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Laboratory Performance Based Cost Assessment of Warm-Mix Asphalt Concrete Technologies

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Abstract: With growing environmental concerns and ever-increasing budgetary constraints, the use of warm-mix asphalt (WMA) is on the rise, since WMA has the potential to reduce cost and provide environmental benefits. One hurdle in the adoption of WMA is the uncertainty of its long-term performance. Currently a literature gap exists on the performance of WMA, as most studies tend to focus on the economics and environmental benefits of the emerging technology. Laboratory experimentation, in the form of rutting, fatigue life, and moisture susceptibility as measured by tensile-strength-ratio (TSR), was conducted on four different WMA technologies in order to compare the change in performance between WMA and hot-mix asphalt. Linear regression models were then fit to the laboratory results to identify variables which were statistically significant in affecting performance.

Life cycle cost analysis principles were then applied to compare the warm mix technologies. The resulting dollar amount from the cost analysis was compared with the regression models, which allow for direct comparison between cost savings and performance. The result of this study shows that addition of low and moderate amounts of WMA additive was found to increase fatigue life; however, high dosages of additive negatively affected the fatigue life. It was also shown that reducing the mixing temperature of any asphalt mixture tested in this study increased the likelihood of rutting. Lastly, TSR and fatigue life were found to be dependent on the type of additive chosen. In general, every WMA technology tested has the potential to reduce costs and improve at least one measure of the expected performance of asphalt mixtures.

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***Key words**: Life Cycle Cost Assessment; Linear Regression; Performance; WMA.*

Introduction

Asphalt pavements comprise an overwhelming majority of paved roads in the United States. The predominant technology for constructing these pavements is hot-mix asphalt (HMA). Growing environmental concerns and increasing budgetary constraints have led to increased use of warm-mix asphalt (WMA). The primary cause of asphalt pavement emissions results from manufacturing, and the reduced heating temperatures provided by WMA have been shown to reduce emissions and energy consumption [1, 2].

One hurdle to the wide-spread acceptance of WMA pavement is the uncertainty of its long-term performance. To date, most studies tend to emphasize the economics and environmental benefits of the emerging technology rather than addressing the long term performance of WMA. Failing to answer the question of “will it work” is a fundamental flaw in previous research and should be the center of research, instead of a corollary. Laboratory testing is one tool that can be employed to study the long term performance of WMA compared to traditional HMA. There is a well-established recognition for the need to relate the performance of WMA pavements to the cost savings in order to justify the use of the product [3-5]. This paper will present a cost assessment of WMA in conjunction with laboratory obtained performance data, in order to establish a comparable metric between WMA technologies. Both the cost and performance are then compared against the cost and performance of a control HMA mixture.

The constituents of both HMA and WMA are identical, with the exception of small amounts of additives blended into WMA to reduce the heating requirements of the mixture. In some cases, this temperature reduction may exceed 40℃ [6, 7]. The reduction in heating translates to as much as 20 percent reduction in consumption of fuel at the plant [8]. Other benefits of WMA include lower plant emissions and less short term aging of binder, due to the reduction in heating at the plant and increased pavement production windows [8, 9].

There are three predominant technologies used to produce WMA: chemical additives, organic additives, and foaming techniques. Chemical additives, such as Evotherm® and Cecabase® RT, are proprietary blend of chemicals which, when mixed with bitumen, disperse the asphalt bitumen and improve aggregate coating and workability at lower temperatures. Organic additives, like Sasobit® and Asphaltan® B, are primarily made of a specially chosen wax. The selected wax has a low melting point, which will reduce the viscosity of the bitumen when heated, due to being a liquid, but at service temperatures, the wax will crystallize and contribute to the overall strength of the pavement [10, 11].

The category of foaming WMA techniques can further be broken down into two sub-categories: foaming admixture and free water system. Both of these methods exploit the use of steam to create WMA. When steam is present inside the binder, the volume expansion it causes will reduce the overall viscosity and increase the workability of the mixture. Eventually, the steam dissipates from the

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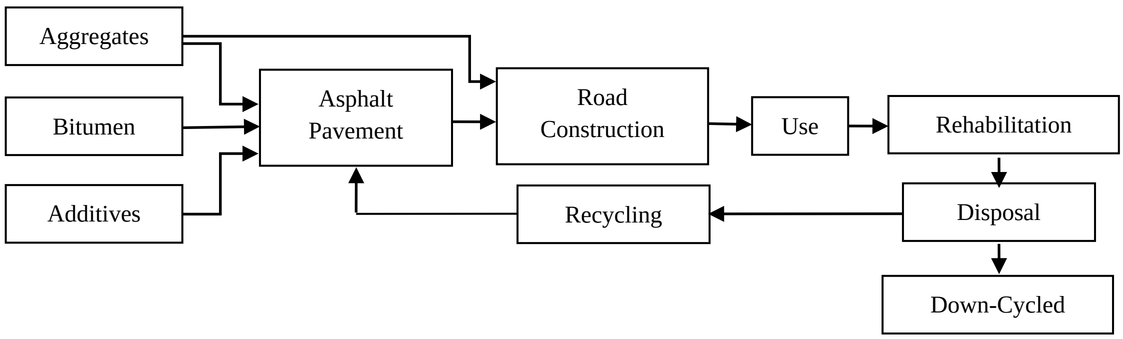


Fig. 1. Typical Life Cycle of an Asphalt Pavement.

pavement as it cools, resulting in a pavement with similar properties to a traditional hot mix asphalt pavement [8, 12].

The foaming admixtures such as the use of hydrophilic additives are comprised of some type of synthetic zeolite, which retains water until it is heated. Once heated, the zeolite releases water, as steam, into the asphalt. For instance, Advera® WMA and Aspha-min® are admixtures that use zeolite to create WMA [13]. Free water system WMA can be achieved either by employing a separate mixing chamber for foaming to occur or by introducing small amounts of water directly into the binder stream of the asphalt plant [14]. Both asphalt foaming chambers and direct water injection require modification of the existing asphalt plants [15, 16]. WAM-Foam® is one of the foaming technologies that uses the separate chamber to introduce water and air into hot asphalt binder. Common types of direct water injection are Double Barrel Green [15] and Ultrafoam GX [17, 18].

This study examined all of the different types of warm-mix technologies mentioned above. Cecabase® RT and Sasobit® represent the chemical and organic admixtures, respectively, that were tested. Advera® WMA was the hydrophilic water-based additive of choice. For the remaining foaming method, direct water injection was chosen, which will simply be referred to as direct injection. Direct injection was replicated in the laboratory by injecting water into hot asphalt binder and employing a high-shear mixer to incorporate the water into the binder.

Life Cycle Assessment Methodology

In order to compare the four different warm mix technologies, life cycle cost analysis principles were applied. A typical life cycle analysis involves a cradle to grave comparison of two or more products. For this study, a complete analysis was not conducted, but rather a subset of the complete analysis. Fig. 1 shows a typical life cycle of an asphalt pavement. Each box represents a stage in which there are many sub-processes that are included within a life cycle cost analysis. For example, the road construction phase would include site clearing, aggregate base layers, and pavement construction. The arrows between the boxes represent the progression of a road construction project, and in some cases, they can include the transportation of materials and equipment between stages.

The importance of an entire life cycle cost analysis should not be understated: according to one study over a 40-year life cycle, the costs from initial construction account for 70-90 percent of the total cost [19]. The same study also mentions that because of the time-value of money, costs from routine maintenance and pavement salvage value have minimal contributions to the overall life cycle cost of a pavement.

This study is not meant to be an exhaustive Life Cycle Cost Assessment (LCCA) for WMA pavements, but rather as a tool to compare existing WMA technologies. This paper will focus on the creation of asphalt pavement components before they are transported to the construction site and placed. This stage (from the second column of Fig. 1) involves quantifying the inputs from bitumen, additives, aggregates, and energy requirements to produce asphalt concrete at the plant. The total costs of those inputs were then compared to performance values obtained from laboratory experimentation. This study does not include the costs imposed by the variation in aggregate selection, transportation distances, base and sub-base construction, user delays, rehabilitations and maintenance or pavement disposal. The monetary contribution from variables that were omitted have no significant contribution to the differences in the cost analysis results between WMA and HMA options, because the costs between scenarios are assumed to be held constant. The resultant total costs were compared to a control sample of HMA mixed at 150°C with no additives.

Experimental Design

For this study, all of the samples were produced in the laboratory at three different mixing temperatures with three different admixture concentrations. All of the samples tested had three replicates for rutting and beam fatigue testing, and five for TSR testing. From these test results, linear regression was implemented. Samples were mixed according to a 5E3 SuperpaveTM mix design from a local asphalt plant [20]. A 5E3-type pavement has a nominal maximum aggregate size of 9.5 mm and less than three million ESAL traffic level. The binder used for all samples was a PG 58-34 grade. Table 1 shows the variables considered. The admixtures were added by percentage of binder weight, with the exception of Advera® WMA, which was added by percentage of total sample weight, as prescribed by the manufacturer.

Compaction was completed with a volume control method to achieve a uniform 4% air voids within all samples, which the author acknowledges to be outside of specification. However, the results are useful for comparison against each other, since all of the samples followed this procedure. Once compacted and cooled, each specimen was cut to final testing dimensions.

Table 1. Variables Used in the Testing.

Percentages of Additive Used					
Dosage	Control	Advera® WMA	Cecabase®	Sasobit®	Direct Injection
Low	N/A	0.15	0.20	0.50	1.00
Medium		0.25	0.35	1.50	1.50
High		0.35	0.50	3.00	2.00

Mixing Temperatures (℃)				
Control	Advera® WMA	Cecabase®	Sasobit®	Direct Injection
115	100	100	100	100
130	115	115	115	115
153	130	130	130	130

The testing of the samples was conducted on the Asphalt Pavement Analyzer (APA) Rutting machine to measure pavement rutting potential in a controlled environment. The samples were cut to dimensions of 150 mm (6 inch) diameter by 75mm (2.95 inch) height. Then, the specimens were tested in excess of 8,000 load cycles at 58℃ (136.4℉) at a constant wheel pressure of 100 psi (689.48 kPa). Amounts for rutting were recorded every 1,000 cycles during the testing in millimeters.

For fatigue resistance, four-point beam fatigue tests were conducted. Fatigue is the damage occurring in a material due to the application of cyclic loading. The purpose of this test is to determine the fatigue life of the asphalt mixture subjected to the repeated bending until failure where the fatigue failure was defined as 50% reduction of initial stiffness. Once the beam's initial stiffness was reduced by 50%, the load cycle number was defined as failure, and that cycle number was then recorded. In this test, a frequency of 10 Hz and 400 micro-strain (constant strain) were used for all the samples tested.

Tensile Strength Ratio (TSR) testing involved two sets of laboratory samples measuring 65 mm height by 100 mm diameter and compacted at 4% air voids. The first set of samples were labeled as unconditioned, while the other set was vacuum-saturated with water and placed inside of a deep freezer to simulate moisture damage. The vacuum saturated samples will be referred to as conditioned. Both sets of samples were then crushed in indirect tension, and the peak load was recorded. By dividing the peak conditioned load by the peak unconditioned load, a ratio of strength loss can be obtained. That ratio is known as the tensile strength ratio (TSR).

Cost Analysis

For this assessment, the functional unit was taken as one lane-mile (1.6 lane-kilometers) of 12 foot (3.66 meters) wide road with a uniform pavement depth of 6 inches (15.24 cm). The same percentages of aggregates, bitumen, and additives from the mixture testing were preserved in the cost analysis. The total weights for one lane-mile were used in calculating for the functional unit. To convert the volumetric approach from laboratory testing to the more common weight measurements, density values from the software program Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) were applied [21]. Table 2 shows the weight percentages of each component used as well as the total weights, in tons (tonnes) that were used in the analysis.

Table 2. Asphalt Mixture Ingredients.

Ingredient	Control	
	Weight %	Total Weight, Tons (Tonnes)
Coarse Aggregate	23.62	358.30 (325.04)
Fine Aggregate	70.86	995.28 (902.90)
Bitumen	5.52	54.41 (49.36)
Total	100	1,407.99 (1,277.31)

Recent unit price data was obtained from a number of sources. Coarse and fine aggregate cost data was obtained through the RS Means database [22]. Binder cost information was an averaged mid-continent market PG 64-22 [23]. The price to heat the asphalt can best be described by Eq. (1). The amount of fuel needed to heat a ton of asphalt at a batch plant was determined for the range of temperatures tested [24, 25]. The cost to operate a batch plant was taken from RS Means. Lastly, using an online Plant Diagnostic Tool (PDT), the cost reduction to operate a batch plant at reduced temperatures was determined for the temperatures tested [26].

$$\$\mathrm{Heat}_T = \mathrm{Fuel}_T * \$\mathrm{Fuel} + \$\mathrm{BP} - \mathrm{PDT}_T \quad (1)$$

$\$\mathrm{Heat}_T$ =Dollars required to heat one ton of asphalt concrete
$\mathrm{Fuel}_T =$ Amount of fuel needed to heat one ton of asphalt concrete (gal/ton)
$\$\mathrm{Fuel} =$ Cost of No. 2 fuel oil ($/gal)
$\$\mathrm{BP} =$ Cost of operating an asphalt batch plant
$\mathrm{PDT}_T =$ Savings given from operating a batch plant at a reduced temperature

Using prices for the added material cost per ton, which were taken from published sources and from the manufacturer, the cost of different additives were taken into account [5, 27]. For the admixtures, the cost is given in terms of added cost per ton of total mixture. For additives where a range of values were given, the average was taken. Although many of the WMA options require asphalt plant modification, those costs were excluded on the assumption over the lifetime of the plant that the cost per ton would be negligible. Table 3 summarizes the cost inputs used in this model. A final cost for each pavement scenario can be determined by taking the summation of the components considered.

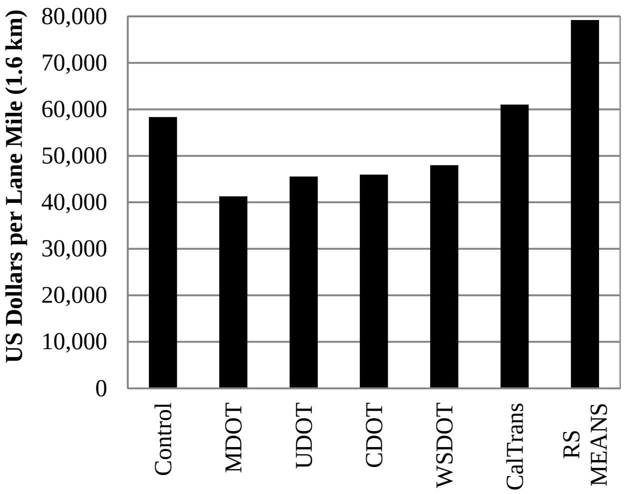
Cost Assessment Verification

In order to compare the results of the calculated pavement cost to known pavement costs, averaged data was taken from several agencies across the country [22, 23, 28]. Fig. 2 shows the comparison of pavement prices. The source of the pavement cost is given on the graph. The control pavement is the one calculated for this assessment. RS MEANS was taken from the RS Means construction database [22]. Although the available data from the sources was for pavements as constructed, using the rule of thumb of twice the material cost as an estimate for the built cost, the materials can be compared against each other. Of the DOT's surveyed, the estimate derived for this analysis is within the ranges of pavements reported.

Table 3. Cost Inputs.

Item	US Dollars/ Ton (Tonne)
Coarse Aggregate	21.50 (32.70)
Fine Aggregate	16.60 (18.30)
Binder	482.50 (537.97)
$Heat$_{100℃}$	2.85 (3.14)
$Heat$_{115℃}$	3.70 (4.08)
$Heat$_{130℃}$	4.51 (4.97)
$Heat$_{150℃}$	5.59 (6.16)
Fuel Oil Price	2.92 (3.13)
Advera® WMA	1.80 (1.98)
Cecabase[a]®	3.75 (4.13)
Sasobit®	1.95 (2.15)
Direct Injection[a]	0.30 (0.33)

[a] Cost data for a similar technology (Double-Barrel Green) was substituted



Note: MDOT – Michigan Department of Transportation
UDOT – Utah Department of Transportation
CDOT – Colorado Department of Transportation
WSDOT – Washington State Department of Transportation
Caltrans – California Department of Transportation

Fig. 2. Pavement Cost Comparison.

Experimental Results

The results of the rutting testing at 8,000 cycles have been plotted and can be found in Fig. 3. Each data point represents the average of three replicates, with the error bars showing the maxima and minima of the experiments.

A statistical analysis was performed to try and explain the variation in the rutting data. Using rut depth as the explanatory variable, a linear regression was fit with compaction temperature, additive type, and relative amount of additive as the explanatory variables. Additive amount was modeled as a factor variable. Relative additive amount of additive was also modeled as a factor, with categories of low, medium, and high dosages of WMA additive. The only variable that tested as significant at the 5% significance level was the mixing temperature.

The insignificant regression variables were removed, and rut depth was predicted based on only temperature. The resulting regression model is shown in Eq. (2). The linear regression has a P-value of 0.017, meaning the effect testing temperature has on expected rut depth is significant. From this result, it is shown that on average as the mixing temperature increases, the expected rut depth of an APA Rutting sample will decrease. Since this result is only dependent on mixing temperature, the effect of warm mix additive amounts or types had no statistical effect on predicted rut depth.

$$\text{Rut Depth(mm)} = 7.54347 \quad - 0.03001 * \text{Mixing Temperature(°C)} \tag{2}$$

The repetition numbers at which failure of the beam occurred for the various combinations of additive percentage and mixing temperature are plotted in Fig. 4. Each bar represents the average of three tests, with the maxima and minima depicted as error bars. Due to errors made during experimentation, the 0.35% of Cecabase® RT at 100℃ and 130℃ and 3% Sasobit® data points only represent two test values.

A similar linear regression approach was taken to explain the variation in the beam fatigue testing. The large variation in fatigue numbers led to use of a logarithmic scale for the independent variable of cycles to failure. Type II ANOVA analysis was conducted on the beam fatigue results. All of the variables tested were significant at the 95% confidence level ($\alpha = 0.05$).

The equation for expected fatigue life is shown below in Eq. (3). Since the relative amount of additive and type of additive were tested as factors, only the relevant factors produce changes in fatigue life. For example, if trying to predict the effect a medium amount of Sasobit® has on fatigue life, the terms involving high additive, low additive, and the remaining WMA admixtures would reduce to zero. Due to singularities associated with linear regression, the samples containing Direct Injection will serve as the base scenario. Therefore a mixing temperature of less than 150℃ and using no factors will yield an expected fatigue life for the Direct Injection case. In general, as the mixing temperature increases, the expected fatigue life would increase as well. Medium and low amounts of WMA additive led to an increase in fatigue life, while high amounts would decrease the expected performance. The addition of Direct Injection and Cecabase R.T. decreased expected fatigue life of the samples, while the remaining WMA additives led to a slight increase in fatigue life.

$$\log(\text{Fatigue Life}) = 2.923 + 0.019 * \text{Mixing Temp.(°C)} - 0.154(\text{High Add.}) + 0.156(\text{Med Add.}) + 0.243(\text{Low Add.}) + 0.405(\text{Advera®WMA}) + 0.313(\text{Cecabase R.T.}) + 0.401(\text{Sasobit®}) \tag{3}$$

The TSR data represents the average ratio of the peak strengths of at least five conditioned specimens to the peak strength of at least five unconditioned specimens. In most test cases, six specimens were sampled. ANOVA analysis was again employed to figure out which variables provided the most explanation for the variance between specimens. Using a 95% confidence level, linear regression was performed on the TSR values of the specimens tested. The possible explanatory variables were the type of WMA additive, relative amount of additive and mixing temperature. The result of this ANOVA analysis yielded two significant explanatory variables:

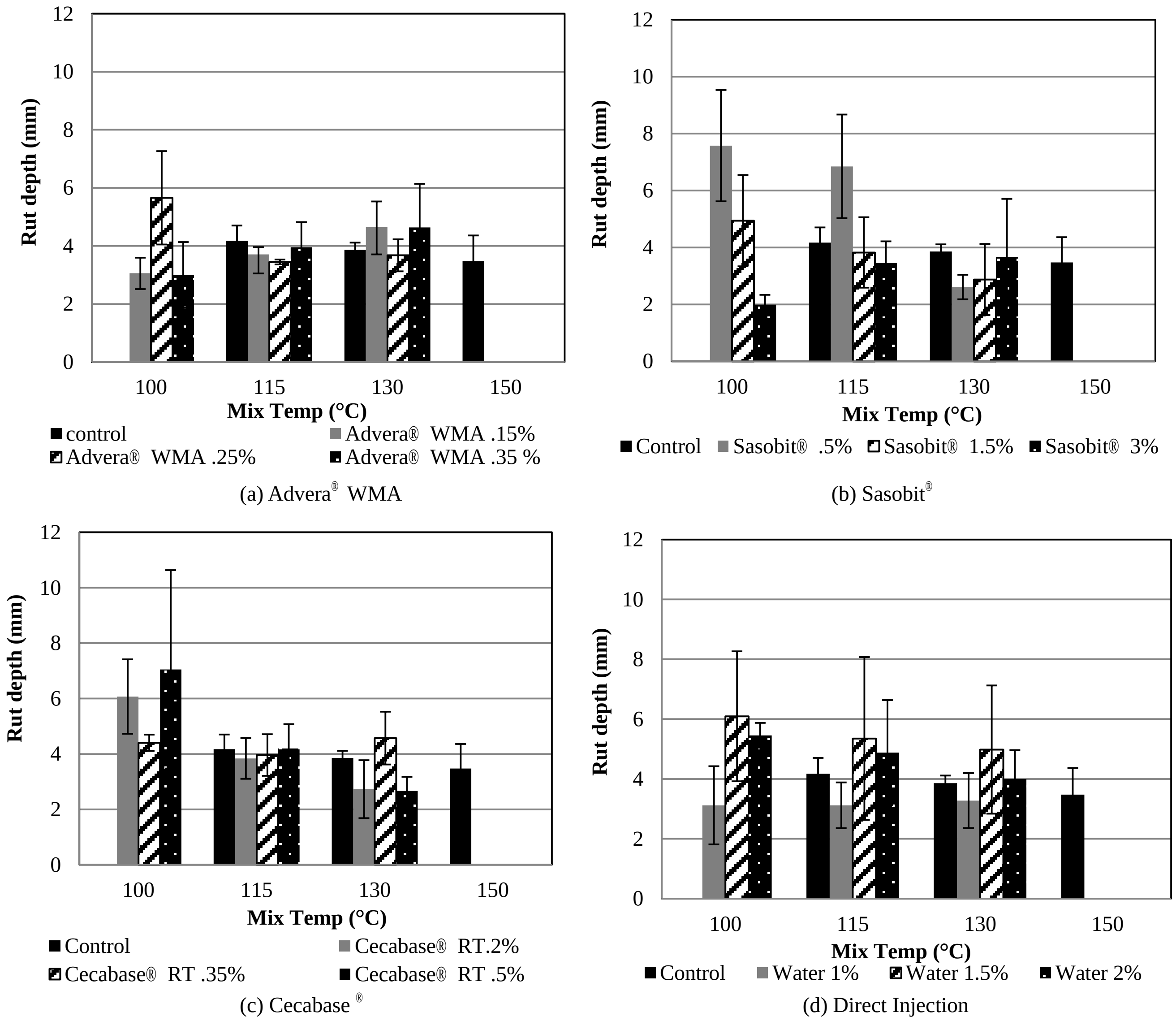


Fig. 3. Rutting Results after 8000 Cycles for (a) Advera ® WMA (b) Sasobit® (c) Cecabase® RT and (d) Direct Injection.

Table 4. Expected Rutting from Regression.

Mixing Temp (℃)	Expected Rutting (mm)	% Increase
150	3.042	-
130	3.642	19.73
115	4.092	34.53
100	4.542	49.33

mixture temperature and the additive type as a factor. Shown below in Eq. (4) is the resulting prediction equation for TSR.

$$\mathrm{TSR} = 0.381 + 0.0037 * \text{Mixing Temperature}(°\mathrm{C}) + 0.0482(\text{Advera®WMA}) + 0.1167(\text{Cecabase R.T.}) + 0.1195(\text{Sasobit®}) + 0.1864(\text{Direct Injection}) \tag{4}$$

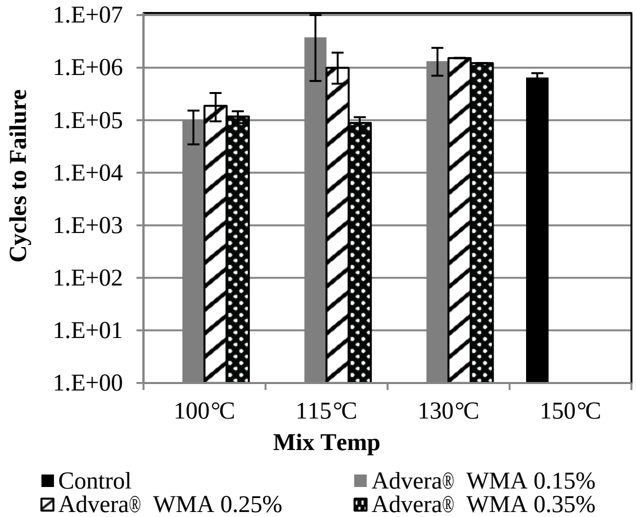
The linear regression shows that every WMA additive tested increased the expected TSR of the specimens. The regression also shows increasing the mixing temperature increases the TSR, which in turn decreases the moisture susceptibility of the specimens.

Result Analysis and Discussion

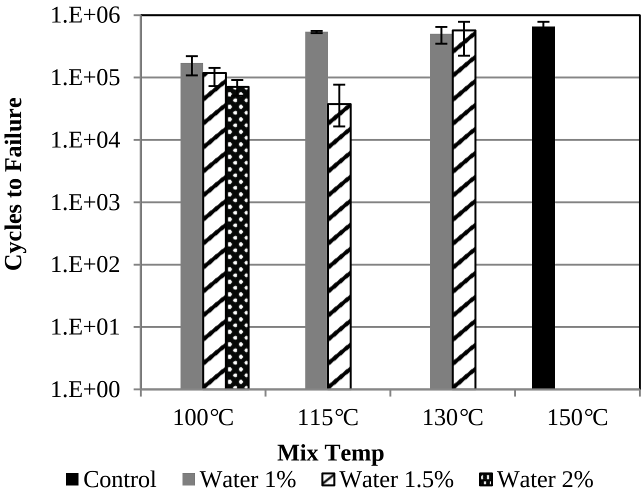
Looking only at the relevant regression terms for the three types of testing conducted, the expected changes in performance for each type of test can be calculated. Since the rutting test was only dependent on mixing temperature, Table 4 lists the expected changes in rutting when mixing temperature is varied. Since the regression model predicted an increase in rutting with a decrease in temperature, every sample of WMA is expected to produce an inferior sample to the control, mixed at 150℃.

Since all of the explanatory variables for fatigue life were statistically significant, each testing variable produced a unique expected fatigue life. Table 5 shows all of the expected fatigue lives for the tests conducted. The combinations that result in an improved fatigue life are highlighted.

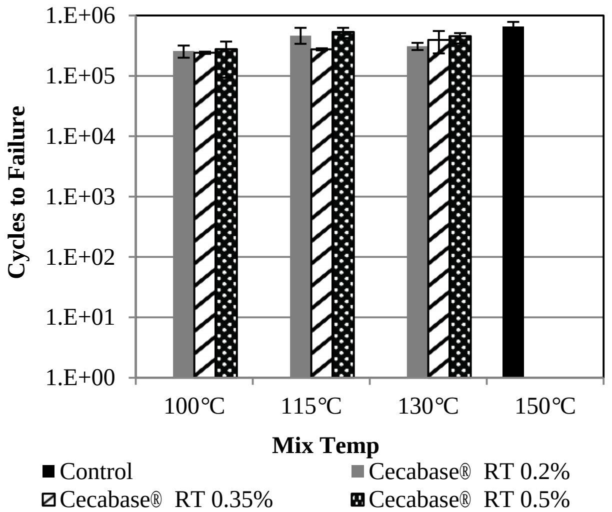
When comparing expected outcomes for TSR, the significant variables were the type of additive used and the mixing temperature. Table 6 shows the expected TSR values obtained from linear



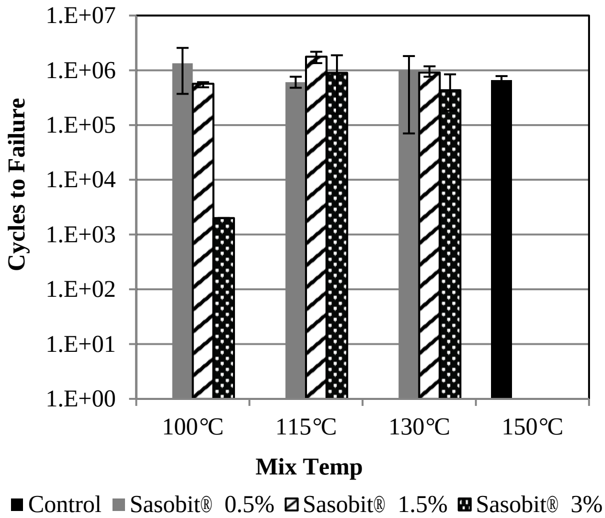
(a) Advera® WMA



(b) Direct Injection



(c)Cecabase® R.T.



(d) Sasobit®

Fig. 4. Beam Fatigue Test Fatigue Life Results for (c) Cecabase® RT and (d) Sasobit®.

regression. The improved TSR values are highlighted for ease of comparison.

The overall costs of the pavements options were compared to the control HMA pavement using the percent reduction in total cost from the control. Despite unique costs for every combination of WMA technology, percent of additive, and mixing temperature, the controlling factor was found to be the reduction in mixing temperature. Fig. 5 shows a scatter plot of the variables to visualize this trend.

With the goal of relating performance and cost of WMA technologies, the results of importance are considered to be cases where there is equal performance or better when compared to the control. The percent difference in performance between the WMA options and the control at 150℃ was calculated for the three sets of tests conducted. The percent difference in cost reduction was then used to compare with the increase in performance obtained from the laboratory testing.

When looking at the regression equation for rutting, there was no improvement on the expected rutting when using WMA; however, there is a cost savings that can be realized. Fig. 6 shows the averaged cost reductions at the different mixing temperatures graphed against the expected decrease in rutting performance.

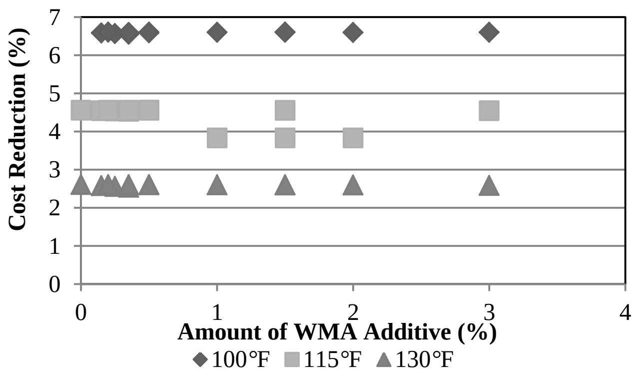


Fig. 5. Cost Reductions for WMA.

Table 5. Expected Fatigue Life from Regression.

Additive	Mix Temp	Additive Amt.	Expected Fatigue Life (Cycles)	% Improvement
Control	150	0	639,913	-
Advera® WMA	100	0.15	311,051	-51
Advera® WMA	115	0.15	604,216	-6
Advera® WMA	130	0.15	1,173,686	83
Advera® WMA	100	0.25	254,961	-60
Advera® WMA	115	0.25	495,230	-23
Advera® WMA	130	0.25	962,040	50
Advera® WMA	100	0.35	124,649	-81
Advera® WMA	115	0.35	242,130	-62
Advera® WMA	130	0.35	470,336	-27
Direct Injection	100	1	122,376	-81
Direct Injection	115	1	237,716	-63
Direct Injection	130	1	461,762	-28
Direct Injection	100	1.5	100,309	-84
Direct Injection	115	1.5	194,849	-70
Direct Injection	130	1.5	378,494	-41
Direct Injection	100	2	49,040	-92
Cecabase®	100	0.2	251,516	-61
Cecabase®	115	0.2	488,568	-24
Cecabase®	130	0.2	949,041	48
Cecabase®	100	0.35	206,161	-68
Cecabase®	115	0.35	400,466	-37
Cecabase®	130	0.35	777,904	22
Cecabase®	100	0.5	100,791	-84
Cecabase®	115	0.5	195,785	-69
Cecabase®	130	0.5	380,313	-41
Sasobit®	100	0.5	307,879	-52
Sasobit®	115	0.5	598,053	-6
Sasobit®	130	0.5	1,161,716	82
Sasobit®	100	1.5	252,360	-61
Sasobit®	115	1.5	490,209	-23
Sasobit®	130	1.5	952,228	49
Sasobit®	100	3	123,378	-81
Sasobit®	115	3	239,660	-63
Sasobit®	130	3	465,539	-27

Table 6. Expected TSR from Regression.

Additive	Mix Temp (℃)	Expected TSR	% Improvement
Control	150	0.943	-
Advera® WMA	100	0.804	-15
	115	0.860	-9
	130	0.916	-3
Direct Injection	100	0.942	<-1
	115	0.998	6
	130	1.054	12
Cecabase®	100	0.872	-7
	115	0.928	-2
	130	0.984	4
Sasobit®	100	0.875	-7
	115	0.931	-1
	130	0.987	5

Fatigue testing was statistically dependent on all of the variables tested; however, only six combinations produced a favorable improvement in fatigue life. All of the combinations with favorable fatigue life were mixed at 130℃. Only the cases with low and medium amounts of additive improved fatigue life. Fig. 7 shows the summary of the combinations that led to an increase in fatigue life compared to the control specimens. The outlined markers are the medium dosage of additive, while the solid markers show low dosages of additive.

The last set of testing examined TSR results. Since TSR was found to be statistically dependent on the WMA additive used and the mixing temperature, Fig. 8 shows all four experimental combinations that resulted in an increase in TSR. Three out of the four additives tested at 130℃ improved the moisture susceptibility of the specimens tested. Direct Injection provided the greatest improvement to moisture susceptibility, since it was the only additive to improve TSR at 115℃.

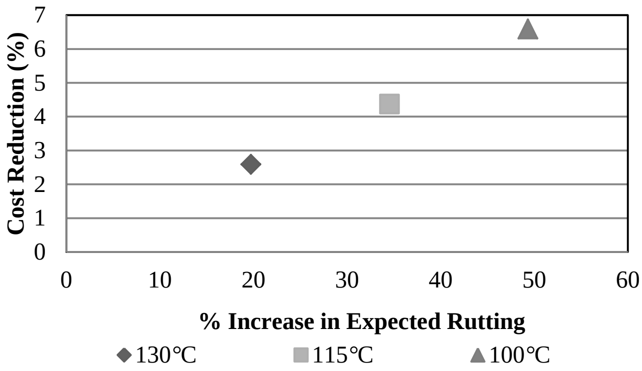


Fig. 1. Cost Reduction and Rutting Performance Comparison.

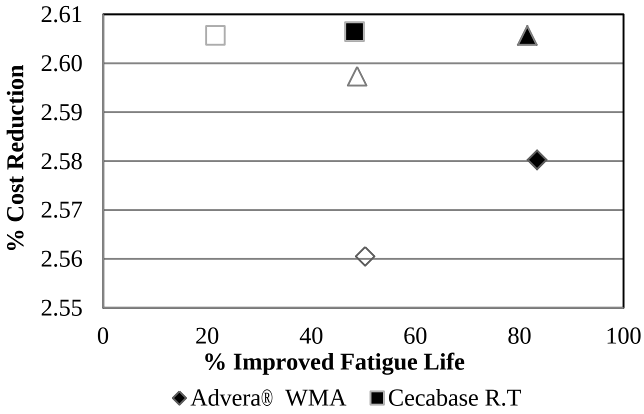


Fig. 7. Cost Reduction and Fatigue Life Comparison.

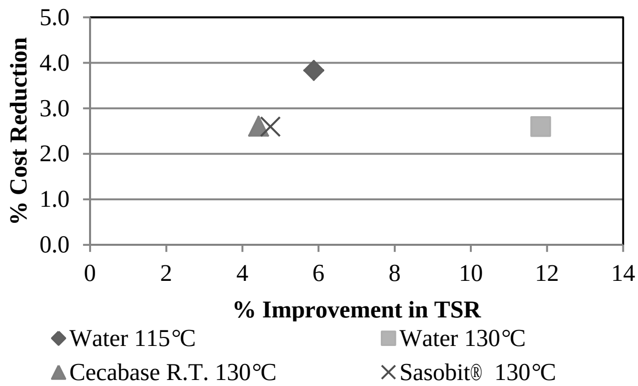


Fig. 2. Cost Reduction and TSR Comparison.

Conclusions

Based upon the APA rutting performance, beam flexure test, and TSR test of various WMA mixtures used in conjunction with a cost analysis the following conclusions were made:

1. When used in conjunction with WMA, a reduction in mixing temperature led to an increase in rutting potential. This was statistically independent of the type or amount of WMA used in the mixture.
2. In terms of fatigue life, on average, higher mixing temperatures let to an increase in fatigue life. Low and moderate amounts of WMA additive were shown to increase fatigue life, while high dosages negatively impacted the expected fatigue life of the laboratory specimens. The water foaming WMA additive was the least effective at improving the fatigue life of the specimens, while Sasobit® and Advera® WMA were the most effective.
3. Increasing the mixing temperature increased the expected TSR of the specimen. The specimens mixed with Advera® had the poorest performance, while the water foaming technology had the best resistance to moisture susceptibility.
4. Based on the cost evaluation, the reduction in mixing temperature has a direct relationship with the reduction in production costs. Using lower dosages of WMA additives was also shown to reduce costs.
5. Every WMA pavement technology tested has the potential to reduce cost and improve the expected performance of laboratory compacted specimens by at least one measure of performance.

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