An Evaluation of Heated Reclaimed Asphalt Pavement (RAP) Material and Wax Modified Asphalt for Use in Recycled Hot Mix Asphalt (HMA)

by

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Abstract

This study was carried out to evaluate the use of heated reclaimed asphalt pavement materials with emulsion and the use of hot mix asphalt with wax (Sasobit) as base course materials. Mixes with lower than optimum and optimum emulsion, as well as with heated reclaimed asphalt pavement material and optimum emulsion were made; also, mixes with conventional asphalt binder and those with asphalt binder and Sasobit were produced at relatively lower temperatures. These mixes were tested for workability, and all but one of the mixes were used for preparation of approximately 0.9 m (35 inches) by 0.9 m (35 inches) 0.125 m (5 inches) slabs. The rates of densification during the compaction of these slabs were compared. Samples cored from the slabs were tested for stiffness, and dry retained tensile strengths. The results showed that heating of reclaimed asphalt pavement material can improve the dispersion as well as densification significantly. The use of asphalt binder was found to be beneficial in improving strength and stiffness, and the use of Sasobit helped to achieve almost similar workabilities and compactabilities at lower temperatures, as compared to those of hot mix asphalt with neat asphalt binder. No significant difference was found between the modulus of the Sasobit and hot mix asphalt samples. The dispersion of asphalt binder seemed to improve with the use of Sasobit at lower mixing temperature. A field project is recommended for evaluating performance of emulsion mixes with heated reclaimed asphalt pavements and asphalt binder mixes with Sasobit.

Introduction

1.1 Background

A general asphalt pavement structure of a low to medium volume pavement in Maine is shown in Figure 1. The subgrade is what exists before the pavement structure is built; the structure is built on the subgrade to help preserve its natural state. Above the subgrade, a typical pavement consists of three layers: subbase, base and surface. The subbase is placed directly over the subgrade. The base layer is placed on top of the subbase and the surface layer sits directly on top of the base.

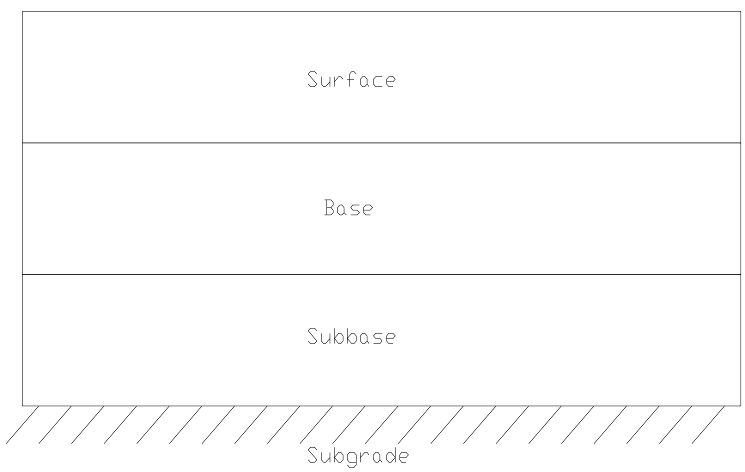

Figure 1. A Typical Pavement Section

The structure usually consists of 75 to 100 mm (3 to 4 inch) of Hot Mix Asphalt (HMA) and 100 to 200 mm (4 to 8 inch) of base underneath and, approximately 600 mm (24 inch) of subbase (1).

Recycled asphalt pavements have been gaining popularity since the mid 1970s because our natural resources are being depleted fast. Also, recycling of a pavement provides a good way of rehabilitation and hence improvement of pavement condition, as shown in Figure 2. There are five methods of asphalt recycling, Cold Planning (CP), Hot

Recycling, Hot In-Place Recycling (HIR), Cold Recycling (CR) and Full Depth Reclamation (FDR). Each method of asphalt recycling has its advantages. The different advantages include, energy conservation, increased project efficiency, reuse of existing materials, and higher productivity without the disruption to the travel public.

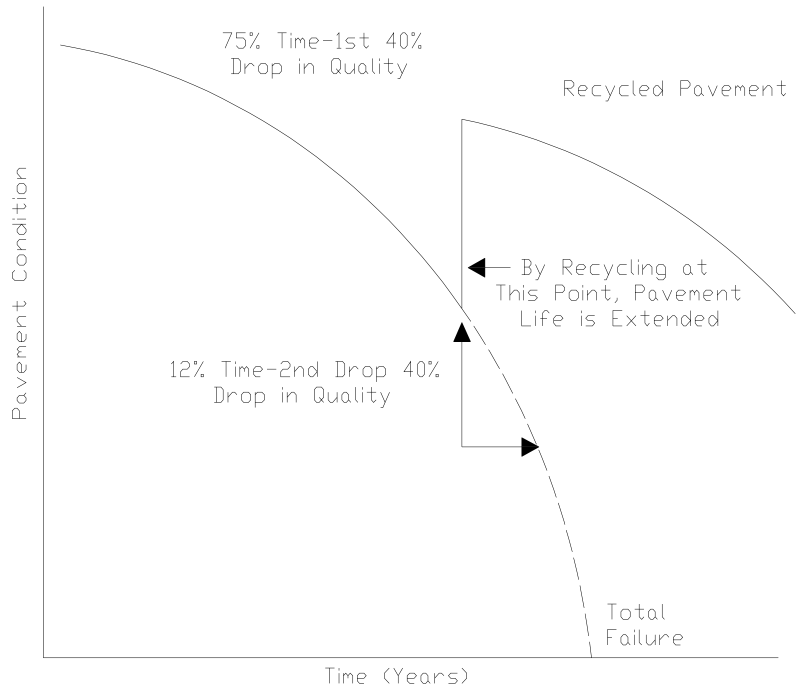

Figure 2. Schematic of Time versus Pavement Condition (2)

Asphalt recycling methods can be used in combination with one another on some rehabilitation projects. For instance, an existing roadway could have a few inches milled or removed from the top layer by CP and the resulting Reclaimed Asphalt Pavement (RAP) could be stockpiled at the asphalt plant. The cold planed surface, once prepared, could be overlaid with hot mix asphalt (HMA) containing the RAP from the milled off layer. Alternatively, HIR, CIR or FDR can be used to prevent distresses such as reflective cracking, in the future (2).

It is important to recognize that asphalt recycling is a powerful method to rehabilitate pavements. When properly applied, it has long term economic benefits, allowing owner agencies to stretch their available funds while providing the public with a safe and reliable driving surface. It is also important to recognize that although asphalt recycling technologies and methods have advanced, not all roadways are appropriate candidates for asphalt recycling. With the almost endless supply of roadways needing rehabilitation, it would be a disservice to the public and the industry to use poor judgment in attempting an inappropriate recycling project (2).

Objective

The objective of this project was to determine the most appropriate method of recycling asphalt pavement for construction of base layers. Specifically the objectives are:

1. Determine and compare workability, compactability, development of stiffness and resistance to moisture damage of several different types of mixes.
2. Recommend the most appropriate recycling method.

Scope

The scope of work consisted of preparing different mixes with RAP (100% RAP), compacting them and testing samples. The RAP material was obtained from an ongoing Maine Department of Transportation (MDOT) milling operation (for recycling) from a typical low-medium volume pavement in Westbrook, Maine. The RAP was tested for moisture and asphalt content as well as gradation.

Two different binders were used in this study, a MS2 emulsion with a base grade PG 64-28 (from MDOT) and a neat PG 64-28 grade asphalt binder (from Aggregate Industries, Swampscott plant). The optimum emulsion/asphalt content was first determined by compacting samples with a gyratory compactor (with a slotted mold) and considering the dry densities and the air voids of the samples. Based on the highest dry density and lowest voids, an optimum of 1.5 percent emulsion (1 percent asphalt) was selected initially. However, on the basis of experience with similar projects, an optimum of 2 percent emulsion (1.5 percent asphalt) was finally selected.

For initial evaluation, two temperatures were selected for heating the RAP prior to mixing with emulsion: 60^{o}C (140^{o}F) to keep it at the same temperature as the emulsion and the 110^{o}C (230^{o}F) to heat the RAP sufficiently to drive off the moisture in the RAP. For the Sasobit mixes, two percentages were selected – 1 percent and 1.5 percent of the binder. Note that these percentages are based on the total asphalt in the mix, which includes the asphalt already present in the RAP and the new asphalt being added during recycling. Sasobit was mixed with the heated virgin asphalt prior to mixing with the RAP. It seemed as though a better mix was obtained with the 1 percent Sasobit than with the 1.5 percent Sasobit (7).

Literature Review

A literature review was conducted to determine relevant theory and practical work that have been performed on recycling of base course materials. This literature review is separated into two parts- Part 1 presents work conducted with recycling of materials, Part 2 discusses the background and use of different test methods that were used in this study.

Part 1: Materials Used in Recycling

2.1 Emulsion

Emulsified asphalt, most commonly called emulsion, is a mixture of water, an emulsifying agent (soap is the most common), and asphalt cement. The asphalt cement does not dissolve in the water. The asphalt and water exist in separate phases with the assistance of the emulsifying agent as shown in Figure 3. Emulsions are made to reduce viscosity so that it may be applied at lower temperatures. Hot asphalt cement and water containing the emulsifying agent are passed under pressure through a colloid mill, shown in Figure 4, to produce extremely small (less than 5-10 microns) droplets of asphalt cement which are suspended in water. The emulsifying agent passes on an electric charge to the surface of the droplets which causes them to repel each other and the droplets do not link together. Emulsified asphalts are also categorized as liquid asphalt because, unlike asphalt cement, they are liquids at ambient temperatures. (3).

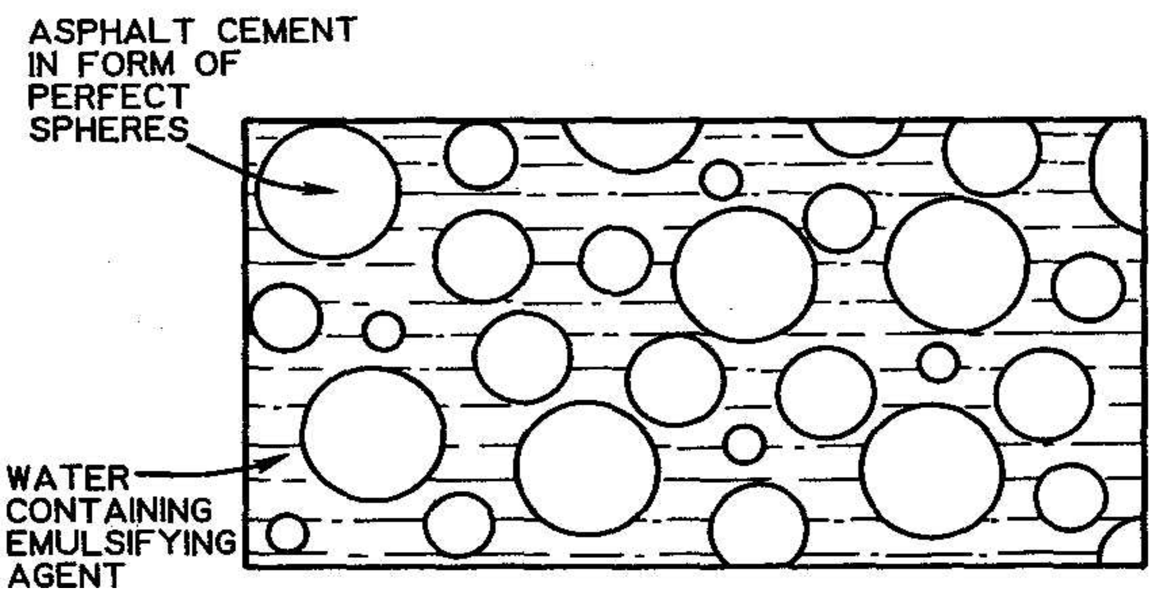

Figure 3. Emulsified Asphalt (3)

If the emulsifying agent is Cationic then the asphalt droplets have a positive charge. If the emulsifying agent is Anionic, the asphalt droplets have a negative charge. Most mineral aggregates have a positive, a negative or a mixed charge on the surface. Most siliceous aggregates, such as sandstone, quartz and siliceous gravel are negatively charged and therefore are generally compatible with the positively charged cationic emulsified asphalt. On the other hand, some aggregates such as limestone have a positive surface charge and are therefore compatible with the negatively charged anionic emulsified asphalts. This happens because opposite charges attract one another (3).

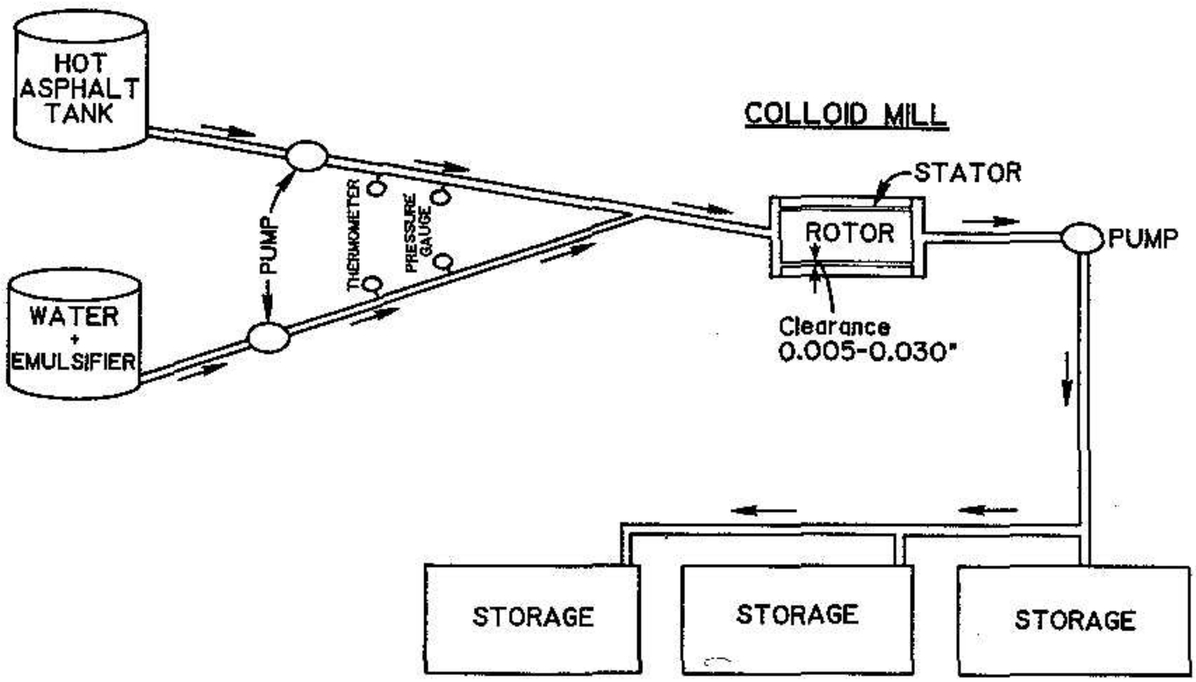

Figure 4. Manufacture of Emulsified Asphalt (3)

When emulsified asphalt is mixed with an aggregate, it "sets" because the asphalt droplets react with the surface of the aggregate and link together, squeezing out the water between them. The evaporation of water is the primary method which finally causes the anionic emulsified asphalt to "set" and produce a continuous film of asphalt on the aggregate or pavement. Cationic emulsified asphalts "sets" primarily by electro-chemical processes (3).

2.2 Warm Mix Asphalt

One of the most crucial steps in HMA production is the temperature control. Temperature control is important for dispersion to ensure proper density, compaction and performance. During construction, the temperature must be high enough to ensure workability of the mix. Increasing mix temperature often results in increased plant emission and fumes at the paving site. Technology is now available to decrease HMA production temperatures by 16 to 55°C (60 to 130°F). This technology is referred to as Warm Mix Asphalt. The goal of warm mix is to achieve a level of durability and strength that is equivalent to or better than HMA. Different technologies are available but this study used Sasobit in the warm mix applications (4).

<u>Sasobit</u>

Sasobit is a product of Sasol Wax. It is a fine crystalline, long chain aliphatic polymethylene hydrocarbon produced from coal gasification using the Fischer-Tropsch (FT) process. Sasobit is described as an "asphalt flow improver", both during the asphalt mixing process and during lay down operations; it is able to assist with flow because it lowers the viscosity of asphalt binder. This decrease in viscosity allows working temperatures to be decreased by 18-54°C (65 to 130°F). Sasobit has a congealing temperature of about 102°C (215°F) and is completely soluble in asphalt binder at temperatures higher than 120°C (250°F).

Sasobit can be applied in many different ways, during production of HMA it has been recommended that Sasobit be added at a rate of 0.8 percent or more by mass of the binder but not to exceed 3 percent. Sasobit can be blended into hot binder at the blending plant without the need for high shear mixing. In other applications Sasobit has been added directly onto the aggregate mix as solid wax balls or as molten liquid through a dosing meter. Sasobit has also been blended with the binder at the terminal and blown directly into the mixing chamber at the same point cellulose fibers are being added to a Stone Matrix Asphalt (SMA) (5).

Hurley and Prowell conducted a study on using Sasobit to reduce the mixing and compaction temperatures of HMA. In the mix design process, two types of aggregate were used (granite and limestone) and two grades of asphalt binder (PG 64-22 and PG 58-28) were used to evaluate the Sasobit. Once the mix design was verified at 149°C (300°F), each combination was then compacted at three lower temperatures 129, 110 and 88°C (265, 230 and 190°F). Asphalt content of 5.1 and 4.8 percent were determined for the granite and limestone aggregate.

Densification was also tested and once the optimum asphalt contents and volumetric properties were determined for each aggregate/binder combination test samples were produced to evaluate the mixes' ability to be compacted over a range of temperatures.

Resilient Modulus was measured by indirect resilient modulus according to ASTM D 4123. The resilient modulus is a non-destructive test, after the test was completed each mixture was placed in the APA (Asphalt Pavement Analyzer) to determine the rut resistance of each combination for the different compaction temperatures.

Volumetric properties revealed that the addition of Sasobit had little effect on the maximum specific gravity of the mixture. There were very slight trends of increasing air voids with decreasing temperature for some of the combinations. The addition of Sasobit resulted in lower air voids than the corresponding control mixture in all aggregate, binder and temperature combinations (5).

Part 2: Test Methods

2.3 Workability

Gudimettla, Cooley, Jr., and Brown (6) conducted a study to assess methods of evaluating the workability of (HMA) mixtures and the use of workability to establish mixing and compaction temperatures. The primary objective of this study was to develop a device to measure the workability of HMA mixes that can identify the change in workability due to changes in mix characteristics. The following conclusions were made mode from this study: the workability of HMA as measured by the device was affected by aggregate type and aggregate properties. Mixes prepared with cubical, angular granite were less workable then mixes prepared with semi-angular crushed gravel. Binder type significantly affected the workability of mixes. Also, the temperature of the mix significantly affected the workability of HMA. More work is needed to better relate compactability to workability. Also, the authors think it would be useful to try the study in the field and monitor density with nondestructive testing (NDT) (6).

Their overall research approach included different tasks (6):

<u>Task 1: Development of the Prototype Device</u>

The initial concept utilized a Hobart mixer and an amp meter. The mix was placed in the mixing bowl and a dough hook pushed the HMA around the bowl. The amperage required to keep the dough hook traveling at a constant speed, while pushing the mix within the bowl, was measured. The amperage was converted to torque.

The study found that at high temperatures torque values were at the lowest and as the temperatures decreased torque values increased. These trends were observed for all of the different mixes tested in this study.

<u>Task 2: Identify Limitations of Prototype Workability Device</u>

Initial work with the prototype device entailed identifying the operating limits of the equipment. This was accomplished by testing five mixtures at expected varying degrees of workability. Workability tests were conducted over a temperature range of approximately 120 to 170^{o}C (250-340^{o}F).

The blades of the paddle were kept at different elevations to minimize the chance of developing shear planes during the test. Once the paddle was designed it was tested with five different types of HMA, these mixes were chosen because they were believed to have different stiffness'. By the end of this stage it was observed that the length of the paddle blades could cause a problem. Aggregate particles got wedged between the bowl and paddle and caused the torque measurements to spike. To reduce this problem the length of the blades were reduced to be 47 mm (1.85 inches) away from the side of the bucket; this length was chosen because the maximum aggregate size was 25 mm (1 inch).

<u>Task 3: Effect of Equipment Variables on Workability</u>

The results from this task were used in an effort to identify the best equipment configuration for measuring the workability of mixes. The equipment factors involved in this task were, paddle configuration and rate of paddle revolution. The paddle configuration should be such that it continuously remixes the sample and does not create a shear plane through the mixture. A shear plane created within the sample would show a consistent workability (torque) over a given temperature range because of a lack of resistance. If the rate of revolution for the paddle is too fast, a shear plane can also be created.

This testing was conducted to select the best rate of revolution of the paddle and type of paddle configuration. The two types of paddles tested were Paddle A with 3 blades and Paddle B with two blades, excluding the top blade used in Paddle A. The rates of revolution chosen for evaluation were: 5 rpm, 10 rpm and 15 rpm's. Testing indicated that 5 rpm was too slow because the motor tended to stop as the mix got very stiff very quickly. The study found that using Paddle A at 15 rpm was the most effective and showed the most consistent results.

<u>Task 4: Evaluation of Material Effects</u>

The effect of material properties was evaluated during this task. Material properties tested were aggregate type, binder type, gradation shape, and Nominal Maximum Aggregate Size (NMAS). Four different types of aggregate were tested: granite, limestone, crushed gravel and rounded gravel. Five different gradations were used. Mix designs were conducted using binders of PG 64-22, PG 70-22 and PG 76-22. The PG 64-22 was an unmodified binder while the other two were polymer-modified binders with varying concentration levels of styrene butadiene styrene (SBS) polymer. The data was conducted over a temperature range of 120 to 170°C (250 to 340°F).

Torque values were determined for each mix at 120, 130, 140, 150, 160 and 170°C (250, 266, 284, 302, 320 and 340°F). Mixes containing crushed gravel had a much lower torque value than mixes containing granite and limestone. Mixes containing the 76-22 binder produced much higher torque value than the mixes with the other two binders. It was found that mixes containing the PG 64-22 binder and PG 70-22 binder had very similar torque values. Based on Analysis of Variance (ANOVA), it was determined that all of the main factors except gradation have a significant effect on workability. Binder type had the largest effect as shown by the highest F-statistic. The next largest was temperature followed by aggregate type and NMAS.

Task 5: Evaluate Method of Determining Compaction Temperature of HMA

This task was to try and verify the compaction temperatures. The superpave gyratory compactor (SGC) was used to measure compactability. The experiment was conducted on 9 of the 36 mixes.

The general trend of the workability curve is similar to the viscosity-temperature curves for different binders. The magnitude of the workability curve was governed not only by the viscosity of the binder but the properties of the aggregates and NMAS as well.

2.4 Compactability

Compaction is the process by which the volume of air in a HMA mixture is reduced through the application of external forces. The removal of air enables the mix to occupy a smaller space thereby increasing the unit weight or density of the mass.

Compactability is the measurement of how compactable the HMA mixture is. The compaction process is affected by the confinement of the HMA being compacted. In the laboratory the sides and bottom of the mold provide confinements. Compaction energy in the laboratory process can be calculated. However, in the field, the surrounding HMA materials, the underlying layer and the compactor contact area provide confinement. The amount of compaction energy put into field material cannot be determined, however, its effectiveness can be determined by measuring the increase in density produced by the compaction energy (3).

For effective compaction to occur the compactive forces exerted by the roller must exceed the forces resisting compaction within the mixture. The mixture resistance is a result of the combined effect of the aggregate phase and the asphalt cement phase which fills the voids in the aggregates.

When liquid asphalt cement is added to an aggregate mass being compacted the lubricating effect of the liquid initially reduces the internal friction between aggregate particles allowing them to slide against each other into a denser configuration. However, at high asphalt contents, the asphalt cement forces the aggregate apart and does not allow the aggregates to be moved into a denser condition. The properties of asphalt do not significantly affect the mass viscosity of the mixture. Since the mass viscosity is the primary force resisting compaction, the aggregate which affect it significantly are much more important than the asphalt properties.

Compaction equipment usually consists of rollers whose objective is to achieve the required density to meet specifications and to provide a smooth surface. The Vibratory Steel-Wheeled Roller is the most recent development in rollers for compacting HMA. The vibratory rollers require more operator discipline in carrying out the roller pattern. Selecting the wrong force level, rolling too fast, and making too many passes with the vibratory roller can cause problems. Vibratory rollers are the only type of HMA compactors that have a dynamic load component and are typically lighter than the non-vibratory rollers. The vibration created by the roller is especially effective on harsh mixtures which have high volume concentrations of coarse aggregate (3).

Test Method and Materials

The test method steps consisted of measuring a 15 kg (33 lbs) bucket of RAP to be mixed with emulsion, asphalt or sasobit. One bucket was tested to determine workability and three 2000 grams (4.4 lbs) samples were compacted and bulk specific gravity (BSG) was run. As the mix was made in 15 kg (33 lbs) buckets it was then placed in the mold and spread evenly. The mold was then compacted with a vibratory roller. After 10 passes the thickness was noted. Figures 5-8 show steps and the Test Plan is shown in Figure 9. Compaction was complete once the mix did not decrease more than 6 mm (0.25 inch) after 10 passes. The test matrix of the material placed and tested in the mold is shown in Table 1.

Figure 5. Pouring Emulsion/Asphalt into RAP and Recording Temperatures

Figure 6. Mixing Using Rotating Electric Mixer

Figure 7. Evenly Spreading the Mix in the Mold

Figure 8. Compacting with Vibratory Roller

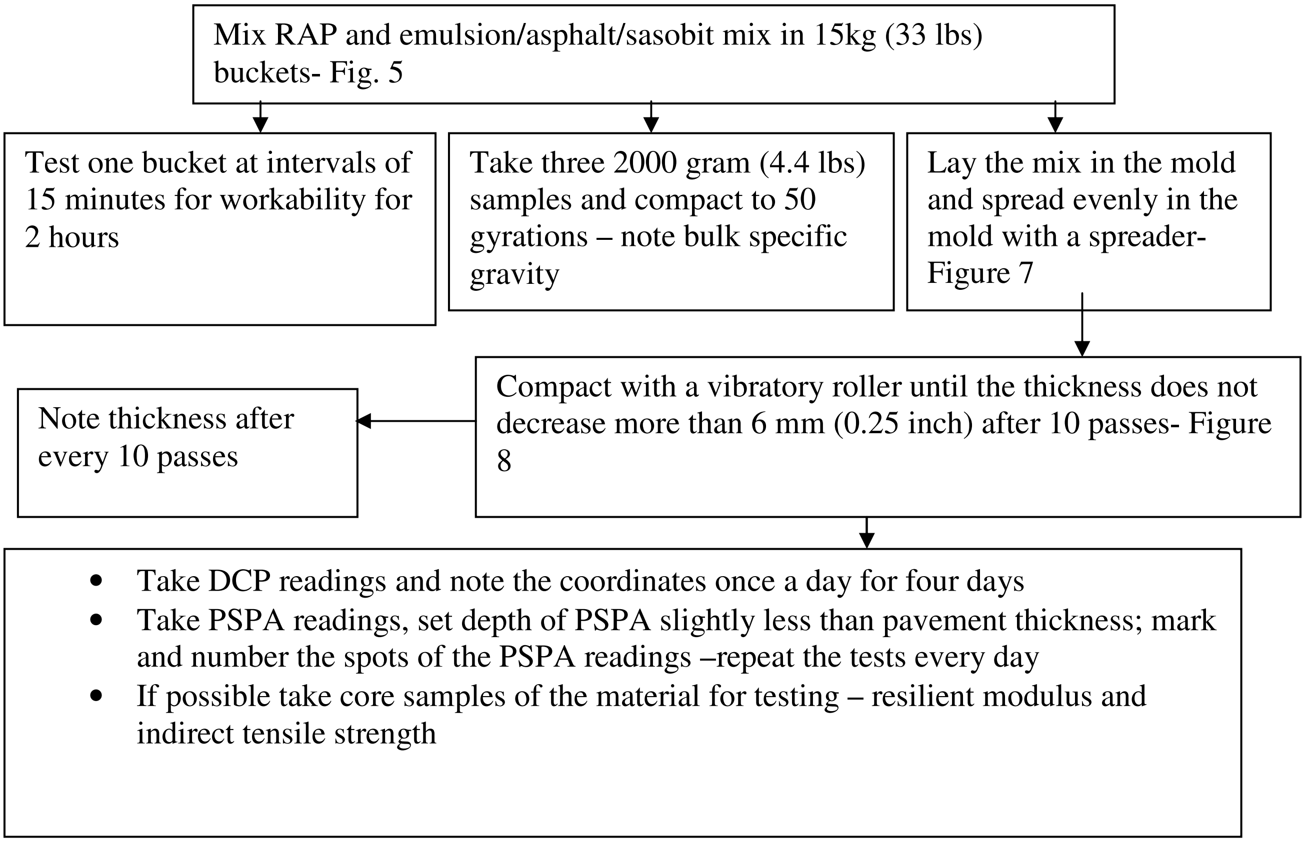

Figure 9. Test Plan

Table 1. Different Mixes

Mix	Method
RAP+Emulsion at 60^{o}C	Unheated RAP was mixed with Emulsion heated to 60^{o}C (140^{o}F); Two different mixes were produced – one with 2 % emulsion and the other with 3 % emulsion.
Heated RAP+ Emulsion at 60^{o}C	Two different mixes were produced – one with RAP and Emulsion heated to 60^{o}C (140^{o}F) and the other with RAP heated to 110^{o}C (230^{o}F) and the emulsion to 60^{o}C (140^{o}F).
Heated RAP+Asphalt Binder+1.5% Sasobit-125^{o}C	Both asphalt binder and RAP were heated to 125^{o}C (257^{o}F), and 1.5 % Sasobit was mixed with the asphalt before mixing it with the RAP; 2 % asphalt binder was used.
Heated RAP+Asphalt Binder+1% Sasobit-125^{o}C	Both asphalt binder and RAP were heated to 125^{o}C (257^{o}F), and 1% Sasobit was mixed with the asphalt before mixing it with the RAP; 2 % asphalt binder was used.
Heated RAP+Asphalt Binder-150 ^{o}C	Both RAP and Asphalt binder were heated to 150^{o}C (302^{o}F), and then mixed at 2 % asphalt content.

Please note that in the following sections the mixes that were produced in the test are abbreviated by:

Table 2. Abbreviated Mix Names

Actual Mix Name	Abbreviated Mix Name
RAP+Emulsion at 60°C	2% Emulsion or 3% Emulsion
Heated RAP+ Emulsion at 60°C	RAP60°C+3%Emulsion or RAP110°C+3%Emulsion
Heated RAP+Asphalt Binder+1.5% Sasobit- 125°C	1.5% Sasobit
Heated RAP+Asphalt Binder+1% Sasobit- 125°C	1% Sasobit
Heated RAP+Asphalt Binder-150°C	HMA

Depending on the material in the mold one or more of the following tests was completed.

3.1 Dynamic Cone Penetrometer

The Dynamic Cone Penetrometer (DCP) was initially developed in South Africa as an in-situ pavement evaluation technique. The DCP is used for continuous measurement with the depth of pavement layers and subgrade soil parameters, shown in Figure 10. Since then, this device has been used extensively in South Africa, United Kingdom, USA, Australia and many other countries because it is simple, economical, and less time consuming than most other available methods (8).

Usually, pavement testing at a given point involves the extrusion of a 100 mm (4 inches) cylindrical core from the top asphalt layer and penetrating the DCP from the top of the base course layer down to the required pavement or subgrade layer. The properties of the asphalt layers could be directly evaluated in the laboratory by a proper mechanical test, if needed. Resistance of other pavement and subgrade layers to penetration is continuously measured and recorded with depth by the DCP. At the end of the test, the shallow 100 mm (4 inches) hole could be easily filled with either Portland Cement Concrete (PCC), or a proper cold mixture. In the case of subgrade evaluation for pavement design purposes, the DCP is penetrated down from the top of the natural soil or compacted subgrade. During testing, the number of blows versus depth is recorded. The "DCP value" is defined as the slope of the blow vs. depth curve (in mm per blow) at a given linear depth segment.

There is a direct correlation between the California Bearing Ratio (CBR) and the DCP. The CBR is an index of shear strength of a soil. In reality, it is a plate bearing test which measures the static penetration resistance of a soil as a function of penetration of a cylinder prior to reaching the ultimate shearing value of the soil. The CBR is defined as a percentage determined by the ratio of the resistance in pounds per square-inch (psi) at 2.5 mm (0.1 inch) penetration of the soil under test to the resistance of a standard, well graded, crushed stone at the same penetration, and then multiplied by 100. This standard penetration stress is usually taken to be 6.9 megapascal (MPa) (1,000 psi).

In order to assess the structural properties of the pavement subgrade, the DCP values are usually correlated with the CBR of the pavement subgrade. During development of this relationship, both CBR and DCP tests were done on a wide range of undisturbed and compacted fine-grain soil samples, with and without saturation in the laboratory. Compacted granular soils were tested in the flexible molds with variable controlled lateral pressures. Field tests were made on the natural and compacted layers representing a wide range of potential pavement and subgrade materials. The research resulted in the following quantitative relationship between the CBR of the material and its DCP value equation 3.1 (8):

$$\text{Log } CBR = 2.20 - 0.71 * (\text{Log } DCP)^{1.5} \qquad 3.1$$

$$(R^2 = 0.95,\ N = 74)$$

where the DCP is in mm per blow.

Once the CBR value of a soil is known, the subgrade modulus could be determined by a relationship between the CBR and the subgrade modulus. Perhaps the most well-known relationship is the one proposed by Heukelom and Foster (8) which has been adopted by the 1993 AASHTO Guide for Design of Pavement Structures

$$M_r = 10\ CBR \qquad 3.2$$

$$M_r = 1500\ CBR \qquad 3.3$$

In equation 3.2, M_r is the subgrade modulus in MPa, while in equation 3.3 M_r is in psi (8). Figure 10 shows a DCP test being conducted in this study.

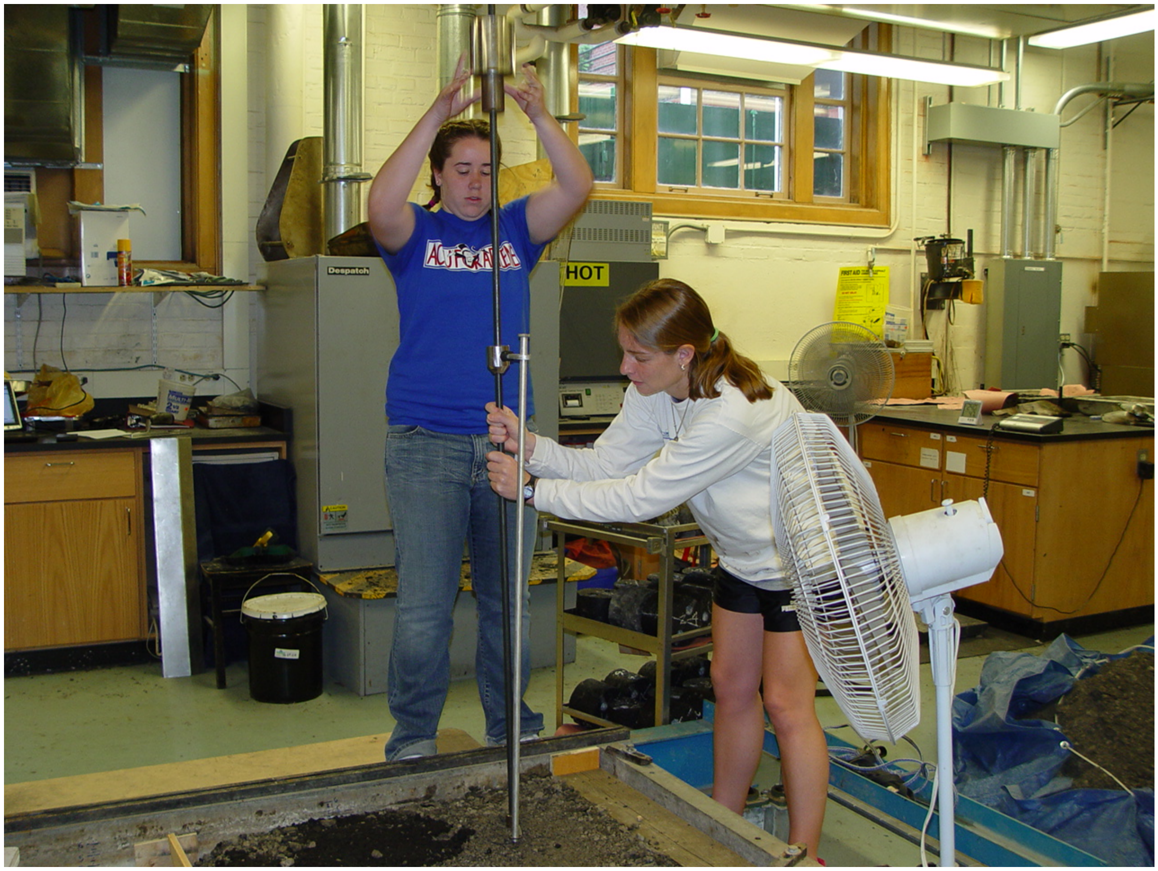

Figure 10. Dynamic Cone Penetrometer

2.2 Portable Seismic Pavement Analyzer (PSPA)

The PSPA, shown in Figure 11, consists of two transducers (accelerometers in this case) and a source. The source is also equipped with a transducer for consistency in triggering and for some advanced analysis of the signals. The PSPA is operable from a computer tethered to a laptop computer through a cable that carries operational commands to the PSPA and returns the measured signals to the laptop computer (9).

The operating principles of the PSPA are based on generating and detecting stress waves in the pavement. The Ultrasonic Surface Wave (USW) interpretation method is used to determine the modulus of the material. Surface waves (R-waves) contain about two-thirds of the seismic energy. Accordingly, the most dominant arrivals are related to the surface waves making them the easiest to measure. At wavelengths less than or equal to the thickness of the uppermost layer, the velocity of propagation is independent of wavelength. Therefore, if one simply generates high-frequency (short-wavelengths) waves and if one assumes that the properties of the upper-most layer are uniform, the modulus of the upper layer, E_{field}, can be determined from (9):

$$E_{field} = 2 \rho \, [(1.13 - 0.16\upsilon) \, V_R]^2 \, (1 + \upsilon)$$

Where V_R = velocity of surface waves

ρ = mass density

υ = Poisson's Ratio

To collect data with the PSPA, the operator initiates the testing sequence through the computer. The high-frequency source is activated four to six times. Pre-recording impacts of the source are used to adjust the gains of the amplifiers in a manner that optimizes the dynamic range of the electronics. The outputs of the three transducers from the final three impacts are saved and stacked (9).

Figure 11. Portable Seismic Pavement Analyzer (10)

In order to test the composition of materials and consequently the modulus of the surface materials, the source sends out a set of seismic waves. The sensors then feel these waves and the time of transit between the source and the sensors is analyzed and the modulus determined.

3.3 Bulk Specific Gravity

In order to find the Bulk Specific Gravity (BSG) of a sample AASHTO T 166-05 "Bulk Specific Gravity of a Compacted Hot-Mix Asphalt Using Saturated Surface-Dry Specimens " was used (11). BSG is one simple way of determining the density. In order to find the BSG the weight of the dry sample is recorded. Then the sample is submerged in room-temperature water for a period of six minutes and the underwater weight recorded. After submersion, the sample is patted-dry on the surface and the new dry weight recorded. The BSG value is calculated by dividing the dry weight (A) by the surface-dry weight (C) minus the submerged weight (B) (11).

$$BSG = \frac{A}{C - B} \qquad 3.4$$

3.4 Indirect Tensile Test

The Indirect Tensile Test (IDT) is a method of determining the tensile strength a sample by applying a compressive load on a cylindrical specimen, shown in Figure 12.

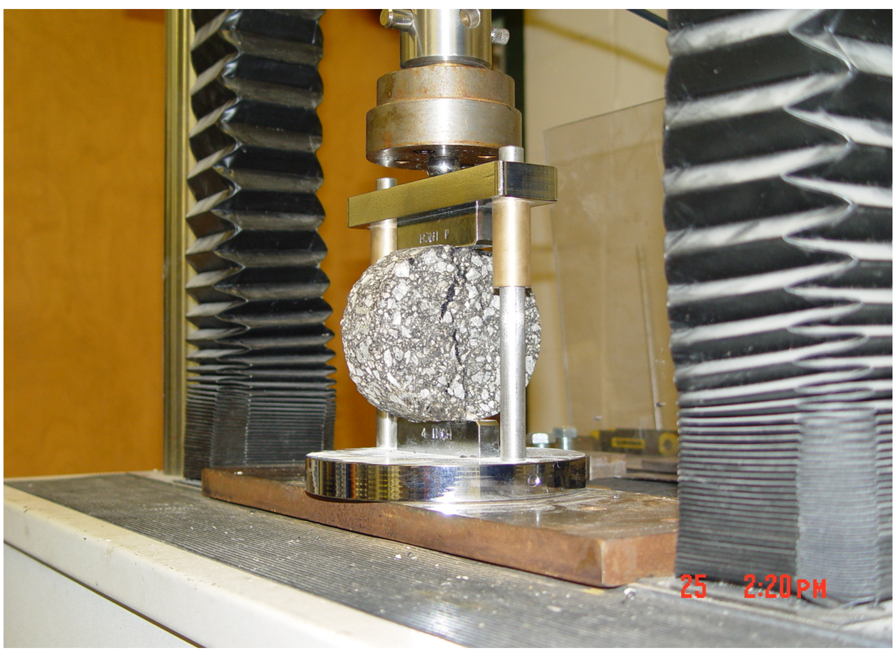

Figure 12. Indirect Tensile Strength Test

The load is applied vertically creating intense stress pressure, and the failure load is measured. Tensile strength can be used to predict the water susceptibility of the sample. In this case the tensile strength was measured before and after water treatment to determine the retained strength percentage. A high percentage retained predicts a good resistance of the sample to moisture damage. The tensile strain at the failure point is often used to predict the susceptibility of the pavement to cracking. Samples which endure high tensile strain values at the failure point are usually more resistant to cracking than those with a failure at low strain values.

The IDT (S) is determined by doubling the peak load (P) and then dividing it by the diameter (d) of the sample and the thickness (t) of the sample and is shown in equation 3.5 (11).

$$S = {}^{2 * P} / {}_{\Pi * d * t} \qquad 3.5$$

During the IDT test, the pressure is usually applied at a rate of 50 mm/minute (2 inches/minute) and at a temperature of 25°C (77^{o}F). The test can be run at lower temperatures if the aim is to evaluate low temperature behavior (such as cracking) (12).

3.5 Workability

A study was conducted to evaluate the effectiveness of the torque bucket made for measuring workability. The bucket was designed and made in the WPI Machine Shop. The torque bucket includes:

- Metal bucket (Figure 13)
- Two foot stands welded to the bottom of the bucket- so that the torque could be measured without the bucket moving.
- The paddle, which can be seen in Figure 14, is what pushes the mix in order to measure the workability of the mix.
- A torque wrench, that is attached to the paddle and measures the torque it takes to move the mix that is in the bucket

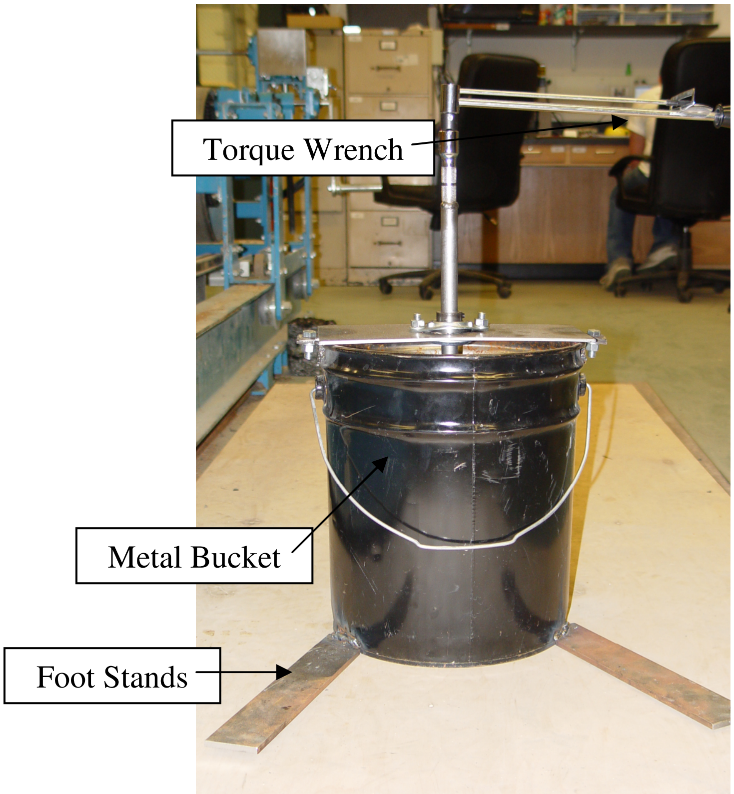

Figure 13. Side View of the Torque Bucket

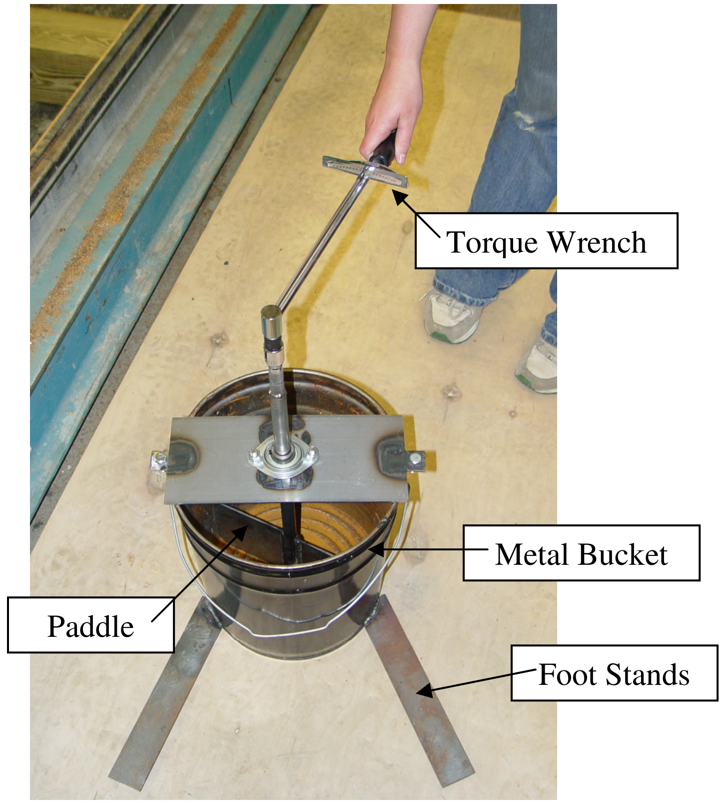

Figure 14. Top View of the Torque Bucket

The test was conducted with each different mix used in the mold. All mixes and binders were heated to the appropriate temperatures in the ovens. Then 15 kg (33 lbs) of the heated sample was placed into the Torque Bucket. The mix was then pushed using the paddle and the torque force was read off of the torque wrench. The reading was taken four times each 15 minutes after the mix was placed into the bucket. The first reading was typically higher than the other three because of the force used to start moving the mix. The subsequent three torque readings were usually similar because they were the torque values that were capable of keeping the mix moving. The test was stopped when the mix reached room temperature (about 24^{o}C or 75^{o}F), the mix could no longer be pushed or two hours had passed. The temperature was taken at the time of each reading. Averaging the four torque values and then inverting the averaged value measured Workabillity. High average torque values were indicative of lower workability and vice versa.

To ensure the test was giving valid results a few things needed to be considered: First was to make sure that the bucket was cleaned after each mix was finished being tested. Making sure the bucket was clean was imperative because the build-up from previous mixes could not allow the paddle to move freely and affect the torque readings. When moving the wrench, it was important to move it at least half of a rotation, or 180^o to ensure an accurate reading. The test results seemed valid because as temperature decreased the workability or torque of the mix increased. Also, the size of the aggregate was found to have significant effect on the workability. This matches with results obtained by Gudimettla, Cooley, Jr., and Brown (6).

3.6 Dispersion

The assumption is that even dispersion of asphalt or emulsion onto the aggregates will result in a higher density. An even dispersion helps to lubricate the aggregates, the asphalt or emulsion acts like a grease or oil, reducing friction, enabling the aggregates to slide over one another and assist in achieving a higher density during compaction. Once the mix has cooled the higher density enables the mix to become very stiff and resist many different pavement distresses. The dispersion will also lower the variability of the bulk specific gravity. A mix with an uneven dispersion will result in a segregated mix and a high variability in the bulk specific gravity. During testing, dispersion of asphalt binder was evaluated by noting the variability of bulk specific gravity of samples compacted with the gyratory compactor as well as of the samples cored from the compacted slabs.

3.7 Compactability

Compactability of the mixes was evaluated with the help of density versus number of roller pass data, developed from thickness versus number of pass data during compaction of the slabs. The slabs were compacted by partitioning a 2.7 m (100 inches) by 0.9 m (35 inches) mold, and using a vibratory roller. Each slab was about 0.9 m (35 inches) by 0.9 m (35 inches) by 0.125 m (5 inches). The roller assembly contains a 0.45 m (18 inches) diameter by 0.9 m (35 inches) steel drum with an 8.9 kN 50/60Hz electric vibrator mounted inside it. The sides of the mold were marked for reading thickness during compaction (Figure 15). Four such readings were taken and averaged to determine the thickness and therefore the density after every 10 roller passes.

Figure 15. Thickness Marks on Mold

3.8 Stiffness

Stiffness of the mixes was evaluated in different ways, as found suitable for each mix. The heated RAP, the Sasobit and the HMA mixes (which could be cored) were tested for resilient modulus by ASTM D4123.

Strength and moisture sensitivity of these mixes were tested using the AASHTO T 283 one freeze-thaw cycle conditioning and testing procedure. These mixes were also tested in-place with the Portable Seismic Analyzer (PSPA). The emulsion mixes were tested with the Dynamic Cone Penetrometer (DCP) and the results were converted to resilient modulus.

Results

Optimum emulsion content was determined by first compacting samples with gyratory compactor (with a slotted mold) and considering the dry densities and the air voids of the sample (Figure 16). Based on the highest dry density and the lowest voids, an optimum of 1.5 percent emulsion (1 percent asphalt) was selected initially. However, on the basis of experience with similar projects, an optimum of 2 percent emulsion (1.5 percent asphalt) was finally selected.

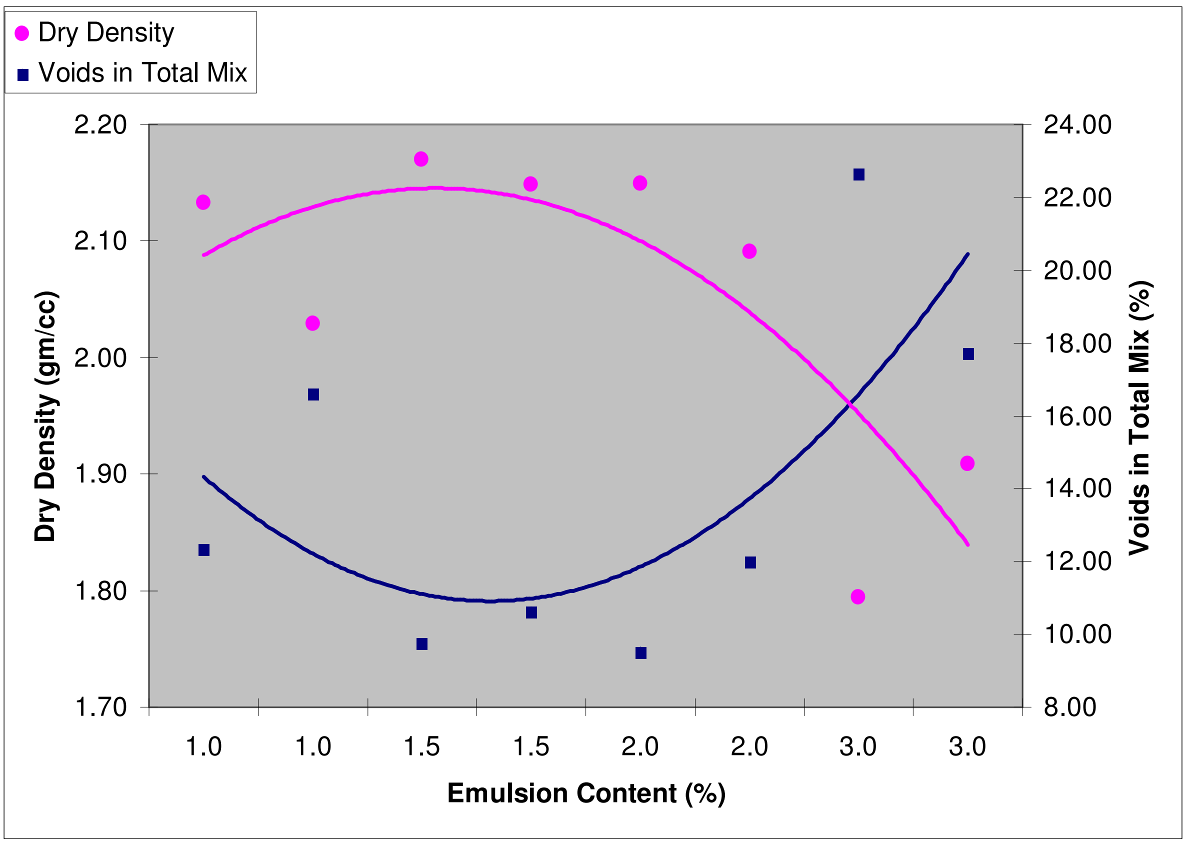

Figure 16. Plots of Dry Density and Voids versus Emulsion Content

The plots of workability (Figure 17) versus time show that workability decreases for all mixes with time. This is because the viscosity of the mix increases, with a decrease in temperature (also seen in Figure 17).

However, the initial workability is different for the different mixes. The mixes with higher emulsion content, heated RAP and Sasobit and HMA show different workabilities. In general workability should increase with a lowering of viscosity and/or higher asphalt content. A higher emulsion content also means higher asphalt content. Therefore, it is expected that a mix with higher emulsion content and/or lower viscosity would show higher workability.

This is confirmed from the plots. The addition of extra emulsion (3% versus 2 %) increases the initial workability; the heating of RAP also increases the workability. This can be explained as follows. Once the RAP and emulsion come in contact during mixing, instantaneously an equilibrium temperature is reached in the mix. The temperature of the RAP controls this equilibrium temperature, since the emulsion is present only in a low percent. Now, if the RAP is at a relatively higher temperature, the equilibrium temperature is relatively high. Since asphalt viscosity is reduced at higher temperatures, the heating of the RAP results in a lowering of the viscosity during mixing and hence an enhanced workability. This increase in workability will be proportional to the increase in temperature and consequently RAP heated to a higher temperature will be expected to show a higher workability – this is also confirmed from the plots, the RAP heated to 110^{o}C (230^{o}F) shows a significantly higher workability compared to the RAP heated to 60^{o}C (140^{o}F).

A review of the Sasobit and HMA mixes shows that the HMA has the highest workability. This is expected, since the asphalt and the RAP were heated to the highest temperature (compared to the other mixes), 150^{o}C (302^{o}F). What is important here is to note that the Sasobit mixes were produced at 125^{o}C (257^{o}F), 25^{o}C (77^{o}F) lower than the temperature at which the HMA was produced. Despite this lower temperature, the Sasobit mixes show workabilities which are comparable to that of the HMA. This is important since it shows that the use of Sasobit can enable the industry to produce a mix which has similar workability as that of conventional HMA, at a much lower temperature and save energy of heating and cut down emissions.

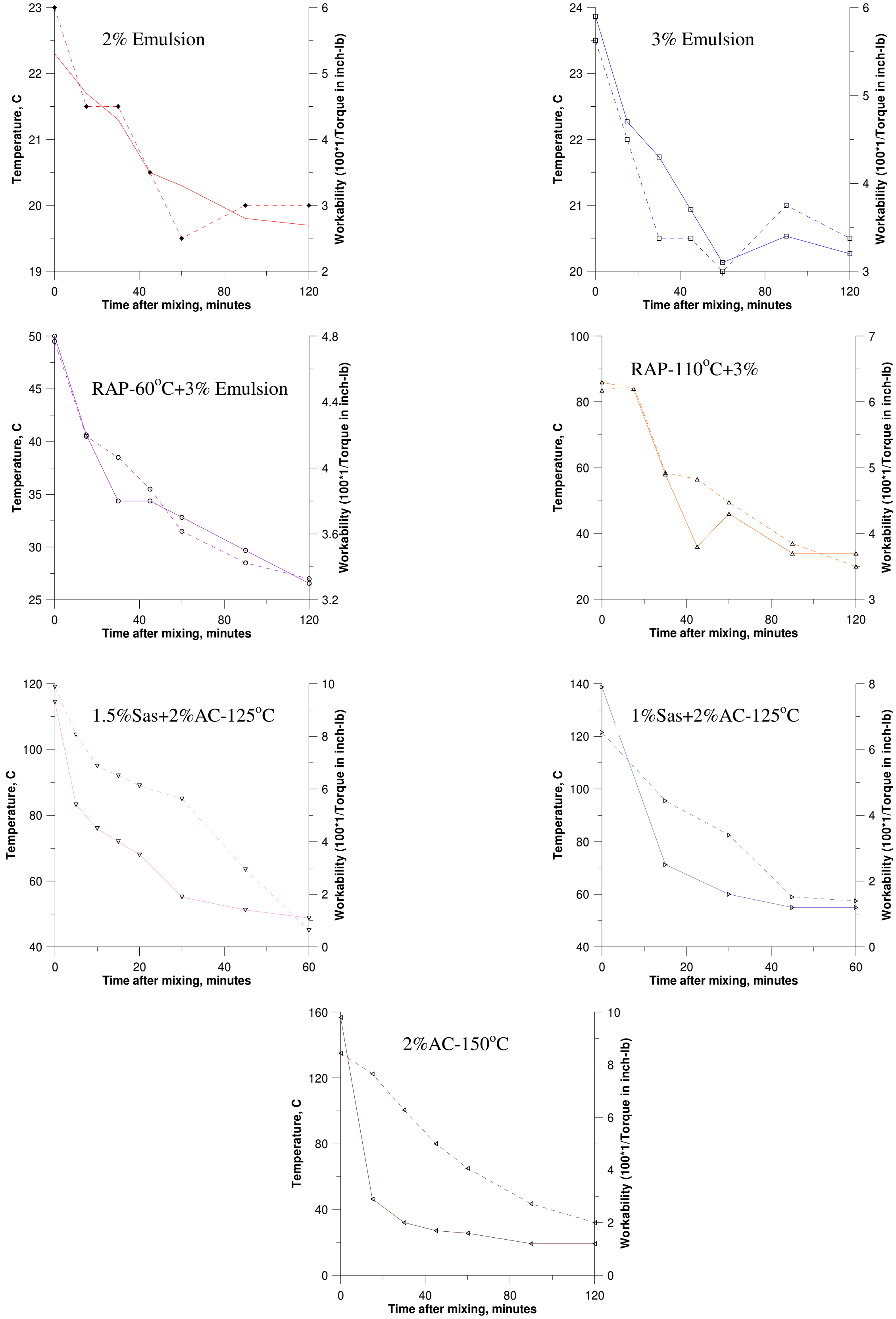

Figure 17. Plots of Temperature and Workability versus Time After Mixing

Note: Dotted line is for temperature and solid line is for workability

With respect to heated RAP as well as Sasobit mixes there a few questions that need to be answered. First, are the performance related properties such as density, stiffness and strength also better than those of conventional emulsion or similar to HMA? It appears to be so from the following tables of bulk specific gravity, modulus and tensile strengths, shown in Tables 3 through 5. However, the second and more important question is, are these results statistically significant? This question is answered in the following sections.

Table 3. Bulk Specific Gravities of Samples

Superpave Gyratory Compactor

Mix	Bulk specific gravities
2 % emulsion	2.188, 2.176, 2.163
Average	**2.176**
3% emulsion	2.193, 2.173, 2.236
Average	**2.200**
RAP-60C+3%Emulsion	2.355, 2.383, 2.371
Average	**2.370**
RAP-110^{o}C+3%Emulsion	2.386, 2.421, 2.389
Average	**2.399**
RAP-125C+ 2% AC+1.5%Sasobit-125^{o}C	2.389, 2.386, 2.379
Average	**2.385**
RAP-125C+ 2% AC+1%Sasobit-125^{o}C	2.394, 2.392, 2.378
Average	**2.388**
RAP-150C + 2% AC-150^{o}C	2.367, 2.389, 2.384
Average	**2.380**

Samples Cored From Compacted Slab

Mix	Bulk specific gravities
RAP-110^{o}C+3%Emulsion	2.304, 2.305, 2.287
Average	**2.297**
RAP-125C+ 2% AC+1.5%Sasobit-125^{o}C	2.304, 2.342, 2.35
Average	**2.332**
RAP-125C+ 2% AC+1%Sasobit-125^{o}C	2.33, 2.329, 2.334
Average	**2.331**
RAP-150C + 2% AC-150^{o}C	2.373, 2.379, 2.365
Average	**2.374**

Table 4. Modulus of Different Mixes

Mix	Resilient Modulus, MPa (at 25C)	Seismic Modulus, MPa (at 25C)	Method Used
RAP + 2 % Emulsion	135 157 147 180 142	--- --- --- --- ---	DCP-->CBR-->Mr
Rap + 3 % Emulsion	433 390 303 323 433 330 254 232 263	--- --- --- --- --- --- --- --- ---	DCP-->CBR-->Mr
RAP-110^{o}C+3%Emulsion	3011,2428,2775, 2123,2377,2211	5175, 4830, 4623, 4209	Mr, PSPA
RAP-125C+ 2% AC+1.5%Sasobit-125^{o}C	2403, 2716, 3341 3472, 3103, 3839	4830, 4692, 4623, 4002, 4209, 4761, 6762, 6555, 6831, 7038, 7659, 7935, 6831, 6831, 6900, 6969, 7314, 7038, 2829, 3243, 3312, 7590, 7590, 7452	Mr, PSPA
RAP-125C+ 2% AC+1%Sasobit-125^{o}C	3484,3076,3995, 3419,3440,4058	5796, 6417, 6003, 7038	Mr, PSPA
RAP-150C + 2% AC-150^{o}C	3759,3873,3664, 3250,3537,3592	8280, 6486, 6486, 6210	Mr, PSPA

Mr = Resilient Modulus, ASTM 4123; PSPA – Portable Seismic Pavement Analyzer; DCP – Dynamic Cone Penetrometer

Table 5. Tensile Strength of Different Mixes

Mix	Dry Strength, kPa	Post Freeze Thaw Strength	Retained Strength, %
RAP-110^{o}C+3%Emulsion	546.5 433.1 507.9	470.6 491.9 528.9	86 114 104
RAP-125C+ 2% AC+1.5%Sasobit-125^{o}C			
RAP-125C+ 2% AC+1%Sasobit-125^{o}C	732.5 806.8 647.6	658.0 706.4 666.7	90 88 103
RAP-150C + 2% AC-150^{o}C (HMA)	1068.7 1246.5 1082.0	1041.5 1039.1 1037.9	97 83 96

The densification data shown in Table 6 is presented for each mix that was compacted in the mold. The density of the mix was determined by using the dimensions of the slab created and using the amount of mix placed into the mold. Once the roller passed over the slab 10 times the thickness was determined from four different points and averaged. Once the mix did not decrease more than 6 mm (0.25 inch) after 10 passes the compaction was complete.

In Figure 18, the graph plots the number of passes versus density of the different mixes. All of the mixes containing emulsion achieved the lowest density. This could be due to uneven dispersion of the emulsion as well as the relatively low temperature. The mixes contained heated RAP have the high density. Heating the RAP helps to drive off moisture in the RAP and also helps the asphalt or emulsion to more evenly disperse over the RAP mix.

Table 6. Densification Data

Mix	Number of passes	Average thickness, m	Dimensions sq m	Total Material, kg	Density, kg/m3
2 % emulsion	10	0.160	0.836	186.36	1309
	20	0.157			1336
	30	0.146			1437
	40	0.138			1520
	50	0.132			1593
	60	0.129			1633
	70	0.127			1653
	80	0.121			1740
3 % emulsion	10	0.156	0.697	172.76	1501
	20	0.146			1599
	30	0.137			1711
	40	0.133			1751
	50	0.132			1772
	60	0.129			1816
	70	0.124			1886
	80	0.121			1936
	90	0.117			1988
RAP-110°C + 3% Emulsion	10	0.125	0.743	187.36	1893
	20	0.116			2049
	30	0.113			2107
	40	0.110			2168
	50	0.108			2200
RAP-125°C+ 2% AC+1.5%Sasobit-125°C	10	0.138	0.743	185.06	1698
	20	0.121			1944
	30	0.110			2141
	40	0.103			2273
	50	0.095			2462
	60	0.087			2686
RAP-125°C+ 2% AC+1%Sasobit-125°C	10	0.138	0.719	188.06	1781
	20	0.122			2013
	30	0.113			2183
	40	0.106			2313
	50	0.105			2348
RAP-150°C + 2% AC-150°C	10	0.122	0.743	185.34	1922
	20	0.114			2055
	30	0.108			2176
	40	0.103			2276
	50	0.097			2426
	60	0.095			2466
	70	0.092			2551

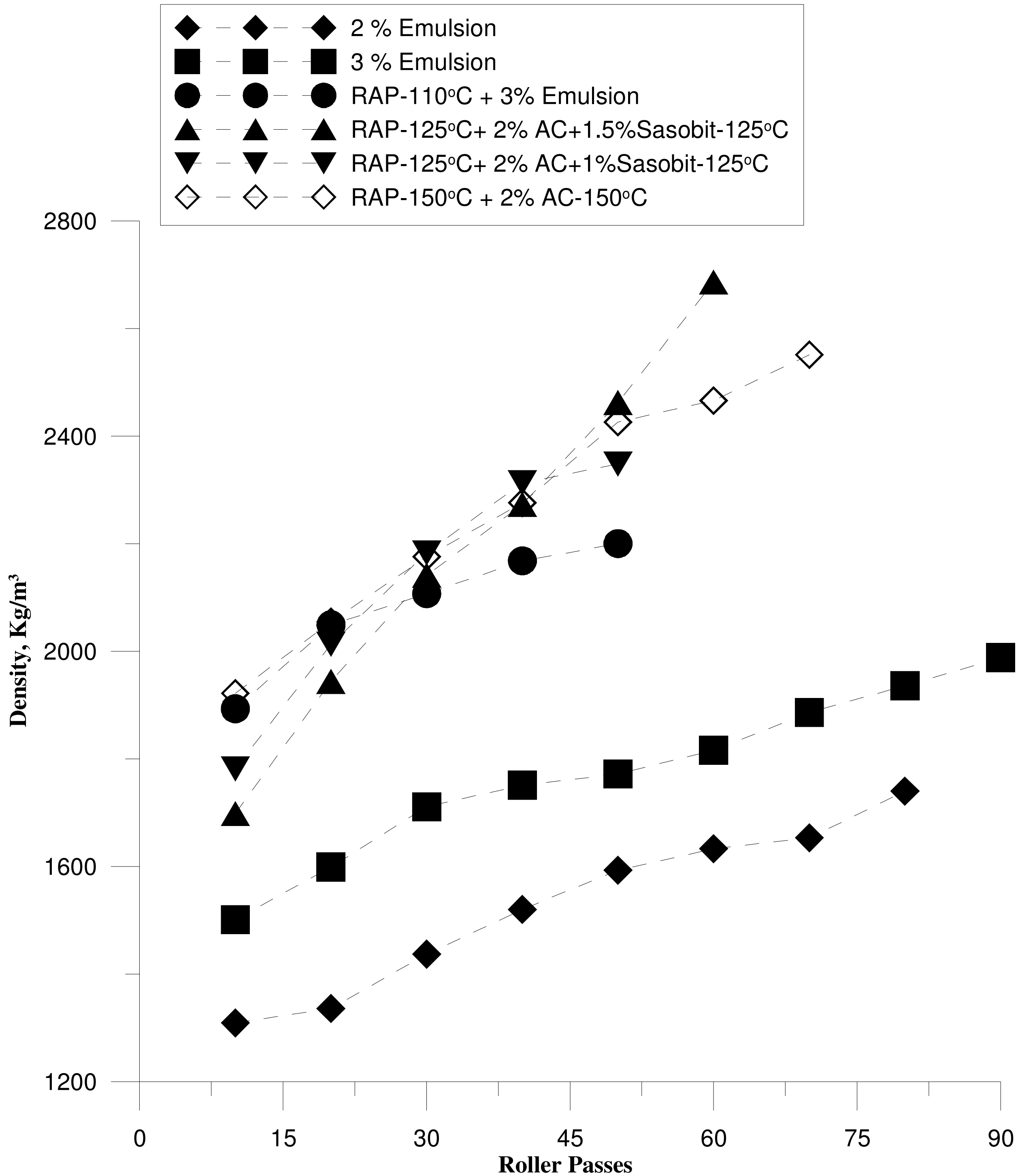

Figure 18. Plots of Number of Passes versus Density for Different Mixes

Analysis of Results

5.1 Analysis of Variance

Analysis of Variance (ANOVA) is a technique used for analyzing the total variation in the response in terms of how much of that variation can be attributed to knowledge of the regressors and how much is unexplainable by the model.

The statistical F-value of each set of data was calculated and analyzed to determine if there was a statistical difference between the sets of data. Then each set of data was comparatively analyzed individually in order to rank the sets of data. Each mix was ranked in the same group if it was found that the mixes were not statistically different. The group rankings increase as the actual number values decrease (13).

ANOVA and mean separation analysis were carried out with the MATLAB software to determine whether the different properties are statistically different or not. The results of analysis are shown in Table 7 through 10.

Table 7. Results of ANOVA with Workability Means

Workability at 0 minutes					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	70.1333	6	11.6889	1443.92	0
Errors	0.1133	14	0.0081		
Total	70.2467	20			
Workability at 15 minutes					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	27.3429	6	4.55714	455.71	3.21965E-15
Errors	0.14	14	0.01		
Total	27.4829	20			
Workability at 30 minutes					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	34.0114	6	5.66857	566.86	6.6134E-16
Errors	0.014	14	0.01		
Total	34.1514	20			
Workability at 45 minutes					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	26.9829	6	4.49714	449.71	3.44169E-15
Errors	0.14	14	0.01		
Total	27.1229	20			
Workability at 60 minutes					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	30.1457	6	5.02429	502.43	1.66533E-15
Errors	0.14	14	0.01		
Total	30.2857	20			
Workability at 90 minutes					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	12.4444	4	3.111	311.1	1.91901E-10
Errors	0.1	10	0.01		
Total	12.544	14			
Workability at 120 minutes					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	11.364	4	2.841	284.1	3.00817E-10
Errors	0.1	10	0.01		
Total	11.464	14			

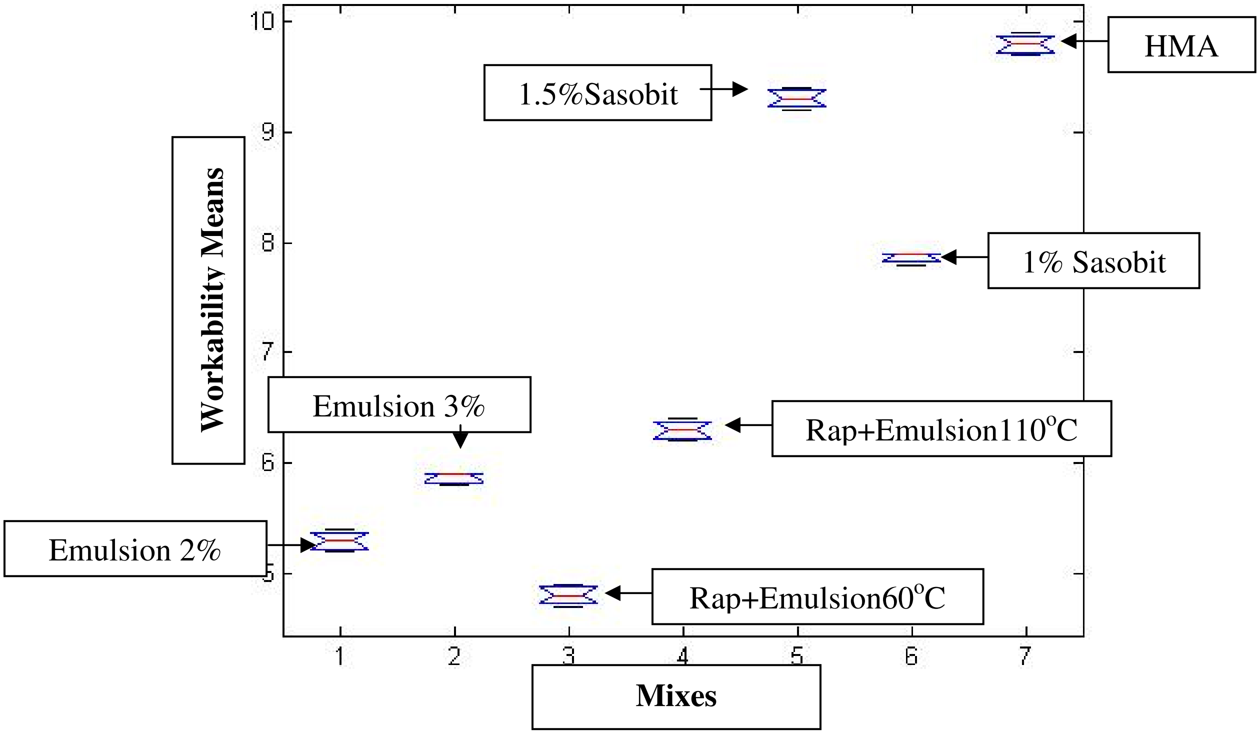

Figure 19. Ranking of Means for Torque Data at 0 Minutes

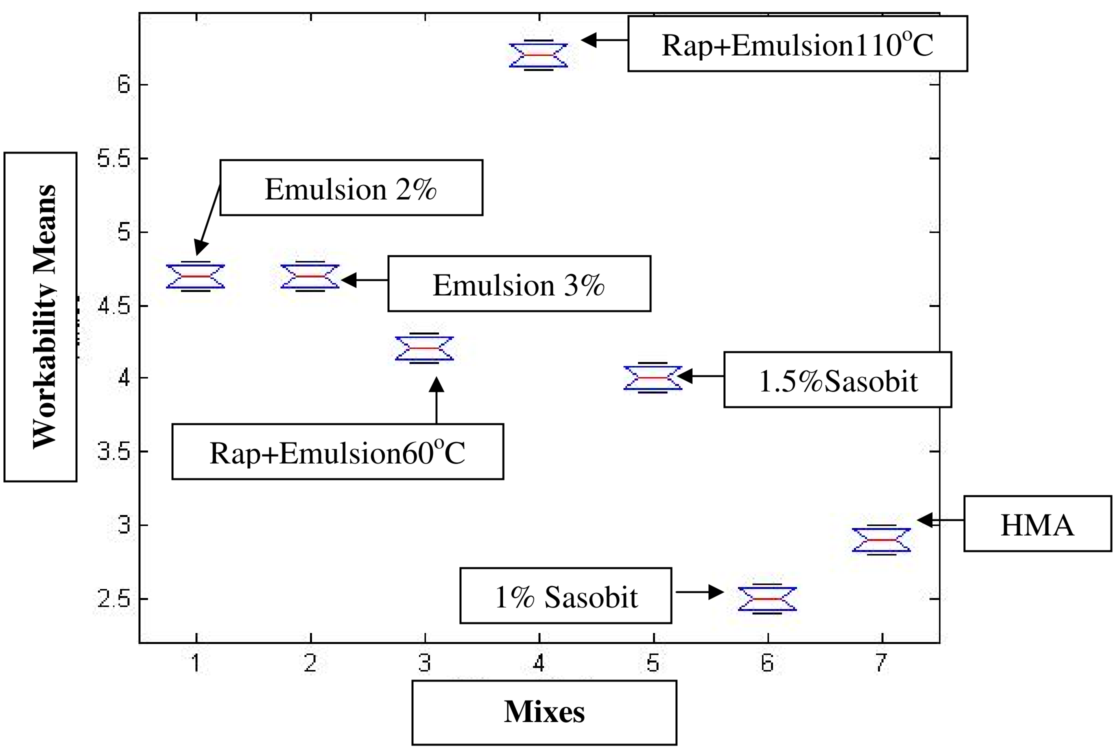

Figure 20. Ranking of Means for Torque Data at 15 Minutes

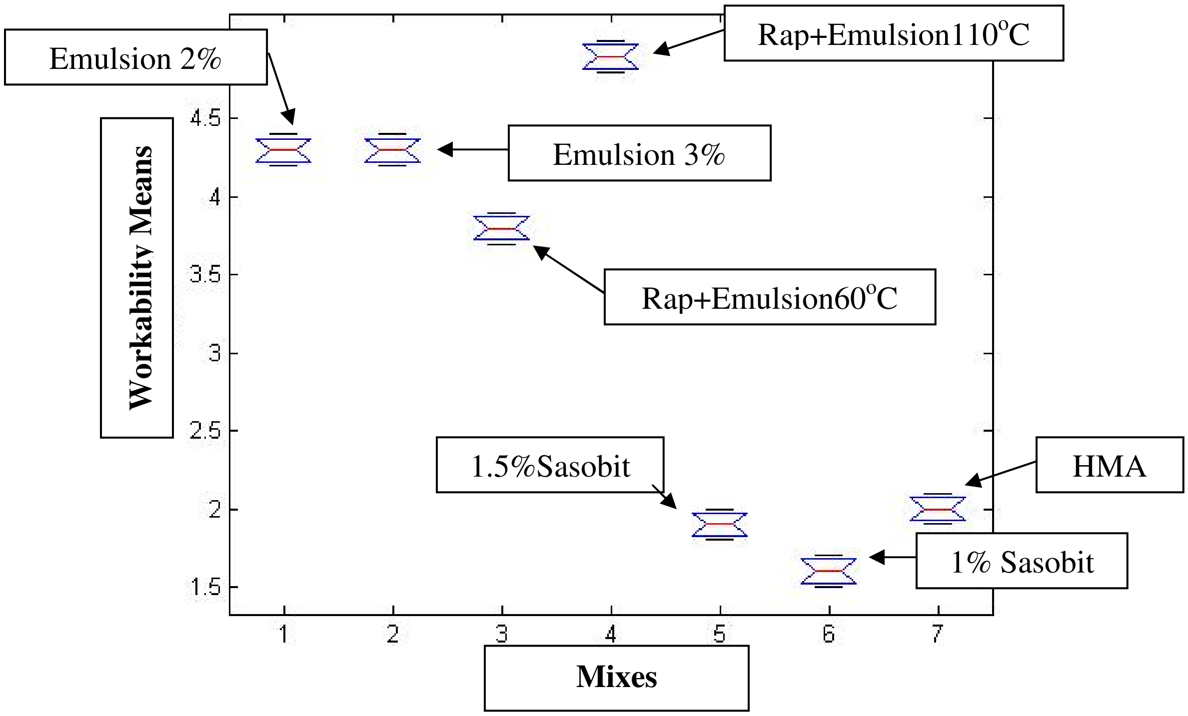

Figure 21. Ranking of Means for Torque Data at 30 Minutes

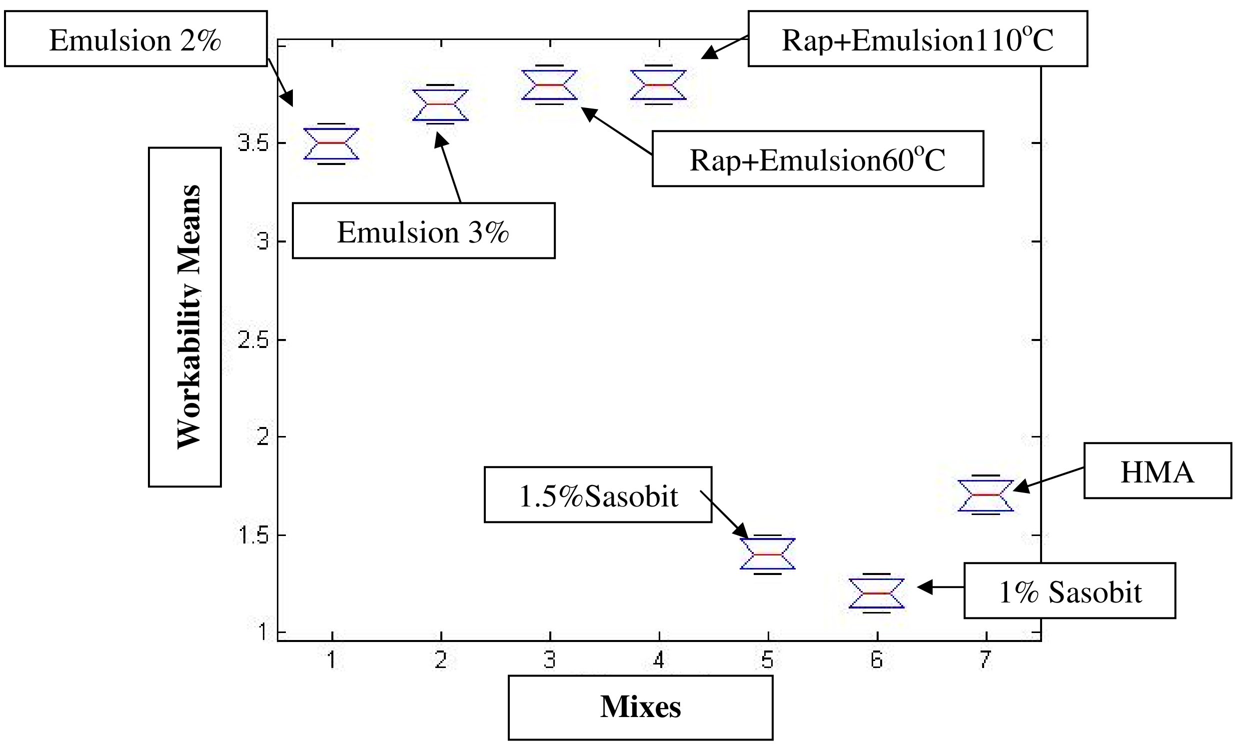

Figure 22. Ranking of Means for Torque Data at 45 Minutes

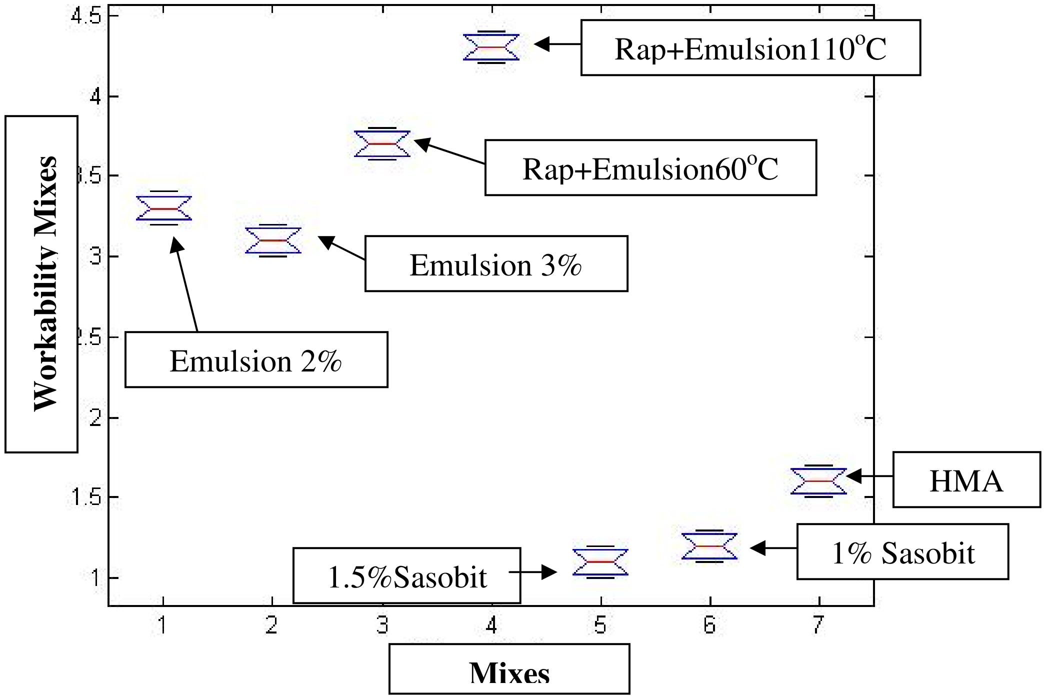

Figure 23. Ranking of Means for Torque Data at 60 Minutes

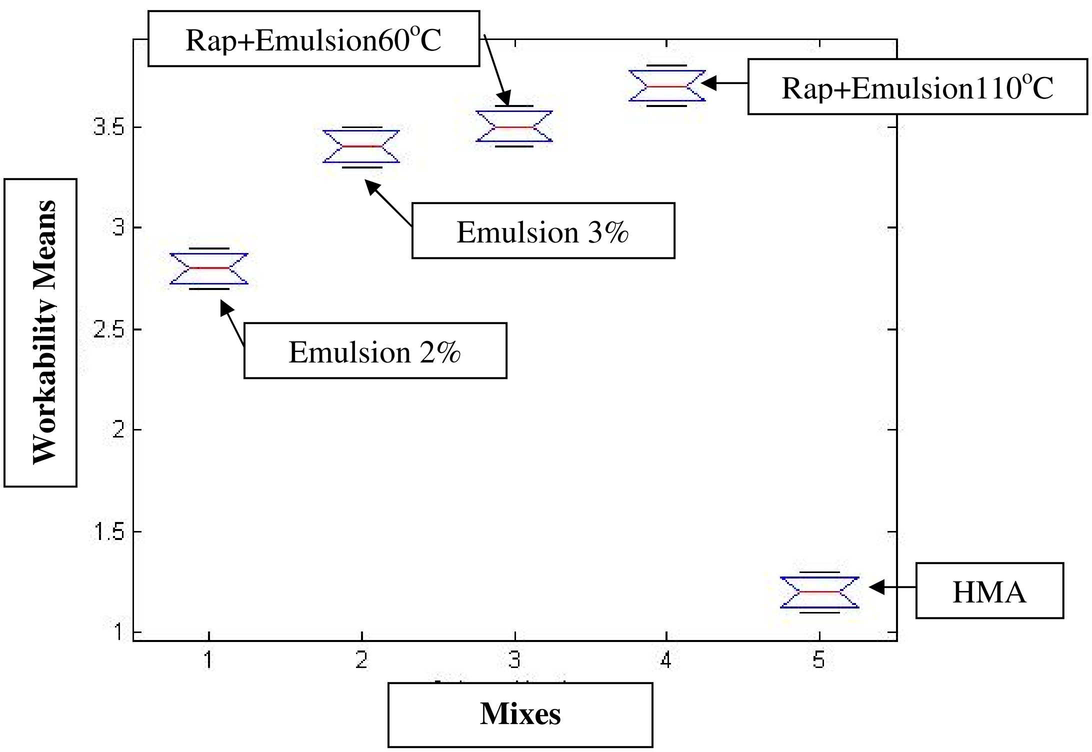

Figure 24. Ranking of Means for Torque Data at 90 Minutes

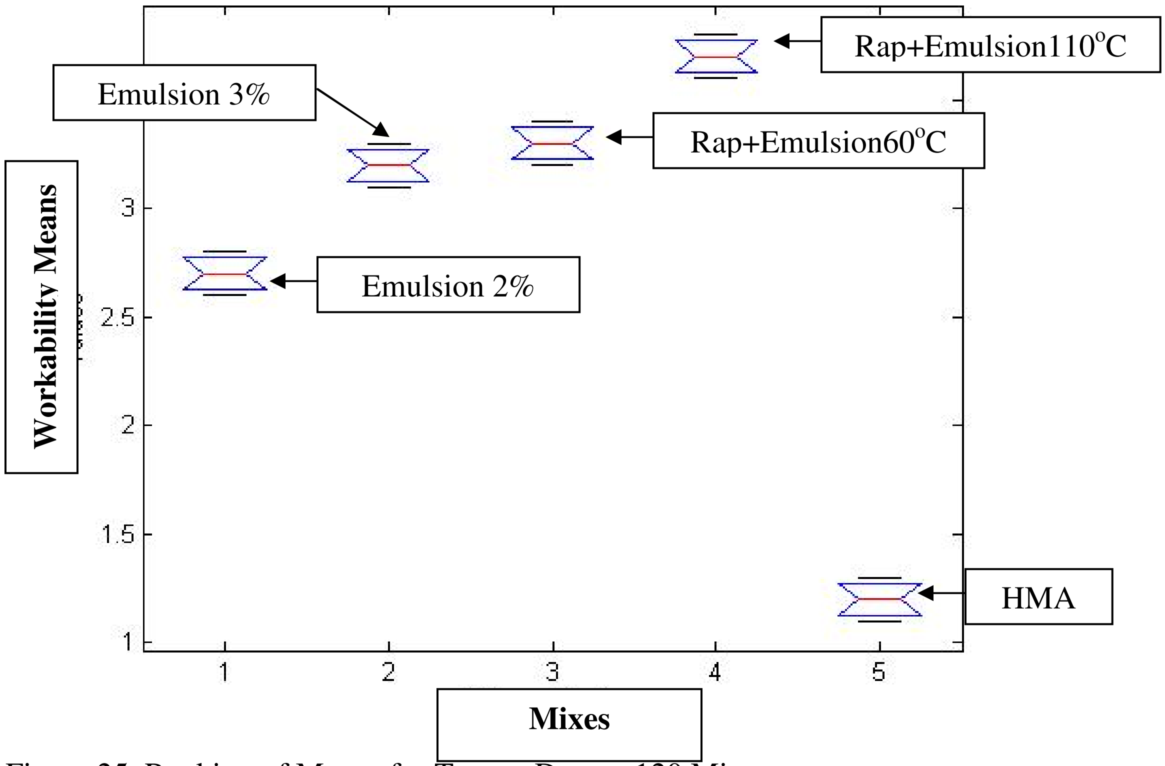

Figure 25. Ranking of Means for Torque Data at 120 Minutes

First, consider workability. For the times for which the data is available for all of the mixes it is seen that there are significant differences and the different mixes can be ranked as follow in order of decreasing workability.

HMA

Sasobit 1.5%

Sasobit 1%

RAP110°C+3%Emulsion

RAP60°C+3% Emulsion

3% Emulsion

2% Emulsion

Table 8. Results of ANOVA with Bulk Specific Gravity Data

Bulk Specific Gravity of Gyratory Samples					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	0.16699	6	0.02783	97.33	0.000000000133
Errors	0.004	14	0.00029		
Total	0.171	20			
Bulk Specific Gravity of Cored Samples					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	0.00819	3	0.00273	14.32	0.0014
Errors	0.00153	8	0.00019		
Total	0.00972	11			

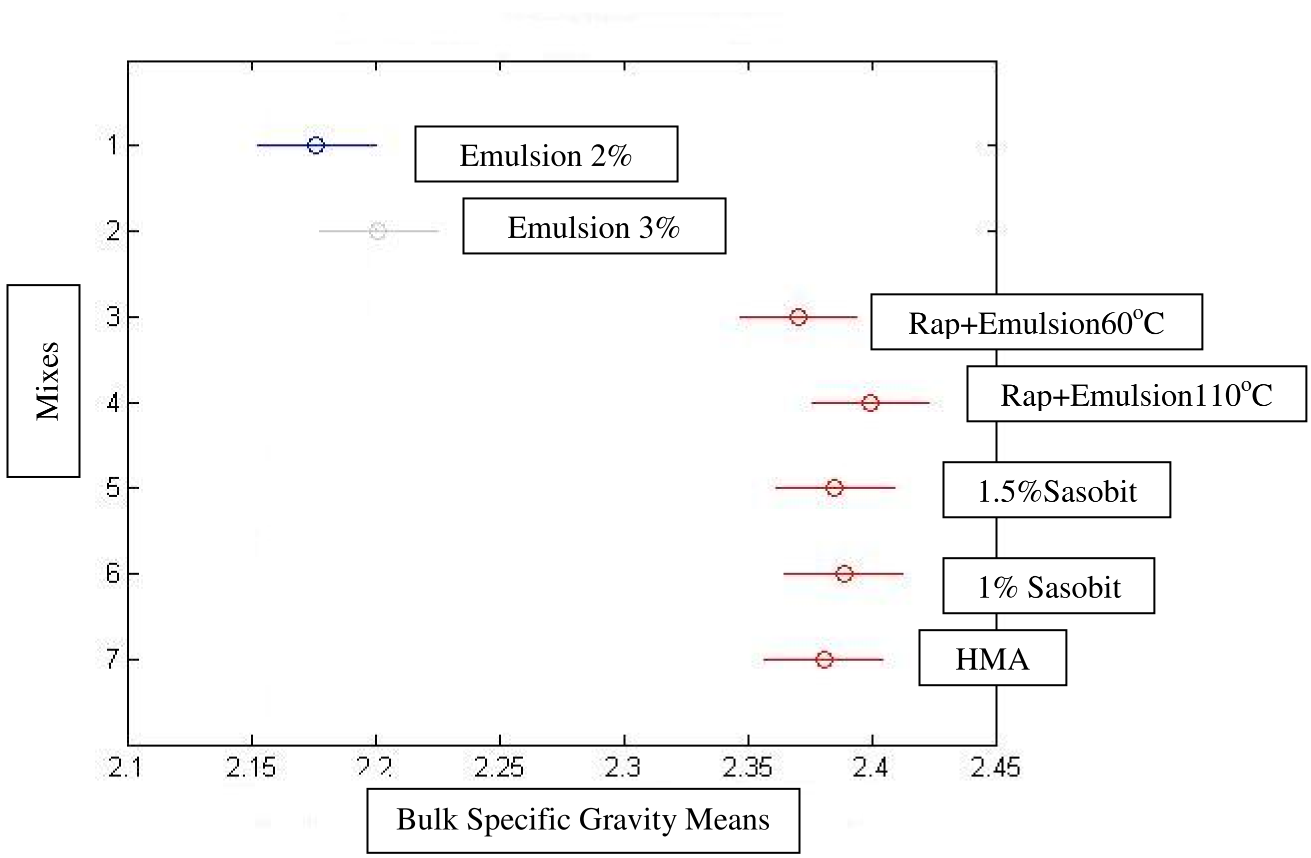

Figure 26. Ranking of Means for Bulk Specific Gravity with Gyratory Compactor

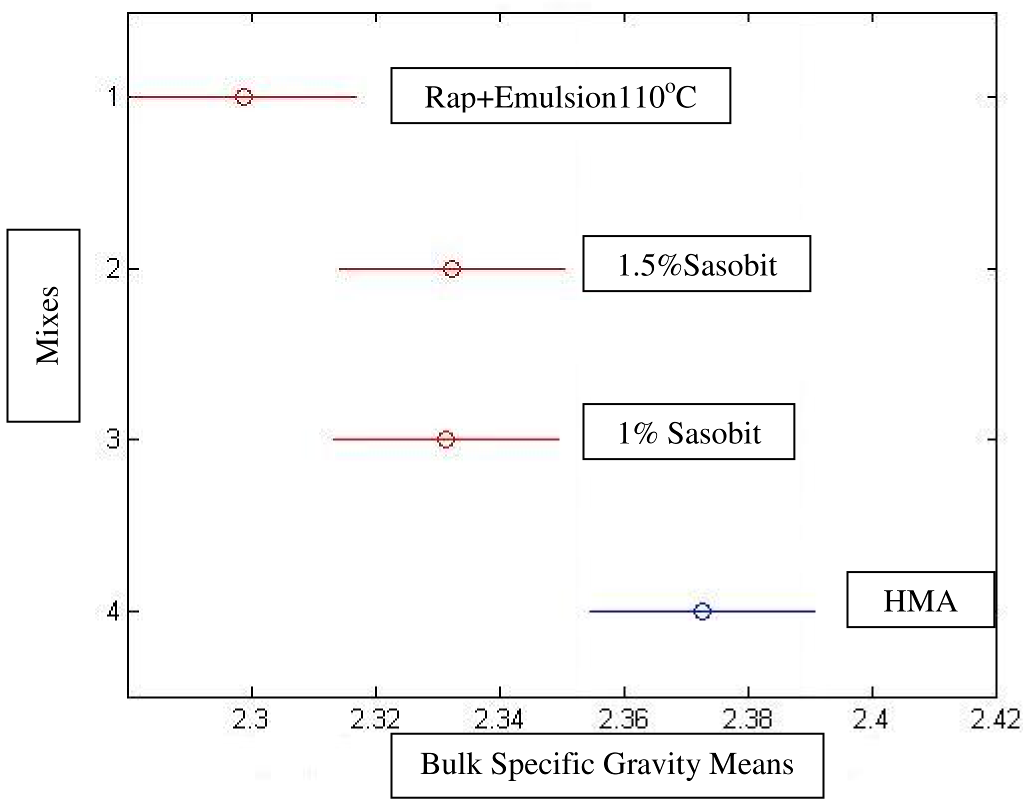

Figure 27. Ranking of Means for Bulk Specific Gravity of Cored Samples

Note that a better dispersion of asphalt would lead to better density, and more uniform density. An analysis of the bulk specific gravity data (Table 8) confirms both points – the mixes with higher workabilities have higher densities, and in general, these mixes also have lower variability (as shown by coefficient of variation) of bulk specific gravity. According to density, the mixes can be ranked as follows, in terms of decreasing density.

HMA

Sasobit 1.5%

Sasobit 1%

RAP110°C+3%Emulsion

RAP60°C+3% Emulsion

3% Emulsion

2% Emulsion

Table 9. Results of ANOVA with PSPA and DCP Data

Seismic Modulus from PSPA Testing					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	13815700	3	4605228.2	5.69	0.0117
Errors	9712230	12	809352.7		
Total	23527900	15			
Resilient Modulus from DCP for 2 and 3% emulsion					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	103632.4	4	103632.4	64.36	0.0000428
Errors	12881.6	8	1610.2		
Total	116514	9			

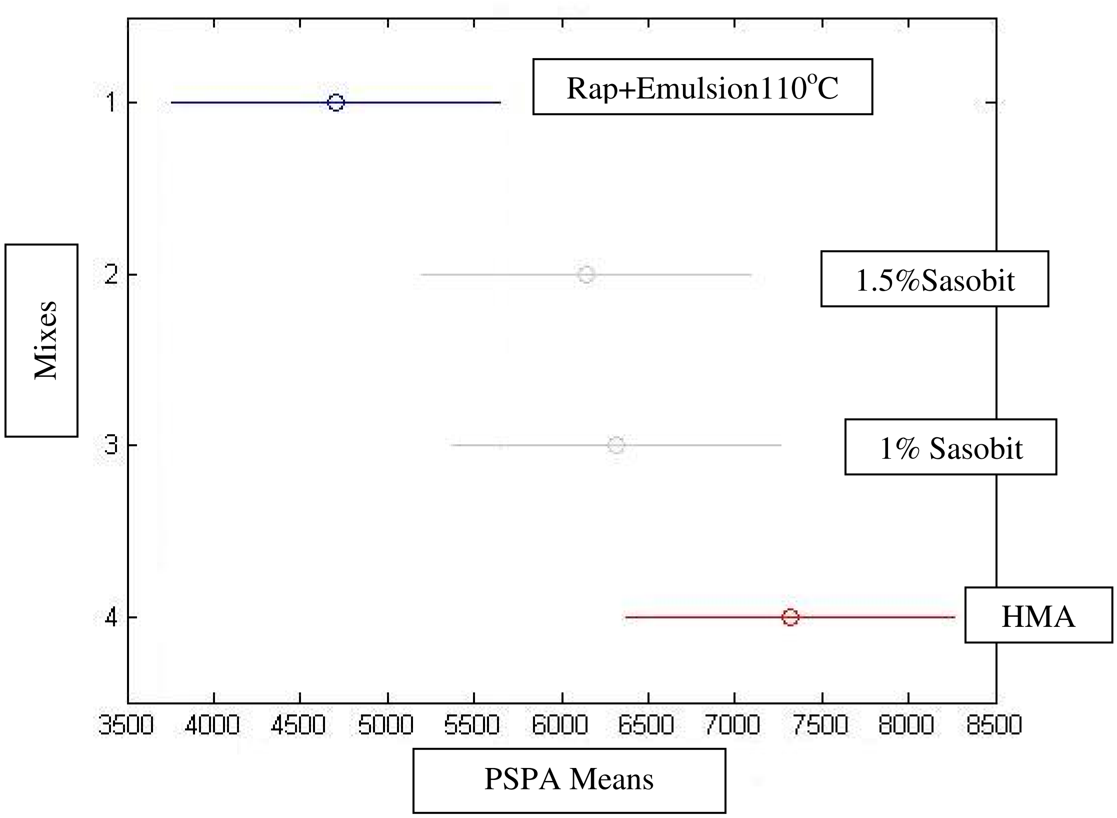

Figure 28. Ranking of Means for PSPA Data

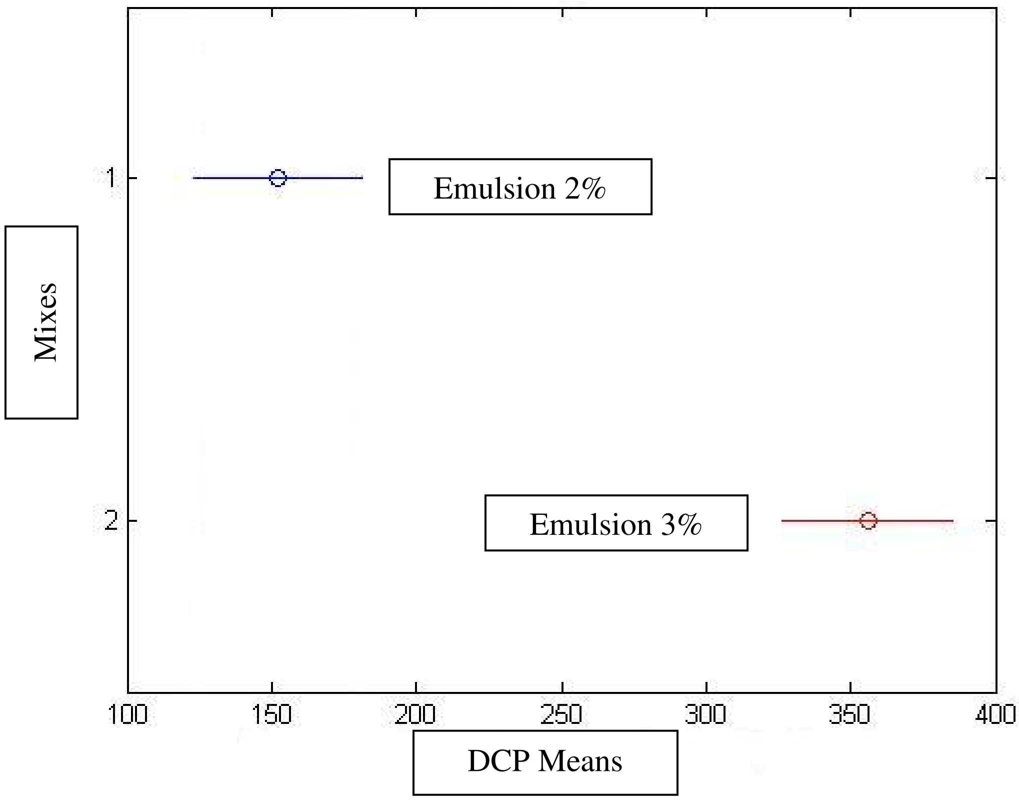

Figure 29. Ranking of Means for DCP Means

Next consider modulus. The moduli values were obtained in different ways and the results of analysis of all the moduli and the rankings are shown in Table 9. Again, there is a significant difference, and the mixes can be ranked as follows, in the order of decreasing modulus.

HMA

Sasobit 1.5%

Sasobit 1%

RAP110^{o}C+3%Emulsion

RAP60^{o}C+3% Emulsion

3% Emulsion

2% Emulsion

Note that the rankings are very similar to those of density values.

Table 10. Results of ANOVA with Indirect Tensile Strength Data

Dry Indirect Tensile Strengths					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	10300.9	1	10300.9	0.15	0.7066
Errors	1122269	16	70141.8		
Total	1132569.9	17			
Post Freeze Thaw Tensile Strengths					
Source	Sum of Squares	df	Mean Square	F	Sig.
Columns	148.667	2	74.333	0.68	0.5424
Errors	657.333	6	109.556		
Total	806	8			

Finally, consider the analysis of the tensile strength values (Table 10). There are significant differences in the dry and conditioned strengths, although no significant difference in the retained strengths. The increased dry and conditioned strengths would actually lead to better performance. The rankings are shown below, and they are similar to those of the density rankings.

<u>Dry</u>

HMA

Sasobit 1.5%

RAP110^{o}C+3%Emulsion

<u>Conditioned</u>

HMA

RAP110^{o}C+3%Emulsion

Sasobit 1.5%

It seems that density is the key parameter that governs all other performance parameters (Figure 30 and 31). The plots show good correlation between density and modulus, and density and dry strength. Workability is also important, since it actually facilitates the compaction of the mix and hence enables us to achieve good density.

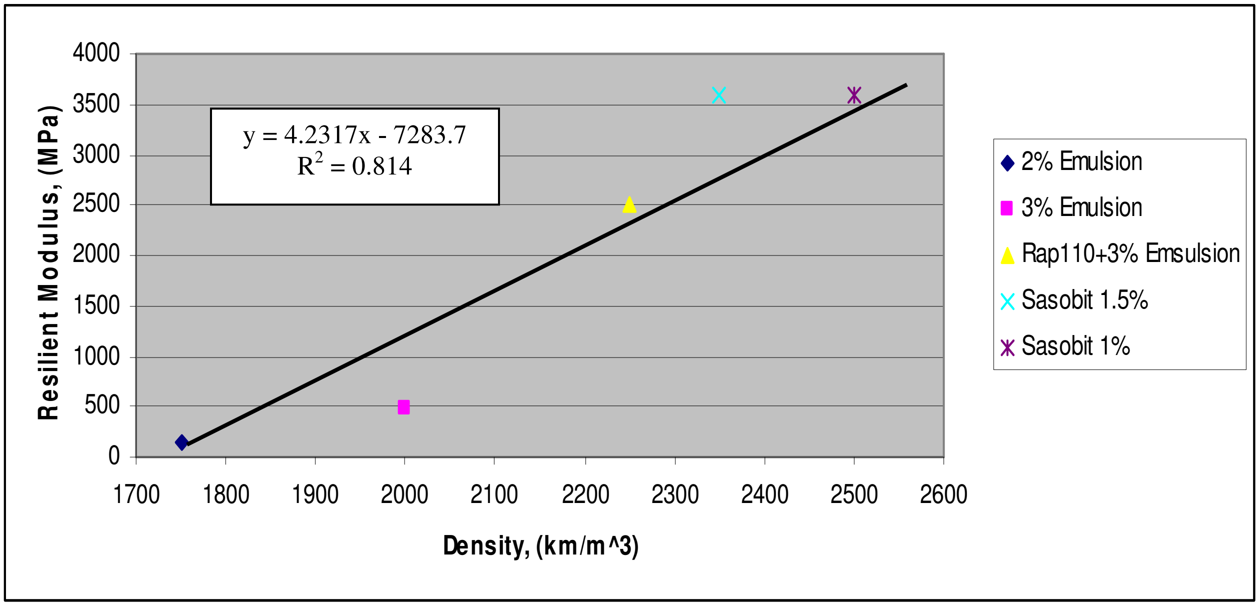

Figure 30. Density versus Resilient Modulus

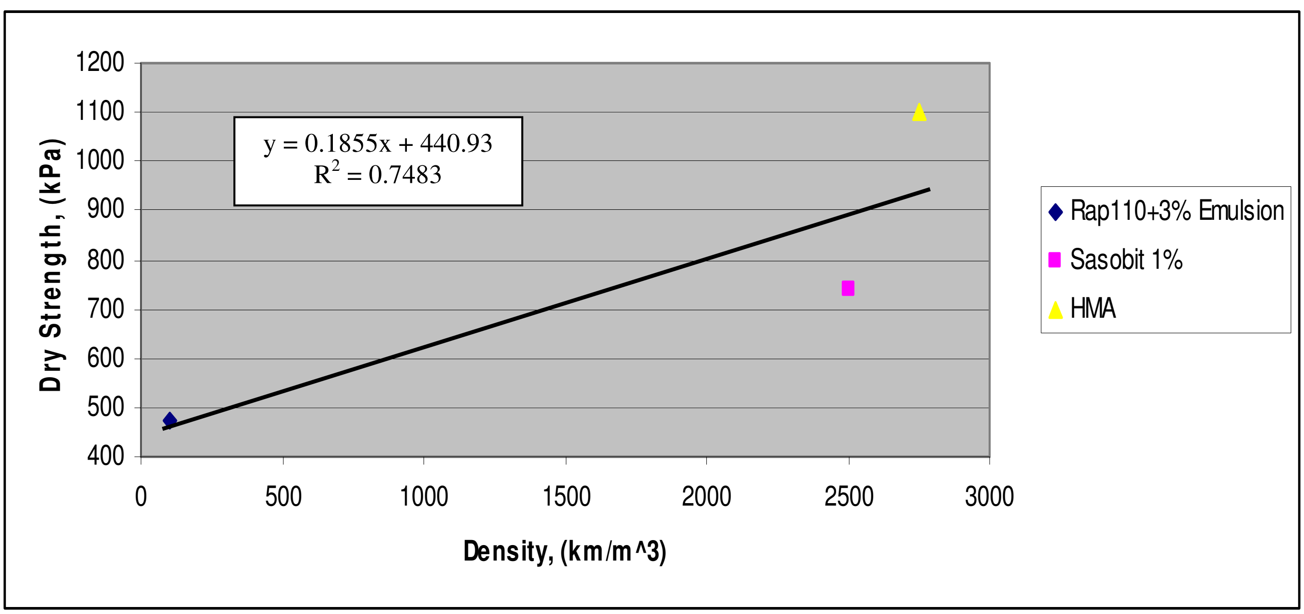

Figure 31. Density versus Dry Strength

Conclusion and Recommendations

Based on this study the following conclusions can be made:

1. Heating the RAP prior to mixing with emulsion improves the dispersion, workability, compactability and stiffness of the mix.
2. For emulsion mixes, RAP heated to 110°C (230°F) produces mixes with significantly better properties than mixes with unheated RAP, at similar emulsion content. The heated RAP mix showed better stiffness and strength.
3. Use of Sasobit with asphalt binder at a mixing temperature of 125°C (257°F) produced mixes with workabilities and compatibilities that are lower but close to those of a mix with neat asphalt binder, produced at 150°C (302°F). No significant difference was found between stiffness and retained strength values of asphalt binder mixes with and without Sasobit. The dispersion of the asphalt binder was found to improve with the use of Sasobit.
4. For mixing temperature of 125°C (257°F), the use of 1% Sasobit, in terms of total asphalt provided a mix with better properties, compared to a mix with 1.5% Sasobit.
5. There seems to be a significant advantage in using heated RAP and/or Sasobit in reducing temperature for using asphalt binder in recycling of HMA for base course.
6. A field project to evaluate emulsion and Sasobit mixes along with HMA should be initiated. The use of heated RAP (110°C or 230°F) with emulsion, and 1% and 1.5% Sasobit with asphalt binder are recommended.

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