EVALUATION OF NEW TECHNOLOGIES FOR USE IN WARM MIX ASPHALT

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EVALUATION OF NEW TECHNOLOGIES FOR USE IN WARM MIX ASPHALT

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Graham Craft Hurley, son of John D., Jr. and Susan W. Hurley, was born October 29, 1976, in Mobile, Alabama. He graduated with honors from Daphne High School in Daphne, Alabama, in 1995. After graduation, Graham attended Faulkner State Community College on a baseball scholarship for two years where he obtained an Associate in Science degree in Pre-engineering before transferring to Auburn University in the Fall of 1997. While working towards his Bachelor's degree at Auburn, Graham completed the Cooperative Education program, in which he was employed by the National Center for Asphalt Technology at Auburn University. After finishing the Cooperative Education program, Graham worked part-time with the National Center for Asphalt Technology. Graham graduated from Auburn University with a Bachelor of Civil Engineering degree in August, 2000. He was then hired full-time by the National Center for Asphalt Technology in August, 2000 in the position of Civil Engineer. After employment, he entered Graduate School at Auburn University in August, 2001, to pursue a Master of Science in Civil Engineering.

THESIS ABSTRACT

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Several new processes have been developed with the goal of reducing the mixing and compaction temperatures of hot mix asphalt without sacrificing the quality of the resulting pavement. Three potential Warm Mix Asphalt processes were evaluated in this study. They were Aspha-min®, Sasobit®, and Evotherm®. A laboratory study was conducted to determine the applicability of these processes to typical paving operations and environmental conditions commonly found in the United States, including the performance of the mixes in quick traffic turn-over situations and high temperature conditions. Superpave gyratory compactor (SGC) results indicated that Aspha-min®, Sasobit®, and Evotherm® increase the density of lab compacted samples. Therefore, it is

currently recommended to determine the optimum asphalt content with a typical PG binder and then substitute in the Warm Mix Asphalt additive.

All three processes were shown to improve the compactability of mixtures in both the SGC and vibratory compactor. Statistics indicated an overall reduction in air voids with the Warm Mix Asphalt processes. Improved compaction was noted at compaction temperatures as low as 190°F (88°C). The addition of Aspha-min®, Sasobit®, or Evotherm® did not affect the resilient modulus of an asphalt mix nor did they increase the rutting potential measured by the Asphalt Pavement Analyzer. The rutting potential did increase with decreasing mixing and compaction temperatures, which may be related to the decreased aging of the binder resulting from the lower temperatures. There was no evidence of a difference in indirect tensile strength over different age times for the mixes containing Aspha-min® and Evotherm® when compared to the control mixes, indicating that a prolonged cure time before opening to traffic is not an issue. Regarding the Sasobit®, statistical analysis conducted on the laboratory data indicated that a cure may be beneficial before opening to traffic. However, field data pertaining to Sasobit® indicated that traffic could be opened quickly with no negative effects. A second potential problem area that was observed deals with moisture susceptibility. The lower mixing and compaction temperature used when producing Warm Mix Asphalt may increase the potential for moisture damage.

Overall, Aspha-min®, Sasobit®, and Evotherm® appear to be viable tools for reducing mixing and compaction temperatures that can be readily added to hot mix asphalt mixtures in the United States. Reductions in the mixing and compaction temperatures are expected to reduce hot mix asphalt (HMA) plant fuel costs, reduce plant emissions, extend the paving season, and facilitate specialized paving applications, such as airport runway construction, where rapid opening to traffic is essential.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

A number of new products have become available that have the capability of reducing the temperature at which hot mix asphalt (HMA) can be efficiently mixed and compacted without compromising the performance of the pavement. These new products can reduce production temperatures by as much as 40 percent (*1*). North American asphalt mixes are generally produced at 300°F (149°C) or higher, depending mainly on the grade of binder used. Mixes produced with these new products are being produced at temperatures of about 250°F (121°C) or lower, a 17 to 18 percent reduction in production temperature. Lower plant mixing temperatures mean fuel cost savings to the HMA producer, and findings have shown that lower plant temperatures can lead to a 30 percent reduction in energy consumption (*1*).

Lower temperatures also mean that any emissions, either visible or non-visible, that may contribute to health, odor problems, or greenhouse gas emissions, will also be reduced (*2*). The decrease in emissions represents a significant cost savings, considering that 30-50 percent of overhead costs at an asphalt plant can be attributed to emission control (*1*). Lower emissions may allow asphalt plants to be sited in nonattainment areas, where there are strict air pollution regulations. An asphalt plant located in a nonattainment area and producing hot mix asphalt with a product that allows for a lower operating temperature will allow shorter haul distances, which will improve production and shorten the construction period, thus reducing the possible headache of traffic congestion. Warm Mix Asphalt (WMA) will also allow longer haul distances and a longer construction season if the mixes are produced at normal operating temperatures. Another potential advantage of lower mixing temperatures is reduced oxidative hardening of the asphalt, which may reduce thermal cracking, raveling, block cracking, and preventing the mix from being tender when placed.

1.2 OBJECTIVES

The primary objective of this study was to determine if three products used in Warm Mix Asphalt applications are applicable to typical paving operations and environmental conditions commonly found in the United States. A laboratory study was conducted to evaluate the three Warm Mix Asphalt processes with respect to compactability, quick turnover to traffic, mix stiffness, rutting potential, and to moisture susceptibility. A second objective was to determine a critical compaction temperature for the three different Warm Mix Asphalt processes.

1.3 SCOPE

To accomplish the objectives of this study, a literature review was first conducted. This review explored the issue of compaction temperatures and their effect on the performance of hot mix asphalt. It also touched on the issue of emissions due to elevated operating temperatures because emissions were a major impetus in the development of processes to lower the compaction temperature of hot mix asphalt. The literature review also investigated several Warm Mix Asphalt processes that have been developed in Europe and in the United States since the early to mid 1990’s.

In order to evaluate the applicability of several different Warm Mix Asphalt additives to asphalt construction practices typically found in the United States, laboratory samples were compacted using the automated vibratory compactor over a range of compaction temperatures. Resilient modulus, rutting resistance, indirect tensile strength, moisture susceptibility, and Hamburg Wheel Tracking Device testing were then performed according to their respective test methods and procedures. Data obtained from the testing was then analyzed and conclusions and recommendations were made, based on the statistical findings.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Warm Mix Asphalt (WMA) was developed in Europe in the mid 1990's (*3*) to combat emissions that were being released into the atmosphere, both at the production plant and at the construction site. This technology is known as *low temperature asphalt* and *warm asphalt mixes* in areas throughout Europe, but has generally been referred to as *Warm Mix Asphalt* in the United States. Warm Mix Asphalt has not only been successful in its intended purpose of lowering asphalt fumes and emissions through lowering mixing and compaction temperatures, but has also been found to possess numerous other benefits for the asphalt paving industry. These additional benefits include reduced plant fuel consumption, reduced odor, less wear of the asphalt plant, reduced binder ageing, and a possible extension to the paving season. Warm Mix Asphalt may also act as a compaction aid for stiffer mixes that are more difficult to compact, such as Stone Matrix Asphalt, when used at typical compaction temperatures. Therefore, this technology caught the interest of the asphalt community here in the United States.

Knowledge of the initial success of this relatively new technology made its way to the United States, and in the summer of 2002, a delegation comprised of asphalt paving technologists and representatives from the National Institute of Occupational Safety and Health (NIOSH) (*3*, *4*) conducted a study tour of asphalt plants, paving sites, and completed roads in Germany and Norway. The main objective of the tour was to investigate different processes that were being used to lower the operating temperatures of asphalt mixtures, and to determine whether or not the concept of Warm Mix Asphalt would work in the United States. Upon completion of the study tour, European experts from Germany's BITUMEN Forum were invited to the United States to give their first-hand experience on the state of art practice of low temperature asphalt (*3*).

The concept of WMA is not complex, even though several totally different approaches exist. An additive is combined with hot mix asphalt (HMA) mixture, reducing the mixture's viscosity, improving its workability, both during production and placement. This, in turn, allows the mixture to be compacted at a lower temperature, while potentially retaining the performance characteristics of asphalt compacted at more "normal" compaction temperatures.

2.2 ASPHALT EMISSIONS AND FUMES

2.2.1 The Kyoto Protocol

Protecting the environment has become an increasingly important issue throughout the world. One of the main issues when discussing the environment is the amount of carbon dioxide (CO_2) emissions being produced around the world. Carbon dioxide is one of the leading causes of the greenhouse effect.

One of the most recent attempts at reducing the amount of emissions produced is in the form of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (*5*). Adopted by a consensus at the third session of the Conference of the Parties in December 1997, it seeks industrialized countries to cut emissions of carbon dioxide and other greenhouse gases by 5.2 percent between the years 2008 and 2012, using emission values from 1990 as the baseline value. For the Protocol to become legally binding for the participating countries, it had to be ratified by countries accounting for at least 55 percent of the total greenhouse gas emissions. This did not occur until November 2004, when Russia ratified the treaty (*6*).

2.2.2 The BITUMEN Forum

Following the terms of the Kyoto Protocol, the European Union (EU) agreed to reduce the production of CO_2 emissions by 15 percent by 2010. As a member of the European Union, the government of Germany took an even stricter approach and set a reduction of 25 percent compared to 1990 emission values, and achieved this reduction in 2005 (*7*).

Germany achieved its desired reduction in emissions partly through the action of the BITUMEN Forum. With support from the German Ministry for Labour and Social Affairs, the BITUMEN Forum was formed in Germany in the early part of 1997 (*3*, *4*). Representing all sectors of the asphalt industry in Germany, the primary objective of the Forum was to tackle the issue of asphalt fumes and aerosols produced from hot bitumen, and have had much success in assessing possible health hazards arising from handling bitumen.

Today, the most important objective of the BITUMEN Forum is the promotion of low temperature asphalt (*4*). This is accomplished through disseminating information on the performance characteristics of low temperature asphalt, the technologies used, and by conducting air monitoring tests on construction sites, to measure the level of exposure of employees to emissions from low temperature asphalt. Examples of these are shown in

Figures 2.1 and 2.2. Within Figure 2.2, the red bars represent hot mix asphalt, while the blue bars represent low temperature asphalt, illustrating the reduction of fumes produced by an asphalt pavement.

Employee	Conventional Asphalt 160-180°C	Low Temperature Asphalt approx. 130°C
Paver Operator	6.5 mg/m^3	0.4 - 3.1 mg/m^3
Screed Operator	10.4 mg/m^3	0.6 - 6.9 mg/m^3

Figure 2.1. Emission Exposure Values of Employees when Working with Conventional and Low Temperature Asphalt (*8*).

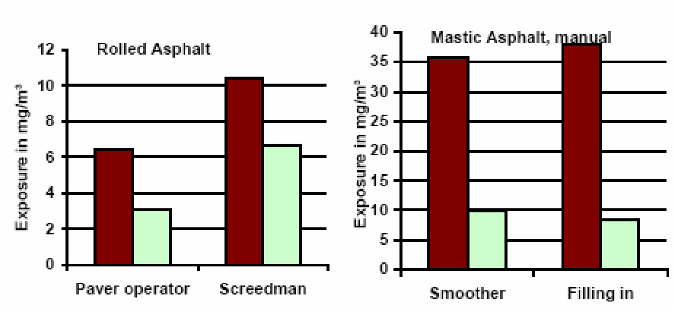

Figure 2.2. Exposure to Fumes and Aerosols from Bitumen by Laying Normal and Low Temperature Asphalt (*4*).

2.2.3 Emission Regulation in the United States

In comparison to other industrialized countries throughout the world, the United States is the world's biggest polluter. However, the United States did not ratify the Kyoto Protocol, citing that costs associated with the necessary changes would be too high, and that the agreement is flawed. This does not mean, however, that the United States is ignoring emissions.

The subject of asphalt fumes and emissions has been a topic of concern for years. The origin of the issue can be traced back to 1977, when NIOSH recommended an exposure limit (REL) for asphalt fumes of 5 mg/m^3 measured as total particulate matter (TPM) during any 15 minute period, based on available data on the health effects of occupational exposure to asphalt and asphalt fumes (*9*). Then, in 1988, NIOSH recommended to the Occupational Safety and Health Association (OSHA) that asphalt fumes be considered a potential occupational carcinogen (*10*). This was based on results from lab generated roofing asphalt fumes. As a result, OSHA proposed a permissible exposure limit (PEL) of 5 mg/m^3 as an eight hour time-weighted average (TWA) for asphalt fumes. This limit was significantly tighter than the NIOSH REL recommended five years before.

The National Asphalt Paving Association (NAPA) objected to this ruling, claiming that coal tar pitch used for roofing asphalt and paving asphalt are not synonymous and should not be labeled the same. NAPA also stated that the roofing asphalt used in the research had to be heated to temperatures as high as 600° F (316°C) to generate the fumes tested. These temperatures were significantly higher than asphalt paving temperatures. Later that same year, OSHA removed asphalt fumes from their list of carcinogens and suspended a final ruling until further research could be conducted.

During the following years, numerous studies were conducted that determined asphalt paving fumes were chemically different than roofing asphalt fumes. Consequently, in 1992, OSHA proposed another limit for asphalt fumes that contained a PEL of 5 mg/m^3 (TPM) for general asphalt use. The proposed limit was to ensure avoidance of possible adverse respiratory effects. This possible irritation also led the American Conference of Governmental Industrial Hygienists (ACGIH) to set a threshold limit value (TLV®) for asphalt fumes at 0.5 mg/m^3 (8-hr. TWA) for benzene-soluble aerosol (the inhalable fraction of asphalt fumes) (*11*). The ACGIH does not classify asphalt fumes as a human carcinogen.

In 2000, the NIOSH published a report (*15*) that stated:

> "Current data are considered insufficient for quantifying the acute and chronic health risks of exposure to asphalt, asphalt-based paint, or asphalt fumes and vapors…..the data available, however, do not preclude a carcinogenic risk from asphalt fumes generated from the asphalt paving process."

NIOSH recommended minimizing possible acute or chronic health effects from asphalt fumes by adhering to the current REL of 5 mg/m^3 during any 15 minute period. What this did for the paving industry was to allow them to concentrate on developing methods of minimizing emissions without having the federal government impose strict regulations on asphalt fumes.

The United States paving industry took notice of the controversy over asphalt fumes and emissions. Not only were there limits being placed on asphalt fumes, but new national air quality regulations were being proposed. An example was the Clean Air Act of 1990, which set limits on gaseous emissions containing air pollutants. Included in these pollutants are sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) (*12*, *13*). All these pollutants exist in emissions from the production of hot mix asphalt. Therefore, in 1996, a joint effort between NAPA, NIOSH, the Asphalt Institute, the Laborers' Health and Safety Fund of North America, and the International Union of Operating Engineers led to the publication of a report (*14*) that set engineering control guidelines for asphalt pavers, with the goal of reducing the amount of exposure of workers to asphalt fumes.

The United States is continuing to regulate air quality today, as evidence by the Clean Air Interstate Rule (CAIR). According to the EPA's website, the CAIR will result in the largest reduction in SO_2 and NO_x emissions in more than a decade. The end result will be a 70 percent decrease in SO_2 and a 60 percent reduction in NO_x in the 28 eastern U.S. states by the year 2015. Although primarily aimed towards power plants, the CAIR will have an effect on the asphalt paving industry due to the fact that SO_2 and NO_x are found in asphalt emissions.

2.3 WARM MIX ASPHALT TECHNOLOGIES

Currently, there are several different processes that are being used to produce Warm Mix Asphalt. Among them are WAM-Foam®, Aspha-min®, Sasobit®, Asphaltan B®, and Evotherm®. These technologies are discussed in the following sections.

2.3.1 WAM-Foam®

Foamed asphalt is not a new idea. The concept was originally developed by Cyansi during the mid 1950's (*16*). A pre-set amount of water is injected into hot bitumen, foaming the binder and creating a volume increase of about 10 to 20 times that of the binder itself. The bitumen foam is then immediately mixed with cold, moist aggregate so the foam can disperse and coat the aggregate. Foamed asphalt has primarily been associated with soil stabilization and cold in-place recycling.

Jenkins et al. (*17*) reported that when the aggregate was heated above ambient temperatures, but below 212°F (100° C), there were additional benefits of foamed asphalt. Included were improved particle coating, mix cohesion and tensile strength, and improved compaction when compared to traditional cold foam mixtures. Heating the aggregate somewhat before the addition of foamed asphalt also allowed for a wider range of mix gradations to be used, where limitations existed in more gap graded gradations with the cold foamed asphalt mixtures.

WAM-Foam® (Warm Asphalt Mixture Foam) is the result of a joint venture between Shell International Petroleum Company Ltd., London, U.K., and Kolo-Veidekke, Oslo, Norway. Initial process development began in 1995 with the objective of compacting asphalt in the intermediate temperature range 176-248°F (80-120°C) without compromising the asphalt mixture performance or quality. These lower operating temperatures are achieved through the combination of a soft binder grade and a hard binder grade with aggregate in a two step mixing approach. The function of the soft binder is to achieve a level of "pre-coating" of the aggregate. The properties of this soft binder control the minimum compaction temperature. Since this initial coating is taking place at or below the boiling point of water, the addition of an adhesion promoter is strongly recommended (*18*).

The hard binder is then added to the "pre-coated" aggregate. The rate at which the hard binder dissolves into the soft binder determines the workability of the mixture and the initial binder composition and properties. Therefore, care must be taken when selecting the binders in order to make this process work. During the initial trials, the hard binder was introduced in three different ways; as a powder, as an emulsion, and as foam (*18*). The foam option was ultimately selected because it did not have the environmental and health risks of the powder, nor did it have the increase in cost of an emulsion (*19*). Figure 2.3 illustrates the WAM-Foam® process and conditions schematically.

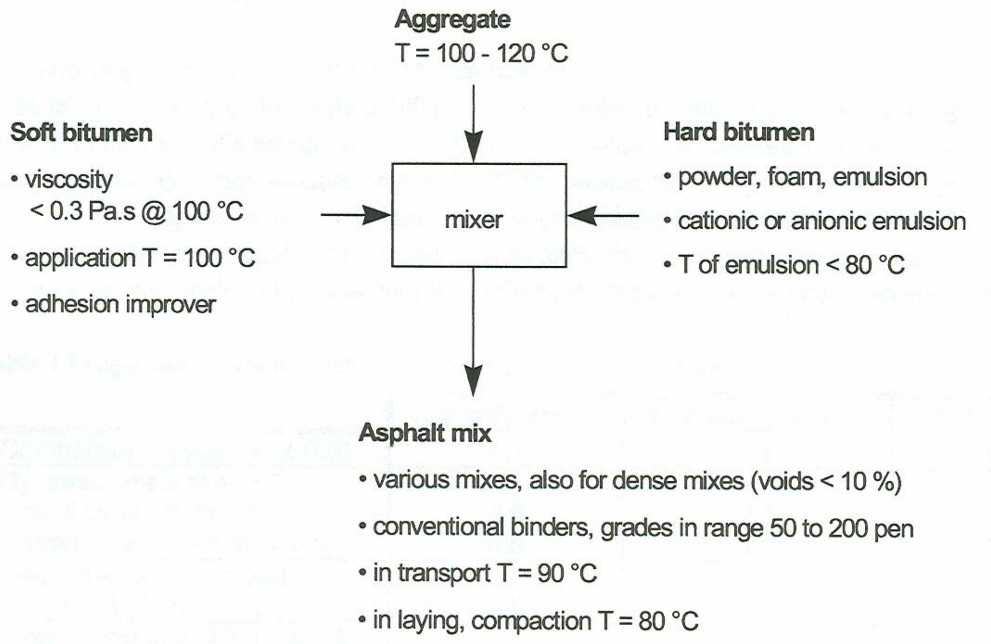

Figure 2.3. Schematic of WAM-Foam® Process (*18*).

Koenders et al. (*18*) reported on constructed field trials in Norway, the United Kingdom, and the Netherlands between 1996 and 2001 to study the WAM-Foam® process in the field. Test results from several of these road trials are summarized in Table 2.1. Within this table, the abbreviations NAT and CAT represent the Nottingham Asphalt Tester and the Californian Abrasion Test, respectively. Table 2.2 and Figure 2.4 show the reduction in fuel consumption, dust, and CO_2 emissions produced between conventional hot mix and mixes with WAM-foam®. Visual observations immediately after and up to three years after construction indicated that the WAM-Foam® process performed similar to conventional hot mix in terms of stability and mix adhesion, based on cores taken.

TABLE 2.1 Road Trial Results at Intermediate Temperatures (*18*)

Location, date, tonnes, type of mix	Voids range, %	cores taken after	Voids in Mix, %	NAT axial str. %	NAT strain rate µm/m/ld	CAT @ 4°C g (± 2g)
Norway, 1996, 190 t, Agb 11						
emulsion 180/200 pen Warm	2.7 - 5.2	6 weeks	5.0	5.4 / 4.6	17.6 / 13.3	27
80/100 pen Hot	4.2 - 7.5	6 weeks	4.5	2.9	6.5	27
emulsion 180/200 pen Warm	-	1 year	2.6 / 3.8	1.6 / 1.8	4.0 / 6.3	26
80/100 pen Hot	-	1 year	4.5 / 5.2	2.4	6.7	27
Norway, 1997, 450 t, Agb 11						
emulsion 50/60 pen Warm	6.0 - 7.0	6 weeks	7.0 / 6.8	1.7 / 3.5	5.5 / 8.0	29
emulsion 60/70 pen Warm	4.7 - 8.6	6 weeks	5.0	2.6	8.8	23
emulsion 80/100 pen Warm	3.8 - 5.3	6 weeks	3.8 / 4.9	3.6 / 2.4	9.2 / 7.5	23
Norway, 1999, 200 t, Agb 11						
foam 180/200 pen Warm	2.5 - 3.6	6 weeks	2.9 ± 0.5	2.8 ± 0.6	8.3 ± 1.0	21
United Kingdom, 1997, 150 t, DCM 0/14						
emulsion 80/100 pen Warm	9.0 - 12.6	3 months	9.0 - 12.6	1.4 / 1.2	3.3 / 3.1	40
80/100 pen Hot	7.9 - 11.5	3 months	7.9 - 11.5	1.2	3.0	40
the Netherlands, 1999, 400 t, DAC 0/11						
emulsion 80/100 pen Warm	4.0 - 8.2	6 weeks	4.0 / 5.7	2.9 / 1.5	5.1 / 4.4	23
80/100 pen Hot	2.8 - 3.7	6 weeks	3.4 / 3.7	2.8 / 2.4	5.5 / 5.0	26

TABLE 2.2 Asphalt Plant Details Illustrating Reduction in Emissions (*18*)

(info ex Veidekke 1996)	warm mixture	hot mixture	requirements
Production Capacity, tonnes/hr	70	120	NA
Fuel Consumption, litres/tonne	4.5	6 to 7	NA
CO_2 emission, %	1.0	3.0	not set
Dust cons. Dry, mg/m^3	1	3	max 150
Dust emission, kg/hr	0.03	0.09	max 5.4

NA = No Requirements Set

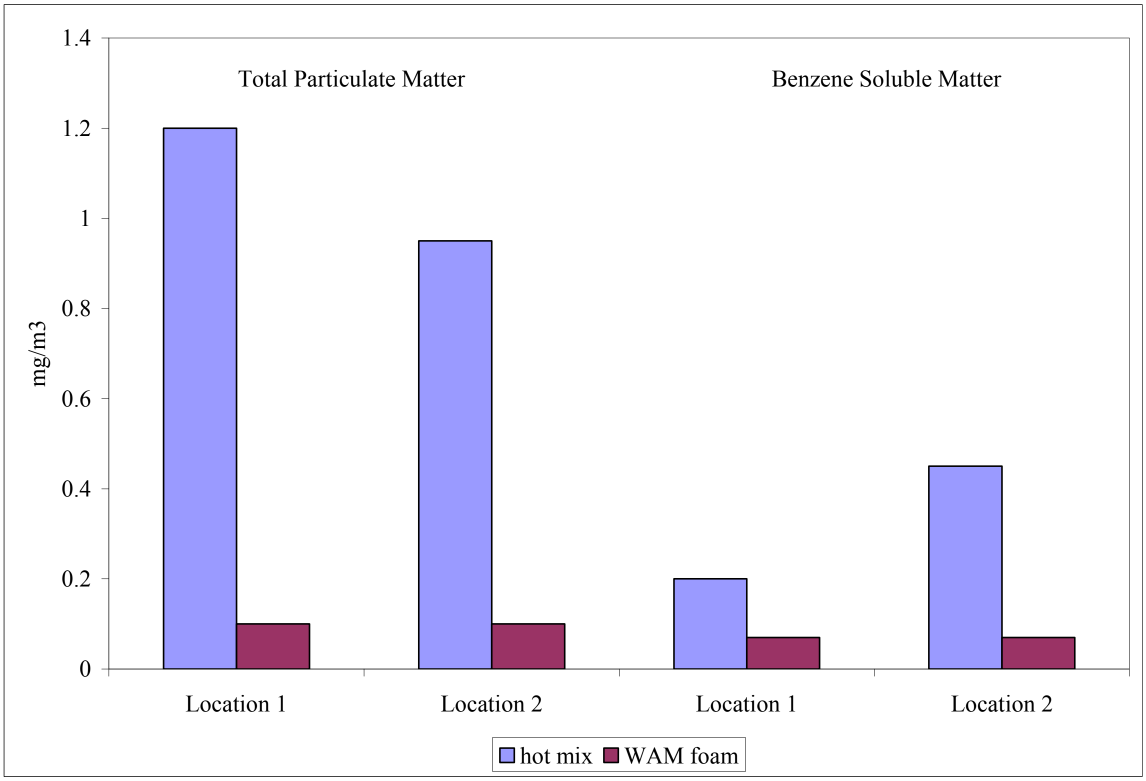

Figure 2.4. Emissions Data at Two Plant Locations (*19*).

2.3.2 Aspha-min®

Aspha-min® is a product of Eurovia Services GmbH, based in Bottrop, Germany. According to Eurovia's website, research efforts on Aspha-min® actually began in the early 1990's. However, in 2000, Eurovia took a more pro-active approach to develop products that would protect the environment. The end result was the development of Aspha-min® – a synthetic zeolite that releases water to create a foamed asphalt effect, capable of lowering operating temperatures by over 54°F (30°C).

Natural zeolites are the result of very low grade metamorphism and typically form in the cavities of volcanic rocks (*20*). They are framework silicates that consist of interlocking tetrahedrons of SiO_4 and AlO_4, and in order to be a zeolite, the ratio of silica and aluminum to oxygen must equal one half. Zeolites are officially tectosilicates, but differ in the fact that zeolites have large vacant spaces in their structures to allow the movement of cations, such as sodium and calcium. They also allow the presence of large cation groups, such as water molecules and ammonia. This is the reason zeolite has many uses; the main use being in water softeners. Zeolites that are charged with sodium ions allow "hard" water containing calcium to pass through its structure. Then the zeolite will exchange the sodium ions with the calcium. This process is reversible. Zeolites have the ability to absorb ions and other molecules, acting as a filter. Water contained in the zeolites can be driven off by heat without losing their structural integrity. Then the zeolite can act as a delivery system for the new fluid. This process is commonly found in the livestock industry, where zeolites contained in livestock feed will absorb toxins that are damaging or even fatal to the growth of animals.

Aspha-min® contains approximately 21 percent water by mass and uses its ability to release water to create a controlled foaming effect when added at the same time as the asphalt binder in the production of hot mix asphalt. This is accomplished at a temperature range of 212 to 392°F (100 to 200°C). As with the WAM-Foam®, Aspha-min® will create a volume expansion of the binder, creating a higher workability of the mixture at a lower temperature.

Barthel et al. (*7*) reported on the laboratory and field trial evaluations of Aspha-min®, investigating both the decrease of temperature on mixture performance and the reduction of emissions, both at the plant and at the paving location. An addition rate of 0.3 percent Aspha-min® by total weight of mix, or about six pounds per ton produced, was recommended for optimum performance.

Aspha-min® is approximately a 50 mesh material and can be added to the plant in a number of different methods; for a batch plant, it can be manually added to the pug mill or automatically using a weigh bucket. For a drum plant, Aspha-min® can be added through the recycled asphalt pavement (RAP) collar, but the preferred method requires a specially built feeder, such as a vane feeder that can control the quantity and can then pneumatically blow the Aspha-min® into the drum. Granulated Aspha-min® is shown in Figure 2.5 (*21*).

Based on the field trials (*7*), production and laying temperatures were reduced, on average, by 54°F (30°C), depending on the type of asphalt plant. Mix performance data obtained from comparative testing on a conventional mixture, a mixture containing Aspha-min® compacted 54°F (30°C) cooler, and a conventional mixture compacted 54°F (30°C) lower than normal is presented in Table 2.3. Results clearly illustrate the increased capability to achieve density of the warm asphalt mixture at lower temperatures.

TABLE 2.3 Field Trial Results, with and without Aspha-min® (*7*)

Mode of Manufacture	Type of Compaction	Samples		
		Voids (%)	Voids corrected for 5 cm (%)	Modulus (mPa)
170°C without zeolite	Immediate compaction	6.7	6.0	11,000
	Differed compaction	8.5	8.4	10,630
140°C with zeolite	Immediate compaction	5.3	6.6	12,400
	Differed compaction	11.8	11.3	9,700
140°C without zeolite	Immediate compaction	8.5	9.2	10,400

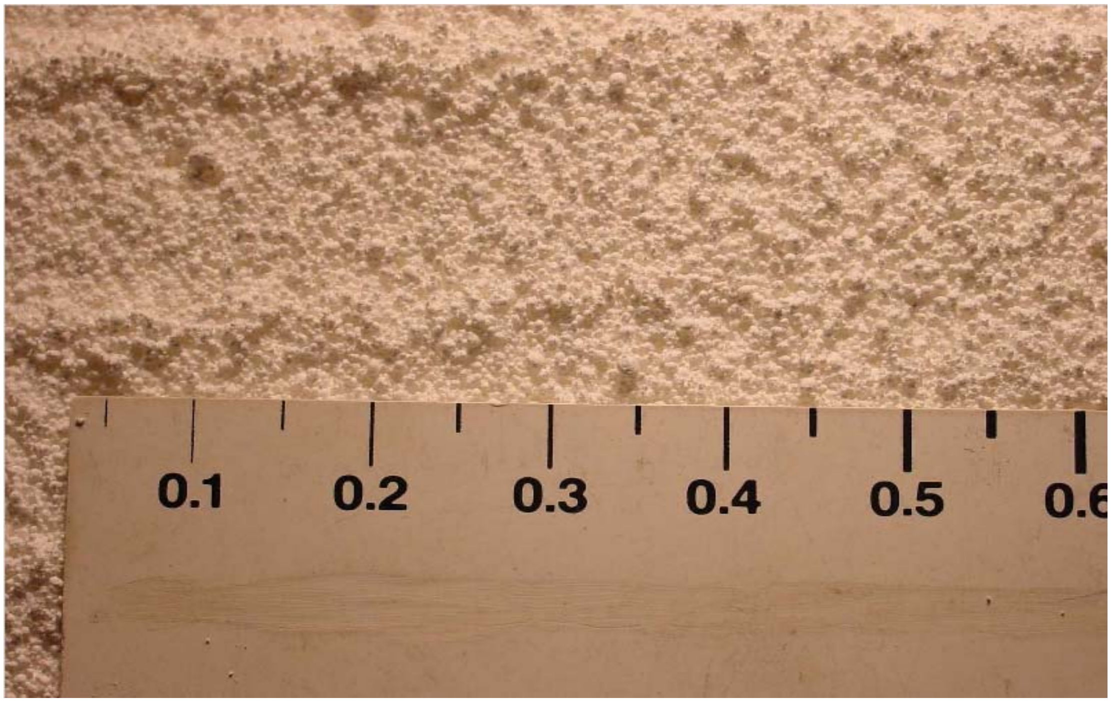

Figure 2.5. Granulated Aspha-min® (*21*).

Emission and energy consumption data collected during the field trials indicated that by reducing the mix temperature by approximately 55°F (30-35°C), the energy consumed was reduced by 30 percent. Barthel put this percentage into actual numbers, indicating that an asphalt mixing plant uses eight liters of fuel per ton of mix produced. A 30 percent reduction is equal to 2.4 liters per metric ton. In Germany, where 65 million metric tons of asphalt is produced annually, this reduction in fuel consumption results in 400,000 metric tons of CO_2 not being released into the atmosphere (*7*). An even more dramatic reduction was found at the paving location, where over 90 percent of the measured fume emissions were removed when mix temperature was lowered by 63°F (35°C) (*7*).

In 2002, Collins and Vaughan (*22*), both of Pavement Technology Inc., reported the findings of a laboratory investigation of Aspha-min® using aggregates native to the state of Georgia. A 12.5mm NMAS coarse-graded Superpave mix was evaluated with and without the use of Aspha-min®. The warm mix was compacted at a temperature 50°F (28°C) lower than the control mixture. Collins noted that the warm mixture appeared to bleed slightly after compaction in the Superpave gyratory compactor, a possible indication that the Aspha-min® could lower the optimum asphalt content of an asphalt mixture. Test results from the Asphalt Pavement Analyzer indicated that the warm asphalt mixture performed as well as the control mixture compacted at normal temperatures (Table 2.4).

TABLE 2.4 Rut Depths with and without Aspha-min® (*22*)

Sample ID	Average APA Rut Depth (mm)	Standard Deviation of Rut Depth (mm)
with zeolite	4.1	1.18
without zeolite	4.4	1.16

By the end of 2004, ten field research projects totaling more than 53,000 tons of Warm Mix Asphalt using Aspha-min® have been produced in France, Germany, and in the United States. These projects have used a wide range of pavement courses, mix formulations, asphalt binder types, productions methods, laying conditions, and road types. Field results from a trial section in Florida of Warm Mix Asphalt using Aspha-min® in early 2004 were published in a report by Hurley and Prowell (*23*). The mixture was a fine-graded Superpave mixture that contained 20 percent RAP, with Aspha-min®

added at a rate of 0.3 percent as recommended by Barthel (*7*). Test results from both the control mixture and warm asphalt mixture are presented in Tables 2.5 and 2.6.

TABLE 2.5 U.S. Field Trial Production and Compaction Temperatures (*23*)

Mix	Temperature, °F			
	Discharge	Stack	Trucks at Plant	Lay Down Behind Screed
Control	336	155	307 to 320	293 to 315
Aspha-min®	300	150	265 to 275	256 to 260

TABLE 2.6 U.S. Field Trial In-place Density Results (*23*)

Lane	Density, pcf	Average Density, pcf
Control 1	139.1	140.2
Control 2	141.3	
Aspha-min® 1	141.2	140.1
Aspha-min® 2	139.0	
Aspha-min® 3	140.0	

After one year, samples were taken from the two sections to determine if the lower compaction temperatures resulted in any moisture damage. From the data in Table 2.7, Aspha-min® was equally resistant to moisture damage as the control mixture, based on tensile strength values.

TABLE 2.7 U.S. Field Trial Core Densities and Indirect Tensile Strengths after One Year (*23*)

Sample	Air Voids, %	Height, in	Tensile Strength, psi
Control Mix			
C1	6.6	1.9	195.2
C2	5.8	1.8	65.5[1]
C3	5.9	1.8	167.6
C4	8.9	1.7	152.2
C5	7.9	1.8	165.6
Average	7.0	1.8	149.2
Aspha-min® Warm Mix			
W1	8.8	1.8	160.1
W2	9.6	1.8	158.2
W3	8.0	1.8	172.1
W4	6.1	1.6	195.1
W5	7.6	2.1	141.2
Average	8.0	1.9	165.3

[1] Appear to be an outlier; average = 170.2 psi without this sample.

2.3.3 Sasobit®

Sasobit® is the trademarked name developed by Sasol Wax, located in South Africa, for a synthetic paraffin wax produced from the gasification of coal or natural gas feedstocks using the Fischer-Tropsch (FT) process. It is also known as FT hard wax. To summarize the Fischer-Tropsch synthesis, originally developed in 1926, coal or natural gas (methane) is partially oxidized into carbon monoxide (CO), which is subsequently reacted with hydrogen (H) under catalytic conditions, producing a mixture of hydrocarbons having molecular chain lengths of C_1 to C_{100} and greater. The process begins with synthesis gas, which is a combination of carbon monoxide (from coal gasification) and hydrogen (from air separation), then reacted with an iron or cobalt catalyst to form products such as synthetic naphtha (i.e. flammable petroleum solvents), kerosene, gasoil and waxes. The liquid products are separated and the FT waxes are recovered or hydrocracked into transportation fuels or chemical feedstocks.

Asphalt binder, or bitumen, is basically the residue remaining from the distillation of certain types of crude oils. The earliest sources of bitumen were naturally occurring wax-free naphthenic crude oils, where the wax was consumed by microorganisms during its formation. Eventually, the more widespread paraffinic crude oils were used for bitumen. Paraffinic crude oils, however, contain four to six percent petrolatum, the wax contained in the crude oil (*24*, *25*). This material has been regarded in some countries as an undesirable ingredient in bitumen, as it can have adverse effects on the bitumen's quality, especially in terms of rutting susceptibility. Research through the Strategic Highway Research Program (SHRP), however, indicated that the content of natural waxes found in asphalt binder has no impact on its quality (*25*). Therefore, no limit exists for wax content in the SHRP specifications and it is an optional requirement in Europe, with some countries (Germany, for example) setting limits of 2.2 or 4.5 percent, depending on the test method used for measuring wax content (*26*).

The Fischer-Tropsch waxes used in bitumen have carbon chain lengths of 40-100 atoms and greater (*26*, *27*). By comparison, macrocrystalline bituminous paraffin waxes have carbon chain lengths ranging from 25-50 carbon atoms (*28*). The longer carbon chains in the FT wax lead to a higher melting point. The fine crystalline structure of the FT wax reduces brittleness at low temperatures as compared to bitumen paraffin waxes (*26*).

Sasobit® is described as an “asphalt flow improver”, both during the asphalt mixing process and during laydown operations, due to its ability to lower the viscosity of the asphalt binder (*25*, *26*). This decrease in viscosity allows working temperatures to be decreased by 32-97°F (18-54°C). Figure 2.6 demonstrates how Sasobit® can reduce viscosity in the mixing and compaction temperature range while producing approximately the same (or in some cases greater) viscosity at in-service pavement temperatures. The compaction temperature for the Sasobit® modified PG 64-22 is approximately 32°F (18°C) less than the compaction temperature for the PG 64-22 control binder (*29*). Sasobit® has a melting temperature of about 216°F (102°C) and is completely soluble in asphalt binder at temperatures higher than 248°F (120°C). At temperatures below its melting point, Sasobit® reportedly forms a crystalline network structure in the binder that leads to the added stability (*26*, *28*). During the production of HMA, Sasol recommends that Sasobit® be added at a rate of 0.8 percent or more by mass of the binder, with an optimum percentage being three percent. Sasobit® should never be added at a rate over four percent by weight of binder due to the possible negative impact on the binder’s low temperature properties (*26*).

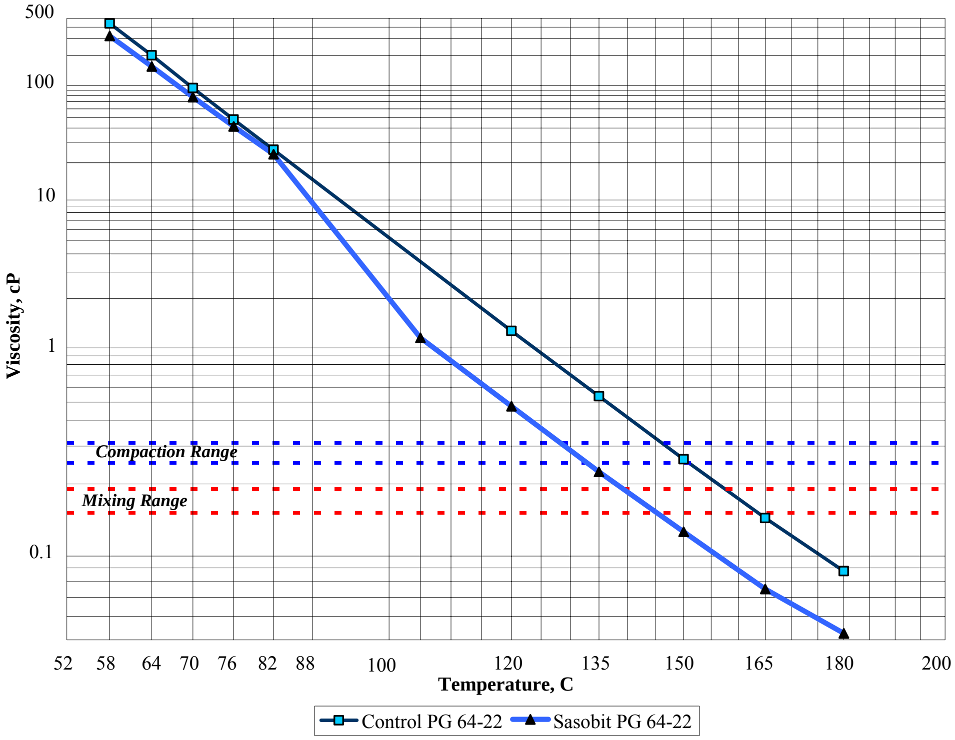

Figure 2.6. Mixing and Compaction Temperatures for PG 64-22 Binder (*29*).

Sasobit® can be introduced into the asphalt plant in several different forms. In commercial applications in Europe, South Africa, and Asia, Sasobit® has been added directly onto the aggregate mix as solid prills (small pellets) or as molten liquid (produced from flakes), as seen in Figure 2.7. In the United States, Sasobit® has been blended with the binder at the terminal (no high shear mixing required) and as prills blown directly into the mixing chamber at the same point cellulose fibers were being added to an SMA (Figure 2.8) (*29*). Commercial supplies of Sasobit® are available in 25 kg bags and 600 kg super-sacks (*27*).

Figure 2.7. Sasobit® Flakes (Left) and Prills (Right) (*29*).

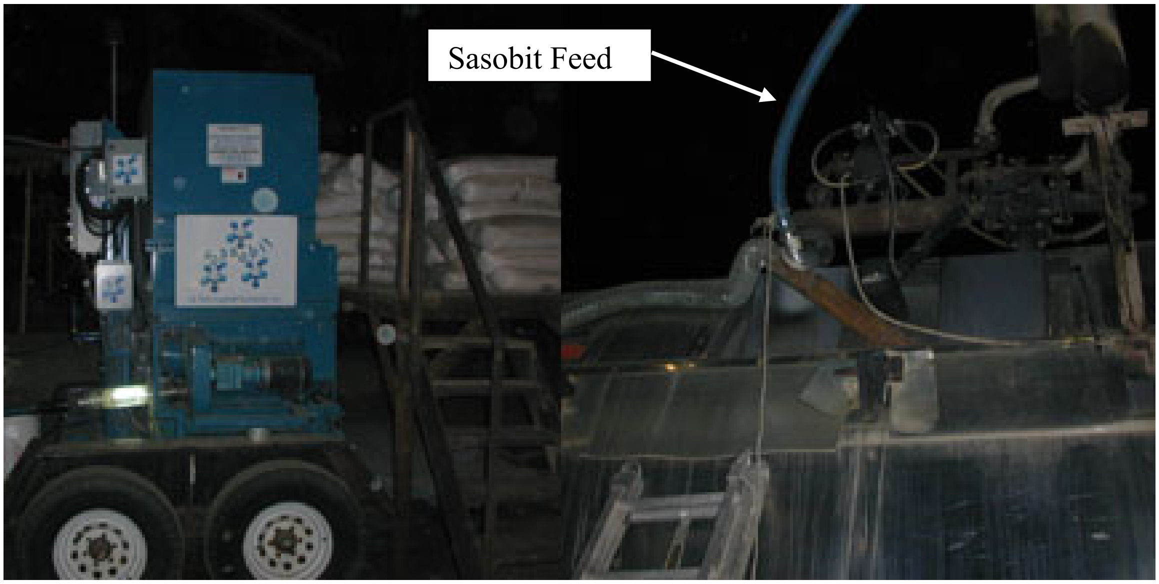

Figure 2.8. Sasobit® Pneumatic Feed to Mixing Chamber (*29*).

Since 1997, over 142 projects have been paved using Sasobit®, totaling more than 2,716,254 square yards (2,271,499 square meters) of pavement (*30*). Projects were constructed in Austria, Belgium, China, Czech Republic, Denmark, France, Germany, Hungary, Italy, Macau, Malaysia, Netherlands, New Zealand, Russia, South Africa, Sweden, Switzerland, the United Kingdom, and the United States. The projects included a wide range of aggregate types and mix types, including dense graded mixes, stone mastic asphalt and Gussasphalt (mastic asphalt). Sasobit® addition rates ranged from 0.8 to four percent by mass of binder.

2.3.4 Asphaltan B®

Asphaltan B® is a second type of synthetic wax and is manufactured by Romonta GmbH, based in Amsdorf, Germany. A member of the Romontan wax family, Asphaltan B® is representative of mountain wax (ozokerite) in general, and is a mixture of Montan wax constituents and high molecular weight hydrocarbons (*26*, *27*).

Crude Montan wax is found in Germany, Eastern Europe, and areas in the United States in certain types of lignite or brown coal deposits. These coal deposits formed over millions of years by the transformation of fossilized sub-tropical vegetation that flourished during the Tertiary Period. The wax that protected the plant leaves from the extremes of climate did not decompose, but enriched the coal instead. The wax's insolubility in water and high stability allowed it to survive over long geological time periods (*26*, *27*).

As the Montan wax was forming, a slight compositional change occurred that led to the formation of high molecular weight substances, mostly in the form of esters. Romontan waxes may also be denoted as esterified wax (*26*). After mining, the Montan wax is extracted from the coal through the use of a toluene solvent that is distilled from the wax solution and removed with super heated steam (*27*).

Romonta currently produces three synthetic waxes for use as "asphalt flow improvers", these being Romonta N®, Asphaltan A®, and Asphaltan B®. The first two are specifically formulated for use with mastic asphalt, while Asphaltan B® is engineered for paving asphalt. In addition to lowering the viscosity of the binder, the greatest effect of Asphaltan B® is increasing the softening point of asphalt binder. However, this increase is not as much as Fischer-Tropsch waxes, due to the difference in molecular size and chain length of Asphaltan B® (Asphaltan B® has carbon lengths in the range of 24-32 atoms). Binder adhesion with the aggregate is also improved by the inclusion of Asphaltan B® (*26*).

Romonta recommends a rate of addition of two to four percent by weight of binder. Compaction temperatures 36°F (20°C) lower than normal have been reported with no adverse effects on the mixture's workability (*26*). Asphaltan B® can be obtained in granular form in 25 kg bags and added directly at the asphalt plant or at the asphalt terminal (*27*).

2.3.5 Evotherm®

Emulsions have been around for close to a hundred years, but the general use of emulsions in the asphalt industry did not occur until the 1920's (*31*). Asphalt emulsion is a combination of asphalt, water, and an emulsifying agent, also known as a surfactant. The emulsifying agent (emulsifier) keeps the droplets of asphalt suspended in the water and controls the "breaking" time. Asphalt emulsions "break" when separation occurs between the asphalt and water, usually shortly after contact with aggregate in a mixer or after spraying on the roadbed. Upon curing, the residual asphalt retains all of the adhesion, durability, and water resistance of the asphalt cement from which it was produced (*31*). Asphalt emulsions have primarily been used in applications ranging from surface treatments to full depth reclamation projects. Other uses can be seen in Table 2.8 (*31*).

TABLE 2.8 Major Uses of Asphalt Emulsions (*31*)

The Major Uses of Asphalt Emulsions			
Surface Treatments	**Asphalt Recycling**	**Other Applications**	
Fog sealing	Cold in-place	Stabilization (soil and base)	Prime coats
Sand sealing	Full depth	Maintenance patching	Crack filling
Slurry sealing	Hot in-place	Tack coats	Protective coatings
Micro-surfacing	Central plant	Dust pallatives	
Cape sealing			

Asphalt emulsions are typically classified based on particle charge and setting properties. Emulsions currently used today are anionic, cationic, or nonionic. The first two are most commonly used in asphalt applications. Emulsions are classified further based on how quickly they "break", and are labeled RS, MS, SS, and QS for anionic emulsions. The abbreviations simply stand for rapid set, medium set, slow set, and quick set. Cationic emulsions use the same abbreviations, but are preceded with a C (CRS, CMS, etc.). Certain types of anionic emulsions are assigned the abbreviation HF, which stands for high float. These emulsions have a gel quality to them, mainly through the addition of certain chemicals, which allows for a thicker film thickness to be placed on the aggregate particles and prevents asphalt from being drained off the aggregate. These particular grades are used primarily for cold and hot plant mixes, seal coats, and road mixes (*31*).

Evotherm® was developed during the summer of 2003 and is a proprietary technology based on a chemistry package that includes additives to improve coating and workability, adhesion promoters, and emulsification agents. It is manufactured by

MeadWestvaco's Asphalt Innovations division, based in Charleston, South Carolina. The total Evotherm® package is typically 0.5 percent by weight of emulsion, as was the case for this study. The chemistry is delivered using a Dispersed Asphalt Technology (D.A.T.) (*32*) system in an emulsion with a relatively high asphalt residue (approximately 70 percent). Unlike traditional asphalt binders, Evotherm® is stored at 176°F (80°C). The water in the emulsion is liberated from the Evotherm® in the form of steam when it is mixed with the heated aggregate. The resulting warm mix appears like hot mix in terms of coating and color.

By October 2005, two Evotherm® field trials have been constructed in South Africa, one in the United States, and two in Canada. The South African trials, constructed in November 2003, used dense-graded 12.5 mm NMAS siliceous aggregates and viscosity-graded AC20 and AC10 binders. Parallel-flow drum plants were used to produce dense-graded mix at temperatures as low as 160°F (71°C); and in the field, laydown and compaction temperatures were as low as 140°F (60°C).

The United States trial was constructed in July 2005, near Indianapolis, Indiana. The asphalt mix was a 12.5 mm NMAS Superpave design produced with a dolomitic limestone aggregate and 15 percent reclaimed asphalt pavement (RAP). The emulsion was produced from a PG 64-22 base binder. Discharge temperatures from the mixing drum were approximately 200°F (93°C). Even at such low temperatures, the aggregate was completely coated and appeared like conventional hot mix with none of the brown or grey coloration often associated with emulsions. Steam release was evident at times from both ends of the mixing drum and the slat conveyor, but varied in quantity throughout the production process. The baghouse was examined after all the warm mix was produced and appeared dry, with no evidence of moisture in the bags or in the fines.

The two Canadian trials with Evotherm® were conducted in August and October 2005 by McAsphalt Engineering Services and Miller Paving. Two separate reports present the findings from these two field trials (*33*, *34*). In the first trial, optimum operating temperatures were established that would satisfy the physical properties of the mix and specification requirements. These temperatures were determined to be 248°F (120°C) for a mixing temperature and 203°F (95°C) as the compaction temperature. By comparison, the control hot mix asphalt was compacted at a temperature of 280°F (138°C), a 77°F (43°C) increase from the Evotherm® warm mix compaction temperature. The in-place densities for the Evotherm mix averaged 95 percent of the maximum theoretical density of the mix.

In addition to the determination of the volumetric properties of the warm mixture, residual asphalt binder was recovered to determine to what degree the binder age hardened during the production process. These test results were compared with test results determined from the base asphalt used in the field trial and with emulsion residue that was obtained when all the water was evaporated from the emulsion. Tests were performed in accordance with SHRP protocols, and the test results are presented in Table 2.9 (*33*). The abbreviation NA represents data that was not available or able to be determined. The data shows that the asphalt cement was not aged to the same extent at the lower temperatures, based on the stiffness values. Some of the difference could be attributed to the fact that the asphalt was held at a temperature of 302°F (150°C) for 30 minutes so all of the solvent used in the distillation process was removed, and this may have prematurely aged the sample.

TABLE 2.9 Binder Results on Lab and Field Samples (*33*)

Sample	Base Asphalt Cement	Emulsion Residue	Recovered Asphalt Cement	Spec
Tests on Original AC				
Rotational Viscosity @ 135°C, Pa.s	0.280	0.290	NA	3.0 max
@ 165°C	0.093	0.090	NA	
Dynamic Shear Rheometer G*/sin δ, kPa, @ 52C				1.0 min
@ 58C	1.180	1.340	NA	
@ 64C	0.540	0.610	NA	
RTFO Residue (AASHTO T240)				
Mass Change, %	0.428	NA	NA	1.0 max
Dynamic Shear Rheometer G*/sin δ, kPa, @ 52C	NA	NA	3.420	2.2 min
@ 58C	3.110	2.880	1.550	
@ 64C	1.360	1.250	NA	
PAV Residue (AASHTO R18) C	100	100	100	
Dynamic Shear Rheometer G* x sin δ, kPa, @ 19C	2717	4142	3596	5000 max
@ 16C	NA	6370	5322	
Bending Beam Rheometer				
Creep Stiffness @ -12C, Mpa	NA	105.0	81.2	
@ -18C, Mpa	233.0	249.5	176.5	300 max
@ -24C, Mpa	468.0	491.5	403.0	
Slope, m-value @ -12C, Mpa	NA	0.377	0.387	.300 min
@ -18C, Mpa	0.310	0.312	0.333	
@ -24C, Mpa	0.262	0.260	0.277	
PGAC Temperature Range (BBR Basis)	**59.3 - 29.3**	**60.2 - 29.6**	**55.3 - 31.9**	
PGAC Temperature Range (Direct Tension)	**NA**	**60.2 - 28.0**	**55.3 - 29.3**	
Penetration @ 25C, 100g, 5 sec	118	110	105	

The second trial conducted in Canada was performed to confirm the findings from the first trial, except on a larger scale. This trial also conducted field emissions and fuel consumption testing between conventional hot mix and warm mix asphalt with Evotherm®. During construction, the hot mix was compacted at a temperature of 293°F (145°C), resulting in an in-place density of 97.5 percent of maximum density. For the

Evotherm® warm mix, the compaction temperature was 199°F (93°C), which represents a decrease of 94°F (52°C), while achieving an in-place density of 97.0 percent of maximum density. This indicated that there was no difficulty in obtaining compaction for the Evotherm® at a much lower temperature, using the same compactive effort as for the control mixture. As with the initial trial, binder testing was performed on the recovered asphalt, with results paralleling the test results from the first field trial.

Emissions testing and fuel consumption evaluations were conducted to determine to what degree the use of Evotherm® would decrease both the emissions released into the atmosphere and the amount of fuel used during production. Regarding emissions, testing was conducted to include oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), and nitrogen oxides (NO_x). Results are presented in Table 2.10 (*34*). The data within the table illustrates the potential reduction in emissions produced at the asphalt plant when using Evotherm®. The production of warm asphalt mix with Evotherm® also lowered the amount of fuel consumed by approximately 55 percent, as seen in Table 2.11, representing a significant decrease in costs at today's prices.

TABLE 2.10 Combustion Gas Sampling Results (*34*)

Combustion Gas	Concentration		Reduction, %
	Hot Mix	Warm Mix	
Oxygen	14.60%	17.50%	
Carbon Dioxide	4.80%	2.60%	45.8
Carbon Monoxide	70.20%	25.90%	63.1
Sulphur Dioxide	17.2 ppm	10.1 ppm	41.2
Oxides of Nitrogen (as NO)	62.2 ppm	26.1 ppm	58.0
Average Stack Gas Temperature, °C	162	121	25.3

TABLE 2.11 Fuel Consumption Results (*34*)

Product	Fuel Level Before (Liters)	Fuel Level After (Liters)	Volume Used (Liters)	Tons of Mix Produced	Volume per Ton (Liters)
Hot Mix	39605.0	28546.7	11058.3	973	11.37
Evotherm® Mix	28546.7	25347.6	3199.2	615	5.20

2.4 PAVEMENT PERFORMANCE AS A FUNCTION OF COMPACTION TEMPERATURE

The following statements have been made about the compaction of hot mix asphalt:

> “The compaction and densification of asphalt mixtures are the most important construction operations with regard to the ultimate performance of the completed pavement, regardless of the thickness of the course being placed.” (*35*)

and

> “The single most important construction control that will provide for long term serviceability is compaction.” (*36*)

These two comments regarding the importance of proper compaction of asphalt mixtures in order to acquire the maximum performance of the asphalt mixture being placed made it necessary to investigate the history of compaction temperatures used during the production of hot mix asphalt. Although other factors are significantly related to the proper compaction of an asphalt mixture, only compaction temperature was investigated for this literature review due to the research objective of ultimately defining a critical compaction temperature when using Warm Mix Asphalt. In order to adequately investigate the history of the range of compaction temperature and its effect on the densification of asphalt mixtures, this particular section of this chapter is in chronological order.

Parr et al. (*37*) conducted a study to offer a field correlation on the comparative behavior of the various asphalt cements used in actual road construction. The authors stated that newer sources of asphalt cements being used in Michigan had different physical characteristics than those with which satisfactory service experience had been obtained, including differences in viscosities and temperature susceptibilities of the various asphalts and their stability towards heat. Therefore, the authors constructed field test sections to evaluate the new asphalt cements. Mix temperature was recorded during construction, and had a range from 265°F to 335°F (129.5 to 168.5°C). In-place densities were also determined for each of the field sections. The significant finding that relates to this research is that little change in density existed between mixes laid at 265°F (129.5°C) and 335°F (168.5°C).

Gallaway (*38*) compared laboratory and field densities of asphalt mixtures in the state of Texas. Twelve test sections were constructed and evaluated, with samples taken from two to nine months after initial construction. As with Parr et al., mix temperatures were recorded at time of construction, ranging from 250 to 310°F (121 to 154.4°C). Densities determined from field samples showed that adequate compaction occurred in asphalt mixtures compacted at the lower temperatures, when compared to those constructed at the higher temperatures.

Parker (*39*) presented the documentation of steel-wheeled rollers of static type used in highway construction. The primary results of this document are not significant to this particular research; however, the author did state that compaction temperature had a big effect on the compaction in a mixture. Asphalt mixes designed for surface and binder courses were compacted in the laboratory at various temperatures using the Marshall method using 50 blows per face. The results are presented in Figure 2.9. This figure illustrates the relationship between air voids and compaction temperature, based on a compaction temperature of 275°F (135°C). At temperatures higher than 275°F (135°C), there was no significant change in air voids, according to the trendline produced from the data. However, at temperatures below 275°F (135°C), the change was dramatic. For instance, samples compacted at 199°F (93°C) had air voids twice as high as those at 275°F (135°C), while a compaction temperature of 151°F (66°C) resulted in an air void content that was four times greater than those at 275°F (135°C). Parker (39) noted that this finding confirmed the compaction problem observed in the field when mix was compacted at low temperatures, especially in fall paving in northern climates.

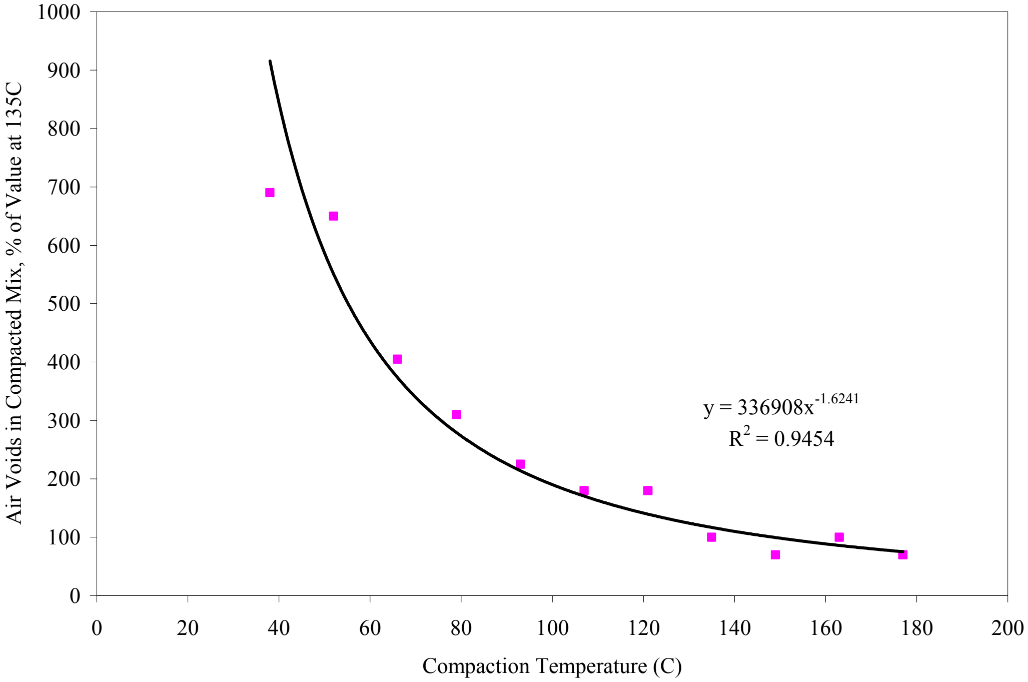

Figure 2.9. Effect of Compaction Temperature on Air Voids (after *39*).

In 1962, Serafin and Kole (*40*) presented the findings of a series of comparative studies focusing on properly evaluating the pneumatic tire rollers that had recently been used in order to achieve higher in-place density. The comparative studies were performed in 1960 and 1961, where standard construction procedures were modified so that rolling operations, mixture deviations, and rolling temperatures were closely controlled or measured.

Results from this research suggested that there was no significant difference in the densities obtained from either steel wheel or pneumatic tire rollers. However, the authors (*40*) confirmed that the compaction temperature of a mixture is a significant factor in the densification of an asphalt pavement. Data of particular importance to this research are presented in Table 2.12. In this table, pavement temperatures with respect to time are reported. It can be observed that the highest mixture temperature prior to compaction was 285°F (140.5°C), with an overall average of about 263°F (128.5°C).

TABLE 2.12 Pavement Cooling Data of Bituminous Concrete Wearing Course Mixture for Various Ranges of Air Temperatures (*40*)

Air Temp. Range	40-50	60-70	75-85	85-95
Time (min.)	Temperature (°F)			
0	285	266	259	240
1	265	251	244	238
2	250	238	235	226
3	248	225	232	222
4	234	222	217	215
5	219	214	215	216
6	217	214	205	210
7	208	204	207	202
8	197	200	200	205
9	200	195	192	196
10	185	190	192	194
11	186	187	192	189
12	177	183	186	188
13	176	180	185	192
14	173	177	184	180
15	169	174	178	182
16	160	168	178	179
17	162	169	171	177
18	153	165	175	179
19	157	164	172	175
20	151	160	165	172
21	150	154	164	168
22	138	158	167	169
23	145	153	162	164
24	141	155	160	166
25	140	145	159	160
26	139	148	157	165
27	131	142	157	158
28	134	143	155	161
29	134	144	148	160
30	125	139	150	157
35	NA	135	147	NA
40	115	127	138	145
45	109	122	135	NA
50	103	120	131	140
55	100	117	128	NA
60	96	113	125	135
65	NA	112	122	NA
70	NA	108	119	NA
75	NA	106	118	NA
80	NA	105	115	NA

NA = No Data Available

Bright et al. (*41*) conducted research to observe the effect of viscosity on the mixing, laying, and compaction operations of hot mix asphalt, using a wider than normal range of viscosities in construction. In addition, the authors wanted to study the changes on the physical properties of the binder over a period of time and the actual performance of the test strips under traffic. This was accomplished through the construction of twenty-four, 600 foot test strips of a one inch asphalt surface mix that had a range of viscosities from 900 to 40 Saybolt Furol Seconds. Twelve sections contained crushed granite, while the other twelve had crushed gravel. For each set of twelve, four different mix temperatures (225, 250, 287, and 345°F (107, 121, 141.5, and 174°C)) were used with a common grade asphalt to give the varying viscosities.

Cores were taken from the sites at 4, 9, and 21 months after construction, with penetrations and viscosities being determined from the recovered asphalt binder. The data showed that there was no visual difference in the mixing and compaction characteristics of the mixes made at the different viscosities used. The average compaction was the highest at the 225°F (107°C) mixes, while compaction was greatest at the 287°F (174°C) mixes. All mixes, however, satisfied density requirements, and in some cases higher densities were obtained on test strips mixed at the lower temperatures. Less hardening of the asphalt takes place at the lower mix temperatures. After 21 months, the penetration values for the lower compaction temperature were lower than those from the higher compaction temperature. This is shown in the data contained in Table 2.13. There also appears to be an optimum mix temperature for best compaction of approximately 287°F (174°C) for this particular study.

TABLE 2.13 Penetrations of Recovered Asphalt from Pavement Samples (*41*)

		Penetrations			
Strip No.	Proposed Mix Temp., °F	Samples Taken at Time of Construction	Samples Taken at Age 4 Months	Samples Taken at Age 9 Months	Samples Taken at Age 21 Months
I-a	225	72	49	35	28
II-a	250	66	49	36	31
III-a	287	67	49	36	33
IV-a	345	52	48	36	33
V-a	225	63	47	34	28
VI-a	250	62	48	37	39
VII-a	287	64	48	47	48
VIII-a	345	54	48	36	35
IX-a	225	63	44	35	30
X-a	250	68	46	35	32
XI-a	287	60	60	49	36
XII-a	345	55	47	35	35
I-b	225	67	53	35	33
II-b	250	70	53	39	30
III-b	287	63	57	39	36
IV-b	345	51	50	33	29
V-b	225	69	54	33	33
VI-b	250	67	46	40	34
VII-b	287	54	48	32	29
VIII-b	345	55	46	33	28
IX-b	225	66	47	35	30
X-b	250	66	45	34	32
XI-b	287	61	42	35	30
XII-b	345	53	40	33	36

In 1967, McLeod (*42*) published his findings on the influence of the viscosity of asphalt cements on compaction of asphalt paving mixtures in the field. He stated that compaction of any given asphalt mixture, whether easy or hard, is influenced by a number of factors, among them the viscosity temperature characteristics of the asphalt cement, the temperature of the mixture during compaction, the gradual increase in stability and density of the mix as compaction proceeds, the rate of cooling of the mix behind the spreader, the type of compaction equipment used, and by the use of low rather than high viscosity asphalt cements. The author's (*42*) findings regarding the compaction temperature of the mix and the use of low versus high viscosity asphalt cements are the significant factors related to this research. Figure 2.10 illustrates the influence of asphalt viscosity on the ease of compaction of paving mixtures. It can be seen that, for a given density, the lower viscosity asphalt will achieve this density at a compaction temperature approximately 50°F (28°C) cooler than the high viscosity asphalt cement. This fact, the author stated, could have practical application for pavement construction in colder weather.

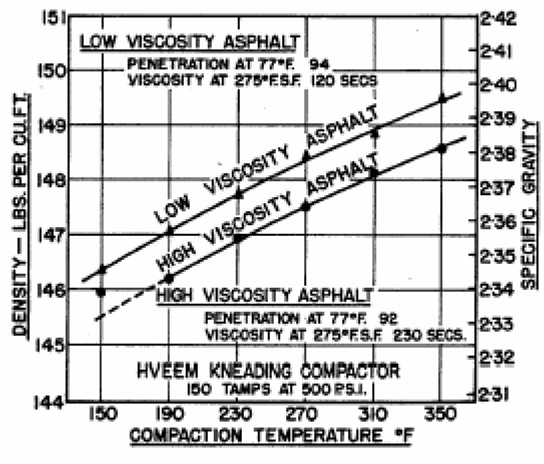

Figure 2.10. Influence of Asphalt Viscosity on Ease of Compaction of Paving Mixtures (*42*).

Epps et al. (*43*) conducted a study to more accurately define the influence of material properties, mix design, weather conditions, and traffic on the long term density gain of pavements. The study evaluated pavement density on 15 projects in Texas over a two-year period. Cores were sampled from the sites after one day, one week, one month, four months, one year, and two years. The authors (*43*) concluded that “eighty percent of the total two-year compaction, due to traffic and environmental effects, was complete within one year of service on all of the projects studied.” This document was included in this review because it contained mixture temperatures for all 15 projects during construction, and are presented in Table 2.14. From the table, it can be seen that compaction temperatures ranged from 145-225°F (62-107°C) at time of breakdown. The authors (*43*) also only labeled five of these projects as having low compaction temperatures, which implies that compaction temperatures around 225°F (107°C) were common.

TABLE 2.14 Aggregates, Asphalts, and Mix Temperatures (*43*)

	Compaction Equipment															Field Initial Air Voids, %
	Breakdown Rolling				Intermediate Rolling				Final Rolling							
	Passes/Section				Passes/Section				Passes/Section				Temperature, °F			
Test Section	A	B	C	Type Roller/Size	A	B	C	Type Roller/Size	A	B	C	Type Roller/Size	Air	Breakdown	Final	Section B, IWP
Childress US 287 25-42-9	4	3	6	3 wheel tandem, 12 ton; 5'-4' diameter	4	4	4	2 wheel tandem, 10 ton; 5'-4' diameter	14	14	14	Pneumatic, 25 ton 60 psi	51	145	125	8.69
Matador US 70 25-145-8	11	11	11	3 wheel 10 ton	5	11	21	Tandem, 10 ton	7	13	25	Pneumatic, 25 ton 75 psi	63	225	145	7.68
Sherman SH 5 1-47-3	6	12	24	3 wheel 10 ton	5	5	9	Tandem, 8 ton	10	20	40	Pneumatic, 12 ton 70 psi	80	200	135	8.26
Cooper SH 24 1-136-3	3	5	9	3 wheel 10 ton	3	5	9	Tandem, 10 ton; 4' diameter	1	4	7	Pneumatic	82	155	75	10.85
Cumby IH 30 1-9-13	3	7	13	3 wheel 10 ton	3	5	9	Tandom, 8 ton	3	5	9	Pneumatic 22.3 ton 102 psi	46	205	100	5.51
Clifton SH 6 9-258-7	3	3	6	3 wheel 10 ton, 60"- 42" diameter	4	8	16	Pneumatic 16.3 ton 75 psi	3	7	14	Tandem, 8.8 ton, 60"- 48" diameter	96	220	150	9.89
Waco US 84 9-55-8	4	3	9	Tandem, 8 ton, 54" diameter	4	4	4	Tandem, 8 ton, 54" diameter	15	15	15	Pneumatic 8 ton 44-52 psi	101	180	135	7.39
Robinson US 77 9-209-1	3	3	7	3 wheel 10 ton, 60"- 42" diameter	4	4	4	Tandem, 8 ton, 54" - 42 ' diameter	12	12	18	Pneumatic, 25 ton 60 psi	98	160	130	8.53
Milano SH 36 17-184-4	3	3	7	3 wheel 10 ton, 60" - 38" diameter	3	3	3	Tandem, 8 ton, 54" diameter	3	7	13	Pneumatic, 25 ton 60 psi	95	160	145	20.79
Bryan Spur 308 17-599-1	3	6	12	3 wheel 10 ton, 60" diameter	3	3	3	Tandem, 8 ton, 54" diameter	4	4	8	Pneumatic, 12 ton 75 psi	95	170	135	18.76
Tamina IH 45 12-110-4	3	7	4	3 wheel 10 ton 42" - 66" diameter	6	6	24	Pneumatic 10 ton 85 psi	2	2	2	Tandem 10 ton 60" diameter	97	185	145	12.72
Conroe FM 1495 12-1062-35	3	7	14	3 wheel 10 ton 60" diameter	10	10	20	Pneumatic 25 ton 65-70 psi	3	3	6	Tandem 8 ton 54" diameter	95	155	135	12.34
Baytown Spur 330 12-508-7	3	6	12	3 wheel 10 ton, 60" diameter	None			None	3	3	3	Tandem 8 ton 60" diameter	108	180	100	25.88
Orange SH 12 20-499-3	5	7	13	3 wheel 10 ton, 5'-3' diameter	None			None	3	5	11	Tandem 12 ton 4.5' - 3.5'	90	200	170	10.02
Bridge City IH 87 20-306-3	5	9	15	None	None			None	5	7	11	Tandem 8 ton 5' - 4'	85	200	165	13.83

Terrel and Holen (*44*) presented the findings from an evaluation of the performance of several projects constructed by use of the drum mixer type of asphalt plant. At the time of this document, drum plants had only been in service for about five years, and many contractors were hesitant in using them. They feared that mixing the binder in the presence of the burner gases would prematurely age harden the binder and worried that the mix was being discharged cooler than usual and contained more moisture than normally was considered acceptable. Even though earlier research had presented results stating that these concerns should be laid aside, more assurance was needed before contractors would begin to accept the drum mix plant.

Five projects that were constructed from 1970 to 1973 were sampled in 1975 to evaluate the overall quality, measured in terms of the Present Serviceability Index (PSI), and to compare the findings with pavements constructed with mixes produced at batch plants. Marshall Stability, in-place density, and penetration tests were performed on the samples taken form the five projects. Results of the laboratory testing are presented in Table 2.15.

TABLE 2.15 Compaction Temperatures and Test Results from Field Projects (*44*)

Project	Compaction Temperature, °F	In-Place Density, %	% Marshall Stability after 24hr. Soak @ 140°F	Retained Penetration, % of Original	PSI, out of 100
Alaska	238	95.5	86	41	NA
Arizona	NA	87.3	96	53	93
Oregon	190	90.6	100	62	90
North Dakota	NA	92.1	100	59	85
Washington	200	92.8	NA	34	NA

NA = No Data Available

From the results, several determinations were made. First, it was concluded that all the projects sampled appeared to be in good condition and had no defects that can be attributed to the drum mix plant. Second, the recovered asphalt penetration was greater than expected, compared to similar projects constructed with batch plants, and the penetration values decreased with age, though not as rapidly as mixes produced with batch plants. Thirdly, the Marshall Stability values determined after the 24 hour soak time ranged from 85 to 100 percent of the original, indicating no tendency toward stripping. The authors (*44*) concluded that the "general quality of drum mixed pavements appears to be at least as good, and maybe somewhat better, than conventionally mixed pavements."

Finn and Epps (*45*) published a state of the art review on the compaction of hot mix asphalt. In this document, the authors summarize why compaction is important and how adequate compaction can be achieved. Factors that influence compaction, including aggregate characteristics, asphalt properties, asphalt concrete properties, cessation temperature, equipment, and related factors (joints and subgrade support) are discussed at length. In addition to the recommendations of a density requirement to assure adequate compaction and a VMA (voids in mineral aggregate) requirement, the authors also recommended a compaction temperature range of 260-285°F (126.5-140.5°C) for most well graded mixes depending on the viscosity of the asphalt and the stability of the mix.

As a result of the decrease in compaction temperatures being used since the introduction of the drum mix plant, Kennedy et al. (*46*) conducted a research study to document the effect of these lower compaction temperatures on the engineering properties of asphalt concrete mixtures, both in the field and in the laboratory. The field study was accomplished by examining the construction data to evaluate factors, including mixing and compaction temperatures and in-place densities. For the laboratory study, samples were made using various compaction temperature and density combinations that were observed in the field in order to determine Hveem stability and static tensile strengths, both in the wet and dry condition.

For the field study, mixing and compaction temperatures were obtained, with the average mixing temperature being 210°F (149°C) and 200°F (93.5°C) being the average compaction temperature. The low temperatures were partly due to the use of an asphalt emulsion that was used for the asphalt binder in the field study. Low densities measurements were determined from cores that were sampled from the road immediately prior to the removal of the road. Therefore, the weakened state of the road may have caused the densities to be low. Indirect tensile strengths were determined, and results indicated an increase of tensile strength with increasing compaction temperature.

In the laboratory portion of this research, test results confirmed the results from the field study; the indirect tensile strengths, both in the wet and dry condition, increased as the compaction increased, illustrated in Figure 2.11. Also noted is that the density of the test samples increased with the compaction temperature, which could have an influence in the tensile strengths determined. [The author notes that the highest compaction temperature used in this study, 250°F (121°C), is the minimum recommended compaction temperature for the Warm Mix Asphalt additives evaluated. All test results determined at 250°F (121°C) in the document by Kennedy et al. (*46*) are adequate values based on today's standard practices.]

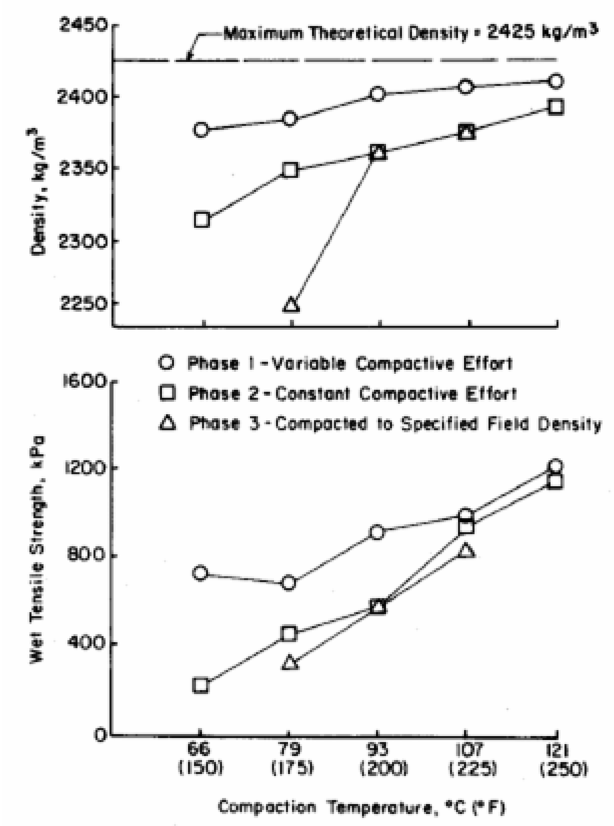

Figure 2.11. Wet Tensile Strengths and Density Values as a Function of Compaction Temperature for Laboratory Study (*46*).

2.5 PAVEMENT PERFORMANCE AS A FUNCTION OF COMPACTION TEMPERATURE – POST SUPERPAVE

Superpave (SUperior PERforming PAVEment) was the result of five years of intense research and development under the Strategic Highway Research Program. Implementation of the Superpave system, which began in 1992, led to several changes in the way asphalt mixtures were designed. These changes led to the use of coarser aggregate structures rather than well graded aggregate gradations and the increased use of modified binders.

These two changes led to changes in the way asphalt mixtures were constructed in the field as well. The typical compaction temperature ranges that were used prior to Superpave to achieve adequate in-place density in the past now were not effective. Therefore, contractors increased the mixing temperatures in order keep the asphalt at an elevated temperature longer to achieve the minimum required in-place density.

In 1999, Brown et al. (*47*) reported the early construction issues that arose after the implementation of Superpave. They also presented an early performance evaluation of Superpave asphalt mixtures. A construction survey was conducted to get a better indication of what the contractors were experiencing with the new Superpave mixes. The survey included topics such as materials, mix design, plant operations, paving operations, compaction, and quality control. The survey results included 68 projects from 20 states, and spanned a wide range of construction factors.

The significant finding for this research is the compaction issues. The authors (*47*) reported that 50 percent of the reviewers stated that the mixing temperature had to be increased 9 to 14°F (5 to 8°C), possibly due to the increased use of modified asphalt binder and coarser aggregate gradations. This, in turn, led to approximately the same amount of increase in the compaction temperature. In fact, the construction problems encountered was the most common issue in the survey. The results indicated that even though the majority of the projects achieved adequate density, more effort was required, in terms of more rollers and the increase in compaction temperature.

Another research project that presented compaction temperature data was NCHRP 9-27, *Relationship of Air Voids, Lift Thickness, and Permeability in Hot Mix Pavements* (*48*). An investigation into the relationships between air voids, lift thickness, and permeability, the study included the evaluation of 20 field projects. Included in the data obtained from these field projects were mixture temperatures at the time of compaction. From data obtained from 15 of the 20 projects evaluated, the compaction temperatures ranged from 255 to 315°F (124 to 157°C), with the overall average being 290°F (143.5°C). A second objective of the study was to recommend a proper lift thickness based on aggregate gradation. To accomplish this task, field trial sections were constructed with different gradations and varying lift thicknesses. Compaction temperatures were recorded during construction of these test sections; the range of compaction temperature was 269 to 320°F (131.5 to 160°C), and averaged 300°F (149°C).

2.6 PERFORMANCE TESTING EQUIPMENT AND METHODS

2.6.1 Resilient Modulus Testing

Resilient modulus, or Repeated Load Indirect Tensile, is defined as the ratio of the applied stress to the recoverable strain when a repeated load is applied, and is used during pavement design to determine pavement thickness. Resilient modulus testing can be conducted using tensile or compressive stress, with tensile stress used more often due to the fact that fatigue cracking is primarily due to tensile failure at the bottom of an HMA layer. Tensile stress can be generated by two modes of loading: axial and diametral. The diametral resilient modulus test uses dynamic pulse loads applied diametrally to cylindrical test samples, and the vertical or horizontal deformations or both are recorded and used to calculate the resilient modulus.

The concept of resilient modulus was first introduced in 1962 by Seed et al. (*49*) through the investigation of the elastic response of subgrade soils and their relation to fatigue failures in asphalt pavements. The resilient modulus was once the preferred and most common method to measure the stiffness of an asphalt mixture, mainly due to its simplicity and applicability to test both laboratory and field samples (*50*). Today, the dynamic modulus test is used over the resilient modulus for mixture stiffness measurement. The standard test specification for determining the resilient modulus of an asphalt mixture is ASTM D 4123, *Indirect Tension Test for Resilient Modulus of Bituminous Mixtures*. The testing apparatus is shown in Figure 2.12.

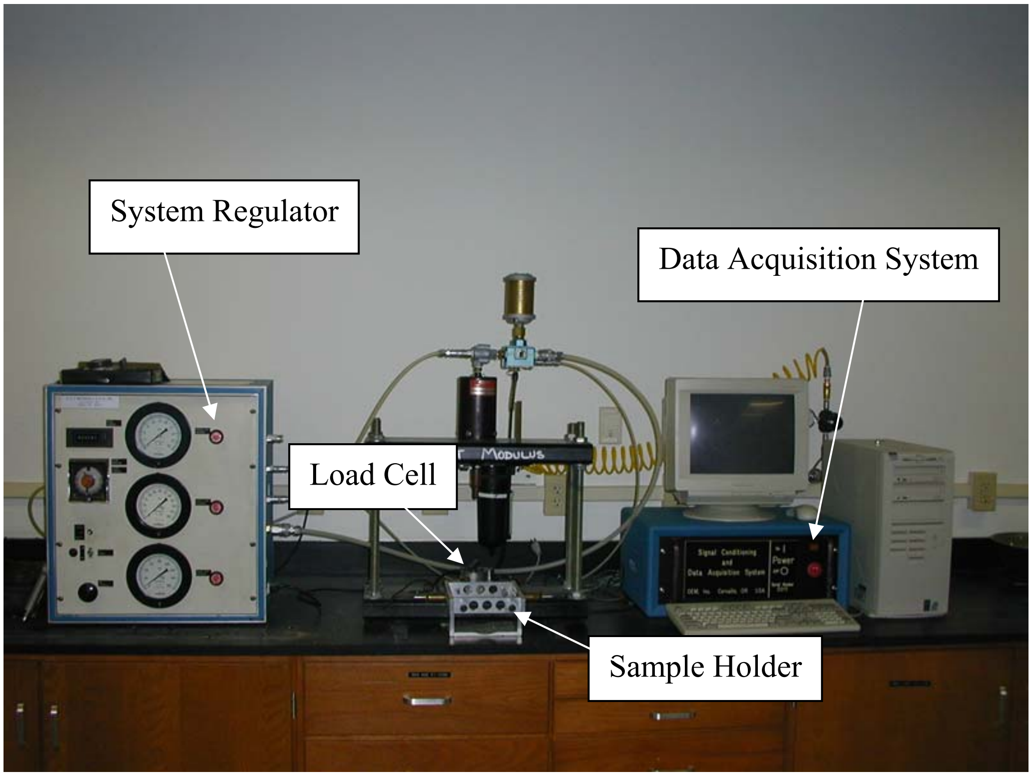

Figure 2.12. Resilient Modulus Testing Apparatus.

2.6.2 Asphalt Pavement Analyzer Testing

With the increase in traffic and heavier pavement loads, it has become extremely important that an asphalt mixture be resistant to permanent deformation, or more commonly termed rutting. The Asphalt Pavement Analyzer (APA) has hence become widely accepted as a straightforward method to evaluate the rutting resistance of HMA.

The APA, first manufactured by Pavement Technology, Inc. in 1996, is a second generation version of the Georgia Loaded Wheel Tester (GLWT) and is shown in Figure 2.13. The initial GLWT was developed in 1985 through a joint effort of the Georgia Department of Transportation (GDOT) and the Georgia Institute of Technology. The original GLWT was based on a machine to test slurry seals, and then was modified to perform efficient and effective laboratory testing and field quality control of asphalt mixtures against rutting susceptibility.

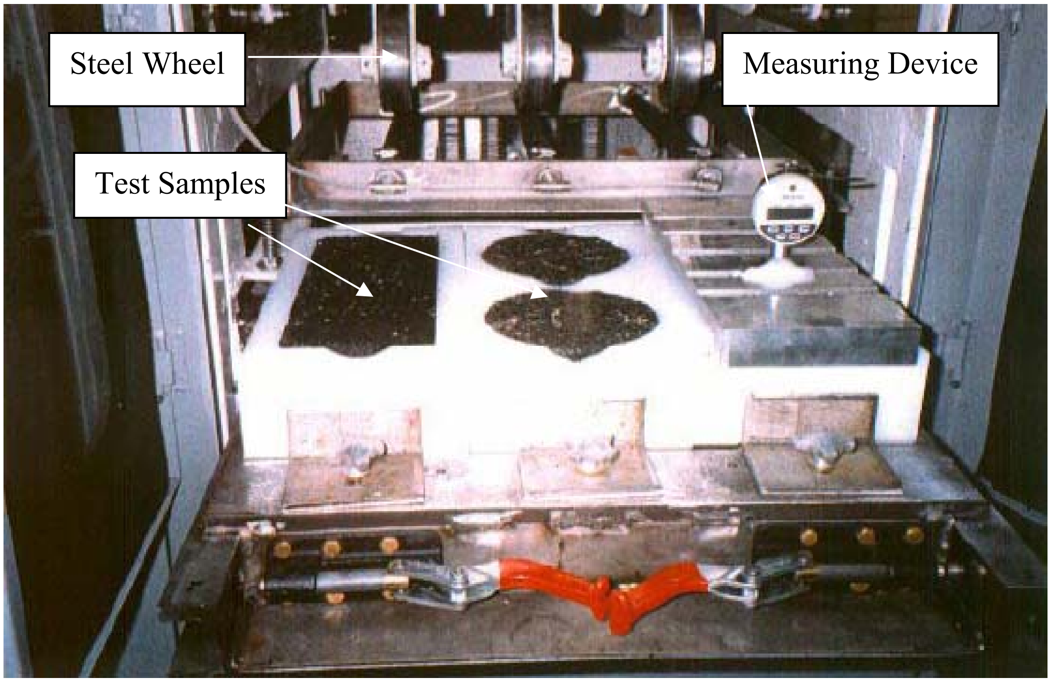

Figure 2.13. Asphalt Pavement Analyzer.

Many research studies have focused on the evaluation of the APA in terms of asphalt performance. In one such study, Kandhal and Mallick (*51*) concluded that the APA appeared to have the potential to predict the relative rutting potential of HMA mixtures. Based on their research data, they recommended terminal rut depths less than 4.5 to 5.0 mm after 8000 loading cycles to ensure a rut resistant pavement in the field. Another study, on a larger scale, was NCHRP 9-17, *Accelerated Laboratory Rutting Tests: Evaluation of the Asphalt Pavement Analyzer* (*52*). The main objectives of this study were to evaluate the APA to determine its applicability as a general method of predicting rutting potential and for use in field QC/QA (quality control/quality assurance) testing and to compare the APA to other loaded wheel testers currently being used and with a simple strength test. The findings determined that the APA correlated well with other methods used to predict the rutting potential of HMA, and a provisional test procedure was developed to determine the rutting potential of an asphalt mixture by the use of the APA.

2.6.3 Indirect Tensile Strength Testing

Several of the new technologies that have been developed to lower the operating temperatures of hot mix asphalt incorporate the use of water or steam to aid in decreasing the mixture’s viscosity. The lower viscosity, in turn, allows the mixture to be more workable at lower temperatures. However, there was concern that a “cure” time would be necessary to allow the moisture in the mixture to fully dissipate out of the asphalt mixture before traffic was allowed on the roadway. In some European countries, a “cure” time is required before traffic is allowed on the pavement (e.g. Germany requires 24 hours for SMA mixtures).

Previous research has been conducted on the cure time of asphalt mixtures, especially when asphalt emulsions were used as the asphalt binder. Maccarrone et al. (*53*) observed the cure time for foamed asphalt and a high binder content emulsion, both in terms of binder type and filler type. Resilient modulus testing was conducted on the test samples. Results for curing at room temperature showed that curing was faster with the higher binder content emulsion. The author also noted that the resistance to moisture was higher with the higher binder content emulsion. For the effect of filler type, Maccarrone et al. (*53*) indicated that almost 80 percent of the dry resilient modulus was obtained after one day of curing when using cement works flue dust as a filler with the foamed asphalt. Koenders et al. (*18*) noted that for all field trials using WAM-Foam®, a rapid structural integrity was obtained, allowing a quick opening of the road, minimizing traffic delays.

2.6.4 Moisture Resistance Testing

Moisture damage has been a significant problem that has resulted in the premature failure of many asphalt pavements. Loosely defined as the "separation of asphalt film from aggregate surfaces due primarily to the action of water" (*54*), moisture damage has been investigated and studied since the introduction of pavement technology in the 1930's (*55*, as cited by *56*). Since then, numerous studies have been conducted to try and define a qualitative and quantitative solution towards understanding and predicting the stripping potential of hot mix asphalt. The end result from these studies is that the issue of moisture damage is not completely understood, even to this day.

Moisture damage can be categorized into two basic types: softening and stripping (*57*). Softening, also known as cohesive stripping, is due to a softening of asphalt cement in the presence of water which weakens the bond between the asphalt concrete and the aggregate. The type labeled here as stripping is also known as adhesive stripping, and involves the loss of adhesion and the physical separation of the asphalt cement and aggregate through the presence of moisture. These two types of failure are interrelated; overall moisture damage within an asphalt pavement may be a combined result of both cohesive and adhesive failures (*58*).

Numerous test procedures have been developed throughout the years to attempt to assess the moisture susceptibility of asphalt mixtures. Among them is the boiling water test (ASTM D3625), the static-immersion test (AASHTO T182), the immersion-compression test (AASHTO T165, ASTM D1075), the Lottman test, the Tunnicliff and Root Conditioning test (ASTM D4867), and the Modified Lottman test (AASHTO T283). The Modified Lottman test has become the most widely accepted by specifying agencies, and is currently included in the Superpave mix design specification. However, the inconsistency of results using the test procedure has led many researchers to question the accuracy of the test results (*61*). Researchers have reported that the test procedures do not accurately correlate the performance of laboratory mixes to the performance of field mixes. Also, the saturation specification may allow mixes to fail the test criteria when saturated to the high end of the specification limits, but pass the criteria when saturated to the low end of the specification limits (*59*).

For this research, the Tunnicliff and Root Conditioning test, which serves as the basis for ASTM D4867, was used as the test procedure to evaluate moisture resistance.

The main reason for this choice was that it does not incorporate the lengthy curing times that the current version of ASSHTO T283 contains. This allowed for a faster determination of the test results. Also, many state agencies have eliminated the cure time.

2.6.5 Hamburg Wheel Tracking Device

The Hamburg Wheel Tracking Device (HWTD) was developed in Hamburg, Germany in the 1970's. This device was based on a similar device developed in Britain that used a rubber tire; the HWTD uses a steel wheel to track across the surface of the test sample. The original use of the Hamburg Wheel Tracking Device was to evaluate the rutting susceptibility of asphalt mixtures (*60*), but it was later found to be sensitive to multiple variables, including the quality of aggregates, the stiffness of the asphalt binder, the length of short term aging, the refining process or crude oil source of the asphalt binder, anti-stripping agents, and compaction temperature (*61*). All these factors are related to the moisture susceptibility of an asphalt mixture. This allows the Hamburg Wheel Tracking Device to be useful in determining the moisture susceptibility of HMA.

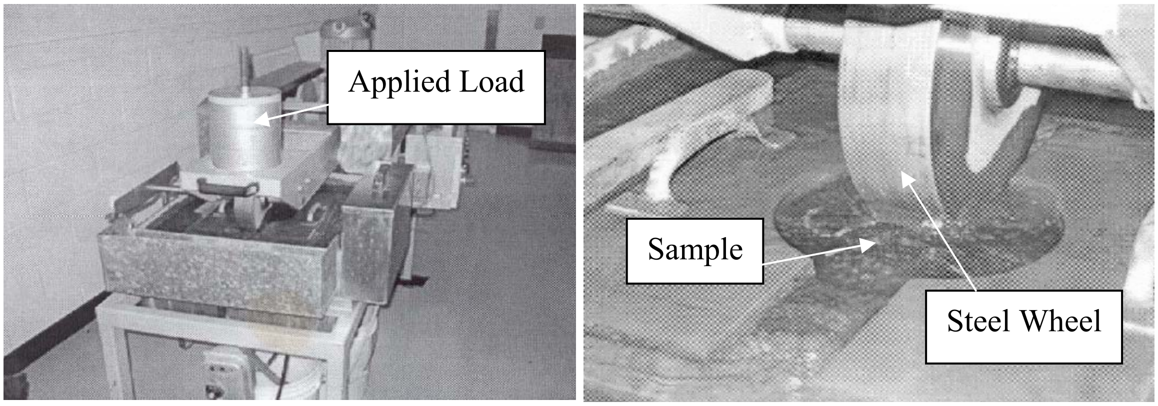

Figure 2.14. Superfos/Couch Hamburg Wheel Tracking Device.

The Hamburg Wheel Tracking Device used for this research study was manufactured by Superfos/Couch Construction and is shown above in Figure 2.14. It differs slightly from the more common version of the HWTD in that is can only test one sample at a time and in the speed of the wheel. Test samples for the HWTD can either be slabs, field cores, or gyratory compacted samples. Testing is accomplished on test samples submerged in a water bath at temperatures ranging from 77 to 158°F (25 to 70°C), with 122°F (50°C) being the most common testing temperature used. The samples are loaded with a vertical load of 158 pounds. The wheel makes 50 passes over the sample per minute. Testing of a sample is completed when either the wheel makes 20,000 total passes (10,000 total cycles) or when 20 mm of deformation occurs.

The results from the Hamburg Wheel Tracking Device include rut depth, creep slope, stripping slope, and stripping inflection point, and are presented in Figure 2.15. The creep slope relates the rutting from plastic flow. It is calculated from the inverse of the rate of deformation in the linear region of the deformation curve after compaction effects have ended and before the onset of stripping. The stripping slope is related to the severity of moisture damage. It is the inverse of the rate of deformation in the linear region after stripping begins. The stripping inflection point is the number of passes at the intersection of the creep slope and the stripping slope. It is related to the resistance of the HMA to moisture damage. Research indicates that moisture resistant pavements have stripping inflection point exceeding 10,000 passes (*61*). The stripping inflection point allows the HWTD to discriminate between pavements of varying field stripping performance.

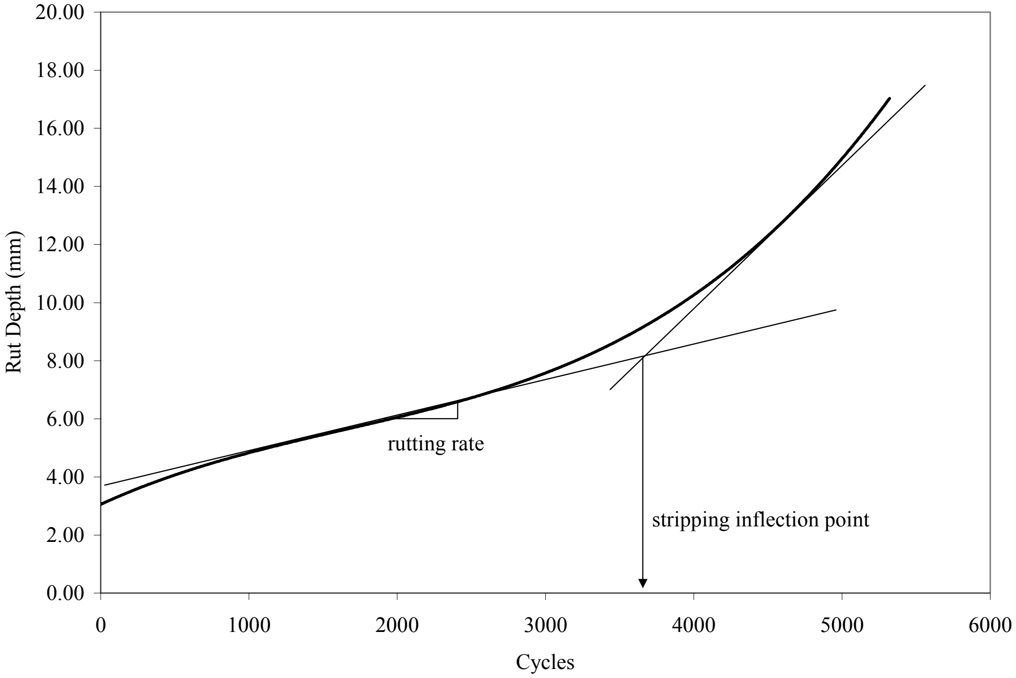

Figure 2.15. Hamburg Test Results, Defining Rutting Rate and Stripping Inflection Point.

Several downsides of the test results from the Hamburg Wheel Tracking Device have been identified. The HWTD, on occasion, can indicate a low resistance to moisture damage for asphalt mixtures with known histories of high stripping resistance. This could lead to the rejection of acceptable mixtures. Also, the data collected cannot be used to determine the modulus of the mixture or layer coefficients used in the AASHTO design guide, due to the complex and unknown state of stress in the samples (*60*).

2.7 SUMMARY OF LITERATURE REVIEW

The concept of using additives in an asphalt mixture for the purpose of lowering the mixing and compaction temperatures was developed in Europe during the early 1990's (*3*). The ensuing technology was termed *low temperature asphalt* or *warm asphalt mixes*.In the United States, it is known as *Warm Mix Asphalt*.

The development of warm asphalt mixes was due to the increase in concern over the environment; as the production temperature of HMA increased, so too did the production of emissions and fumes that were being released into the atmosphere. The literature indicated that concern over emissions produced in the manufacture of hot mix asphalt began in the 1970's. The NIOSH recommended an exposure limit (REL) for asphalt fumes of 5 mg/m^3 measured as total particulate matter (TPM) during any 15 minute period, based on available data on the health effects of occupational exposure to asphalt and asphalt fumes (*9*). As the asphalt industry argued that the results were not representative of emissions produced by the asphalt paving industry, more research was conducted. The final result was that NIOSH could find no significant evidence to quantify the chronic health risks associated with asphalt paving fumes and recommended minimizing possible acute or chronic health effects from asphalt fumes by adhering to the current REL of 5 mg/m^3 during any 15 minute period (*15*).

Several different additives are used to lower the operating temperatures of an asphalt mixture, including WAM-Foam®, Aspha-min®, Sasobit®, Asphaltan B®, and Evotherm®. These technologies target the reduction of viscosity of the asphalt mixture, both during production and placement. The lower viscosity allows the mixture to be compacted at lower temperatures, yet potentially retaining all the performance characteristics of asphalt compacted at more standard temperatures. The different technologies employ several different technologies to achieve the lower operating temperatures.

Literature also indicated that compaction temperature significantly influences the density of an asphalt mixture. As the temperature decreases, the viscosity of the mix increases, thus making the asphalt mixture more difficult to compact. Prior to Superpave, the compaction temperature of a typical dense graded asphalt mixture was generally in the range of 275°F (135°C). The literature presented data that stated compaction temperatures was lowered to around 200°F (93.5°C) without any adverse affects. [The author believes that lowering the compaction temperature of an asphalt mixture to about 200°F (93.5°C) would generally results in potential problems.] With the implementation of Superpave, the compaction temperatures started to increase, partly due to the coarser nature of the aggregate structure and the increased use of modified binders. These factors made the asphalt mixture harder to compact; therefore more effort had to be used to ensure proper density. As a result, compaction temperature increased as well. Today, the compaction temperature of most mixes are in the range of approximately 300°F (149°C) or more.

The literature also described new technologies and processes have been developed in Europe that will lower the operating temperatures of an asphalt mixture, thus reducing emissions and fumes, reduces the age hardening of the asphalt binder, reduces the wear and tear of an asphalt plant, acts as a compaction aid for stiff mixes, and reduces fuel consumption of an asphalt plant. These benefits have been observed in Europe for several years. However, no long term performance has been evaluated. An in-depth evaluation is needed to assess the possible applicability of these technologies and processes to the different mix designs and paving practices that exist in the United States.

CHAPTER 3: RESEARCH APPROACH

3.1 INTRODUCTION

A test plan was conceived that would thoroughly evaluate the Warm Mix Asphalt processes for paving practices commonly found in the United States using laboratory procedures. Table 3.1 presents the experimental plan for this investigation. It should be noted that only three potential processes were evaluated for this research.

TABLE 3.1 Experimental Designs for Evaluating the Influence of Warm Asphalt Processes on Mixture Volumetrics and Performance

	Number of Samples Tested							
	Granite				Limestone			
	Control	Aspha-min®	Sasobit®	Evotherm®	Control	Aspha-min®	Sasobit®	Evotherm®
Mix Design	6				6			
Volumetrics	8	8	8	8	8	8	8	8
Compactability	24	24	24	24	24	24	24	24
Resilient Modulus	24	24	24	24	24	24	24	24
APA Rutting	24	24	24	24	24	24	24	24
Moisture Sensitivity	6	6	6	6	6	6	6	6
Strength Change with Time	10	10	10	10	10	10	10	10

3.2 MATERIAL VARIABLES

3.2.1 Aggregates

This study used two different aggregate sources to evaluate the three Warm Mix Asphalt processes. These two aggregate sources were granite and limestone. The aggregates were selected due to their known differences in moisture susceptibility; granite aggregates have a tendency to be sensitive to moisture, while limestone aggregates are known to be more moisture resistant. Both aggregate sources are widely used for hot mix asphalt construction in several states throughout the Southeastern United States.

3.2.2 Asphalt Cements

The analysis of all data determined for this research was based on a PG 64-22 binder grade. However, two base binder grades were used for this study. They were a PG 58-28 binder and a PG 64-22 binder grade. To achieve the PG 64-22 binder used with the Sasobit® additive, 2.5 percent Sasobit® was added to a base PG 58-28 binder to produce the PG 64-22 binder. The Aspha-min® and Evotherm® additives used the base PG 64-22 binder.

3.2.3 Blend Gradations

A single blend gradation was used for all testing in this study. The mix design gradation replicated a 12.5mm nominal maximum aggregate size Superpave coarse-graded crushed granite mix produced by Hubbard Construction, Orlando, Florida. The mix design gradation used for both aggregate types is shown in Table 3.2 and

Figure 3.1. This gradation was used in the first field trial evaluated in the United States using Aspha-min®. The aggregates used in this field evaluation were obtained and used for this research study. The gradations for the granite and limestone aggregates shown in Table 3.2 differed from the job mix formula due to several possible reasons. One, the stockpile gradations used in the laboratory blending of the aggregates were different than the ones used for the field trial. This was most likely the cause for the granite. Two, a possible cause for the limestone aggregate is due to adherent fines. The coarse aggregate portion of the gradation contained some adherent fines, which produced a higher dust content when a washed gradation of the mix design blend was performed. The difference in the laboratory gradations may have also resulted in the difference in the optimum asphalt contents that were determined in the laboratory.

TABLE 3.2 Target Gradations and Asphalt Contents

	% Passing		
Sieve Size	JMF[1]	Granite	LMS[2]
19.0	100.0	99.0	100.0
12.5	90.0	87.9	90.9
9.5	83.0	79.9	83.6
4.75	52.0	49.6	52.7
2.36	34.0	32.2	32.6
1.18	25.0	23.6	23.7
0.600	19.0	18.6	17.5
0.300	13.0	14.7	12.3
0.150	5.0	5.3	6.0
0.075	2.9	2.9	3.1
AC, %	5.3	5.1	4.8

1: Job Mix Formula; 2: Limestone

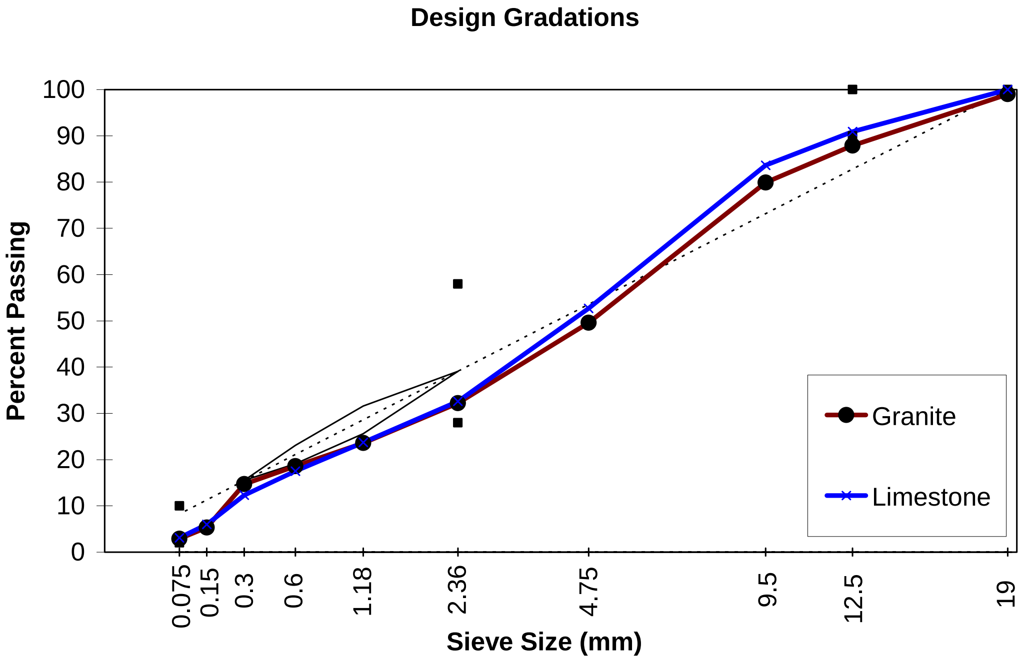

Figure 3.1. Target Gradations for Granite and Limestone Aggregates.

3.3 TEST PLAN

3.3.1 Mix Designs

As was mentioned earlier in this chapter, a single blend gradation was used for both aggregates. Based on the information obtained from the job mix formula from Hubbard Construction, the optimum asphalt content was 5.3 percent at the design gyration level of 125 gyrations. The asphalt content was adjusted slightly to achieve four percent air voids for the granite and limestone aggregates using the same design gyration level. Once the mix designs were performed at 300°F (149°C), each combination was then compacted at three lower temperatures (265, 230, and 190°F (129, 110, 88°C)). The mixing temperature was approximately 35°F (14°C) above the compaction temperature. This was done to determine the volumetric properties of each mixture combination at the different compaction temperatures evaluated.

3.3.2 Compactability

Once the optimum asphalt contents and volumetric properties for each aggregate/binder combination were determined, test samples were then produced to evaluate the different mixes' compactability over a range of temperatures. These test samples were prepared using oven dried aggregate. Before test samples were made, the anticipated number of test specimens were batched and then randomized for each of the different sets to eliminate potential bias in the test results.

The evaluation of each mixture combination's compactability was achieved by compacting a set of six samples per mix at the three lower temperatures mentioned previously (265, 230, and 190°F (129, 110, 88°C)), as well as a set compacted at 300°F (149°C). Again, the mixing temperature was approximately 35°F (14°C) above the compaction temperature. Each sample was aged for two hours at its corresponding compaction temperature prior to compaction. No coating problems were observed for any of the Warm Mix Asphalt processes. Test samples were compacted using a vibratory compactor, as seen in Figure 3.2. The vibratory compactor was selected for several reasons. One reason was that the literature suggested that the Superpave gyratory compactor was insensitive to temperature changes due to its constant strain behavior. A second reason was that it was found to be easier to produce samples for the Asphalt Pavement Analyzer (APA) with the vibratory compactor than with a Marshall hammer, both of which exhibit a constant stress type of behavior. A third reason was that the vibratory compactor applies a vertical load, frequency, and amplitude that is comparable to those found in a typical vibratory roadway compactor.

Test samples, 6 inches in diameter and 3.75 inches tall, were compacted in the vibratory compactor for a time period of 30 seconds. This was the length of time that produced an air void content of 7 percent in preliminary testing using the PG 64-22 control mixture with the granite aggregate. Once the air void content was determined, these same samples were then used to determine the resilient modulus and APA rut resistance of each mix at the various compaction temperatures.

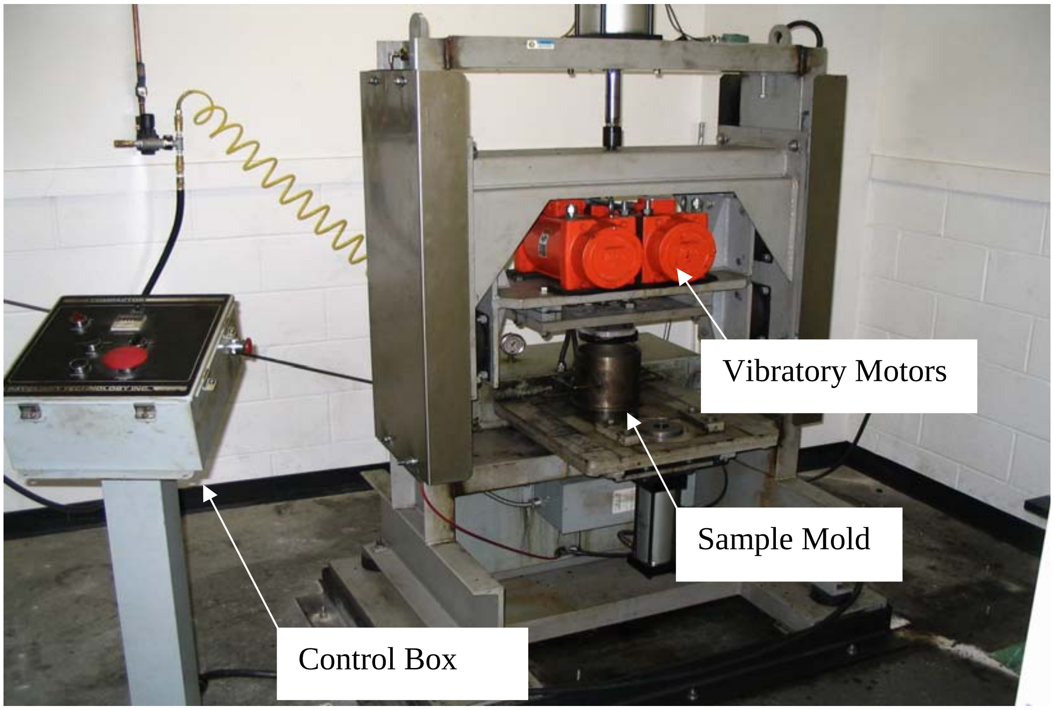

Figure 3.2. Vibratory Compactor used for Compaction of Test Samples.

3.3.3 Resilient Modulus

Resilient modulus is a measure of the stiffness of the hot mix asphalt. The resilient modulus was determined according to ASTM D4123, *Indirect Tension Test for Resilient Modulus of Bituminous Mixtures*. The testing was conducted at 73°F (23°C) as recommended by Lottman (*62*). Resilient modulus was selected as the test method to determine mixture stiffness over the dynamic modulus mainly because of the time factor. Resilient modulus can be determined relatively quickly, where as the dynamic modulus is time intensive. Since resilient modulus is also a non-destructive test, additional testing was conducted on the same set of test samples for each mix combination.

3.3.4 APA Rutting

Once the resilient modulus testing was completed, each mixture set was placed in the APA to determine the rut resistance of each Warm Mix Asphalt mixture combination for the different compaction temperatures. All testing was conducted at 147°F (64°C). Testing was conducted using a hose pressure of 120 psi and a vertical load of 120 pounds, based on recommendations from previous research (*53*).

3.3.5 Indirect Tensile Strength

An evaluation of indirect tensile strength change with time was also conducted because of the possible changes in the stiffness of the asphalt due to the lower operating temperatures from the inclusion of Warm Mix Asphalt additives. This was done to address the concern that the workability of the mixture would not dissipate prior to being opened to traffic, thus creating the potential for rutting. Ten samples of each mix were prepared for short-term and long-term mix aging per AASHTO PP2. The mixing temperature was approximately 275°F (135°C). Mixture strength was evaluated based on indirect tensile strength at 77°F (25 °C). The indirect tensile strength of an asphalt mixture is sensitive to binder (or mastic) stiffness. Indirect tensile strength testing was performed on samples after the aging periods shown in Table 3.3.

TABLE 3.3 Indirect Tensile Strength Experiment Aging Periods

Set	Short Term Aging (hours) at 250°F (121 °C) (prior to compaction)	Long Term Aging (days) of Compacted Samples at 185°F (85 °C)
1	2	0
2	4	0
3	2	1
4	2	3
5	2	5

3.3.6 Moisture Resistance

If the moisture contained in the aggregate does not completely evaporate during mixing due to the lower mix temperatures, water may be retained in the aggregate which could in turn lead to increased susceptibility to moisture damage. Therefore, test samples were produced and tested according to ASTM D4867, *Effect of Moisture on Asphalt Concrete Paving Mixtures*, to assess the potential for moisture susceptibility of each mixture combination. The ASTM procedure is similar to the AASHTO T283 procedure except for the aging times.

To simulate the actual mixing process of a typical drum plant, a bucket mixer and a propane torch were used to heat the aggregate and mix the samples for making the TSR test samples. This was selected based on a methodology developed to study the effects of residual moisture on compaction, primarily for tender mixes (*63*). The bucket mixer used can be seen in Figure 3.3. Before the aggregate was combined with the binder, three percent water in addition to the absorption value of each aggregate was added to the mix before it was heated. For example, the granite aggregate had an absorption value of 1.1 percent, so a total of 4.1 percent water by aggregate weight was added to the oven dry material before the binder was added.

The addition of the aggregate to the bucket mixer took place in two steps because it was found that when the entire gradation was added at once, by the time the aggregate was heated to the mixing temperature of 275°F (135°C), all of the fine material had moved to the bottom of the bucket. This caused a problem with inadequate coating of the fine material. This was alleviated by adding the coarse and fine aggregate separately. The appropriate percentage of moisture was added to the fine aggregate portion, and then was set aside. The coarse aggregate was added to the bucket, and the appropriate percentage of moisture was introduced to the coarse aggregate (Figure 3.3) and then it was heated to 250°F (121°C) (Figure 3.4). Then the fine aggregate portion was added to the bucket and the aggregate was heated with the propane torch back to the intended mixing temperature. When this temperature was reached, the dust proportion of the blend and the binder was added to the bucket, mixing continued until the aggregates were thoroughly coated. Each bucket mix produced three test samples. During the mixing process, some temperature was lost, so each test sample was placed in an oven until the compaction temperature (250°F (121°C)) was reached, usually about 10-15 minutes. Compaction was achieved using the Superpave Gyratory Compactor, with a target air void content of 7 ± 1 percent. This process is shown in Figures 3.3-3.5.

Figure 3.3. Introduction of Moisture to Aggregate for TSR Samples.

Figure 3.4. Heating of Wet Aggregate to Mixing Temperature.

Figure 3.5. Warm Mix Asphalt in Bucket Mixer.

3.3.7 Hamburg Wheel Tracking Device

As a second method for evaluating moisture damage potential, test samples were prepared and tested in the Hamburg Wheel Tracking Device. This test has been found to be sensitive to several factors, including asphalt cement stiffness, length of short-term aging, compaction temperature, and anti-stripping treatments (*61*). All these factors have previously been observed as possible problem areas in the evaluation of Warm Mix Asphalt, so the test results generated from the Hamburg Wheel Tracking Device were thought to be vital in accurately establishing a good performing Warm Mix Asphalt.

Test samples were produced using the Superpave Gyratory Compactor. Individual compacted gyratory samples of 95 mm in height were then saw cut to produce two 40 mm tall samples with an air void content of 7 ± 1 percent. Duplicate test samples of each mixture combination were then evaluated in the Hamburg Wheel Tracking Device. Testing was performed at a temperature of 122°F (50°C).

CHAPTER 4: RESEARCH DATA AND ANALYSIS

4.1 MIX DESIGN

Volumetric properties of the SGC compacted specimens for each of the 32 mix design combinations (one binder grade, two aggregates, three processes and one control mix type, and four compaction temperatures) are presented in Tables 4.1 and 4.2. Individual results for each data set are presented in Tables 4.1 and 4.2 are reported in Appendix A. The data for both aggregates with Sasobit® compacted at 190°F (88°C) were not obtained due to a limited quantity of the binder. It was decided not to acquire additional binder to prevent any variability due to different binder sources. From the results of the mix design verifications using the control mixtures, asphalt contents of 5.1 and 4.8 percent were determined for the granite and limestone aggregate, respectively. These asphalt contents were used throughout the study.

TABLE 4.1 Volumetric Mix Design Data for Granite Aggregate

Process	Temperature, F	AC, %	G_{mm}	% G_{mm} @ N_i	G_{mb}	Air Voids, %	VMA	VFA
Control	300	5.1	2.467	88.0	2.365	4.1	13.6	69.6
Control	265	5.1	2.467	88.2	2.371	3.9	13.3	71.0
Control	230	5.1	2.467	87.7	2.360	4.4	13.8	68.4
Control	190	5.1	2.467	87.5	2.356	4.5	13.9	67.6
Aspha-min®	300	5.1	2.457	88.8	2.376	3.3	13.9	76.4
Aspha-min®	265	5.1	2.457	88.9	2.382	3.0	13.6	77.7
Aspha-min®	230	5.1	2.457	88.7	2.378	3.2	13.1	75.5
Aspha-min®	190	5.1	2.457	88.3	2.368	3.6	13.5	73.2
Sasobit®	300	5.1	2.461	88.4	2.375	3.5	13.9	74.8
Sasobit®	265	5.1	2.461	88.0	2.377	3.4	13.8	75.5
Sasobit®	230	5.1	2.461	88.0	2.360	4.1	14.4	71.7
Sasobit®	190	5.1	2.461	NA	NA	NA	NA	NA
Evotherm®	300	5.1	2.465	88.7	2.389	3.1	12.7	75.7
Evotherm®	265	5.1	2.465	88.5	2.387	3.2	12.8	75.2
Evotherm®	230	5.1	2.465	88.4	2.384	3.3	12.9	74.5
Evotherm®	190	5.1	2.465	88.6	2.390	3.0	12.7	76.0

NA = No Data Available

TABLE 4.2 Volumetric Mix Design Data for Limestone Aggregate

Process	Temperature, F	AC, %	G_{mm}	% G_{mm} @ N_i	G_{mb}	Air Voids, %	VMA	VFA
Control	300	4.8	2.544	85.4	2.433	4.4	15.0	70.8
Control	265	4.8	2.544	85.1	2.430	4.5	15.1	70.3
Control	230	4.8	2.544	85.3	2.435	4.3	14.9	71.3
Control	190	4.8	2.544	85.5	2.439	4.1	14.8	72.1
Aspha-min®	300	4.8	2.544	85.8	2.442	4.0	14.7	72.8
Aspha-min®	265	4.8	2.544	85.8	2.449	3.7	14.4	74.3
Aspha-min®	230	4.8	2.544	85.7	2.444	3.9	14.6	73.2
Aspha-min®	190	4.8	2.544	84.8	2.418	4.9	15.5	68.2
Sasobit®	300	4.8	2.545	86.1	2.459	3.4	14.1	76.1
Sasobit®	265	4.8	2.545	86.3	2.463	3.2	14.0	76.7
Sasobit®	230	4.8	2.545	86.3	2.465	3.1	13.9	77.4
Sasobit®	190	4.8	2.545	NA	NA	NA	NA	NA
Evotherm®	300	4.8	2.547	86.0	2.472	3.0	13.6	78.4
Evotherm®	265	4.8	2.547	85.6	2.458	3.5	14.1	75.3
Evotherm®	230	4.8	2.547	86.2	2.477	2.8	13.5	79.6
Evotherm®	190	4.8	2.547	85.2	2.451	3.8	14.4	73.9

NA = No Data Available

Tables 4.1 and 4.2 indicated that the different processes had little effect on the maximum specific gravity (G_{mm}) of the mixture. Previous research has indicated that the Superpave gyratory compactor (SGC) was insensitive to compaction temperature (*64*, *65*). In Tables 4.1 and 4.2 there are very slight trends of increasing air voids with decreasing temperature for some of the combinations. An Analysis of Variance (ANOVA) test was conducted on the gyratory data to better assess the effect of compaction temperature. The results are shown in Table 4.3. These data show that for each Warm Mix Asphalt additive and the control mix, the results were not sensitive to the change in compaction temperature using the SGC. It can also be seen from the data that the different additives are significant in the laboratory densification of hot mix asphalt. Based on the reduction of air voids and VMA for each of the WMA additives, it can be estimated that the optimum asphalt content would be reduced by 0.1 to 0.5 percent for the WMA mixtures. Similar reductions in air voids were noted in previous research on Sasobit® (*26*). However, as stated previously, the asphalt contents presented in Table 3.2 were used for the production of the remaining test samples to reduce the number of variables.

TABLE 4.3 ANOVA Results for Gyratory Data

Source	DF	Adj. MS	F-stat	p-value	Significant[1]
Temperature	2	0.0154	0.14	0.872	No
Additive	3	1.3526	12.16	0.000	Yes
Aggregate	1	0.0704	0.63	0.437	No
Error	17	0.1112			
Total	23				

[1] Significant at the 95 percent confidence interval ($\alpha = 0.05$)

4.2 COMPACTABILITY

As described in Chapter 3, samples were compacted in the vibratory compactor over a range of temperatures. The average densification results for both the granite and limestone mixes are shown in Figures 4.1 and 4.2. Complete test results are presented in Appendix B. The results in Figures 4.1 and 4.2 show that the addition of Aspha-min®, Sasobit®, and Evotherm® improved compaction over the control mixture for all binder, aggregate, and temperature combinations. Figure 4.1 shows that the air void content for the control mixtures increased when the mix temperature was lowered from 300°F (149°C) to 265°F (129°C), but did not increase at the lower compaction temperatures. This was thought to be due to less aging of the binder at the lower temperature, or possibly from the coarse nature of the mix. To verify if the coarse nature of the mix had an influence on the densification of the mixtures, a fine gradation was evaluated in the vibratory compactor at the different compaction temperatures, and their corresponding air voids was determined. Figure 4.3 presents the gradation used to evaluate the fine mixture. The results from this evaluation are shown in Figure 4.4 and indicated a gradual increase in the air void content with the decrease in compaction temperature. The coarse nature of the mix is hence believed to have some influence in the fluctuation of the densification at the lower compaction temperatures. The test results for the fine gradation can be seen in Appendix B.

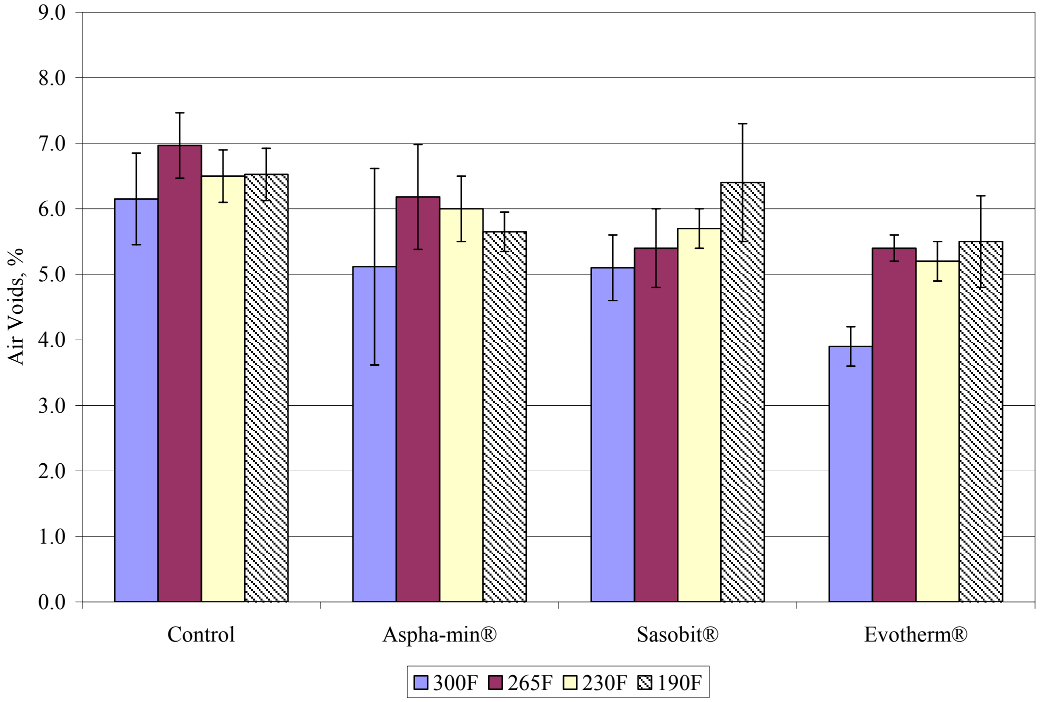

Figure 4.1. Densification Results over Range of Compaction Temperatures – Granite Mix.

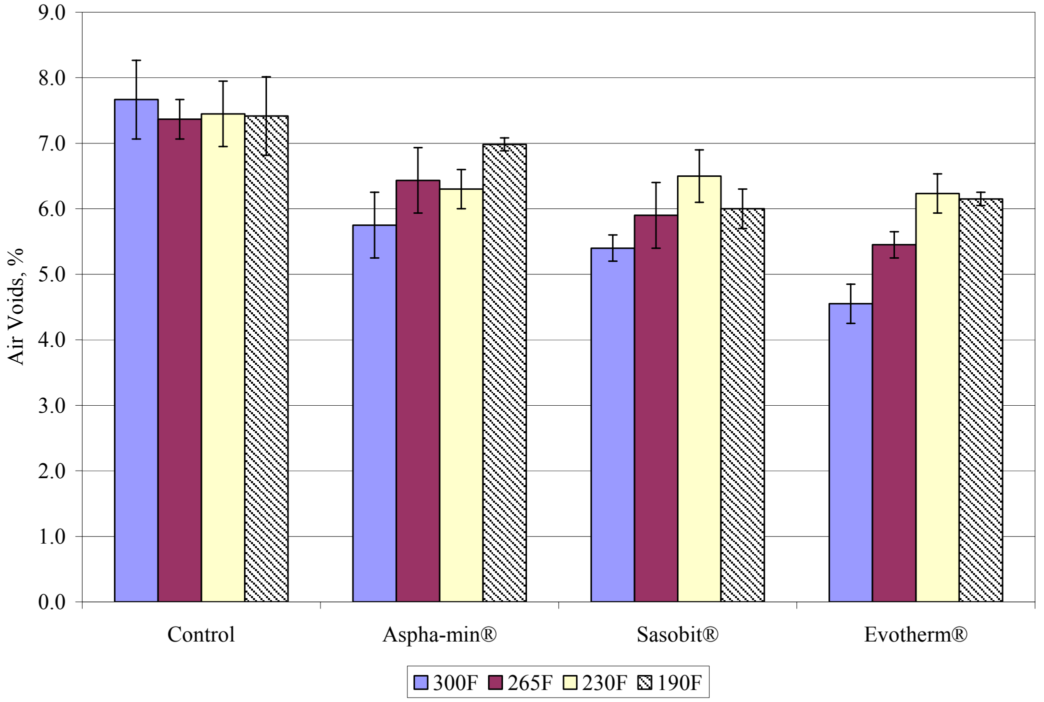

Figure 4.2. Densification Results over Range of Compaction Temperatures – Limestone Mix.

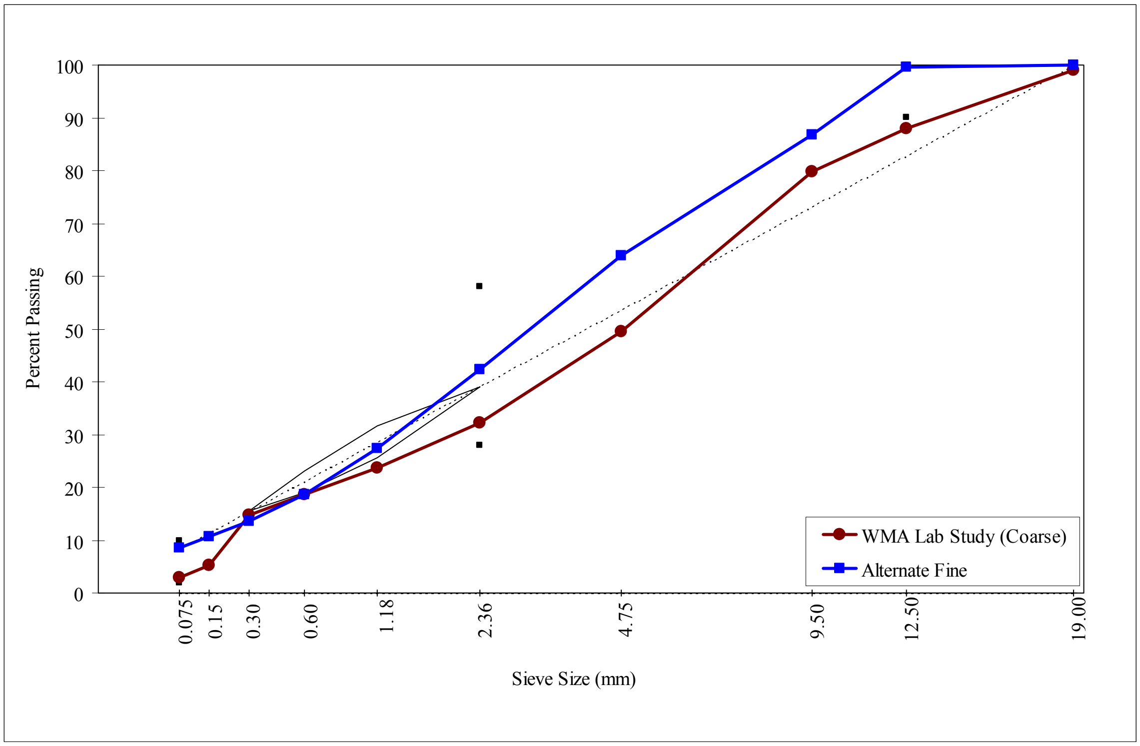

Figure 4.3. Comparison of Coarse and Fine Mix Gradations.

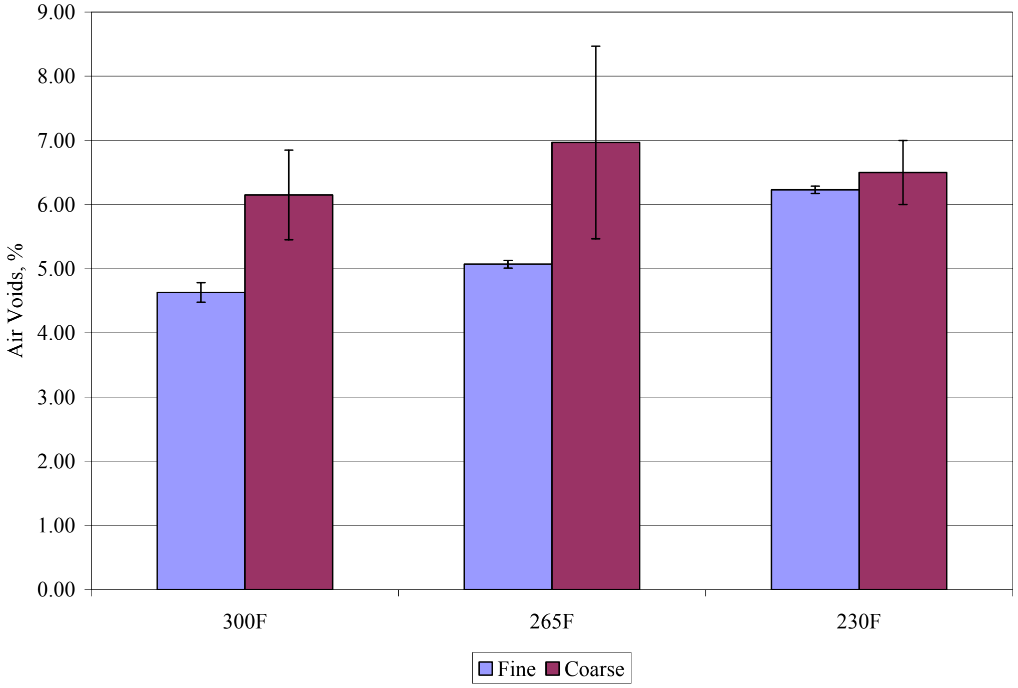

Figure 4.4. Densification Results over Range of Compaction Temperatures – Fine Graded Mix (No WMA Additive).

An ANOVA was conducted to analyze the densification data with air voids as the response variable and aggregate type, presence of additive, and compaction temperature as factors. The results from the ANOVA are presented in Table 4.4. From the results, all factors along with all possible interactions are statistically significant.

TABLE 4.4 ANOVA Results for Densification

Source	DF	Adj. MS	F-stat	p-value	Significant[1]
Temp	3	8.8115	31.33	0.000	Yes
Additive	3	18.8782	67.13	0.000	Yes
Agg	1	28.5208	101.42	0.000	Yes
Temp*Additive	9	2.2346	7.95	0.000	Yes
Temp*Agg	3	1.3168	4.68	0.004	Yes
Additive*Agg	3	1.4257	5.07	0.002	Yes
Temp*Additive*Agg	9	0.5641	2.01	0.042	Yes
Error	160	0.2812			
Total	191				

[1] Significant at the 95 percent confidence interval (α = 0.05)

A Tukey's post-ANOVA test was then conducted on the data for several reasons. One was to compare the different additives to the control and to each other, to see if any additive was statistically different from another additive. A second reason was to determine how much each additive lowered the air void content, based on the fact that the optimum asphalt content might be altered by the addition of a Warm Mix Asphalt additive, discussed earlier in the report. Based on the results from the Tukey's test, Evotherm® lowered the air void content the most, with Sasobit® next, and Aspha-min® lowered the air void content the least. Statistically speaking, all additives significantly lowered the air void content, compared to the control. The statistical analysis results can be seen in Appendix H.

Interaction plots for the densification data are shown in Figure 4.5. Interaction plots are one way to graphically visualize the data. From these plots, a couple of observations can be made. One, the granite aggregate consistently produced lower air void contents, based on both compaction temperature and the presence of any additive. And two, Evotherm® produced lower air void contents over the range of compaction temperatures.

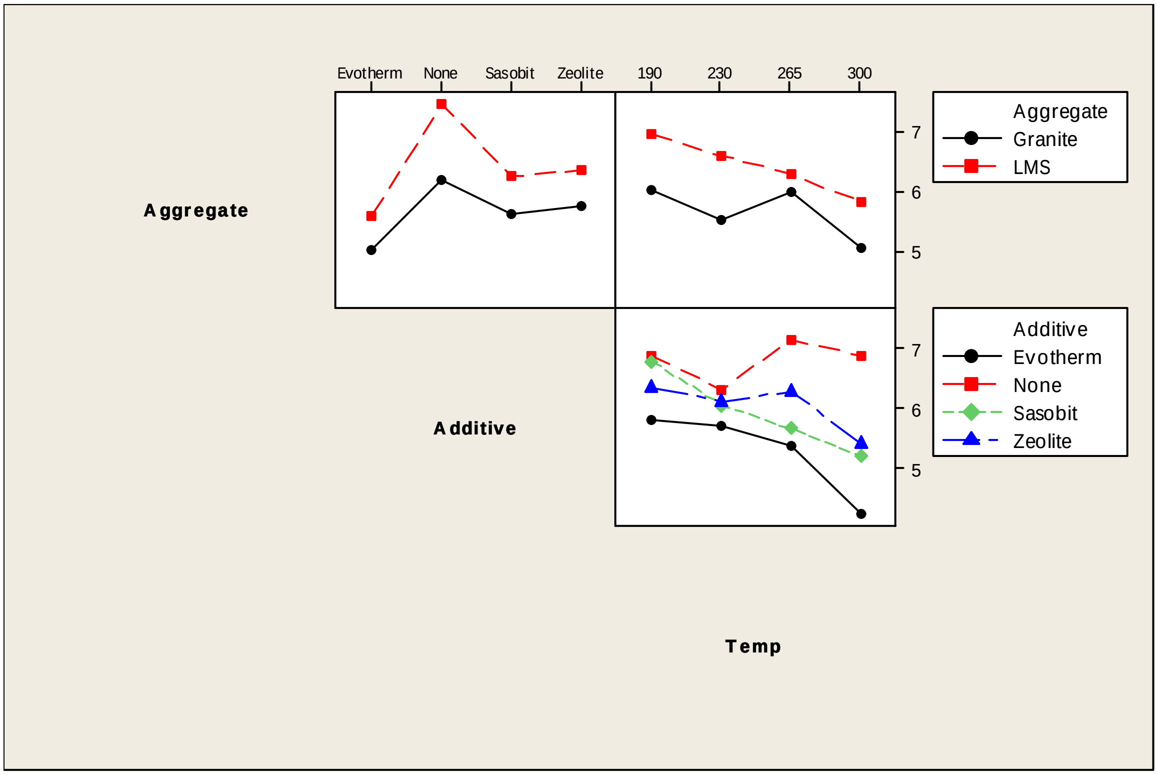

Figure 4.5. Interaction Plots for Densification Data.

As can be seen from the statistical data contained in Appendix H, the Evotherm® lowered the air void content by an average of 1.5 percent, with a 95 percent confidence interval of 1.2 to 1.8 percent. The Sasobit® lowered the air void content by 0.9 percent, with a 95 percent confidence interval of 0.6 to 1.2 percent. Aspha-min® lowered the air void content by an average of 0.8 percent, with a 95 percent confidence interval of 0.5 to 1.1 percent. All results were compared to the control mixtures data compacted at 300°F (149°C). It is ultimately believed that the addition of any additive will ease the field compaction of hot mix asphalt, based upon the statistical findings from the densification data.

4.3 RESILIENT MODULUS

An ANOVA was performed to determine which factors (aggregate type, additive, and compaction temperature) significantly affected the measured resilient modulus. These results are presented in Table 4.5. Based on the results, only two factors (compaction temperature and additive) and two interactions (between compaction temperature and additive and between additive and aggregate type) had a significant effect on the resilient modulus.

TABLE 4.5 ANOVA Results for Resilient Modulus

Source	DF	Adj. MS	F-stat	p-value	Significant[1]
Temp	3	5.68E+10	5.51	0.001	Yes
Additive	3	2.96E+10	2.87	0.038	Yes
Agg	1	2.23E+10	2.16	0.143	No
Temp*Additive	9	2.90E+10	2.81	0.004	Yes
Temp*Agg	3	7.92E+09	0.77	0.514	No
Additive*Agg	3	4.08E+10	3.96	0.009	Yes
Temp*Additive*Agg	9	1.18E+10	1.14	0.336	No
Error	160	1.03E+10			
Total	191				

[1] Significant at the 95 percent confidence interval (α = 0.05)

Tukey's post-ANOVA test was conducted on the resilient modulus data to compare the different additives to the control and to each other, as was done for the densification data. From these results, located in Appendix H, it was observed that Evotherm® increased the measured resilient modulus the most, with Aspha-min® next. Sasobit® actually decreased the measured resilient modulus, according to the data. However, none of the additives significantly affected the measured resilient modulus values, one way or the other, based on the Tukey's rankings.

Interaction plots for the measured resilient modulus data are shown in Figure 4.6. Interaction plots are just another way to graphically visualize the data. From these plots, a couple of observations can be made. First, the limestone aggregate consistently produced higher resilient modulus values for two of the three additives and over the range of compaction temperatures. And second, Evotherm® produced higher resilient modulus values over the range of compaction temperatures, except for the 300°F (149°C) compaction temperature. Several attempts were made to try and explain the scatter in the data for the WMA additives at the 300°F (149°C) compaction temperature. First, Grubbs Test (*66*) was performed to try and identify any outliers in the data for the Sasobit® and Aspha-min® mixtures; the results indicated that no outliers existed in the data for the two additives. Then a comparison was conducted between air voids and resilient modulus to try and determine if the density of the compacted samples had any influence on the resilient modulus. This can be seen graphically in Appendix C. The results indicated that for the data obtained, no relationship existed between density and resilient modulus at the 300°F (149°C) compaction temperature. Additional research is needed to validate the collected data for the Sasobit® and Aspha-min® mixtures at the 300°F (149°C) compaction temperature.

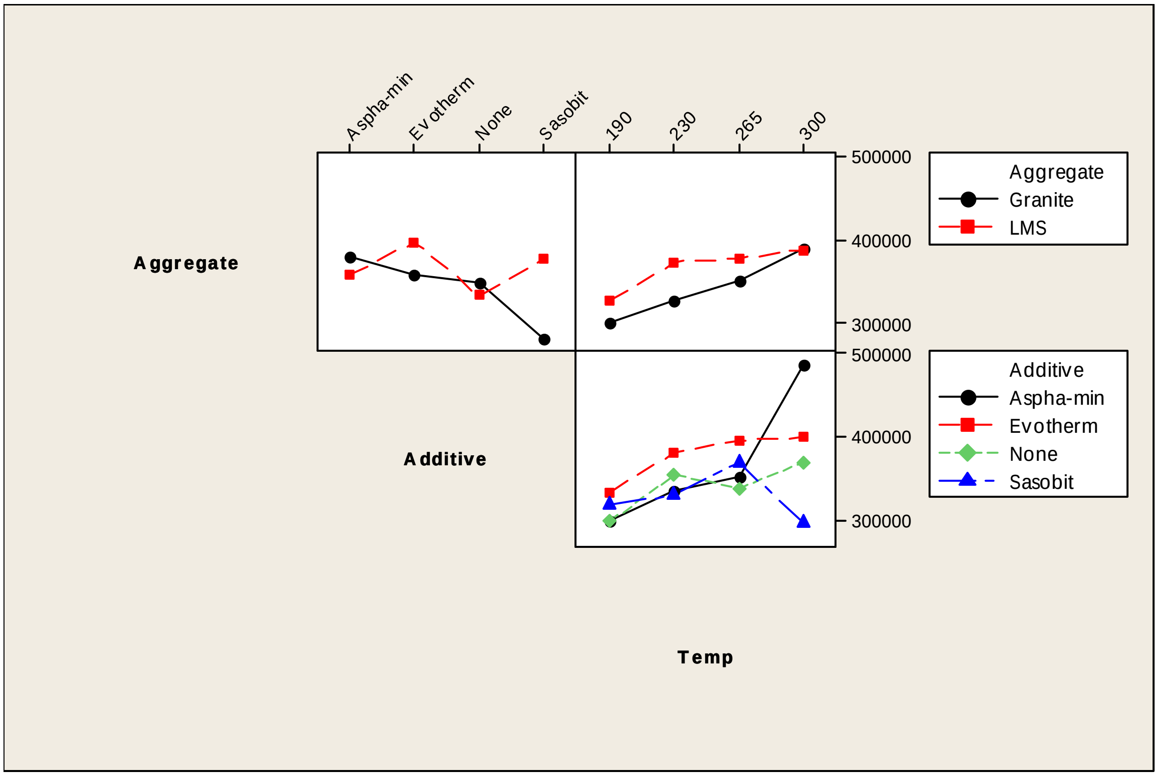

Figure 4.6. Interaction Plots for Resilient Modulus.

4.4 ASPHALT PAVEMENT ANALYZER

Once each set of test samples was tested to determine its resilient modulus value, it was placed in an oven at 147°F (64°C) for a minimum of six hours to ensure that it was equilibrated to the APA test temperature. Each set was then placed in the Asphalt Pavement Analyzer to determine their rutting potential at a temperature of 147°F (64°C). The average rutting results for the granite and limestone aggregates are shown in Figures 4.7 and 4.8. The whisker marks represent the standard deviation of each data set.

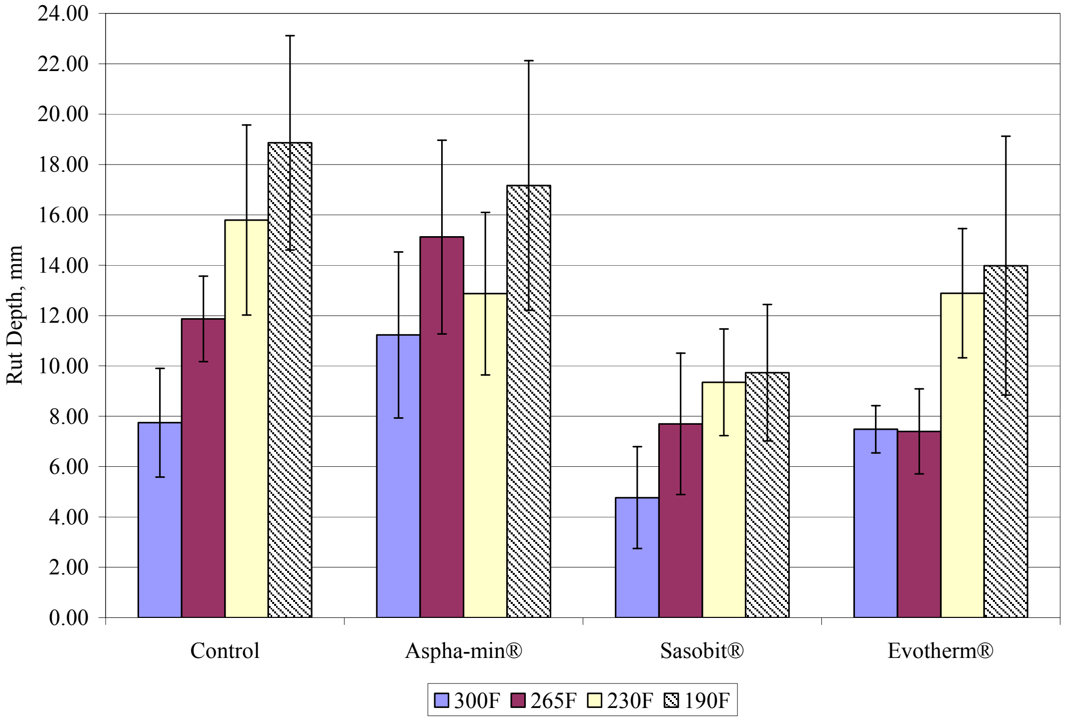

Figure 4.7. APA Rutting Results for Granite Aggregate.

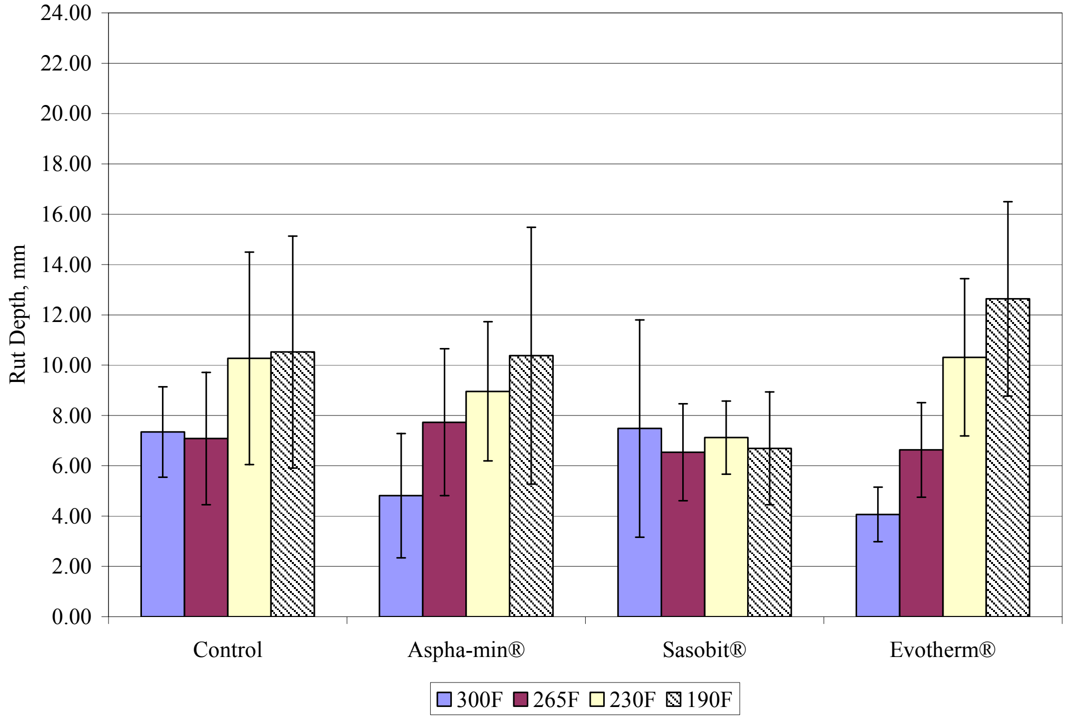

Figure 4.8. APA Rutting Results for Limestone Aggregate.

From the data contained in Tables 4.7 and 4.8, several observations were made. One, as the compaction temperature decreased, the rutting increased. This was most likely due to the decreased aging of the binder. And two, the limestone aggregate, on average, had lower rut depths compared to the granite aggregate. This was possibly due to the higher binder content for the granite aggregate and/or the higher dust content with the limestone aggregate.

ANOVA results from the rutting data are presented in Table 4.6. Based on these results, all factors and interactions except for the one three-way interaction between compaction temperature, additive, and aggregate type were found to be significant factors.

TABLE 4.6 ANOVA Results for APA Rutting

Source	DF	Adj. MS	F-stat	p-value	Significant[1]
Comp. Temp.	3	483.59	36.64	0.000	Yes
Additive	3	37.67	2.85	0.039	Yes
Agg	1	591.93	44.85	0.000	Yes
Comp.Temp.*Additive	9	32.23	2.44	0.012	Yes
Comp. Temp.*Agg	3	40.73	3.09	0.029	Yes
Additive*Agg	3	64.88	4.92	0.003	Yes
Comp. Temp.*Additive*Agg	9	24.82	1.88	0.058	No
Error	160	13.20			
Total	191				

[1] Significant at the 95 percent confidence interval ($\alpha = 0.05$)

A Tukey's post-ANOVA test was performed on the rutting results to determine how much the WMA additives would, if any, decrease the measured rut depths, compared to the control mixture. The results from the Tukey's suggested that the Evotherm® lowered the rut depths the most (by an average of 1.8 mm); Sasobit® decreased the rut depths by 1.4 mm, while the Aspha-min® decreased the rutting potential by an average of 0.2 mm. However, none of the additives significantly increased or decreased the rutting potential compared to rutting results from the hot mix asphalt control samples at all compaction temperatures, based on Tukey's rankings. The complete statistical analysis is presented in Appendix H.

Interaction plots for the measured rutting data are shown in Figure 4.9. From these plots, a couple of observations can be made. First, the limestone aggregate consistently produced lower rutting values for all mixtures for all compaction temperatures. And second, the additives produced lower rutting values over the range of compaction temperatures, except for the Aspha-min® at the 265°F (129°C) compaction temperature, but this may be caused by variability in the test data.

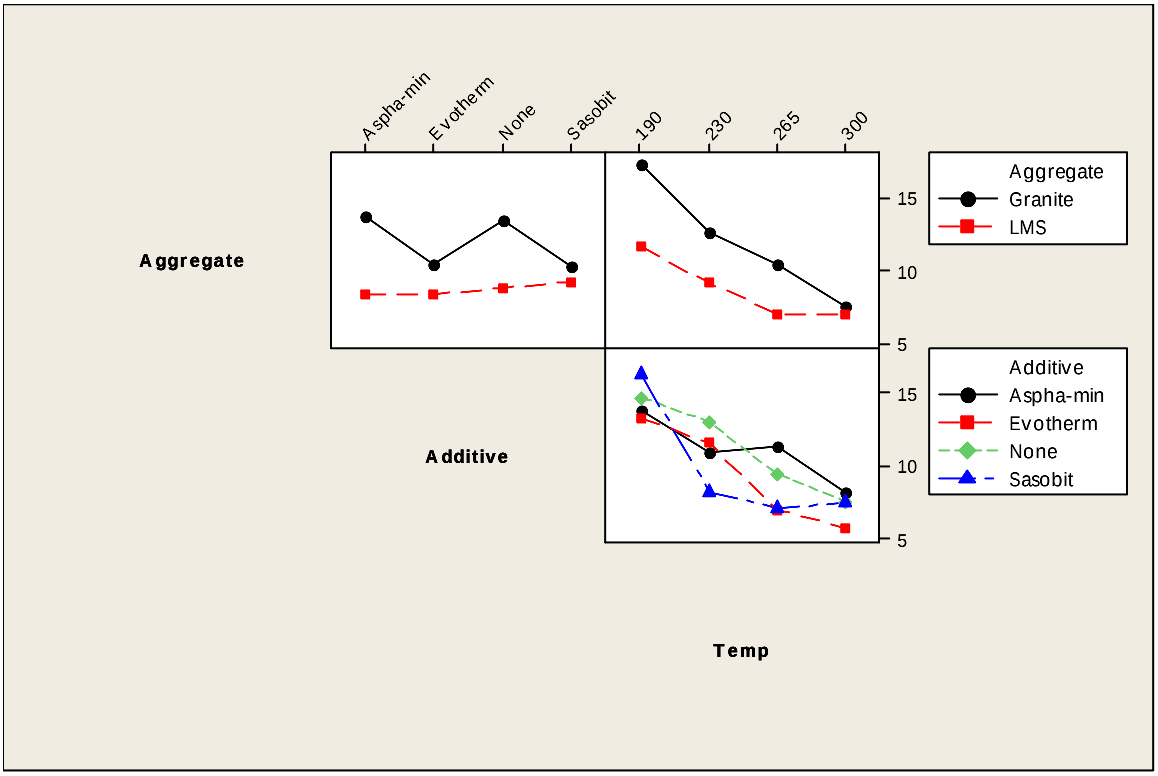

Figure 4.9. Interaction Plots for APA Rutting.

4.5 INDIRECT TENSILE STRENGTH

The indirect tensile strength experiment was conducted to evaluate the rutting potential immediately after construction. The average results from the strength gain experiment for both aggregates are presented in Figures 4.10 and 4.11. The results generally showed that the tensile strengths decreased at the first long term aging period, compared to the tensile strengths from only short term aging. This was possibly due to the testing procedure used; no confinement was used to prevent possible slumping of the samples during the aging process. Even though these tensile strengths varied over the range of aging periods, there was no statistical difference in the tensile strengths between the control mixture and either the Aspha-min® or Evotherm® mixtures. This can be seen from the statistical data in Table 4.7. This suggests that there is no evidence to support the need for a cure time before traffic can be allowed on an asphalt mixture containing Aspha-min® or Evotherm®.

TABLE 4.7 Two Sample t-Test Results for Tensile Strength

	Control	*Aspha-min®*	*Sasobit®*	*Evotherm®*
Mean	97.167	99.350	63.668	103.615
Variance	553.253	360.398	247.703	786.049
Observations	9	10	10	9
Hypothesized Mean Difference	0			
Degrees of Freedom		15	14	16
t Statistic		-0.221	3.607	-0.529
P(T<=t) one-tail		0.414	0.001	0.302
t Critical one-tail		1.753	1.761	1.746
P(T<=t) two-tail		0.828	0.003	0.604
t Critical two-tail		2.131	2.145	2.120

The data for the Sasobit® generally indicated reduced tensile strength, except for the long term aging samples for the limestone aggregate. Statistical results from Table 4.7 indicated that there was a significant difference in tensile strengths between the control mixture and the Sasobit® mixture, over the range of aging periods. This indicates that, based on the laboratory data, a cure time may be beneficial for the Sasobit® mixture before opening to traffic. However, previous research conducted at 41°F (5°C) on a Stone

Matrix Asphalt (SMA) mixture containing Sasobit® indicated no difference in tensile strength between the control and Sasobit® mixes (*67*).

Based on the rutting data discussed earlier, there is no evidence to support the need for a cure time before traffic can be allowed on the asphalt mixture containing Sasobit®. This is consistent with the reported congealing point (212°F (100°C)) for Sasobit® (*26*). Schumann Sasol (now Sasol Wax) reported that a project in Italy was opened to traffic five hours after paving began (*68*). Sasobit® was also used in the repaving of the main runway at the Frankfurt, Germany airport. Twenty-four inches of HMA was placed in a 7.5 hour period. The runway was then reopened to jet aircraft at a temperature of 185 °F (85°C) (*69*).

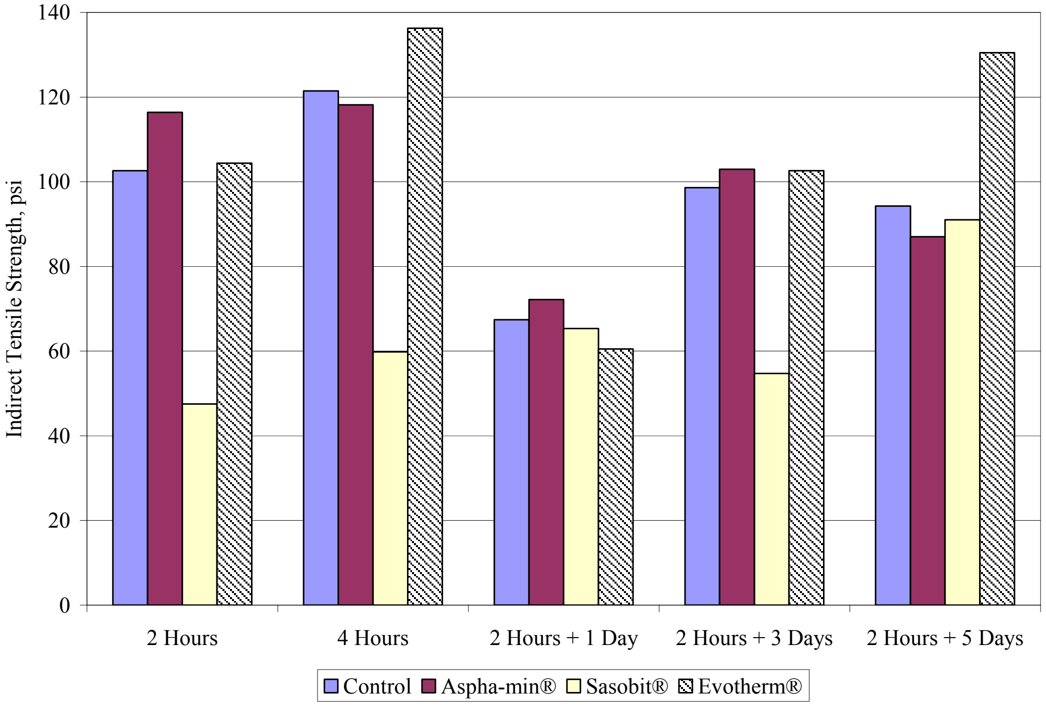

Figure 4.10. Tensile Strength Results – Granite.

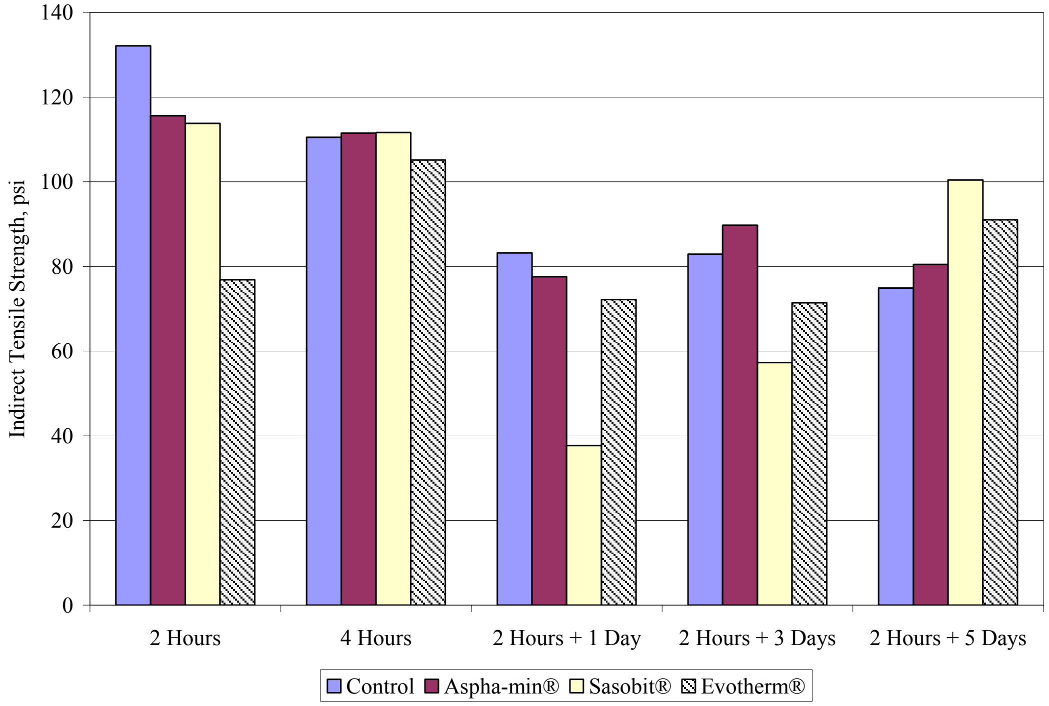

Figure 4.11. Tensile Strength Results – Limestone.

4.6 MOISTURE RESISTANCE

As was mentioned in Chapter 3, ASTM D 4867 was used to determine the moisture sensitivity test results. A compaction temperature of 250°F was selected based on compaction, resilient modulus, and rutting results to be an acceptable temperature for all three WMA technologies. The TSR results for both aggregates are shown in Table 4.8. Also included in Table 4.8 are test results from samples that were prepared using oven dried aggregate and compacted in the gyratory compactor after being aged at 300°F (149°C) for two hours. This testing was conducted to see what kind of behavior the additives exhibited in the mixture. From the test results for samples prepared with oven dried aggregate, the presence of Aspha-min® decreased the TSR value, but still resulted in an acceptable value.

TABLE 4.8 Tensile Strength Results for Granite and Limestone

Aggregate	Mix Type	Indirect Tensile Strength		TSR, %
		Unsaturated, psi	Saturated, psi	
Granite	Control	126.6	123.4	0.97[1]
Granite	Aspha-min®	155.0	126.3	0.81[1]
Granite	Control	75.9	80.9	1.07
Granite	Aspha-min®	72.5	48.7	0.67
Granite	Sasobit®	53.2	38.0	0.71
Granite	Evotherm®	70.8	67.7	0.96
Limestone	Control	109.5	71.2	0.65
Limestone	Aspha-min®	86.6	44.2	0.51
Limestone	Sasobit®	53.9	49.1	0.91
Limestone	Evotherm®	75.0	46.8	0.62

[1] Samples were prepare in SGC following ASTM D 4867 at 300°F compaction temperature

Once this testing was concluded, TSR samples were then produced at a lower compaction temperature (250°F (121°C)) using the bucket mixer, previously discussed in Chapter 3. These results are presented in Table 4.8. Initially, testing was performed without the presence of any type of anti-stripping agent. Results from this testing showed that the Aspha-min® lowered the TSR value as compared to the control mixture; the resulting TSR value does not satisfy the recommended minimum value for Superpave mixes (minimum of 0.80). The test results also exhibited some variability in the data from one aggregate type to the next. For example, the Sasobit® increased the resistance to moisture for the limestone, but decreased the resistance for the granite, compared to their corresponding control mixes, whereas the Evotherm® did the opposite; increasing the TSR value with the granite aggregate and decreasing the TSR with the limestone aggregate, compared to the corresponding control. It is believed that the testing precision is decreased when the tensile strength values are low, which is apparent by the data presented in Table 4.8.

Figure 4.12 presents a sample containing Aspha-min® exhibiting a cohesive failure. It is believed that the binder was somewhat emulsified due to the moisture released from the Aspha-min®, causing the cohesive failure. It is possible that a cure time would dissipate the moisture in the binder, eliminating the potential of a cohesive failure.

In Figure 4.13, the conditioned control sample exhibited an adhesive failure. But the unconditioned control samples also exhibited visual stripping resulting from adhesive failures. It is expected that the adhesive failure resulted from moisture remaining in the aggregate from the lower mixing and compaction temperature. However, the cohesive failure in the samples containing the Aspha-min® resulted in lower tensile strengths.

Figure 4.12. Example of Cohesive Stripping Failure – Granite.

Figure 4.13. Example of Adhesive Stripping Failure – Granite.

4.6.1 Treatment Options

It is believed that the failing TSR values were possibly due to several factors, those being moisture retained in the aggregate, or due to residual moisture left behind by the microscopic foaming process of the Aspha-min®. To evaluate these hypotheses, additional TSR tests were conducted with the granite aggregate as shown in Table 4.9.

4.6.1.1 Oven Dry Aggregate

To determine if the lower TSR values were caused by moisture in the aggregate, TSR testing was conducted using oven dry aggregate. The aggregate was placed in a 250°F (121°C) oven prior to mixing to make sure there was no internal moisture present. Test results from the oven dry aggregate also resulted in failing TSR values; therefore the decrease in tensile strength is not believed to be solely due to internal aggregate moisture.

4.6.1.2 Liquid Anti-stripping Agents

To determine if the moisture resistance could be increased, anti-stripping agents were then evaluated. First, one type of liquid anti-stripping agent, ARMAZ LOF 6500, was used with the control and Aspha-min® mixtures. This additive is routinely used with the granite aggregate source. For the control mixture, the liquid anti-strip visually reduced the adhesive failure, increased the unconditioned tensile strengths while the conditioned tensile strengths remained the same as the control mixture without liquid anti-strip. For the mixture with Aspha-min®, the liquid anti-strip increased the unconditioned tensile strengths, but it decreased the conditioned tensile strengths, thus resulting in a low TSR value (0.38). The decrease in the saturated tensile strength may possibly be the result of a reduction in binder viscosity from the liquid anti-stripping agent.

Regarding the Sasobit®, Sasol Wax recommended adding a liquid anti-stripping agent that has been commonly used in commercial paving applications. Kling Beta 2912 is manufactured by AKZO Nobel and is more commonly known as Magnabond. Additional TSR testing was conducted using Magnabond at 0.4 percent by weight of binder. These test results are also included in Table 4.9. The results indicated a substantial increase in the TSR value, compared to the test results from the PG 64-22 binder with only Sasobit® added. The additional TSR testing using the liquid anti-stripping agent resulted in an acceptable value, based on Superpave requirements. However, the individual tensile strengths (both unsaturated and saturated) were substantially lower than the other strengths obtained.

TABLE 4.9 Additional Tensile Strength Results for Granite Aggregate

Anti-Stripping Additive	Mix Type	Indirect Tensile Strength		TSR
		Unconditioned, psi	Conditioned, psi	
None	Aspha-min®; Oven Dry Aggregate	67.2	40.4	0.60
0.75% LOF 6500	Control	104.7	90.5	0.86
0.75% LOF 6500	Aspha-min®	96.0	36.2	0.38
1% Lime	Aspha-min®	110.6	85.5	0.77
1.5% Lime	Aspha-min®; Two-stage addition	79.9	69.3	0.87
1.5% Lime	Aspha-min®; All Added Dry	90.2	67.3	0.75
0.4% Magnabond	Sasobit®	17.5	16.5	0.94
None	Evotherm®; New LMS Formula	85.6	93.9	1.10

4.6.1.3 Hydrated Lime

Hydrated lime was then evaluated. Hydrated lime was used in two different percentages (1 and 1.5 percent), while for the 1.5 percent hydrated lime, the mixture was evaluated in two methods – all added dry and in a two stage addition (0.5 percent added to wet aggregate and the remaining percent added to the dry aggregate). For the addition of just the one percent hydrated lime, it was added to the dry aggregate. From the results in Table 4.9, the Aspha-min® mixture with one percent hydrated lime increased the TSR value to just below the minimum requirement for Superpave mixes.

As was mentioned before, the use of 1.5 percent hydrated lime was added by two methods. First, 0.5 percent was added to the wet aggregate. This was performed to try and improve the adhesion problem exhibited in the previous trials. The remaining one percent was added to the dry aggregate to possibly solve the cohesive problem seen in the previous trial as well. From the test results, this added amount of hydrated lime produced an acceptable TSR value. But the split addition process may add unnecessary cost, so the 1.5 percent hydrated lime was evaluated again, but added all at once to the dry aggregate. These results, shown in Table 4.9, indicated a decrease in TSR value to an unacceptable value.

4.7 HAMBURG WHEEL TRACKING DEVICE

Average test results from the Hamburg wheel-tracking device are presented in Table 4.10. Also included are the corresponding TSR values for each of the mix types. Different conclusions can be made regarding the moisture damage resistance of the mixtures based on both the Hamburg and TSR tests. In some cases, the Hamburg confirmed the data determined from the TSR test (e.g. Evotherm®), while in other cases the Hamburg data showed a decrease in the moisture resistance of a particular mix. This is mainly true for the mixes containing Sasobit®. The Hamburg test results also confirmed the observation that the mixture containing Aspha-min® had a lower resistance to moisture than the control mixture. This is based on the stripping inflection point. When describing the stripping inflection point, it is the number of cycles at which the deformation of the sample is the result of moisture damage and not rutting alone. Illustration of the stripping inflection point was shown in Figure 2.15. It is related to the resistance of the mix to moisture damage. A lower stripping inflection point is an indication of a decrease in the resistance to moisture for an asphalt mix. Stripping inflection points over 10,000 cycles, in a general sense, represent good mixes.

TABLE 4.10 Hamburg Wheel Tracking Device Results

Aggregate	Mix Type	Treatment	Stripping Inflection Point, cycles	Rutting Rate, mm/hr	TSR
Granite	Control	None	6500*	1.841	1.16
Granite	Sasobit®	None	3975	2.961	0.71
Granite	Aspha-min®	None	3450	5.139	0.67
Granite	Evotherm®	None	> 10,000	1.708	0.96
Granite	Aspha-min®	1.5% Hydrated Lime 2 Stage Addition	8500*	1.912	0.87
Granite	Aspha-min®	1.5% Hydrated Lime All Added Dry	> 10,000	0.687	0.75
Granite	Sasobit®	0.4% Magnabond	> 10,000	0.164	0.94
Limestone	Control	None	2500	4.284	0.65
Limestone	Aspha-min®	None	1700	2.835	0.51
Limestone	Sasobit®	None	2900	3.976	0.91
Limestone	Evotherm®	None	2550	3.178	0.62

Note: * individual sample did not have a stripping inflection point; reported value is average of 10,000 cycles and recorded stripping inflection point of second sample

The rutting rate determined from the HWTD test results correlated well with the stripping inflection point; that as the inflection point increased, indicating an increase in moisture resistance, the rutting rate decreased. This is shown in Figure 4.14. Rutting rate is defined as the slope of the secondary consolidation tangent. The addition of Sasobit® improved the rutting rate in all cases as compared to the control mixes, except for the granite aggregate. This corresponds to the findings with the APA. The test results indicated that the addition of a liquid anti-stripping agent in combination with Sasobit® produced the lowest rutting rate, which in turn will result in an added benefit of decreased rutting potential of asphalt mixes produced at lower operating temperatures.

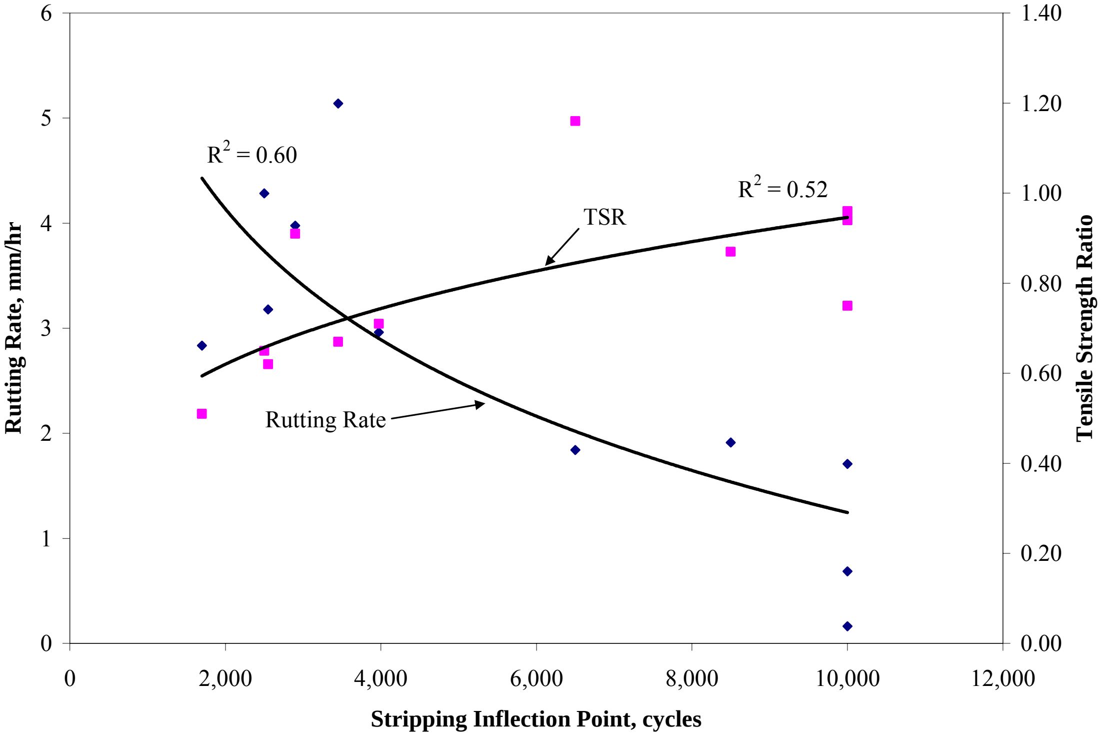

Figure 4.14 Rutting Rate and TSR Results versus Stripping Inflection Point.

The HWTD results also indicated the split addition of 1.5 percent hydrated lime improved both the stripping inflection point and the rutting rate, when compared to the results with just Aspha-min® added. In terms of rutting rate, this was an improvement of 63 percent. The addition of 1.5 percent dry lime resulted in of a stripping inflection point greater than 10,000 cycles and further improvement in the rutting rate.

The results from the Hamburg Wheel Tracking Device, also shown in Figure 4.14, correlated well with the TSR values, validating the earlier claim that the addition of Aspha-min® increased the potential for moisture damage. The Hamburg results for the addition of 1.5 percent dry lime indicate a mixture resistant to moisture susceptibility while the TSR results were marginal. Generally, the Hamburg Wheel Tracking Device test is considered to be the more accurate predictor of moisture damage as compared to the TSR test. Lime will also stiffen the binder (*70*), thus also providing a benefit in the rutting potential of WMA's that are compacted at a lower temperature (less than 250°F (121°C)).

4.8 CRITICAL COMPACTION TEMPERATURE

In order to accurately evaluate the warm asphalt additives, a comparison was made between the test results for each of the different processes and the test results for the control mix at a normal compaction temperature, this being 300°F (149°C) for this particular study.

The reason for this comparison was to determine a critical compaction temperature; more specifically, a minimum compaction temperature at which Warm Mix Asphalt compacted at any temperature below this compaction temperature, the performance of in-place asphalt mixture may not perform as well as hot mix asphalt laid at normal compaction temperatures. The results of these comparisons can be seen in Table 4.11. In Table 4.11, the row labeled “none” refers to hot mix asphalt without any WMA additives added. It does not mean hot mix that was mixed at normal temperatures and let cool to a particular compaction temperature, but rather mixed and compacted at the three different temperatures evaluated, these being 265°F (129°C), 230°F (110°C), and 190°F (88°C). The less than (<) sign means the performance is not as good as typical hot mix asphalt, where the greater than (>) sign indicates performance that is better than HMA. All equal signs in Table 4.11 indicate that there is no statistical difference between the additive in question and hot mix asphalt at 300°F (149°C). The values in parentheses indicate the p-value of each comparison, to illustrate the significance of the comparison.

TABLE 4.11 Results of Comparison of Additives to Hot Mix at 300°F (149°C)

	Density			**Resilient Modulus**			**Rutting Resistance**		
Temperature	**265**	**230**	**190**	**265**	**230**	**190**	**265**	**230**	**190**
None	= (0.8895)	= (0.1161)	= (1.0000)	= (0.9695)	= (0.9969)	= (0.2692)	= (0.3071)	< (0.0002)	< (0.0095)
Aspha-min®	= (0.2250)	> (0.0122)	= (0.9842)	= (0.9968)	= (0.9391)	= (0.2720)	< (0.0025)	< (0.0420)	< (0.0317)
Sasobit®	> (0.0006)	> (0.0059)	= (0.0525)	= (1.0000)	= (0.8911)	= (0.6002)	= (0.9926)	= (0.9752)	< (0.0009)
Evotherm®	> (0.0000)	> (0.0001)	> (0.0000)	= (0.9801)	= (0.9987)	= (0.8520)	= (0.9833)	< (0.0087)	= (0.0557)

In regard to compactability, these results indicated all processes were either not statistically different from the control mixture, or significantly improved the compaction of the laboratory samples, down to 190°F (88°C). For example, based on the p-values determined at a 95 percent confidence level, at the 230°F (110°C) compaction temperature, each of the Warm Mix Asphalt technologies significantly improved the densification of compacted samples.

Regarding resilient modulus, all processes neither significantly increased nor decreased the measured resilient modulus values, down to 190°F (88°C). This holds true for the mix type with no additive as well. This indicates that no Warm Mix Asphalt additive significantly affect the stiffness of an asphalt mixture.

Based on the results for the APA rutting tests, Sasobit® neither increased nor decreased the rutting potential, down to 230°F (110°C). For the Aspha-min®, there was a significant increase in the rutting results for all compaction temperatures. Observation of the p-values suggests that the rutting was more significant at the 265°F (129°C) compaction temperature; however, this may be due to some testing variability from the APA device. The test results for the Evotherm® suggest that there may be an increased potential for rutting at the 230°F (110°C) compaction temperature.

4.9 SUMMARY OF FINDINGS

The primary objective of this research study was to determine if three products used in the production of Warm Mix Asphalt are applicable to typical paving operations and environmental conditions commonly found in the United States. To accomplish this objective, a literature review was conducted partly to investigate several Warm Mix Asphalt processes that have been developed in Europe since the early to mid 1990's and one process developed in the United States since 2003. These processes include Aspha-min®, Sasobit®, and Evotherm®.

Once the literature review was completed, a test plan was produced to effectively evaluate the three Warm Mix Asphalt technologies. Laboratory samples were compacted using the automated vibratory compactor over a range of compaction temperatures. Resilient modulus, rutting resistance, indirect tensile strength, Tensile Strength Ratio, and Hamburg Wheel Tracking testing were then performed according to their respective test methods and procedures. Once the testing was completed, a thorough statistical analysis was conducted, from which conclusions and recommendations were made.

To accomplish the test plan, laboratory samples were prepared and compacted over a range of temperatures, from 300°F (149°C) down to 190°F (88°C) to measure the compactability of each aggregate/additive mixture combination at lower temperatures. The data obtained were then analyzed using an ANOVA to determine what factors, if any, were significant in the densification of the different mixtures. From the analysis, several conclusions could be made. One, the coarse nature of the aggregate structure has some influence on the densification of the mixture at the lower compaction temperatures. Two, all additives significantly improved the compactability of the mixtures when compared to their respective control samples. And three, the Evotherm® reduced the air void content the most, by an average of 1.5 percent. Therefore, it is ultimately believed that the addition of any additive will reduce the effort required for field compaction of HMA, based upon the statistical findings from the densification data.

After the samples were analyzed with regards to compactability, they were then used to determine the resilient modulus values at the different compaction temperatures. This testing was conducted to determine if the addition of any WMA additive would potentially affect asphalt thickness in the mix design procedure. Once the test results were determined, an ANOVA was performed to see if any factors significantly affected the resilient modulus of the mixtures. From the analysis, it was concluded that the resilient modulus increased as the compaction temperature increased, which increased the densification of the test samples. So it can be concluded that resilient modulus increases with increasing densification. Also, based on Tukey's post-ANOVA analysis, no WMA additive significantly affected the resilient modulus. Therefore, no changes in pavement thickness design would be required from the inclusion of a WMA additive.

The test samples were then analyzed in the Asphalt Pavement Analyzer (APA) to determine their resistance to rutting at the lower compaction temperatures. The data were then compared to the control samples. From a Tukey's post-ANOVA performed on the data, it was determined that Evotherm® lowered the rutting potential by an average of 1.8 mm; Sasobit® lowered the potential by 1.4 mm, and Aspha-min® lowered the rut depths by an average of 0.2 mm. These results were compared to the rut depths for the control mixture. However, the addition of any of the three WMA additives did not significantly increase or decrease the rutting potential, based on the results from the Tukey's post-ANOVA analysis.

To determine if the inclusion of any WMA additive would require a cure time before opening to traffic, samples were prepared and aged for various time periods. Tensile strength testing was then conducted after the aging process. This was done to address the concern that the workability of the mixture would not dissipate prior to being opened to traffic, thus creating the potential for rutting. The results indicated no statistical difference in tensile strength between the control mixture and the Aspha-min® or Evotherm® mixtures. Therefore, no cure time would be required when using any of these two additives. For the Sasobit®, a statistical difference in tensile strengths was determined when compared to the control mixture. Hence, based upon laboratory tests, a cure time may be beneficial before opening to traffic. However, field data collected from previous research suggest that no cure time is necessary.

Lower operating temperatures may not allow for complete evaporation of moisture that may be retained in the aggregate, which could lead to increased susceptibility to moisture damage. Moisture testing in accordance to ASTM D4867 was conducted for each mixture combination to address this concern. TSR testing was conducted at a compaction temperature of 250°F (121°C) based on the densification, resilient modulus, and rutting results obtained from this study for all three WMA technologies. Test results indicated that the lower compaction temperatures resulted in increased moisture sensitivity for all three WMA additives. Anti-stripping additives were then evaluated to mitigate the potential for moisture damage. Hydrated lime in a two-stage addition procedure improved the moisture resistance for Aspha-min®, while the liquid anti-stripping agent Magnabond increased the resistance for the mixtures containing Sasobit®. For the Evotherm®, an adjustment made in the chemical package was evaluated, and resulted in improved moisture resistance. Therefore, moisture damage from the lower compaction temperatures could be mitigated in the laboratory.

Hamburg Wheel Tracking Device testing was conducted to verify the test results from the TSR procedure. Test results generated from the Hamburg Wheel Tracking Device were thought to be vital in accurately establishing a good performing Warm Mix Asphalt. Generally, the results from the HWTD correlated well with the TSR results, especially for the rutting rate values, shown in Figure 4.14. The lower resistance to moisture for each mixture combination was verified by an increase in the rutting rate, compared to the control mixtures. The Hamburg Wheel Tracking Device also determined that the addition of the various anti-stripping agents used improved the HWTD test results.

A secondary objective for this research study was to determine a critical compaction temperature for WMA. This is a minimum compaction temperature at which WMA should be compacted to ensure optimal performance. At any temperature below this minimum compaction temperature, the performance of WMA may not perform as well as HMA laid at normal compaction temperatures. Test results were compared to HMA that was compacted and evaluated at a compaction temperature of 300°F (149°C). From the comparisons in Table 4.11, it was observed that the performance of the Warm Mix Asphalt additives at a compaction temperature somewhere between 265 and 230°F (129 and 110°C) was significantly less than the performance of HMA produced at 300°F (149°C). Therefore, a minimum compaction of 250°F (121°C) is recommended for optimum performance of Warm Mix Asphalt, with a minimum mixing temperature of 275°F (135°C) to ensure complete coating of the aggregate and a compaction temperature of at least 250°F (121°C).

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

After applying the analysis procedures to the data produced for all three Warm Mix Asphalt technologies investigated in this study, the following conclusions and recommendations could be developed.

5.2 CONCLUSIONS

1. The gyratory compactor was shown not to be sensitive to the reduction in compaction temperature. Therefore, all test samples to simulate field compactability were compacted in the vibratory compactor.
2. The addition of any of the three Warm Mix Asphalt additives evaluated lowers the measured air voids of specimens compacted in the gyratory compactor by 0.8 to 1.5 percent. Improved compactability was noted at temperatures as low as 190°F (88°C) for all three additives. The new Evotherm® formulation was obtained and only evaluated to improve the moisture resistance. Therefore, this reduction in air voids was not confirmed for the new formulation of Evotherm®.
3. The addition of the WMA additives evaluated in this study did not affect the resilient modulus for mixtures having the same PG binder. Therefore, there

would not be any potential effect on pavement thickness design when using Warm Mix Asphalt.

4. Based on the Asphalt Pavement Analyzer results, the addition of WMA additives evaluated in this study did not increase the rutting potential of an asphalt mix, compared to the control mixtures. The rutting potential for all mixes increased with decreasing mixing and compaction temperatures and this may be related more to the decreased aging of the binder when heated to lower temperatures.
5. It appears that the addition of Aspha-min® or Evotherm® does not require a cure time for the asphalt mixture prior to opening to traffic. The study indicated that a cure time may be beneficial for the Sasobit®. However, field experience from Europe has indicated that the addition of Sasobit® does not require a cure time prior to opening to traffic.
6. Lower temperatures used when producing WMA may increase the potential for moisture damage. The lower mixing temperatures can result in incomplete drying of the aggregate, leading to moisture damage. Reduced tensile strength and visual stripping were observed in the WMA samples compacted at 250°F (121°C).
7. Hydrated lime (1.5 percent in two-stage addition) used with Aspha-min® appeared to be effective in improving the resistance to moisture damage with the granite aggregate. The addition of AKZO Nobel Magnabond (Kling Beta 2912) improved the TSR values to acceptable levels for the Sasobit®; however, the Magnabond greatly reduced the individual tensile strengths in

both the conditioned and unconditioned samples. The new formulation of Evotherm® increased the moisture resistance to acceptable levels with the limestone aggregate.

8. Hamburg wheel-tracking tests indicated good performance in terms of moisture susceptibility and rutting for the mixtures containing Sasobit® and Magnabond. Hamburg results also showed the lime will improve the rutting resistance of Warm Mix Asphalt mixtures with Aspha-min® compacted at lower temperatures due to the lime stiffening the asphalt binder.
9. A good correlation was observed between the stripping inflection point from the Hamburg Wheel Tracking Device and Tensile Strength Ratio.

5.3 RECOMMENDATIONS

1. The modified binder containing Sasobit® must be engineered to meet the desired Performance Grade. As an example, in this study a PG 58-28 was used as the base asphalt with the addition of 2.5 percent Sasobit® to produce a PG 64-22.
2. The optimum asphalt content should be determined without the addition of any Warm Mix Asphalt additive. Additional samples should then be produced with the additive at the anticipated reduced production temperatures so the field target density can be adjusted (e.g. If the laboratory air void content with any additive included was decreased in the lab by 0.5 percent, then the field target density should be increased by 0.5 percent).

3. Additional research should be performed to determine if the new Evotherm® package would lower the air void content in gyratory-prepared samples. While this could be used to indicate a reduction in the optimum asphalt content, at this time it is believed that additional research is required.
4. Based on the critical compaction temperature analysis, a minimum field mixing temperature of 275°F (135°C) and a minimum field compaction temperature of 250°F (121°C) are recommended.
5. Tensile strength ratio testing should be conducted on specimens mixed and compacted at the anticipated field production temperatures. If test results are determined to be unfavorable, anti-stripping agents should be added to the mix to increase the tensile strength ratio.
6. More research is needed to further evaluate both long term and short term field performance, the selection of the optimum asphalt content, the effect of Warm Mix Asphalt additives on mixture volumetrics, and the selection of binder grades for lower production temperatures.

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APPENDICES

APPENDIX A:

MIX DESIGN VERIFICATION DATA

TABLE A1 Mix Design Verification Summary for Granite with No Additive

Aggregate: Granite
Ndesign: 125
Ninitial: 9

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa): 2.673
Effective Specific Gravity (Gse): 2.667
Bulk Specific Gravity (Gsb): 2.597

Sample Number	Asphalt Content, %	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %	Effective Asphalt Content, %
1	4.8	4674.9	2717.3	4685.6	2.375	2.478	4.2	12.9	67.9	3.8
2	4.8	4684.5	2706.8	4699.4	2.351	2.478	5.1	13.8	62.9	3.8
Avg.					2.363	2.478	4.6	13.4	65.4	3.8
3	5.3	4731.5	2747.9	4737.6	2.378	2.460	3.3	13.3	74.9	4.3
4	5.3	4724.3	2745.5	4729.4	2.381	2.460	3.2	13.2	75.7	4.3
Avg.					2.380	2.460	3.3	13.2	75.3	4.3
5	5.8	4707.2	2733.4	4711.8	2.379	2.442	2.6	13.7	81.3	4.8
6	5.8	4746.4	2764.9	4748.6	2.393	2.442	2.0	13.2	84.7	4.8
Avg.					2.386	2.442	2.3	13.5	83.0	4.8

TABLE A2 Mix Design Verification Summary for Limestone with No Additive

Aggregate: Limestone
Ndesign: 125
Ninitial: 9

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa): 2.755
Effective Specific Gravity (Gse): 2.749
Bulk Specific Gravity (Gsb): 2.725

Sample Number	Asphalt Content, %	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %	Effective Asphalt Content, %
1	4.5	4363.8	2580.2	4370.6	2.437	2.552	4.5	14.6	69.2	4.2
2	4.5	4343.3	2566.8	4363.8	2.417	2.552	5.3	15.3	65.4	4.2
Avg.					2.427	2.552	4.9	14.9	67.3	4.2
3	5.0	4373.1	2595.1	4379.1	2.451	2.532	3.2	14.5	78.1	4.7
4	5.0	4389.5	2600.4	4398.4	2.441	2.532	3.6	14.9	75.9	4.7
Avg.					2.446	2.532	3.4	14.7	77.0	4.7
5	5.5	4386.6	2620.7	4389.6	2.480	2.513	1.3	14.0	90.6	5.2
6	5.5	4407.5	2620.8	4412.4	2.460	2.513	2.1	14.7	85.7	5.2
Avg.					2.470	2.513	1.7	14.3	88.1	5.2

APPENDIX B:

COMPACTABILITY DATA

TABLE B1 Compactability Data for Granite - No Additive

Aggregate: Granite
Ndesign: 125
Ninitial: 9

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa): 2.673
Effective Specific Gravity (Gse): 2.667
Bulk Specific Gravity (Gsb): 2.597

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Height @ Ninitial, (mm)	Height @ Ndesign, (mm)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %	% Gmm @ Ninitial, %
1	5.1	300	4725.3	2734.9	4734.4	125.8	115.5	2.363	2.467	4.2	13.6	69.2	88.0
2	5.1	300	4725.5	2742.4	4738.3	126.4	116.0	2.368	2.467	4.0	13.5	70.1	88.1
Avg.								2.365	2.467	4.1	13.6	69.6	88.0
3	5.1	265	4727.1	2744.7	4735.1	125.3	115.1	2.375	2.467	3.7	13.2	71.8	88.4
4	5.1	265	4727.9	2739.4	4736.0	125.4	115.0	2.368	2.467	4.0	13.5	70.2	88.0
Avg.								2.371	2.467	3.9	13.3	71.0	88.2
5	5.1	230	4710.4	2725.6	4720.7	125.5	115.2	2.361	2.467	4.3	13.7	68.7	87.8
6	5.1	230	4728.6	2737.9	4743.2	126.2	115.6	2.358	2.467	4.4	13.8	68.1	87.6
Avg.								2.360	2.467	4.4	13.8	68.4	87.7
7	5.1	190	4724.8	2728.0	4739.9	126.1	115.7	2.348	2.467	4.8	14.2	66.1	87.3
8	5.1	190	4733.0	2735.4	4733.9	126.9	116.0	2.368	2.467	4.0	13.5	70.3	87.8
Avg.								2.358	2.467	4.4	13.8	68.2	87.5

TABLE B2 Compactability Data for Granite - Aspha-min® Zeolite

Aggregate: Granite
Ndesign: 125
Ninitial: 9

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa): 2.673
Effective Specific Gravity (Gse): 2.655
Bulk Specific Gravity (Gsb): 2.597

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Height @ Ninitial, (mm)	Height @ Ndesign, (mm)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %	% Gmm @ Ninitial, %
1	5.1	300	4733.8	2760.5	4743.7	125.7	115.3	2.387	2.457	2.9	12.8	77.7	89.1
2	5.1	300	4707.7	2729.8	4719.6	125.9	115.5	2.366	2.457	3.7	13.5	72.6	88.3
Avg.								2.376	2.457	3.3	13.2	75.2	88.7
3	5.1	265	4713.3	2742.7	4718.3	124.7	114.3	2.386	2.457	2.9	12.8	77.4	89.0
4	5.1	265	4714.2	2743.3	4725.0	125.8	115.4	2.379	2.457	3.2	13.1	75.7	88.8
Avg.								2.382	2.457	3.0	12.9	76.5	88.9
5	5.1	230	4736.8	2757.4	4745.7	126.2	115.6	2.382	2.457	3.0	12.9	76.5	88.8
6	5.1	230	4731.0	2746.1	4739.0	125.7	115.3	2.374	2.457	3.4	13.3	74.5	88.6
Avg.								2.378	2.457	3.2	13.1	75.5	88.7
7	5.1	190	4749.5	2752.5	4758.3	126.3	115.8	2.368	2.457	3.6	13.5	73.1	88.4
8	5.1	190	4743.6	2750.1	4752.6	126.3	115.6	2.369	2.457	3.6	13.4	73.3	88.2
Avg.								2.368	2.457	3.6	13.5	73.2	88.3

TABLE B3 Compactability Data for Granite - Sasobit®

Aggregate: Granite
Ndesign: 125
Ninitial: 9

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa): 2.673
Effective Specific Gravity (Gse): 2.660
Bulk Specific Gravity (Gsb): 2.597

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Height @ Ninitial, (mm)	Height @ Ndesign, (mm)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %	% Gmm @ Ninitial, %
1	5.1	300	4707.2	2734.1	4711.7	124.3	113.9	2.380	2.461	3.3	13.0	74.8	88.6
2	5.1	300	4694.5	2720.4	4702.1	125.8	115.3	2.369	2.461	3.7	13.4	72.2	88.2
Avg.								2.375	2.461	3.5	13.2	73.5	88.4
3	5.1	265	4723.1	2747.3	4726.9	126.2	115.7	2.386	2.461	3.1	12.8	76.2	88.9
4	5.1	265	4716.7	2736.4	4727.4	126.2	115.4	2.369	2.461	3.7	13.4	72.2	88.0
Avg.								2.377	2.461	3.4	13.1	74.2	88.5
5	5.1	230	4703.6	2718.7	4712.4	126.2	115.8	2.359	2.461	4.1	13.8	70.0	88.0
6	5.1	230	4748.0	2750.1	4760.8	126.6	116.1	2.361	2.461	4.0	13.7	70.5	88.0
Avg.								2.360	2.461	4.1	13.7	70.2	88.0

TABLE B4 Compactability Data for Granite - Evotherm®

Aggregate: Granite
Ndesign: 125
Ninitial: 9

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa): 2.673
Effective Specific Gravity (Gse): 2.664
Bulk Specific Gravity (Gsb): 2.597

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Height @ Ninitial, (mm)	Height @ Ndesign, (mm)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %	% Gmm @ Ninitial, %
1	5.1	300	4713.7	2738.6	4719.0	124.2	114.2	2.380	2.465	3.4	13.0	73.6	88.8
2	5.1	300	4743.7	2768.2	4746.9	124.0	113.9	2.397	2.465	2.7	12.4	77.9	89.3
Avg.								2.389	2.465	3.1	12.7	75.7	89.1
3	5.1	265	4734.8	2756.2	4738.8	124.5	114.3	2.388	2.465	3.1	12.7	75.5	88.9
4	5.1	265	4739.1	2756.3	4743.0	124.5	114.3	2.385	2.465	3.2	12.8	74.8	88.8
Avg.								2.387	2.465	3.2	12.8	75.2	88.9
5	5.1	230	4735.5	2751.6	4738.9	124.2	113.9	2.383	2.465	3.3	12.9	74.2	88.7
6	5.1	230	4739.0	2757.3	4744.2	124.4	114.3	2.385	2.465	3.2	12.8	74.8	88.9
Avg.								2.384	2.465	3.3	12.9	74.5	88.8
7	5.1	190	4753.1	2768.7	4757.7	124.8	114.5	2.390	2.465	3.1	12.7	75.9	88.9
8	5.1	190	4746.8	2764.6	4750.6	124.6	114.1	2.390	2.465	3.0	12.7	76.0	88.8
Avg.								2.390	2.465	3.0	12.7	76.0	88.9

TABLE B5 Compactability Data for Limestone - No Additive

Aggregate: Limestone
Ndesign: 125
Ninitial: 9

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa): 2.755
Effective Specific Gravity (Gse): 2.749
Bulk Specific Gravity (Gsb): 2.725

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Height @ Ninitial, (mm)	Height @ Ndesign, (mm)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %	% Gmm @ Ninitial, %
1	4.8	300	4369.3	2579.8	4376.7	115.9	103.5	2.432	2.545	4.5	15.1	70.4	85.3
2	4.8	300	4371.3	2583.0	4379.2	116.0	103.6	2.434	2.545	4.4	15.0	70.8	85.4
Avg.								2.433	2.545	4.4	15.0	70.6	85.4
3	4.8	265	4376.6	2586.1	4385.1	116.4	103.8	2.433	2.545	4.4	15.0	70.6	85.2
4	4.8	265	4374.5	2582.5	4385.4	116.6	103.9	2.426	2.545	4.7	15.2	69.4	85.0
Avg.								2.430	2.545	4.5	15.1	70.0	85.1
5	4.8	230	4380.7	2593.5	4388.5	116.1	103.6	2.441	2.545	4.1	14.7	72.1	85.6
6	4.8	230	4383.5	2586.0	4390.7	116.7	104.0	2.429	2.545	4.6	15.1	69.9	85.1
Avg.								2.435	2.545	4.3	14.9	71.0	85.3
7	4.8	190	4370.8	2586.7	4377.1	116.3	103.7	2.441	2.545	4.1	14.7	72.3	85.5
8	4.8	190	4375.1	2587.2	4382.8	116.6	103.9	2.437	2.545	4.3	14.9	71.4	85.3
Avg.								2.439	2.545	4.2	14.8	71.8	85.4

TABLE B6 Compactability Data for Limestone - Aspha-min® Zeolite

Aggregate: Limestone
Ndesign: 125
Ninitial: 9

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa): 2.755
Effective Specific Gravity (Gse): 2.748
Bulk Specific Gravity (Gsb): 2.725

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Height @ Ninitial, (mm)	Height @ Ndesign, (mm)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %	% Gmm @ Ninitial, %
1	4.8	300	4371.9	2584.3	4382.6	116.3	104.1	2.431	2.544	4.4	15.1	70.6	85.5
2	4.8	300	4370.4	2596.7	4377.9	109.6	103.3	2.454	2.544	3.6	14.3	75.1	90.9
Avg.								2.442	2.544	4.0	14.7	72.8	88.2
3	4.8	265	4389.2	2608.7	4394.6	116.1	103.5	2.458	2.544	3.4	14.1	76.0	86.1
4	4.8	265	4389.4	2599.8	4397.8	117.0	104.1	2.441	2.544	4.0	14.7	72.6	85.4
Avg.								2.449	2.544	3.7	14.4	74.3	85.8
5	4.8	230	4391.5	2600.4	4399.5	116.5	103.9	2.441	2.544	4.1	14.7	72.5	85.6
6	4.8	230	4395.1	2607.6	4403.2	116.4	103.9	2.448	2.544	3.8	14.5	73.9	85.9
Avg.								2.444	2.544	3.9	14.6	73.2	85.7
7	4.8	190	4392.1	2582.1	4404.8	117.8	105.0	2.410	2.544	5.3	15.8	66.6	84.4
8	4.8	190	4386.8	2591.6	4398.9	117.2	104.7	2.427	2.544	4.6	15.2	69.8	85.2
Avg.								2.418	2.544	4.9	15.5	68.2	84.8

TABLE B7 Compactability Data for Limestone - Sasobit®

Aggregate: Limestone
Ndesign: 125
Ninitial: 9

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa): 2.755
Effective Specific Gravity (Gse): 2.748
Bulk Specific Gravity (Gsb): 2.725

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Height @ Ninitial, (mm)	Height @ Ndesign, (mm)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %	% Gmm @ Ninitial, %
1	4.8	300	4351.5	2588.9	4356.0	115.0	102.5	2.463	2.545	3.2	14.0	76.8	86.2
2	4.8	300	4348.6	2584.9	4355.3	116.1	103.3	2.456	2.545	3.5	14.2	75.4	85.9
Avg.								2.459	2.545	3.4	14.1	76.1	86.1
3	4.8	265	4370.6	2600.9	4375.5	114.8	102.5	2.463	2.545	3.2	14.0	76.9	86.4
4	4.8	265	4366.1	2598.8	4370.2	115.2	102.7	2.465	2.545	3.2	13.9	77.3	86.3
Avg.								2.464	2.545	3.2	13.9	77.1	86.4
5	4.8	230	4373.3	2602.4	4381.2	114.8	102.6	2.459	2.545	3.4	14.1	75.9	86.3
6	4.8	230	4385.8	2617.0	4391.3	115.4	102.6	2.472	2.545	2.9	13.6	78.9	86.4
Avg.								2.465	2.545	3.1	13.9	77.4	86.3

TABLE B8 Compactability Data for Limestone - Evotherm®

Aggregate: Limestone
Ndesign: 125
Ninitial: 9

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa): 2.755
Effective Specific Gravity (Gse): 2.751
Bulk Specific Gravity (Gsb): 2.725

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Height @ Ninitial, (mm)	Height @ Ndesign, (mm)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %	% Gmm @ Ninitial, %
1	4.8	300	4485.2	2675.5	4489.9	117.3	104.4	2.472	2.547	2.9	13.6	78.4	86.4
2	4.8	300	4475.7	2668.7	4479.6	116.9	104.3	2.472	2.547	3.0	13.7	78.3	86.6
Avg.								2.472	2.547	3.0	13.6	78.4	86.5
3	4.8	265	4474.1	2658.4	4480.0	117.6	104.9	2.456	2.547	3.6	14.2	74.9	86.0
4	4.8	265	4481.9	2667.1	4488.6	117.6	104.9	2.461	2.547	3.4	14.0	75.8	86.2
Avg.								2.458	2.547	3.5	14.1	75.3	86.1
5	4.8	230	4484.8	2675.8	4488.7	116.6	103.9	2.474	2.547	2.9	13.6	78.8	86.5
6	4.8	230	4482.8	2679.4	4487.1	116.7	104.0	2.480	2.547	2.6	13.4	80.3	86.8
Avg.								2.477	2.547	2.8	13.5	79.6	86.7
7	4.8	190	4486.5	2667.8	4494.9	118.2	105.2	2.456	2.547	3.6	14.2	74.7	85.8
8	4.8	190	4491.4	2664.9	4500.2	118.5	105.6	2.447	2.547	3.9	14.5	73.0	85.6
Avg.								2.451	2.547	3.8	14.4	73.9	85.7

TABLE B9 Compactability Data for Granite; Fine Graded Mix - No Additive

Aggregate: Granite
Ndesign:
Ninitial:

Asphalt Specific Gravity (Gb): 1.028
Apparent Specific Gravity (Gsa):
Effective Specific Gravity (Gse): 2.848
Bulk Specific Gravity (Gsb):

Sample Number	Asphalt Content, %	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	VMA, %	VFA, %
1	5.5	300	3079.7	1839.2	3081.8	2.478	2.595	4.5		
2	5.5	300	3091.0	1843.8	3092.6	2.475	2.595	4.6		
3	5.5	300	3100.3	1850.4	3105.5	2.470	2.595	4.8		
Avg.						2.477	2.595	4.6		
4	5.5	265	3090.4	1838.5	3091.9	2.466	2.595	5.0		
5	5.5	265	3089.2	1837.3	3091.8	2.462	2.595	5.1		
6	5.5	265	3089.9	1838.6	3093.4	2.462	2.595	5.1		
Avg.						2.464	2.595	5.0		
7	5.5	230	3088.2	1823.4	3092.3	2.434	2.595	6.2		
8	5.5	230	3089.9	1823.3	3092.6	2.434	2.595	6.2		
9	5.5	230	3092.6	1829.4	3100.7	2.433	2.595	6.3		
Avg.						2.434	2.595	6.2		

APPENDIX C:

RESILIENT MODULUS DATA

TABLE C1 Resilient Modulus Data for Granite - No Additive

Aggregate: Granite
Test Temperature: 77° F (25° C)
Asphalt Content: 5.1%
Poisson's Ratio: 0.35
Maximum Specific Gravity (Gmm): 2.467

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Sample Height, (mm)	Resilient Modulus (psi)
18	300	3123.6	1782.0	3150.1	2.283	7.5	79.4	467,171
39	300	3127.9	1790.0	3138.2	2.320	6.0	78.1	294,065
42	300	3134.5	1783.1	3135.4	2.318	6.0	78.8	572,998
49	300	3125.3	1795.2	3133.3	2.336	5.3	79.3	420,863
51	300	3136.3	1795.1	3149.6	2.315	6.1	80.0	215,163
85	300	3121.7	1789.7	3131.6	2.326	5.7	78.7	218,717
Average:						6.1	79.1	364,830
Standard Deviation:						0.7	0.7	145,399
8	265	3112.1	1782.4	3123.2	2.321	5.9	78.4	272,652
29	265	3088.1	1772.1	3097.3	2.330	5.5	78.2	239,237
53	265	3129.6	1821.3	3226.3	2.227	9.7	82.8	289,367
67	265	3120.5	1788.2	3150.5	2.291	7.1	79.2	577,025
88	265	3110.3	1780.5	3136.0	2.295	7.0	79.6	281,952
89	265	3117.6	1784.8	3138.0	2.304	6.6	79.2	366,632
Average:						7.0	79.6	337,811
Standard Deviation:						1.5	1.7	124,486
101	230	3124.7	1804.6	3127.8	2.361	4.3	77.0	315,579
105	230	3127.0	1787.8	3132.9	2.325	5.8	78.0	310,433
109	230	3122.4	1788.7	3127.6	2.332	5.5	78.5	426,761
122	230	3124.5	1792.3	3131.1	2.334	5.4	77.4	349,150
104	230	3119.1	1794.7	3123.9	2.347	4.9	76.5	485,897
125	230	3127.6	1791.6	3133.4	2.331	5.5	77.0	276,334
Average:						5.2	77.4	360,692
Standard Deviation:						0.5	0.7	79,815
108	190	3122.6	1781.8	3131.8	2.313	6.2	77.9	332,202
112	190	3131.5	1783.8	3142.4	2.305	6.6	79.8	230,832
117	190	3123.6	1782.8	3136.9	2.307	6.5	78.1	368,541
127	190	3125.8	1780.9	3140.8	2.299	6.8	79.5	288,445
120	190	3124.2	1787.5	3133.2	2.322	5.9	78.0	432,910
116	190	3123.6	1784.4	3137.0	2.309	6.4	78.0	310,051
Average:						6.4	78.6	327,164
Standard Deviation:						0.3	0.9	69,270

TABLE C2 Resilient Modulus Data for Granite – Aspha-min® Zeolite

Aggregate: Granite
Poisson's Ratio: 0.35
Test Temperature: 77° F (25° C)
Maximum Specific Gravity (Gmm): 2.457
Asphalt Content: 5.1%

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Sample Height, (mm)	Resilient Modulus (psi)
36	300	3107.7	1789.4	3121.3	2.333	5.0	77.8	687,767
46	300	3106.5	1783.1	3123.0	2.318	5.6	79.4	682,167
48	300	3109.5	1783.2	3126.0	2.316	5.8	79.7	487,386
76	300	3110.8	1793.2	3128.8	2.329	5.2	77.8	433,168
82	300	3107.9	1793.5	3120.8	2.342	4.7	77.1	529,635
91	300	3107.9	1794.0	3117.7	2.348	4.4	76.9	477,301
Average:						5.1	78.1	549,571
Standard Deviation:						0.5	1.1	109,286
1	265	3103.0	1778.7	3118.5	2.316	5.7	78.7	509,675
16	265	3104.7	1781.6	3114.1	2.330	5.2	77.9	272,691
30	265	3105.1	1777.4	3117.7	2.317	5.7	78.6	543,764
58	265	3092.7	1770.8	3112.4	2.305	6.2	79.2	280,185
66	265	3097.1	1773.5	3130.0	2.283	7.1	80.9	290,417
77	265	3109.8	1779.4	3142.7	2.281	7.2	80.4	254,065
Average:						6.2	79.3	358,466
Standard Deviation:						0.8	1.1	131,313
11	230	3098.2	1765.8	3118.6	2.290	6.8	78.8	401,439
44	230	3102.8	1773.1	3123.9	2.297	6.5	76.2	169,512
69	230	3091.4	1770.9	3112.0	2.305	6.2	79.7	320,211
86	230	3104.2	1782.4	3112.8	2.333	5.0	76.2	596,461
97	230	3107.9	1777.8	3121.5	2.313	5.9	76.2	300,014
98	230	3106.8	1785.7	3125.3	2.319	5.6	76.2	458,273
Average:						6.0	77.2	374,318
Standard Deviation:						0.6	1.6	146,646
103	190	3114.9	1781.9	3121.3	2.326	5.3	77.1	397,954
113	190	3117.1	1777.1	3126.1	2.311	6.0	78.4	318,320
124	190	3115.1	1781.4	3129.0	2.312	5.9	77.5	261,642
119	190	3118.7	1784.4	3132.9	2.313	5.9	78.9	301,191
100	190	3115.8	1781.8	3128.1	2.314	5.8	77.3	260,236
107	190	3114.5	1781.8	3125.4	2.318	5.7	77.7	201,267
Average:						5.8	77.8	290,102
Standard Deviation:						0.2	0.7	66,551

TABLE C3 Resilient Modulus Data for Granite - Sasobit®

Aggregate: Granite
Test Temperature: 77° F (25° C)
Asphalt Content: 5.1%
Poisson's Ratio: 0.35
Maximum Specific Gravity (Gmm): 2.461

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Sample Height, (mm)	Resilient Modulus (psi)
34	300	3105.2	1782.0	3114.1	2.331	5.3	77.0	256,341
51	300	3104.9	1780.0	3112.0	2.331	5.3	77.4	345,309
16	300	3096.8	1776.4	3106.0	2.329	5.4	76.6	216,508
21	300	3109.2	1788.7	3117.3	2.340	4.9	77.2	296,066
3	300	3098.6	1789.5	3104.1	2.357	4.2	77.3	408,657
22	300	3100.2	1781.4	3111.9	2.330	5.3	77.9	291,797
Average:						5.1	77.2	302,446
Standard Deviation:						0.4	0.4	67,503
28	265	3096.9	1776.5	3104.3	2.332	5.2	78.2	294,986
27	265	3095.8	1768.0	3106.0	2.314	6.0	77.7	220,596
13	265	3112.5	1775.9	3121.8	2.313	6.0	78.7	199,955
35	265	3109.5	1781.9	3118.5	2.326	5.5	78.4	459,184
42	265	3105.0	1786.1	3114.1	2.338	5.0	78.3	376,923
52	265	3093.4	1778.9	3100.5	2.341	4.9	76.9	232,128
Average:						5.4	78.0	297,295
Standard Deviation:						0.5	0.6	102,136
37	230	3114.4	1790.5	3126.0	2.332	5.2	77.6	245,023
20	230	3095.9	1767.9	3105.8	2.314	6.0	77.2	400,953
11	230	3104.4	1780.1	3119.3	2.318	5.8	78.2	230,897
33	230	3112.8	1780.8	3121.6	2.322	5.7	78.5	196,361
41	230	3091.7	1770.4	3106.8	2.313	6.0	77.2	288,890
39	230	3090.9	1773.8	3103.2	2.325	5.5	79.0	270,607
Average:						5.7	77.9	272,122
Standard Deviation:						0.3	0.7	70,788
1	190	3114.1	1797.8	3118.9	2.357	4.2	76.6	353,533
2	190	3056.4	1758.6	3064.8	2.340	4.9	76.6	392,056
3	190	3073.3	1764.5	3080.5	2.335	5.1	76.0	329,561
4	190	3079.7	1769.8	3088.1	2.336	5.1	75.7	458,088
5	190	3074.6	1768.9	3081.9	2.342	4.8	76.8	335,651
6	190	3087.2	1780.5	3095.2	2.348	4.6	75.9	335,933
Average:						4.8	76.3	367,470
Standard Deviation:						0.3	0.5	49,909

TABLE C4 Resilient Modulus Data for Granite - Evotherm®

Aggregate: Granite
Poisson's Ratio: 0.35
Test Temperature: 77° F (25° C)
Maximum Specific Gravity (Gmm): 2.465
Asphalt Content: 5.1%

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Sample Height, (mm)	Resilient Modulus (psi)
1	300	3071.0	1776.9	3076.0	2.364	4.1	76.1	494,925
2	300	3073.2	1778.0	3079.4	2.361	4.2	75.8	255,852
3	300	3073.8	1777.4	3079.0	2.362	4.2	76.4	325,132
4	300	3077.2	1793.3	3083.6	2.385	3.3	75.8	398,841
5	300	3067.4	1774.1	3073.4	2.361	4.2	76.3	422,122
6	300	3067.8	1773.7	3072.1	2.363	4.1	76.5	471,223
Average:						4.0	76.2	394,683
Standard Deviation:						0.4	0.3	90,320
3	265	3085.9	1776.6	3094.2	2.342	5.0	76.1	396,105
12	265	3087.2	1773.7	3103.9	2.321	5.8	76.6	721,394
20	265	3082.9	1777.7	3095.8	2.339	5.1	75.5	302,279
21	265	3083.5	1774.2	3092.4	2.339	5.1	75.9	252,856
24	265	3083.0	1773.7	3098.0	2.328	5.6	76.1	264,369
30	265	3071.2	1762.3	3080.9	2.329	5.5	76.0	502,908
Average:						5.4	76.0	406,652
Standard Deviation:						0.3	0.4	180,682
1	230	3080.7	1762.8	3088.6	2.324	5.7	76.7	305,878
4	230	3077.7	1752.0	3092.2	2.296	6.8	77.3	256,110
7	230	3087.9	1769.9	3092.1	2.335	5.3	75.8	286,165
14	230	3040.6	1755.2	3046.6	2.354	4.5	75.3	364,771
22	230	3066.7	1769.7	3072.4	2.354	4.5	76.6	360,688
39	230	3089.0	1782.8	3094.6	2.355	4.5	76.1	230,165
Average:						5.2	76.3	300,630
Standard Deviation:						0.9	0.7	54,599
2	190	3091.6	1781.2	3099.2	2.346	4.8	76.6	395,008
9	190	3096.4	1777.5	3106.7	2.330	5.5	77.3	265,107
23	190	3097.3	1781.5	3106.5	2.338	5.2	76.3	350,227
25	190	3106.3	1783.6	3116.3	2.331	5.4	77.1	314,235
32	190	3094.9	1779.2	3105.9	2.333	5.4	76.8	417,382
35	190	3061.0	1739.6	3071.3	2.299	6.8	76.3	212,857
Average:						5.5	76.7	325,803
Standard Deviation:						0.7	0.4	77,907

TABLE C5 Resilient Modulus Data for Limestone - No Additive

Aggregate: Limestone
Poisson's Ratio: 0.35
Test Temperature: 77° F (25° C)
Maximum Specific Gravity (Gmm): 2.545
Asphalt Content: 4.8%

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Sample Height, (mm)	Resilient Modulus (psi)
2	300	3074.8	1790.2	3103.3	2.342	8.0	76.9	298,143
7	300	3139.1	1822.5	3151.2	2.363	7.2	76.7	327,752
9	300	3129.7	1824.1	3141.7	2.375	6.7	75.4	497,695
44	300	3121.6	1811.0	3140.1	2.349	7.7	76.9	295,254
70	300	3144.3	1821.6	3167.7	2.336	8.2	76.3	396,668
94	300	3152.2	1824.6	3177.1	2.331	8.4	76.7	420,900
Average:						7.7	76.5	372,735
Standard Deviation:						0.7	0.6	80,123
11	265	3119.8	1813.8	3137.2	2.357	7.4	75.9	337,083
21	265	3119.9	1813.1	3139.5	2.352	7.6	76.4	435,035
54	265	3109.0	1810.5	3129.6	2.357	7.4	76.3	287,729
55	265	3114.7	1807.4	3127.7	2.359	7.3	75.5	337,065
69	265	3119.6	1811.0	3136.2	2.354	7.5	76.8	338,496
72	265	3119.0	1810.1	3131.0	2.361	7.2	76.0	303,359
Average:						7.4	76.2	339,795
Standard Deviation:						0.1	0.4	51,236
8	230	3113.8	1811.1	3136.7	2.349	7.7	77.1	398,798
24	230	3115.2	1814.8	3135.1	2.359	7.3	76.3	222,463
26	230	3118.2	1816.7	3144.6	2.348	7.7	77.6	302,232
60	230	3117.1	1810.6	3135.8	2.352	7.6	76.6	316,623
78	230	3119.3	1815.8	3135.3	2.364	7.1	76.9	454,714
82	230	3115.5	1817.8	3139.7	2.357	7.4	76.1	390,027
Average:						7.5	76.8	347,476
Standard Deviation:						0.2	0.5	83,153
120	190	3116.8	1819.5	3142.3	2.356	7.4	76.6	270,330
121	190	3117.2	1821.9	3143.2	2.359	7.3	77.2	202,146
108	190	3118.8	1815.9	3139.2	2.357	7.4	75.9	409,698
123	190	3115.7	1814.9	3132.6	2.364	7.1	75.8	245,769
118	190	3116.7	1818.0	3145.7	2.347	7.8	77.0	274,062
112	190	3117.7	1817.1	3143.5	2.350	7.6	76.2	219,205
Average:						7.4	76.5	270,202
Standard Deviation:						0.2	0.6	73,896

TABLE C6 Resilient Modulus Data for Limestone - Aspha-min® Zeolite

Aggregate: Limestone
Test Temperature: 77° F (25° C)
Asphalt Content: 4.8%
Poisson's Ratio: 0.35
Maximum Specific Gravity (Gmm): 2.544

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Sample Height, (mm)	Resilient Modulus (psi)
20	300	3111.4	1815.2	3118.1	2.388	6.1	74.5	478,491
27	300	3107.2	1809.0	3115.1	2.379	6.5	74.8	350,333
31	300	3112.1	1822.4	3119.9	2.399	5.7	76.2	475,634
45	300	3105.3	1817.5	3111.4	2.400	5.7	75.0	666,245
75	300	3105.7	1824.0	3112.0	2.411	5.2	74.0	322,710
79	300	3107.2	1823.1	3113.2	2.408	5.3	74.2	604,166
Average:						5.8	74.8	482,930
Standard Deviation:						0.5	0.8	135,372
3	265	3112.4	1808.6	3126.8	2.361	7.2	76.3	418,459
13	265	3111.6	1820.5	3120.6	2.393	5.9	76.2	309,849
16	265	3112.1	1813.5	3127.4	2.369	6.9	75.3	329,377
37	265	3105.8	1810.9	3114.2	2.383	6.3	75.5	315,048
40	265	3110.8	1816.4	3116.7	2.392	6.0	75.7	378,661
64	265	3114.5	1816.9	3123.0	2.385	6.3	76.0	324,986
Average:						6.4	75.8	346,063
Standard Deviation:						0.5	0.4	43,127
89	230	3117.0	1823.0	3127.2	2.390	6.1	74.6	434,645
92	230	3122.0	1823.9	3133.4	2.384	6.3	75.4	282,399
100	230	3115.6	1822.7	3124.0	2.394	5.9	74.7	278,984
104	230	3118.6	1818.9	3131.3	2.376	6.6	76.1	378,760
105	230	3116.1	1818.9	3126.8	2.383	6.3	75.0	205,147
106	230	3115.1	1817.8	3126.7	2.380	6.4	76.3	206,560
Average:						6.3	75.4	297,749
Standard Deviation:						0.3	0.7	92,500
115	190	3118.9	1821.3	3142.7	2.360	7.2	75.8	308,882
119	190	3119.3	1825.1	3142.7	2.367	6.9	76.0	364,895
127	190	3119.2	1825.8	3146.3	2.362	7.1	75.8	241,164
99	190	3120.3	1821.1	3138.8	2.368	6.9	76.4	353,368
114	190	3119.6	1824.0	3140.1	2.370	6.8	75.3	270,390
126	190	3120.7	1824.4	3144.1	2.365	7.0	77.1	307,420
Average:						7.0	76.1	307,687
Standard Deviation:						0.1	0.6	47,281

TABLE C7 Resilient Modulus Data for Limestone - Sasobit®

Aggregate: Limestone
Test Temperature: 77° F (25° C)
Asphalt Content: 4.8%
Poisson's Ratio: 0.35
Maximum Specific Gravity (Gmm): 2.545

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Sample Height, (mm)	Resilient Modulus (psi)
10	300	3139.1	1841.7	3145.5	2.408	5.4	74.8	337,358
17	300	3132.2	1838.8	3141.6	2.404	5.5	75.8	297,320
26	300	3137.9	1843.7	3149.6	2.403	5.6	75.5	471,217
40	300	3136.4	1845.7	3147.5	2.409	5.3	75.4	255,892
48	300	3134.3	1844.6	3146.2	2.408	5.4	75.9	181,684
39	300	3142.8	1845.9	3147.2	2.415	5.1	75.2	209,677
Average:						5.4	75.4	292,191
Standard Deviation:						0.2	0.4	104,360
29	265	3139.6	1831.4	3146.9	2.387	6.2	76.1	636,016
52	265	3141.3	1841.0	3147.4	2.405	5.5	75.4	446,225
38	265	3138.4	1829.1	3146.5	2.382	6.4	75.7	253,693
34	265	3174.6	1860.5	3182.6	2.401	5.7	76.8	332,667
49	265	3163.7	1856.3	3168.7	2.411	5.3	75.5	542,245
23	265	3132.5	1824.8	3140.5	2.381	6.4	75.4	434,460
Average:						5.9	75.8	440,884
Standard Deviation:						0.5	0.5	137,965
7	230	3154.5	1840.3	3174.6	2.364	7.1	76.4	298,667
9	230	3165.0	1850.8	3172.9	2.394	5.9	75.9	333,557
54	230	3133.4	1826.6	3145.9	2.375	6.7	75.5	444,113
8	230	3141.5	1830.2	3151.8	2.377	6.6	76.7	600,905
36	230	3141.4	1829.3	3149.1	2.380	6.5	75.9	330,688
51	230	3158.0	1843.1	3163.0	2.393	6.0	75.6	317,233
Average:						6.5	76.0	387,527
Standard Deviation:						0.4	0.4	116,373
1	190	3177.5	1853.7	3186.2	2.385	6.3	76.3	365,072
2	190	3142.3	1838.1	3149.6	2.396	5.9	75.7	500,290
3	190	3150.1	1843.4	3157.4	2.397	5.8	76.1	245,273
4	190	3149.2	1840.6	3154.7	2.396	5.8	75.3	425,107
5	190	3161.2	1848.5	3167.3	2.397	5.8	75.7	398,810
6	190	3133.2	1825.1	3139.6	2.384	6.3	75.0	314,439
Average:						6.0	75.7	374,832
Standard Deviation:						0.3	0.5	88,736

TABLE C8 Resilient Modulus Data for Limestone - Evotherm®

Aggregate: Limestone
Poisson's Ratio: 0.35
Test Temperature: 77° F (25° C)
Maximum Specific Gravity (Gmm): 2.547
Asphalt Content: 4.8%

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Sample Height, (mm)	Resilient Modulus (psi)
7	300	3257.9	1918.7	3262.7	2.424	4.8	77.2	347,682
17	300	3253.5	1916.1	3257.4	2.426	4.8	77.3	563,202
25	300	3263.5	1923.4	3267.4	2.428	4.7	76.4	271,011
29	300	3257.4	1922.3	3261.8	2.432	4.5	77.5	537,561
30	300	3260.4	1929.2	3265.3	2.440	4.2	76.2	375,629
37	300	3252.0	1920.0	3254.3	2.437	4.3	76.2	337,883
Average:						4.5	76.8	405,495
Standard Deviation:						0.3	0.6	117,647
1	265	3252.0	1906.2	3260.7	2.401	5.7	77.6	310,068
6	265	3255.7	1913.8	3261.5	2.416	5.2	76.6	279,233
9	265	3254.6	1911.4	3262.5	2.409	5.4	77.5	410,908
11	265	3252.9	1908.3	3257.4	2.411	5.3	77.8	538,571
23	265	3261.8	1914.1	3267.6	2.410	5.4	77.2	430,599
38	265	3253.9	1903.9	3259.1	2.401	5.7	77.1	336,251
Average:						5.5	77.3	384,272
Standard Deviation:						0.2	0.4	95,404
8	230	3260.0	1901.1	3269.9	2.382	6.5	78.6	435,817
12	230	3258.9	1905.0	3266.1	2.394	6.0	77.7	453,508
28	230	3260.8	1901.6	3268.7	2.385	6.4	78.0	716,368
32	230	3255.7	1905.4	3265.4	2.394	6.0	77.5	379,249
36	230	3260.6	1907.7	3267.6	2.398	5.9	77.6	352,414
42	230	3256.3	1895.9	3264.0	2.380	6.6	78.5	424,074
Average:						6.2	78.0	460,238
Standard Deviation:						0.3	0.5	130,948
1	190	3119.5	1821.2	3126.9	2.389	6.2	74.4	297,219
2	190	3126.5	1826.4	3137.1	2.385	6.3	75.4	408,175
15	190	3288.9	1919.1	3297.6	2.386	6.3	78.4	327,303
24	190	3256.5	1906.5	3267.1	2.393	6.0	77.7	311,189
26	190	3253.0	1903.0	3263.1	2.392	6.1	78.9	420,200
35	190	3256.8	1906.4	3266.7	2.394	6.0	78.9	289,257
Average:						6.2	77.3	342,224
Standard Deviation:						0.1	1.9	57,353

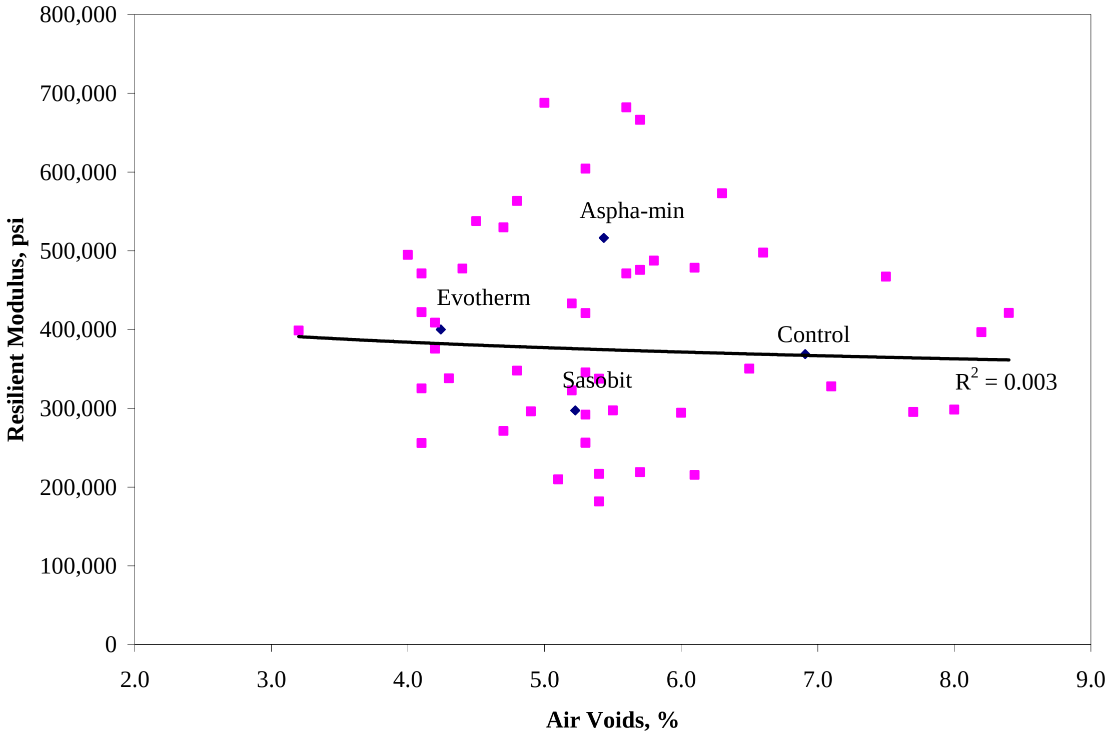

Figure C1. Relationship between Resilient Modulus and Air Voids.

APPENDIX D:

ASPHALT PAVEMENT ANALYZER DATA

TABLE D1 Asphalt Pavement Analyzer Data for Granite - No Additive

Aggregate:	Granite	Applied Wheel Load (lbs):	120
Test Temperature:	64° F (147° C)	Hose Presure (psi):	120
Asphalt Content:	5.1%	Maximum Specific Gravity (Gmm):	2.467

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Rut Depth, (mm)
18	300	3123.6	1782.0	3150.1	2.283	7.5	10.4
39	300	3127.9	1790.0	3138.2	2.320	6.0	8.1
42	300	3134.5	1783.1	3135.4	2.318	6.0	9.2
49	300	3125.3	1795.2	3133.3	2.336	5.3	7.6
51	300	3136.3	1795.1	3149.6	2.315	6.1	7.0
85	300	3121.7	1789.7	3131.6	2.326	5.7	4.1
Average:						6.1	7.7
Standard Deviation:						0.7	2.2
8	265	3112.1	1782.4	3123.2	2.321	5.9	13.4
29	265	3088.1	1772.1	3097.3	2.330	5.5	12.5
53	265	3129.6	1821.3	3226.3	2.227	9.7	9.0
67	265	3120.5	1788.2	3150.5	2.291	7.1	12.1
88	265	3110.3	1780.5	3136.0	2.295	7.0	13.4
89	265	3117.6	1784.8	3138.0	2.304	6.6	10.9
Average:						7.0	11.9
Standard Deviation:						1.5	1.7
101	230	3124.7	1804.6	3127.8	2.361	4.3	18.9
105	230	3127.0	1787.8	3132.9	2.325	5.8	10.8
109	230	3122.4	1788.7	3127.6	2.332	5.5	18.1
122	230	3124.5	1792.3	3131.1	2.334	5.4	15.9
104	230	3119.1	1794.7	3123.9	2.347	4.9	19.5
125	230	3127.6	1791.6	3133.4	2.331	5.5	11.6
Average:						5.2	15.8
Standard Deviation:						0.5	3.8
108	190	3122.6	1781.8	3131.8	2.313	6.2	19.4
112	190	3131.5	1783.8	3142.4	2.305	6.6	23.9
117	190	3123.6	1782.8	3136.9	2.307	6.5	22.0
127	190	3125.8	1780.9	3140.8	2.299	6.8	20.3
120	190	3124.2	1787.5	3133.2	2.322	5.9	13.6
116	190	3123.6	1784.4	3137.0	2.309	6.4	13.8
Average:						6.4	18.9
Standard Deviation:						0.3	4.3

TABLE D2 Asphalt Pavement Analyzer Data for Granite – Aspha-min® Zeolite

Aggregate:	Granite	Applied Wheel Load (lbs):	120
Test Temperature:	64° F (147° C)	Hose Presure (psi):	120
Asphalt Content:	5.1%	Maximum Specific Gravity (Gmm):	2.457

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Rut Depth, (mm)
36	300	3107.7	1789.4	3121.3	2.333	5.0	10.1
46	300	3106.5	1783.1	3123.0	2.318	5.6	11.7
48	300	3109.5	1783.2	3126.0	2.316	5.8	13.8
76	300	3110.8	1793.2	3128.8	2.329	5.2	15.5
82	300	3107.9	1793.5	3120.8	2.342	4.7	10.4
91	300	3107.9	1794.0	3117.7	2.348	4.4	5.9
Average:						5.1	11.2
Standard Deviation:						0.5	3.3
1	265	3103.0	1778.7	3118.5	2.316	5.7	10.6
16	265	3104.7	1781.6	3114.1	2.330	5.2	15.1
30	265	3105.1	1777.4	3117.7	2.317	5.7	14.3
58	265	3092.7	1770.8	3112.4	2.305	6.2	12.9
66	265	3097.1	1773.5	3130.0	2.283	7.1	22.0
77	265	3109.8	1779.4	3142.7	2.281	7.2	15.8
Average:						6.2	15.1
Standard Deviation:						0.8	3.9
11	230	3098.2	1765.8	3118.6	2.290	6.8	12.8
44	230	3102.8	1773.1	3123.9	2.297	6.5	9.8
69	230	3091.4	1770.9	3112.0	2.305	6.2	14.1
86	230	3104.2	1782.4	3112.8	2.333	5.0	8.9
97	230	3107.9	1777.8	3121.5	2.313	5.9	13.9
98	230	3106.8	1785.7	3125.3	2.319	5.6	17.8
Average:						6.0	12.9
Standard Deviation:						0.6	3.2
103	190	3114.9	1781.9	3121.3	2.326	5.3	14.4
113	190	3117.1	1777.1	3126.1	2.311	6.0	22.6
124	190	3115.1	1781.4	3129.0	2.312	5.9	13.6
119	190	3118.7	1784.4	3132.9	2.313	5.9	13.4
100	190	3115.8	1781.8	3128.1	2.314	5.8	14.7
107	190	3114.5	1781.8	3125.4	2.318	5.7	24.4
Average:						5.8	17.2
Standard Deviation:						0.2	5.0

TABLE D3 Asphalt Pavement Analyzer Data for Granite - Sasobit®

Aggregate:	Granite	Applied Wheel Load (lbs):	120
Test Temperature:	64° F (147° C)	Hose Presure (psi):	120
Asphalt Content:	5.1%	Maximum Specific Gravity (Gmm):	2.461

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Rut Depth, (mm)
34	300	3105.2	1782.0	3114.1	2.331	5.3	6.7
51	300	3104.9	1780.0	3112.0	2.331	5.3	2.2
16	300	3096.8	1776.4	3106.0	2.329	5.4	7.1
21	300	3109.2	1788.7	3117.3	2.340	4.9	5.4
3	300	3098.6	1789.5	3104.1	2.357	4.2	2.8
22	300	3100.2	1781.4	3111.9	2.330	5.3	4.5
Average:						5.1	4.8
Standard Deviation:						0.4	2.0
28	265	3096.9	1776.5	3104.3	2.332	5.2	4.4
27	265	3095.8	1768.0	3106.0	2.314	6.0	10.2
13	265	3112.5	1775.9	3121.8	2.313	6.0	10.0
35	265	3109.5	1781.9	3118.5	2.326	5.5	10.4
42	265	3105.0	1786.1	3114.1	2.338	5.0	6.2
52	265	3093.4	1778.9	3100.5	2.341	4.9	5.0
Average:						5.4	7.7
Standard Deviation:						0.5	2.8
37	230	3114.4	1790.5	3126.0	2.332	5.2	11.5
20	230	3095.9	1767.9	3105.8	2.314	6.0	11.4
11	230	3104.4	1780.1	3119.3	2.318	5.8	6.0
33	230	3112.8	1780.8	3121.6	2.322	5.7	8.4
41	230	3091.7	1770.4	3106.8	2.313	6.0	8.6
39	230	3090.9	1773.8	3103.2	2.325	5.5	10.3
Average:						5.7	9.4
Standard Deviation:						0.3	2.1
1	190	3114.1	1797.8	3118.9	2.357	4.2	8.2
2	190	3056.4	1758.6	3064.8	2.340	4.9	12.3
3	190	3073.3	1764.5	3080.5	2.335	5.1	6.6
4	190	3079.7	1769.8	3088.1	2.336	5.1	7.9
5	190	3074.6	1768.9	3081.9	2.342	4.8	13.5
6	190	3087.2	1780.5	3095.2	2.348	4.6	10.0
Average:						4.8	9.7
Standard Deviation:						0.3	2.7

TABLE D4 Asphalt Pavement Analyzer Data for Granite - Evotherm®

Aggregate: Granite
Test Temperature: 64° F (147° C)
Asphalt Content: 5.1%
Applied Wheel Load (lbs): 120
Hose Presure (psi): 120
Maximum Specific Gravity (Gmm): 2.465

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Rut Depth, (mm)
1	300	3071.0	1776.9	3076.0	2.364	4.1	6.4
2	300	3073.2	1778.0	3079.4	2.361	4.2	7.0
3	300	3073.8	1777.4	3079.0	2.362	4.2	8.4
4	300	3077.2	1793.3	3083.6	2.385	3.3	6.7
5	300	3067.4	1774.1	3073.4	2.361	4.2	8.6
6	300	3067.8	1773.7	3072.1	2.363	4.1	7.7
Average:						4.0	7.5
Standard Deviation:						0.4	0.9
3	265	3085.9	1776.6	3094.2	2.342	5.0	6.4
12	265	3087.2	1773.7	3103.9	2.321	5.8	7.0
20	265	3082.9	1777.7	3095.8	2.339	5.1	4.8
21	265	3083.5	1774.2	3092.4	2.339	5.1	8.6
24	265	3083.0	1773.7	3098.0	2.328	5.6	8.3
30	265	3071.2	1762.3	3080.9	2.329	5.5	9.3
Average:						5.4	7.4
Standard Deviation:						0.3	1.7
1	230	3080.7	1762.8	3088.6	2.324	5.7	10.1
4	230	3077.7	1752.0	3092.2	2.296	6.8	12.3
7	230	3087.9	1769.9	3092.1	2.335	5.3	14.7
14	230	3040.6	1755.2	3046.6	2.354	4.5	10.1
22	230	3066.7	1769.7	3072.4	2.354	4.5	16.6
39	230	3089.0	1782.8	3094.6	2.355	4.5	13.6
Average:						5.2	12.9
Standard Deviation:						0.9	2.6
2	190	3091.6	1781.2	3099.2	2.346	4.8	11.1
9	190	3096.4	1777.5	3106.7	2.330	5.5	16.9
23	190	3097.3	1781.5	3106.5	2.338	5.2	13.1
25	190	3106.3	1783.6	3116.3	2.331	5.4	5.5
32	190	3094.9	1779.2	3105.9	2.333	5.4	19.2
35	190	3061.0	1739.6	3071.3	2.299	6.8	18.1
Average:						5.5	14.0
Standard Deviation:						0.7	5.1

TABLE D5 Asphalt Pavement Analyzer Data for Limestone - No Additive

Aggregate:	Limestone	Applied Wheel Load (lbs):	120
Test Temperature:	64° F (147° C)	Hose Presure (psi):	120
Asphalt Content:	4.8%	Maximum Specific Gravity (Gmm):	2.545

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Rut Depth, (mm)
2	300	3074.8	1790.2	3103.3	2.342	8.0	5.4
7	300	3139.1	1822.5	3151.2	2.363	7.2	7.8
9	300	3129.7	1824.1	3141.7	2.375	6.7	7.8
44	300	3121.6	1811.0	3140.1	2.349	7.7	6.8
70	300	3144.3	1821.6	3167.7	2.336	8.2	10.4
94	300	3152.2	1824.6	3177.1	2.331	8.4	5.9
					Average:	7.7	7.3
					Standard Deviation:	0.7	1.8
11	265	3119.8	1813.8	3137.2	2.357	7.4	5.7
21	265	3119.9	1813.1	3139.5	2.352	7.6	4.1
54	265	3109.0	1810.5	3129.6	2.357	7.4	6.3
55	265	3114.7	1807.4	3127.7	2.359	7.3	10.1
69	265	3119.6	1811.0	3136.2	2.354	7.5	10.6
72	265	3119.0	1810.1	3131.0	2.361	7.2	5.7
					Average:	7.4	7.1
					Standard Deviation:	0.1	2.6
8	230	3113.8	1811.1	3136.7	2.349	7.7	7.6
24	230	3115.2	1814.8	3135.1	2.359	7.3	5.0
26	230	3118.2	1816.7	3144.6	2.348	7.7	9.9
60	230	3117.1	1810.6	3135.8	2.352	7.6	8.7
78	230	3119.3	1815.8	3135.3	2.364	7.1	16.1
82	230	3115.5	1817.8	3139.7	2.357	7.4	14.4
					Average:	7.5	10.3
					Standard Deviation:	0.2	4.2
120	190	3116.8	1819.5	3142.3	2.356	7.4	17.4
121	190	3117.2	1821.9	3143.2	2.359	7.3	7.2
108	190	3118.8	1815.9	3139.2	2.357	7.4	15.3
123	190	3115.7	1814.9	3132.6	2.364	7.1	6.9
118	190	3116.7	1818.0	3145.7	2.347	7.8	8.4
112	190	3117.7	1817.1	3143.5	2.350	7.6	8.0
					Average:	7.4	10.5
					Standard Deviation:	0.2	4.6

TABLE D6 Asphalt Pavement Analyzer Data for Limestone - Aspha-min® Zeolite

Aggregate: Limestone
Test Temperature: 64° F (147° C)
Asphalt Content: 4.8%
Applied Wheel Load (lbs): 120
Hose Presure (psi): 120
Maximum Specific Gravity (Gmm): 2.544

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Rut Depth, (mm)
20	300	3111.4	1815.2	3118.1	2.388	6.1	4.3
27	300	3107.2	1809.0	3115.1	2.379	6.5	3.9
31	300	3112.1	1822.4	3119.9	2.399	5.7	8.3
45	300	3105.3	1817.5	3111.4	2.400	5.7	7.4
75	300	3105.7	1824.0	3112.0	2.411	5.2	2.9
79	300	3107.2	1823.1	3113.2	2.408	5.3	2.1
					Average:	5.8	4.8
					Standard Deviation:	0.5	2.5
3	265	3112.4	1808.6	3126.8	2.361	7.2	6.7
13	265	3111.6	1820.5	3120.6	2.393	5.9	5.7
16	265	3112.1	1813.5	3127.4	2.369	6.9	4.5
37	265	3105.8	1810.9	3114.2	2.383	6.3	9.8
40	265	3110.8	1816.4	3116.7	2.392	6.0	7.3
64	265	3114.5	1816.9	3123.0	2.385	6.3	12.5
					Average:	6.4	7.7
					Standard Deviation:	0.5	2.9
89	230	3117.0	1823.0	3127.2	2.390	6.1	10.9
92	230	3122.0	1823.9	3133.4	2.384	6.3	13.0
100	230	3115.6	1822.7	3124.0	2.394	5.9	7.8
104	230	3118.6	1818.9	3131.3	2.376	6.6	5.2
105	230	3116.1	1818.9	3126.8	2.383	6.3	9.6
106	230	3115.1	1817.8	3126.7	2.380	6.4	7.4
					Average:	6.3	9.0
					Standard Deviation:	0.3	2.8
115	190	3118.9	1821.3	3142.7	2.360	7.2	17.8
119	190	3119.3	1825.1	3142.7	2.367	6.9	7.9
127	190	3119.2	1825.8	3146.3	2.362	7.1	5.9
99	190	3120.3	1821.1	3138.8	2.368	6.9	15.6
114	190	3119.6	1824.0	3140.1	2.370	6.8	5.8
126	190	3120.7	1824.4	3144.1	2.365	7.0	9.3
					Average:	7.0	10.4
					Standard Deviation:	0.1	5.1

TABLE D7 Asphalt Pavement Analyzer Data for Limestone - Sasobit®

Aggregate:	Limestone	Applied Wheel Load (lbs):	120
Test Temperature:	64° F (147° C)	Hose Presure (psi):	120
Asphalt Content:	4.8%	Maximum Specific Gravity (Gmm):	2.545

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Rut Depth, (mm)
10	300	3139.1	1841.7	3145.5	2.408	5.4	8.4
17	300	3132.2	1838.8	3141.6	2.404	5.5	14.7
26	300	3137.9	1843.7	3149.6	2.403	5.6	4.8
40	300	3136.4	1845.7	3147.5	2.409	5.3	7.9
48	300	3134.3	1844.6	3146.2	2.408	5.4	9.0
39	300	3142.8	1845.9	3147.2	2.415	5.1	15.9
					Average:	5.4	10.1
					Standard Deviation:	0.2	4.3
29	265	3139.6	1831.4	3146.9	2.387	6.2	8.4
52	265	3141.3	1841.0	3147.4	2.405	5.5	6.9
38	265	3138.4	1829.1	3146.5	2.382	6.4	5.8
34	265	3174.6	1860.5	3182.6	2.401	5.7	3.1
49	265	3163.7	1856.3	3168.7	2.411	5.3	8.0
23	265	3132.5	1824.8	3140.5	2.381	6.4	7.1
					Average:	5.9	6.5
					Standard Deviation:	0.5	1.9
7	230	3154.5	1840.3	3174.6	2.364	7.1	5.2
9	230	3165.0	1850.8	3172.9	2.394	5.9	7.2
54	230	3133.4	1826.6	3145.9	2.375	6.7	8.1
8	230	3141.5	1830.2	3151.8	2.377	6.6	8.3
36	230	3141.4	1829.3	3149.1	2.380	6.5	5.5
51	230	3158.0	1843.1	3163.0	2.393	6.0	8.5
					Average:	6.5	7.1
					Standard Deviation:	0.4	1.5
1	190	3177.5	1853.7	3186.2	2.385	6.3	8.1
2	190	3142.3	1838.1	3149.6	2.396	5.9	5.6
3	190	3150.1	1843.4	3157.4	2.397	5.8	10.3
4	190	3149.2	1840.6	3154.7	2.396	5.8	4.1
5	190	3161.2	1848.5	3167.3	2.397	5.8	6.9
6	190	3133.2	1825.1	3139.6	2.384	6.3	5.1
					Average:	6.0	6.7
					Standard Deviation:	0.3	2.2

TABLE D8 Asphalt Pavement Analyzer Data for Limestone - Evotherm®

Aggregate:	Limestone	Applied Wheel Load (lbs):	120
Test Temperature:	64° F (147° C)	Hose Presure (psi):	120
Asphalt Content:	4.8%	Maximum Specific Gravity (Gmm):	2.547

Sample Number	Compaction Temperature (°F)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Rut Depth, (mm)
7	300	3257.9	1918.7	3262.7	2.424	4.8	2.4
17	300	3253.5	1916.1	3257.4	2.426	4.8	5.1
25	300	3263.5	1923.4	3267.4	2.428	4.7	3.2
29	300	3257.4	1922.3	3261.8	2.432	4.5	4.3
30	300	3260.4	1929.2	3265.3	2.440	4.2	4.3
37	300	3252.0	1920.0	3254.3	2.437	4.3	5.1
Average:						4.5	4.1
Standard Deviation:						0.3	1.1
1	265	3252.0	1906.2	3260.7	2.401	5.7	9.0
6	265	3255.7	1913.8	3261.5	2.416	5.2	6.9
9	265	3254.6	1911.4	3262.5	2.409	5.4	4.4
11	265	3252.9	1908.3	3257.4	2.411	5.3	4.6
23	265	3261.8	1914.1	3267.6	2.410	5.4	6.7
38	265	3253.9	1903.9	3259.1	2.401	5.7	8.2
Average:						5.5	6.6
Standard Deviation:						0.2	1.9
8	230	3260.0	1901.1	3269.9	2.382	6.5	14.0
12	230	3258.9	1905.0	3266.1	2.394	6.0	12.2
28	230	3260.8	1901.6	3268.7	2.385	6.4	6.1
32	230	3255.7	1905.4	3265.4	2.394	6.0	11.3
36	230	3260.6	1907.7	3267.6	2.398	5.9	11.5
42	230	3256.3	1895.9	3264.0	2.380	6.6	6.9
Average:						6.2	10.3
Standard Deviation:						0.3	3.1
1	190	3119.5	1821.2	3126.9	2.389	6.2	18.6
2	190	3126.5	1826.4	3137.1	2.385	6.3	8.1
15	190	3288.9	1919.1	3297.6	2.386	6.3	9.5
24	190	3256.5	1906.5	3267.1	2.393	6.0	11.0
26	190	3253.0	1903.0	3263.1	2.392	6.1	14.2
35	190	3256.8	1906.4	3266.7	2.394	6.0	14.4
Average:						6.2	12.6
Standard Deviation:						0.1	3.9

APPENDIX E:

INDIRECT TENSILE STRENGTH DATA

TABLE E1 Strength Gain Data for Granite - No Additive

Aggregate:		Granite							
Asphalt Content:		5.1%	Maximum Specific Gravity (Gmm):					2.467	
Sample Number	Short Term Age @ 110°C (230°F) (hrs)	Long Term Age @ 85°C (185°F) (days)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Maximum Load (lbs)	Tensile Strength (psi)
1	2	0	3696.6	2110.1	3723.2	2.292	7.1	3600	104.4
2	2	0	3698.0	2104.0	3722.5	2.285	7.4	3475	100.8
Average:							7.2	3538	102.6
Standard Deviation:							0.2	88	2.5
3	4	0	3713.5	2130.9	3740.3	2.307	6.5	5075	147.2
4	4	0	3708.8	2113.4	3737.7	2.283	7.4	3300	95.7
Average:							7.0	4188	121.5
Standard Deviation:							0.7	1255	36.4
5	2	1	3718.8	2119.1	3740.9	2.293	7.1	2250	65.3
6	2	1	3715.9	2116.3	3735.2	2.295	7.0	2400	69.6
Average:							7.0	2325	67.5
Standard Deviation:							0.1	106	3.0
7	2	3	3696.8	2112.1	3727.2	2.289	7.2	3200	92.8
8	2	3	3691.4	2114.1	3716.0	2.304	6.6	3600	104.4
Average:							6.9	3400	98.6
Standard Deviation:							0.4	283	8.2
9	2	5	3698.0	2110.8	3727.6	2.287	7.3	3250	94.3
10	2	5							
Average:							7.3	3250	94.3
Standard Deviation:									

TABLE E2 Strength Gain Data for Granite - Aspha-min® Zeolite

Aggregate:		Granite							
Asphalt Content:		5.1%	Maximum Specific Gravity (Gmm):					2.457	
Sample Number	Short Term Age @ 110°C (230°F) (hrs)	Long Term Age @ 85°C (185°F) (days)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Maximum Load (lbs)	Tensile Strength (psi)
1	2	0	3699.9	2126.5	3725.8	2.313	5.8	4175	121.1
2	2	0	3696.7	2105.6	3719.5	2.291	6.8	3850	111.7
						Average:	6.3	4013	116.4
						Standard Deviation:	0.7	230	6.6
3	4	0	3693.4	2098.8	3714.4	2.286	7.0	4000	116.0
4	4	0	3695.1	2104.7	3716.9	2.292	6.7	4150	120.4
						Average:	6.8	4075	118.2
						Standard Deviation:	0.2	106	3.1
5	2	1	3694.9	2108.1	3719.3	2.293	6.7	2450	71.1
6	2	1	3695.9	2105.1	3713.3	2.298	6.5	2525	73.2
						Average:	6.6	2488	72.2
						Standard Deviation:	0.1	53	1.5
7	2	3	3694.0	2103.6	3722.0	2.283	7.1	3350	97.2
8	2	3	3705.1	2114.2	3734.4	2.287	6.9	3750	108.8
						Average:	7.0	3550	103.0
						Standard Deviation:	0.1	283	8.2
9	2	5	3696.7	2110.4	3718.4	2.299	6.4	2900	84.1
10	2	5	3698.5	2115.1	3727.9	2.293	6.7	3100	89.9
						Average:	6.5	3000	87.0
						Standard Deviation:	0.2	141	4.1

TABLE E3 Strength Gain Data for Granite - Sasobit®

	Aggregate:	Granite							
	Asphalt Content:	5.1%	Maximum Specific Gravity (Gmm):					2.461	
Sample Number	Short Term Age @ 110°C (230°F) (hrs)	Long Term Age @ 85°C (185°F) (days)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Maximum Load (lbs)	Tensile Strength (psi)
1	2	0	3671.5	2086.4	3709.9	2.261	8.1	1600	46.4
2	2	0	3699.2	2104.6	3723.5	2.285	7.2	1675	48.6
						Average:	7.6	1638	47.5
						Standard Deviation:	0.7	53	1.5
3	4	0	3666.5	2082.4	3702.4	2.263	8.0	2025	58.7
4	4	0	3698.4	2106.7	3724.7	2.286	7.1	2100	60.9
						Average:	7.6	2063	59.8
						Standard Deviation:	0.6	53	1.5
5	2	1	3694.7	2095.0	3719.2	2.275	7.6	2250	65.3
6	2	1	3695.2	2093.9	3725.3	2.265	8.0	2250	65.3
						Average:	7.8	2250	65.3
						Standard Deviation:	0.3	0	0.0
7	2	3	3688.6	2099.3	3721.2	2.274	7.6	1825	52.9
8	2	3	3676.0	2092.0	3707.0	2.276	7.5	1950	56.6
						Average:	7.5	1888	54.7
						Standard Deviation:	0.1	88	2.6
9	2	5	3681.2	2096.1	3709.8	2.281	7.3	3200	92.8
10	2	5	3680.6	2089.9	3718.3	2.260	8.2	3075	89.2
						Average:	7.7	3138	91.0
						Standard Deviation:	0.6	88	2.6

TABLE E4 Strength Gain Data for Granite - Evotherm®

Aggregate:		Granite							
Asphalt Content:		5.1%	Maximum Specific Gravity (Gmm):					2.465	
Sample Number	Short Term Age @ 110°C (230°F) (hrs)	Long Term Age @ 85°C (185°F) (days)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Maximum Load (lbs)	Tensile Strength (psi)
1	2	0	3760.9	2150.1	3781.6	2.305	6.5	3700	107.3
2	2	0	3685.3	2093.6	3714.8	2.273	7.8	3500	101.5
						Average:	7.1	3600	104.4
						Standard Deviation:	0.9	141	4.1
3	4	0	3686.1	2101.4	3714.5	2.285	7.3	4700	136.3
4	4	0							
						Average:	7.3	4700	136.3
						Standard Deviation:			
5	2	1	3753.2	2117.8	3771.2	2.270	7.9	2075	60.2
6	2	1	3764.3	2147.6	3782.8	2.302	6.6	2100	60.9
						Average:	7.3	2088	60.5
						Standard Deviation:	0.9	18	0.5
7	2	3	3754.7	2145.4	3778.8	2.299	6.7	3575	103.7
8	2	3	3748.2	2146.5	3781.1	2.293	7.0	3500	101.5
						Average:	6.9	3538	102.6
						Standard Deviation:	0.2	53	1.5
9	2	5	3763.9	2133.3	3785.6	2.278	7.6	4350	126.2
10	2	5	3765.5	2148.6	3783.9	2.303	6.6	4650	134.9
						Average:	7.1	4500	130.5
						Standard Deviation:	0.7	212	6.2

TABLE E5 Strength Gain Data for Limestone - No Additive

	Aggregate:	Limestone							
	Asphalt Content:	4.8%				Maximum Specific Gravity (Gmm):		2.545	
Sample Number	Short Term Age @ 110°C (230°F) (hrs)	Long Term Age @ 85°C (185°F) (days)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Maximum Load (lbs)	Tensile Strength (psi)
1	2	0	3894.8	2278.6	3915.2	2.380	6.5	4600	133.4
2	2	0	3895.0	2281.7	3921.4	2.375	6.7	4550	132.0
						Average:	6.6	4575	132.7
						Standard Deviation:	0.1	35	1.0
3	4	0	3890.5	2273.7	3917.6	2.367	7.0	3750	108.8
4	4	0	3895.5	2281.9	3919.2	2.379	6.5	3900	113.1
						Average:	6.8	3825	110.9
						Standard Deviation:	0.3	106	3.1
5	2	1	3895.2	2280.7	3919.5	2.377	6.6	3150	91.4
6	2	1	3897.6	2283.6	3919.9	2.382	6.4	2600	75.4
						Average:	6.5	2875	83.4
						Standard Deviation:	0.1	389	11.3
7	2	3	3880.9	2264.6	3908.9	2.360	7.3	2900	84.1
8	2	3	3889.4	2275.3	3915.2	2.372	6.8	2800	81.2
						Average:	7.0	2850	82.7
						Standard Deviation:	0.3	71	2.1
9	2	5	3896.5	2283.7	3921.8	2.379	6.5	2575	74.7
10	2	5	3886.1	2273.2	3911.8	2.372	6.8	2575	74.7
						Average:	6.7	2575	74.7
						Standard Deviation:	0.2	0	0.0

TABLE E6 Strength Gain Data for Limestone - Aspha-min® Zeolite

Aggregate:		Limestone							
Asphalt Content:		4.8%	Maximum Specific Gravity (Gmm):					2.544	
Sample Number	Short Term Age @ 110°C (230°F) (hrs)	Long Term Age @ 85°C (185°F) (days)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Maximum Load (lbs)	Tensile Strength (psi)
1	2	0	3908.4	2287.1	3925.2	2.386	6.2	4000	115.6
2	2	0	3906.7	2283.5	3926.6	2.378	6.5	4000	115.6
						Average:	6.4	4000	115.6
						Standard Deviation:	0.2	0	0.0
3	4	0	3907.4	2293.1	3933.3	2.382	6.4	3800	110.2
4	4	0	3910.9	2291.5	3932.1	2.384	6.3	3900	112.8
						Average:	6.3	3850	111.5
						Standard Deviation:	0.0	71	1.8
5	2	1	3906.0	2291.0	3926.4	2.388	6.1	2700	77.9
6	2	1	3908.8	2292.5	3929.2	2.388	6.1	2675	77.3
						Average:	6.1	2688	77.6
						Standard Deviation:	0.0	18	0.4
7	2	3	3905.1	2287.5	3930.6	2.377	6.6	3100	90.0
8	2	3	3901.9	2283.1	3925.9	2.375	6.6	3075	89.3
						Average:	6.6	3088	89.7
						Standard Deviation:	0.0	18	0.5
9	2	5	3916.7	2291.7	3935.7	2.382	6.4	2750	79.7
10	2	5	3910.0	2293.1	3934.8	2.382	6.4	2800	81.3
						Average:	6.4	2775	80.5
						Standard Deviation:	0.0	35	1.1

TABLE E7 Strength Gain Data for Limestone - Sasobit®

Aggregate:		Limestone							
Asphalt Content:		4.8%	Maximum Specific Gravity (Gmm):					2.545	
Sample Number	Short Term Age @ 110°C (230°F) (hrs)	Long Term Age @ 85°C (185°F) (days)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Maximum Load (lbs)	Tensile Strength (psi)
1	2	0	3878.5	2256.0	3898.8	2.361	7.2	3900	113.1
2	2	0	3881.2	2259.0	3900.8	2.364	7.1	3950	114.6
Average:							7.2	3925	113.8
Standard Deviation:							0.1	35	1.0
3	4	0	3874.9	2267.7	3900.4	2.373	6.7	3950	114.6
4	4	0	3884.9	2269.6	3911.0	2.367	7.0	3750	108.8
Average:							6.9	3850	111.7
Standard Deviation:							0.2	141	4.1
5	2	1	3883.9	2277.3	3907.5	2.382	6.4	1300	37.7
6	2	1	3878.1	2261.1	3902.2	2.363	7.1	1300	37.7
Average:							6.8	1300	37.7
Standard Deviation:							0.5	0	0.0
7	2	3	3883.9	2267.0	3903.2	2.374	6.7	1725	50.0
8	2	3	3884.9	2263.5	3903.0	2.370	6.9	2225	64.5
Average:							6.8	1975	57.3
Standard Deviation:							0.1	354	10.3
9	2	5	3863.2	2247.5	3895.6	2.344	7.9	3000	87.0
10	2	5	3878.5	2261.0	3904.9	2.359	7.3	3925	113.8
Average:							7.6	3463	100.4
Standard Deviation:							0.4	654	19.0

TABLE E8 Strength Gain Data for Limestone - Evotherm®

	Aggregate:	Limestone							
	Asphalt Content:	4.8%	Maximum Specific Gravity (Gmm):					2.547	
Sample Number	Short Term Age @ 110°C (230°F) (hrs)	Long Term Age @ 85°C (185°F) (days)	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	VTM, %	Maximum Load (lbs)	Tensile Strength (psi)
1	2	0	3832.1	2246	3879.9	2.345	7.9	2600	75.4
2	2	0	3829.1	2243.9	3869.3	2.356	7.5	2700	78.3
						Average:	7.7	2650	76.9
						Standard Deviation:	0.3	71	2.1
3	4	0	3830.1	2248.6	3881	2.346	7.9	3700	107.3
4	4	0	3831.9	2246.5	3883.7	2.341	8.1	3550	103.0
						Average:	8.0	3625	105.1
						Standard Deviation:	0.2	106	3.1
5	2	1	3832.9	2254.6	3880.8	2.357	7.5	2500	72.5
6	2	1	3832.7	2253.8	3876.3	2.362	7.3	2475	71.8
						Average:	7.4	2488	72.2
						Standard Deviation:	0.1	18	0.5
7	2	3	3834.4	2251.4	3881.1	2.353	7.6	2525	73.2
8	2	3	3834.2	2249.1	3885.4	2.343	8.0	2400	69.6
						Average:	7.8	2463	71.4
						Standard Deviation:	0.3	88	2.6
9	2	5	3839	2241.1	3872.3	2.353	7.6	3200	92.8
10	2	5	3847.1	2246.8	3877.4	2.359	7.4	3075	89.2
						Average:	7.5	3138	91.0
						Standard Deviation:	0.2	88	2.6

APPENDIX F:

MOISTURE RESISTANCE DATA

TABLE F1 Moisture Resistance Results for Granite – ASTM D4867

Sample Identification: Granite; PG 64-22 Control: ASTM D 4867

	Conditioned Samples			Unconditioned Samples		
Sample Number	3	6	7	2	4	5
(A) Diameter, in	5.920	5.920	5.920	5.920	5.920	5.920
(B) Height, in	3.710	3.710	3.710	3.710	3.710	3.710
(C) Weight in Air, gm	3703.4	3698.8	3699.9	3701.3	3702.6	3704.4
(D) SSD Weight, gm	3733.7	3729.7	3733.2	3734.4	3737.8	3738.6
(E) Submerged Weight, gm	2108.2	2110.3	2111.3	2114.6	2112.5	2110.6
(F) Bulk Specific Gravity [A/(D - E)]	2.278	2.284	2.281	2.285	2.278	2.275
(G) Theoretical Maximum Gravity	2.467	2.467	2.467	2.467	2.467	2.467
(H) % Air Voids [100*(1-F/G)]	7.6	7.4	7.5	7.4	7.7	7.8
(I) Volume of Air Voids [H*(D - E)/100]	124.324	120.089	122.143	119.476	124.449	126.419
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3797.6	3793.0	3787.1	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	94.20	94.20	87.20			
(L) % Saturation [100*(K/I)]	75.8	78.4	71.4			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	4325	4125	4325	4800	4100	4200
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	139.1	118.8	121.7
(R) Conditioned S_T, psi [2P/(A*B*π)]	125.4	119.6	125.4	N/A	N/A	N/A
(S) Average S_T, psi	123.4			126.6		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.98		

TABLE F2 Moisture Resistance Results for Granite – ASTM D4867 with Aspha-min® Zeolite

Sample Identification: Granite; PG 64-22 with Zeolite: ASTM D 4867

	Conditioned Samples			Unconditioned Samples		
Sample Number	1	3	4	1	3	5
(A) Diameter, in	5.931	5.911	5.929	5.910	5.910	5.920
(B) Height, in	3.726	3.727	3.739	3.720	3.730	3.730
(C) Weight in Air, gm	3747.1	3760.3	3739.8	3736.6	3774.6	3760.5
(D) SSD Weight, gm	3765.2	3776.7	3765.7	3756.4	3787.4	3777.4
(E) Submerged Weight, gm	2136.7	2142.3	2132.1	2122.9	2153.2	2143.5
(F) Bulk Specific Gravity [A/(D - E)]	2.301	2.301	2.289	2.287	2.310	2.302
(G) Theoretical Maximum Gravity	2.457	2.457	2.457	2.457	2.457	2.457
(H) % Air Voids [100*(1-F/G)]	6.4	6.4	6.8	6.9	6.0	6.3
(I) Volume of Air Voids [H*(D - E)/100]	103.429	103.956	111.500	112.702	97.936	103.375
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3816.5	3825.3	3819.7	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	69.40	65.00	79.90			
(L) % Saturation [100*(K/I)]	67.1	62.5	71.7			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	4450	4400	4300	5175	5325	5600
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	149.9	153.8	161.4
(R) Conditioned S_T, psi [2P/(A*B*π)]	128.2	127.1	123.5	N/A	N/A	N/A
(S) Average S_T, psi	126.3			155.0		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.81		

TABLE F3 Moisture Resistance Results for Granite – ASTM D4867 with Sasobit® and 250°F Compaction Temperature

Sample Identification: Granite; PG 64-22 Sasobit @ 250F with 2 hr. Age: ASTM D 4867

	Conditioned Samples			Unconditioned Samples		
Sample Number	6	8	9	1	5	7
(A) Diameter, in	5.928	5.924	5.926	5.934	5.935	5.928
(B) Height, in	3.726	3.728	3.721	3.727	3.738	3.722
(C) Weight in Air, gm	3753.5	3719.8	3723.2	3726.8	3741.7	3717.7
(D) SSD Weight, gm	3765.8	3746.2	3742.3	3743.4	3763.0	3745.0
(E) Submerged Weight, gm	2140.3	2121.6	2117.0	2117.6	2144.6	2114.3
(F) Bulk Specific Gravity [A/(D - E)]	2.309	2.290	2.291	2.292	2.312	2.280
(G) Theoretical Maximum Gravity	2.461	2.461	2.461	2.461	2.461	2.461
(H) % Air Voids [100*(1-F/G)]	6.2	7.0	6.9	6.9	6.1	7.4
(I) Volume of Air Voids [H*(D - E)/100]	100.307	113.101	112.419	111.456	98.002	120.054
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3826.7	3803.8	3811.3	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	73.20	84.00	88.10			
(L) % Saturation [100*(K/I)]	73.0	74.3	78.4			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	1525	1325	1375	2100	2100	2000
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	60.4	60.3	57.7
(R) Conditioned S_T, psi [2P/(A*B*π)]	44.0	38.2	39.7	N/A	N/A	N/A
(S) Average S_T, psi	40.6			59.5		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.68		

TABLE F4 Moisture Resistance Results for Granite – No Additives

Sample Identification: Granite; PG 64-22 Control @ 250F with 0 hr. Age

	Conditioned Samples			Unconditioned Samples		
Sample Number	4		6	1		3
(A) Diameter, in	5.917		5.916	5.904		5.910
(B) Height, in	3.709		3.710	3.727		3.723
(C) Weight in Air, gm	3693.5		3692.2	3692.7		3697.0
(D) SSD Weight, gm	3713.1		3705.5	3716.3		3720.1
(E) Submerged Weight, gm	2104.1		2093.3	2102.2		2105.2
(F) Bulk Specific Gravity [A/(D - E)]	2.296		2.290	2.288		2.289
(G) Theoretical Maximum Gravity	2.467		2.467	2.467		2.467
(H) % Air Voids [100*(1-F/G)]	7.0		7.2	7.3		7.2
(I) Volume of Air Voids [H*(D - E)/100]	111.837		115.564	117.262		116.319
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3763.5		3755.6	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	70.00		63.40			
(L) % Saturation [100*(K/I)]	62.6		54.9			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	2650		2925	2650		2600
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	76.7		75.2
(R) Conditioned S_T, psi [2P/(A*B*π)]	76.9		84.8	N/A	N/A	N/A
(S) Average S_T, psi	80.9			75.9		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				1.06		

TABLE F5 Moisture Resistance Results for Granite – Aspha-min® Zeolite

Sample Identification: Granite; PG 64-22 Warm @ 250F with 0 hr. Age

	Conditioned Samples			Unconditioned Samples		
Sample Number	3	4	6	1	2	5
(A) Diameter, in	5.889	5.919	5.919	5.905	5.896	5.920
(B) Height, in	3.699	3.711	3.711	3.679	3.702	3.694
(C) Weight in Air, gm	3688.2	3682.7	3688.5	3682.1	3684.7	3682.7
(D) SSD Weight, gm	3707.1	3701.9	3709.1	3693.2	3696.2	3701.9
(E) Submerged Weight, gm	2088.0	2082.5	2093.4	2087.0	2089.0	2082.0
(F) Bulk Specific Gravity [A/(D - E)]	2.278	2.274	2.283	2.292	2.293	2.273
(G) Theoretical Maximum Gravity	2.457	2.457	2.457	2.457	2.457	2.457
(H) % Air Voids [100*(1-F/G)]	7.3	7.4	7.1	6.7	6.7	7.5
(I) Volume of Air Voids [H*(D - E)/100]	118.001	120.540	114.479	107.584	107.526	121.040
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3759.3	3776.2	3776.0	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	71.10	93.50	87.50			
(L) % Saturation [100*(K/I)]	60.3	77.6	76.4			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	1850	1600	1575	2550	2400	2500
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	74.7	70.0	72.8
(R) Conditioned S_T, psi [2P/(A*B*π)]	54.1	46.4	45.6	N/A	N/A	N/A
(S) Average S_T, psi	48.7			72.5		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.67		

TABLE F6 Moisture Resistance Results for Granite – Sasobit®

Sample Identification: Granite; PG 64-22 Sasobit® @ 250F with 0 hr. Age

	Conditioned Samples			Unconditioned Samples		
Sample Number	2	3	4	5	6	
(A) Diameter, in	5.922	5.930	5.934	5.929	5.930	
(B) Height, in	3.726	3.715	3.709	3.710	3.703	
(C) Weight in Air, gm	3771.8	3734.0	3766.6	3766.7	3740.4	
(D) SSD Weight, gm	3783.0	3750.1	3774.8	3773.5	3753.7	
(E) Submerged Weight, gm	2151.6	2129.3	2147.0	2139.9	2137.0	
(F) Bulk Specific Gravity [A/(D - E)]	2.312	2.304	2.314	2.306	2.314	
(G) Theoretical Maximum Gravity	2.461	2.461	2.461	2.461	2.461	
(H) % Air Voids [100*(1-F/G)]	6.1	6.4	6.0	6.3	6.0	
(I) Volume of Air Voids [H*(D - E)/100]	98.771	103.531	97.284	103.043	96.830	
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3844.3	3814.0	3831.2	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	72.50	80.00	64.60			
(L) % Saturation [100*(K/I)]	73.4	77.3	66.4			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	1300	1300	1350	1875	1800	
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	54.3	52.2	
(R) Conditioned S_T, psi [2P/(A*B*π)]	37.5	37.6	39.0	N/A	N/A	N/A
(S) Average S_T, psi	38.0			53.2		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.71		

TABLE F7 Moisture Resistance Results for Granite – Evotherm®

Sample Identification: Granite; PG 64-22 Evotherm® @ 250F with 0 hr. Age

	Conditioned Samples			Unconditioned Samples		
Sample Number	2	3	6	7	8	
(A) Diameter, in	5.948	5.961	5.969	5.962	5.972	
(B) Height, in	3.701	3.707	3.715	3.732	3.725	
(C) Weight in Air, gm	3710.9	3713.4	3745.7	3753.8	3760.3	
(D) SSD Weight, gm	3727.7	3728.1	3765.4	3768.8	3773.6	
(E) Submerged Weight, gm	2099.8	2091.1	2119.4	2115.2	2120.6	
(F) Bulk Specific Gravity [A/(D - E)]	2.280	2.268	2.276	2.270	2.275	
(G) Theoretical Maximum Gravity	2.465	2.465	2.465	2.465	2.465	
(H) % Air Voids [100*(1-F/G)]	7.5	8.0	7.7	7.9	7.7	
(I) Volume of Air Voids [H*(D - E)/100]	122.464	130.550	126.446	130.760	127.523	
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3805.3	3812.2	3845.1	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	94.40	98.80	99.40			
(L) % Saturation [100*(K/I)]	77.1	75.7	78.6			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	2300	2200	2550	2550	2400	
(Q) Dry S_T, psi [$2P/(A*B*\pi)$]	N/A	N/A	N/A	73.0	68.7	
(R) Conditioned S_T, psi [$2P/(A*B*\pi)$]	66.5	63.4	73.2	N/A	N/A	N/A
(S) Average S_T, psi	67.7			70.8		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:					0.96	

TABLE F8 Moisture Resistance Results for Limestone – No Additives

Sample Identification: LMS; PG 64-22 Control @ 250F with 0 hr. Age

	Conditioned Samples			Unconditioned Samples		
Sample Number	3	5	6	1	2	4
(A) Diameter, in	5.922	5.946	5.924	5.913	5.913	5.929
(B) Height, in	3.711	3.690	3.686	3.712	3.700	3.684
(C) Weight in Air, gm	3834.5	3841.6	3837.4	3843.6	3833.2	3837.1
(D) SSD Weight, gm	3850.5	3849.5	3845.7	3858.1	3850.3	3844.9
(E) Submerged Weight, gm	2241.2	2241.8	2240.9	2246.9	2244.1	2240.1
(F) Bulk Specific Gravity [A/(D - E)]	2.383	2.390	2.391	2.386	2.387	2.391
(G) Theoretical Maximum Gravity	2.544	2.544	2.544	2.544	2.544	2.544
(H) % Air Voids [100*(1-F/G)]	6.3	6.1	6.0	6.2	6.2	6.0
(I) Volume of Air Voids [H*(D - E)/100]	102.028	97.637	96.388	100.351	99.439	96.506
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3908.6	3910.2	3900.5	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	74.10	68.60	63.10			
(L) % Saturation [100*(K/I)]	72.6	70.3	65.5			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	2450	2350	2550	3800	3850	3650
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	110.2	112.0	106.4
(R) Conditioned S_T, psi [2P/(A*B*π)]	71.0	68.2	74.3	N/A	N/A	N/A
(S) Average S_T, psi	71.2			109.5		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.65		

TABLE F9 Moisture Resistance Results for Limestone – Aspha-min® Zeolite

Sample Identification: LMS; PG 64-22 Warm @ 250F with 0 hr. Age

	Conditioned Samples			Unconditioned Samples		
Sample Number	2	3	5	1	6	
(A) Diameter, in	5.918	5.915	5.921	5.916	5.910	
(B) Height, in	3.698	3.693	3.695	3.704	3.659	
(C) Weight in Air, gm	3817.3	3821.0	3814.5	3816.0	3818.8	
(D) SSD Weight, gm	3830.1	3835.1	3826.4	3830.3	3829.5	
(E) Submerged Weight, gm	2210.3	2218.8	2229.4	2214.0	2233.3	
(F) Bulk Specific Gravity [A/(D - E)]	2.357	2.364	2.389	2.361	2.392	
(G) Theoretical Maximum Gravity	2.544	2.544	2.544	2.544	2.544	
(H) % Air Voids [100*(1-F/G)]	7.4	7.1	6.1	7.2	6.0	
(I) Volume of Air Voids [H*(D - E)/100]	119.289	114.335	97.590	116.300	95.099	
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3901.0	3908.7	3883.2	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	83.70	87.70	68.70			
(L) % Saturation [100*(K/I)]	70.2	76.7	70.4			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	1500	1550	1500	2950	2975	
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	85.7	87.6	
(R) Conditioned S_T, psi [2P/(A*B*π)]	43.6	45.2	43.6	N/A	N/A	N/A
(S) Average S_T, psi	44.2			86.6		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.51		

TABLE F10 Moisture Resistance Results for Limestone – Sasobit®

Sample Identification: LMS; PG 64-22 Sasobit® @ 250F with 0 hr. Age

	Conditioned Samples			Unconditioned Samples		
Sample Number	2	4	5	1	3	6
(A) Diameter, in	5.934	5.934	5.925	5.961	5.921	5.922
(B) Height, in	3.686	3.678	3.679	3.688	3.675	3.685
(C) Weight in Air, gm	3812.7	3819.8	3817.7	3814.9	3818.5	3811.1
(D) SSD Weight, gm	3823.3	3828.1	3828.1	3824.9	3828.1	3822.0
(E) Submerged Weight, gm	2214.8	2220.6	2216.2	2204.8	2227.3	2213.7
(F) Bulk Specific Gravity [A/(D - E)]	2.370	2.376	2.368	2.355	2.385	2.370
(G) Theoretical Maximum Gravity	2.545	2.545	2.545	2.545	2.545	2.545
(H) % Air Voids [100*(1-F/G)]	6.9	6.6	6.9	7.5	6.3	6.9
(I) Volume of Air Voids [H*(D - E)/100]	110.386	106.596	111.821	121.122	100.407	110.815
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3888.4	3891.2	3885.9	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	75.70	71.40	68.20			
(L) % Saturation [100*(K/I)]	68.6	67.0	61.0			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	1800	1575	1675	1900	1850	1800
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	55.0	54.1	52.5
(R) Conditioned S_T, psi [2P/(A*B*π)]	52.4	45.9	48.9	N/A	N/A	N/A
(S) Average S_T, psi	49.1			53.9		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.91		

TABLE F11 Moisture Resistance Results for Limestone – Evotherm®

Sample Identification: LMS; PG 64-22 Evotherm® @ 250F with 0 hr. Age

	Conditioned Samples			Unconditioned Samples		
Sample Number	2	3	5	1	4	6
(A) Diameter, in	5.915	5.920	5.925	5.921	5.934	5.921
(B) Height, in	3.673	3.685	3.681	3.685	3.673	3.671
(C) Weight in Air, gm	3830.9	3839.1	3834.9	3829.4	3833.5	3839.8
(D) SSD Weight, gm	3847.6	3860.4	3848.3	3850.2	3845.1	3852.4
(E) Submerged Weight, gm	2233.5	2239.4	2231.2	2229.4	2225.7	2233.0
(F) Bulk Specific Gravity [A/(D - E)]	2.373	2.368	2.371	2.363	2.367	2.371
(G) Theoretical Maximum Gravity	2.547	2.547	2.547	2.547	2.547	2.547
(H) % Air Voids [100*(1-F/G)]	6.8	7.0	6.9	7.2	7.1	6.9
(I) Volume of Air Voids [H*(D - E)/100]	110.017	113.697	111.446	117.306	114.296	111.822
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3904.5	3917.6	3909.3	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	73.60	78.50	74.40			
(L) % Saturation [100*(K/I)]	66.9	69.0	66.8			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	1600	1600	1600	2550	2550	2600
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	74.4	74.5	76.2
(R) Conditioned S_T, psi [2P/(A*B*π)]	46.9	46.7	46.7	N/A	N/A	N/A
(S) Average S_T, psi	46.8			75.0		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.62		

TABLE F12 Moisture Resistance Results for Granite – Aspha-min® and Oven Dry Aggregate

Sample Identification: Granite; PG 64-22 Warm @ 250F with 0 hr. Age: Oven Dry Aggregate

	Conditioned Samples			Unconditioned Samples		
Sample Number	2	3	6	1	4	5
(A) Diameter, in	5.905	5.926	5.920	5.921	5.930	5.924
(B) Height, in	3.725	3.728	3.724	3.728	3.729	3.732
(C) Weight in Air, gm	3724.0	3722.3	3719.6	3719.3	3721.4	3723.9
(D) SSD Weight, gm	3746.8	3746.4	3738.7	3741.6	3738.9	3741.5
(E) Submerged Weight, gm	2116.7	2123.0	2121.0	2119.4	2107.3	2118.9
(F) Bulk Specific Gravity [A/(D - E)]	2.285	2.293	2.299	2.293	2.281	2.295
(G) Theoretical Maximum Gravity	2.457	2.457	2.457	2.457	2.457	2.457
(H) % Air Voids [100*(1-F/G)]	7.0	6.7	6.4	6.7	7.2	6.6
(I) Volume of Air Voids [H*(D - E)/100]	114.430	108.422	103.821	108.443	116.989	106.971
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3813.8	3802.8	3793.4	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	89.80	80.50	73.80			
(L) % Saturation [100*(K/I)]	78.5	74.2	71.1			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	1375	1250	1575	2525	2175	2300
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	72.8	62.6	66.2
(R) Conditioned S_T, psi [2P/(A*B*π)]	39.8	36.0	45.5	N/A	N/A	N/A
(S) Average S_T, psi	40.4			67.2		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.60		

TABLE F13 Moisture Resistance Results for Granite – No Additives and 0.75% ADHERE

Sample Identification: Granite; PG 64-22 w/ 0.75% ADHERE @ 250F with 0 hr. Age - Control

	Conditioned Samples			Unconditioned Samples		
Sample Number	2	5	6	1	3	4
(A) Diameter, in	5.923	5.911	5.931	5.928	5.915	5.915
(B) Height, in	3.698	3.715	3.720	3.709	3.714	3.705
(C) Weight in Air, gm	3679.7	3682.4	3679.5	3672.2	3677.4	3679.3
(D) SSD Weight, gm	3694.1	3696.5	3696.3	3687.6	3699.6	3693.9
(E) Submerged Weight, gm	2081.1	2086.8	2085.9	2075.0	2091.5	2076.8
(F) Bulk Specific Gravity [A/(D - E)]	2.281	2.288	2.285	2.277	2.287	2.275
(G) Theoretical Maximum Gravity	2.452	2.452	2.452	2.452	2.452	2.452
(H) % Air Voids [100*(1-F/G)]	7.0	6.7	6.8	7.1	6.7	7.2
(I) Volume of Air Voids [H*(D - E)/100]	112.307	107.906	109.788	114.965	108.345	116.570
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3753.1	3750.4	3750.0	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	73.40	68.00	70.50			
(L) % Saturation [100*(K/I)]	65.4	63.0	64.2			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	3000	3275	3100	3725	3400	3700
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	107.9	98.5	107.5
(R) Conditioned S_T, psi [2P/(A*B*π)]	87.2	94.9	89.4	N/A	N/A	N/A
(S) Average S_T, psi	90.5			104.6		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.87		

TABLE F14 Moisture Resistance Results for Granite – Aspha-min® Zeolite and 0.75% ADHERE

Sample Identification: Granite; PG 64-22 Warm @ 250F with 0 hr. Age; 0.75% ADHERE

	Conditioned Samples			Unconditioned Samples		
Sample Number	1	3	6	2	4	5
(A) Diameter, in	5.919	5.937	5.939	5.945	5.943	5.935
(B) Height, in	3.711	3.699	3.682	3.699	3.701	3.708
(C) Weight in Air, gm	3663.8	3666.3	3667.6	3668.0	3669.3	3667.6
(D) SSD Weight, gm	3690.5	3697.7	3689.1	3694.2	3688.4	3691.2
(E) Submerged Weight, gm	2085.3	2083.2	2083.3	2091.0	2077.7	2081.4
(F) Bulk Specific Gravity [A/(D - E)]	2.282	2.271	2.284	2.288	2.278	2.278
(G) Theoretical Maximum Gravity	2.466	2.466	2.466	2.466	2.466	2.466
(H) % Air Voids [100*(1-F/G)]	7.4	7.9	7.4	7.2	7.6	7.6
(I) Volume of Air Voids [H*(D - E)/100]	119.474	127.760	118.533	115.771	122.744	122.533
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3746.6	3756.0	3746.6	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	82.80	89.70	79.00			
(L) % Saturation [100*(K/I)]	69.3	70.2	66.6			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm			Broke	N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	1300	1200		3500	3150	3300
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	101.3	91.2	95.5
(R) Conditioned S_T, psi [2P/(A*B*π)]	37.7	34.8		N/A	N/A	N/A
(S) Average S_T, psi	36.2			96.0		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.38		

TABLE F15 Moisture Resistance Results for Granite – Aspha-min® Zeolite and 1% Hydrated Lime

Sample Identification: Granite; PG 64-22 Warm @ 250F with 1% Hydrated Lime

	Conditioned Samples			Unconditioned Samples		
Sample Number	1	3	5	2	4	6
(A) Diameter, in	5.930	5.930	5.930	5.930	5.930	5.930
(B) Height, in	3.713	3.720	3.685	3.717	3.701	3.693
(C) Weight in Air, gm	3681.6	3679.3	3677.2	3681.9	3676.9	3675.2
(D) SSD Weight, gm	3698.5	3698.6	3688.7	3702.7	3688.1	3685.4
(E) Submerged Weight, gm	2089.1	2087.0	2091.0	2091.4	2081.9	2081.7
(F) Bulk Specific Gravity [A/(D - E)]	2.288	2.283	2.302	2.285	2.289	2.292
(G) Theoretical Maximum Gravity	2.457	2.457	2.457	2.457	2.457	2.457
(H) % Air Voids [100*(1-F/G)]	6.9	7.1	6.3	7.0	6.8	6.7
(I) Volume of Air Voids [H*(D - E)/100]	110.987	114.123	101.078	112.765	109.700	107.892
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3758.0	3761.3	3743.5	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	76.40	82.00	66.30			
(L) % Saturation [100*(K/I)]	68.8	71.9	65.6			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	2975	2800	3075	3875	3700	3875
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	111.9	107.3	112.6
(R) Conditioned S_T, psi [2P/(A*B*π)]	86.0	80.8	89.6	N/A	N/A	N/A
(S) Average S_T, psi	85.5			110.6		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:					0.77	

TABLE F16 Moisture Resistance Results for Granite – Aspha-min® Zeolite and 1.5% Hydrated Lime; Two Stage Addition

Sample Identification: Granite; PG 64-22 Warm @ 250F with 1.5% Hydrated Lime; Two Stage Addition

	Conditioned Samples			Unconditioned Samples		
Sample Number	2	4	6	1	3	5
(A) Diameter, in	5.921	5.933	5.929	5.921	5.924	5.931
(B) Height, in	3.709	3.704	3.703	3.707	3.701	3.719
(C) Weight in Air, gm	3750.8	3719.1	3723.7	3749.0	3748.6	3723.4
(D) SSD Weight, gm	3766.9	3730.8	3740.4	3762.5	3764.2	3736.0
(E) Submerged Weight, gm	2146.6	2109.9	2124.9	2140.5	2143.9	2109.9
(F) Bulk Specific Gravity [A/(D - E)]	2.315	2.294	2.305	2.311	2.314	2.290
(G) Theoretical Maximum Gravity	2.452	2.452	2.452	2.452	2.452	2.452
(H) % Air Voids [100*(1-F/G)]	5.6	6.4	6.0	5.7	5.6	6.6
(I) Volume of Air Voids [H*(D - E)/100]	90.610	104.138	96.862	93.044	91.507	107.585
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3822.7	3800.6	3795.6	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	71.90	81.50	71.90			
(L) % Saturation [100*(K/I)]	79.4	78.3	74.2			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	2800	1925	2450	2950	3025	2300
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	85.6	87.8	66.4
(R) Conditioned S_T, psi [2P/(A*B*π)]	81.2	55.8	71.0	N/A	N/A	N/A
(S) Average S_T, psi	69.3			79.9		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.87		

TABLE F17 Moisture Resistance Results for Granite – Aspha-min® Zeolite and 1.5% Hydrated Lime; All Added Dry

Sample Identification: Granite; PG 64-22 Warm w/ 1.5% Hydrated Lime Added ALL Dry@ 250F

	Conditioned Samples			Unconditioned Samples		
Sample Number	5	8	9	4	6	7
(A) Diameter, in	5.937	5.925	5.922	5.948	5.940	5.928
(B) Height, in	3.706	3.693	3.694	3.714	3.689	3.683
(C) Weight in Air, gm	3688.9	3690.2	3691.1	3689.0	3686.6	3687.6
(D) SSD Weight, gm	3706.0	3704.4	3703.9	3705.5	3702.3	3699.9
(E) Submerged Weight, gm	2094.1	2093.2	2091.1	2088.6	2087.7	2096.1
(F) Bulk Specific Gravity [A/(D - E)]	2.289	2.290	2.289	2.282	2.283	2.299
(G) Theoretical Maximum Gravity	2.451	2.451	2.451	2.451	2.451	2.451
(H) % Air Voids [100*(1-F/G)]	6.6	6.6	6.6	6.9	6.8	6.2
(I) Volume of Air Voids [H*(D - E)/100]	106.841	105.610	106.843	111.800	110.479	99.271
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3771.1	3768.5	3772.7	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	82.20	78.30	81.60			
(L) % Saturation [100*(K/I)]	76.9	74.1	76.4			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	2300	2400	2250	3100	3100	3125
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	89.3	90.1	91.1
(R) Conditioned S_T, psi [2P/(A*B*π)]	66.5	69.8	65.5	N/A	N/A	N/A
(S) Average S_T, psi	67.3			90.2		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.75		

TABLE F18 Moisture Resistance Results for Granite – Sasobit® and 0.4% Magnabond

Sample Identification: Granite; PG 64-22 Sasobit® @ 250F with 0 hr. Age and 0.4% Magnabond

	Conditioned Samples			Unconditioned Samples		
Sample Number	1	2	6	4	5	
(A) Diameter, in	5.915	5.928	5.933	5.936	5.928	
(B) Height, in	3.693	3.690	3.678	3.668	3.671	
(C) Weight in Air, gm	3716.7	3716.7	3685.7	3682.0	3685.7	
(D) SSD Weight, gm	3723.7	3724.2	3693.5	3690.0	3693.1	
(E) Submerged Weight, gm	2113.4	2117.4	2097.0	2092.2	2096.4	
(F) Bulk Specific Gravity [A/(D - E)]	2.308	2.313	2.309	2.304	2.308	
(G) Theoretical Maximum Gravity	2.469	2.469	2.469	2.469	2.469	
(H) % Air Voids [100*(1-F/G)]	6.5	6.3	6.5	6.7	6.5	
(I) Volume of Air Voids [H*(D - E)/100]	104.954	101.454	103.709	106.508	103.909	
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3775.4	3773.3	3746.7	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	58.70	56.60	61.00			
(L) % Saturation [100*(K/I)]	55.9	55.8	58.8			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	625	625	450	650	550	
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	19.0	16.1	
(R) Conditioned S_T, psi [2P/(A*B*π)]	18.2	18.2	13.1	N/A	N/A	N/A
(S) Average S_T, psi	16.5			17.5		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				0.94		

TABLE F19 Moisture Resistance Results for Limestone – Evotherm®; New Formula

Sample Identification: LMS; PG 64-22 Evotherm® @ 250F with 0 hr. Age - New Formula

	Conditioned Samples			Unconditioned Samples		
Sample Number	2	3	6	1	4	5
(A) Diameter, in	5.932	5.941	5.937	5.933	5.967	5.925
(B) Height, in	3.714	3.703	3.691	3.698	3.694	3.692
(C) Weight in Air, gm	3824.9	3827.6	3824.4	3826.7	3818.5	3822.3
(D) SSD Weight, gm	3844.9	3844.0	3838.6	3840.1	3837.0	3837.9
(E) Submerged Weight, gm	2221.6	2219.5	2216.5	2222.4	2203.1	2219.9
(F) Bulk Specific Gravity [A/(D - E)]	2.356	2.356	2.358	2.366	2.337	2.362
(G) Theoretical Maximum Gravity	2.539	2.539	2.539	2.539	2.539	2.539
(H) % Air Voids [100*(1-F/G)]	7.2	7.2	7.1	6.8	8.0	7.0
(I) Volume of Air Voids [H*(D - E)/100]	116.841	116.977	115.838	110.532	129.961	112.565
Initial Vacuum Saturation Conditioning						
(J) SSD Weight, gm	3893.0	3895.0	3895.2	N / A		
(K) Vol. Of Absorbed Water, cc [J - C]	68.10	67.40	70.80			
(L) % Saturation [100*(K/I)]	58.3	57.6	61.1			
Second Vacuum Saturation Conditioning (If required)						
(M) SSD Weight, gm				N / A		
(N) Vol. Of Absorbed Water, cc [M - C]						
(O) % Saturation [100*(N/I)]						
Tensile Strength (S_T) Calculations						
(P) Failure Load, lbs	3425	3425	2875	3075	2550	3225
(Q) Dry S_T, psi [2P/(A*B*π)]	N/A	N/A	N/A	89.2	73.6	93.9
(R) Conditioned S_T, psi [2P/(A*B*π)]	99.0	99.1	83.5	N/A	N/A	N/A
(S) Average S_T, psi	93.9			85.6		
Tensile Strength Ratio [Avg Conditioned S_T / Avg Dry S_T]:				1.10		

APPENDIX G:

HAMBURG WHEEL TRACKING DEVICE DATA

TABLE G1 Hamburg Wheel Tracking Device Results - Granite

Aggregate:	Granite	Sample Height (mm):	40
Asphalt Content (%):	5.1	Testing Temperature (°F)	122
Compaction Temperature (°F):	250		

Sample Number	Additive	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	Stripping Inflection Point (cycles)	Creep Slope (cycles)	Stripping Slope Slope	Rutting Rate (mm/hr)
1	None	1587.2	901.6	1598.0	2.279	2.467	7.6	NA	4340	NA	0.581
2	None	1590.9	897.6	1598.1	2.271	2.467	7.9	3000	379	249	3.100
Avg.					2.275	2.467	7.8	6500	2360	NA	1.841
3	Zeolite	1511.7	864.9	1523.8	2.294	2.457	6.6	3900	616	148	4.088
4	Zeolite	1688.1	961.9	1698.8	2.291	2.457	6.8	3000	407	123	6.189
Avg.					2.293	2.457	6.7	3450	512	136	5.139
5	Sasobit®	1616.6	913.6	1622.1	2.282	2.461	7.3	3000	893	248	2.822
6	Sasobit®	1590.6	897.7	1593.6	2.286	2.461	7.1	4950	813	317	3.100
Avg.					2.284	2.461	7.2	3975	853	283	2.961
7	Evotherm®	1709.4	972.9	1722.0	2.282	2.465	7.4	NA	3537	NA	0.713
8	Evotherm®	1589.7	905.3	1598.3	2.294	2.465	6.9	NA	932	NA	2.703
Avg.					2.288	2.465	7.2	NA	2235	NA	1.708

TABLE G2 Hamburg Wheel Tracking Device Results - Limestone

Aggregate:	Limestone	Sample Height (mm):	40
Asphalt Content (%):	4.8	Testing Temperature (°F)	122
Compaction Temperature (°F):	250		

Sample Number	Additive	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	Stripping Inflection Point (cycles)	Creep Slope (cycles)	Stripping Slope Slope	Rutting Rate (mm/hr)
1	None	1626.4	953.9	1642.0	2.364	2.544	7.1	3000	471	281	5.348
2	None	1613.6	941.6	1623.5	2.366	2.544	7.0	2000	783	99	3.220
Avg.					2.365	2.544	7.1	2500	627	190	4.284
3	Zeolite	1677.6	978.5	1688.5	2.363	2.544	7.1	1800	1667	61	1.512
4	Zeolite	1643.4	958.3	1653.2	2.365	2.544	7.0	1600	606	182	4.158
Avg.					2.364	2.544	7.1	1700	1137	122	2.835
5	Sasobit®	1701.0	985.9	1705.3	2.364	2.545	7.1	3250	865	286	2.912
6	Sasobit®	1706.5	989.5	1710.2	2.368	2.545	7.0	2550	500	159	5.040
Avg.					2.366	2.545	7.1	2900	683	223	3.976
7	Evotherm®	1642.1	962.2	1648.5	2.393	2.547	6.0	2600	1136	135	2.218
8	Evotherm®	1626.3	953.9	1634.6	2.389	2.547	6.2	2500	609	100	4.138
Avg.					2.391	2.547	6.1	2550	873	118	3.178

TABLE G3 Hamburg Wheel Tracking Device Results - Granite with Anti-stripping Additives

Aggregate:	Granite	Sample Height (mm):	40
Asphalt Content (%):	5.1	Testing Temperature (°F)	122
Compaction Temperature (°F):	250		

Sample Number	Additive	Anti-Stripping Additive	In Air (gms)	In Water (gms)	SSD (gms)	Bulk (Gmb)	TMD (Gmm)	VTM, %	Stripping Inflection Point (cycles)	Creep Slope (cycles)	Stripping Slope Slope	Rutting Rate (mm/hr)
1	Zeolite	1.5% Hydrated Lime; All Added Dry	1616.8	924.2	1631.3	2.287	2.451	6.7	NA	4301	NA	0.586
2	Zeolite	1.5% Hydrated Lime; All Added Dry	1480.6	841.1	1488.3	2.288	2.451	6.7	NA	3203	NA	0.787
Avg.						2.287	2.451	6.700	NA	3752	NA	0.687
3	Zeolite	1.5% Hydrated Lime; Two Stage Addition	1495.2	856.8	1510.5	2.287	2.452	6.7	7000	1030	457	2.446
4	Zeolite	1.5% Hydrated Lime; Two Stage Addition	1522.6	871.8	1532.7	2.304	2.452	6.0	NA	1828	NA	1.378
Avg.						2.296	2.452	6.350	8500	1429	457	1.912
5	Sasobit®	0.4% Magnabond	1548.0	884.2	1565.3	2.273	2.469	7.9	NA	15417	NA	0.613
6	Sasobit®	0.4% Magnabond										
Avg.						2.273	2.469	7.9	NA	15417	NA	0.613

APPENDIX H:

MINITAB® STATISTICAL ANALYSIS

COMBINED STATISTICAL ANALYSIS

General Linear Model: Air Voids, Modulus, ... versus Aggregate, Additive, ...

```
Factor     Type   Levels  Values
Aggregate  fixed       2  Granite, LMS
Additive   fixed       4  Evotherm, None, Sasobit, Zeolite
Temp       fixed       4  190, 230, 265, 300


Analysis of Variance for Air Voids, using Adjusted SS for Tests

Source                   DF    Seq SS   Adj SS   Adj MS       F      P
Aggregate                 1   28.5208  28.5208  28.5208  101.42  0.000
Additive                  3   56.6346  56.6346  18.8782   67.13  0.000
Temp                      3   26.4346  26.4346   8.8115   31.33  0.000
Aggregate*Additive        3    4.2771   4.2771   1.4257    5.07  0.002
Aggregate*Temp            3    3.9504   3.9504   1.3168    4.68  0.004
Additive*Temp             9   20.1117  20.1117   2.2346    7.95  0.000
Aggregate*Additive*Temp   9    5.0767   5.0767   0.5641    2.01  0.042
Error                   160   44.9933  44.9933   0.2812
Total                   191  189.9992


S = 0.530291   R-Sq = 76.32%   R-Sq(adj) = 71.73%


Unusual Observations for Air Voids

Obs  Air Voids      Fit   SE Fit  Residual  St Resid
  1    7.50000  6.15000  0.21649   1.35000      2.79 R
 25    5.90000  6.96667  0.21649  -1.06667     -2.20 R
 26    5.50000  6.96667  0.21649  -1.46667     -3.03 R
 27    9.70000  6.96667  0.21649   2.73333      5.65 R
 32    5.20000  6.18333  0.21649  -0.98333     -2.03 R
 36    7.20000  6.18333  0.21649   1.01667      2.10 R
 58    5.00000  6.00000  0.21649  -1.00000     -2.07 R
 68    6.90000  5.23333  0.21649   1.66667      3.44 R
 96    6.80000  5.51667  0.21649   1.28333      2.65 R
 99    6.60000  7.66667  0.21649  -1.06667     -2.20 R

R denotes an observation with a large standardized residual.


Analysis of Variance for Modulus, using Adjusted SS for Tests

Source                   DF       Seq SS       Adj SS       Adj MS     F
Aggregate                 1  22292009605  22292009605  22292009605  2.16
Additive                  3  88943262649  88943262649  29647754216  2.87
Temp                      3  1.70506E+11  1.70506E+11  56835234602  5.51
Aggregate*Additive        3  1.22546E+11  1.22546E+11  40848692842  3.96
Aggregate*Temp            3  23765618753  23765618753   7921872918  0.77
Additive*Temp             9  2.61039E+11  2.61039E+11  29004291952  2.81
Aggregate*Additive*Temp   9  1.06004E+11  1.06004E+11  11778172014  1.14
Error                   160  1.65028E+12  1.65028E+12  10314255595
Total                   191  2.44538E+12
```

```
Source                       P
Aggregate                0.143
Additive                 0.038
Temp                     0.001
Aggregate*Additive       0.009
Aggregate*Temp           0.514
Additive*Temp            0.004
Aggregate*Additive*Temp  0.336
S = 101559   R-Sq = 32.51%   R-Sq(adj) = 19.44%


Unusual Observations for Modulus

Obs  Modulus     Fit  SE Fit  Residual  St Resid
  3   572998  364829   41461    208169      2.25 R
 28   577025  337811   41461    239214      2.58 R
 44   721394  406652   41461    314742      3.39 R
 56   169512  374318   41461   -204806     -2.21 R
 58   596461  374318   41461    222143      2.40 R
133   636016  440884   41461    195132      2.10 R
135   253693  440884   41461   -187191     -2.02 R
160   600905  387527   41461    213378      2.30 R
165   716368  460238   41461    256130      2.76 R
183   188353  383625   41461   -195272     -2.11 R

R denotes an observation with a large standardized residual.


Analysis of Variance for Rut Depth, using Adjusted SS for Tests

Source                    DF   Seq SS   Adj SS  Adj MS      F      P
Aggregate                  1   591.93   591.93  591.93  44.85  0.000
Additive                   3   113.00   113.00   37.67   2.85  0.039
Temp                       3  1450.77  1450.77  483.59  36.64  0.000
Aggregate*Additive         3   194.65   194.65   64.88   4.92  0.003
Aggregate*Temp             3   122.18   122.18   40.73   3.09  0.029
Additive*Temp              9   290.10   290.10   32.23   2.44  0.012
Aggregate*Additive*Temp    9   223.35   223.35   24.82   1.88  0.058
Error                    160  2111.86  2111.86   13.20
Total                    191  5097.83


S = 3.63306   R-Sq = 58.57%   R-Sq(adj) = 50.55%


Unusual Observations for Rut Depth

Obs  Rut Depth      Fit  SE Fit  Residual  St Resid
 35    22.0300  15.1167  1.4832    6.9133      2.08 R
 84    24.3500  17.1650  1.4832    7.1850      2.17 R
 87    36.7600  19.5500  1.4832   17.2100      5.19 R
 89    10.6800  19.5500  1.4832   -8.8700     -2.67 R
 94     5.5300  13.9750  1.4832   -8.4450     -2.55 R
169    17.4300  10.5200  1.4832    6.9100      2.08 R
175    17.7800  10.3800  1.4832    7.4000      2.23 R

R denotes an observation with a large standardized residual.
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Air Voids
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive   Lower  Center   Upper   --+---------+---------+---------+----
None      1.2483  1.5292  1.8101                           (--*--)
Sasobit   0.3628  0.6438  0.9247                   (-*--)
Zeolite   0.4795  0.7604  1.0413                    (--*-)
                                   --+---------+---------+---------+----
                                  -1.0       0.0       1.0       2.0


Additive = None  subtracted from:

Additive   Lower   Center    Upper   --+---------+---------+---------+----
Sasobit   -1.166  -0.8854  -0.6045   (--*--)
Zeolite   -1.050  -0.7687  -0.4878     (-*--)
                                     --+---------+---------+---------+----
                                    -1.0       0.0       1.0       2.0


Additive = Sasobit  subtracted from:

Additive    Lower  Center   Upper   --+---------+---------+---------+----
Zeolite   -0.1642  0.1167  0.3976             (--*--)
                                    --+---------+---------+---------+----
                                   -1.0       0.0       1.0       2.0


Tukey Simultaneous Tests
Response Variable Air Voids
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
None          1.5292      0.1082   14.127    0.0000
Sasobit       0.6438      0.1082    5.947    0.0000
Zeolite       0.7604      0.1082    7.025    0.0000


Additive = None  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Sasobit      -0.8854      0.1082   -8.180    0.0000
Zeolite      -0.7687      0.1082   -7.102    0.0000


Additive = Sasobit  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Zeolite       0.1167      0.1082    1.078    0.7036
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Air Voids
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center   Upper  --------+---------+---------+--------
LMS        0.6197  0.7708  0.9220  (--------------*--------------)
                                   --------+---------+---------+--------
                                         0.70      0.80      0.90


Tukey Simultaneous Tests
Response Variable Air Voids
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of           Adjusted
Aggregate    of Means  Difference  T-Value   P-Value
LMS            0.7708     0.07654    10.07    0.0000


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Air Voids
All Pairwise Comparisons among Levels of Temp
Temp = 190  subtracted from:

Temp   Lower  Center    Upper  ------+---------+---------+---------+
230   -0.691  -0.410  -0.1295              (-----*----)
265   -0.625  -0.344  -0.0628                (----*-----)
300   -1.310  -1.029  -0.7483  (----*-----)
                               ------+---------+---------+---------+
                                  -1.00     -0.50      0.00      0.50


Temp = 230  subtracted from:

Temp    Lower   Center    Upper  ------+---------+---------+---------+
265   -0.2142   0.0667   0.3476                        (----*-----)
300   -0.8997  -0.6188  -0.3378          (-----*----)
                                 ------+---------+---------+---------+
                                    -1.00     -0.50      0.00      0.50


Temp = 265  subtracted from:

Temp    Lower   Center    Upper  ------+---------+---------+---------+
300   -0.9663  -0.6854  -0.4045         (----*-----)
                                 ------+---------+---------+---------+
                                    -1.00     -0.50      0.00      0.50
```

```
Tukey Simultaneous Tests
Response Variable Air Voids
All Pairwise Comparisons among Levels of Temp
Temp = 190  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
230       -0.410      0.1082   -3.792    0.0012
265       -0.344      0.1082   -3.176    0.0096
300       -1.029      0.1082   -9.508    0.0000


Temp = 230  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
265       0.0667      0.1082    0.616    0.9269
300      -0.6188      0.1082   -5.716    0.0000


Temp = 265  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
300      -0.6854      0.1082   -6.332    0.0000


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Modulus
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive    Lower  Center  Upper  -------+---------+---------+---------
None       -91209  -37411  16386    (--------*--------)
Sasobit   -102573  -48775   5023  (--------*--------)
Zeolite    -55436   -1639  52159          (--------*--------)
                                  -------+---------+---------+---------
                                    -60000         0     60000


Additive = None  subtracted from:

Additive   Lower  Center  Upper  -------+---------+---------+---------
Sasobit   -65161  -11364  42434        (--------*--------)
Zeolite   -18025   35773  89571                (--------*--------)
                                 -------+---------+---------+---------
                                   -60000         0     60000


Additive = Sasobit  subtracted from:

Additive  Lower  Center   Upper  -------+---------+---------+---------
Zeolite   -6662   47136  100934                  (--------*--------)
                                 -------+---------+---------+---------
                                   -60000         0     60000
```

```
Tukey Simultaneous Tests
Response Variable Modulus
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of            Adjusted
Additive    of Means  Difference  T-Value    P-Value
None          -37411       20731   -1.805     0.2750
Sasobit       -48775       20731   -2.353     0.0907
Zeolite        -1639       20731   -0.079     0.9998


Additive = None  subtracted from:

          Difference       SE of            Adjusted
Additive    of Means  Difference  T-Value    P-Value
Sasobit       -11364       20731  -0.5482     0.9469
Zeolite        35773       20731   1.7256     0.3139


Additive = Sasobit  subtracted from:

          Difference       SE of            Adjusted
Additive    of Means  Difference  T-Value    P-Value
Zeolite        47136       20731    2.274     0.1086


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Modulus
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate  Lower  Center  Upper  -----+---------+---------+---------+-
LMS        -7399   21550  50500  (-----------------*------------------)
                                 -----+---------+---------+---------+-
                                      0     16000     32000     48000


Tukey Simultaneous Tests
Response Variable Modulus
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of            Adjusted
Aggregate    of Means  Difference  T-Value    P-Value
LMS             21550       14659    1.470     0.1435
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Modulus
All Pairwise Comparisons among Levels of Temp
Temp = 190  subtracted from:

Temp   Lower  Center   Upper  --------+---------+---------+--------
230   -16267   37530   91328       (----------*---------)
265    -2457   51341  105139          (---------*----------)
300    29249   83046  136844                (----------*---------)
                              --------+---------+---------+--------
                                      0     50000    100000


Temp = 230  subtracted from:

Temp   Lower  Center  Upper  --------+---------+---------+--------
265   -39987   13811  67608  (----------*----------)
300    -8282   45516  99314        (----------*----------)
                             --------+---------+---------+--------
                                     0     50000    100000


Temp = 265  subtracted from:

Temp   Lower  Center  Upper  --------+---------+---------+--------
300   -22093   31705  85503      (---------*----------)
                             --------+---------+---------+--------
                                     0     50000    100000


Tukey Simultaneous Tests
Response Variable Modulus
All Pairwise Comparisons among Levels of Temp
Temp = 190  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
230        37530       20731    1.810    0.2723
265        51341       20731    2.477    0.0675
300        83046       20731    4.006    0.0006


Temp = 230  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
265        13811       20731   0.6662    0.9097
300        45516       20731   2.1956    0.1289


Temp = 265  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
300        31705       20731    1.529    0.4224
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive   Lower  Center  Upper  -------+---------+---------+---------
None      -0.163  1.7615  3.686                  (---------*--------)
Sasobit   -1.575  0.3498  2.274           (---------*--------)
Zeolite   -0.315  1.6092  3.534                 (---------*---------)
                                 -------+---------+---------+---------
                                     -2.0       0.0       2.0


Additive = None  subtracted from:

Additive   Lower  Center   Upper  -------+---------+---------+---------
Sasobit   -3.336  -1.412  0.5128  (---------*---------)
Zeolite   -2.077  -0.152  1.7722         (--------*---------)
                                  -------+---------+---------+---------
                                      -2.0       0.0       2.0


Additive = Sasobit  subtracted from:

Additive    Lower  Center  Upper  -------+---------+---------+---------
Zeolite   -0.6651   1.259  3.184                 (--------*---------)
                                  -------+---------+---------+---------
                                      -2.0       0.0       2.0


Tukey Simultaneous Tests
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
None          1.7615      0.7416   2.3752    0.0861
Sasobit       0.3498      0.7416   0.4717    0.9652
Zeolite       1.6092      0.7416   2.1699    0.1362


Additive = None  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Sasobit       -1.412      0.7416   -1.904    0.2307
Zeolite       -0.152      0.7416   -0.205    0.9969


Additive = Sasobit  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Zeolite        1.259      0.7416    1.698    0.3280
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center   Upper     +---------+---------+---------+------
LMS        -4.547  -3.512  -2.476     (------*-----)
                                      +---------+---------+---------+------
                                   -4.5      -3.0      -1.5       0.0


Tukey Simultaneous Tests
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of           Adjusted
Aggregate    of Means  Difference  T-Value   P-Value
LMS            -3.512      0.5244   -6.697    0.0000


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Temp
Temp = 190  subtracted from:

Temp   Lower  Center   Upper    -+---------+---------+---------+-----
230   -5.497  -3.573  -1.648                 (-----*------)
265   -7.684  -5.760  -3.835         (------*-----)
300   -9.249  -7.325  -5.400    (------*-----)
                                -+---------+---------+---------+-----
                              -9.0      -6.0      -3.0       0.0


Temp = 230  subtracted from:

Temp   Lower  Center   Upper    -+---------+---------+---------+-----
265   -4.112  -2.187  -0.263                     (------*-----)
300   -5.676  -3.752  -1.827                (-----*------)
                                -+---------+---------+---------+-----
                              -9.0      -6.0      -3.0       0.0


Temp = 265  subtracted from:

Temp   Lower  Center   Upper    -+---------+---------+---------+-----
300   -3.489  -1.565  0.3597                       (------*-----)
                                -+---------+---------+---------+-----
                              -9.0      -6.0      -3.0       0.0
```

```
Tukey Simultaneous Tests
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Temp
Temp = 190  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
230       -3.573      0.7416   -4.818    0.0000
265       -5.760      0.7416   -7.767    0.0000
300       -7.325      0.7416   -9.877    0.0000


Temp = 230  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
265       -2.187      0.7416   -2.949    0.0190
300       -3.752      0.7416   -5.059    0.0000


Temp = 265  subtracted from:

      Difference       SE of           Adjusted
Temp    of Means  Difference  T-Value   P-Value
300       -1.565      0.7416   -2.110    0.1543
```

STATISTICAL ANALYSIS FOR 265°F COMPACTION TEMPERATURE

General Linear Model: Air Voids, Modulus, ... versus Aggregate, Additive

```
Factor     Type   Levels  Values
Aggregate  fixed       2  Granite, LMS
Additive   fixed       5  Evotherm, HMA, None, Sasobit, Zeolite


Analysis of Variance for Air Voids, using Adjusted SS for Tests

Source              DF   Seq SS   Adj SS  Adj MS      F      P
Aggregate            1   4.5375   4.5375  4.5375   9.51  0.003
Additive             4  27.8583  27.8583  6.9646  14.59  0.000
Aggregate*Additive   4   3.7617   3.7617  0.9404   1.97  0.113
Error               50  23.8683  23.8683  0.4774
Total               59  60.0258


S = 0.690917   R-Sq = 60.24%   R-Sq(adj) = 53.08%


Unusual Observations for Air Voids

Obs  Air Voids      Fit   SE Fit  Residual  St Resid
  1    7.50000  6.15000  0.28207   1.35000      2.14 R
  8    5.50000  6.96667  0.28207  -1.46667     -2.33 R
  9    9.70000  6.96667  0.28207   2.73333      4.33 R

R denotes an observation with a large standardized residual.


Analysis of Variance for Modulus, using Adjusted SS for Tests

Source              DF       Seq SS       Adj SS       Adj MS     F      P
Aggregate            1   8453173032   8453173032   8453173032  0.62  0.434
Additive             4  21688401978  21688401978   5422100495  0.40  0.809
Aggregate*Additive   4  55563647537  55563647537  13890911884  1.02  0.405
Error               50  6.79997E+11  6.79997E+11  13599931505
Total               59  7.65702E+11


S = 116619   R-Sq = 11.19%   R-Sq(adj) = 0.00%

Unusual Observations for Modulus

Obs  Modulus     Fit  SE Fit  Residual  St Resid
 10   577025  337811   47609    239214      2.25 R
 26   721394  406652   47609    314742      2.96 R

R denotes an observation with a large standardized residual.

Analysis of Variance for Rut Depth, using Adjusted SS for Tests

Source              DF   Seq SS   Adj SS   Adj MS      F      P
Aggregate            1  125.976  125.976  125.976  21.35  0.000
Additive             4  174.345  174.345   43.586   7.39  0.000
Aggregate*Additive   4  112.525  112.525   28.131   4.77  0.002
Error               50  294.994  294.994    5.900
Total               59  707.840
```

```
S = 2.42897   R-Sq = 58.32%   R-Sq(adj) = 50.82%
Unusual Observations for Rut Depth

Obs  Rut Depth      Fit  SE Fit  Residual  St Resid
 13    10.6300  15.1167  0.9916   -4.4867     -2.02 R
 17    22.0300  15.1167  0.9916    6.9133      3.12 R
 48    12.4800   7.7317  0.9916    4.7483      2.14 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Air Voids
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive    Lower  Center  Upper  -----+---------+---------+---------+-
HMA        0.7105  1.5083  2.306                     (----*----)
None       0.9689  1.7667  2.564                       (-----*----)
Sasobit   -0.5228  0.2750  1.073              (----*----)
Zeolite    0.1105  0.9083  1.706                  (----*----)
                                  -----+---------+---------+---------+-
                                    -1.5       0.0       1.5       3.0


Additive = HMA  subtracted from:

Additive   Lower  Center    Upper  -----+---------+---------+---------+-
None      -0.539   0.258   1.0561             (-----*----)
Sasobit   -2.031  -1.233  -0.4355   (-----*----)
Zeolite   -1.398  -0.600   0.1978       (----*----)
                                   -----+---------+---------+---------+-
                                     -1.5       0.0       1.5       3.0


Additive = None  subtracted from:

Additive   Lower  Center    Upper  -----+---------+---------+---------+-
Sasobit   -2.289  -1.492  -0.6939  (----*----)
Zeolite   -1.656  -0.858  -0.0605      (----*-----)
                                   -----+---------+---------+---------+-
                                     -1.5       0.0       1.5       3.0


Additive = Sasobit  subtracted from:

Additive    Lower  Center  Upper  -----+---------+---------+---------+-
Zeolite   -0.1645  0.6333  1.431                (----*-----)
                                  -----+---------+---------+---------+-
                                    -1.5       0.0       1.5       3.0
```

```
Tukey Simultaneous Tests
Response Variable Air Voids
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
HMA           1.5083      0.2821   5.3475    0.0000
None          1.7667      0.2821   6.2633    0.0000
Sasobit       0.2750      0.2821   0.9749    0.8652
Zeolite       0.9083      0.2821   3.2203    0.0183


Additive = HMA  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
None           0.258      0.2821    0.916    0.8895
Sasobit       -1.233      0.2821   -4.373    0.0006
Zeolite       -0.600      0.2821   -2.127    0.2250


Additive = None  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Sasobit       -1.492      0.2821   -5.288    0.0000
Zeolite       -0.858      0.2821   -3.043    0.0293


Additive = Sasobit  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Zeolite       0.6333      0.2821    2.245    0.1803


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Air Voids
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center   Upper    +---------+---------+---------+------
LMS        0.1917  0.5500  0.9083    (-----------------*----------------)
                                     +---------+---------+---------+------
                                   0.20      0.40      0.60      0.80


Tukey Simultaneous Tests
Response Variable Air Voids
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of           Adjusted
Aggregate    of Means  Difference  T-Value   P-Value
LMS            0.5500      0.1784    3.083    0.0033
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Modulus
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive    Lower  Center   Upper  ---------+---------+---------+-------
HMA       -161339  -26679  107980     (------------*-------------)
None      -191319  -56659   78001  (------------*-------------)
Sasobit   -161032  -26372  108288     (------------*-------------)
Zeolite   -177857  -43197   91463   (-------------*------------)
                                   ---------+---------+---------+-------
                                      -100000         0    100000


Additive = HMA  subtracted from:

Additive    Lower  Center   Upper  ---------+---------+---------+-------
None      -164639  -29980  104680     (------------*------------)
Sasobit   -134352     307  134967        (------------*------------)
Zeolite   -151177  -16518  118142      (------------*-------------)
                                   ---------+---------+---------+-------
                                      -100000         0    100000


Additive = None  subtracted from:

Additive    Lower  Center   Upper  ---------+---------+---------+-------
Sasobit   -104373   30287  164947           (------------*------------)
Zeolite   -121198   13462  148122         (------------*-------------)
                                   ---------+---------+---------+-------
                                      -100000         0    100000


Additive = Sasobit  subtracted from:

Additive    Lower  Center   Upper  ---------+---------+---------+-------
Zeolite   -151485  -16825  117835      (------------*-------------)
                                   ---------+---------+---------+-------
                                      -100000         0    100000
```

```
Tukey Simultaneous Tests
Response Variable Modulus
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
HMA           -26679       47609   -0.560    0.9801
None          -56659       47609   -1.190    0.7570
Sasobit       -26372       47609   -0.554    0.9810
Zeolite       -43197       47609   -0.907    0.8928


Additive = HMA  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
None          -29980       47609  -0.6297    0.9695
Sasobit          307       47609   0.0065    1.0000
Zeolite       -16518       47609  -0.3469    0.9968


Additive = None  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Sasobit        30287       47609   0.6362    0.9684
Zeolite        13462       47609   0.2828    0.9986


Additive = Sasobit  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Zeolite       -16825       47609  -0.3534    0.9965


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Modulus
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center  Upper       +---------+---------+---------+------
LMS        -36740   23739  84218       (----------------*----------------)
                                       +---------+---------+---------+------
                                  -35000         0     35000     70000


Tukey Simultaneous Tests
Response Variable Modulus
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of           Adjusted
Aggregate    of Means  Difference  T-Value   P-Value
LMS             23739       30111   0.7884    0.4342
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive   Lower  Center  Upper  -----+---------+---------+---------+-
HMA       -2.275  0.5300  3.335           (-------*-------)
None      -0.345  2.4600  5.265                (-------*-------)
Sasobit   -2.702  0.1025  2.907         (-------*-------)
Zeolite    1.604  4.4092  7.214                      (-------*-------)
                                 -----+---------+---------+---------+-
                                   -3.5       0.0       3.5       7.0


Additive = HMA  subtracted from:

Additive   Lower   Center  Upper  -----+---------+---------+---------+-
None      -0.875   1.9300  4.735               (-------*-------)
Sasobit   -3.232  -0.4275  2.377        (-------*-------)
Zeolite    1.074   3.8792  6.684                    (-------*-------)
                                  -----+---------+---------+---------+-
                                    -3.5       0.0       3.5       7.0


Additive = None  subtracted from:

Additive   Lower  Center   Upper  -----+---------+---------+---------+-
Sasobit   -5.162  -2.358  0.4472  (-------*-------)
Zeolite   -0.856   1.949  4.7539               (-------*-------)
                                  -----+---------+---------+---------+-
                                    -3.5       0.0       3.5       7.0


Additive = Sasobit  subtracted from:

Additive  Lower  Center  Upper  -----+---------+---------+---------+-
Zeolite   1.502   4.307  7.111                     (-------*-------)
                                -----+---------+---------+---------+-
                                  -3.5       0.0       3.5       7.0
```

```
Tukey Simultaneous Tests
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
HMA           0.5300      0.9916   0.5345    0.9833
None          2.4600      0.9916   2.4808    0.1115
Sasobit       0.1025      0.9916   0.1034    1.0000
Zeolite       4.4092      0.9916   4.4464    0.0005


Additive = HMA  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
None          1.9300      0.9916   1.9463    0.3071
Sasobit      -0.4275      0.9916  -0.4311    0.9926
Zeolite       3.8792      0.9916   3.9119    0.0025


Additive = None  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Sasobit       -2.358      0.9916   -2.377    0.1385
Zeolite        1.949      0.9916    1.966    0.2975


Additive = Sasobit  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Zeolite        4.307      0.9916    4.343    0.0006


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center   Upper  -----+---------+---------+---------+-
LMS        -4.158  -2.898  -1.638  (----------*---------)
                                   -----+---------+---------+---------+-
                                     -3.6      -2.4      -1.2       0.0


Tukey Simultaneous Tests
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of           Adjusted
Aggregate    of Means  Difference  T-Value   P-Value
LMS            -2.898      0.6272   -4.621    0.0000
```

STATISTICAL ANALYSIS FOR 230°F COMPACTION TEMPERATURE

General Linear Model: Air Voids, Modulus, ... versus Aggregate, Additive

```
Factor     Type   Levels  Values
Aggregate  fixed       2  Granite, LMS
Additive   fixed       5  Evotherm, HMA, None, Sasobit, Zeolite


Analysis of Variance for Air Voids, using Adjusted SS for Tests

Source              DF   Seq SS   Adj SS   Adj MS      F      P
Aggregate            1  20.0682  20.0682  20.0682  63.11  0.000
Additive             4   9.0277   9.0277   2.2569   7.10  0.000
Aggregate*Additive   4   6.6277   6.6277   1.6569   5.21  0.001
Error               50  15.8983  15.8983   0.3180
Total               59  51.6218


S = 0.563885   R-Sq = 69.20%   R-Sq(adj) = 63.66%


Unusual Observations for Air Voids

Obs  Air Voids      Fit   SE Fit  Residual  St Resid
  1    7.50000  6.15000  0.23021   1.35000      2.62 R
 26    6.90000  5.23333  0.23021   1.66667      3.24 R
 33    6.60000  7.66667  0.23021  -1.06667     -2.07 R

R denotes an observation with a large standardized residual.


Analysis of Variance for Modulus, using Adjusted SS for Tests

Source              DF       Seq SS       Adj SS       Adj MS     F      P
Aggregate            1  22380599681  22380599681  22380599681  2.04  0.159
Additive             4  21892539815  21892539815   5473134954  0.50  0.736
Aggregate*Additive   4  1.12300E+11  1.12300E+11  28074882969  2.56  0.050
Error               50  5.47943E+11  5.47943E+11  10958869641
Total               59  7.04516E+11


S = 104685   R-Sq = 22.22%   R-Sq(adj) = 8.22%


Unusual Observations for Modulus

Obs  Modulus     Fit  SE Fit  Residual  St Resid
  3   572998  364830   42737    208169      2.18 R
 14   169512  374318   42737   -204806     -2.14 R
 16   596461  374318   42737    222143      2.32 R
 52   600905  387527   42737    213378      2.23 R
 57   716368  460238   42737    256130      2.68 R

R denotes an observation with a large standardized residual.
```

```
Analysis of Variance for Rut Depth, using Adjusted SS for Tests

Source              DF   Seq SS   Adj SS   Adj MS      F      P
Aggregate            1  128.715  128.715  128.715  15.90  0.000
Additive             4  256.354  256.354   64.088   7.91  0.000
Aggregate*Additive   4   44.025   44.025   11.006   1.36  0.261
Error               50  404.860  404.860    8.097
Total               59  833.953


S = 2.84556   R-Sq = 51.45%   R-Sq(adj) = 42.71%


Unusual Observations for Rut Depth

Obs  Rut Depth      Fit  SE Fit  Residual  St Resid
 38     4.9600  10.2717  1.1617   -5.3117     -2.04 R
 41    16.1200  10.2717  1.1617    5.8483      2.25 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Air Voids
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive    Lower  Center   Upper  -----+---------+---------+---------+-
HMA        0.5239  1.1750  1.8261                      (------*-----)
None      -0.0428  0.6083  1.2595                 (-----*------)
Sasobit   -0.3095  0.3417  0.9928              (-----*------)
Zeolite   -0.2511  0.4000  1.0511              (------*------)
                                   -----+---------+---------+---------+-
                                     -1.0       0.0       1.0       2.0


Additive = HMA  subtracted from:

Additive   Lower   Center    Upper  -----+---------+---------+---------+-
None      -1.218  -0.5667   0.0845     (-----*------)
Sasobit   -1.484  -0.8333  -0.1822  (------*-----)
Zeolite   -1.426  -0.7750  -0.1239   (-----*------)
                                    -----+---------+---------+---------+-
                                      -1.0       0.0       1.0       2.0


Additive = None  subtracted from:

Additive    Lower   Center   Upper  -----+---------+---------+---------+-
Sasobit   -0.9178  -0.2667  0.3845        (-----*------)
Zeolite   -0.8595  -0.2083  0.4428        (------*-----)
                                    -----+---------+---------+---------+-
                                      -1.0       0.0       1.0       2.0


Additive = Sasobit  subtracted from:

Additive    Lower   Center   Upper  -----+---------+---------+---------+-
Zeolite   -0.5928  0.05833  0.7095           (------*-----)
                                    -----+---------+---------+---------+-
                                      -1.0       0.0       1.0       2.0
```

```
Tukey Simultaneous Tests
Response Variable Air Voids
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
HMA           1.1750      0.2302    5.104    0.0001
None          0.6083      0.2302    2.643    0.0778
Sasobit       0.3417      0.2302    1.484    0.5774
Zeolite       0.4000      0.2302    1.738    0.4210


Additive = HMA  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
None         -0.5667      0.2302   -2.462    0.1161
Sasobit      -0.8333      0.2302   -3.620    0.0059
Zeolite      -0.7750      0.2302   -3.367    0.0122


Additive = None  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Sasobit      -0.2667      0.2302   -1.158    0.7746
Zeolite      -0.2083      0.2302   -0.905    0.8937


Additive = Sasobit  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Zeolite      0.05833      0.2302   0.2534    0.9991


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Air Voids
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center  Upper  ------+---------+---------+---------+
LMS        0.8642   1.157  1.449  (------------------*-----------------)
                                  ------+---------+---------+---------+
                                      0.96      1.12      1.28      1.44


Tukey Simultaneous Tests
Response Variable Air Voids
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of           Adjusted
Aggregate    of Means  Difference  T-Value   P-Value
LMS             1.157      0.1456    7.944    0.0000
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Modulus
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive    Lower  Center   Upper  -------+---------+---------+---------
HMA       -132531  -11652  109228      (-----------*-----------)
None      -147229  -26350   94530    (-----------*-----------)
Sasobit   -171489  -50609   70270  (-----------*-----------)
Zeolite   -165280  -44400   76479  (------------*-----------)
                                   -------+---------+---------+---------
                                    -100000         0    100000


Additive = HMA  subtracted from:

Additive    Lower  Center   Upper  -------+---------+---------+---------
None      -135578  -14698  106181     (------------*-----------)
Sasobit   -159837  -38958   81921   (-----------*-----------)
Zeolite   -153628  -32749   88131    (-----------*-----------)
                                   -------+---------+---------+---------
                                    -100000         0    100000


Additive = None  subtracted from:

Additive    Lower  Center   Upper  -------+---------+---------+---------
Sasobit   -145139  -24260   96620    (------------*-----------)
Zeolite   -138930  -18050  102829     (-----------*-----------)
                                   -------+---------+---------+---------
                                    -100000         0    100000


Additive = Sasobit  subtracted from:

Additive    Lower  Center   Upper  -------+---------+---------+---------
Zeolite   -114670    6209  127089        (-----------*-----------)
                                   -------+---------+---------+---------
                                    -100000         0    100000
```

```
Tukey Simultaneous Tests
Response Variable Modulus
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
HMA           -11652       42737   -0.273    0.9987
None          -26350       42737   -0.617    0.9718
Sasobit       -50609       42737   -1.184    0.7603
Zeolite       -44400       42737   -1.039    0.8361


Additive = HMA  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
None          -14698       42737  -0.3439    0.9969
Sasobit       -38958       42737  -0.9116    0.8911
Zeolite       -32749       42737  -0.7663    0.9391


Additive = None  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Sasobit       -24260       42737  -0.5676    0.9791
Zeolite       -18050       42737  -0.4224    0.9931


Additive = Sasobit  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Zeolite         6209       42737   0.1453    0.9999


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Modulus
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center  Upper  -----+---------+---------+---------+-
LMS        -15663   38627  92917  (-----------------*-----------------)
                                  -----+---------+---------+---------+-
                                       0     30000     60000     90000


Tukey Simultaneous Tests
Response Variable Modulus
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of           Adjusted
Aggregate    of Means  Difference  T-Value   P-Value
LMS             38627       27029    1.429    0.1592
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive   Lower  Center    Upper  ------+---------+---------+---------+
HMA       -7.337  -4.052  -0.7659   (------*-----)
None      -1.851   1.435   4.7208              (------*-----)
Sasobit   -6.646  -3.360  -0.0742     (-----*------)
Zeolite   -3.967  -0.682   2.6041          (------*-----)
                                   ------+---------+---------+---------+
                                      -5.0       0.0       5.0      10.0


Additive = HMA  subtracted from:

Additive   Lower  Center  Upper  ------+---------+---------+---------+
None       2.201  5.4867  8.772                        (------*------)
Sasobit   -2.594  0.6917  3.977             (-----*------)
Zeolite    0.084  3.3700  6.656                  (------*-----)
                                 ------+---------+---------+---------+
                                    -5.0       0.0       5.0      10.0


Additive = None  subtracted from:

Additive   Lower  Center   Upper  ------+---------+---------+---------+
Sasobit   -8.081  -4.795  -1.509  (-----*------)
Zeolite   -5.402  -2.117   1.169       (------*-----)
                                  ------+---------+---------+---------+
                                     -5.0       0.0       5.0      10.0


Additive = Sasobit  subtracted from:

Additive    Lower  Center  Upper  ------+---------+---------+---------+
Zeolite   -0.6074   2.678  5.964                 (-----*------)
                                  ------+---------+---------+---------+
                                     -5.0       0.0       5.0      10.0
```

```
Tukey Simultaneous Tests
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of            Adjusted
Additive    of Means  Difference  T-Value    P-Value
HMA           -4.052       1.162   -3.488     0.0087
None           1.435       1.162    1.235     0.7310
Sasobit       -3.360       1.162   -2.892     0.0429
Zeolite       -0.682       1.162   -0.587     0.9764


Additive = HMA  subtracted from:

          Difference       SE of            Adjusted
Additive    of Means  Difference  T-Value    P-Value
None          5.4867       1.162   4.7230     0.0002
Sasobit       0.6917       1.162   0.5954     0.9752
Zeolite       3.3700       1.162   2.9009     0.0420


Additive = None  subtracted from:

          Difference       SE of            Adjusted
Additive    of Means  Difference  T-Value    P-Value
Sasobit       -4.795       1.162   -4.128     0.0013
Zeolite       -2.117       1.162   -1.822     0.3727


Additive = Sasobit  subtracted from:

          Difference       SE of            Adjusted
Additive    of Means  Difference  T-Value    P-Value
Zeolite        2.678       1.162    2.306     0.1602


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center   Upper  -------+---------+---------+---------
LMS        -4.405  -2.929  -1.454  (------------*-----------)
                                   -------+---------+---------+---------
                                       -3.6      -2.4      -1.2


Tukey Simultaneous Tests
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of            Adjusted
Aggregate    of Means  Difference  T-Value    P-Value
LMS            -2.929      0.7347   -3.987     0.0002
```

STATISTICAL ANALYSIS FOR 190°F COMPACTION TEMPERATURE

General Linear Model: Air Voids, Modulus, ... versus Aggregate, Additive

```
Factor     Type   Levels  Values
Aggregate  fixed       2  Granite, LMS
Additive   fixed       5  Evotherm, HMA, None, Sasobit, Zeolite


Analysis of Variance for Air Voids, using Adjusted SS for Tests

Source              DF   Seq SS   Adj SS   Adj MS      F      P
Aggregate            1  16.6427  16.6427  16.6427  76.98  0.000
Additive             4  10.3967  10.3967   2.5992  12.02  0.000
Aggregate*Additive   4   1.3440   1.3440   0.3360   1.55  0.201
Error               50  10.8100  10.8100   0.2162
Total               59  39.1933


S = 0.464973   R-Sq = 72.42%   R-Sq(adj) = 67.45%


Unusual Observations for Air Voids

Obs  Air Voids      Fit   SE Fit  Residual  St Resid
  1    7.50000  6.15000  0.18982   1.35000      3.18 R
  4    5.30000  6.15000  0.18982  -0.85000     -2.00 R
  9    6.60000  7.66667  0.18982  -1.06667     -2.51 R
 36    6.80000  5.51667  0.18982   1.28333      3.02 R
 51    6.40000  7.25000  0.18982  -0.85000     -2.00 R

R denotes an observation with a large standardized residual.


Analysis of Variance for Modulus, using Adjusted SS for Tests

Source              DF       Seq SS       Adj SS       Adj MS     F      P
Aggregate            1   7917139062   7917139062   7917139062  1.10  0.299
Additive             4  40863477858  40863477858  10215869465  1.42  0.241
Aggregate*Additive   4  54378971105  54378971105  13594742776  1.89  0.127
Error               50  3.59371E+11  3.59371E+11   7187410097
Total               59  4.62530E+11


S = 84778.6   R-Sq = 22.30%   R-Sq(adj) = 8.32%


Unusual Observations for Modulus

Obs  Modulus     Fit  SE Fit  Residual  St Resid
  3   572998  364830   34611    208168      2.69 R
 51   188353  383625   34611   -195272     -2.52 R
 53   566745  383625   34611    183120      2.37 R

R denotes an observation with a large standardized residual.
```

```
Analysis of Variance for Rut Depth, using Adjusted SS for Tests

Source              DF   Seq SS   Adj SS  Adj MS      F      P
Aggregate            1   327.09   327.09  327.09  12.76  0.001
Additive             4   529.89   529.89  132.47   5.17  0.001
Aggregate*Additive   4   151.50   151.50   37.87   1.48  0.223
Error               50  1282.02  1282.02   25.64
Total               59  2290.49


S = 5.06363   R-Sq = 44.03%   R-Sq(adj) = 33.95%


Unusual Observations for Rut Depth

Obs  Rut Depth      Fit  SE Fit  Residual  St Resid
 27    36.7600  19.5500  2.0672   17.2100      3.72 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Air Voids
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive     Lower  Center  Upper  ---+---------+---------+---------+---
HMA       0.538095  1.0750  1.612                      (-----*------)
None      0.538095  1.0750  1.612                      (-----*------)
Sasobit   0.438095  0.9750  1.512                    (------*------)
Zeolite   0.004762  0.5417  1.079               (------*-----)
                                   ---+---------+---------+---------+---
                                   -0.80      0.00      0.80      1.60


Additive = HMA  subtracted from:

Additive   Lower   Center     Upper  ---+---------+---------+---------+---
None      -0.537   0.0000  0.536905        (------*------)
Sasobit   -0.637  -0.1000  0.436905       (------*-----)
Zeolite   -1.070  -0.5333  0.003571  (-----*------)
                                     ---+---------+---------+---------+---
                                     -0.80      0.00      0.80      1.60


Additive = None  subtracted from:

Additive   Lower   Center     Upper  ---+---------+---------+---------+---
Sasobit   -0.637  -0.1000  0.436905       (------*-----)
Zeolite   -1.070  -0.5333  0.003571  (-----*------)
                                     ---+---------+---------+---------+---
                                     -0.80      0.00      0.80      1.60


Additive = Sasobit  subtracted from:

Additive    Lower   Center   Upper  ---+---------+---------+---------+---
Zeolite   -0.9702  -0.4333  0.1036   (------*-----)
                                    ---+---------+---------+---------+---
                                    -0.80      0.00      0.80      1.60
```

```
Tukey Simultaneous Tests
Response Variable Air Voids
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
HMA           1.0750      0.1898    5.663    0.0000
None          1.0750      0.1898    5.663    0.0000
Sasobit       0.9750      0.1898    5.136    0.0001
Zeolite       0.5417      0.1898    2.854    0.0472


Additive = HMA  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
None          0.0000      0.1898    0.000    1.0000
Sasobit      -0.1000      0.1898   -0.527    0.9842
Zeolite      -0.5333      0.1898   -2.810    0.0525


Additive = None  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Sasobit      -0.1000      0.1898   -0.527    0.9842
Zeolite      -0.5333      0.1898   -2.810    0.0525


Additive = Sasobit  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Zeolite      -0.4333      0.1898   -2.283    0.1676


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Air Voids
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center  Upper  ------+---------+---------+---------+
LMS        0.8122   1.053  1.294  (---------------*---------------)
                                  ------+---------+---------+---------+
                                      0.90      1.05      1.20      1.35


Tukey Simultaneous Tests
Response Variable Air Voids
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of           Adjusted
Aggregate    of Means  Difference  T-Value   P-Value
LMS             1.053      0.1201    8.774    0.0000
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Modulus
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive    Lower  Center   Upper  -------+---------+---------+---------
HMA        -63125   34769  132663             (--------*---------)
None      -133225  -35331   62563      (--------*---------)
Sasobit   -113243  -15349   82545        (--------*---------)
Zeolite   -133013  -35119   62775      (--------*---------)
                                   -------+---------+---------+---------
                                    -100000         0    100000


Additive = HMA  subtracted from:

Additive    Lower  Center  Upper  -------+---------+---------+---------
None      -167994  -70100  27794  (---------*---------)
Sasobit   -148012  -50118  47776    (---------*---------)
Zeolite   -167782  -69888  28006  (---------*---------)
                                  -------+---------+---------+---------
                                   -100000         0    100000


Additive = None  subtracted from:

Additive   Lower   Center   Upper  -------+---------+---------+---------
Sasobit   -77912  19982.0  117876           (---------*---------)
Zeolite   -97682    211.5   98105         (---------*---------)
                                   -------+---------+---------+---------
                                    -100000         0    100000


Additive = Sasobit  subtracted from:

Additive    Lower  Center  Upper  -------+---------+---------+---------
Zeolite   -117664  -19771  78123       (---------*---------)
                                  -------+---------+---------+---------
                                   -100000         0    100000


Tukey Simultaneous Tests
Response Variable Modulus
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
HMA            34769       34611    1.005    0.8520
None          -35331       34611   -1.021    0.8446
Sasobit       -15349       34611   -0.443    0.9917
Zeolite       -35119       34611   -1.015    0.8474


Additive = HMA  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
None          -70100       34611   -2.025    0.2692
Sasobit       -50118       34611   -1.448    0.6002
Zeolite       -69888       34611   -2.019    0.2720
```

```
Additive = None  subtracted from:

          Difference       SE of            Adjusted
Additive    of Means  Difference   T-Value   P-Value
Sasobit      19982.0       34611  0.577336    0.9778
Zeolite        211.5       34611  0.006111    1.0000

Additive = Sasobit  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Zeolite       -19771       34611  -0.5712    0.9787


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Modulus
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center  Upper  --------+---------+---------+--------
LMS        -20993   22974  66941  (----------------*-----------------)
                                  --------+---------+---------+--------
                                          0     25000     50000


Tukey Simultaneous Tests
Response Variable Modulus
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of           Adjusted
Aggregate    of Means  Difference  T-Value   P-Value
LMS             22974       21890    1.050    0.2990


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

Additive   Lower  Center    Upper  -----+---------+---------+---------+-
HMA       -11.61  -5.758  0.08864  (-------*------)
None       -4.46   1.384  7.23114           (-------*------)
Sasobit    -2.84   3.004  8.85114             (-------*------)
Zeolite    -5.38   0.469  6.31614          (-------*------)
                                   -----+---------+---------+---------+-
                                     -8.0       0.0       8.0      16.0


Additive = HMA  subtracted from:

Additive   Lower  Center  Upper  -----+---------+---------+---------+-
None      1.2955   7.142  12.99                   (------*------)
Sasobit   2.9155   8.762  14.61                     (------*------)
Zeolite   0.3805   6.227  12.07                 (-------*------)
                                 -----+---------+---------+---------+-
                                   -8.0       0.0       8.0      16.0
```

```
Additive = None  subtracted from:

Additive   Lower   Center  Upper  -----+---------+---------+---------+-
Sasobit   -4.227   1.6200  7.467            (------*------)
Zeolite   -6.762  -0.9150  4.932         (------*------)
                                  -----+---------+---------+---------+-
                                    -8.0       0.0       8.0      16.0


Additive = Sasobit  subtracted from:

Additive   Lower  Center  Upper  -----+---------+---------+---------+-
Zeolite   -8.382  -2.535  3.312       (------*------)
                                 -----+---------+---------+---------+-
                                   -8.0       0.0       8.0      16.0


Tukey Simultaneous Tests
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Additive
Additive = Evotherm  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
HMA           -5.758       2.067   -2.786    0.0557
None           1.384       2.067    0.670    0.9620
Sasobit        3.004       2.067    1.453    0.5969
Zeolite        0.469       2.067    0.227    0.9994


Additive = HMA  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
None           7.142       2.067    3.455    0.0095
Sasobit        8.762       2.067    4.239    0.0009
Zeolite        6.227       2.067    3.013    0.0317


Additive = None  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Sasobit       1.6200       2.067   0.7837    0.9342
Zeolite      -0.9150       2.067  -0.4426    0.9918


Additive = Sasobit  subtracted from:

          Difference       SE of           Adjusted
Additive    of Means  Difference  T-Value   P-Value
Zeolite       -2.535       2.067   -1.226    0.7362
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

Aggregate   Lower  Center   Upper  ------+---------+---------+---------+
LMS        -7.296  -4.670  -2.044  (------------*------------)
                                   ------+---------+---------+---------+
                                      -6.0      -4.0      -2.0       0.0


Tukey Simultaneous Tests
Response Variable Rut Depth
All Pairwise Comparisons among Levels of Aggregate
Aggregate = Granite  subtracted from:

           Difference       SE of            Adjusted
Aggregate    of Means  Difference  T-Value   P-Value
LMS            -4.670       1.307   -3.572    0.0008
```