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Reducing Greenhouse Gas Emissions from Asphalt Materials

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by

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1. asphalt
2. Sasobit®
3. emissions

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Executive Summary

Through the construction of new asphalt pavements, the asphalt industry has been contributing to greenhouse gas emissions released into our atmosphere. Recently, there have been products developed, such as Sasobit®, that decrease viscosity of asphalt at a lower than conventional mix temperature, which can in turn reduce greenhouse gas emissions. The objectives of this study were to determine if emissions can be reduced with the use of Warm Mix Asphalt (WMA), and whether any material properties can be expected to improve in mixes produced at lower temperatures (WMA versus Hot Mix Asphalt, or HMA). Another objective was to determine economic benefits, if any, of producing mixes at lower temperatures.

Testing for this study included emission testing for pure asphalt and asphalt mixes. HMA and WMA samples were also mixed and compacted to test material properties. All tests completed were done on 3 separate mixes: HMA with 5.3% asphalt, WMA with 5.3% asphalt and 1% Sasobit® (by mass of asphalt), and WMA with 4.8% asphalt and 1% Sasobit® (by mass of asphalt).

For all emission tests, Drager testing equipment was used. The set up used for these tests consisted of flasks, ovens, a Drager pump and Drager tubes. To measure carbon dioxide (CO_2), the Drager pump needed 10 full strokes and it took approximately four minutes for the test to be completed. The color change in the chemical inside the tube indicated the amount of gas in the sample in parts per million (ppm). Preliminary testing of emissions emitted from pure asphalt was done to develop a procedure since there are no test standards for this available at this time. For this study, approximately sixty grams of asphalt mix, both WMA and HMA, and approximately twenty-five grams of pure asphalt were tested for emissions.

The three asphalt mixes in this study were tested for both unaged and aged conditions of material properties according to standards developed by the American Society for Testing and Materials. The tests conducted to determine volumetric and mechanical properties were Bulk Specific Gravity, Theoretical Maximum Density, and Indirect Tensile Strength. The volumetric properties analyzed were percent air voids, absorption and effective asphalt content.

After thorough testing and analysis of the three different asphalt mixes, it is determined that the additive Sasobit® is a beneficial material to be used in WMA. The changes in material properties result in stronger and longer lasting asphalt mixes as well as a longer paving season. With the addition of Sasobit® the temperature of HMA production can be cut down by 20°C and

as a result, the carbon dioxide emissions let off by the asphalt industry could be reduced as much as 43.9% per year. This includes emissions from the fuel used as well as from the asphalt materials used to produce the Hot Mix Asphalt. In addition, the decreased temperature required for Sasobit® asphalt mixes can save over $69 million in energy costs.

The ecological impacts that the use of Sasobit® in asphalt mixes can have for the asphalt industry are significant. The reduction of greenhouse gases from asphalt mix materials and energy consumed by the asphalt industry can make a difference in the world we live in and have the potential to improve the earth's atmosphere. From this study, it was calculated that 3.774 million tonnes of CO_2 could be prevented from being released into the atmosphere per year from the asphalt mix materials as well as energy used during production. In 10 years, 37.74 million metric tons of CO_2 could be prevented. It is essential for the asphalt industry to start caring about their effects on the environment, and the addition of Sasobit® to asphalt mixes would be a great start for this.

Abstract

The additive Sasobit® was tested in three asphalt mixes at two temperatures. Volumetric properties, carbon dioxide emissions and mechanical properties were tested to determine if Sasobit® would be an effective additive for the asphalt industry. It was found that the use of Sasobit® in Warm Mix Asphalt can help reduce carbon dioxide emissions, costs and energy used by the asphalt industry without affecting the quality of asphalt pavements.

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Chapter 1: Introduction and Objectives

Through the construction of new asphalt pavements, the asphalt industry has been contributing to greenhouse gas emissions released into our atmosphere. Recently, there have been products developed that decrease viscosity of asphalt at a lower than conventional mix temperature. These lower temperatures can in turn reduce greenhouse gas emissions. In addition to environmental benefits, the asphalt industry could greatly profit from these products. On average 30-50% of the costs at an asphalt plant are for emission control (1). Companies are limited to specific areas to operate asphalt plants in, but if emissions were reduced, asphalt plants could be built in areas with strict pollution regulations. This would mean shorter haul distances to construction sites, less costly operations, and savings for the tax paying public also.

1.1 Greenhouse Gas Emissions

Over the past few decades, as our culture has become more environmentally conscious, we have taken more notice to the problem of greenhouse gas emissions. Greenhouse gas emissions come mostly from the burning of fossil fuels and industry processes (2). The main emissions that are present in our atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and many engineered gases.

Greenhouse gas emissions cause many environmental problems for our earth. Many gas emissions soak up infrared radiation from the atmosphere, trapping heat in our lower atmosphere (2). This is called the Greenhouse Effect, and if it were not present the earth's natural temperature would be around -19ºC (-2.2ºF). The Greenhouse Effect is not a negative process, and keeps our earth at a more tolerable 14ºC. However, many scientists and researchers believe in the process of Global Warming. They believe that with the increasing amounts of gases emitted into the atmosphere each year, the temperature of our earth is rising. According to computer-stimulated models, the increase in gases will always result in Earth's temperature rising. Although these are just computer models, the actual temperature of the Earth has increased 0.6ºC over the past 100 years (2).

These rising temperatures, of both land and ocean, have the ability to create changes in our weather patterns on Earth. We have seen a lot changes over the past decade in our weather patterns and an increase in severe storms and hurricanes. These changes have yet to be proven a sole result of human activities, as opposed to natural variations having an impact (2).

1.1.1 Reducing Greenhouse Gas Emissions

The actions taken in response to concerns of Global Warming come from organizations such as the Domestic Policy Council and the National Academy of Sciences (2). The National Academy of Sciences through National Research Council prepared a statement on Global Response to Climate Change. The statement indicates that not only is climate change real, but it caused by human activity. It went on to say that nations should begin taking steps to reduce the growth of greenhouse gas emissions, as well as prepare for future climate changes.

Over the past few years, as an increasing number of people have recognized the problems associated with greenhouse gas emissions, more efforts have been made to lower emissions. In 1992, the Energy Policy Act was put in place, mandating the Energy Information Administration (EIA) to produce an inventory of aggregate U.S. national emissions updated each year (2). Although this report is useful to recognize our specific problems, U.S. emissions are still far above what they should be. In 2002, U.S. energy-related carbon dioxide emissions totaled more than 5,746 million metric tons, making up approximately 24 percent of the worlds' total emissions.

There have been some actions taken to control the amount of emissions caused by asphalt production. Title V of the Clean Air Act, 1990, states that "(it) requires the accurate estimation of emissions from all U.S. manufacturing processes, and places the burden of proof for that estimate on the process owner" (3, p.1). Although some general actions have been taken towards the reduction of greenhouse gas emissions, there needs to be more focus on improving the asphalt industry.

1.2 Asphalt Properties

The majority of paving asphalt cement used at this time is obtained by processing crude oils (4). Distillation is the first step in processing all crude oil. There are several techniques to produce asphalt cements with straight reduction to grade being the most commonly used. The processed asphalt must be workable to be mixed with other substances, such as aggregates, which requires a low viscosity. This can be achieved by heating the asphalt to a high temperature (such as 150ºC).

1.2.1 Viscosity and Temperature

Two intrinsic properties that affect asphalt's physical state and performance are viscosity and temperature. Temperature and viscosity are very much related to each other. In order to construct asphalt pavements, the asphalt must be heated to a very high temperature (150ºC) to get a low viscosity, and thus a good coating of aggregates (4). The mix also has to be workable such that it can be compacted to an adequate density to obtain a strong and durable road.

The resistance of flow of a given fluid is defined as viscosity.

> Viscosity at any given temperature and shear rate is essentially the ratio of shear stress to shear strain rate. At high temperatures such as 135ºC, asphalt cements behave as simple Newtonian liquids; that is the ratio of shear stress to shear strain rate is constant. At low temperature, the ratio of shear stress to shear strain is not a constant, and the asphalt cements behave like non-Newtonian liquids….viscosity is a fundamental consistency measurement in absolute units that is generally not affected by changes in test configurations or geometry of the samples (4, p. 48-49).

The quantity of light fractions retained in asphalt after processing affects the viscosity (5). Gasoline, kerosene and fuel oils are types of light fractions. The atomic structure of the fractions exhibit different behaviors. Even after experiencing the same processing, asphalts from different sources will contain different amounts of light fractions and have different viscosities.

Asphalt binder is considered a thermoplastic material (4). The consistency of asphalt changes according to the temperature it is subjected to. The rate this occurs at is very important and is referred to as temperature susceptibility. Temperature not only affects the viscosity of the asphalt, but it also affects the amount of emissions released from the material. It is impossible to create an asphalt mix unless the asphalt has a relatively low viscosity. The low viscosity allows the asphalt to coat and mix with the aggregates properly. To obtain the low viscosity it is generally necessary to heat the asphalt and the aggregates to a relatively high temperature.

1.3 Asphalt Mix

Asphalt, by definition, is the tar-like substance that serves as the binder for flexible pavement materials. Asphalt mixing is the process of combining the asphalt with mineral aggregate to form a mixture. Asphalt can also be mixed with RAP (Reclaimed Asphalt Product) to recycle old pavements.

1.3.1. Production of Asphalt Mix

Asphalt mixing can be done one of two ways, either at a drum plant or a batch plant (6). In either case, the mineral aggregates are heated to a temperature between 135ºC and 180ºC. In a batch mix plant, the aggregates are heated and dried first and then transferred to a pug mill to be mixed with liquid asphalt. In a drum mix plant, the aggregate is placed in a dryer that also serves as a mixer to blend with the liquid asphalt. After mixing, the Hot Mix Asphalt (HMA) is sometimes transferred into a storage tank to be temporarily stored until paving. These processes can be seen in Figure 1. When the road is ready to be paved, the HMA is transported by trucks to the project site.

When the HMA is placed onto the road, it is usually done by crews of five to nine people (6). The HMA remains at a high temperature, of up to 200°C, all the way to the paving site.

1.3.2 Emissions Produced during Construction

Although not hazardous to humans, asphalt lets off many hazardous emissions, especially carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbons (6). Another form of emissions that are dangerous to our atmosphere is Blue smoke, a visible aerosol emission formed from condensed hydrocarbons. Blue smoke is capable of traveling long distances before dissipating sufficiently to become invisible. It is an industry-wide concern for several reasons. These include regulatory limitations, organized opposition, community concerns, and control equipment requirements.

One form in which greenhouse gas emissions are let off is through the road construction industry, primarily in the production and laying of asphalt (6). In production of asphalt, the materials need to be heated to increase viscosity of the asphalt to create a homogeneous mix and to increase workability to effectively place onto the road. Each of these processes results in high temperatures; traditionally asphalt is heated to a temperature of 177ºC, resulting in a high level of emissions.

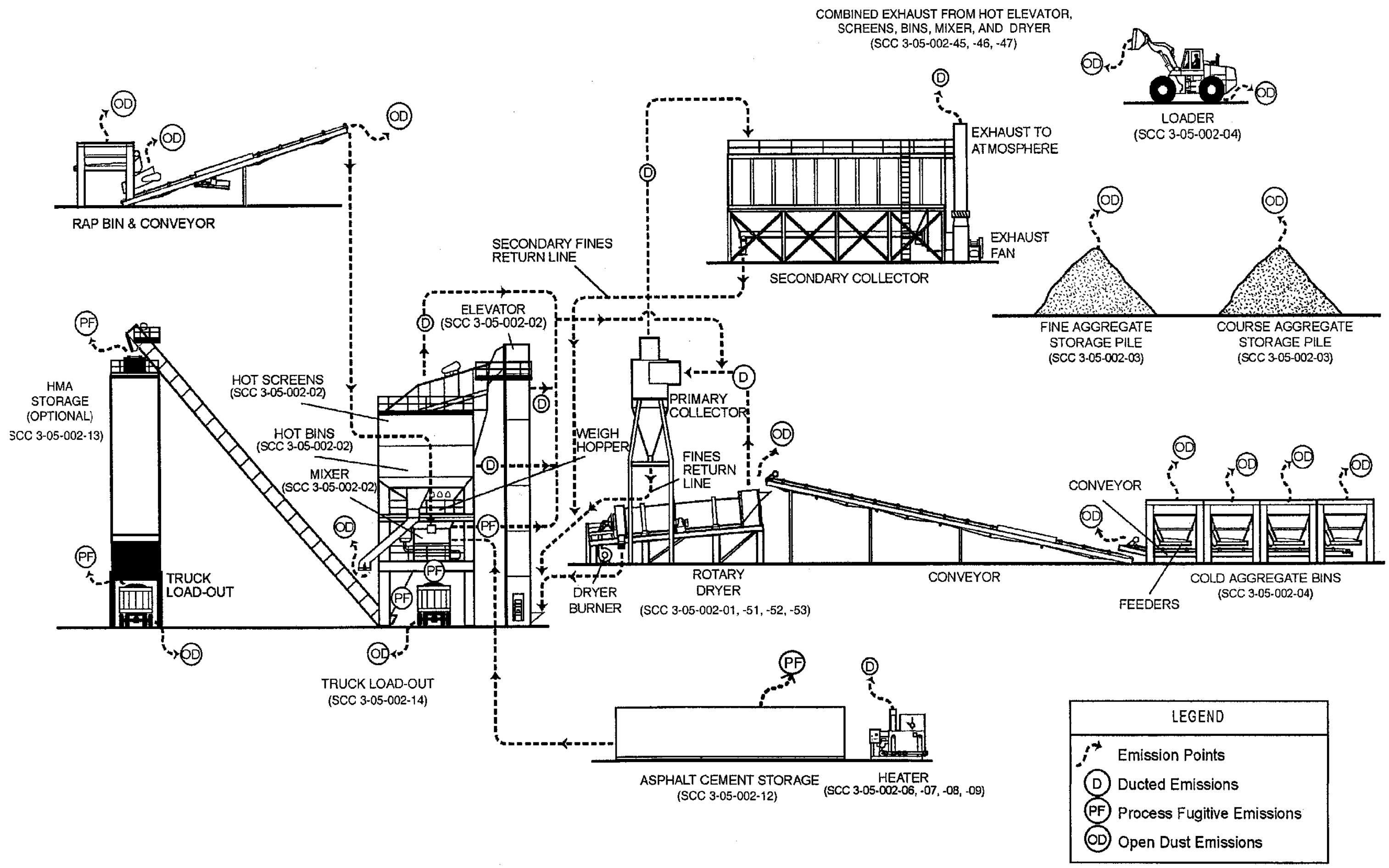


Figure 1: Production of Asphalt Map (6)

1.4 Additives to Reduce Mix Temperature

Greenhouse gas emissions produced during the construction of asphalt pavements have led to a need to develop a way to control emissions. In recent years, several additives have been formulated that claim to maintain a low viscosity at a lower temperature than conventional asphalt mix without affecting the quality of the pavement (1). Since the temperature is lower, there is the possibility of reducing greenhouse gas emissions released during production. These additives could take the industry to a more environmentally cautious future.

1.4.1 Sasobit®

One promising chemical additive that will reduce the temperature needed for an asphalt mix to have a low viscosity is called Sasobit®, a wax manufactured by Sasol (1). Sasobit®'s characteristics have led it to be described as an "asphalt flow improver" while it has been proven to reduce temperatures of asphalt mixes by 18-54ºC (1, p. 7). Figure 2 illustrates an asphalt mix's decreased viscosity at a lower than conventional temperature. This additive congeals at an approximate temperature of 102ºC and at temperatures higher than 120ºC, is completely soluble.

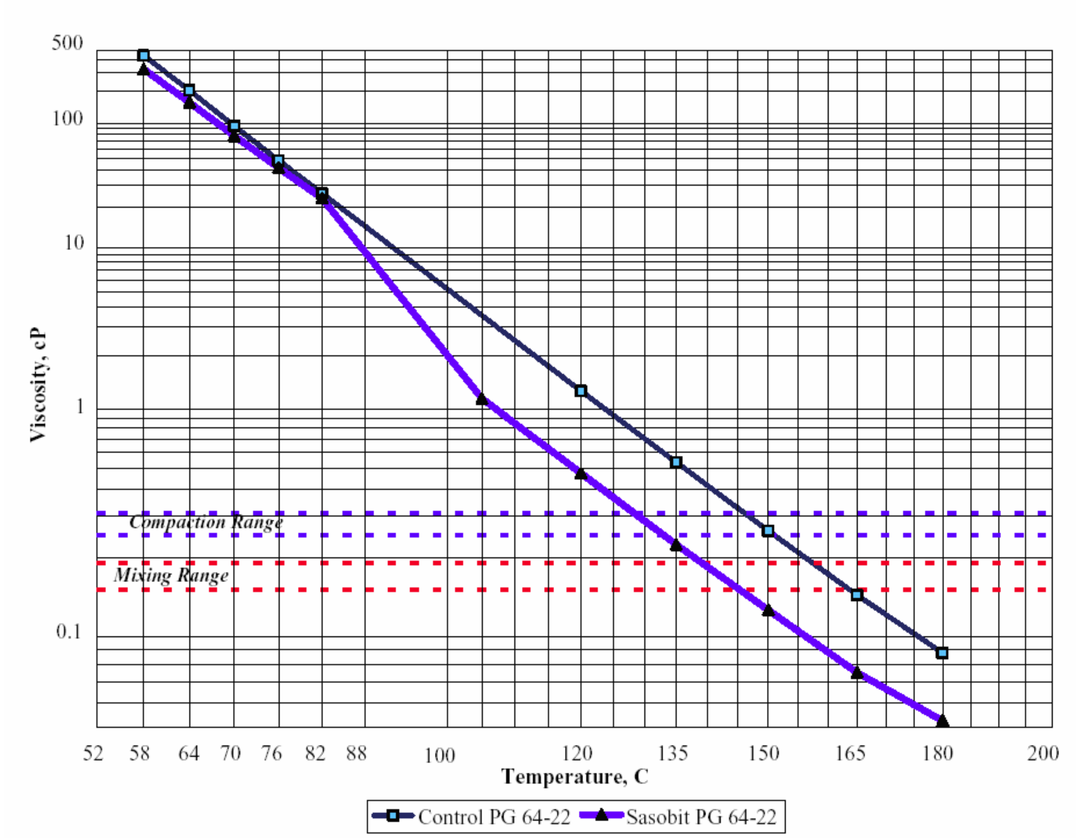


Figure 2: Mixing and Compaction Temperature for PG 64-22 Binders (4)

Sasol's Sasobit® wax "is a fine crystalline, long-chain aliphatic polymethylene hydrocarbon produced from coal gasification using the Fisher-Tropsch (FT) process. It is also known as FT hard wax" (1, p. 6; see Appendix A for explanation of FT process). The crystalline network structure Sasobit® forms reportedly adds stability.

When producing HMA, it is recommended that Sasobit® occupies 0.8 percent to 3 percent by mass of the asphalt binder (1). There are different forms of Sasobit® available. Flakes of Sasobit® are convenient for molten additions, while small pellets can be added directly to a mix. Both of these forms will result in an asphalt mix with a low viscosity at a low temperature.

1.4.2 Possible Reduction of Mix Emissions

Reductions in mix temperatures could lead to reduced fuel costs, lower emissions, more opportunities to lay pavement in cold weather and areas that need to be rapidly open to traffic (1). Lower asphalt mix temperatures means a reduction in both visible and non-visible emissions that contribute greenhouse gas emissions.

Carbon dioxide (CO_2) is the most common and harmful greenhouse gas emission (2). "It is claimed that CO_2 emissions in manufacture are reduced by a factor of 2 for every 10ºC reduction in temperature" (7, p. 1). The rate of oxidation of HMA doubles for every 25ºF (13.9ºC) increase over 200ºF (93.3ºC; 5). A chemical reaction occurs when a substance combines with oxygen, known as oxidation. As the upper mix surface oxidizes, carbon dioxide forms. Therefore, lowering the temperature of the mix will in turn lower the carbon dioxide formed and released to the atmosphere. HMA that is produced at a lower temperature (using an additive such as Sasobit®) is known as Warm Mix Asphalt, or WMA (7).

1.5 Objectives

The objectives of this study were to determine if emissions can be reduced with the use of WMA, and whether any material properties can be expected to improve in mixes produced at lower temperatures (WMA versus HMA). Another objective was to determine economic benefits, if any, of producing mixes at lower temperatures.

Chapter 2: Scope of Work

The following hypotheses were made:

- In WMA produced at 130°C, Carbon Dioxide, Carbon Monoxide and Hydrocarbon emissions would be less than emissions released for HMA at a typical temperature (150°C);
- WMA produced at lower than conventional temperature (130°C) would have better or equal material properties when compared to HMA produced at a typical temperature (150°C);
- Using WMA at a lower than conventional temperature (130°C) would lead to economic benefits. The benefits include cost savings in purchasing asphalt, fuel needed to heat asphalt and aggregates to high temperatures (150°C) for mixing, and emission control for asphalt plants.

2.1 Testing Procedures

Testing for this study included emission testing for pure asphalt and asphalt mixes. HMA (Hot Mix Asphalt) and WMA (Warm Mix Asphalt) samples were also mixed and compacted to test material properties. All tests completed were done on 3 separate mixes: HMA with 5.3% asphalt, WMA with 5.3% asphalt and 1% Sasobit® (by mass of asphalt), and WMA with 4.8% asphalt and 1% Sasobit® (by mass of asphalt). A generic flow chart detailing the order of testing for the HMA and WMA is given in Figure 3, the actual flow charts for the 3 samples can be found in Appendix B. HMA samples were mixed at 155°C and compacted at 150°C. WMA samples were mixed at 135°C and compacted at 130°C.

The emission testing for pure asphalt was done before any testing on asphalt mixes began, and will be referred to as preliminary testing.

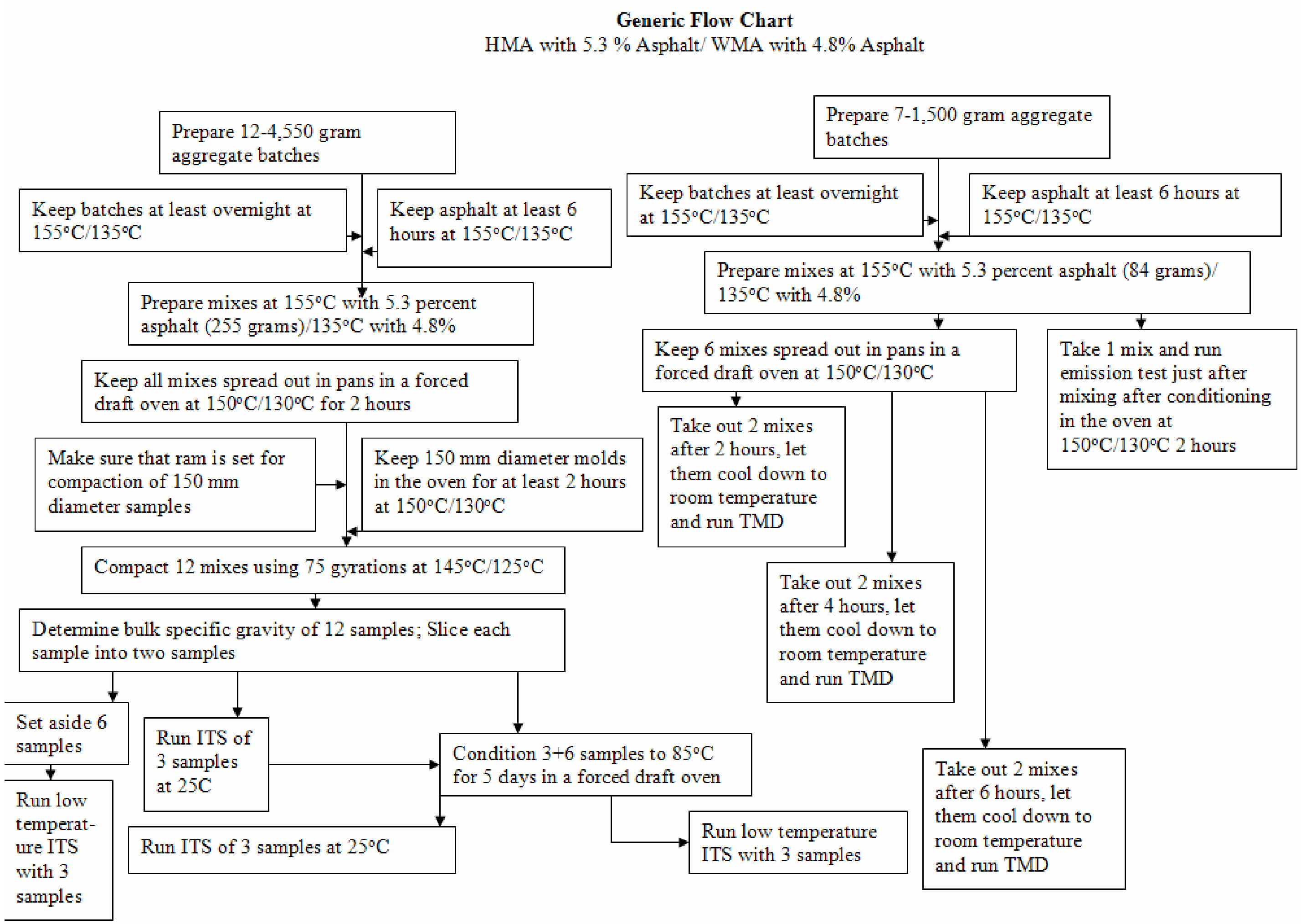


Figure 3: Generic Flow Chart of Testing for HMA and WMA

2.1.1 Drager Equipment for Emission Testing

The set up used for this test consists of flasks, ovens and Drager sensors. The Drager pump and an unused Carbon Dioxide Drager Tube are shown in Figure 4. The principle of operation is as follows. A Drager tube is inserted inside a flask filled with HMA/WMA. The pump is used to draw gas into the tube. The tube has chemicals which register the amount of emissions present in the flask (carbon dioxide, carbon monoxide or hydrocarbons). Before the Drager Tube can be inserted into the Drager pump, both ends of the tube need to be cut off using the Drager Tube Opener (Figure 5).

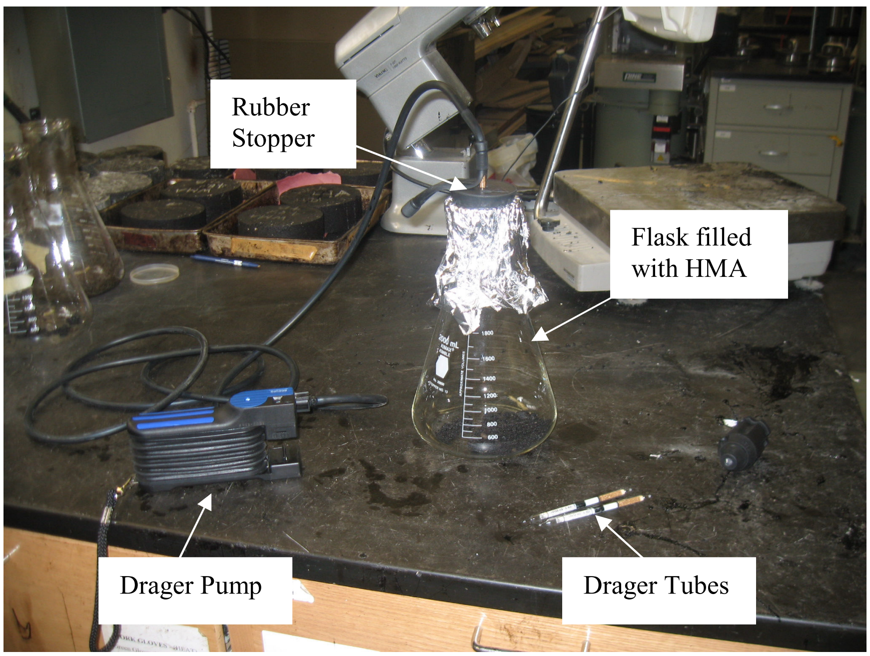


Figure 4: Drager Testing Materials

Figure 5: Drager Tube Opener

To measure carbon dioxide (CO_2) and carbon monoxide (CO), the Drager pump needs 10 full strokes and it takes approximately four minutes for the test to be completed. The color change in the chemical inside the tube indicates the amount of gas in the sample in parts per million (ppm). To measure Hydrocarbons, the number of pump stokes it takes for color change reflects the amount of Hydrocarbons in the sample. This can be anywhere from three to twenty-four strokes, as shown in Figure 6. After twenty-four strokes, if there is no color change, it is assumed there is less than 3 milligrams per liter (mg/L) of hydrocarbons in the sample. Figure 7 shows an unused and unopened Hydrocarbon Drager Tube.

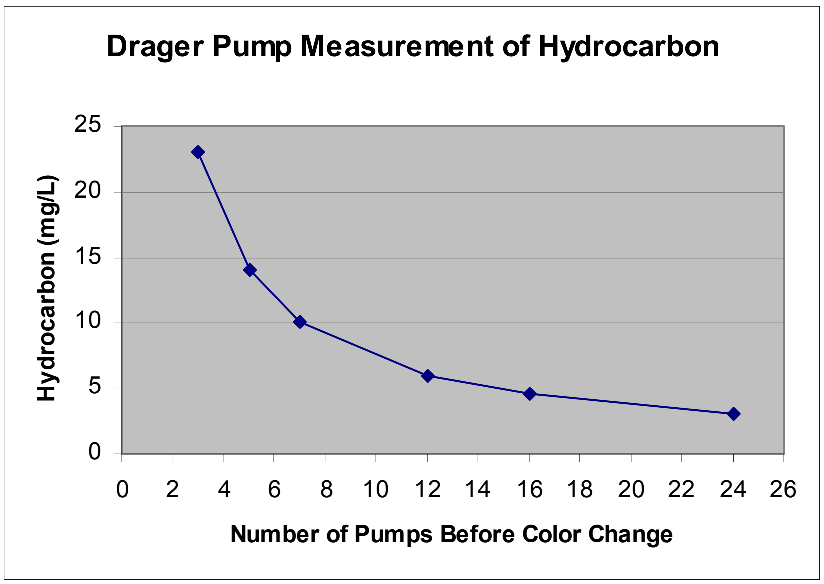


Figure 6: Drager Pump Measurement of Hydrocarbon

Figure 7: Hydrocarbon Drager Tube

2.1.2 Preliminary Testing Procedures

Preliminary testing was completed to determine the best way to collect data on emissions from asphalt and asphalt mixes since there is not standard procedure. An empty flask was used as a control test to determine the amount, if any, of emissions currently in the air. The individual materials asphalt and aggregates were heated separately in covered containers to our desired temperature in the oven. A mixer was used to mix the asphalt mix, and the asphalt mix contained approximately 5% asphalt.

After the asphalt and aggregate materials were mixed, they were quickly transferred into a flask. They were poured into the flask using a tin funnel, and the flask was capped with tinfoil immediately. The material sat in a covered flask for 15 minutes to allow enough time to off-gas.

After 15 minutes, one at a time, the tubes were inserted into the Drager pump with the arrow pointing towards the pump. The other end was inserted through the rubber stopper and through the tinfoil to measure their respective emissions. The rubber stopper ensured no emissions leaked out before the test began. The top of the stopper had two holes drilled into it; one to place the Drager tube into and the other one so the pumping did not create a vacuum in the flask. This set up is shown in Figure 8.

Figure 8: Drager Pump in Flask

After completing the preliminary testing procedures, there was a need to adjust the amount of asphalt used, the length of aging, and the procedure for capping the flasks.

The amount of asphalt used was a property that had to be tested and readjusted before determining an amount that provided readable results from the Drager tubes.

After numerous tests with pure asphalt, it was determined that readable results could only be obtained for carbon dioxide (CO_2) if 25-30 grams of pure asphalt were tested. The carbon monoxide (CO) and hydrocarbon emissions were repeatedly too great for the Drager tube to read. It was finally determined that the best results would be obtained using an asphalt mix, as opposed to only pure asphalt. The length of aging was adjusted to two hours, and the flask was placed back into the oven for those two hours. The two hours gives the sample adequate time to fill the head space with emissions before testing. This more closely replicates the actual process used in the field for asphalt mixing.

2.1.3 Mixing and Compacting

This study analyzed three different asphalt mixes: HMA with 5.3% asphalt, WMA with 5.3% asphalt and 1% Sasobit® (by mass of asphalt), and WMA with 4.8% asphalt and 1% Sasobit® (by mass of asphalt). In total, thirty-six samples were compacted, twelve samples for each of the three mixes. The compacted samples were made with the 4,550 gram aggregate batches. The mixes used for emission testing and Theoretical Maximum Density (TMD) testing were made with the 1,500 gram aggregate batches. Before mixing or compacting could take place, aggregates were sieved to create 36 4,550 gram batches and 24 1,500 gram batches, from washed and dried aggregates received from All States Asphalt. The PG 64-28 grade asphalt binder was obtained from the Maine Department of Transportation (MDOT).

2.1.3.1 Sieving Aggregates

The Sieving followed the standards found in ASTM C136-92. Prior to each sieving, the sieves were thoroughly cleaned to remove any loose particles. The sieve process consisted of nine sizes of sieves, as well as dust from the pan. The sizes used were: 1/2 inch, 3/8 inch, No 4, No 8, No 16, No 30, No 50, No 100, and No 200. The sieving was preformed in two steps; the first one for coarse aggregates (1/2 inch, 3/8 inch, No 4, and No 8), the second one for fine aggregates (No 8, No 16, No 50, No 100, and No 200).

Figure 9: Mechanical Shaker with Sieves

For each sieving the sieves were stacked, largest to smallest with the pan on the bottom. Then 10,000 grams of aggregates were poured onto the top sieve. The top lid was then secured. The stack of sieves was then placed into the mechanical shaker, as seen in Figure 9, and the shaker was run for 10 minutes. After sieving was completed each size of aggregate was placed in a bucket for making batches at a later time.

2.1.3.2 4,550 Gram Batches for Compaction and Testing

The aggregate batches used to create the HMA and WMA samples consisted of the following blend percentages: 25% of 1/2 inch coarse aggregates, 15% of 3/8 inch coarse aggregates, 27% of Natural Sand, 27% of Stone Sand and 6% of Stone Dust. Each 4,550 gram batch of aggregates contained the amount of each aggregate size specified in Table 1.

Table 1: Blend of 4,550 gram Aggregate Batches

Size of Passing Aggregate (mm)	Individual Weights (grams)
12.5	172.9
9.5	648.4
4.75	655.4
2.36	661.6
1.18	729.1
0.60	537.4
0.30	558.7
0.150	301.2
0.075	144.2
Pan	141.1
Sum:	**4550.0**

Before the aggregate batches were used to mix with asphalt, they were heated in an oven for approximately twenty-four hours before mixing. The aggregates were heated to either 155ºC or 135ºC, depending on what asphalt mix they were being used for (refer to Table 2). Approximately 4 to 6 hours before mixing occurred, the asphalt was put into the oven to heat to the temperature needed for mixing. If Sasobit® was used in the mix, it was added to the asphalt approximately 2 hours before mixing to allow the Sasobit® time to disperse throughout the asphalt material.

Table 2: Asphalt Mixes Used for 4,550 gram Batches

Asphalt Mix	Sasobit®	Temperature at Mixing	Aging Temperature	Number of Mixes
HMA - 5.3% Asphalt	0%	155ºC	150ºC	12
WMA - 5.3% Asphalt	1%	135ºC	130ºC	12
WMA - 4.8% Asphalt	1%	135ºC	130ºC	12

A mixer was used to mix the heated aggregate batches and asphalt for approximately thirty to forty-five seconds (Figure 10). After the materials were mixed, they were spread out in pans and placed into a forced draft oven for two hours. One hour after the first asphalt mix was placed in the oven, the mixes made were removed from the oven and remixed by hand to ensure no aggregates were left uncoated by asphalt.

Figure 10: Mixer

After each mix was aged for two hours, they were removed from the oven and compacted using the Gyratory Compactor for seventy-five gyrations to produce samples with a diameter of 150 mm (6 inches). After compaction, the height of each sample was recorded from the Gyratory Compactor and the sample was numbered and left to cool overnight at room temperature.

2.1.3.3 1,500 Gram Batches for Emission Testing and Theoretical Maximum Density

The aggregate batches used to create the HMA and WMA samples consisted of the following blend percentages: 25% of 1/2 inch coarse aggregates, 15% of 3/8 inch coarse aggregates, 27% of Natural Sand, 27% of Stone Sand and 6% of Stone Dust. Each 1,500 gram batch of aggregates contained the amount of each aggregate size specified in Table 3.

Table 3: Blend of 1,500 gram Aggregate Batches

Size of Passing Aggregate (mm)	Individual Weights (grams)
12.5	57.0
9.5	213.8
4.75	216.1
2.36	218.1
1.18	240.4
0.60	177.2
0.30	184.2
0.150	99.3
0.075	47.6
Pan	46.5
Sum:	**1500.0**

Before the aggregate batches were used to mix with asphalt, they were heated in an oven for approximately twenty-four hours before mixing. The aggregates were heated to either 155ºC or 135ºC, depending on what asphalt mix they were being used for (refer to Table 2). Approximately 4 to 6 hours before mixing occurred, the asphalt was put into the oven to heat to the temperature needed for mixing. If Sasobit® was used in the mix, it was added to the asphalt approximately 2 hours before mixing to allow the Sasobit® time to disperse throughout the asphalt material. A mixer was used to mix the heated aggregate batches and asphalt for approximately thirty to forty-five second.

Table 4: Asphalt Mixes Used for 1,500 gram Batches

Asphalt Mix	Sasobit®	Temperature at Mixing	Aging Temperature
HMA - 5.3% Asphalt	0%	155ºC	150ºC
WMA - 5.3% Asphalt	1%	135ºC	130ºC
WMA - 4.8% Asphalt	1%	135ºC	130ºC

2.1.4 Emission Tests of Asphalt Mixes

In this study, six asphalt mix samples with different amounts of asphalt and at different temperatures were tested for carbon dioxide (CO_2) emissions (Table 5). Three mixes had 1% Sasobit® (by mass of asphalt) and were aged for 2 hours at 130ºC,while the other three mixes contained no Sasobit® and were aged for 2 hours at 150ºC. Immediately after mixing, approximately 60 grams of each of the 6 samples were placed into individual flasks and covered with two sheets of aluminum foil held in place with wire. A funnel was used to assist the transfer of the mix into the flask (Figure 11). The remainder of each of the 6 asphalt mixes were placed into their own flasks and covered with aluminum foil and held in place with wire as well. The aluminum foil and wire were used to prevent emissions from the mix from leaving the headspace of the flask. This allowed 6 emission tests on approximately 60 grams of mix, and 6 emission tests on approximately 1,400 grams of mix, totaling 12 emission tests.

Table 5: Asphalt Mixes Tested for Emissions

Asphalt Content	**Sasobit®**	**Temperature During 2 Hour Aging**
5.70%	0%	150ºC
5.60%	1%	130ºC
5.40%	1%	130ºC
5.30%	0%	150ºC
5.30%	0%	150ºC
4.80%	1%	130ºC

Figure 11: Glass Flask and Funnel

Each flask was placed into a forced draft oven for two hours to allow ample time for the emissions to fill the head space of the flask. When the flasks were removed from the oven, a rubber stopper was placed onto the top of the flask to ensure no emissions were leaked out before testing began. The top of the stopper had two holes drilled into it, one to place the Drager tube into and the other so the pumping of the Drager pump did not create a vacuum. The asphalt mixes were tested for CO_2 emissions only. Section 2.1.1 explains the procedure for using the Drager pump and interpreting its data.

2.1.5 Volumetric and Mechanical Properties for Unaged and Aged Samples

The three asphalt mixes in this study were tested for both unaged and aged conditions according to standards developed by the American Society for Testing and Materials (ASTM). The tests conducted to determine volumetric and mechanical properties were Bulk Specific Gravity, Theoretical Maximum Density, and Indirect Tensile Strength.

2.1.5.1 Bulk Specific Gravity (BSG)

The cylindrical samples of asphalt mix were tested to determine their bulk specific gravity (ASTM D1189 and D2726). The dry weight of the sample was taken and recorded. The sample was submerged in water at 25°C for six minutes, and the submerged weight was recorded at the end of the six minutes. The sample was then removed from the water and the surface dried off with a towel, and the saturated surface dry weight was then taken and recorded. The bulk specific gravity was then calculated using the following equation.

Equation 1: Bulk Specific Gravity, Saturated Surface Dry (SSD)

$$BSG = \frac{A}{(C - B)}$$

Where:
A = Dry Weight
B = Saturated Weight
C = Saturated Surface Dry Weight

After the Bulk Specific Gravity was determined for each sample, the samples were sliced in half. After slicing, each sample had an approximate height of 50 mm (2 inches).

2.1.5.2 Theoretical Maximum Density (TMD)

The Theoretical Maximum Density was measured using ASTM D2041. Samples of Asphalt Mix were mixed according to the procedure in Section 2.1.2.3 to create 1,500 gram batches. Each mix was broken up while still hot after mixing, separating the aggregates as much as possible. The separated sample was then spread out into pan and aged in a forced draft oven for either two, four or six hours at the desired temperature. The HMA was aged at 150°C and the WMA was aged at 130°C. The different periods of aging were used to determine the increase in absorption with time of aging, if any.

When the samples were removed from the oven, they were allowed to cool down to room temperature. At room temperature, an empty bowl was weighed in air and while submerged in water, and recorded. The separated mix was then placed into the empty bowl and the weight of the bowl and the mix was recorded in air. The bowl was then filled with water to a height of approximately one inch above the mix. The bowl was placed into the Gilson Vibro-Deairator and the lid was secured in place. Then the vacuum pump was turned on until the air pressure inside the bowl reached 27 Hg. At that point, the Deairator was turned on and allowed to run for ten minutes. After ten minutes, the Deairator and vacuum pump were turned off and the valve was slowly released to remove the pressure inside the bowl. Then without disturbing the mix, the bowl with the aggregates was submerged into water at 25°C. After ten minutes, the submerged weight was recorded. The Theoretical Maximum Density of the mix was calculated using the following equation.

Equation 2: Theoretical Maximum Density, TMD

$$TMD = \frac{(A-C)}{[(A-C)-(B-D)]}$$

Where:
A = Sample weight in Air (with bowl)
B = Sample weight in H_20 (with bowl)
C = Weight of bowl in Air
D = Weight of bowl in H_20

The BSG and TMD, along with the specific gravities of the aggregates and asphalt (known), allowed the determination of percentage of asphalt absorbed and the effective asphalt content in the mix.

2.1.5.3 Indirect Tensile Strength (ITS)

To test Indirect Tensile Strength (ITS), the ASTM D4123 procedure was followed. Computer controlled equipment with a data acquisition system was used to determine ITS (Figure 12). Before the samples were placed into the equipment, the thicknesses of the samples were measured and recorded (Figure 13). The Indirect Tensile Test is a method of determining the tensile strength of a sample by applying a compressive load vertically on a cylindrical specimen. The load is applied vertically creating tensile stress horizontally, the machine records the maximum or peak load (in pounds) the sample can withstand before breaking. The tensile strength is determined by the following equation.

Equation 3: Indirect Tensile Strength, ITS

$$ITS(psi) = \frac{2 * Peak\ Load(lb)}{\pi * diameter\ of\ sample(in) * thickness\ of\ sample(in)}$$

During the ITS test, the pressure is usually applied at a rate of 50mm/minute (2 inches/minute). All ITS tests were conducted at 25°C.

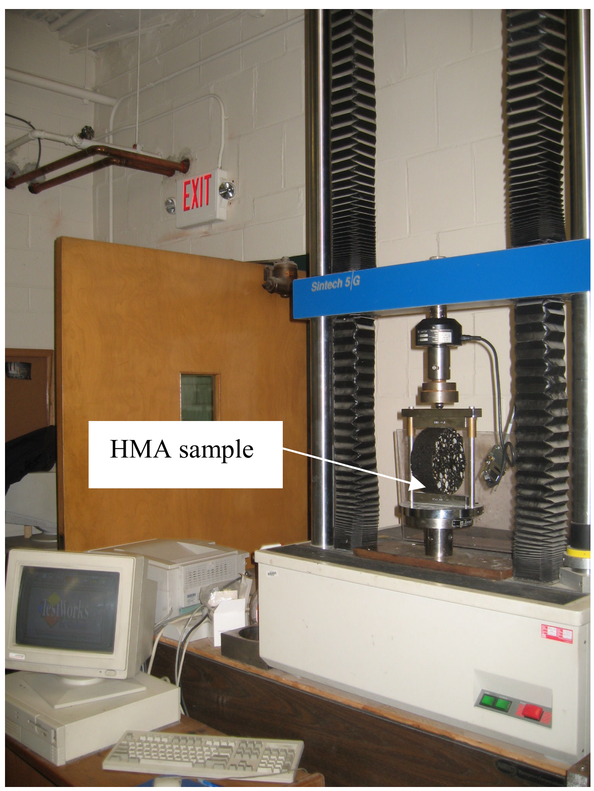


Figure 12: Machine Performing ITS Testing

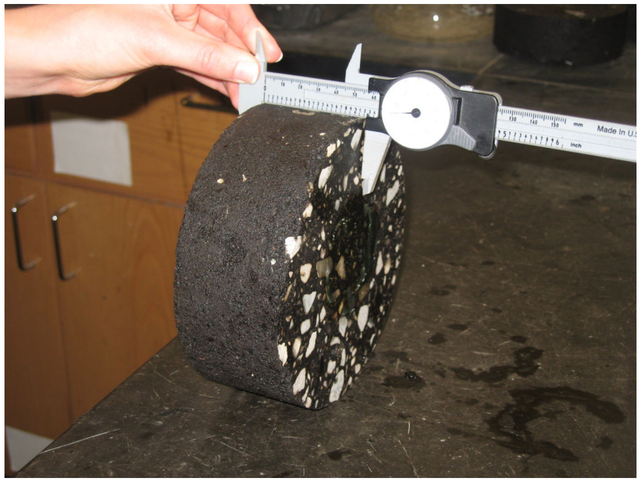


Figure 13: Measuring thickness values for the samples

2.1.5.4 Aged Samples

After each of the previous tests were run, 3 samples from each of the *HMA–5.3%AC-150°C Asphalt*, *WMA – 5.3%AC-130°C Asphalt*, and *WMA–4.8%AC-130°C Asphalt* mixes were set aside for aging. The samples were placed in an oven at 85°C for 5 days (SHRP Protocol). At the end of the 5 days, the samples were allowed to cool to room temperature and then tested for Indirect Tensile Strength according the procedure listed in Sections 2.1.4.3.

Chapter 3: Results

The results of this study are organized into three sections: Volumetric Properties, Emissions and Mechanical Properties. The volumetric property results discuss percent air voids, absorption and effective asphalt content. The emission results show measured emissions from both pure asphalt and asphalt mixes. The mechanical property results discuss Indirect Tensile Strength of both aged and unaged samples.

3.1 Volumetric Properties

The volumetric properties of the three different asphalt mixes calculated were percent air voids, absorption, and effective asphalt content. With the values of bulk specific gravity and theoretical maximum density, percent air voids could be calculated. This allowed the comparison of absorption and effective asphalt content.

3.1.1. Percent Air Voids

The percent Air Voids for each sample are shown in Table 6 below. Each percent air void was found after calculating the Bulk Specific Gravity and Theoretical Maximum Density (results in Section 3.1.2). The value for Theoretical Maximum Density used is the value calculated after being aged for 2 hours, the standard aging time for Theoretical Maximum Density. The percent Air Voids are calculated by the following equation.

Equation 4: Percent Air Void

$$\%\,Air\ Void = 100 - \left(\frac{100 * BSG}{TMD}\right)$$

Where:
BSG = Bulk Specific Gravity
TMD = Theoretical Maximum Density

Table 6: Bulk Specific Gravity & Percent Air Voids

Mix	Sample	Dry, g	Under Water, g	SSD, g	BSG	Gmm/TMD	Air voids	Density
HMA-5.3%AC-150C	1	4624	2693	4628.5	2.38905	2.513	4.9	95.1
HMA-5.3%AC-150C	2	4723	2741	4724.5	2.38114		5.2	94.8
HMA-5.3%AC-150C	3	4745.5	2762	4748.5	2.38887		4.9	95.1
HMA-5.3%AC-150C	4	4774	2776.5	4779	2.38402		5.1	94.9
HMA-5.3%AC-150C	5	4732.5	2747	4742	2.37218		5.6	94.4
HMA-5.3%AC-150C	6	4721	2743.5	4727	2.38014		5.3	94.7
HMA-5.3%AC-150C	7	4615.5	2689	4619.5	2.39083		4.9	95.1
HMA-5.3%AC-150C	8	4653	2704	4658.5	2.38066		5.3	94.7
HMA-5.3%AC-150C	9	4623.5	2681	4628.5	2.37407		5.5	94.5
HMA-5.3%AC-150C	10	4707.5	2736.5	4711	2.38415		5.1	94.9
HMA-5.3%AC-150C	11	4642	2697	4644	2.38418		5.1	94.9
HMA-5.3%AC-150C	12	4748	2757.5	4753	2.37935		5.3	94.7
						Average	5.2	94.8
WMA-5.3%AC-130C	13-5.3%	4758	2773	4760.5	2.39396	2.491	3.9	96.1
WMA-5.3%AC-130C	14-5.3%	4737	2749	4740	2.37921		4.5	95.5
WMA-5.3%AC-130C	15-5.3%	4779	2784	4782.5	2.39129		4.0	96.0
WMA-5.3%AC-130C	16-5.3%	4722	2753.5	4723.5	2.39695		3.8	96.2
WMA-5.3%AC-130C	17-5.3%	4707.5	2737	4711.5	2.38415		4.3	95.7
WMA-5.3%AC-130C	18-5.3%	4703	2733.5	4706.5	2.38368		4.3	95.7
WMA-5.3%AC-130C	19-5.3%	4749.5	2742.5	4723.5	2.39753		3.8	96.2
WMA-5.3%AC-130C	20-5.3%	4779.5	2791	4782.5	2.39995		3.7	96.3
WMA-5.3%AC-130C	21-5.3%	4671.5	2725	4676	2.39441		3.9	96.1
WMA-5.3%AC-130C	22-5.3%	4702	2759	4699	2.42371		2.7	97.3
WMA-5.3%AC-130C	23-5.3%	4732.5	2781.5	4725.5	2.43441		2.3	97.7
WMA-5.3%AC-130C	24-5.3%	4716	2767	4717	2.41846		2.9	97.1
WMA-5.3%AC-130C	1-4.8%	4663.4	2675.5	4670.5	2.33754		6.2	93.8
						Average	3.9	96.1
WMA-4.8%AC-130C	2-4.8%	4757.5	2736.1	4765.1	2.34475	2.51	6.6	93.4
WMA-4.8%AC-130C	3-4.8%	4706.5	2699	4713	2.33689		6.9	93.1
WMA-4.8%AC-130C	4-4.8%	4707.5	2702.5	4717.6	2.33611		6.9	93.1
WMA-4.8%AC-130C	5-4.8%	4705.6	2707.5	4715.2	2.34378		6.6	93.4
WMA-4.8%AC-130C	6-4.8%	4647.9	2669.1	4654.4	2.34116		6.7	93.3
WMA-4.8%AC-130C	7-4.8%	4707	2719.2	4712	2.362		5.9	94.1
WMA-4.8%AC-130C	8-4.8%	4632.4	2660.5	4637.7	2.34291		6.7	93.3
WMA-4.8%AC-130C	9-4.8%	4659.1	2684.5	4667.2	2.34988		6.4	93.6
WMA-4.8%AC-130C	10-4.8%	4672.9	2698.1	4682.2	2.35517		6.2	93.8
WMA-4.8%AC-130C	11-4.8%	4650.5	2678.7	4659.8	2.34743		6.5	93.5
WMA-4.8%AC-130C	12-4.8%	4603.7	2650.2	4613.8	2.34452		6.6	93.4
						Average	**6.5**	93.5

As is shown in the table and the chart below, the Asphalt Mix with the highest amount of Air Voids is the WMA-4.8%AC-130ºC. As asphalt content decreases it is natural for the Percent Air Voids to increase in a sample. This does not mean that using 4.8% asphalt instead of 5.3% asphalt is worse for a given asphalt mix. Instead, the sample needs to be compacted more to eliminate air voids. Asphalt mixes with a smaller percent asphalt content need to be compacted more.

However, the more important thing is that the use of Sasobit® at a lower temperature of 130ºC (20ºC lower than 150ºC) produced a higher density with the same compaction effort. A higher density in an asphalt mix means that there are less air voids. This higher density should produce asphalt mixes with better mechanical properties, as well as lower in-place oxidation and aging.

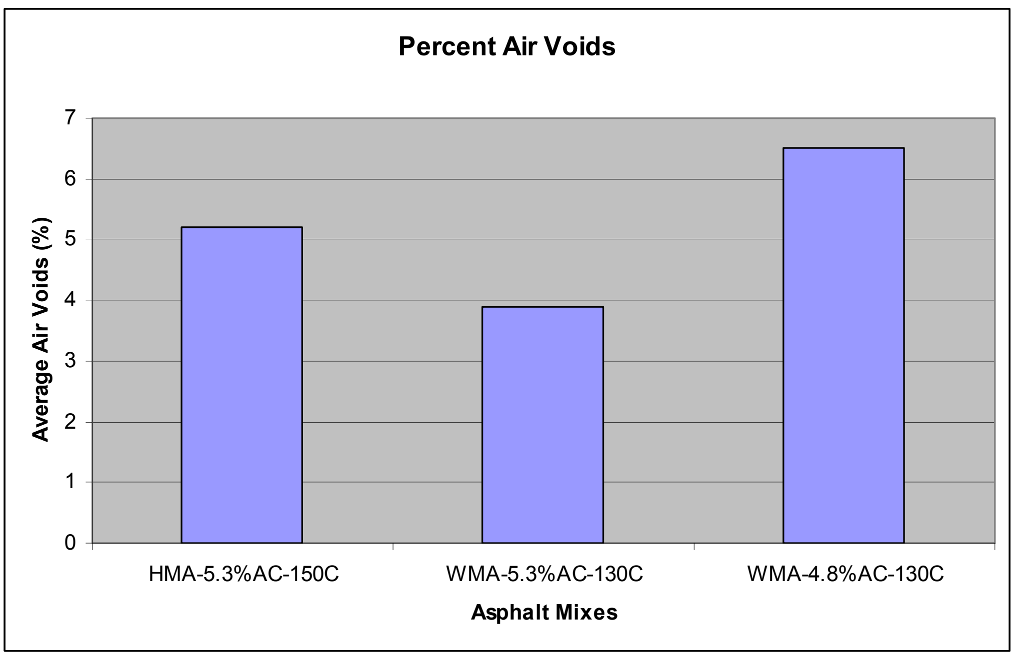


Figure 14: Average Air Voids

3.1.2 Absorption & Effective Asphalt Content

The TMD values were used to find the Effective Specific Gravity as shown in the equation below.

Equation 5: Effective Specific Gravity, G_{se}

$$G_{SE} = \frac{P_s}{\left(\frac{100}{TMD} - \frac{P_b}{G_b}\right)}$$

Where:
P_s = Percent Stone
P_b = Percent Binder
TMD = Theoretical Maximum Density
G_b = Specific Gravity of Binder
(assumed to be 1.03)

Then the Bulk Volume of Stone and Effective Volume of Stone are calculated using the following equations.

Equation 6: Bulk Volume of Stone, V_{sb}

$$V_{sb} = \frac{(100 - P_b)}{G_{sb}}$$

Where:
V_{sb} = Bulk Volume of Stone
P_b = Percent Binder
G_{sb} = Bulk Specific Gravity = 2.627

Equation 7: Effective Volume of Stone, V_{se}

$$V_{se} = \frac{(100 - P_b)}{G_{se}}$$

Where:
V_{sb} = Effective Volume of Stone
P_b = Percent Binder
G_{se} = Effective Specfic Gravity

Then the Absorbed Asphalt Content can be calculated by subtracting the Effective Volume of Stone from the Bulk Volume of Stone. Finally, an Effective Asphalt Content can be calculated by subtracting the Absorbed Asphalt Content from the Total Volume of Asphalt for a given mix of 100 grams. These results are shown in Table 7.

$$Effective\ Asphalt\ Content = Total\ Volume\ of\ \ Asphalt - Abosorbed\ \ Asphalt\ Content$$

Table 7: Volume of Effective Asphalt

Mix	Temperature, Mixing and Aging, C	Aging Period, hours	TMD	Pb	Ps	Gse	Total volume of asphalt (Consider 100gm of mix)	Gsb	Vsb,cc	Vse,cc	Absorbed AC, cc	Volume of Effective Asphalt, cc
HMA-5.3%AC-150C	150	2	2.513	5.3	94.7	2.733	5.146	2.627	36.049	34.647	1.401	3.744
HMA-5.3%AC-150C	150	4	2.535	5.3	94.7	2.761	5.146	2.627	36.049	34.302	1.747	3.399
HMA-5.3%AC-150C	150	6	2.519	5.3	94.7	2.741	5.146	2.627	36.049	34.553	1.496	3.650
WMA-5.3%AC-130C	125	2	2.491	5.3	94.7	2.706	5.146	2.627	36.049	34.999	1.050	4.096
WMA-5.3%AC-130C	125	4	2.502	5.3	94.7	2.720	5.146	2.627	36.049	34.822	1.226	3.919
WMA-5.3%AC-130C	125	6	2.505	5.3	94.7	2.723	5.146	2.627	36.049	34.775	1.274	3.871
WMA-4.8%AC-130C	125	2	2.51	4.8	95.2	2.706	4.660	2.627	36.239	35.180	1.059	3.602
WMA-4.8%AC-130C	125	4	2.511	4.8	95.2	2.707	4.660	2.627	36.239	35.165	1.074	3.586
WMA-4.8%AC-130C	125	6	2.515	4.8	95.2	2.712	4.660	2.627	36.239	35.101	1.138	3.522

As the table above shows, the Volume of Effective Asphalt was largest for the *WMA – 5.3%AC – 130ºC* asphalt mix, and about the same for the other two mixes. Since the *HMA – 5.3% - 150ºC* and the *WMA – 5.3% - 130ºC* both have the same amount of asphalt; the higher temperature has an effect on the amount of asphalt absorbed by the stone. This shows that by using the additive Sasobit®, with Warm Mix Asphalt, a lower absorption and hence a higher effective asphalt content compared to that in the HMA can be obtained. This high effective asphalt content should mean greater durability of the mixture.

3.2 Emissions

Greenhouse gas emissions were tested for both pure asphalt and asphalt mixes. Approximately twenty-five to two hundred grams of pure asphalt was tested for different lengths of time at different temperatures. The asphalt mixes were tested only for carbon dioxide with half of the mixes containing Sasobit® and half without, at a range of temperatures. As testing was completed, the final testing procedure was determined for this study.

3.2.1 Emissions of Asphalt

There is no standard procedure for measuring emissions produced by asphalt materials in the laboratory. The procedures used for these tests were found by trial and error. The mass of asphalt tested and the time allowed for the headspace to fill the headspace were the most important variables that needed to be determined. Materials were obtained to measure carbon dioxide (CO_2), carbon monoxide (CO) and hydrocarbons with the Drager pump of the asphalt after a given amount of time.

The first trial (9/27/2006) of emission tests were done after allowing approximately 199 grams of asphalt to off-gas for 24 hours at 2 temperatures, 130ºC and 160ºC (Table 8). The results for all 3 emissions of the asphalt held at 160ºC were larger than Drager tubes measured. The CO and hydrocarbon content were also larger than what Drager tubes could detect for the asphalt held at 130ºC for 24 hours. Although for the same asphalt at 130 ºC, the CO_2 was measured to be 2,500 ppm.

Table 8: Pure Asphalt Emissions

				Measured Emissions			
				[redacted]		Hydrocarbons (mg/L)	
Date	Asphalt Temperature (ºC)	Time allowed in oven at temperature	Mass of Asphalt (grams)	Carbon Dioxide (ppm)	Carbon Monoxide (ppm)	Number of strokes	mg/L
9/27/2006	130	24 hours	199.1	2500	> 300	4	18.5
9/27/2006	160	24 hours 20 minutes	199	> 3000	> 300	2	> 23
10/10/2006	120	24 hours	50.5	1400	200	5	14
10/10/2006	170	24 hours 20 minutes	50	> 3000	> 300	1	> 23
11/3/2006	150	24 hours	23.5	> 3000	> 300	1	> 23
11/9/2006	150	2 hours	30	800	> 300	1	> 23
11/10/2006	125	2 hours	27.5	600			
11/10/2006	150	2 hours	30	800			
11/10/2006	170	2 hours	25	1300			
	Maximum Emissions read by Drager Tube			3000	300	3	23

The second trial (10/10/2006) of emission tests were done after allowing approximately 50 grams to off-gas for 24 hours at 120 ºC and 170 ºC (Table 8). The results for all 3 emissions of the asphalt held at 170ºC were larger than Drager tubes measured. The emission results for the asphalt held at 120ºC for 24 hours were obtainable. The CO_2 present was measured to be 1,400 ppm, the CO was measured at 200 ppm and the hydrocarbon was found to be 14 mg/L. The lower mass of asphalt, 50 grams instead of 199 grams, was more promising and found results measurable by Drager products.

The third trial (11/2/2006) of emission tests were done on 23.5 grams of asphalt after off-gassing for 24 hours at 150ºC. The results for CO_2, CO and hydrocarbon were all immeasurable by Drager products since they were so high. The results for this test were expected, since the mass of asphalt was decreased by half from approximately 50 grams to 23.5 grams. The higher temperature of 150ºC caused more emissions to be off-gassed than at 120ºC.

In an attempt to have CO_2, CO and hydrocarbon be measurable by the Drager pump, the time allowed for the asphalt to fill the headspace of the flask was reduced to 2 hours from 24 hours. The fourth trial (11/9/2006) was completed with 30 grams of asphalt held at 150ºC for 2 hours. The CO_2 present was measured to be 800 ppm, while the CO and hydrocarbon was still too large for the Drager pump to measure. Because results for emissions of CO and hydrocarbon could not be measured from asphalt unless it was at a temperature below 130ºC, the procedure was amended to only measure CO_2 emissions. CO_2 emissions were most likely to be measured at any temperature ranging from 120ºC to 150ºC from the tests completed to this point.

The final trial (11/10/2006) measuring CO_2 emissions from pure asphalt was done after holding asphalt at 125ºC, 150ºC and 170ºC for 2 hours. The CO_2 measured for 27.5 grams of asphalt at 125ºC was 600 ppm. The CO_2 measured for 30 grams of asphalt at 150ºC was found to be 800 ppm and the CO_2 measured for 25 grams of asphalt at 170ºC was 1,300 ppm (Figure 15).

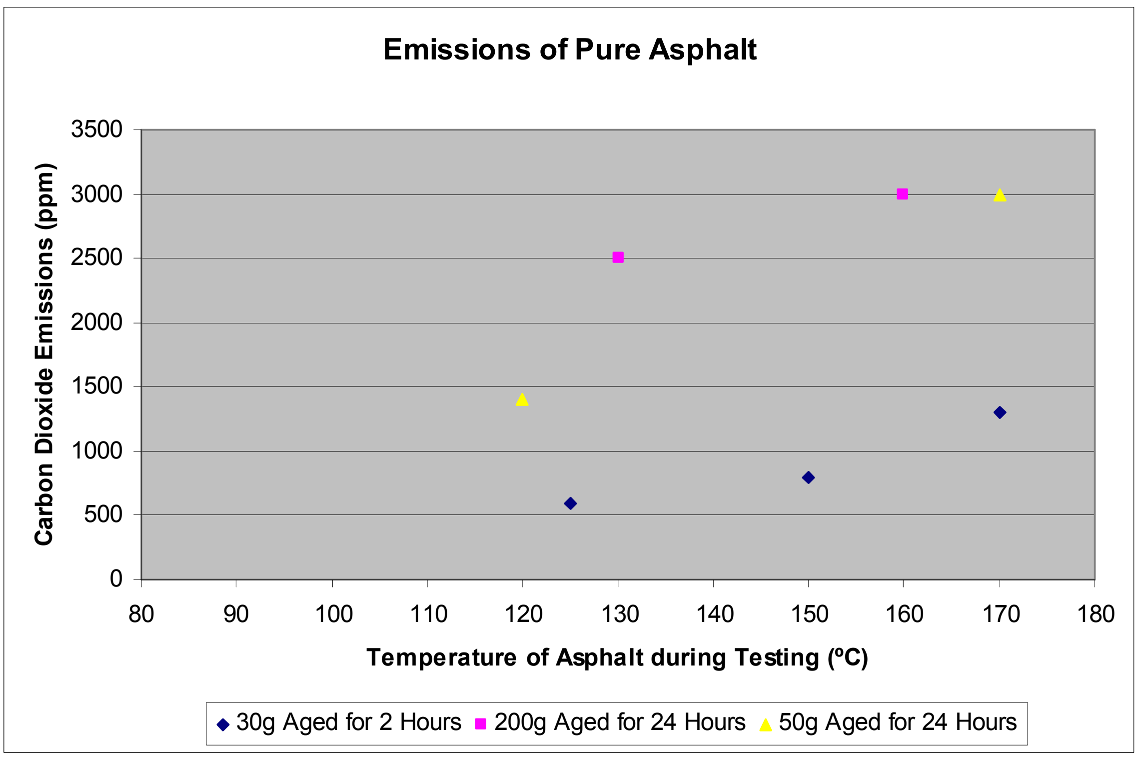


Figure 15: Carbon Dioxide (CO_2) Emissions of Pure Asphalt

From the procedures described on measuring emissions from pure asphalt, the best combination of mass of asphalt tested and time allowed for the material to off-gas was chosen. The time chosen for off-gassing was 2 hours, and the desired amount of pure asphalt to be tested was approximately 30 grams.

3.2.2 Emissions of Asphalt Mixes

The procedure developed to test Carbon Dioxide (CO_2) emissions from asphalt mixes was to allow approximately 60 grams of asphalt mix to off-gas for 2 hours. This was done for 3 mixes with 1% Sasobit® (by mass of asphalt) that off-gassed in an oven for 2 hours are 130ºC, and 3 mixes without Sasobit® that off-gassed for 2 hours at 150ºC (Table 9). This asphalt content of the different mixes tested ranged from 4.8% to 5.7%.

Table 9: Carbon Dioxide (CO_2) Emissions from Asphalt Mixes

Mix	Sasobit® (%)	Temperature (ºC) During 2 Hour Aging	Mass of Mix (grams)	Asphalt Content (%)	Time in Oven (hours)	CO_2 (ppm)
HMA	0	150	61.2	5.7	2	700
HMA	0	150	59.5	5.3	2	700
HMA	0	150	60.7	5.3	2	750
WMA	1	130	61.3	5.6	2	550
WMA	1	130	62.3	5.4	2	550
WMA	1	130	62.7	4.8	2	450

There is a clear difference in the amount of CO_2 present in the headspace of the HMA with Sasobit® at 130ºC and the WMA without Sasobit® at 150ºC. The amount of CO_2 present in the HMA mixes range from 700 ppm to 750 ppm while the amount present in the WMA range from 450 ppm to 550 ppm.

3.3 Mechanical Properties

The mechanical property of the three different asphalt mixes tested was Indirect Tensile Strength (ITS). The ITS results showed the most positive impacts of the Sasobit® additive in the mixes.

3.3.1 Indirect Tensile Strength

The Indirect Tensile Strength values we found are shown in Table 10 below. The averages for each set of samples were taken and shown in the graph as well. Finally, the Average change in Tensile Strength after aging was calculated by using the following equation.

Equation 8: Average Change after Aging

$$Average\ Change\ After\ Aging = 100 * \frac{(Aged\ Average\ Strength - Unaged\ Average\ Strength)}{Unaged\ Average\ Strength}$$

Table 10: Indirect Tensile Strength

Mix	Condition	Sample	Thickness, in	Peak Load, lb	Tensile strength, psi	Tensile Strength, kpa	Average change after aging (+increase)
HMA-5.3%AC-150C	Unaged	HMA-2a-unaged	2.134	2201.6	343.89	2372.86	
		HMA-6a-unaged	2.367	3280.7	462.01	3187.84	
		HMA-8a-unaged	2.207	2496.3	377.03	2601.49	
					Average	**2720.73**	
	Aged	HMA-2b-aged	2.134	2999.7	468.56	3233.04	
		HMA-6a-aged	2.367	3288.2	463.06	3195.12	
		HMA-8b-aged	2.207	3001.7	453.36	3128.19	
					Average	**3185.45**	**17.08**
WMA-5.3%AC-130C	Unaged	WMA-22a-unaged	2.06275	2770.9	447.77	3089.60	
		WMA-24a-unaged	2.056	2775	449.90	3104.33	
		WMA-15b-unaged	2.20675	2239.2	338.23	2333.82	
					Average	**2842.58**	
	Aged	WMA-22a-aged	2.06275	2629.7	424.95	2932.16	
		WMA-24a-aged	2.056	3280.3	531.83	3669.60	
		WMA-15b-aged	2.20675	2932.4	442.94	3056.31	
					Average	**3219.36**	**13.25**
WMA-4.8%AC-130C	Unaged	WMA-3b-unaged	2.40225	2230.9	309.56	2135.94	
		WMA-5a-unaged	2.2305	2465.9	368.51	2542.73	
		WMA-6b-unaged	2.2065	1524.9	230.36	1589.52	
					Average	**2089.40**	
	Aged	WMA-4a-aged	2.139	3154.5	491.58	3391.94	
		WMA-7b-aged	2.252	3146.3	465.70	3213.36	
		WMA-9a-aged	2.213	3047.4	459.01	3167.20	
					Average	**3257.50**	**55.91**

Above, in Table 10, is a summary of the ITS values, density and the average change in ITS after aging. After analyzing the table, it can be concluded that the most effective asphalt mix is the *WMA-5.3%-AC-130ºC* because of the high density and ITS and the low change after aging. The high density means that the mix will have few air voids, which make it a more desirable asphalt mix. The mix also has a high tensile strength unaged and a relatively low change in the strength after aging the sample. This means that in the field the sample will maintain a high strength as the asphalt ages over time.

Chapter 4: Analysis

The Analysis of this study can be separated into three distinct areas: volumetric properties analysis, asphalt mix emission analysis, and mechanical properties analysis. The volumetric properties analysis describes the Bulk Specific Gravity (BSG) and Percent Air Voids in the asphalt mixes. The emissions analysis illustrates the decrease in carbon dioxide emissions through the use of Sasobit® wax in WMA as opposed to HMA. Finally, the mechanical properties are analyzed by looking at the strengths and durability of the WMA and HMA samples measured in the lab.

4.1 Volumetric Properties Analysis

The relationship between asphalt content and percent air voids can be seen in Figure 16. As is shown in the graph, the samples with the highest asphalt content have the lowest percentage of air voids. When the samples were mixed, both the *HMA-150°C* and the first *WMA-130°C* had the same percentage of asphalt, 5.3%. However, due to absorption, the *WMA-130°C* has a higher effective asphalt content. The other *WMA-130°C* sample had 4.8% asphalt content at mixing.

When there is more asphalt in a mix, more of the air voids between aggregates are filled with the asphalt, creating an overall lower percent air void (8). Effective asphalt content (EAC) is the amount of asphalt that is left coating the aggregates after absorption. It is not possible to avoid some absorption of asphalt into the aggregates. On the other hand there needs to be a sufficient amount of effective asphalt content not absorbed to bind the aggregates together. For these reasons, determining appropriate effective asphalt content is complicated. It is desirable to have high enough effective asphalt content, so the aggregates have a layer of film on them and low air voids, but not too high so that asphalt is wasted and used in excess. Some states even enforce a minimum film thickness in all asphalt mix designs.

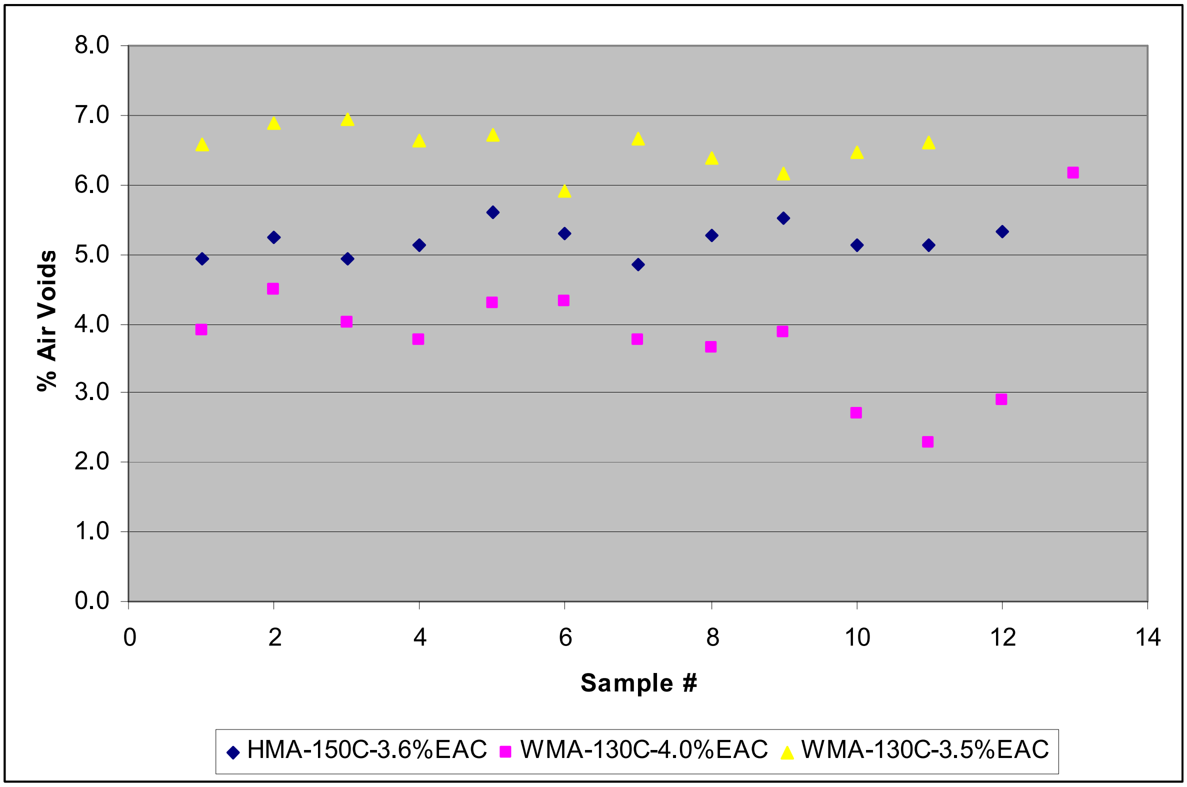


Figure 16: Effective Asphalt Content vs. % Air Voids

Low air voids prevent water and excess moisture from getting into the asphalt mix, as well as decrease the rate of aging of the mix (9). When moisture gets into asphalt mixes because of high air voids, the mix is susceptible to moisture damage and cracking during freeze-thaw conditions. As the moisture freezes and thaws, it results in a loss of adhesion between asphalt and aggregate. The desired air voids percentage is between 3.0% and 5.0% for lab samples (4). The Sasobit® helps in lowering the air void percentage at the same asphalt content. The *WMA-130ºC-4.8%* mix had 4.8% asphalt content and more air voids than the *WMA-130ºC-5.3%* mix, with 5.3% asphalt content. Using the Sasobit® in a Warm Mix Asphalt with 5.3% asphalt content leads to the lowest percentage of air voids, as shown in Figure 16.

Increased density can be achieved by either increasing the asphalt content or by increasing the gyrations in the lab for compaction, or by both. It is not necessary to increase the asphalt content, because you can obtain the same desired density by increasing the compaction effort. In the field, this translates to having the roller compact the asphalt for a greater time period or using more rollers. This may not be practical because it uses more time, energy, and is more cost prohibiting. Therefore, when using Sasobit® to create an asphalt mix at a lower temperature, the asphalt content should not be reduced so that the density of the mix is not compromised. Using the same asphalt content and compaction effort as HMA, one can expect a higher density for WMA, as shown in Figure 17.

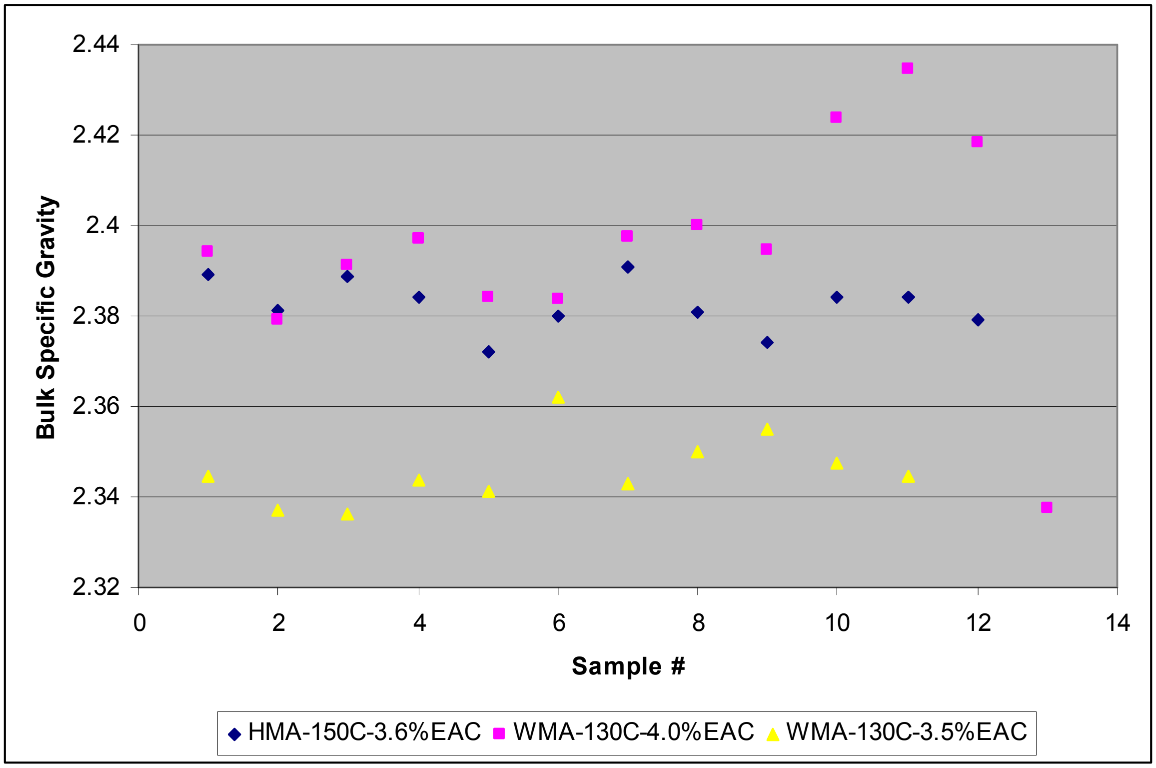


Figure 17: Effective Asphalt Content vs. Bulk Specific Gravity

4.2 Asphalt Mix Emissions Analysis

The emission tests completed on asphalt mixes at 130ºC and 150ºC, with and without Sasobit® respectively, prove that a mix heated to a lower temperature produces less greenhouse gas than a mix at a higher temperature with the same amount of asphalt. While 61.2 grams of HMA with 5.7% asphalt produced 700 ppm of CO_2, 61.3 grams of WMA with 5.6% of asphalt and 1% of Sasobit® (by mass of asphalt) produced only 550 ppm of CO_2 (Table 9 shown in Section 3.2.2). This difference is significant, and shows that asphalt mix heated to a lower temperature emits less harmful greenhouse gas emissions, especially CO_2. The use of Sasobit® in an asphalt mix allows the mix to be produced at a lower temperature and hence helps reduce the amount of CO_2 released into the atmosphere.

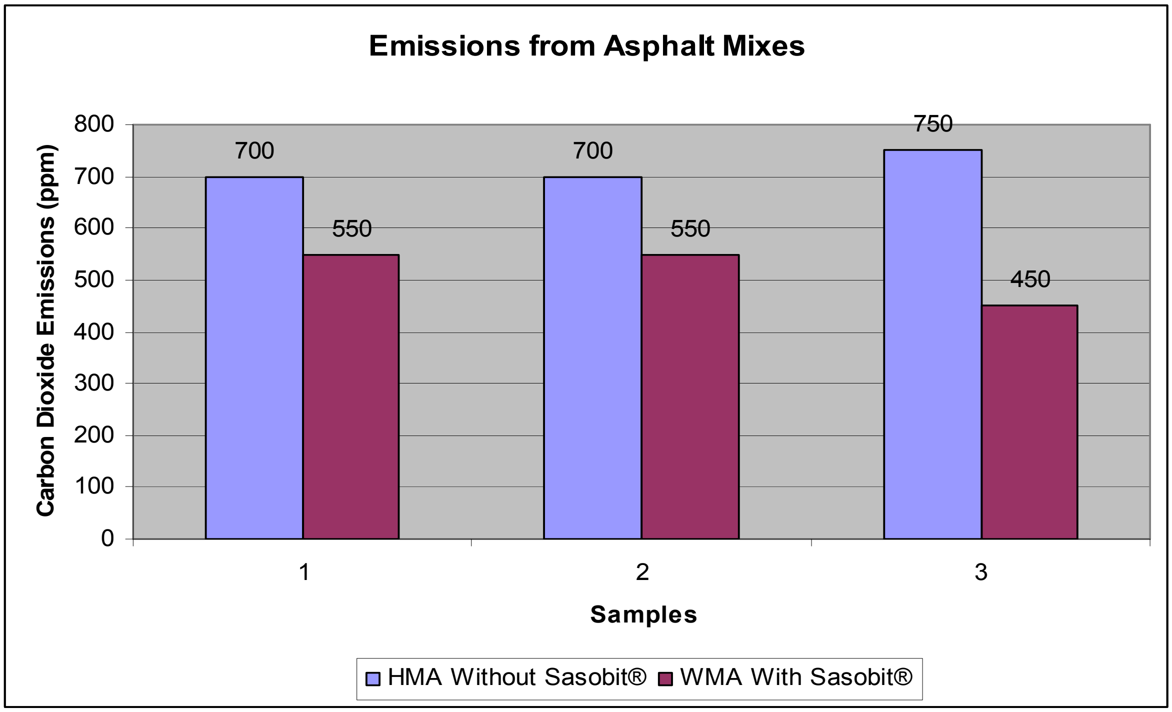


Figure 18: Carbon Dioxide (CO_2) Emission from Asphalt Mixes

4.3 Mechanical Properties Analysis

In an asphalt mix it is desirable to have high effective asphalt content after absorption. In turn, this high effective asphalt content results in a low percentage of air voids in the mixture. An HMA with low air voids will age slower than an HMA with higher air voids. It is not desirable for asphalt mixes to age at a high rate because the performance deteriorates greatly as a mix ages (5).

A summary of each asphalt mix's change in mechanical properties after aging is described in Table 11. As shown, the *WMA-5.3%AC-130ºC* mix had the highest density and ITS in its unaged samples. This mix also had the lowest percent increase in ITS after aging. The mix *WMA-5.3%AC-130ºC* is the most desirable out of the three mixes since ITS is the best measurement of aging, and according to the data in this study this mix has aged the least in a given amount of time. The *WMA-5.3%A-10ºC* asphalt mix results in the most desirable mechanical properties.

Table 11: Summary of Mix Mechanical Properties Changes after Aging

	HMA-5.3%AC-150ºC	WMA-5.3%AC-130ºC	WMA-4.8%AC-130ºC
Unaged Density (% of TMD)	94.8	96.1	93.5
Unaged ITS (kPa)	2720.73	2842.58	2089.40
Average Change after Aging in ITS (% increase)	17.08	13.25	55.91

The *WMA-5.3%AC-130ºC* mix has the highest effective asphalt content, 4.0%, of the three mixes, and this produces a high density. Also, as an effect of the high effective asphalt content, the sample contains the lowest percentage of air voids. This low air void percentage is one of the main factors that contribute to the high indirect tensile strength of the sample. The sample is more densely compacted and the bonds between aggregates are stronger from the higher effective asphalt content, creating a stronger sample altogether.

The chart below, Figure 19, shows that the *WMA-5.3%A-130ºC* has the lowest change in ITS after aging. A large increase in tensile strength after aging is bad because it shows the sample is aging at a faster rate, and the mechanical properties are changing too drastically. The mechanical properties should not differ greatly after aging, because if the asphalt mix becomes too stiff it can lead to cracking.

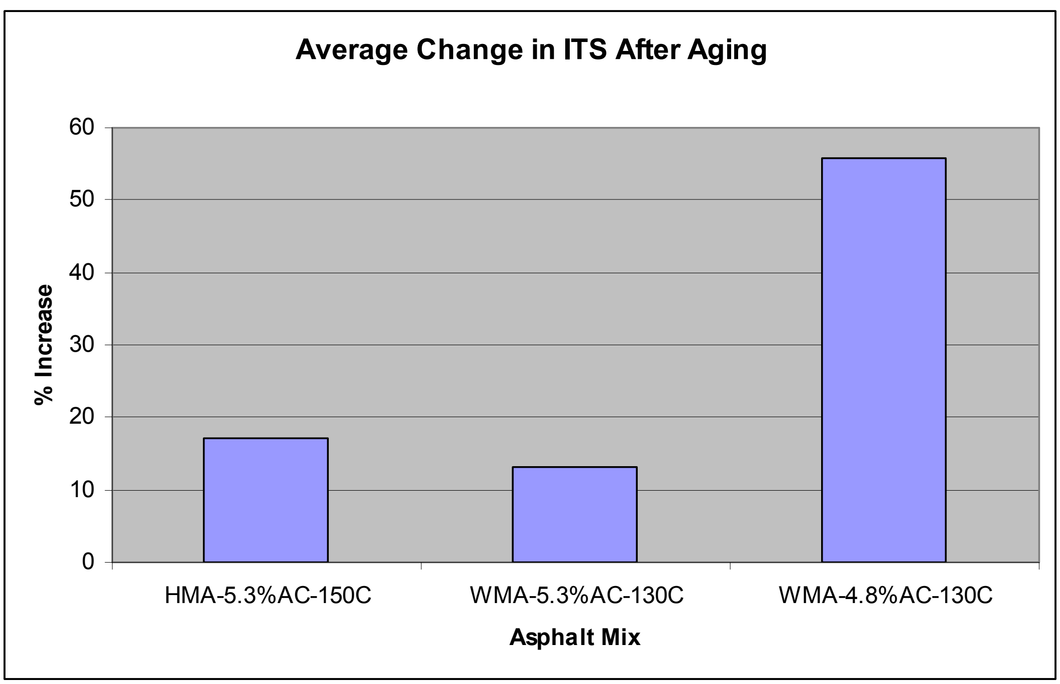


Figure 19: Average Change in ITS After Aging

Chapter 5: Benefits

After thorough testing and analysis of the three different asphalt mixes, it is determined that the additive Sasobit® is a beneficial material to be used in WMA. The changes in material properties result in stronger and longer lasting asphalt mixes as well as a longer paving season. With the addition of Sasobit® the temperature of HMA production can be cut down by 20°C and as a result, the carbon dioxide emissions let off by the asphalt industry could be reduced as much as 43.9% per year. This includes emissions from the fuel used as well as from the asphalt used to produce the Hot Mix Asphalt. In addition, the decreased temperature required for Sasobit® asphalt mixes can save over $69 million in energy costs. Although it is an added cost to use Sasobit® in HMA mixes, there is still an overall savings, both monetary and ecologically.

5.1 Carbon Dioxide Emissions Reduction from Energy and Materials

Using Sasobit® in asphalt mixes allows the reduction of carbon dioxide (CO_2) emissions since the temperature needed to mix is approximately 20ºC lower, 130ºC instead of 150ºC, than the conventional temperature. The benefits that the use of Sasobit® bring to the asphalt industry include reduction in CO_2 emissions, reduction in energy used to heat aggregates for mixing and cost savings in energy costs.

5.1.1 Carbon Dioxide (CO_2) Emissions from Energy Needed to Produce HMA

Heat energy required to raise the temperature of mass to a given temperature is given by the following equation.

Equation 9: Heat Energy

$$Q = c * m * \Delta T$$

Where:
Q = Heat Energy (J)
c = specific heat (J/kg*K)
m = mass (kg)
ΔT = temperature change (K)

The heat energy needed to heat the total amount of asphalt mix produced in the United States each year, 500 million tonnes (500 billion kg), was calculated to be

$5.75*10^{16}$ J. This calculation considered the total mass of 500 million tonnes, the temperature change of ambient temperature, 25ºC, to 150ºC and the specific heat of aggregates only, 920 J/kg*K. Since asphalt is required to be kept at very high temperatures already to maintain workability, the savings in energy for heating asphalt was not considered for these purposes.

From Table 11.4 (p. 11-5) of the *Transportation Energy Data Book: Edition 25*, 2006, it was found that 1,666.2 million tonnes ($1.67*10^{12}$ kg) of CO_2 were produced in the United States for energy needed for industrial activity in 2003. From Table 2.1 (p. 2-3), it was found that 32.7 quadrillion BTUs ($3.45*10^{19}$ J) of energy were produced for the industrial sector in 2003. The ratio of CO_2 produced for industry in a year (2003) to energy produced for industry in a year (2003) multiplied with the heat energy needed for 500 million tonnes of asphalt mix produced, equals the CO_2 produced by the asphalt industry per year, 2.78 million tonnes (Table 12). This was calculated based on 100% transmission efficiency from the energy source, which is very conservative.

Table 12: Carbon Dioxide (CO_2) Emissions Savings per Year Based on Energy Needed for Asphalt Industry

Q (per year for 500 million tonnes)	5.75E+16 J
U.S. Carbon Dioxide Emissions	1.67E+09 tonnes
	1.67E+12 kg
U.S. Total Energy Use	3.27E+16 BTU
	3.45E+19 J
CO_2 Emissions Per Year (asphalt industry)	2.78E+09 kg
	2.78E+06 tonnes
CO_2 Emission Prevented Per Year (16%)	**4.44E+05 tonnes**

The heat energy needed to heat an asphalt mix from ambient temperature, 25ºC, to 130ºC is a 16% savings from the heat energy needed to heat an asphalt mix from ambient temperature to a conventional temperature of 150ºC (Appendix C).

Equation 10: Percent Savings in Energy

$$Savings\ in\ energy = \frac{Q_1 - Q_2}{Q_1} * 100\% = \frac{125\ J - 105\ J}{125\ J} * 100\% = 16\%$$

This 16% savings of CO_2 emissions is calculated to be 444,000 tonnes per year emitted to produce the energy needed in the asphalt industry to make 500 million tonnes of asphalt mix in the United States (Table 12).

5.1.2 Carbon Dioxide (CO_2) Emissions from Asphalt Mix Materials

The CO_2 emissions measured in this study allowed a calculation of reduction of emissions released directly from asphalt mix materials. The emissions were measured from approximately sixty grams of asphalt mix that was assumed to have reached equilibrium after two hours in a two liter flask. On average, 300 ppm (mg/L) of CO_2 is expected to be found in ambient air. The volume of the flask multiplied by the concentration of CO_2 measured less the ambient CO_2 equals the mass of CO_2 emitted (Table 13). This value was determined to be 833 mg for approximately 60 g of asphalt mix after 2 hours of being held at 150ºC. This mass projected onto the total amount of asphalt mix produced in a year in the United States, 500 million tonnes, becomes 6.94 million tonnes of CO_2 emitted directly from asphalt mix materials.

Table 13: Carbon Dioxide (CO_2) Emissions Savings per Year Based on Measured Emissions from Asphalt Mix Materials

Mass of CO_2 emitted (based on 60g HMA)	8.33E+02 mg
	8.33E-04 kg
CO_2 Emissions Released Per Year	6.94E+06 tonnes
CO_2 Emissions Prevented Per Year	**3.33E+06 tonnes**

The average CO_2 levels measured from the emission tests in this study are summarized in Table 14. With these average amounts, the CO_2 emissions that have the potential to be prevented with the use of Sasobit® in asphalt mixes were determined to be 3.33 million tonnes. This was calculated with the use of the following equation, with the ambient CO_2 present considered to be 300 ppm.

Equation 11: CO_2 Prevented

$$CO_2 \ prevented = \left[\frac{(716.67 - 300) - (516.67 - 300)}{(716.67 - 300)} \right] * CO_2 \ released$$

Table 14: Asphalt Mixes Tested with Average Carbon Dioxide (CO_2) levels

Mix	Sasobit® (%)	Temperature (°C) During 2 Hour Aging	Mass of Mix (grams)	Asphalt Content (%)	CO_2 (ppm)	Average CO_2 (ppm)
HMA	0	150	61.2	5.7	700	
HMA	0	150	59.5	5.3	700	
HMA	0	150	60.7	5.3	750	716.67
WMA	1	130	61.3	5.6	550	
WMA	1	130	62.3	5.4	550	
WMA	1	130	62.7	4.8	450	516.67

This works out to be a 27.9% reduction in emissions. The amount of CO_2 emissions, 3.33 million tonnes, which could be prevented per year from entering the earth's atmosphere directly from asphalt mix materials with the use of Sasobit®, is significant.

5.1.3 Total Carbon Dioxide (CO_2) Emissions Reduction

CO_2 emissions that have the potential to be prevented from entering the earth's atmosphere with the use of WMA was calculated based on the average production of 500 million tonnes of asphalt mix per year in the United States. Based on energy used in 2003, 444,000 tons of CO_2 emissions can be prevented per year from the amount of energy needed to heat asphalt mixes to only 130°C instead of 150°C. From the measured CO_2 amounts in this study, 3,330,000 tonnes of CO_2 emissions can be prevented per year directly from asphalt mix materials. Therefore, the total amount of CO_2 emissions that can be prevented per year with the use of WMA is 3,774,000 tonnes, a 43.9% reduction (Table 15).

Table 15: Total Carbon Dioxide (CO_2) Emissions Prevented Per Year with the Use of WMA

Emissions Prevented from Energy Per Year	444,000 tonnes	16%
Emissions Prevented from Materials Per year	3,330,000 tonnes	27.9%
Total Emissions Prevented Per Year	**3,774,000 tonnes**	**43.9%**

The benefits associated with CO_2 emissions are purely ecological at this point in time, though they are still significant. Along with the ecological benefits from using WMA instead of HMA, there are cost benefits that can result from reduced energy and prolonged pavement life.

5.2 Cost Savings

The cost savings that the use of WMA instead of HMA brings to the asphalt industry are from two distinct areas. There are cost savings that results from using less energy to heat asphalt mix to 130°C, rather than 150°C. There are also cost savings associated with the increased pavement life of WMA, which allows a decrease in future maintenance costs. Both of these cost savings greatly add to the benefits of using WMA instead of HMA.

5.2.1 Cost Savings from Energy Reduction

This cost saving comes from the energy saved by heating the aggregates used in the mix to only 130ºC instead of 150ºC, which Sasobit® in WMA allows the asphalt industry to do. As seen in Table 16, the amount of heat energy needed to heat a year's worth of aggregates used in asphalt mixes from ambient temperature to 150ºC is $5.75*10^{16}$ J ($5.45*10^{8}$ therms). The amount of heat energy required to heat the same amount of aggregates from ambient temperature to 130ºC is $4.83*10^{16}$ J ($4.58*10^{8}$ therms). It costs 3 therms of natural gas to make a ton of asphalt mix. Natural gas retails at about $0.80 per therm. At this cost, the asphalt industry can save $69.8 million per year with the use of Sasobit® in WMA, for an average annual rate of 500 million tonnes of asphalt mix produced.

Table 16: Summary of Energy Cost Savings

Temperature of Mix	150ºC	130ºC
Heat Energy, Q (per year for 500 million tonnes)	5.75E+16 J	4.83E+16 J
	5.45E+08 therms	4.58E+08 therms
	$ 4.36E+08	$ 3.66E+08
Monetary Savings in Energy Costs	**$ 69,800,000**	

5.2.2 Cost Savings from Increased Pavement Life Using WMA

There are cost savings in using WMA in terms of the pavement life. For example, to pave a one lane road (width of twelve feet), one mile long, and four inches thick with traditional HMA would cost about $86,100. When the life of the asphalt mix is taken into consideration, using Sasobit® in WMA results in an 11% monetary savings.

The life of an ordinary HMA asphalt mix is 12 years. The life of a WMA asphalt mix with Sasobit® was calculated to be 13.5 years. This is based upon the air void percentages for both the *HMA-5.3%AC-150°C* and the *WMA-5.3%-130°C* mixes. For every 1% the air voids are lowered, another 10% is added onto the pavement life (11). Since the air voids were lowered on average from 5.2% to 3.9% the percent lowering is 1.3%.

Equation 12: Percent Air Voids Lowered

$$Percent\ \ Air\ Voids\ Lowered = 5.2\% - 3.9\% = 1.3\%$$

This percent lowering of 1.3% translates to a 13% increase in the pavement life.

Equation 13: Extension of Pavement Life

$$Pavement\ Life = 12\ \ years * 1.13 = 13.56\ \ years$$

The *HMA-5.3%AC-150°C* mix will have to be replaced every 12 years, while the *WMA-5.3%AC-130°C* will have to be replaced 13.5 years. The cost per year of each mix is calculated in the equations below; showing that without Sasobit®, the cost is about an extra $880 per year for this 1 lane road, 1 mile long. The total savings from using Sasobit® results in an 11% savings in cost per year, which can be applied to any amount of asphalt mix being used on a project. The savings are shown in the Table 17.

Equation 14: Annual Cost without Sasobit®

$$Cost\ \ per\ Year = \frac{\$94{,}930}{12} = \$7{,}910.87$$

Equation 15: Annual Cost with Sasobit®

$$Cost\ \ per\ Year = \frac{\$94{,}930}{13.5} = \$7{,}031.89$$

Equation 16: Percent Annual Savings for Pavement Life

$$\%\ Savings = \frac{\$7910.87 - \$7031.89}{\$7910.87} * 100 = 11.11\%$$

Table 17: Percent Savings in Cost from Materials on an Annual Basis

	Without Sasobit®	**With Sasobit®**
Pavement Life	12 years	13.5 years
Cost	$94,930.45	$94,930.45
Cost per year	$7,910.87	$7,031.89
% Savings		**11.11%**

Although the addition of Sasobit® to asphalt mixes drastically reduces the energy costs, it does cost more money to add Sasobit® to asphalt mixes. The current cost of producing one ton of asphalt mix is $60. The addition of Sasobit® creates a $2 increase in this cost per ton of asphalt mix; making the total cost $62 per ton of asphalt mix. Even though initially, the cost is more to make asphalt mix using Sasobit®, over the course of many years the Sasobit® asphalt mix results in a monetary gain. Additionally, the cost of Sasobit® is rapidly decreasing, making the monetary gains even greater.

The savings from a gain in pavement life is due to lowering the air voids, hence an increase in density. Pavements with lower initial air voids last longer. Of the many things that contribute to this enhanced life, one very important factor is the reduction in aging of the binder, because of less oxidation, due to the presence of lower amount of air voids. The WMA mixes did show slower aging, as discusses in the following section.

5.3 Material Property Benefits of Using WMA

The following chart shows the material properties for the three asphalt mixes in the areas of Density and Change in Indirect Tensile Strength after Aging. As the graph indicated the *WMA-5.3%AC-130°C* mix has the highest Density and the lowest change in ITS after aging. These properties make this mix the most desired mix. The *HMA-5.3%AC-130°C* mix is the mix most widely used currently in the asphalt industry. With the addition of Sasobit® to asphalt mix, the most striking change in mechanical properties is the decrease in change of the ITS. The values are shown below in Figure 20.

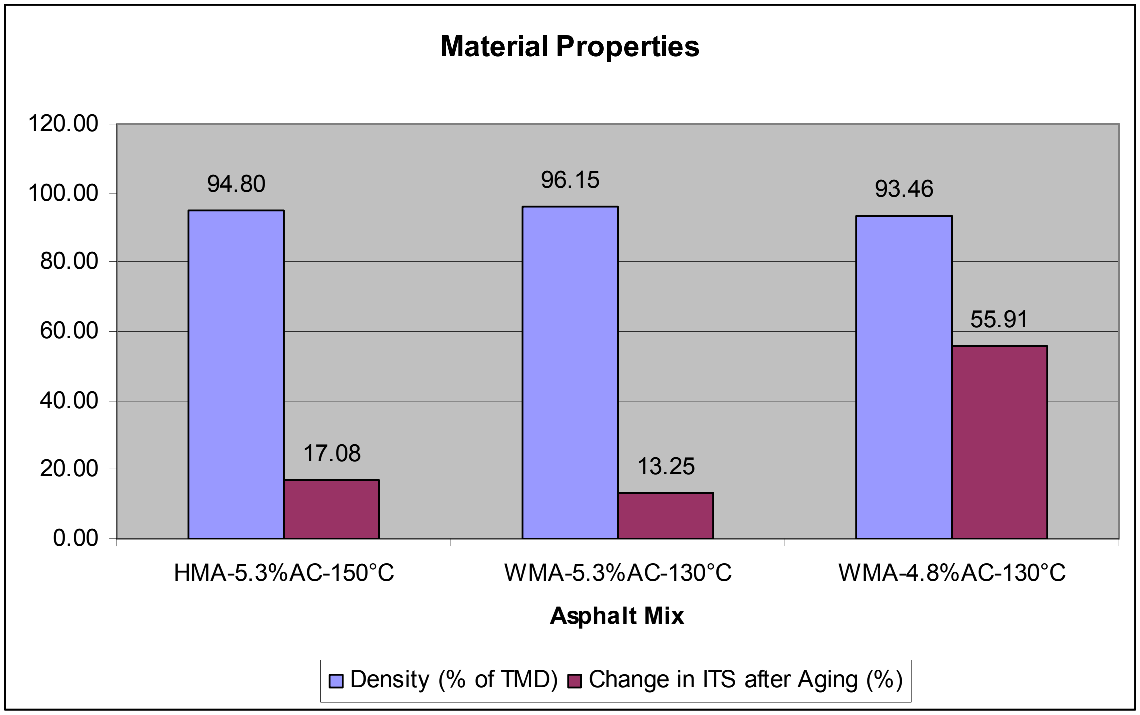


Figure 20: Material Properties

The most beneficial change in mechanical properties with the addition of Sasobit® is the decrease in changes after aging. This indicates that there is a slower aging process for the *WMA-5.3%AC-130°C* mix, which contains Sasobit®. A slower aging process means that the life of the asphalt mix is much longer, and will last longer when applied to pave a roadway or driveway. In turn, this saves money because roadways will have to be re-paved, patched, and have general maintenance done less often.

5.4 Benefits of Extending the Paving Season

The use of Sasobit® allows the HMA to be produced and compacted at a lower than conventional temperature. This means, for those areas which have relatively short paving seasons, for example New England, the use of Sasobit® will help in extending the paving season. More work will get done in a typical year and hence improvements in road conditions will be much faster.

5.5 Conclusion

The use of Sasobit® in WMA has the potential to reduce the asphalt industry's contribution to greenhouse gas emissions as well as save them money. It will reduce CO_2 emissions produced both from the material and energy needed to make asphalt mixes. It can save energy costs since an asphalt mix will not need to be heated to the conventional temperature of 150°C, it will be able to be heated to a lower temperature, such as 130°C. On top of all of these ecological and economic benefits, it also produces the same quality, or better, than conventional HMA.

Not only does Sasobit® not negatively change the material properties, but it actually produces a stronger and longer lasting asphalt mix. The addition of Sasobit® allows better compaction of HMA, which produces lower air voids. This decrease in air voids results in a longer lasting asphalt mix. The asphalt mixes with Sasobit® have shown a slower aging process than conventional HMA in this study, which will result in the longer life of a pavement.

Although Sasobit® may not be beneficial for small paving jobs, for large scale projects it is a necessity. It can save the asphalt industry money and energy. The cost savings come from energy costs as well as the ability to delay repaving jobs, since the pavements containing Sasobit® have a longer in-service life.

The ecological impacts that the use of Sasobit® in asphalt mixes can have for the asphalt industry are significant. The reduction of greenhouse gases from asphalt mix materials and energy consumed by the asphalt industry can make a difference in the world we live in and have the potential to improve the earth's atmosphere. From this study, it was calculated that 3.774 million tonnes of CO_2 could be prevented from being released into the atmosphere per year from the asphalt mix materials as well as energy used during production. In 10 years, 37.74 million metric tons of CO_2 could be prevented. It is essential for the asphalt industry to start caring about their effects on the environment, and the addition of Sasobit® to asphalt mixes would be a great start for this.

Bibliography

1. Hurley, G.C., Prowell, B.D. *Evaluation of Sasobit® for Use in Warm Mix Asphalt.* National Center for Asphalt Technology: Auburn University. June 2005.

2. Energy Information Administration. *Emissions of Greenhouse Gases in the United States 2004.* U.S. Department of Energy Washington, D.C. December 2005.

3. Trumbore, D.C. *Estimates of Air Emissions from Asphalt Storage Tanks and Truck Loading.* Asphalt Technology Laboratory. Owens Corning, Summit, IL.

4. Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D., & Kennedy, T.W. *Hot Mix Asphalt Materials, Mixture Design, and Construction, Second Edition.* National Asphalt Pavement Association Research and Education Foundation: Lanham, Maryland. 1996.

5. Sutton, C.L. *Technical Paper T-143 Blue Smoke Emission Report.* Astec: Chattanooga, TN. 2002.

6. Environmental Protection Agency. *Hot Mix Asphalt Plants Emission Assessment Report*. Research Triangle Park, North Carolina. December 2000.

7. *Warm Mix Asphalt: A State-of-the-Art Review.* Advisory Note 17.Australian Asphalt Pavement Association.

8. Kandhal, Prithvi S. and Sanjoy Chakraborty. *Effect of Asphalt Film Thickness on Short and Long Term Aging of Asphalt Paving Mixtures*. National Center for Asphalt Technology: Auburn University. Jan 1996.

9. Hunter, Elizabeth Rae. *Evaluating Moisture Susceptibility of Asphalt Mixes. University of Wyoming*. Laramie, WY. 2001.

10. Bell, Chris A. and Dan Sosnovske. *Aging: Binder Validation*. Strategic Highway Research Program: Corvallis, Oregon. 1994.

11. Linden, Robert N., Joe P. Mahoney, and Newton C. Jackson. *Asphalt Construction, Premature Rutting and Surface Friction Courses - Effect of Compaction on Asphalt Concrete Performance*. National Research Council: Transportation Research Record 1917. Washington, D.C. 1989.

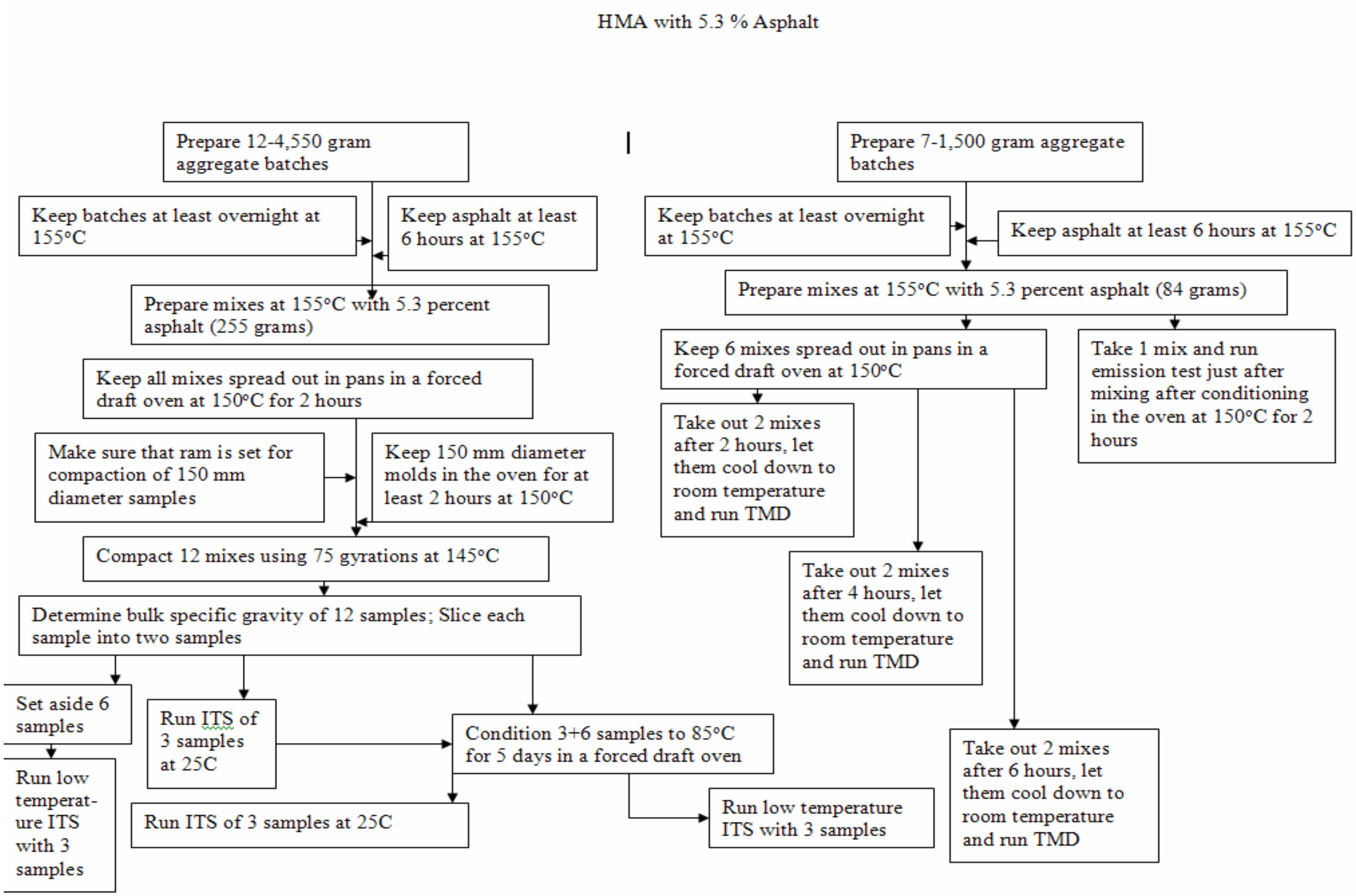
Appendix A: Production of Sasobit®

Fisher-Tropsch (FT) Process

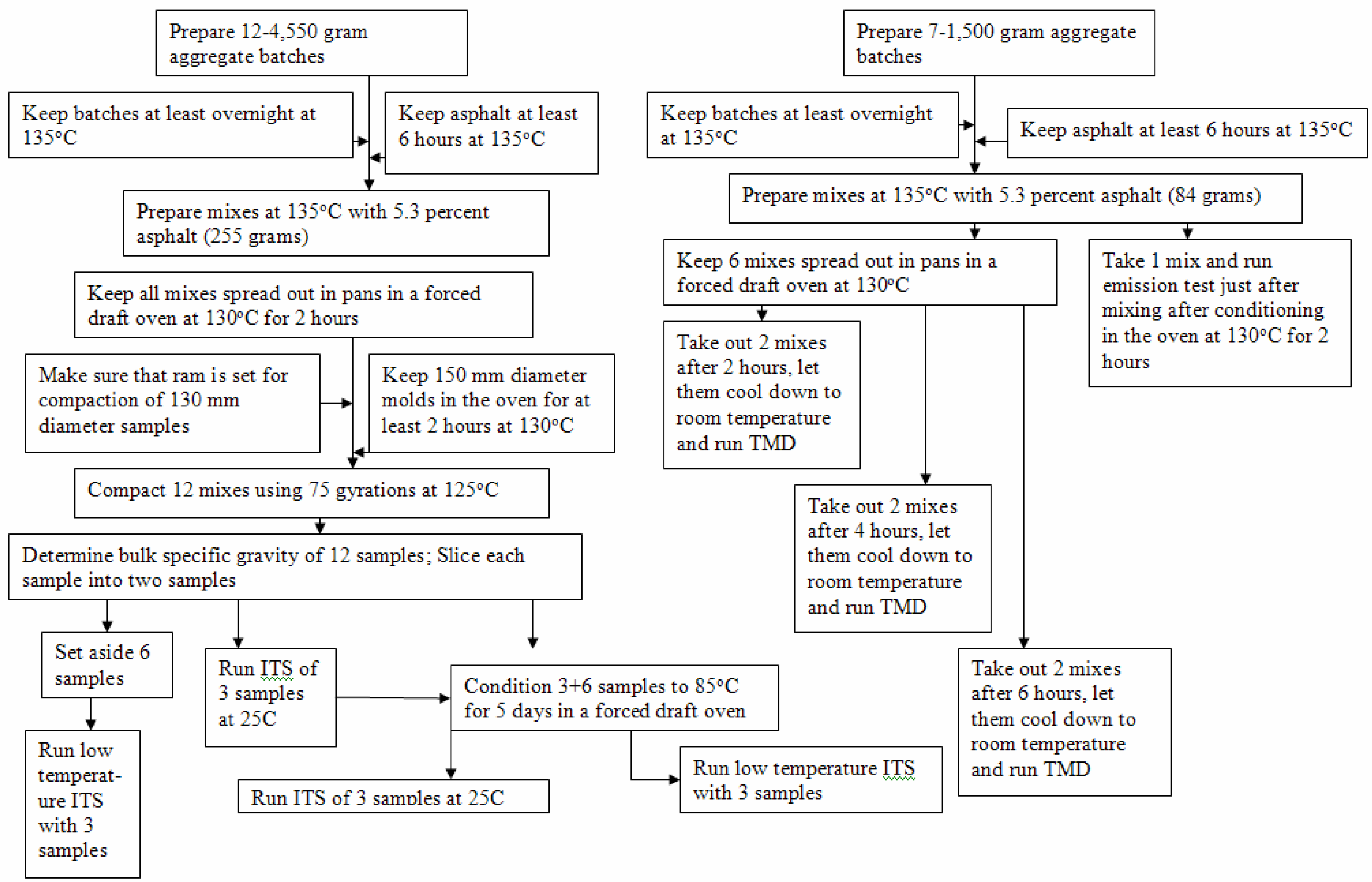
Hurley, G.C., Prowell, B.D. *Evaluation of Sasobit® for Use in Warm Mix Asphalt.* National Center for Asphalt Technology: Auburn University. June, 2005. Page 6.

"In summary, in the Fischer-Tropsch synthesis, coal or natural gas (methane) is partially oxidized to carbon monoxide (CO) which is subsequently reacted with hydrogen (H_2) under catalytic conditions producing a mixture of hydrocarbons having molecular chain lengths of carbon $(C)_5$ to C_{100} plus carbon atoms. The process beings with the generation of synthesis gas then reacted with either an iron or cobalt catalyst to form products such as synthetic naphtha, kerosene, gasoil and waxes. The liquid products are separated and the FT waxes are recovered or hydrocracked into transportation fuels or chemical feedstocks. The Sasobit® recovered is in the carbon chain length range of C_{45} to C_{100} plus. By comparison, macrocrystalline bituminous paraffin waxes have carbon chain lengths ranging from C_{25} to C_{50}. The longer the carbon chains in the FT wax lead to a higher melting point. The smaller crystalline structure of the FT wax reduces brittleness as low temperatures as compared to bitumen paraffin waxes."

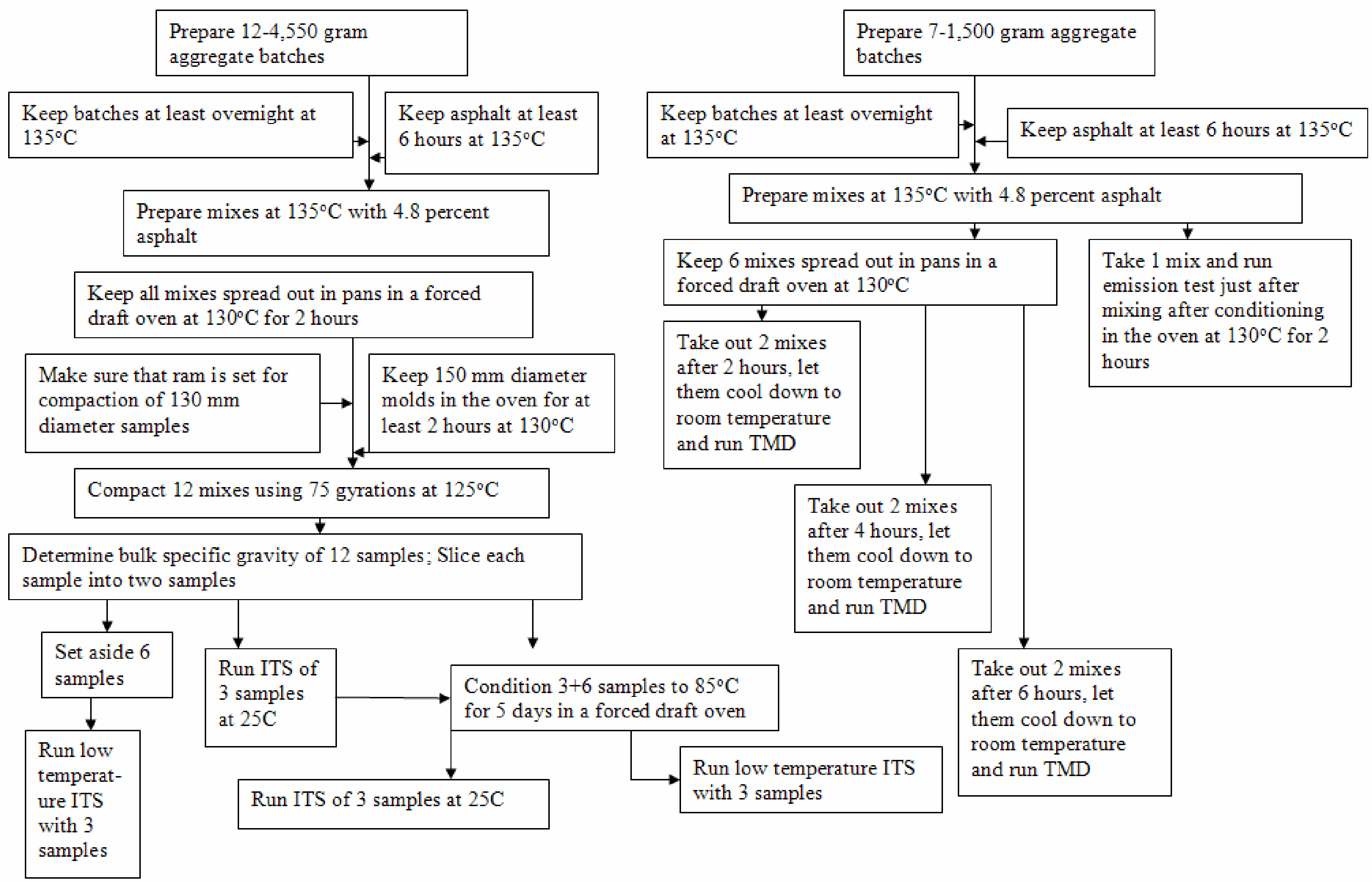
Appendix B: Testing Flow Charts



WMA with 5.3 % Asphalt



WMA with 4.8 % Asphalt



Appendix C: Heat Energy Calculations

Heat energy required to raise the temperature of a mass, m, through delta (T), where the mass has a specific heat of c, is given by,

Q = c*m*delta(t)

Q is in Joules
c is in Joules per gram degree C
delta (t) is in C

Consider heat required to raise temperature of aggregates
from ambient, say 25C, to 150C

Q1	c*m*	125	joules

Now consider the case where we use warm mix asphalt
Heat required to raise temperature of aggregates
from 25C to 130C

Q2	c*m*	105	joules
Savings in energy		20	joules

Savings in energy (Q1-Q2)*100/Q1
16 %

If we burn 16 % less fuel (say natural gas)
how much do we cut down CO_2 production
from burning of fuel only? (percent wise?)

16 %

Add this 16 % with the cut down in CO2 production from heating HMA
It was 716.67 ppm for 150C
and 516.67 ppm for 130 C.

Hence cut down in CO_2 production
27.906847 %

Total reduction in CO_2 production
43.906847 percent

Savings ($) by burning less fuel
16 %

Minus cost of additive Sasobit®

added cost	$	2	per ton of mix
One ton of mix costs		60	per ton of mix
added cost		3.33	percent