

NCAT Report 05-05

REFINEMENT OF THE HOT MIX ASPHALT IGNITION METHOD FOR HIGH LOSS AGGREGATES

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Sponsored by

Alabama Department of Transportation

NCAT Report 05-05

June 2005

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ABSTRACT

This study evaluated four methodologies for determining the asphalt content of mixtures containing high loss aggregates in the ignition furnace. The methodologies tested were the standard method using the Thermolyne furnace (control), the Troxler NTO Infrared furnace, the Ontario Method using the Thermolyne furnace and a Tempyrox glass cleaning oven.

Six aggregate sources with high ignition furnace aggregate correction factors were obtained from around the country: four dolomites, a basalt, and a serpentinite/chlorite. Calibration factors were determined for each method at optimum asphalt content. Additional samples were then tested at optimum plus 0.5 percent asphalt content and the measured asphalt content calculated using the correction factor determined for that method/aggregate source.

The Tempyrox Pyro-Clean oven, commonly used for cleaning laboratory glassware, produced the lowest aggregate correction factors. The correction factors are consistent with results from thermogravimetric analysis. The standard method and the Ontario method, both using the Thermolyne ignition furnace produced the smallest bias or error in measured asphalt content. The standard deviation of the corrected asphalt contents for these high loss sources was higher than the within-lab standard deviation reported for AASHTO T308. The only exception was the Alabama source using the standard method. The Ontario Method and Tempyrox Oven generally reduced the variability of asphalt content measurements for high loss aggregates.

None of the methods evaluated statistically reduced aggregate breakdown on the NMAS and 4.75 mm sieves. The Ontario method significantly reduced, but did not eliminate aggregate breakdown on the 0.075 mm sieve. A gradation correction factor, developed from the same samples used to determine the correction factor for asphalt content, greatly reduced the measured biases, in most cases to less than 1 percent.

The Ontario method is recommended for immediate implementation for determining the asphalt content by the ignition method for high loss aggregates. The method consists of using an altered end point of less than 1 gram change over three consecutive minutes and using the highest test temperature of 538, 480 or 450°C (1,100, 896, or 842°F) that produces a correction factor less than 1 percent. The current AASHTO procedure specifies a 0.01 percent change over three consecutive minutes at either 538 or 482° (1100 or 900 °F).

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INTRODUCTION

The asphalt content of hot-mix asphalt (HMA) mixtures is critical to their performance, affecting the pavement's tendency for permanent deformation, fatigue life, and susceptibility to moisture damage. Historically, the asphalt content of HMA samples was obtained using solvent extraction. However, due to environmental and technician health and safety concerns, alternative methods to determine asphalt content were investigated in the 1990s.

The asphalt ignition test was developed at the National Center for Asphalt Technology (NCAT) for determining the asphalt content (P_b) in HMA mixtures (1,2). Asphalt content is calculated as the ratio of the difference between the initial mass of the HMA and the mass of the residual aggregate (after ignition) to the initial mass of the sample expressed as a percentage. The ignition test provides a clean aggregate sample, which can be used for gradation analysis.

A correction factor is applied to the asphalt content determined from the difference between the initial mass of the sample and the mass of the residual aggregate. This correction factor accounts for changes in the mass of the aggregate which occur as a result of the ignition process. Generally the correction factors are negative, indicating a loss of aggregate mass during ignition, however, in some cases, particularly when hydrated lime is used the correction factor may be positive indicating an increase in mass of the aggregate. Correction factors larger than 1.0 percent can be cause for concern. Some agencies routinely use the ignition furnace with correction factors larger than 1.0 percent and still obtain accurate repeatable results. The correction factor is obtained by burning laboratory prepared samples of known asphalt content.

The presence of dolomitic aggregates or high loss material in general, has shown to result in higher measured asphalt contents due to excessive aggregate weight loss during the ignition test. The ignition furnace cannot distinguish between the binder being removed from the sample and the aggregate weight loss, thus resulting in a higher measured asphalt content. This may cause the contractor to be out of the allowable range on the high side, which could lead to the possible removal of HMA that may well be within specification.

Several states have experienced the excessive aggregate weight loss when dealing with dolomitic or other high loss aggregates. Limited research has been conducted by states using these aggregate types to resolve this problem. Illinois Department of Transportation identified a few carbonate sources in the northwestern part of the state for which a consistent correction factor could not be determined. Thermogravimetric Analysis (TGA) was conducted to compare the temperature/burn-off characteristics of these carbonate aggregates versus others that performed acceptably. TGA indicated that for the problematic aggregates, $MgCO_3$ compounds began to burn off at 400°C and did not cease until about 820°C (3).

Iowa Department of Transportation (DOT) experienced problems with dolomites from the upper Mississippi River Valley. Iowa DOT routinely performs TGA as a tool for characterizing the potential for aggregates to cause D-cracking in Portland cement concrete. Unusual TGA loss curves were observed for the problematic ignition furnace aggregates that contained high chemically bound chloride contents. Iowa DOT modified their TGA to use a nitrogen atmosphere and found a high correlation between the rate of weight loss and temperature. Iowa DOT also observed that given sufficient time, the decomposition would continue until all of the dolomite was consumed. Therefore, they determined that problems with ignition furnace asphalt contents could be controlled by controlling temperature and burn time (4).

Ontario Ministry of Transportation has conducted significant investigations into aggregate weight loss in the ignition furnace, including the development of a modified test method. Recently, the Ontario Ministry of Transportation conducted a study on the decomposition of quartz rich aggregates. Quartz transforms from low to high (beta) quartz when heated above approximately 573°C. The conversion causes an expansion of the aggregate. This expansion is believed to be related to increased aggregate breakdown as measured by gradation, LA Abrasion and Micro Deval tests. Aggregate reverts to low quartz when the temperature cools below 573°C. Ontario Ministry of Transportation modified their ignition furnace to include an infrared thermometer to measure flame temperatures during ignition. Temperatures were consistently measured above 600°C but did not exceed 750°C (5).

OBJECTIVE

The main objective of this study is to refine the current ignition method so that it can also be used effectively for hot mix asphalt mixtures containing some dolomitic or high loss aggregates which tend to lose mass excessively during the ignition test. A secondary objective is to compare the degradation of aggregate produced for each test alternative used in this study.

MATERIALS

Six production mix designs were used in this study. Four of the mix designs contained dolomitic aggregates, while the other two mix designs contained other high loss aggregates (a basalt aggregate and a serpentinite/chlorite aggregate). The mix designs were selected to represent the different types of high loss aggregates used in hot mix asphalt throughout the United States. Three nominal maximum aggregate sizes, NMA, (9.5, 12.5 and 19.0 mm) were used in this study. One 9.5 mm NMA, two 12.5 mm NMA mixes, and three 19.0 mm NMA mixes made up the six total mix designs used. The design gradations and optimum asphalt contents are shown in Table 1. Aggregate from each source was fractionated into individual sieve sizes then recombined to meet the gradations in Table 1.

The optimum asphalt content was verified for each mix design by compacting samples to the design compactive effort specified for that particular mix design in the Superpave gyratory compactor. A single, unmodified PG 64-22 binder was used for all testing except for the Arizona mix design, in which a PG 64-28 binder supplied by the agency was used.

Table 1. Design Gradations and Optimum Asphalt Contents

Sieve Size, mm	Alabama (Dolomite)	Indiana (Dolomite)	Missouri (Dolomite)	Wisconsin (Dolomite)	Maryland (Serpentine/ Chlorite)	Arizona (Basalt)
25.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	95.1	100.0	100.0	97.1	100.0	100.0
12.5	80.7	100.0	98.3	84.1	98.8	84.0
9.5	69.3	94.8	89.8	72.2	88.3	75.3
4.75	44.5	57.4	54.1	52.0	43.5	58.3
2.36	27.7	35.8	38.0	34.5	25.5	42.9
1.18	17.1	28.0	25.6	21.7	19.1	29.7
0.60	12.0	20.0	17.7	13.1	16.0	19.3
0.30	9.2	10.0	10.5	6.7	12.9	10.4
0.15	7.6	5.6	6.1	4.4	5.3	6.0
0.075	3.9	4.4	3.3	3.7	4.2	4.2
Optimum AC% ¹	4.5	5.6	5.3	4.6	5.0	4.7

¹Asphalt contents are reported as percent by weight of total mix in Table 1 and throughout the paper.

TESTING EQUIPMENT

Along with using the standard ignition furnace (from Barnstead International), three alternative methods were evaluated and compared to the standard ignition furnace. These included: the Troxler NTO Infrared furnace, the Ontario Method using the Thermolyne furnace, and the Tempyrox Pyro-Clean oven used for cleaning glassware and metals. Each of the four methods is described below.

Thermolyne Ignition Furnace

In a conventional ignition furnace, the furnace chamber is heated using a radiant heat source consisting of an electric heating element encased in a refractory ceramic material (6). These elements typically make up the walls of the ignition furnace. The heating elements heat the air in the furnace chamber, which in-turn heats the sample. This is known as convection heating. The asphalt binder ignites when the sample reaches a temperature of approximately 480°C. In order to maintain ignition, a blower pulls air into the sample chamber. The exhaust gases pass out of the main chamber into a secondary chamber, generally at a higher temperature (750°C), where additional oxidation occurs. This helps to reduce volatiles in the exhaust stream as required by AASHTO T308 and ASTM D6307.

The standard ignition furnace uses an internal balance to measure the mass loss during ignition. The standard ignition furnace meets the requirements for AASHTO T308 Method A and ASTM D6307 Method A.

Troxler NTO Infrared Furnace

The Troxler Model 4730 ignition furnace uses an infrared heating element to heat the sample. Infrared light (or radiation) is found between the visible light and microwave portions of the

electromagnetic spectrum (7). Infrared heat is used in numerous other industries such as food preparation. Unlike convection heating, where the air in the sample chamber must first be heated, infrared heating uses electromagnetic energy waves to excite the molecules in the sample producing heat (8). The sample then heats the furnace chamber by conduction/convection. The Troxler Model 4730 furnace does not incorporate an after-burner system. However, Troxler reports reduced emissions compared to the standard furnace. The Troxler furnace has three burn profiles: option 1, option 2, and a default profile. The default profile is recommended for the most common HMA mix types. Option 2 profile is a more “aggressive” burn profile and is suggested for higher asphalt content mixes, such as stone matrix asphalt, produced with aggregates that do not readily degrade during ignition. Option 1 is a less aggressive burn profile and is suggested for mix types produced with high loss aggregates, such as dolomite. Troxler does not define what parameter(s) (air flow or temperature) is changed by the setting. For this study, Option 1 burn profile was used for all samples tested in the Troxler infrared furnace.

The Troxler NTO infrared furnace uses an internal balance to measure the mass loss during ignition. The Troxler NTO infrared furnace meets the requirements for AASHTO T308 Method A and ASTM D6307 Method A.

Ontario Method

The Ontario Method uses the standard ignition furnace. However, the end point is altered. AASHTO T308 (Method A) specifies the end point as the point when the sample mass does not change by more than 0.01 percent for three consecutive minutes. With high loss aggregates, the degradation of the aggregate can exceed this amount even after all of the binder is removed. The Ontario Ministry of Transportation Test Method LS-292 specifies that the sample has reached the end point when the sample mass changes less than 1 gram for three consecutive minutes. This converts to a percentage loss of 0.07 percent for a 1500 gram sample and 0.05 percent for a 2000 gram sample. Further, the calibration samples are burned at 540, 480, and 450°C. The highest temperature which results in a correction factor less than 1.0 percent is selected.

Tempyrox Pyro-Clean

The Tempyrox Pyro-Clean was developed to clean precision laboratory glassware such as viscometers. Careful control of the temperature in the furnace is important to prevent distortion of the glassware. Rogers et al reported aggregate surface temperatures in excess of 600°C but not exceeding 750°C for the standard ignition furnace using a set point of 540°C (5). The temperatures in excess of the set point are due to the combustion of the asphalt in the standard ignition furnace. It was thought that the Pyro-Clean system could be used to more precisely control the maximum furnace temperature for high loss aggregates.

The Pyro-Clean system functions on the basis of *pyrolysis oxidation*. This process allows for the volatile organics to be removed from a material in an oxygen deprived atmosphere to the point at which there is nothing remaining except carbon ash. Room air is then pumped into the cleaning chamber to release the carbon ash. What remains is free of any and all organics. Smoke and hydrocarbons produced during this procedure are destroyed inside a high temperature *oxidation chamber* located on top of the cleaning chamber.

A sample of material is placed in the chamber of the Pyro-Clean. The chamber door has a double gasket system to insure that no outside air is allowed to leak into the chamber during the cleaning cycle. Once the process is started, the heating elements inside the *oxidation chamber* turn on to achieve the set temperature of 732°C. The cleaning chamber temperature can be set for any temperature between 370 and 510°C. There are two separate temperature controllers on the system. One controller regulates the temperature of the oxidation chamber; the other regulates the temperature inside the chamber. When the temperature of the oxidation chamber has reached a specific level, the elements inside the cleaning chamber are energized and begin heating.

The draft inducer blower also turns on when the cycle is started. This blower draws air horizontally through the oxidation chamber. This horizontal air-flow passes over the opening of a tube that is the output of the cleaning chamber. This air-flow creates a “*venturi-effect*,” which produces a slightly negative pressure inside the cleaning chamber.

The cleaning chamber contains two stainless steel shelves for holding glassware. The upper steel shelf was removed so that a complete basket from the Thermolyne furnace could be used. A bottom tray inside the chamber contains a catalyst. When the temperature inside the chamber reaches a level that begins to drive off volatile organics in the form of smoke or hydrocarbons, the catalyst will begin to react with the smoke and hydrocarbons and reduce the oxygen level inside the chamber to around 15 percent or less. This prevents ignition from occurring. With the absence of ignition, it is capable to control the temperature of the cleaning process to near exact values. Smoke being generated during the pyrolysis stage enters the oxidation chamber where it is subjected to a temperature of 732°C and another catalyst for near 100 percent destruction.

When the oxidation chamber detects the absence of smoke coming from the cleaning chamber, an air pump located inside the control panel pumps room air into the cleaning chamber. The introduction of air into the cleaning chamber releases the carbon ash remaining on the glassware or in this case test sample and it passes through the oxidation chamber where the high temperatures reduce it to carbon dioxide (CO₂) and water. When the air pump is turned on an internal timer is started and the process continues for a preset time period and then the cycle ends (9).

Testing with the Tempyrox oven generally followed the procedures described in AASHTO T308 Method B or ASTM D6306 Method B. The samples were initially weighed on an external balance. Testing was conducted with a set point of 482°C. After the Tempyrox oven completed its cycle, the samples were removed from the chamber and allowed to cool to room temperature. The samples were then weighed again on the same external balance. Normally in Method B, after the second weighing the sample would be returned to the furnace and burned for at least an additional 15 minutes once the furnace reaches its set point temperature (which will drop when the chamber door is opened to load the samples). After 15 minutes, the sample would be removed from the furnace, allowed to cool and reweighed. This cycle would be repeated until a constant mass (within 0.01 percent) was achieved. With the Tempyrox oven, the removal of the asphalt is in effect monitored by the smoke coming off the samples during the pyrolysis stage, after which air is introduced into the chamber to remove the carbon ash as described above. Therefore, multiple weighing cycles to constant mass were not used.

RESEARCH APPROACH

For each of the six sources, the aggregate (and asphalt for the AZ source) was shipped to NCAT's central lab. Each of the aggregates was oven dried and fractionated into individual sieve sizes, then recombined to achieve the design gradation. Each mix design was then verified using a one-point verification. This was performed by preparing three samples at the optimum asphalt content and compacting them to the design gradation level on a Superpave gyratory compactor. The bulk specific gravity was determined on the three gyratory samples to determine the sample density. Two additional samples were made so a maximum theoretical density could be determined.

To simulate the field mixing process, for the Arizona source, lime was added in a slurry form. The slurry consisted of 2 percent water and 0.3 percent hydrated lime by total weight of mix that was added to the samples during the mixing process.

Before the samples were burned in the various ignition furnaces, all testing samples were made to reduce any variability in the batching and mixing processes. A total of 60 test samples were made for each source, 39 at optimum asphalt content and 21 at optimum plus 0.5 percent asphalt. Additional samples were batched using the same process to determine washed gradations. Testing was conducted according to a split-plot design. The samples from each aggregate source were first randomly assigned to an furnace/method (e.g. Standard, Ontario, etc.). Then the testing order of all of the samples at a given asphalt content were randomized for a given furnace/method. The calibration samples at optimum asphalt content were tested first for each furnace/method. Once the appropriate calibration factors were determined, the optimum plus 0.5 percent asphalt samples were tested as the "test" samples for evaluation of bias and variability.

The correction factors for the standard furnace and for the Troxler furnace were determined first. This allowed for faster testing, since two samples could be tested at the same time. After the test samples were burned, a washed gradation was performed to determine the gradation of the sample.

Once all the test samples were tested in the standard and Troxler furnaces, the Ontario method was performed using the Thermolyne ignition furnace. The temperature was left at 538°C and the end point was increased to 0.05 percent mass loss for three consecutive minutes. Correction factors were then determined for the six sources. After the correction factors were determined, the sources that had correction factors greater than 1.0 percent were tested again at 480°C. These sources included all except for the Alabama source. When the correction factors were determined for the sources tested at 480°C, the Indiana, Arizona, and Missouri sources still had correction factors greater than 1.0 percent. So these sources were tested at 450°C, where they were found to have correction factors less than 1.0 percent, except for the Arizona source. The Arizona source was not tested at a lower temperature for this study.

The Tempyrox oven was the last method tested. The correction factors were determined for all six sources. Once the correction factors were calculated, the test samples prepared with optimum plus 0.5 percent asphalt were tested. The mass of each test sample was 2000 grams, but it was found that this sample size was too large to run in the Tempyrox oven. So each individual sample

was reduced into two 1000 gram samples. This meant only 1.5 test samples (three 1000 gram samples) could be tested per day. The result reported is the average of the two samples. Washed gradations were performed on the combined extracted aggregate to determine the gradation of the samples after being tested in the Tempyx.

Once all testing was completed, statistical analyses were conducted on the results to see if a difference could be found between the alternative test methods compared to the standard ignition method. These analyses are described in the following section.

RESULTS AND DISCUSSION

Correction Factors

The correction factors, determined at optimum asphalt content, for all six sources from the four different ignition methods are summarized in Table 2 and shown in Figure 1. The complete results are provided in the Appendix, Table A-1. The Tempyx oven produced the smallest correction factors in all cases. It is expected that the lower correction factors observed for the Tempyx oven occur because the oxygen deprived environment prevents flames and therefore carefully controls the ignition temperature. The Thermolyne ignition furnace using the standard ignition method produced the highest correction factors. Both the Troxler furnace and the Ontario method showed reduced correction factors as compared to the standard test procedure.

Table 2. Correction Factors by Method

Source	Ignition Method				
	NCAT	Troxler	Ontario Factor, %	Tempyx Temperature, C	
AL	0.74	0.19	0.46	540	0.14
IN	2.65	1.25	0.85	450	0.59
AZ	2.53	1.82	1.89	450	1.38
MO	3.26	1.10	0.78	450	0.32
WI	1.62	0.48	0.75	480	0.08
MD	1.62	0.76	0.69	480	0.42

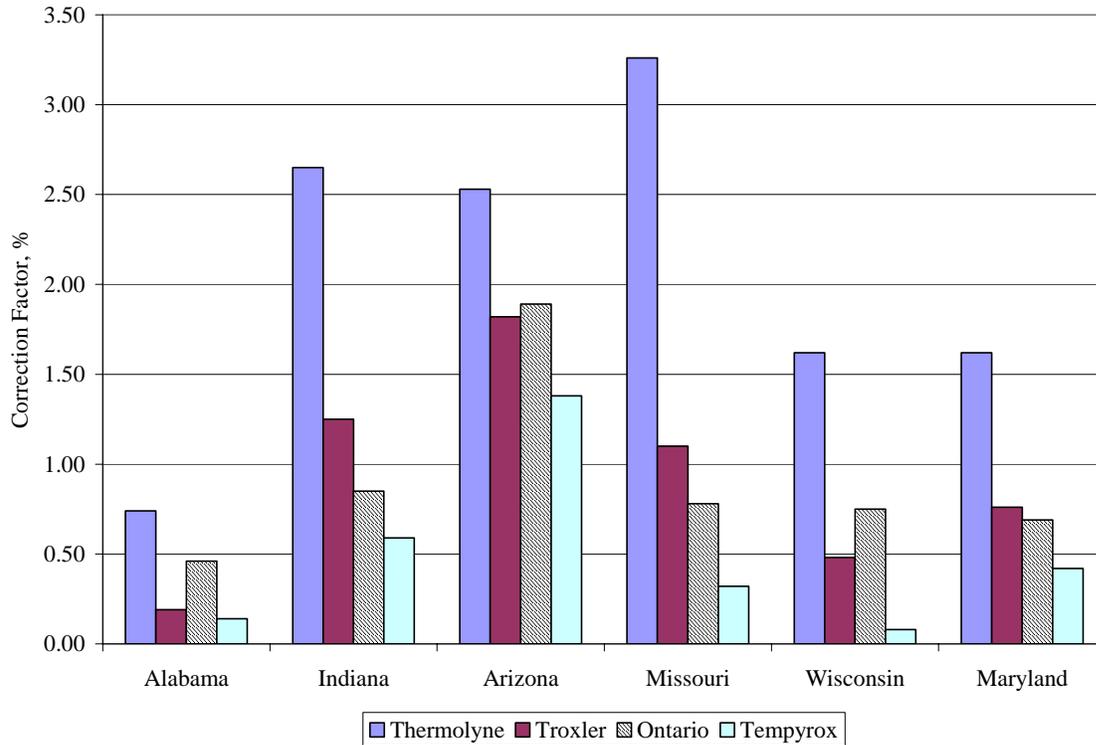


Figure 1. Comparison of Furnace Correction Factors by Method

Accuracy and Variability of Measured Asphalt Contents

The correction factors for aggregate loss, determined at optimum asphalt contents, were then applied to the optimum plus 0.5 percent asphalt samples to evaluate the accuracy and variability (repeatability) of the measured asphalt contents for the four methods. Samples from each source were prepared at optimum plus 0.5 percent asphalt. Then they were burned using each of the four test methods. The aggregate correction factors determined at the optimum asphalt content for each of the test methods were used in the determination of the measured asphalt content for the optimum plus 0.5 percent asphalt samples.

When evaluating a new test method, both the accuracy and the variability must be considered. The accuracy of the asphalt contents is measured by the bias, or the difference between the measured and known asphalt content of the sample. The variability is measured by the standard deviation (square-root of variance) of the test results. A summary of the bias for the four test methods are shown in Figure 2. The complete results are shown in the Appendix, Table A-2.

Based on observation of Figure 2, the Troxler infrared furnace produced the highest error, or bias, and the Thermolyne furnace, using either the standard test method or the Ontario Method, produced the least error. Previous research indicated that the Troxler infrared furnace produced similar bias as compared to the Thermolyne ignition furnace using the default burn profile (10).

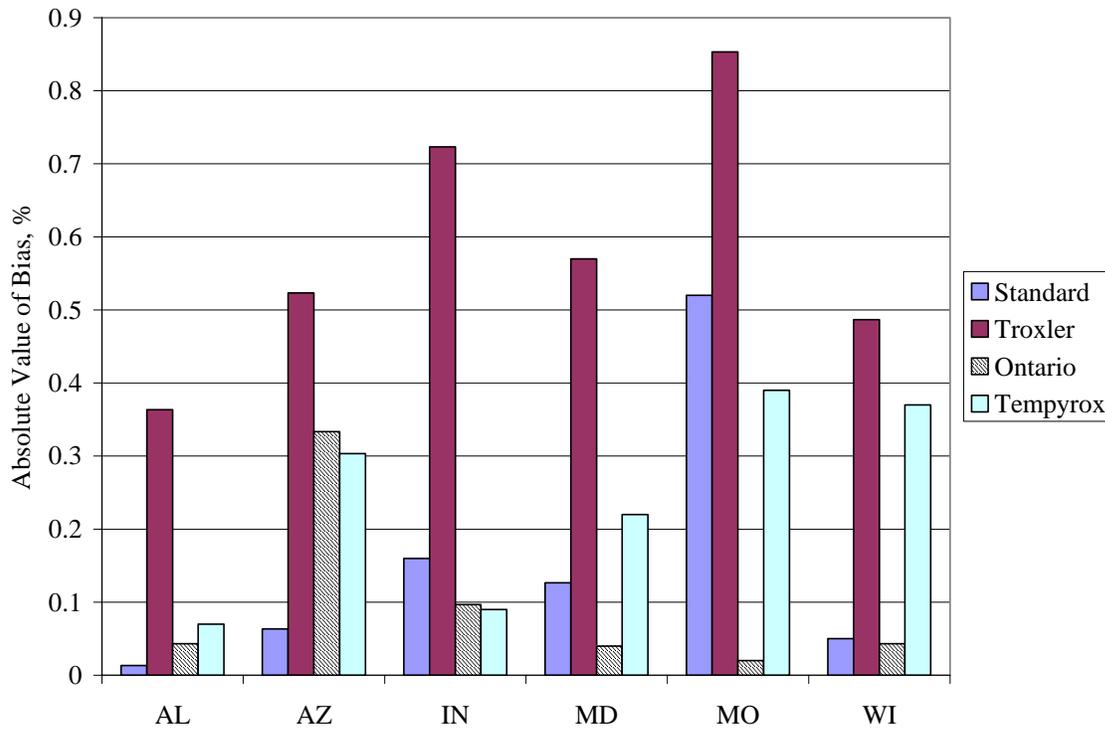


Figure 2. Summary of Bias for Correction Factors

Prowell (11) suggested a slight trend of increasing calibration factors for increasing asphalt content with the Thermolyne ignition furnace. This phenomenon may be amplified for mixes with high correction factors and may help explain the large bias observed with some method/source combinations. Initially, Virginia Department of Transportation performed ignition furnace calibrations by testing two samples at optimum asphalt content and two samples each at optimum ± 0.5 percent asphalt content. This was done to examine the effect of asphalt content on correction factor. During the development of the AASHTO test procedure, this practice was dropped in favor of testing just two samples at optimum asphalt content. However, few, if any, high loss aggregate had been tested at this point.

In an effort to understand why the increased bias at higher asphalt contents may occur, the average maximum observed furnace temperature was calculated for each method. All three furnaces have thermocouples mounted on the back wall of the furnace chamber. The results are shown in Figures 3 and 4, respectively for temperature and test time. Figure 3 indicates that for the Ontario and Troxler methods the maximum observed furnace temperature was higher for the optimum plus 0.5 percent samples. The average temperature for the optimum plus 0.5 percent samples tested in the Troxler furnace was 38°C (68°F) higher than for the samples tested at optimum asphalt content. This corresponds to the positive (larger measured) bias observed for the Troxler Optimum plus 0.5 percent samples, most likely due to additional aggregate loss resulting from the higher temperature. It should be noted that the maximum temperatures were measured by a thermocouple in the furnace chamber and do not necessarily represent the surface temperature of the aggregate.

The error was also somewhat higher for the measurements made using the Tempyx oven. The Tempyx furnace does not record the chamber temperature during the test. The temperature shown on the Y-axis in Figure 3 is the set point for the furnace. Since combustion is suppressed, the chamber temperature should be close to the set point. The increased bias may be due to the fact that the asphalt content was determined using method “B,” where the asphalt content is determined from measurements (both before and after) taken on an external scale.

The chamber set point is reduced for the Ontario method, to produce a calibration factor less than 1.0 percent. The maximum observed chamber temperature at the set points of 480 and 450°C were 574 and 551°C, respectively. Figure 3 indicates that using lower temperatures with the Ontario method does reduce the maximum observed temperature as compared to the Standard Method at 538°C. The Troxler infrared furnace using the Option 1 heating profile produces the lowest chamber temperatures with an average reduction of 110°C as compared to the Thermolyne furnace.

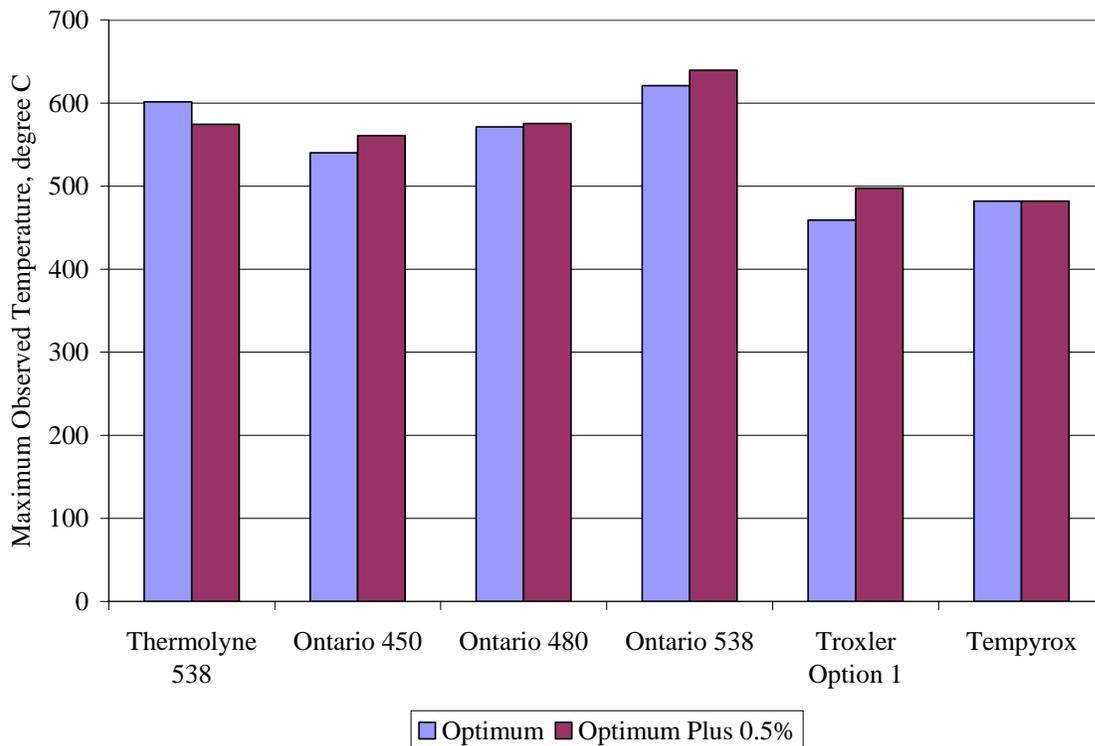


Figure 3. Average Maximum Chamber Temperature by Method

No real differences were observed in the average test times between the optimum and optimum plus 0.5 percent samples (Figure 4). The average differences between the test times for the optimum plus 0.5 percent and optimum asphalt contents for each method ranged from four minutes shorter to seven minutes longer. The cycle time for the Tempyx oven was fixed at 120 minutes. As noted previously, Iowa DOT (4) suggests that aggregate degradation in the furnace is related to both temperature and time. It might be expected that the Ontario method utilizing a lower test temperature would produce a longer test time. However, Figure 4 indicates that the test times for the Ontario Method were shorter than those for the Standard Method. The shorter

test time results from the altered end point for the Ontario Method. The end point for the Ontario Method is defined as a change of less than 1.0 gram over three consecutive minutes. For a 2000 gram sample (used in this study) this equates to a 0.05 percent change as compared to the 0.01 percent change used with the Standard Method. It should be noted that AASHTO T308 allows the end point to be altered to a 0.02 percent change for high loss aggregates (12). The Troxler infrared furnace produced the shortest test times, averaging 37 minutes faster than the Standard Method. The Ontario method averaged 20 and 13 minutes faster than the Standard Method, respectively at 480 and 450°C.

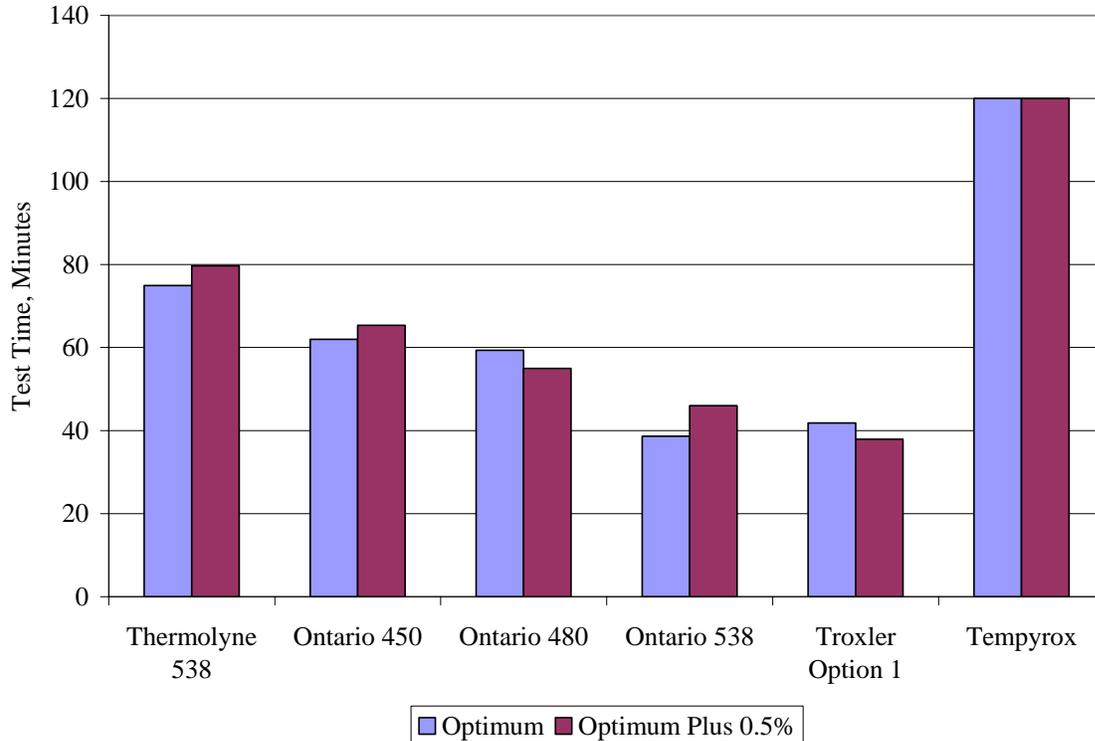


Figure 4. Average Test Time by Method

The within-laboratory standard deviation for the determination of asphalt content by the ignition furnace is reported to be 0.04 percent based on samples prepared in the same manner as in this study (12). Figure 5 indicates that though the standard test method produced the smallest average bias or error, it had the highest pooled standard deviation when determining the corrected asphalt content. The pooled standard deviation shown in the figure is not statistically as the standard deviations are actually too different to be pooled, however, they are useful for comparison purposes. The variability for the Thermolyne ignition furnace is skewed by the results for the Missouri and Arizona aggregates. The Missouri aggregate source had the highest correction factor, using the standard method 3.26 percent and the Arizona aggregate source had the third highest correction factor, 2.53 percent. For two-thirds of the sources (exceptions being the Missouri and Arizona sources), the Troxler NTO using the Option 1 burn profile consistently produced a higher standard deviation than the other methods. A previous study using the normal burn profile indicated similar precision for the Troxler NTO furnace as compared to the Thermolyne Ignition Furnace (10). Similarly for two-thirds of the sources (exceptions being the

Alabama and Wisconsin sources), the Ontario Method and Tempyrox furnace offer improved precision over the Thermolyne furnace/standard method for high-loss aggregates. The aggregate correction factor using the standard method was 0.74 percent for the Alabama source and 1.62 percent for the Wisconsin source. This may indicate that the techniques for high loss aggregates should not be applied until the correction factor exceeds a larger number, possibly 2.0 percent.

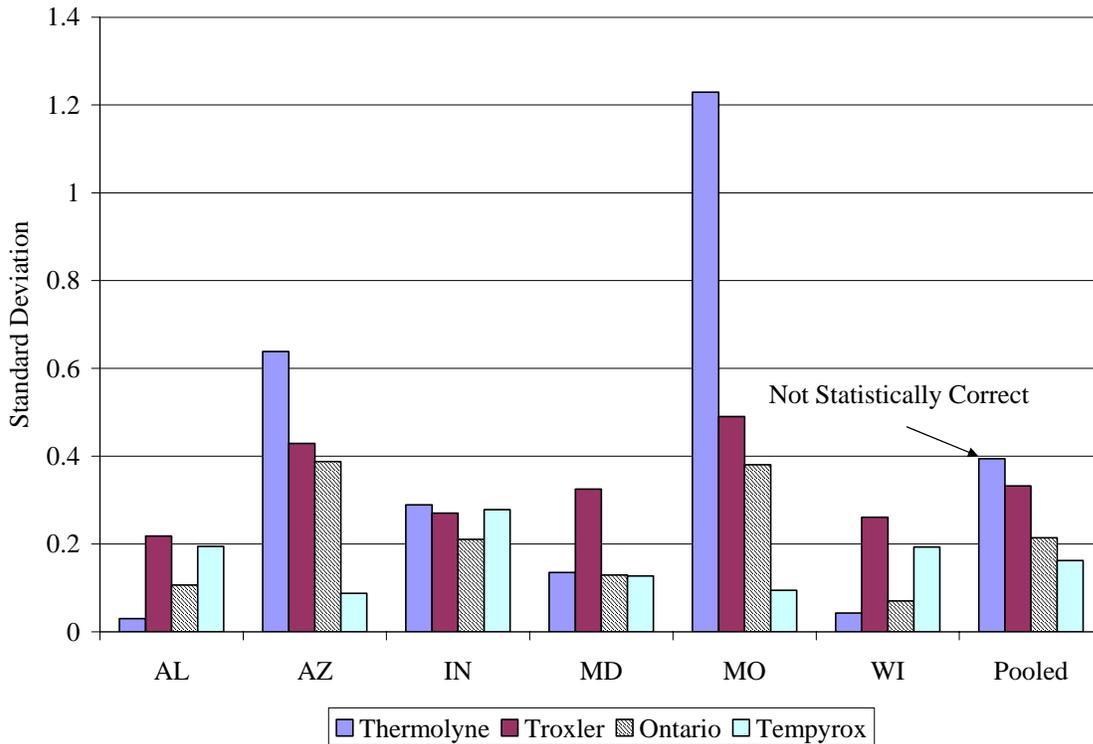


Figure 5. Summary of Variability of Corrected Asphalt Contents

Thermogravimetric Analysis

In an effort to better understand why the different methodologies may have worked better for one aggregate or another, thermogravimetric analysis (TGA) was performed on samples of the coarse aggregates used in the study. A SPEX mill grinder was used to pulverize representative samples of the coarse aggregate to material passing the 0.075 mm sieve. Iowa DOT recommended crushing coarse aggregate samples for testing as opposed to using material passing the 0.075 mm sieve from the gradation to reduce variability from contaminants (4).

The samples were tested in a TA Instruments Q50 TGA by Auburn University’s Agronomy and Soils Lab. In TGA, a small sample of the material (approximately 50 mg) is heated at a prescribed temperature rate while determining the sample mass. An inert gas is used to purge any combustion products. The results are generally evaluated by looking at the derivative of weight loss or percent loss per °C. Compounds can be identified by the temperature at which they burn off. In this study, the samples were tested in an argon atmosphere with a 10°C per minute temperature rise to a maximum temperature of 725°C.

Limestone is a generic term for aggregates that contain calcium carbonate (CaCO_3), magnesium carbonate (MgCO_3) or combinations thereof. Dolomite refers to limestone containing a high proportion (40.7 to 45.6 percent) of magnesium carbonate. Dolomitic limestone has lesser magnesium carbonate contents (4.5 to 22.6 percent) (14). Limestone decomposes or calcinates at high temperatures to produce quick lime (CaO) or lime (really hydrated lime $\text{Ca}(\text{OH})_2$) according to Equation 1 (15).



The temperature at which the reaction occurs is dependent on the magnesium content. For pure dolomite, decomposition occurs between 419 and 480°C; for limestone decomposition occurs above 900°C (14, 15). Thus, dolomite will decompose within the typical operating temperatures of the ignition furnace.

When using TGA to examine the loss upon heating, one can determine the cumulative water loss from the sample. Figure 6 shows the cumulative water loss determined from the TGA tests between 50 and 540°C versus the correction factor from the standard ignition furnace test. Shaw, (16) observed this relationship when assisting with the interpretation of the data. Recall that ignition furnace samples are oven dry when they the test is begun. Therefore, the lost water is most likely chemically bound and released by decomposition of compounds at higher temperatures. The chemically bound water loss, shown in Figure 6, appears to account for the majority of the ignition furnace correction factor.

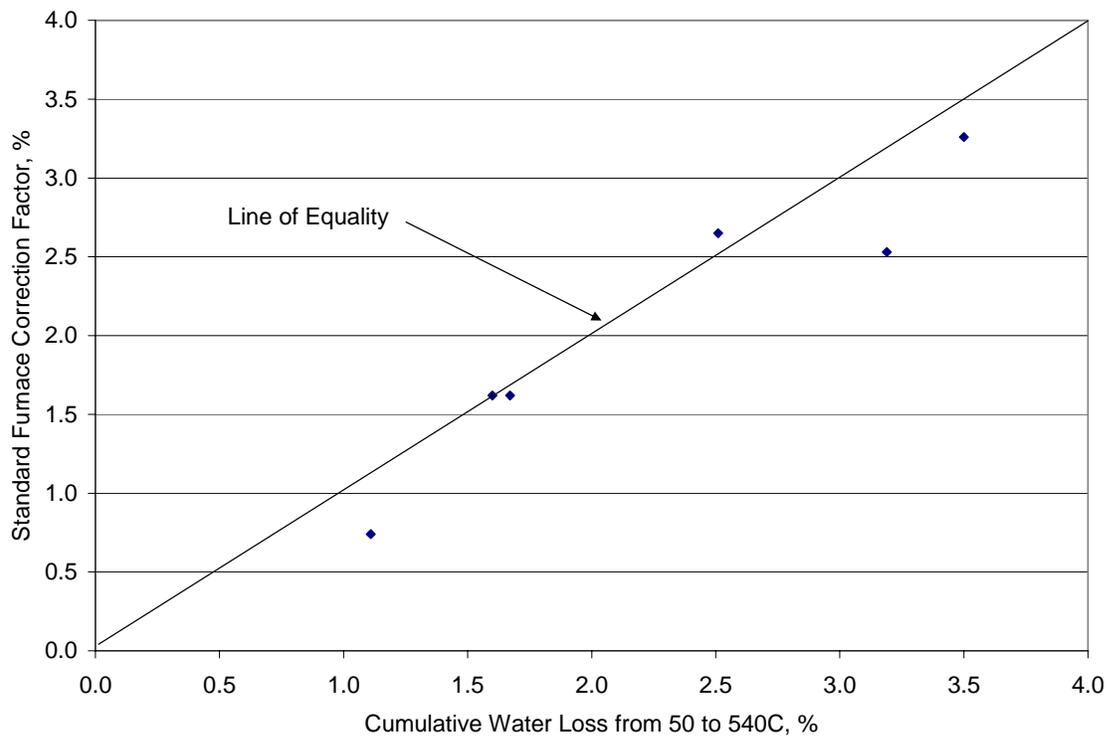


Figure 6. Cumulative Water Loss versus Ignition Furnace Correction Factor

Figure 7 shows the TGA results for the four dolomitic limestone sources. Recall that the MO dolomite had the largest correction factor (3.26 percent) when tested in the standard ignition furnace at 538°C followed by the IN (2.65 percent), WI (1.62 percent) and AL (0.74 percent). The occurrences of spikes, representing decomposition of compounds below 538°C, for the MO and IN samples correspond to their correction factors using the standard ignition furnace (more/higher spikes results in a larger correction factor). The lower rate of decomposition for the WI and AL samples also corresponds to their correction factors.

Powder X-ray diffraction was used to further analyze the compounds in the AL and MO coarse aggregate. Powder X-ray diffraction (XRD) is one of the most common techniques used by scientists to examine the physio-chemical make-up of unknown solids (17). A powdered sample of the material is exposed to fixed wave-length x-rays. X-rays are reflected as they pass through a solid. A sensor records the reflections from the x-rays that have passed through the powdered material (17, 18). The reflection angles are analyzed and used to calculate the inter-atomic spacing of the material using the Bragg equation. Each crystalline solid has a unique X-ray powder pattern which may be used as a “fingerprint” for its identification.” (18). X-ray diffraction indicates that the AL source is a relatively pure dolomite. This corresponds with the minimal number of spikes between 400 and 550°C shown in Figure 7 (16). X-ray diffraction on the MO source confirms that dolomite is the only carbonate mineral present in the coarse aggregate; however the presence of kaolinite was suggested. Kaolinite is a clay mineral produced from the decomposition of feldspar. Water is present between the plate-like crystalline

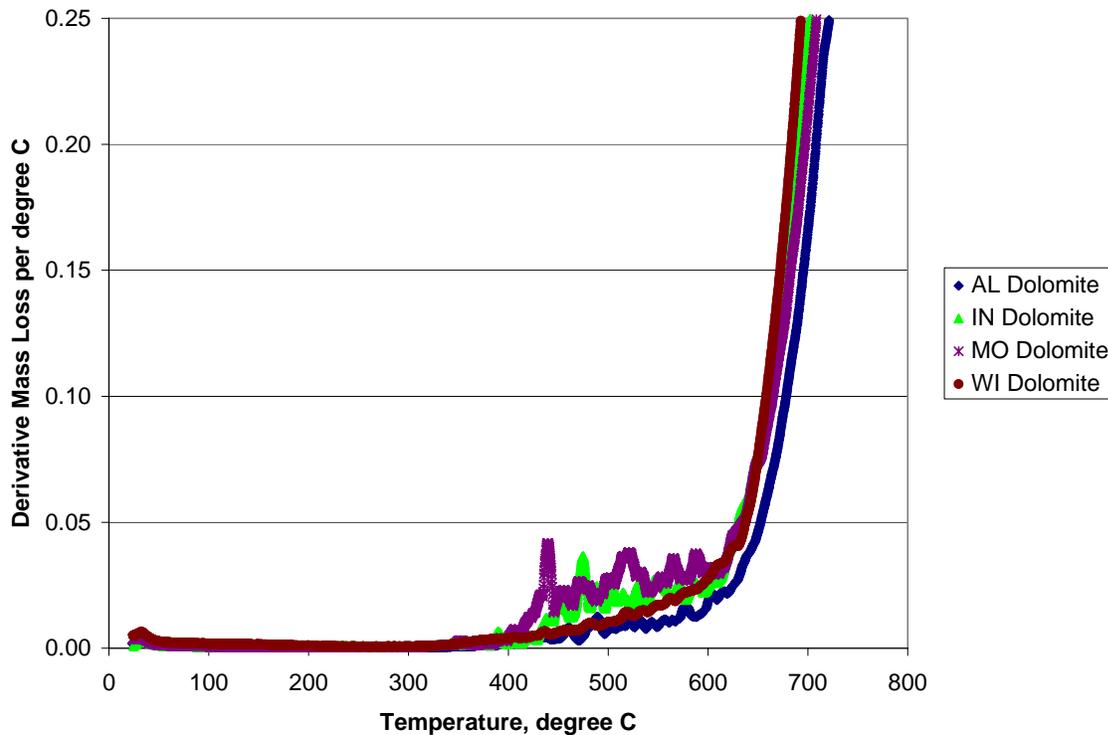


Figure 7. Derivative Mass Loss from TGA for Dolomite Samples

structures of this mineral. The presence of kaolinite would explain the higher correction factor for this source (16).

Figure 8 shows the derivative mass loss from TGA tests for the AZ and MD samples. The AZ basalt samples shows losses at much lower temperatures (less than 100°C). This is more indicative of water loss from clay or possibly gypsum. This corresponds with the results in Table 2 that indicated that none of the furnace methods reduced the correction factor below 1.0 percent because much of the loss is occurring at very low temperatures. The lowest correction factor was for the Tempyrox furnace (1.38 percent).

X-ray diffraction was also performed on the AZ source. X-ray diffraction indicated a significant presence of the mineral analcite. Analcite is a naturally occurring sodium zeolite. Zeolites are naturally occurring or synthetic materials. Their crystalline structure allows them to hold internal moisture which is liberated upon heating. Analcite liberates its internal moisture between 200 and 400°C accounting for 1.8 percent water loss during TGA (16). X-ray diffraction also indicated the presence of phyllosilicates and a little gypsum, which most likely contribute to the weight loss during ignition (16).

Rogers et al (5) report that chlorite decomposes at between 500 and 600°C and that Serpentine decomposes into olivine, silica and water at temperature between 600 and 750°C. This corresponds to the derivative of the mass loss shown in Figure 7 for the Maryland serpentinite/chlorite.

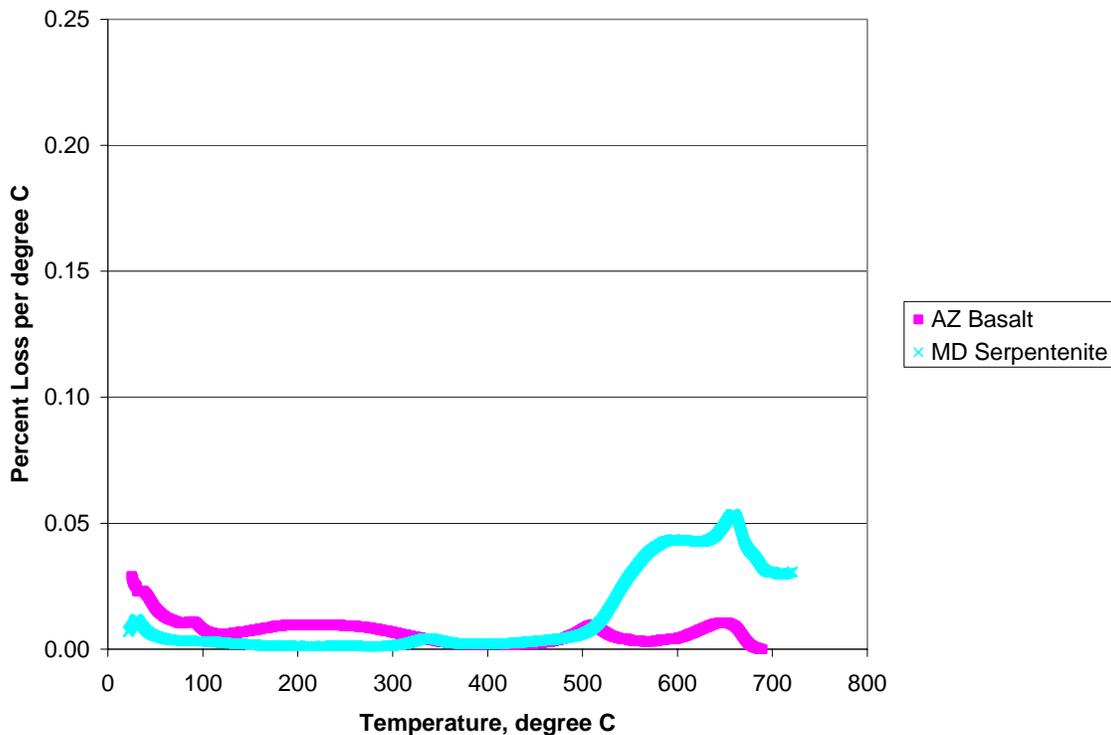


Figure 8. Derivative Mass Loss from TGA for Basalt and Serpentine Samples

Measured Gradation

The aggregate for each source was fractionated and then recombined to meet the target gradations shown in Table 1. Critical sieves for control of HMA tend to be near the NMAS, the 4.75 mm or the 2.36 mm sieves, and the 0.075 mm sieve. The average percents passing the 4.75 mm sieve for each source/method combination are shown in Figure 9 for the optimum and optimum plus 0.5 percent samples. Analysis of variance indicated that there was not a significant effect resulting from method/furnace for the percentages of aggregate breakdown on both the NMAS and the 4.75 mm sieves. Therefore, none of the test methods improved, or reduced, the aggregate loss during the ignition test. Figure 10 summarizes the average percent passing the 0.075 mm sieve for each source/method combination for the optimum and optimum plus 0.5 percent samples. From the data in Figure 10, the Ontario Method consistently reduced the aggregate breakdown for the percent passing the 0.075 mm sieve, even though it did not produce the lowest correction factor. ANOVA confirmed that furnace/method was significant for the percent passing the 0.075 mm sieve. It was concluded that the Tempyrox oven produced a higher than expected (based on the lower correction factor) percentage passing the 0.075 mm sieve due to the long testing time.

A calibration factor for the measured gradation was also considered. Basically, the same calibration samples used to determine the asphalt content calibration factor could also be used to develop a calibration factor for aggregate breakdown on the sieves of interest. If this methodology is used, it is paramount that the target gradation be based on a washed gradation of

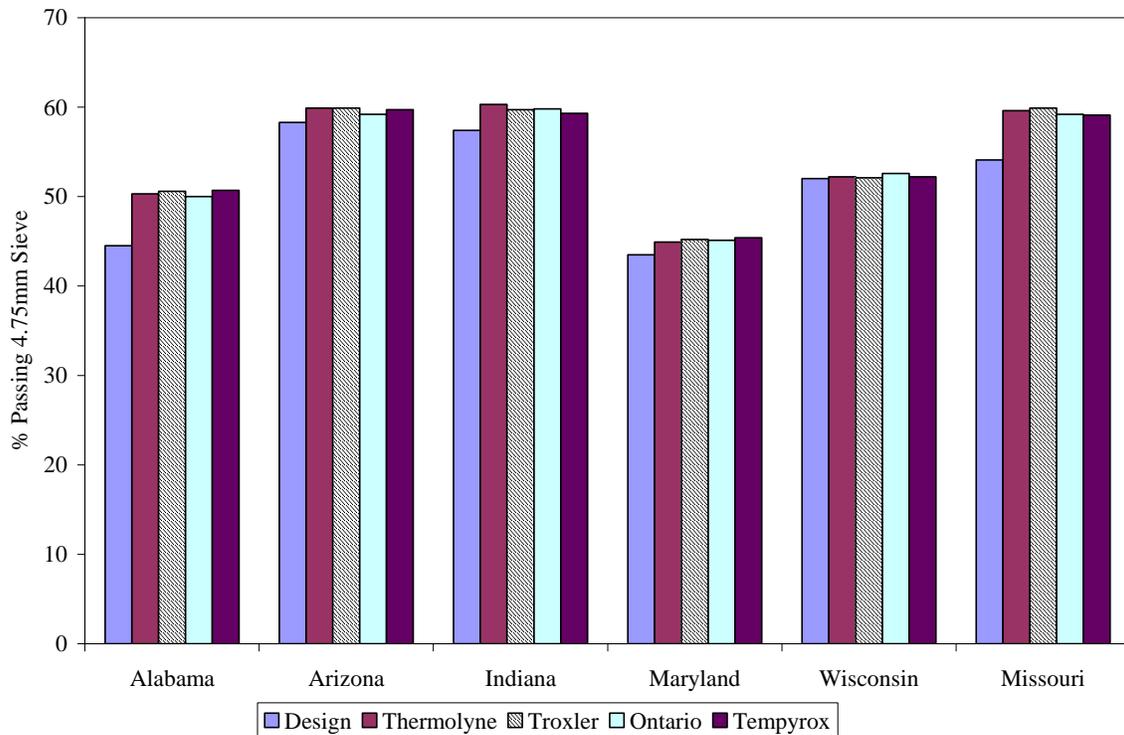


Figure 9. Summary of Average Percent Passing 4.75 mm Sieve

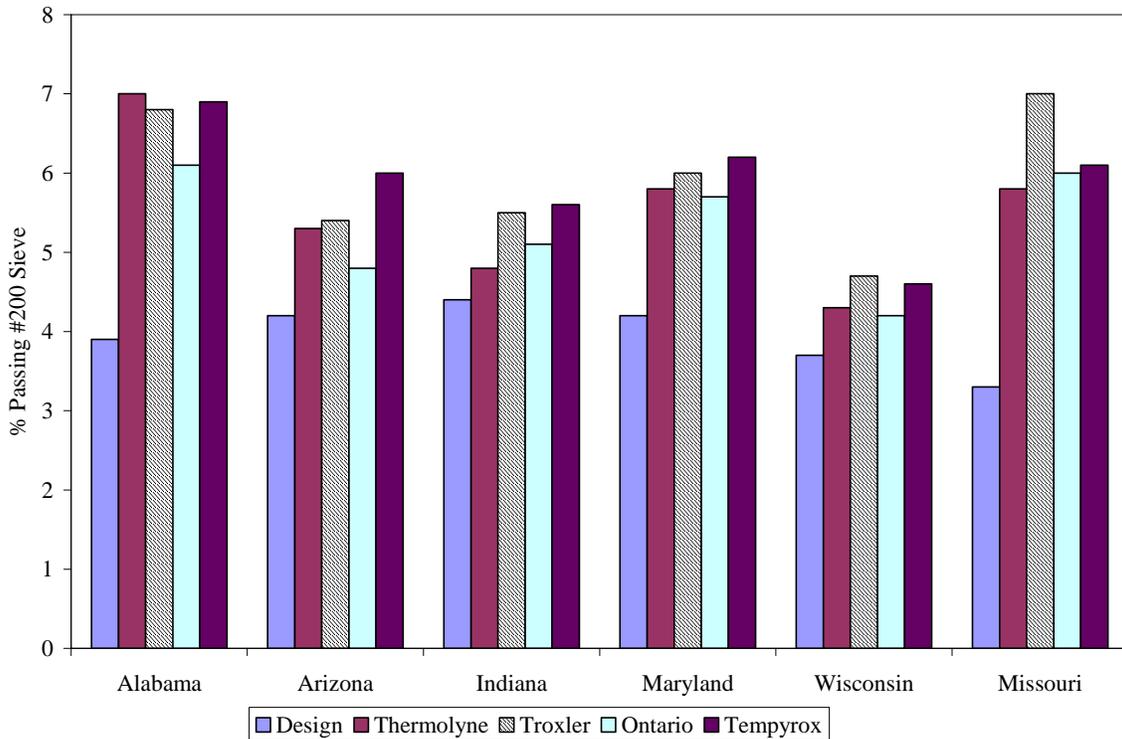


Figure 10. Summary of Average Percent Passing 0.075 mm Sieve

samples batched in the same manner as the furnace samples and not mathematically combined samples. Tables 3-8 show the design gradation, average measured gradation from the samples used to develop the correction factor, average measured gradation on the optimum plus 0.5 percent samples, corrected optimum plus 0.5 percent gradations and resulting bias for the samples tested in the Thermolyne Furnace according to AASHTO T308 Method A. The correction factor is the design minus the measured gradation from the calibration samples. Correction factors as large as 9.9 percent were observed for the Alabama source (Table 3 2.36 mm sieve). With the exception of two cases, IN 1.18 mm sieve and MO 12.5 mm sieve, all of the resulting biases in the corrected gradations were less than 1 percent. This indicates that a gradation factor for gradation can be successfully used for high loss aggregates.

Table 3. Gradation Comparison for Alabama Dolomite Samples

Sieve Size, mm	Design	Avg. Measured from CF Samples	Gradation CF	Avg. Measured from Optimum plus 0.5 percent Samples	Std. Measured from Optimum plus 0.5 percent Samples	Optimum plus 0.5 percent Gradation with CF Applied	Bias
25.0	100.0	100.0	0.0	100.0	0.00	100.0	0.0
19.0	95.1	96.0	-0.9	95.5	0.70	94.6	0.5
12.5	80.7	81.8	-1.1	82.8	2.78	81.7	-1.0
9.5	69.3	70.1	-0.8	70.8	0.70	70.0	-0.7
4.75	44.5	49.9	-5.4	50.3	0.38	44.9	-0.4
2.36	27.7	37.6	-9.9	38.6	0.51	28.7	-1.0
1.18	17.1	19.4	-2.3	20.1	0.80	17.8	-0.7
0.60	12.0	14.4	-2.4	15.1	0.75	12.7	-0.7
0.30	9.2	12.7	-3.5	13.4	0.70	9.9	-0.7
0.15	7.6	11.1	-3.5	11.8	0.85	8.3	-0.7
0.075	3.9	6.2	-2.3	7.0	1.12	4.8	-0.9

Table 4. Gradation Comparison for Arizona Basalt Samples

Sieve Size, mm	Design	Avg. Measured from CF Samples	Gradation CF	Avg. Measured from Optimum plus 0.5 percent Samples	Std. Measured from Optimum plus 0.5 percent Samples	Optimum plus 0.5 percent Gradation with CF Applied	Bias
25.0	100.0	100.0	0.0	100.0	0.00	100.0	0.0
19.0	100.0	100.0	0.0	100.0	0.00	100.0	0.0
12.5	84.0	86.9	-2.9	86.2	1.01	83.3	0.7
9.5	75.3	76.7	-1.4	76.5	0.51	75.1	0.2
4.75	58.3	59.5	-1.2	59.9	0.12	58.8	-0.5
2.36	42.9	44.3	-1.4	44.7	0.20	43.3	-0.4
1.18	29.7	30.8	-1.1	31.2	0.12	30.1	-0.4
0.60	19.3	20.5	-1.2	20.8	0.21	19.6	-0.3
0.30	10.4	12.1	-1.7	12.2	0.35	10.5	-0.1
0.15	6.0	7.7	-1.7	7.7	0.38	6.0	0.0
0.075	4.2	5.6	-1.4	5.3	0.15	4.0	0.2

Table 5. Gradation Comparison for Maryland Serpentinite Samples

Sieve Size, mm	Design	Avg. Measured from CF Samples	Gradation CF	Avg. Measured from Optimum plus 0.5 percent Samples	Std. Measured from Optimum plus 0.5 percent Samples	Optimum plus 0.5 percent Gradation with CF Applied	Bias
25.0	100.0	100.0	0.0	100.0	0.00	100.0	0.0
19.0	100.0	100.0	0.0	99.8	0.00	99.8	0.2
12.5	98.8	98.9	-0.1	98.7	0.00	98.6	0.2
9.5	88.3	89.2	-0.9	89.1	0.06	88.3	0.0
4.75	43.5	45.2	-1.7	44.9	0.80	43.2	0.3
2.36	25.5	26.7	-1.2	26.7	0.76	25.5	0.0
1.18	19.1	20.1	-1.0	20.0	0.72	19.0	0.1
0.60	16.0	17.0	-1.0	16.9	0.71	15.9	0.1
0.30	12.9	14.7	-1.8	14.6	0.62	12.8	0.1
0.15	5.3	7.0	-1.7	6.9	0.59	5.2	0.1
0.075	4.2	6.0	-1.8	5.8	0.47	4.0	0.2

Table 6. Gradation Comparison for Indiana Dolomite Samples

Sieve Size, mm	Design	Avg. Measured from CF Samples	Gradation CF	Avg. Measured from Optimum plus 0.5 percent Samples	Std. Measured from Optimum plus 0.5 percent Samples	Optimum plus 0.5 percent Gradation with CF Applied	Bias
25.0	100.0	100.0	0.0	100.0	0.00	100.0	0.0
19.0	100.0	100.0	0.0	100.0	0.35	100.0	0.0
12.5	100.0	100.0	0.0	100.0	0.10	100.0	0.0
9.5	94.8	95.1	-0.3	95.1	0.51	94.9	-0.1
4.75	57.4	59.6	-2.2	60.3	0.30	58.1	-0.7
2.36	35.8	36.1	-0.3	36.3	0.36	36.0	-0.2
1.18	28.0	26.0	2.0	27.6	0.32	29.6	-1.6
0.60	20.0	19.5	0.5	19.7	0.32	20.3	-0.3
0.30	10.0	11.1	-1.1	11.5	0.35	10.4	-0.4
0.15	5.6	6.7	-1.1	7.0	0.26	5.9	-0.3
0.075	4.4	4.3	0.1	4.8	0.21	4.9	-0.5

Table 7. Gradation Comparison for Missouri Dolomite Samples

Sieve Size, mm	Design	Avg. Measured from CF Samples	Gradation CF	Avg. Measured from Optimum plus 0.5 percent Samples	Std. Measured from Optimum plus 0.5 percent Samples	Optimum plus 0.5 percent Gradation with CF Applied	Bias
25.0	100.0	100.0	0.0	100.0	0.00	100.0	0.0
19.0	100.0	100.0	0.0	100.0	0.00	100.0	0.0
12.5	98.3	98.7	-0.4	94.5	1.22	94.0	4.3
9.5	89.8	91.4	-1.6	91.3	0.50	89.7	0.1
4.75	54.1	60.0	-5.9	59.6	0.47	53.8	0.3
2.36	38.0	42.4	-4.4	41.9	0.31	37.6	0.4
1.18	25.6	29.8	-4.2	29.3	0.15	25.1	0.5
0.60	17.7	22.0	-4.3	21.5	0.10	17.2	0.5
0.30	10.5	16.5	-6.0	16.0	0.17	10.0	0.5
0.15	6.1	11.7	-5.6	11.2	0.26	5.6	0.5
0.075	3.3	6.1	-2.8	5.8	0.49	3.0	0.3

Table 8. Gradation Comparison for Wisconsin Dolomite Samples

Sieve Size, mm	Design	Avg. Measured from CF Samples	Gradation CF	Avg. Measured from Optimum plus 0.5 percent Samples	Std. Measured from Optimum plus 0.5 percent Samples	Optimum plus 0.5 percent Gradation with CF Applied	Bias
25.0	100.0	100.0	0.0	100.0	0.00	100.0	0.0
19.0	97.1	95.7	1.4	95.9	0.40	97.3	-0.2
12.5	84.1	82.8	1.3	83.0	0.66	84.3	-0.2
9.5	72.2	72.1	0.1	72.2	0.35	72.3	-0.1
4.75	52.0	51.9	0.1	52.2	0.44	52.3	-0.3
2.36	34.5	34.5	0.0	34.9	0.38	34.9	-0.4
1.18	21.7	21.6	0.1	22.1	0.36	22.2	-0.5
0.60	13.1	13.3	-0.2	13.5	0.20	13.3	-0.2
0.30	6.7	7.6	-0.9	7.7	0.26	6.8	-0.1
0.15	4.4	5.3	-0.9	5.5	0.06	4.6	-0.2
0.075	3.7	4.1	-0.4	4.3	0.10	3.9	-0.2

CONCLUSIONS

- The Tempyrox Pyro-Clean furnace, commonly used for cleaning laboratory glassware, produced the lowest aggregate correction factors.
- The standard method and the Ontario method, both using the Thermolyne ignition furnace produced the smallest bias or error in measured asphalt content.
- The standard deviation of the corrected asphalt contents for these high loss aggregate sources was higher than the within-lab standard deviation reported for AASHTO T308. The only exception was the Alabama source using the standard method.
- The Ontario Method and Tempyrox Oven generally reduced the variability of asphalt content measurements for high loss aggregates.
- None of the methods evaluated statistically reduced aggregate breakdown on the NMA5 and 4.75 mm sieves.
- The Ontario method significantly reduced, but did not eliminate aggregate breakdown on the 0.075 mm sieve.
- An aggregate correction factor for the measured gradation reduced the bias in measured gradation for high loss aggregate samples recovered in the ignition furnace.

RECOMMENDATIONS

- The Ontario method, using an altered end point of less than 1.0 gram change over three consecutive minutes and using highest test temperature of 538, 480 or 450°C that produces a correction factor less than 1.0 percent, should be adopted by AASHTO and ASTM for determining the asphalt content by the ignition method for high loss aggregates.
- A furnace should be developed using the Tempyrox technology but including an internal scale. This may be the best solution to problems with high loss aggregates.
- Evaluate a furnace using the Tempyrox technology for testing recycled asphalt pavement (RAP) sources. Determination of a correction factor for RAP can be very difficult. Such a device could virtually eliminate the need for a correction factor when testing most RAP.
- A gradation calibration factor should be determined for high loss aggregates.

ACKNOWLEDGEMENTS

The authors thank Dr. Joey Shaw and Peggy Mitchell from Auburn University's Soils and Agronomy Laboratory for their assistance in conducting and analyzing TGA tests on the aggregate samples. The authors also thank Alabama Department of Transportation for funding this study.

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Appendix
Sample Data

Table A-1. Data for Samples at Optimum Asphalt Content (Used to Develop Calibration Factors)

Source	Sample #	Method	Temp, °C	Max		Design AC, %	Uncorrected AC, %	Correction Factor	Corrected AC, % (Temp. Corr. Added)	AC% Bias	% Passing										
				Observed Temp	Test Time						25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AL	1	Thermolyne	538	630	60	4.5	5.04	0.00	4.90	0.40	100.0	95.8	82.7	70.9	50.1	37.7	19.7	14.6	12.8	11.2	6.3
AL	2	Thermolyne	538	592	50	4.5	5.27	0.00	5.13	0.63	100.0	94.9	80.7	69.8	50.1	37.8	19.4	14.3	12.6	10.9	5.9
AL	3	Thermolyne	538	577	63	4.5	5.42	0.00	5.28	0.78	100.0	97.3	82.0	69.5	49.5	37.3	19.1	14.4	12.7	11.1	6.3
IN	1	Thermolyne	538	563	104	5.6	8.14	0.00	8.00	2.40	100.0	100.0	100.0	94.9	59.9	36.5	27.8	19.7	11.3	6.8	4.6
IN	2	Thermolyne	538	574	109	5.6	8.47	0.00	8.33	2.73	100.0	100.0	100.0	95.1	59.8	35.9	27.8	19.5	11.2	6.7	4.5
IN	3	Thermolyne	538	583	78	5.6	8.15	0.00	8.01	2.41	100.0	100.0	100.0	95.2	59.0	35.9	22.3	19.2	10.7	6.6	3.7
WI	1	Thermolyne	538	578	66	4.6	6.15	0.00	6.01	1.41	100.0	95.3	82.5	71.8	52.0	34.3	21.6	13.2	7.6	5.3	4.2
WI	2	Thermolyne	538	648	74	4.6	6.13	0.00	5.99	1.39	100.0	95.5	83.5	72.6	51.6	34.7	21.3	13.2	7.6	5.4	4.2
WI	3	Thermolyne	538	605	77	4.6	6.38	0.00	6.24	1.64	100.0	96.3	82.3	72.0	52.0	34.5	21.9	13.4	7.6	5.2	4.0
MO	1	Thermolyne	538	576	93	5.3	8.32	0.00	8.18	2.88	100.0	100.0	99.1	91.5	59.1	41.8	29.2	21.6	16.1	11.2	5.8
MO	2	Thermolyne	538	575	132	5.3	9.02	0.00	8.88	3.58	100.0	100.0	98.5	91.8	60.4	42.5	30.0	22.1	16.6	11.6	6.0
MO	3	Thermolyne	538	614	82	5.3	8.35	0.00	8.21	2.91	100.0	100.0	98.6	90.9	60.4	42.8	30.2	22.3	16.8	12.2	6.6
AZ	1	Thermolyne	538	622	42	4.7	7.35	0.00	7.21	2.51	100.0	100.0	86.9	76.8	59.6	44.4	31.0	20.7	12.2	7.8	5.6
AZ	2	Thermolyne	538	626	57	4.7	7.16	0.00	7.02	2.32	100.0	100.0	86.7	76.2	59.3	44.0	30.6	20.2	11.8	7.4	5.3
AZ	3	Thermolyne	538	668	50	4.7	7.18	0.00	7.04	2.34	100.0	100.0	87.2	77.2	59.5	44.5	30.9	20.7	12.2	7.8	5.8
MD	1	Thermolyne	538	595	74	5.0	6.63	0.00	6.49	1.49	100.0	100.0	98.9	89.5	44.7	26.2	19.6	16.6	14.4	6.9	5.7
MD	2	Thermolyne	538	593	63	5.0	6.63	0.00	6.49	1.49	100.0	100.0	99.1	89.2	46.1	28.0	21.2	18.1	15.7	7.8	7.0
MD	3	Thermolyne	538	608	75	5.0	6.61	0.00	6.47	1.47	100.0	100.0	98.8	88.8	44.8	26.0	19.5	16.4	13.9	6.2	5.2
AL	1	Troxler	446	446	60	4.5	4.46	0.00	4.46	-0.04	100.0	95.6	80.9	70.4	49.9	38.2	19.8	14.7	12.9	11.2	6.2
AL	2	Troxler	461	461	39	4.5	4.69	0.00	4.69	0.19	99.1	95.0	81.0	69.8	51.2	39.2	20.6	15.4	13.6	11.9	6.9
AL	3	Troxler	465	465	31	4.5	4.93	0.00	4.93	0.43	100.0	95.8	82.1	71.2	51.1	38.8	20.9	15.4	13.5	11.8	7.3
IN	1	Troxler	492	492	33	5.6	6.87	0.00	6.87	1.27	100.0	100.0	100.0	95.5	59.6	37.0	28.1	20.2	12.3	7.9	5.7
IN	2	Troxler	462	462	33	5.6	6.77	0.00	6.77	1.17	100.0	100.0	100.0	95.1	59.0	36.3	28.0	20.5	12.5	8.1	5.8
IN	3	Troxler	471	471	31	5.6	6.91	0.00	6.91	1.31	100.0	100.0	100.0	95.0	59.5	36.0	27.5	20.0	12.2	7.9	5.6
WI	1	Troxler	451	451	36	4.6	5.28	0.00	5.28	0.68	100.0	96.0	83.4	72.5	52.6	35.3	22.6	14.0	8.1	5.9	4.7
WI	2	Troxler	451	451	40	4.6	4.98	0.00	4.98	0.38	100.0	96.4	82.3	71.2	52.0	34.2	21.9	13.7	8.3	6.0	4.7
WI	3	Troxler	466	466	39	4.6	4.98	0.00	4.98	0.38	100.0	97.1	84.0	72.0	51.7	33.8	21.2	13.3	7.8	5.5	4.4
MO	1	Troxler	461	461	60	5.3	6.25	0.00	6.25	0.95	100.0	100.0	98.5	91.5	59.4	42.4	30.1	22.7	17.4	12.5	7.1
MO	2	Troxler	455	455	60	5.3	6.41	0.00	6.41	1.11	100.0	100.0	98.5	91.9	59.9	42.1	29.8	22.4	17.0	12.1	6.8
MO	3	Troxler	471	471	36	5.3	6.55	0.00	6.55	1.25	100.0	100.0	99.0	91.6	59.7	42.7	30.3	22.7	17.4	12.5	7.1
AZ	1	Troxler	452	452	42	4.7	6.44	0.00	6.44	1.74	100.0	100.0	85.6	76.6	59.7	44.1	30.6	20.5	11.9	7.5	4.9
AZ	2	Troxler	438	438	47	4.7	6.29	0.00	6.29	1.59	100.0	100.0	86.8	76.3	59.3	44.2	30.4	20.0	11.5	7.1	4.8
AZ	3	Troxler	439	439	47	4.7	6.82	0.00	6.82	2.12	100.0	100.0	86.5	77.6	59.9	44.6	31.2	20.8	12.3	7.9	5.8
MD	1	Troxler	494	494	56	5.0	5.84	0.00	5.84	0.84	100.0	100.0	98.8	88.8	45.0	26.6	20.0	14.9	14.4	6.8	5.7
MD	2	Troxler	453	453	46	5.0	5.56	0.00	5.56	0.56	100.0	100.0	99.1	88.9	44.8	26.6	20.0	16.8	14.3	6.6	5.5
MD	3	Troxler	461	461	38	5.0	5.89	0.00	5.89	0.89	100.0	100.0	98.9	89.3	45.4	26.6	20.0	17.0	14.6	6.9	5.8

Source	Sample #	Method	Temp, °C	Max		Design AC, %	Uncorrected AC, %	Correction Factor	Corrected AC, % (Temp. Corr. Added)	AC% Bias	% Passing										
				Observed Temp	Test Time						25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AL	31	Ontario	480	603	62	4.5	4.81	0.00	4.67	0.17	100.0	96.8	81.0	70.9	50.9	38.6	20.5	15.4	13.7	12.1	7.1
AL	15	Ontario	480	640	46	4.5	4.90	0.00	4.76	0.26	100.0	96.6	84.0	70.1	50.5	38.3	20.1	15.0	13.2	11.6	6.5
AL	29	Ontario	480	620	44	4.5	4.55	0.00	4.41	-0.09	100.0	96.2	81.6	70.1	50.9	39.0	20.6	15.0	13.2	11.3	5.8
IN	6	Ontario	480	575	60	5.6	7.06	0.00	6.92	1.32	100.0	100.0	100.0	95.1	60.1	36.7	27.8	20.0	11.7	7.2	5.0
IN	25	Ontario	480	547	74	5.6	6.31	0.00	6.17	0.57	100.0	100.0	100.0	95.3	59.2	36.8	28.1	20.3	12.0	7.3	5.1
IN	35	Ontario	480	559	74	5.6	6.60	0.00	6.46	0.86	100.0	100.0	100.0	99.0	58.4	36.9	28.6	20.7	12.4	7.9	5.3
WI	16	Ontario	480	587	61	4.6	5.37	0.00	5.23	0.63	100.0	95.5	83.0	72.4	52.7	35.4	22.7	14.0	8.2	5.7	4.4
WI	29	Ontario	480	584	53	4.6	5.39	0.00	5.25	0.65	100.0	94.1	83.8	72.2	52.1	34.6	21.8	13.5	7.9	5.6	4.4
WI	26	Ontario	480	545	75	4.6	5.29	0.00	5.15	0.55	100.0	95.0	82.8	72.5	52.2	35.0	22.3	13.7	7.9	5.6	4.4
MO	6	Ontario	480	564	66	5.3	6.52	0.00	6.38	1.08	100.0	100.0	99.2	91.6	59.6	42.3	30.0	22.2	16.9	11.7	6.6
MO	35	Ontario	480	541	74	5.3	6.61	0.00	6.47	1.17	100.0	100.0	98.7	91.6	59.4	42.2	29.7	22.1	16.8	11.8	6.5
MO	4	Ontario	480	589	61	5.3	6.11	0.00	5.97	0.67	100.0	100.0	98.1	91.7	58.7	42.1	29.7	22.2	16.8	11.4	6.4
AZ	5	Ontario	480	587	51	4.7	7.04	0.00	6.90	2.20	100.0	99.3	86.4	76.7	59.6	44.5	31.1	20.7	12.1	7.6	5.5
AZ	20	Ontario	480	588	39	4.7	7.12	0.00	6.98	2.28	100.0	100.0	86.3	76.5	60.1	44.9	31.5	21.3	12.7	8.1	5.8
AZ	8	Ontario	480	587	48	4.7	6.88	0.00	6.74	2.04	100.0	99.1	86.3	76.6	59.5	44.5	31.1	20.9	12.3	7.7	5.5
MD	30	Ontario	480	569	51	5.0	5.94	0.00	5.80	0.80	100.0	100.0	98.8	88.7	45.3	26.7	20.1	17.0	14.4	6.7	5.6
MD	20	Ontario	480	612	59	5.0	5.89	0.00	5.75	0.75	100.0	100.0	98.7	89.5	45.0	26.8	20.2	17.1	14.6	7.0	5.9
MD	14	Ontario	480	532	57	5.0	5.24	0.00	5.10	0.10	100.0	100.0	98.5	88.3	44.7	26.7	20.0	17.0	14.5	7.0	5.8
IN	13	Ontario	450	549	65	5.6	6.53	0.00	6.39	0.79	100.0	100.0	100.0	95.9	58.2	36.8	28.3	20.2	11.7	7.2	4.9
IN	38	Ontario	450	533	68	5.6	6.57	0.00	6.43	0.83	100.0	100.0	100.0	95.3	60.1	36.6	28.4	20.6	12.6	8.0	5.6
IN	33	Ontario	450	539	75	5.6	6.67	0.00	6.53	0.93	100.0	100.0	100.0	94.9	58.2	36.0	27.5	19.9	12.1	7.7	5.4
MO	36	Ontario	450	568	56	5.3	6.12	0.00	5.99	0.69	100.0	100.0	98.6	91.7	59.1	41.9	29.7	22.0	16.6	11.3	6.2
MO	25	Ontario	450	527	63	5.3	6.47	0.00	6.33	1.03	100.0	100.0	98.2	90.6	59.3	42.1	29.7	22.1	16.6	11.4	6.2
MO	19	Ontario	450	559	67	5.3	6.03	0.00	5.92	0.62	100.0	100.0	99.3	90.6	58.7	41.5	29.1	21.5	16.1	10.8	6.1
AZ	15	Ontario	450	510	54	4.7	6.69	0.00	6.55	1.85	100.0	100.0	86.9	76.5	59.9	44.6	31.1	20.7	12.1	7.6	5.5
AZ	38	Ontario	450	552	56	4.7	6.84	0.00	6.70	2.00	100.0	100.0	85.4	76.4	59.7	44.8	31.1	20.5	11.8	7.3	4.8
AZ	26	Ontario	450	525	54	4.7	6.66	0.00	6.52	1.82	100.0	100.0	86.5	76.8	59.8	44.6	31.0	20.5	11.9	7.4	5.3
AL	30	Ontario	538	608	37	4.5	4.86	0.00	4.72	0.22	100.0	96.9	81.5	69.4	50.0	38.1	19.4	14.1	12.4	10.7	5.8
AL	39	Ontario	538	627	39	4.5	5.00	0.00	4.86	0.36	100.0	94.2	80.6	71.0	50.5	38.5	19.7	14.5	12.7	10.9	5.6
AL	25	Ontario	538	628	40	4.5	5.02	0.00	4.88	0.38	100.0	94.8	81.9	70.0	49.7	38.0	19.5	14.3	12.5	10.7	5.5
AL	23	Tempyrox	900F			4.5	4.67	0.00	4.67	0.17	100.0	96.2	84.8	70.0	50.1	38.5	20.3	14.7	12.9	10.9	5.6
AL	35	Tempyrox	900F			4.5	4.69	0.00	4.69	0.19	100.0	96.3	83.2	71.1	50.6	39.0	20.2	15.2	13.5	11.6	6.4
AL	14	Tempyrox	900F			4.5	4.56	0.00	4.56	0.06	100.0	95.0	83.1	70.0	51.2	39.2	21.0	15.8	14.1	12.3	7.0
AZ	17	Tempyrox	900F			4.7	5.99	0.00	5.99	1.29	100.0	100.0	84.9	76.1	59.5	44.8	31.3	21.0	12.3	7.8	5.7
AZ	33	Tempyrox	900F			4.7	6.16	0.00	6.16	1.46	100.0	100.0	85.7	76.3	59.7	44.8	31.5	20.9	12.2	7.7	5.3
AZ	19	Tempyrox	900F			4.7	6.09	0.00	6.09	1.39	100.0	100.0	85.3	76.2	59.6	44.8	31.4	21.0	12.3	7.8	5.5
IN	2	Tempyrox	900F			5.6	5.97	0.00	5.97	0.37	100.0	100.0	100.0	94.9	60.4	36.5	27.7	19.9	11.5	6.8	5.0

Source	Sample #	Method	Temp, °C	Max		Design AC, %	Uncorrected AC, %	Correction Factor	Corrected AC, % (Temp. Corr. Added)	AC% Bias	% Passing										
				Observed Temp	Test Time						25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
IN	19	Tempyrox	900F			5.6	6.34	0.00	6.34	0.74	100.0	100.0	100.0	95.1	60.0	36.3	27.7	19.9	11.6	7.0	5.1
IN	23	Tempyrox	900F			5.6	6.28	0.00	6.28	0.68	100.0	100.0	100.0	95.4	60.1	36.6	27.9	19.9	11.4	6.9	5.1
MO	14	Tempyrox	900F			5.3	5.50	0.00	5.50	0.20	100.0	100.0	98.5	90.6	57.9	40.4	27.8	20.3	14.4	9.1	5.5
MO	1	Tempyrox	900F			5.3	5.59	0.00	5.59	0.29	100.0	100.0	98.2	91.2	58.8	41.3	28.6	20.9	14.9	9.7	5.8
MO	21	Tempyrox	900F			5.3	5.78	0.00	5.78	0.48	100.0	100.0	98.3	91.3	58.7	41.9	29.4	21.6	15.7	10.2	6.1
MD	3	Tempyrox	900F			5.0	5.43	0.00	5.43	0.43	100.0	100.0	98.2	88.3	45.7	27.1	20.4	19.4	14.9	7.2	6.2
MD	16	Tempyrox	900F			5.0	5.60	0.00	5.60	0.60	100.0	100.0	98.1	88.3	44.7	26.9	20.3	17.3	14.9	7.2	6.2
MD	32	Tempyrox	900F			5.0	5.22	0.00	5.22	0.22	100.0	100.0	98.7	88.1	44.9	27.0	20.3	17.3	14.9	7.2	6.2
WI	15	Tempyrox	900F			4.6	4.55	0.00	4.55	-0.05	100.0	94.8	82.0	71.5	51.2	33.3	20.9	13.1	7.7	5.3	4.4
WI	17	Tempyrox	900F			4.6	4.76	0.00	4.76	0.16	100.0	97.0	82.8	71.8	51.2	33.6	21.1	13.2	7.7	5.3	4.3
WI	33	Tempyrox	900F			4.6	4.71	0.00	4.71	0.11	100.0	97.2	84.0	72.9	52.8	35.4	22.4	13.7	7.8	5.3	4.3

Table A-2. Data for Samples at Optimum plus 0.5 percent Asphalt Content

Mix	Sample #	Method	Temp, °C	Max		Design AC, %	Uncorrected AC, %	Correction Factor	Corrected AC, % (Temp. Corr. Added)	AC% Bias	% Passing										
				Observed Temp	Test Time						25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
WI	40	Tempyrox	900F			5.1	5.53	0.08	5.45	0.35	100.0	95.8	82.4	72.3	52.3	35.2	22.5	14.1	8.5	6.1	4.8
WI	42	Tempyrox	900F			5.1	5.45	0.08	5.37	0.27	100.0	95.6	83.6	72.4	51.9	34.5	21.6	13.4	7.8	5.4	4.4
WI	52	Tempyrox	900F			5.1	5.67	0.08	5.59	0.49	100.0	94.3	83.5	72.2	52.3	35.0	22.0	13.8	8.2	5.8	4.6
AL	42	Tempyrox	900F			5.0	5.30	0.14	5.16	0.16	100.0	96.0	81.0	70.4	49.9	38.7	20.5	15.3	13.6	11.9	7.1
AL	55	Tempyrox	900F			5.0	5.21	0.14	5.07	0.07	100.0	95.3	84.1	70.9	51.0	38.6	20.3	15.4	13.8	12.2	6.9
AL	58	Tempyrox	900F			5.0	5.12	0.14	4.98	-0.02	100.0	95.9	83.7	69.5	51.1	38.7	20.1	15.1	13.2	11.5	6.6
AL	49	Troxler	475	475	34	5.0	5.58	0.19	5.39	0.39	100.0	96.6	82.4	70.4	50.5	38.9	19.8	14.6	12.9	11.1	6.3
AL	60	Troxler	505	505	33	5.0	5.52	0.19	5.33	0.33	100.0	94.5	80.0	70.6	50.8	38.8	20.4	15.4	13.6	12.1	8.7
AL	56	Troxler	475	475	43	5.0	5.56	0.19	5.37	0.37	100.0	95.5	83.1	71.4	50.5	38.0	18.8	13.9	12.2	10.5	5.5
MO	45	Tempyrox	900F			5.8	6.51	0.32	6.19	0.39	100.0	100.0	98.2	90.8	59.2	41.3	28.8	21.4	15.6	10.1	5.8
MO	49	Tempyrox	900F			5.8	6.44	0.32	6.12	0.32	100.0	100.0	98.3	91.3	58.5	41.0	28.5	20.9	15.2	10.1	6.2
MO	52	Tempyrox	900F			5.8	6.58	0.32	6.26	0.46	100.0	100.0	98.0	92.2	59.6	42.1	29.6	22.0	16.2	10.1	6.3
MD	42	Tempyrox	900F			5.5	6.22	0.42	5.80	0.30	100.0	100.0	98.7	88.6	45.7	27.1	20.4	17.4	15.0	7.4	6.3
MD	53	Tempyrox	900F			5.5	5.99	0.42	5.57	0.07	100.0	100.0	99.0	88.9	45.3	26.8	20.0	16.9	14.6	6.8	5.8
MD	56	Tempyrox	900F			5.5	6.21	0.42	5.79	0.29	100.0	100.0	99.8	89.0	45.3	27.3	20.6	17.6	15.4	7.6	6.4
AL	54	Ontario	538	659	42	5.0	5.61	0.46	5.01	0.01	100.0	95.9	82.2	70.5	50.6	38.1	19.4	14.4	12.6	10.8	5.7
AL	57	Ontario	538	613	53	5.0	5.67	0.46	5.07	0.07	100.0	95.3	80.5	70.6	49.8	38.0	19.3	14.2	12.3	10.6	6.9
AL	59	Ontario	538	647	43	5.0	5.65	0.46	5.05	0.05	100.0	97.3	81.7	70.5	49.5	37.5	18.7	13.8	12.2	10.5	5.6
WI	48	Troxler	496	496	31	5.1	6.17	0.48	5.69	0.59	100.0	97.0	82.9	72.6	52.1	34.7	21.9	13.5	7.9	5.7	4.6
WI	54	Troxler	462	462	37	5.1	5.89	0.48	5.41	0.31	100.0	95.6	82.5	71.7	51.6	34.4	21.6	13.5	7.9	5.8	4.7
WI	45	Troxler	473	473	29	5.1	6.14	0.48	5.66	0.56	100.0	96.6	84.4	73.2	52.6	35.1	22.3	13.8	8.1	5.9	4.7
IN	51	Tempyrox	900F			6.1	6.53	0.59	5.94	-0.16	100.0	100.0	100.0	95.4	60.4	36.3	27.5	20.0	11.7	7.3	5.4
IN	54	Tempyrox	900F			6.1	6.69	0.59	6.10	0.00	100.0	100.0	100.0	99.0	58.3	36.6	28.1	20.4	12.1	7.8	5.7
IN	58	Tempyrox	900F			6.1	6.58	0.59	5.99	-0.11	100.0	100.0	100.0	95.3	59.1	36.5	27.9	20.3	12.4	7.8	5.6
MD	57	Ontario	480	563	58	5.5	6.34	0.69	5.54	0.04	100.0	100.0	97.9	88.8	45.0	26.6	19.9	16.8	14.4	6.7	5.7
MD	46	Ontario	480	581	53	5.5	6.41	0.69	5.58	0.08	100.0	99.6	98.9	88.9	45.0	26.8	20.1	17.1	14.8	7.0	5.8
MD	58	Ontario	480	604	58	5.5	6.33	0.69	5.50	0.00	100.0	100.0	98.6	89.0	45.3	26.8	20.1	16.9	14.7	6.8	5.7
AL	45	Thermolyne	538	576	60	5.0	5.85	0.74	4.97	-0.03	100.0	94.8	81.7	70.7	50.6	39.0	20.9	15.8	14.1	12.6	8.0
AL	47	Thermolyne	538	576	62	5.0	5.85	0.74	4.97	-0.03	100.0	95.4	80.8	71.5	50.5	38.7	20.2	15.2	13.5	11.9	7.3
AL	40	Thermolyne	538	574	63	5.0	5.90	0.74	5.02	0.02	100.0	96.2	86.0	70.1	49.9	38.0	19.3	14.3	12.7	10.9	5.8
WI	59	Ontario	480	559	56	5.1	6.09	0.75	5.21	0.11	100.0	96.8	83.3	72.2	52.2	34.9	22.0	13.5	7.6	5.3	4.2
WI	58	Ontario	480	555	56	5.1	6.06	0.75	5.17	0.07	100.0	96.2	84.0	72.5	52.5	34.9	22.1	13.6	7.8	5.4	4.2
WI	50	Ontario	480	591	49	5.1	5.94	0.75	5.05	-0.05	100.0	96.8	83.0	73.0	53.0	35.5	22.7	13.9	8.0	5.5	4.3
MD	54	Troxler	489	489	42	5.5	6.90	0.76	6.14	0.64	100.0	100.0	98.9	89.3	44.9	26.7	20.0	16.9	14.7	6.9	5.8
MD	40	Troxler	502	502	38	5.5	6.72	0.76	5.96	0.46	100.0	100.0	98.9	89.5	45.5	27.3	20.6	17.6	15.3	7.5	6.4
MD	55	Troxler	475	475	37	5.5	6.87	0.76	6.11	0.61	100.0	100.0	98.7	88.9	45.3	26.7	20.1	17.0	14.6	6.9	5.7

Mix	Sample #	Method	Temp, °C	Max Observed Temp	Test Time	Design AC, %	Uncorrected AC, %	Correction Factor	Corrected AC, % (Temp. Corr. Added)	AC% Bias	% Passing										
											25	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
MO	44	Ontario	450	536	66	5.8	6.98	0.78	6.09	0.29	100.0	100.0	98.6	91.5	59.4	42.4	30.0	22.4	17.0	11.7	6.3
MO	56	Ontario	450	587	72	5.8	6.62	0.78	5.70	-0.10	100.0	100.0	98.8	91.4	59.1	41.5	29.0	21.4	16.0	10.2	5.9
MO	42	Ontario	450	595	72	5.8	6.44	0.78	5.55	-0.25	100.0	100.0	98.9	90.9	59.1	41.7	29.4	21.8	16.2	10.8	5.9
IN	55	Ontario	450	580	65	6.1	6.80	0.85	5.81	-0.29	100.0	100.0	99.7	95.4	59.5	36.6	27.6	19.9	12.0	7.5	5.3
IN	45	Ontario	450	593	69	6.1	6.95	0.85	5.96	-0.14	100.0	100.0	100.0	95.1	60.4	37.0	28.2	20.2	11.8	7.3	5.1
IN	50	Ontario	450	537	68	6.1	7.23	0.85	6.24	0.14	100.0	100.0	100.0	94.7	59.5	36.5	27.7	19.8	11.5	7.0	4.9
MO	53	Troxler	496	496	39	5.8	7.78	1.10	6.68	0.88	100.0	100.0	98.8	91.6	60.0	42.1	29.8	22.3	17.0	12.4	7.0
MO	46	Troxler	516	516	40	5.8	7.85	1.10	6.75	0.95	100.0	100.0	99.1	92.0	59.9	42.4	29.9	22.1	16.9	11.6	6.8
MO	59	Troxler	521	521	43	5.8	7.63	1.10	6.53	0.73	100.0	100.0	98.9	92.0	59.9	42.3	30.0	22.5	17.1	12.5	7.2
IN	46	Troxler	578	578	41	6.1	8.20	1.25	6.95	0.85	100.0	100.0	100.0	95.7	58.8	37.6	28.7	20.7	12.0	7.4	5.2
IN	43	Troxler	531	531	37	6.1	8.31	1.25	7.06	0.96	100.0	100.0	100.0	95.6	61.1	37.2	28.9	21.0	12.8	8.3	5.7
IN	53	Troxler	497	497	34	6.1	7.71	1.25	6.46	0.36	100.0	100.0	100.0	95.5	59.2	36.3	27.3	19.8	12.1	7.9	5.6
AZ	44	Tempyrox	900F			5.2	6.99	1.38	5.61	0.41	100.0	99.7	85.5	76.3	59.8	44.9	31.4	21.3	12.8	8.4	5.9
AZ	47	Tempyrox	900F			5.2	6.80	1.38	5.42	0.22	100.0	100.0	85.2	75.9	59.6	44.5	31.1	20.8	12.3	7.9	5.9
AZ	55	Tempyrox	900F			5.2	6.86	1.38	5.48	0.28	100.0	100.0	85.6	75.7	59.8	44.6	31.3	21.0	12.6	8.2	6.2
WI	51	Thermolyne	538	580	62	5.1	6.88	1.62	5.12	0.02	100.0	95.7	83.1	71.9	52.0	34.6	21.8	13.3	7.4	5.4	4.2
WI	55	Thermolyne	538	574	72	5.1	6.88	1.62	5.12	0.02	100.0	95.7	82.3	72.2	52.7	35.3	22.5	13.7	7.9	5.5	4.4
WI	49	Thermolyne	538	569	80	5.1	6.97	1.62	5.21	0.11	100.0	96.4	83.6	72.6	51.9	34.7	22.0	13.5	7.8	5.5	4.3
MD	52	Thermolyne	538	573	77	5.5	7.21	1.62	5.45	-0.05	100.0	100.0	98.8	89.7	44.9	26.6	19.9	16.8	14.4	6.8	5.7
MD	48	Thermolyne	538	577	61	5.5	7.05	1.62	5.29	-0.21	100.0	99.4	98.7	88.7	44.6	26.4	19.8	16.7	14.4	6.7	5.6
MD	43	Thermolyne	538	569	72	5.5	7.14	1.62	5.38	-0.12	100.0	100.0	98.6	89.0	45.2	27.1	20.4	17.3	15.0	7.2	6.0
AZ	60	Troxler	490	490	33	5.2	7.54	1.82	5.72	0.52	100.0	100.0	85.8	76.9	59.9	44.5	31.0	20.7	11.9	7.3	5.2
AZ	54	Troxler	486	486	31	5.2	7.64	1.82	5.82	0.62	100.0	100.0	87.8	77.1	60.4	44.9	31.5	21.1	12.5	7.9	5.7
AZ	42	Troxler	464	464	40	5.2	7.45	1.82	5.63	0.43	100.0	100.0	86.3	76.6	59.5	44.6	31.1	20.9	12.3	7.7	5.2
AZ	41	Ontario	450	530	60	5.2	6.96	1.89	4.93	-0.27	100.0	99.0	85.0	76.0	59.1	44.4	30.7	20.3	11.7	7.1	4.4
AZ	45	Ontario	450	575	52	5.2	7.07	1.89	5.04	-0.16	100.0	98.6	84.5	75.6	59.4	44.2	30.9	20.6	12.2	7.7	5.2
AZ	49	Ontario	450	516	64	5.2	6.66	1.89	4.63	-0.57	100.0	99.5	84.8	76.0	59.2	44.2	30.7	20.3	11.8	7.2	4.7
AZ	43	Thermolyne	538	576	51	5.2	7.87	2.53	5.20	0.00	100.0	100.0	85.6	76.4	60.0	44.7	31.3	21.0	12.5	8.1	5.5
AZ	40	Thermolyne	538	575	59	5.2	7.94	2.53	5.27	0.07	100.0	100.0	85.7	76.1	60.0	44.9	31.3	20.9	12.2	7.5	5.3
AZ	57	Thermolyne	538	569	66	5.2	7.99	2.53	5.32	0.12	100.0	100.0	87.4	77.1	59.8	44.5	31.1	20.6	11.8	7.4	5.2
IN	42	Thermolyne	538	569	84	6.1	8.40	2.65	5.61	-0.49	100.0	100.0	100.0	95.2	61.1	37.2	28.4	20.5	12.2	7.7	5.3
IN	49	Thermolyne	538	569	108	6.1	9.08	2.65	6.29	0.19	100.0	100.0	100.0	95.1	60.3	36.0	27.4	19.6	11.3	6.8	4.6
IN	52	Thermolyne	538	588	84	6.1	8.71	2.65	5.92	-0.18	100.0	100.0	100.0	95.1	59.5	35.8	27.0	19.1	11.0	6.6	4.4
MO	50	Thermolyne	538	574	87	5.8	8.54	3.26	5.14	-0.66	100.0	100.0	98.4	91.4	59.1	41.6	29.1	21.5	16.2	11.5	6.4
MO	40	Thermolyne	538	575	101	5.8	9.55	3.26	6.15	0.35	100.0	100.0	98.6	90.8	60.0	42.0	29.3	21.4	15.9	11.1	5.6
MO	43	Thermolyne	538	578	185	5.8	11.07	3.26	7.67	1.87	100.0	100.0	96.4	91.8	59.8	42.2	29.4	21.6	15.9	11.0	5.5