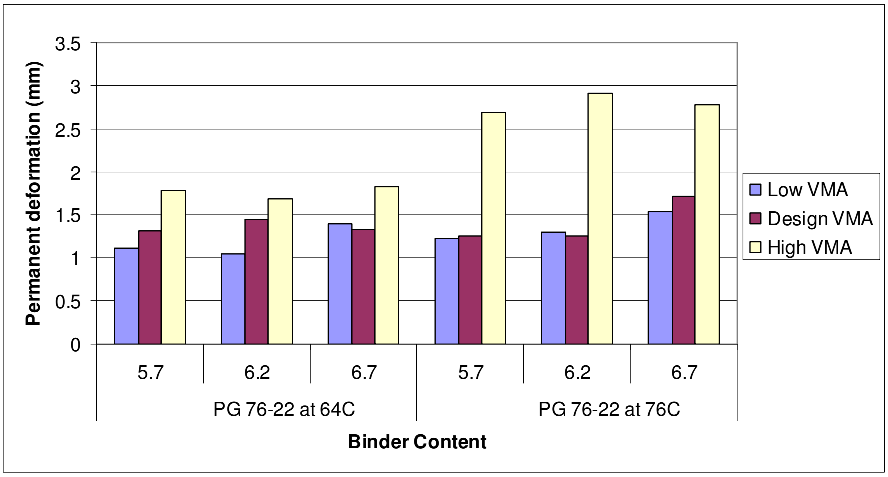

Figure 4.17 Effect of Binder content and VMA in permanent deformation

4.7. Summary and Recommendations

The APA device was used to characterize the impacts of various mix factors on the measured permanent deformation in dense-graded mixes. Current practice requires that all tests be conducted at 64C and limits the maximum acceptable permanent deformation to 8 mm after 8000 cycles when air voids in the compacted mixes is seven percent.

The research reported herein focused on the effects of voids in mineral aggregate (VMA), binder type, binder content, and test temperature. Each of the factors was considered at different levels. For the variables and conditions investigated in this study, the following conclusions and recommendations appeared herein are warranted:

- Permanent deformation results are affected by the interaction effect of VMA and the test temperature. It was difficult to separate this interaction effect due to the limited data of this study. However, all mixes showed the same trend (regardless of the test temperature); with an increase in the VMA levels, there was a tendency for the mix to rut more.

- There was no statistical evidence that changes in binder content, within the range investigated here, affects APA-measured permanent deformation of the mixes. The effect of the binder content when using the PG 70-22 binder was small at the two different test temperatures. This suggests that for a given test temperature, small variations in binder content will not result in a large increase in APA-measured permanent deformation, assuming that the APA results correlates to the permanent deformation measured in the field.

- In the case of the mixes using the PG 76-22 binder, there was modest evidence that increase in binder content, within the range investigated here, increases the permanent deformation of the mixes.

- The use of higher test temperature (i.e. 70C instead of 64C) has a moderate impact in permanent deformation measurements for the mixes using the PG 70-22 asphalt binder; this may be due to the fact that the temperature difference was relative small (6C). However, the temperature effect depends on the VMA.

- In the case of the mixtures using the PG 76-22 asphalt binder, it was found that the use of higher test temperature had a big impact in permanent deformation measurements. However, the temperature effect also depends on the VMA level. It was difficult to separate this interaction effect.

Based on the results from this study, it is recommended to use the high temperature of the standard performance binder grade for a project location during the test, when using the APA device. This approach (test temperature) has been assessed by other researchers (Kandhal and Coley, 2003) and they suggest that its use, when testing in the APA device, gives a good correlation with rutted field mixes. The APA device has a potential to predict the relative rutting potential of the hot mix asphalt mixes. In general, this research confirmed what was hypothesized in last chapter. It suggests that the APA device is relatively sensitive to changes in mix properties when the test temperature matches the high temperature rating of the binder.

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CHAPTER 5. "Effect of Modified Asphalt Binders on Permanent Deformation Characteristics of Dense-Graded Mixes Using Asphalt Pavement Analyzer"

Jesús A. Sandoval-Gil and James R. Lundy

To Be Submitted to:

Association of Asphalt Paving Technologists

5.1. Abstract

Pavement deformation, also termed rutting, has been a primary concern for pavement engineers for decades. Permanent deformation frequently results a lack of shear strength in the asphalt mixtures, mainly influenced by a variety of material properties. The Asphalt Pavement Analyzer (APA) device was used to characterize the impacts of various mix factors on the development of permanent deformation in dense-graded mixes. Factors investigated included voids in mineral aggregate (VMA) at three levels (high, design, low), binder content (low, design, high) and binder type (PG 70-22 and PG 70-22 Modified). A 19.0 mm maximum aggregate size was used for this study. A compactive effort of 100 gyrations was used for all the tested specimens. The specimens were tested at 70C. It was observed that permanent deformation increased with increased asphalt binder content for the mixes used in this study; however, the results were affected by the VMA level in the mixture. The analysis showed that mixes using the PG 70-22 modified asphalt binder demonstrated less permanent deformation than the unmodified binder mixes, but the permanent deformation was always influenced by VMA level in the mix.

Key Words: Asphalt Pavement Analyzer, permanent deformation, VMA, modified binder.

5.2. Introduction

Permanent deformation is defined as the load-induced permanent deformation along the wheel path of flexible pavements due to repeated movement of traffic (Roberts et al., 1996). Premature deformation may be attributed to softer binders resulting from higher temperatures, which increases the likelihood of permanent deformation. Permanent deformation may be caused by an asphalt mixture that is too low in shear strength to resist the repeated heavy loads to which it is subjected (McGennis et al., 1995).

In order to mitigate this problem, the use of polymer modification has become a more common practice in road building to meet today's high traffic loadings (Maccarrone et al., 1995). One of the main reasons to modify asphalt with polymers is to produce stiffer binders at high temperatures without sacrificing low temperature performance (Roberts et al., 1996).

Currently, it is widely accepted that the conventional mix design procedures, Marshall and Hveem, are inadequate to address the present in-service performance problems (Choubane et al., 2000). One of the main challenges facing the highways agencies is the lack of reliable standard protocols to ensure quality of modified asphalts (Bahia et al., 2001). The current Superpave binder specifications were developed on unmodified, and presently exhibit assume that modified binders exhibit similar rheological behavior. However, this assumption is not necessarily valid for all types of modified binders (Hussain et al., 1999). Furthermore, The Superpave mix design and analysis system does not presently specify a proof test to assess the relative rutting susceptibility of hot mix asphalt (HMA). Therefore, there is a need for a test to evaluate the performance of the modified asphalt mixes. Such a test would assure that the proposed mix would resist permanent deformation for the design life of the road. One such device, the Asphalt Pavement Analyzer (APA), was developed to test asphalt concrete mixes for rutting susceptibility.

5.3. Objective

Permanent deformation is being influenced by a variety of factors (e.g. VMA, asphalt content, temperature). It is difficult to separate these factors due to their compounded effect. The APA can be used to assess the influence each of these factors produce in the HMA mixes. Therefore, it can be hypothesized that permanent deformation of unmodified and modified asphalt mixes can be assessed by using the APA device. The objective of this study is to assess the suitability of the APA device as a tool for evaluating unmodified and modified mixes and judge the effects of varying mix properties on APA results. The factors (mix properties) to be investigated are:

- Binder Types – PG 70-22 and PG 70-22 Modified
- Voids in Mineral Aggregate (VMA) – Low, Design and High
- Asphalt Content- Low, Optimum, and High.

There are a total of 18 cells, as shown in Table 5.1. The main factors (as listed above) and the two-way interactions are investigated. A total of 108 asphalt cylinders are prepared using the Superpave Gyratory Compactor (SGC).

Table 5.1 Fractional factorial experimental design

VMA	***Binder Grade and Content***					
	PG 70-22 at 70C			**PG 70-22 Modified at 70C**		
	Low	Optimum	High	Low	Optimum	High
Low VMA	**X**	**X**	**X**	**X**	**X**	**X**
Design VMA	**X**	**X**	**X**	**X**	**X**	**X**
High VMA	**X**	**X**	**X**	**X**	**X**	**X**

Note: tests were conducted at the temperature corresponding to the high temperature of the binder, 70C.

5.4. Materials and Procedures

The specimens were compacted using a SGC located at Oregon State University (OSU) in Corvallis, Oregon. Following the approach taken by ODOT standard test procedures (ODOT, 2003) all specimens received a compactive effort of 100 gyrations.

5.4.1. Aggregate Tests

Aggregate property tests were performed and summary results are listed in Table 5.2. All the aggregates used in this study met the ODOT specifications. ODOT requires the Soundness Loss Test, ODOT TM 206, for both coarse and fine aggregates, with a weighted loss not exceeding 12 percent when subjected to five cycles. This test estimates the resistance of aggregate to in-service weathering. The Abrasion Loss Test (AASHTO T96, 1993) provides durability testing of coarse aggregate. ODOT specification limit is 30 percent.

The Fracture Faces test, ODOT TM 213, was conducted in this study. ODOT specifications require a minimum of 75 percent for materials retained on 2.36 mm sieve (#8) sieve (one fractured face) and a minimum of 75 percent for materials retained on 37.5, 25.0, 19.0, 12.5 and 4.75 mm sieves (two fractured faces), (ODOT, 2003).

Table 5.2 Summary of aggregate test results

COARSE AGGREGATE		**FINE AGGREGATE**		
Size, mm	19.0-4.75	Size, mm	4.75-2.36	2.36-0
Soundness Loss %	1.0	Soundness Loss %	6.0	7.0
Abrasion loss % (LAR)	12.7			
Sediment Height, mm	16.0	Sediment Height, mm	17.0	17.0
% passing 0.85mm (No. 20)	13.1	% passing 0.85mm (No. 20)	9.7	9.7
Bulk Specific Gravity (Gsb)	2.629	Bulk Specific Gravity (Gsb)	2.587	2.591
Absorption, %	1.7	Absorption, %	2.3	2.3
Fracture Faces, %	minimum met	Fracture Faces, %	minimum met	minimum met
Lightweight Pieces, %	0.0	Lightweight Pieces, %	0.0	

ODOT also requires the aggregate degradation test, ODOT TM 208. The degradation test is used to measure the quantity and quality of the material produced by attrition similar to that produced in the roadway under repeated traffic loading and unloading. The quantity is indicated by a percentage (by weight) of fine material produced. The quality is measured by means of a modified sand equivalent test. The fine material is made by the rubbing action of one particle against another in the presence of water by mean of air jets. These results are shown in Table 5.2 under "sediment height" and "percent passing 0.85 mm (No. 20)". The maximum limit for sediment height for coarse and fine aggregate is 75 mm and 100 mm, respectively. The maximum value in the percent passing 0.850 mm (No. 20) sieve test, for coarse and fine aggregate, corresponds to 30 percent. The lightweight pieces test was done according to AASHTO T113 (1993) procedure. ODOT allows a maximum value of 1.0 percent for coarse aggregates.

5.4.2. Polymer modification tests

ODOT requires that modified asphalt binders meet the elastic recovery test specification (ODOT, 2003). The elastic recovery test is a measure of the tensile properties of the polymer modified asphalt cement. This test method is useful in confirming that a material has been added to the asphalt to provide significant elastomeric characteristics. It does not necessarily identify the type or amount of material added (ASTM, 2004). The elastic recovery is measured by the percentage to which the asphalt cement residue will recover its original length after it has been elongated to a specific distance (20 cm) at a specified rate of speed (5 cm/min) and then cut in half. The distance to which the specimen contracts during a specified time (60 min) is measured[1] and the elastic recovery is calculated as follows:

$$Percent\ \ Elastic\ \text{Recovery} = [\frac{20 - x}{20}] * 100,$$

Where x (< 20) is the elongation measured[1]

ODOT specifies an elastic recovery of at least 60 percent. The asphalt binders used in this study were PG 70-22 and PG 70-22 Modified. It was assumed that the PG 70-22 Modified was modified with SBS polymers. Unfortunately, there was no way to confirm this assumption since the supplier was not willing to share this kind of information. Summary results of the asphalt characteristics used in this study are listed in Table 5.3.

Table 5.3 Asphalt binder characteristics

Original properties	**PG 70-22**	**PG 70-22 Mod.**	**Specification**
Specific Gravity @ 15.6C (60F)	1.0419	1.0323	
Flashpoint, C	322	326	230+
Absolute Viscosity, P	4460	6360	
Dynamic Shear, G*/sin δ, 70C, kPa	1.28	1.36	1.0+
Rotational Viscosity, 135C, Pas	0.688	1.087	3.00 -
Penetration, 4C, mm/10	23	26	
Elastic Recovery, ODOT TM 429, %		62.5	
RTFO Residue Properties			
Loss on Heat, %	0.319	0.277	1.00 -
Dynamic Shear, G*/sin δ, 70C, kPa	3.61	2.65	2.20+
PAV Residue Properties			
Dynamic Shear, G*/sin δ, 28C, kPa	3480	1990	5000 -
Creep Stiffness, -12C, MPa	162	95	300 -
m-value, -12 C	0.330	0.361	0.300+

Note: "-" denotes a maximum value of, and "+" denotes a minimum value of.

5.5. Mix Design

The Job Mix Formula (JMF) for this project was developed based on a Level 3 mix design from ODOT specifications (ODOT, 2003). In the State of Oregon Hot Mixed Asphalt Concrete (HMAC) Level 3 designs are assigned to road applications exposed to moderated truck traffic (1 to 10 million ESAL's) during the design life. A summary of the mix design values obtained is shown in Table 5.4.

The same optimum binder content, used for the control mix in Chapter 3, determined for a 100 gyration mix using a PG 64-22 asphalt binder (commonly used in Oregon) was used. The design (optimum) asphalt content was 6.2. The high and low binder contents were selected at 0.5 percent above and below the optimum binder content. This approach yielded, low, design and high binder contents of 5.7, 6.2 and 6.7 percent. The same binder contents (5.7, 6.2, and 6.7) were used for both binders (PG 70-22 and PG 70-22 Modified).

Table 5.4 Summary of mix design results for the mix with the PG 64-22 binder

MIXTURE PROPERTIES		JOB MIX FORMULA	Percent Passing
Maximum Specific Gravity (Gmm)	2.454	25.0mm	100
Gyro. Bulk Specific Gravity (Gmb)	2.357	19.0mm	94
Air Voids, % (Va)	4.0	12.5mm	81
VMA, %	15.5	9.5mm	71
VFA, %	74	6.3mm	66
Effective Asphalt Content (Pbe), %	4.9	4.75mm	59
P0.075/Asphalt Content Ratio	1.0	2.36mm	42
P0.075/Pbe Ratio	1.3	0.600mm	19
Target Maximum Density, Kg/m^3	2454	0.075mm	6.3
Combined Aggregate Gsb	2.606		
		Asphalt Content, %	6.2
		Asphalt Grade	64-22
		Mix Temperature Range, C	156-161
		Compaction Temperature Range, C	142-147
		Asphalt Sp. Gr. (Gb) at 15.6C	1.033

The voids in mineral aggregate (VMA) was adjusted by modifying the aggregate gradations as shown in Table 5.5.

Table 5.5 Aggregate gradation for the 19.0 mm mix

Sieve Size (mm)	Low VMA	Design VMA	High VMA
25.0	100	100	100
19.0	92	94	98
12.5	79	81	85
9.5	69	71	73
6.3	66	66	54
4.75	60	59	46
2.36	44	42	30
0.600	21	19	12
0.075	6.5	6.3	3.5
Expected VMA, %	14.1	15.5	18.1

5.5.1. Superpave Gyratory Compactor (SGC)

The Superpave Gyratory Compactor (SGC), as shown in Figure 5.1, was used to prepare the asphalt cylinders. The SGC produces asphalt mix specimens to densities approximating those achieved under actual construction conditions. The SGC consists of a rigid reaction frame, a loading system, a specimen height measurement and recording system. It compacts the asphalt mixture specimen at a constant pressure of 600 kPa. The mixture is compacted by a gyratory kneading action using a compaction angle of 1.25 degrees and operating at 30 rpm.

Figure 5.1 Superpave Gyratory Compactor

5.5.2. APA Testing

Testing was conducted with a tube pressure of 690 kPa and an applied mass of 450 N. Each test in the APA device consisted of six cylinders for each combination of the factor levels. Permanent deformation measurements were automatically recorded and sent to a computer.

It is particularly important to note that the testing was conducted at 70C (that is, using the high temperature of standard performance binder grade), as suggested by in a recent study by Kandhal and Cooley (2003). This was done with the purpose of assessing the effects of test temperature on permanent deformation.

As previously mentioned, specimens were prepared with a standard compactive effort of 100 gyrations, rather than attempting to adjust the compactive effort to achieve constant air voids of 4 or 7 percent. As a consequence, there was no control for the air voids in the specimens. The compaction temperatures used for the mixes in this study were in the range of 148C – 154C and 157C – 161C, for the mixes using the PG 70-22 and PG 70-22 Modified asphalt binders, respectively. These temperatures were determined and provided by the asphalt binder supplier, and they were used during the compaction process.

5.6. Results and Analysis

The rut depths, air voids and the VMA values are shown in Table 5.6. Only the mean values of the six specimens of the measured permanent deformation, air voids, and the calculated VMA results are shown. Complete results are included in Appendix A.

Table 5.6 Summary Data for mixes

		Binder Grade					
		PG 70-22			**PG 70-22 Modified**		
VMA Level	**Averages**	*5.7*	*6.2*	*6.7*	*5.7*	*6.2*	*6.7*
Low VMA	Rut Depth (mm)	1.54	1.50	2.14	0.93	1.46	1.98
	Air content (%)	2.90	1.20	0.60	1.90	0.60	0.30
	VMA	13.9	12.6	13.2	13.3	12.5	13.4
Des VMA	Rut Depth (mm)	1.38	1.50	1.93	0.99	1.03	1.37
	Air content (%)	2.90	1.40	0.90	2.70	1.50	0.70
	VMA	13.9	12.9	13.5	13.8	13.0	13.4
High VMA	Rut Depth (mm)	3.57	4.07	3.76	2.54	2.93	2.97
	Air content (%)	6.30	4.90	3.70	6.10	4.80	3.10
	VMA	17.2	16.3	16.3	17.1	16.2	15.9

5.6.1. Discussion of the Results

The discussion of permanent deformation refers to APA results not to field performance. A brief discussion of the raw data is included before the statistical analysis. In the case of the mixes using the PG 70-22 binder, as shown in Figure 5.2, the air voids content decreases when the binder content is increased, regardless of the VMA level. A similar trend on the mixes in previous chapters, when testing at 64C, was observed. There is also a marked difference among the VMA levels, especially high VMA compared to the other two levels.

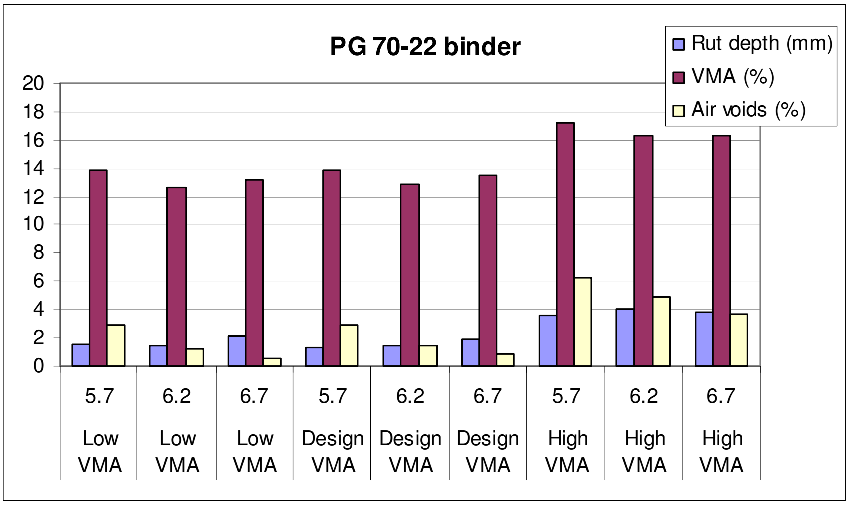

Figure 5.2 Effect of VMA and air voids on permanent deformation

As observed in this figure within the VMA levels, there is a decrease in the VMA values for its different binder contents. There is a modest correlation (R^2 = 0.5548) between the air void contents and the permanent deformation on the mixes using the PG 70-22 binder. As shown in Figure 5.3, higher air voids creates more permanent deformation. The air voids in the mixture ranged from 0.6 to 6.3 percent. Though, most of the air voids were in the range from 0.6 to 3 percent.

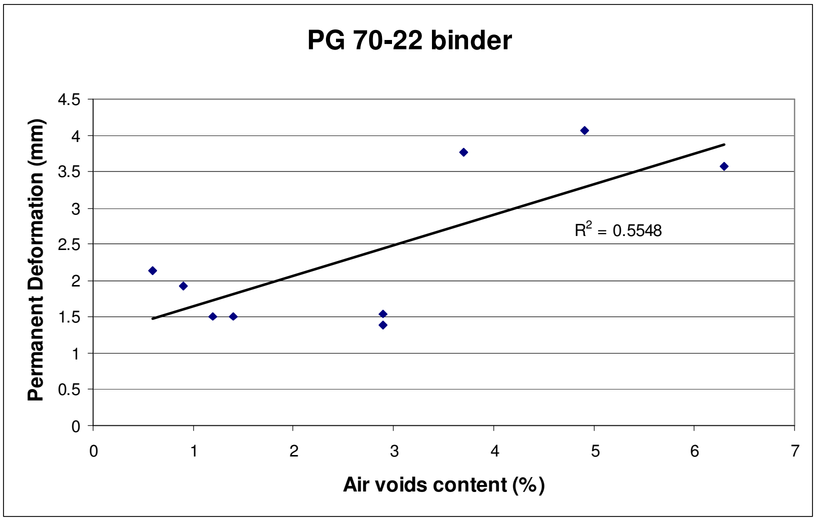

Figure 5.3 Effect of air voids on permanent deformation

In the case of the mixes using the PG 70-22 modified binder, as shown in Figure 5.4, the air voids content decreases when the binder content is increased, regardless of the VMA level. This is expected since the increased binder content tends to fill the air space in the mix.

The air voids content decreases when the binder content is increased, regardless of the VMA level. In this case, there is also a marked difference among the VMA levels, especially high VMA compared to the other two levels.

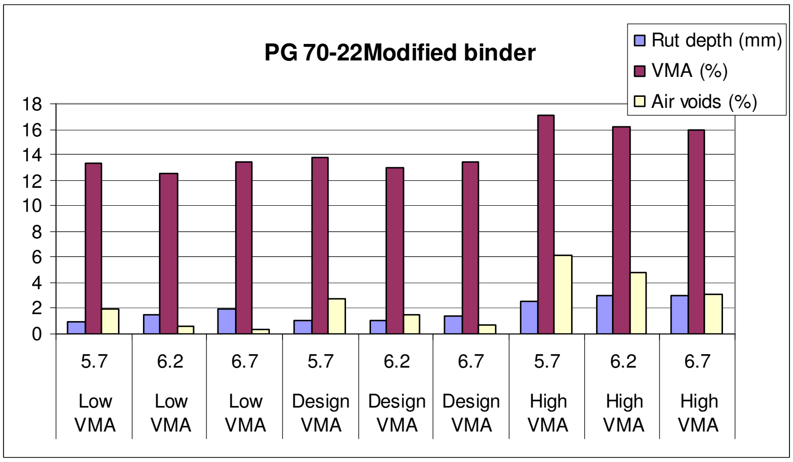

Figure 5.4 Effect of VMA and air voids on permanent deformation

There is also a modest correlation (R^2 = 0.3767) between the air void contents and the permanent deformation on the mixes using the PG 70-22 modified binder. As shown in Figure 5.5, higher air voids creates more permanent deformation. The air voids in the mixture ranged from 0.3 to 6.1 percent. Though, most of the air voids were in the range from 0.6 to 3 percent.

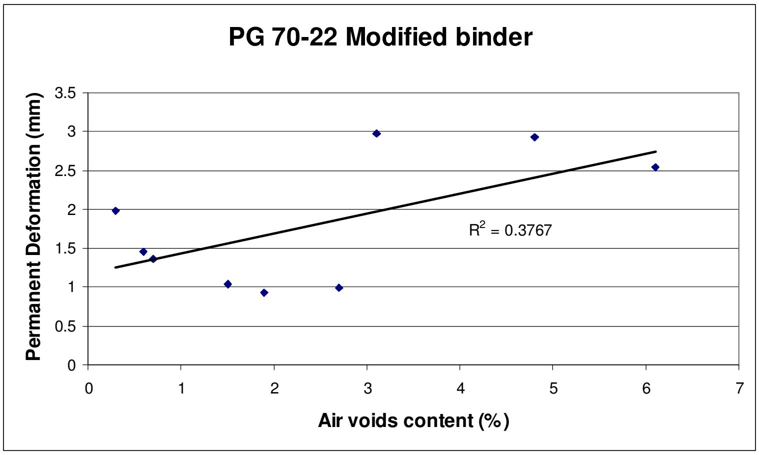

Figure 5.5 Effect of air voids on permanent deformation

Figure 5.6 shows the effects of the modified asphalt binder used in the mix. As shown in these figures, there is approximately a 25 percent reduction in permanent deformation.

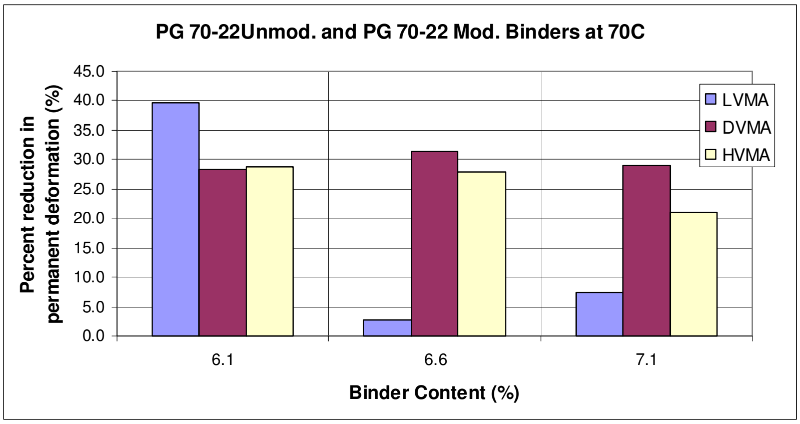

Figure 5.6 Effect of the PG 70-22 Modified asphalt binder in permanent deformation

In summary, it was noticed that the air voids were varied for all mixes when applying a fixed compactive effort. However, the air voids ranges, in both, modified and unmodified mixes were similar. The VMA values were also similar for the low and design levels. Mixes using the PG 70-22 modified binder had less permanent deformation that the mixes using the unmodified binder.

Although the raw analysis indicated some relationships between the mix factors and permanent deformation, only single factors were reviewed. As mentioned in the previous chapters, permanent deformation is really affected by the combination of all the factors. To try to assess the effect of each factor after taking into account the rest of the other mix factors, it is necessary to apply statistical tools that can give a closer look of all mix factors on permanent deformation. In the next section, the ANOVA procedure is used to accomplish this task.

5.6.2. Statistical Approach

The results of this study were analyzed by conducting an ANOVA test, using SAS software (SAS, 2001; Little et al., 2002; Kuehl, 2000). Following ANOVA, the levels of significance and two-way interactions were assessed using multiple comparisons with a Tukey-Kramer adjustment. There were a total of 18 cells with permanent deformation values; each cell containing 6 rut values.

The model considered for this study contained rut depth as the "dependent variable". The independent variables were: binder content (3 levels), asphalt binder type (two levels), and VMA content (3 levels).

After taking into account all other factors, the questions to be addressed in this study were:

- Are the effects of polymer modification apparent in the APA device for these mixes?
- Does VMA affect permanent deformation results as measured by the APA device?
- Does binder content affect permanent deformation results as measured by the APA device?

5.6.3. Statistical Analysis

A Type I ANOVA was used because the experiment was balanced (ANOVA tables are shown in Appendix B). The statistical analysis in this study included both PG 70-22 and PG 70-22 Modified asphalt binders. Similar to the data analysis from previous chapters, the ANOVA results described below do not include the covariate air content.

Cooley et al. (2003) established that the use of polymer modified mixes tend to lower permanent deformation of HMA. From the statistical analysis of the APA results of this study, it was found that the measured permanent deformation for all the mixes was affected by the VMA level, the binder content and the binder type.

Statistical analysis showed that the interaction effect between the binder type and the VMA level has a moderate influence on the measured APA rut depths (p-value = 0.0420). As a consequence, as shown in Figure 5.7, the rut depth mean values varied for the different levels of VMA in the mix. However, both mixes showed the same trend.

There is a statistical evidence that the VMA level has a significant effect on permanent deformation results (p-value = 0.0001). As shown in this figure, when using the modified asphalt binder, it may be possible to get approximately a 27% reduction on the APA-measured rut depth values compared to results measured when using a neat PG 70-22 binder in the mix. This percentage is for both, the design and high VMA levels. A summary of this analysis is shown in Appendix B.

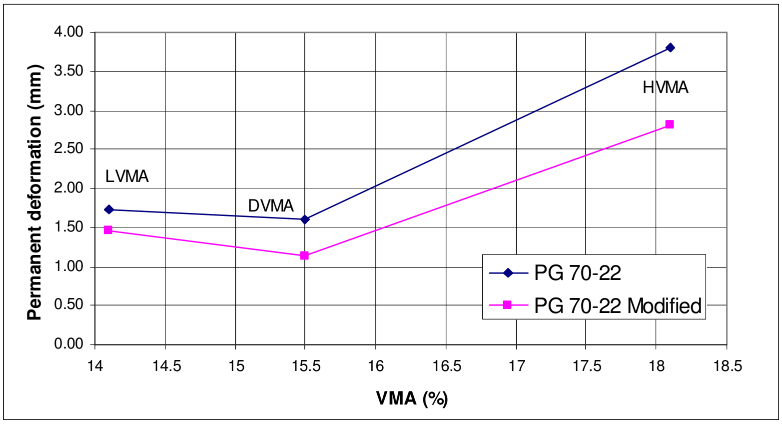

Figure 5.7 Effect of VMA and Test temperature on permanent deformation

Statistical analysis showed that the binder type has a significant influence on the measured APA rut depths (p-value = 0.0017). In Figure 5.8, the effect of the binder type can be easily depicted. This figure shows that the mix with the PG 70-22 modified asphalt binder had approximately 25 percent less permanent deformation. However, as shown in the previous figure, the permanent deformation values are influenced by the VMA level in the mix. The estimated rut mean value for the mix with the PG 70-22 asphalt binder was 2.37 mm (95% confidence interval: 2.25 to 2.5). The estimated rut mean value for the mix with the PG 70-22 modified asphalt binder was 1.80 mm (95% confidence interval: 1.68 to 1.91).

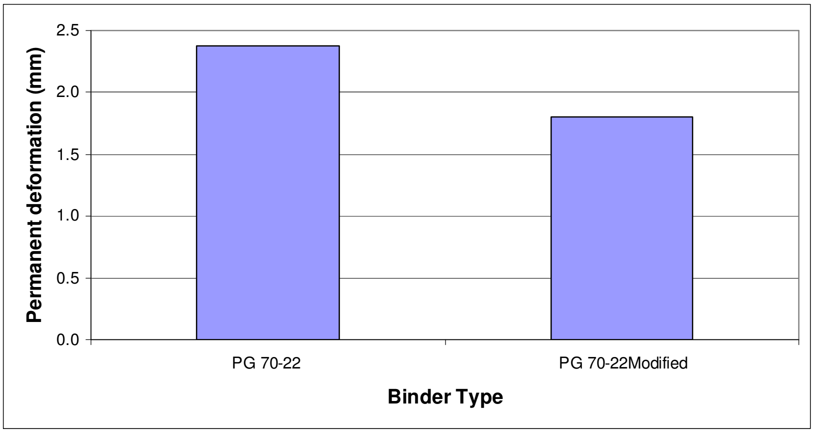

Figure 5.8 Effect of Test temperature on permanent deformation

Statistical analysis showed that the binder content has a suggestive, but inconclusive influence on the measured APA rut depths (p-value = 0.0121). Figures 5.9 and 5.10 show the effects of binder content for the mixes. As shown in both figures, as the binder content increases, the APA rut depths also tend to increase.

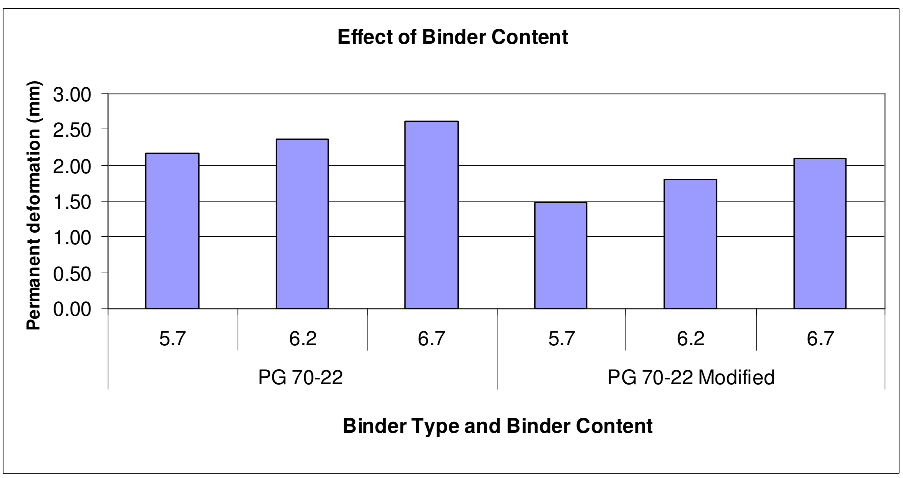

Figure 5.9 Effect of Binder content in permanent deformation

In Figure 5.9 it is also noticed that the mixes using the PG 70-22 Modified binder had lower permanent deformation values.

The effects of VMA and binder content are shown in Figure 5.10. As shown in this figure, the VMA has a small variation for the different binder contents. Statistical analysis didn't show any effects of this interaction (VMA and binder content) on permanent deformation. However, Figure 5.10 shows a marked difference in permanent deformation results, especially between the high VMA level and the low and design VMA levels.

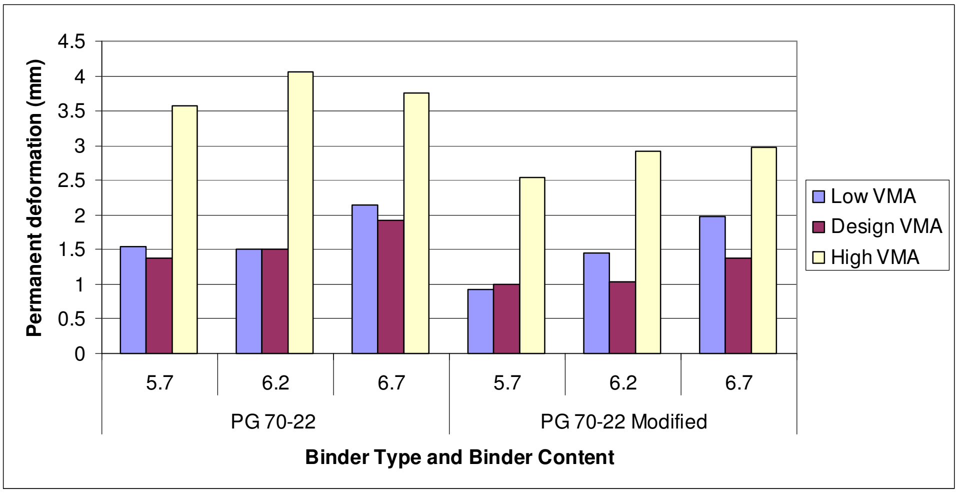

Figure 5.10 Effect of Binder content and VMA on permanent deformation

5.7. Summary and Recommendations

The APA device was used to characterize the impacts of various mix factors on the measured permanent deformation in dense-graded mixes. The research reported herein focused on the effects of voids in mineral aggregate (VMA), binder type, and binder content. Each of the factors was considered at three levels, except that only two binders and a single maximum aggregate size were used. For the variables and conditions investigated in this study the following conclusions and recommendations appeared herein are warranted:

- Statistical analysis showed that the measured permanent deformation in all the mixes was affected by the VMA level, the binder content and the binder type.

- Statistical analysis showed that the interaction effect between the binder type and the VMA level has a moderate influence on the measured APA rut depths. Unfortunately, it was not possible to separate this interaction effect.

- Statistical analysis also showed that the binder type has a significant influence on the measured APA rut depths.

- Results also showed that the binder content has a moderate influence on the measured APA rut depths.

- The analysis showed that mixes using the PG 70-22 modified asphalt binder demonstrated less permanent deformation than the mixes using the unmodified binder, but the permanent deformation was always influenced by VMA level (content) in the mix.

The data from this study indicate that the APA device was sensitive to changes in the mix factors. The APA has a potential to predict the relative rutting potential of the hot mix asphalt mixes even when polymer modified mixes are used. However, it is recommended for future research to keep assessing polymer modified asphalt mixes and try to correlate their APA tests results to actual roadway rutting.

5.8. References

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CHAPTER 6. Summary and Recommendations

The APA device was used to characterize the impacts of various mix factors on the measured permanent deformation in dense-graded mixes. This device is used by agencies to judge the likelihood that a given mix will deform in the field. Current practice tests all mixes at 64C and limits the maximum acceptable permanent deformation to 8 mm after 8000 cycles when air voids in compacted mixes is seven percent.

The research reported herein focused on the effects of voids in mineral aggregate (VMA), binder type, binder content, maximum aggregate size, fines content and test temperature. Each of the factors was considered at three levels, except that only two maximum aggregate sizes were included from single crushed basaltic source in western Oregon. For the variables and conditions investigated in this study the following conclusions and recommendations appeared herein are warranted:

- Mixes using stiffer binders (PG 70-22 Modified, and PG 76-22) had lower measured permanent deformation compared to mixes using lower binder grades (e.g. PG 64-22, PG 70-22).

- The effect of VMA on permanent deformation depends on the aggregate size used, test temperature, binder type and the fines content. It was not possible to separate these interaction effects. However, although it was confounded with the effect of other factors in the mix, it is an important parameter value to take into account when assessing permanent deformation.

- Permanent deformation increased with the increasing content of the PG 64-22 binder for the 19.0 mm dense graded mixes, but this trend was not totally evident for stiffer binders.

- The average permanent deformation for the 19.0 mm mixes was 2.5 mm, for the 12.5 mm was 2.3 mm, and for the 19.0 mm using an extra 3 percent of P200 was 3.41 mm, when testing them all at 64C. However, the difference (0.9 mm) between the two compared 19.0 mm mixes, using the design fines content (P200) and the design P200 plus three percent, was not statistically significant.

- When testing the 19.0 mm dense graded mixes at the high temperature of standard performance asphalt binder grade (e.g. 70C for a PG 70-22 asphalt binder), it is observed that increasing the binder content also increases the rutting potential (same conclusion obtained for mixes with a PG 64-22 asphalt binder when tested at 64C).

- The use of higher test temperature (i.e. 70C instead of 64C) has moderate impact in permanent deformation measurements for the mixes using the PG 70-22 asphalt binder. In the case of the mixtures using the PG 76-22 asphalt binder, it was found that the use of higher test temperature had a big impact in permanent deformation measurements.

- The use of a stiffer binder than required by the standard APA test temperature (e.g., PG 70-22 rather than a PG 64-22) appears to limit APA-measured permanent deformation, even when a variation in mix properties occurs.

Based on the test results presented herein, the APA device appears to be relatively insensitive to changes in mix properties when the mixes use stiff binders and the test temperature is set up at the current practice test temperature (e.g. 64C). However, the APA device is sensitive when the APA test temperature matches the high temperature of the standard performance binder grade (e.g. 70C for a PG 70-22 binder).

Although some of the mix factors have an interactive effect in the mixes, the APA may still have the potential to predict the relative rutting potential of the hot mix asphalt mixes even when polymer modified mixes are used, assuming that the APA-measured rut results correlate to the permanent deformation measured in the field.

Therefore, more research is needed in the future to try to correlate laboratory rut results from the APA device to actual roadway rutting from known field mixes.

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APPENDICES

APPENDIX A : Raw APA Data

(See included CD)

APPENDIX B : Statistical Tables

Table B 1 ANOVA type I

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BType	2	36.96280370	18.48140185	72.63	<.0001
BContent	2	0.55647037	0.27823519	1.09	0.3489
P200	1	0.40041667	0.40041667	1.57	0.2200
VMA	2	13.50147037	6.75073519	26.53	<.0001
BType*BContent	4	0.52544074	0.13136019	0.52	0.7244
BType*VMA	4	1.28994074	0.32248519	1.27	0.3062
BType*P200	2	0.31107778	0.15553889	0.61	0.5497
BContent*P200	2	0.03330000	0.01665000	0.07	0.9368
BContent*VMA	4	0.27854074	0.06963519	0.27	0.8925
P200*VMA	2	2.20930000	1.10465000	4.34	0.0228

Table B 2 ANOVA type III

Source	DF	Type III SS	Mean Square	F Value	Pr > F
BType	2	36.96280370	18.48140185	77.46	<.0001
BContent	2	0.55647037	0.27823519	1.17	0.3245
P200	1	0.09388889	0.09388889	0.39	0.5349
VMA	2	13.50147037	6.75073519	28.29	<.0001
AggS	1	0.00347222	0.00347222	0.01	0.9047
BType*BContent	4	0.52544074	0.13136019	0.55	0.7000
BType*VMA	4	1.28994074	0.32248519	1.35	0.2726
BType*AggS	2	0.31107778	0.15553889	0.65	0.5279
BContent*P200	2	0.29000333	0.14500167	0.61	0.5508
BContent*VMA	4	0.26993968	0.06748492	0.28	0.8869
BContent*AggS	2	0.42758333	0.21379167	0.90	0.4182
P200*VMA	2	4.50661333	2.25330667	9.44	0.0006
VMA*AggS	2	1.57225333	0.78612667	3.29	0.0500

Table B 3 Square Means for effect VMA and Aggregate size

Dependent Variable: Rut, Where i = VMA and j= Aggregate size.

i/j	1	2	3	4	5	6	VMA	AggS	LSMEANS
1		0.4070	0.9946	0.2644	0.1227	0.4008	D	12.5	1
2	0.4070		0.0763	<.0001	0.9926	0.9983	D	19.0	2
3	0.9946	0.0763		0.7366	0.0384	0.1525	H	12.5	3
4	0.2644	<.0001	0.7366		0.0002	0.0002	H	19.0	4
5	0.1227	0.9926	0.0384	0.0002		0.9719	L	12.5	5
6	0.4008	0.9983	0.1525	0.0002	0.9719		L	19.0	6

Table B 4 Least Squares Means fir the effect Fines Content (P200) and VMA

Dependent Variable: Rut, Where i= P200 and j= VMA.

i/j	1	2	3	4	5	6	P200	VMA	LSMEANS
1		0.9471	0.0412	0.0140	0.4714	0.0253	D	D	1
2	0.9471		0.2542	0.0312	0.2037	0.2022	D	H	2
3	0.0412	0.2542		0.9622	0.0002	1.0000	D	L	3
4	0.0140	0.0312	0.9622		<.0001	0.8852	H	D	4
5	0.4714	0.2037	0.0002	<.0001		<.0001	H	H	5
6	0.0253	0.2022	1.0000	0.8852	<.0001		H	L	6

Table B 5 ANOVA type I (Mixes with the PG 70-22 asphalt binder at 64C and 70C)

Source	**DF**	**Type I SS**	**Mean Square**	**F Value**	**Pr > F**
BContent	2	0.07501111	0.03750556	0.41	0.6742
VMA	2	11.94114444	5.97057222	65.30	<.0001
Temp	1	0.09533889	0.09533889	1.04	0.3313
VMA*Temp	2	0.89121111	0.44560556	4.87	0.0333

Table B 6 Least Squares Means for the effect of VMA and Temperature

Dependent Variable: Rut, Where i = VMA and j= Temperature.

i/j	1	2	3	4	5	6	VMA	Temp	LSMEANS
1		0.1413	0.0110	0.0011	0.5822	0.2840	D	64C	1
2	0.1413		0.0003	<.0001	0.8624	0.9950	D	70C	2
3	0.0110	0.0003		0.5973	0.0011	0.0005	H	64C	3
4	0.0011	<.0001	0.5973		0.0002	<.0001	H	70C	4
5	0.5822	0.8624	0.0011	0.0002		0.9867	L	64C	5
6	0.2840	0.9950	0.0005	<.0001	0.9867		L	70C	6

Table B 7 ANOVA type I (Mixes with PG 76-22 asphalt binder at 64C and 76C)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BContent	2	0.13210000	0.06605000	3.81	0.0588
VMA	2	3.67103333	1.83551667	105.96	<.0001
Temp	1	0.77293889	0.77293889	44.62	<.0001
VMA*Temp	2	0.85474444	0.42737222	24.67	0.0001

Table B 8 Least Squares Means for the effect of VMA and Temperature

Dependent Variable: Rut, Where i = VMA and j= Temperature.

i/j	1	2	3	4	5	6	VMA	Temp	LSMEANS
1		0.9974	0.0327	<.0001	0.5742	1.0000	D	64C	1
2	0.9974		0.0632	<.0001	0.3541	0.9936	D	76C	2
3	0.0327	0.0632		<.0001	0.0029	0.0284	H	64C	3
4	<.0001	<.0001	<.0001		<.0001	<.0001	H	76C	4
5	0.5742	0.3541	0.0029	<.0001		0.6263	L	64C	5
6	1.0000	0.9936	0.0284	<.0001	0.6263		L	76C	6

Table B 9 ANOVA type I (Mixes with the PG 70-22 and PG 70-22 Modified asphalt binders)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
BType	1	1.49645000	1.49645000	56.77	0.0017
BContent	2	0.85373333	0.42686667	16.19	0.0121
VMA	2	13.51090000	6.75545000	256.29	<.0001
BType*VMA	2	0.40923333	0.20461667	7.76	0.0420
BType*BContent	2	0.02413333	0.01206667	0.46	0.6622
BContent*VMA	4	0.31976667	0.07994167	3.03	0.1540

Table B 10 Least Squares Means for the effect of Binder Type and VMA

Dependent Variable: Rut, Where i = BType and j= VMA.

i/j	1	2	3	4	5	6	BType	VMA	LSMEANS
1		.0013	0.3116	0.1211	0.0002	0.0593	70 MOD	D	1
2	0.0013		0.0031	0.0047	0.0102	0.0071	70 MOD	H	2
3	0.3116	0.0031		0.8582	0.0004	0.4507	70 MOD	L	3
4	0.1211	0.0047	0.8582		0.0005	0.9192	70 UNMOD.	D	4
5	0.0002	0.0102	0.0004	0.0005		0.0006	70 UNMOD.	H	5
6	0.0593	0.0071	0.4507	0.9192	0.0006		70 UNMOD.	L	6