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# ANALYSIS OF THE HAMBURG WHEEL TRACKING DEVICE TO PREDICT BEHAVIOR OF ASPHALT MIXTURES AT DIFFERENT TEST TEMPERATURES

**Prepared For:**

Utah Department of Transportation
Research Division

**Submitted by:**

University of Utah
Department of Civil & Environmental Engineering

**Authored by:**

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Kevin M. VanFrank, P.E.
Jason N. Nielson

**October 2008**

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16. Abstract

The Hamburg Wheel Tracking Device (HWTD) has been used by Utah Department of Transportation to evaluate the asphalt mixture potential for failure in rutting and moisture damage. The test is run at 50 ºC regardless of the type of mix or the grade of asphalt binder used to prepare the mixture. This work shows that this one temperature is adequate to capture the performance of mixtures prepared with modified binders with a high temperature grade of 64 but not for mixtures prepared with high performance binders with a high temperature grade of 70. It is therefore recommended that the test temperature be raised to 54 ºC when PG 70 binders are used.

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# EXECUTIVE SUMMARY

The Hamburg Wheel Tracking Device (HWTD) has been used by Utah Department of Transportation to evaluate the asphalt mixture potential for failure in rutting and moisture damage. The test is run at 50 ºC regardless of the type of mix or the grade of asphalt binder used to prepare the mixture. This work evaluates the effect of test temperature on the results from the HWTD and their relation to potential mixture performance.
Slabs were prepared using a linear kneading compactor and tested in the HWTD at multiple temperatures. Three binder grades were evaluated, a PG 58-28 unmodified, a PG 70-28 modified with polymers and polyphosphoric acid (PPA), and a PG 64-28 obtained by blending the PG 70 and the PG 58. A second set of PG 70-28 modified with polymers but no PPA was also evaluated. The binders were obtained from two different sources common to the state of Utah resulting in a total of eight different binder combinations.

Based on the tests performed at different temperatures, it was determined that failure caused by moisture damage in the HWTD is a function of the presence of water, the wheel load, the chemistry, and the test temperature. The data shows that there is a Critical Stripping Temperature (CST) that provides the energy, in the form of heat, which reduces the stiffness and de-bonds the binder from the aggregate so stripping occurs. Below the CST, the results indicate that there will be no stripping. Depending on how the CST is determined, the difference between the CST and the binder grade is between 10 to 16 ºC for modified binders.

For the testing of mixtures prepared with modified binders, the current test temperature of 50° C does not reach the CST. Since modified binders are intended for used in environments where the pavement temperature reaches values well above 50 ºC, it was therefore concluded that a higher testing temperature is needed.

Based on the data collected, testing at the current temperature of 50 ºC is suggested for mixtures intended to be used in environments where a PG 64-XX binder is recommended. This recommendation is based on the premise that currently all HWTD tests have been done at this temperature and, by keeping this temperature, material

engineers can take advantage of the wealth of data that has been collected over the years instead of having to change the specifications. PG 64-XX is a very common high temperature binder grade for the state of Utah. However, mixtures intended to be used in an environment where a PG 70 – XX binder is recommended should be tested in the Hamburg Wheel Tracking Device at a higher temperature of 54 ºC.

The data from this work shows that a mixture prepared with a PG 58-XX binder will most likely fail the test at 50 ºC so a lower temperature of 46 ºC is recommended if warranted by the expected environment. This mixture test temperature is based on the recommended binder grade for the specific environment in which the mixtures are intended and not necessarily the actual binder grade used in the mixture.

Temperature sweeps done on the modified binders showed that a higher binder grade does not necessarily mean higher stiffness, as measured by the parameter $G^*/\sin\delta$, at the mixture test temperature. For one binder source, the PG 64-28 had a higher $G^*/\sin\delta$ than the PG 70-28 at the temperatures used for HWTD testing. This shows that the binder grades, by themselves, might not be a good indicator of total mixture performance. Binder tests were unable to match the results obtained from the mixture test, even at the same temperature.

Finally, even though some literature suggests that Polyphosphoric acid (PPA) added to the binder improves the moisture performance of the mix, this was not the case for the binders and aggregates used in this research as no difference in performance was observed between the PG70-28 binders modified with and without phosphorous. It is clear that the issue of chemistry is a complex variable in all work that relates to mixture performance. More work is needed to confirm how the chemistry of a binder affects its performance in terms of rutting and moisture susceptibility and the possible benefits of lime or anti-stripping agents.

# 1.0 Introduction

The Hamburg Wheel Tracking Device (HWTD) is used to evaluate the performance of hot-mix asphalt (HMA) at high in-service temperatures for rutting and moisture susceptibility. The test starts by placing two asphalt slabs, 320 mm (12.5 in) long by 260 mm (10 in) wide, which are prepared to be representative of paving asphalt, in a high temperature water bath. While submerged, one steel wheel for each slab is tracked back and forth over the surface and the depth of the wheel imprint is measured at each pass and stored electronically. The steel wheel has a diameter of 203.5 mm (8 in) and a width of 47 mm (1.8 in). A fixed load of 685 N is applied at a rate of 52 ± 2 wheel passes per minute. The speed of the wheel changes from zero at the end of the slab to a maximum value at the middle. Also, the contact area of the wheel increases as the rut depth increases thus the contact stress is variable with an average static value of 0.73 MPa. The actual testing takes approximately 6.5 hours [Romero and Stuart 1998].

The HWTD was developed in Hamburg, Germany in the 1970's, and has been used by the Federal Highway Administration (FHWA) along with many state agencies, including the Utah Department of Transportation (UDOT), as a way to test an asphalt mixture's susceptibility to rutting and moisture damage. Through the years, there have been significant improvements to the test procedures in an effort to reduce variability caused by sample preparation as well as consideration of the wheel speed. However, for the most part, this test is considered by many as a pass-fail screening test capturing only gross differences in mixture performance. The intent of the test is to eliminate asphalt mixtures with potential for poor performance in terms of rutting and moisture damage. It is not intended to provide detailed performance predictions (e.g., 5-mm rut in 6 years).

To analyze the data, the depth in millimeters that the wheel sinks into the slab or rut depth is represented on the Y axis of a graph, while the pass number is represented on the X axis. Initially, the graph shows an increase in rut depth representing initial compaction. As the test progresses the rut depth increases at a constant rate. If moisture damage is present, a typically flat creep line becomes a steep line of stripping. The point in which the tangents of these two lines intersect is known as the stripping inflection point. This point describes the number of passes an asphalt sample can withstand at a given temperature before the rock and binder begin to separate (or strip) from each other. If a slab withstands 20,000 passes without stripping and has less than 10 mm of rutting, the mixture is considered adequate.  Figure 1 shows a schematic of the results while figure 2 shows actual results from a slab tested in the HWTD at the University of Utah. The test results show initial compaction at the start, an inflection point around 16,500 passes, and a final rut depth of about 16 mm.

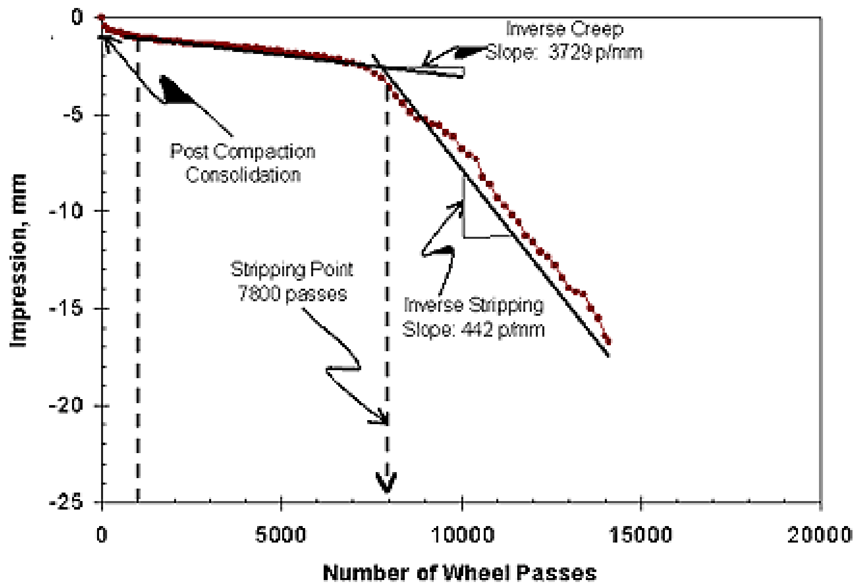


**Figure 1: Schematic of the Hamburg WTD results from Romero and Stuart, 1998**

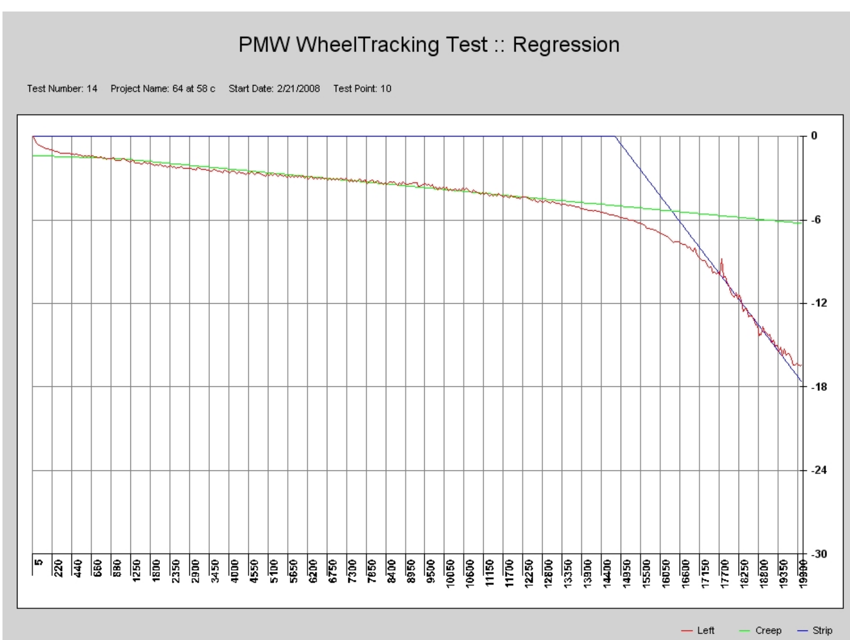


**Figure 2: Results from a HWTD test**

## 2.0 Objectives

The most commonly used test temperature in the HWTD by both state and federal agencies is 50º C. This temperature was selected based on research done by Colorado Department of Transportation prior to the Performance Grade system being adopted by highway agencies [Aschembrener, et al., 1994; Aschembrener, 1995]. Currently, Utah Department of Transportation (UDOT), Manual of Instruction (MOI) Part 8 Section 990 specifies that the same temperature of 50 ºC be used for testing in the HWTD regardless of the type of mix, the grade of asphalt binder being tested, or the intended environment for the material.

This work attempts to evaluate the validity of existing test protocols in terms of test temperature. The objectives of this work are:

- to evaluate the effect of test temperature on the results from the HWTD and its effect on the prediction of potential mixture behavior and,
- to determine if different temperatures are needed when modified or high-performance grade binders are used.

The hypothesis throughout this work is that the performance of different grades of asphalt binder within a mixture will be affected by the temperature at which they are tested in terms of rutting and moisture susceptibility. Therefore, a single testing temperature cannot adequately evaluate the performance of mixtures prepared with different binder grades and used in different environmental conditions.

## 3.0 Test Procedures

### 3.1 Materials

In order to minimize variables, a single aggregate source and aggregate gradation was used. A dense-graded aggregate gradation, shown in figure 3, was mixed with a binder content of 4.7% by total mass of the mixture. The aggregate was obtained from a pit source in central Utah. This aggregate was selected because it is a soft limestone with a known history of stripping, thus representing a 'worst case scenario'.

Two asphalt binder sources were used as a way of comparing and confirming results between typical binder grades. These two sources are from common suppliers in Utah. The first asphalt binder source used in testing is referred to as Binder A and the second is referred to as Binder B. Binder A comes from a single base source which originates in Canada. Binder B uses the same base, but is blended at the terminal with material from other sources. The base asphalt binders were modified by the suppliers to obtain a PG 70-28. The PG 70-28 and the base PG 58-28 were blended by UDOT to obtain a PG 64-28 according to UDOT specifications. UDOT specifications have additional requirements for asphalt binders from those listed on the AASHTO M320. UDOT requires that the asphalt binders have a minimum value of phase angle. This means that a PG 70-28 graded according to UDOT specifications might results in a higher grade (i.e., PG 76-28) if only AASHTO M320 requirements are follow. In this report, the binders will be referred as PG 70-28, PG 64-28, and PG 58-28 with the understanding that these are based on UDOT specifications. The test results from each binder are shown in Appendix A.

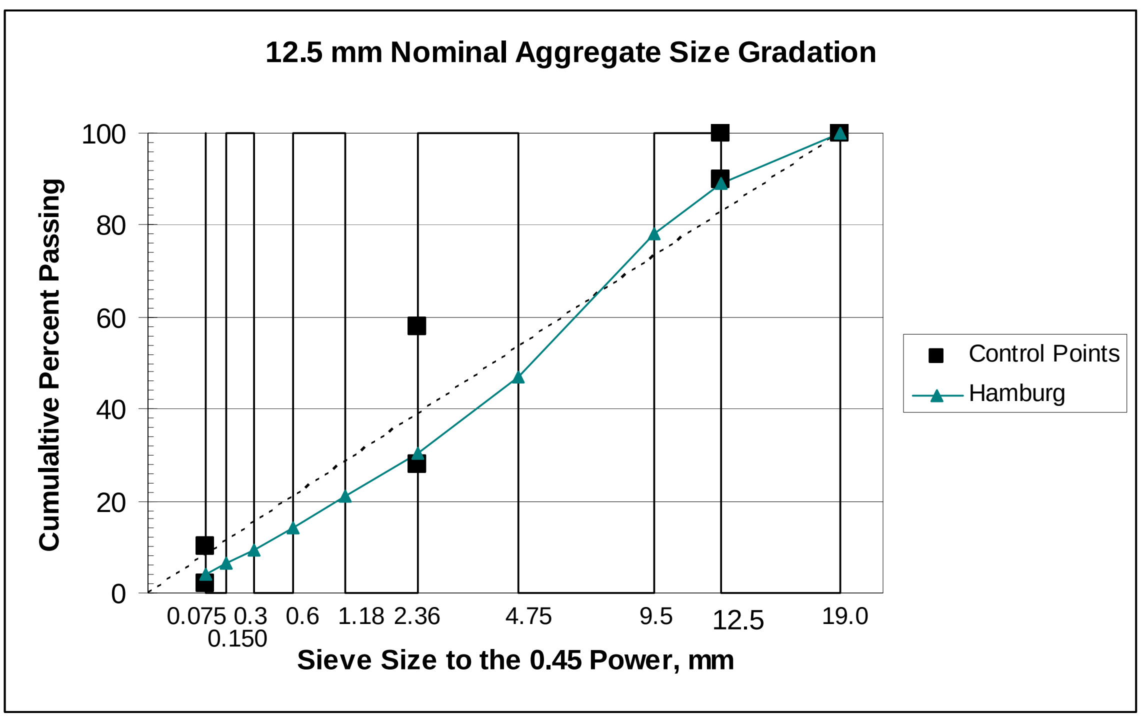


**Figure 3: Aggregate gradation used in this study**

## 3.2 Sample Variability

One of the concerns regarding the results from the HWTD is the inherent variability of the results [Izzo and Tahmoressi, 1999]. UDOT has been working to address this issue by establishing consistent protocols for sample preparation, sample conditioning, and testing. Data collected as part of this effort has shown that when protocols are followed in a consistent manner, the coefficient of variation in the results of rut depth measurements between different laboratories falls below 0.30 [VanFrank, 2006; Anderson and VanFrank, 2007]. These protocols have been outlined in the UDOT Manual of Instructions (MOI) and follow AASHTO standards.

Before formal testing was performed, staff from the University of Utah trained at the UDOT Central laboratory; UDOT engineers inspected the university's laboratory, and traded samples for variability testing between both labs. The Job Mix Formula (JMF) for optimum aggregate gradation and optimum binder content were provided by UDOT in accordance with the Superpave volumetric mix design procedures. The volumetrics were verified at the University of Utah's Bituminous Materials Laboratory prior to testing. In addition, testing for maximum theoretical specific gravity and percentage air voids in the sample slabs were conducted throughout the research testing. Air void criteria are generally accepted as 7% ± 1 for HWTD testing. However, for this research the goal of 7% ± 0.5 was set and achieved as discussed next.

## 3.3 Analysis of Air Voids

Analysis of data has shown that to obtain consistent results in the HWTD it is important to control not only the total air voids but also the distribution of the air voids within a slab. A large variation of air voids within a slab is an indication of lack of compaction uniformity and possibly poor laboratory practices. Thus, before any testing was conducted, slabs were fabricated and an analysis of the air voids distribution within a slab was conducted.

Two slabs were prepared using loose mix obtained from a local plant. The loose mix was heated and the slabs were compacted following UDOT protocols. The slabs were allowed to cool and cut into 8 pieces. The air voids of each individual piece were measured.  Figure 4 shows how the pieces were cut and the difference in air voids from the overall voids of each piece.

Overall Voids: 12.13 %

| | |
|---|---|
| +3.43 | +1.99 |
| +2.37 | +3.55 |
| +2.91 | +2.28 |
| +2.31 | +1.96 |

Overall Voids: 8.57 %

| | |
|---|---|
| +2.87 | +2.22 |
| +2.79 | +2.71 |
| +2.15 | +2.52 |
| +2.69 | +2.70 |

**Figure 4: Distribution of air voids within slabs prepared from loose mix.**
**The numbers indicate the difference in percent air voids from the overall void in the slab.**

Figure 4 shows that cut pieces have about 2.5% higher voids than the overall slab.  This is caused by the introduction of cut surfaces on one or two sides of each cut piece.  The first slab, shown on the left, has a range of air voids of $\pm$ 0.79 %.  The second slab, shown on the right shows a range of air voids of $\pm$ 0.36%.  Also, just as important, is the lack of any gradients indicating non uniform areas.  As the lab personnel became more proficient in the protocols for preparing slabs, the uniformity of the samples increased.  A final check of uniformity was made using the aggregates used as part of this research and Binder A.  The material was mixed and compacted using established protocols.  Once the slab was cooled, it was cut into 12 pieces discarding the edges so that all pieces had 4 cut faces.  The air voids for each individual piece was measured and compared to the overall voids and to each other.  The results are shown in figure 5. This figure shows that the laboratory at the University of Utah can consistently achieve the target air voids of 7% and that the protocols for mixing and compaction result in a uniform slab with a range of internal voids of $\pm$ 0.58%.  Further testing confirmed that the range of total air voids of each of the slabs tested was 7% $\pm$ 0.5.

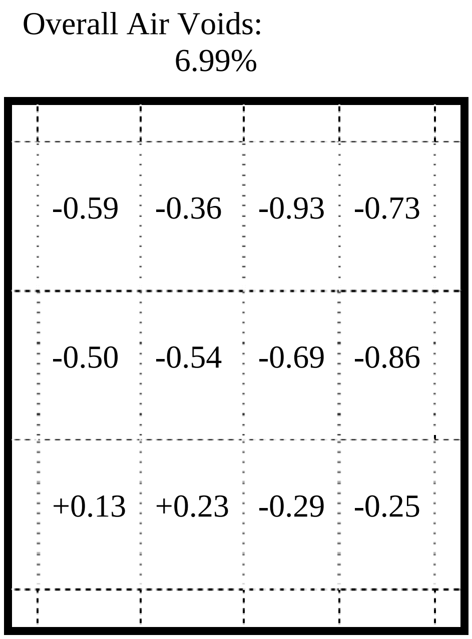


**Figure 5: Distribution of air voids within slabs prepared using the research material. The numbers indicate the difference in percent air voids from the overall slab.**

### 3.4 Test Protocols

The guidelines for laboratory mixing of HMA section 988 from UDOT's MOI were followed to prepare the HMA, excluding section 988.06 and 988.07, the sections for lime and RAP. The guidelines for compaction and HWTD testing section 990 from the MOI were used to prepare and test the asphalt slabs. The binder supplier recommended temperatures were followed during preparation of each slab depending on the grade. The temperature of the water bath in the HWTD varied for each test.

## 4.0 Results

### 4.1 Data Acquisition and Analysis

As discussed in the introduction, both the load and speed of the wheel vary during the test. Asphalt materials are visco-elastic and thus a different response is expected at the center of the slab, where the speed is highest, than at the end where the speed is zero. To allow for this difference, 11 points are collected during each wheel cycle, some points representing a more severe condition. Figure 6 shows results from Binder A, PG 70-28 at 55 ºC. The different lines represent the rut depth at a different location along the wheel path. Lines 5, 6 and 7, measured at the middle of the slab, show the deepest rut. Line 1 shows the least rutting while the others show values somewhere in between.

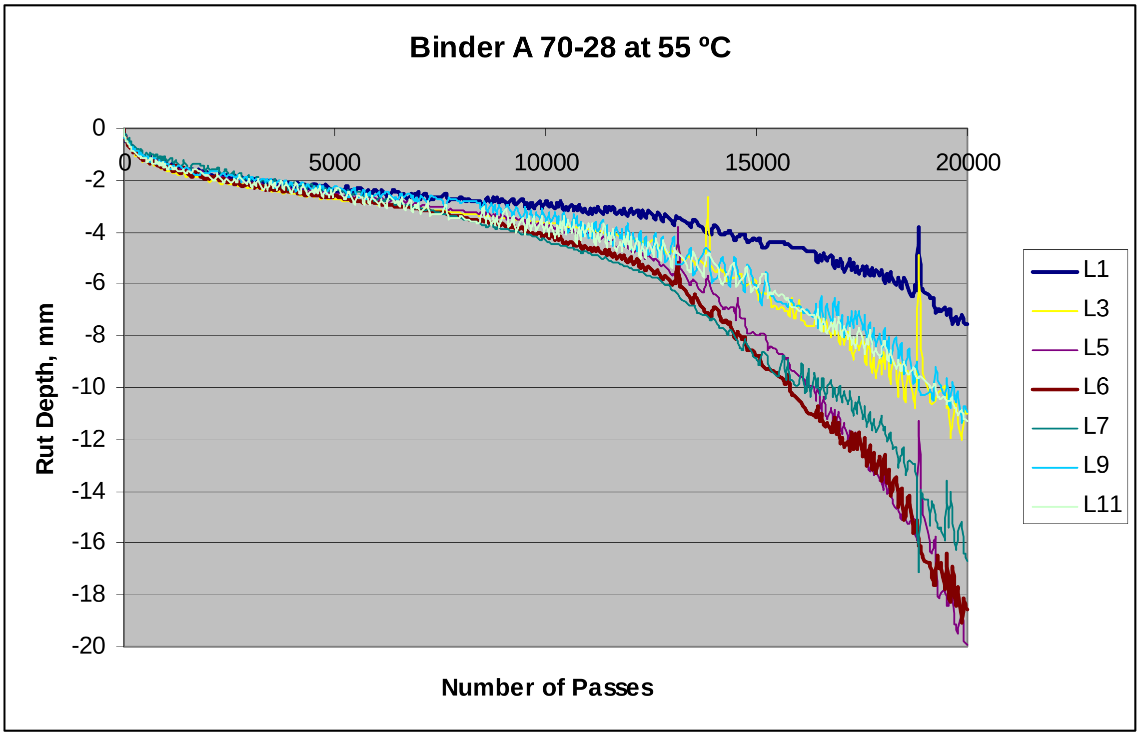


**Figure 6: Rut depth measured at different locations throughout the path of the wheel.**

From figure 6 it can be seen that the maximum rut depth and the stripping inflection point can vary depending on where the data is acquired. The maximum deformation might actually occur at a location other than the middle. For acceptance, UDOT specifies maximum rut depth, regardless of location. In this work, for consistency, the analysis of data was done using location 6. All values in this report are based on this location.

## 4.2 Critical Stripping Temperature

The first asphalt mixture tested contained Binder A, PG 70-28. As expected, the trend shows that the asphalt performed better in both resistance to rutting and resistance to stripping as the temperature decreased. However, as shown in figure 7, the results indicate that there is not a monotonic change in post-failure performance as the temperature changes (i.e., the material seems to perform better at 60 ºC than at 58 ºC). Instead, two distinct behaviors are observed, one in which the material shows no signs of moisture damage and another in which the material shows significant moisture damage.

Such difference in behavior is attributed to a critical temperature that causes the material to change. Below this critical temperature the material responds by deforming based on its structural stability but shows no stripping. Above this temperature, the material changes and the asphalt is stripped from the aggregate; the material literally disintegrates showing catastrophic failure.

The critical temperature for stripping is referred in this report as the Critical Stripping Temperature (CST). From figure 7, it can be determined that the CST for Binder A PG 70-28 is between 54 ºC and 56 ºC.

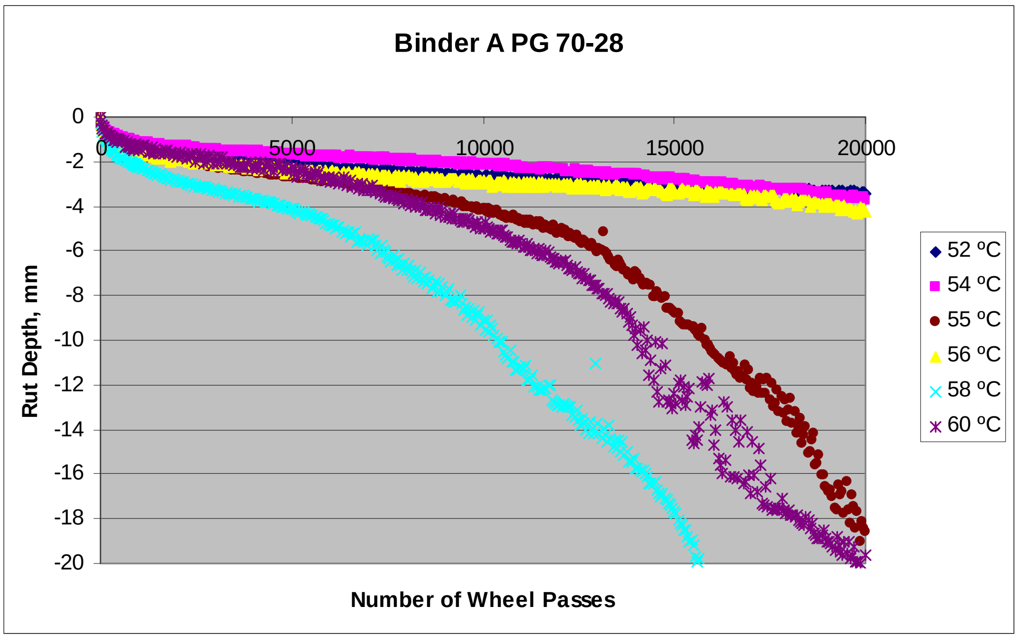


**Figure 7: Test results from binder A 70-28 at different temperatures**

A large amount of data was collected on Binder A PG 70-28 in an attempt to find a relationship between the temperature and the number of passes before the asphalt stripped. These results are shown in table 1. Each test consists of two slabs. Detailed analysis of the data collected indicated that there were some problems with the data acquired on one side of the machine. Several attempts were made to try and determine the cause of the problem. Unfortunately, while diagnostics were being performed, significant amount of data was collected in the process. Due to this uncertainty in rut depth measurements, the data for both slabs is reported in the table but only the data for the left slab is shown on the graphs. This in no way affects the analysis since stripping is self evident and not subjected to interpretation of any measurements; if there is gravel instead of mix then the mix stripped.  Table 1 shows essentially the same results as figure 7.  The CST for Binder A PG 70-28 is estimated as 55 ºC.

Based on the data collected on Binder A PG 70-28, it was determined that a given binder grade blended with a specific aggregate source has a transitional temperature of one or two degrees. It is hypothesized that during stripping there are at least two mechanisms at work: as the temperature increases, the energy reaches a value high enough to de-bond the binder from the aggregate; this effect is further confounded by the decrease in binder stiffness allowing the binder to be forced and displaced by water.  At lower temperatures, the hydrostatic stresses caused by the wheel forcing the water into the mix are not always enough to break the bond and displace the asphalt binder from the aggregate.  However, once enough energy is available in the form of heat the mixture will likely strip.

**Table 1: HWTD testing on binder A, PG 70-28**

| Binder | Binder Grade | Test Temp. ºC | # passes to Inflection | | Max Rut Depth | |
|---|---|---|---|---|---|---|
| | | | Left Slab | Right Slab | Left Slab | Right Slab |
| A | 70 -28 | 52 | No Stripping | No Stripping | < 5 | < 7 |
| A | 70 -28 | 54 | No Stripping | No Stripping | < 4 | < 7 |
| A | 70 -28 | 55 | < 16,000 | < 19,000 | > 12 | < 7 |
| A | 70 -28 | 56 | No Stripping | < 16,000 | < 6 | > 12 |
| A | 70 -28 | 57 | < 10,000 | < 10,000 | > 22 | > 24 |
| A | 70 -28 | 58 | < 12,000 | < 8,000 | > 24 | > 24 |
| A | 70 -28 | 60 | < 14,000 | < 16,000 | > 20 | > 14 |

Stripping is a catastrophic failure mode, resulting from the material undergoing compositional changes.  Thus it is argued that, after stripping, the rut depth has no physical meaning since it represents the behavior of a different material than the one originally prepared.  Only a mixture that does not strip can be evaluated based on its rut depth, a mixture that strips simply fails and should be rejected.

Table 2 shows the results for the rest of the binders.

**Table 2: HWTD testing on remaining binders**

| Binder | Binder Grade | Test Temp. | # passes to Inflection | | Max Rut Depth | |
|---|---|---|---|---|---|---|
| | | | Left Slab | Right Slab | Left Slab | Right Slab |
| A | 64 -28 | 50 | No Stripping | No Stripping | < 5 | < 6 |
| A | 64 -28 | 54 | No Stripping | No Stripping | < 5 | < 5 |
| A | 64 -28 | 55 | < 15,000 | No Stripping | > 16 | < 7 |
| A | 64 -28 | 56 | < 16,000 | < 15,000 | > 16 | > 22 |
| A | 64 -28 | 58 | < 14,000 | < 10,000 | > 16 | > 30 |
| | | | | | | |
| A | 58 -28 | 49 | No Stripping | < 20,000 | < 5 | < 9 |
| A | 58 -28 | 51 | < 14,000 | < 14,000 | > 24 | > 24 |
| A | 58 -28 | 53 | < 10,000 | < 14,000 | > 30 | > 20 |
| A | 58 -28 | 55 | < 10,000 | < 12,000 | > 30 | > 24 |
| | | | | | | |
| B | 70-28 | 51 | No Stripping | < 20,000 | < 7 | < 13 |
| B | 70 -28 | 53 | No Stripping | < 20,000 | < 7 | < 10 |
| B | 70 -28 | 55 | < 12,000 | < 16,000 | > 30 | > 18 |
| | | | | | | |
| B | 64-28 | 47 | No Stripping | No Stripping | < 5 | < 10 |
| B | 64 -28 | 49 | < 19,000 | < 19,000 | < 12 | < 12 |
| B | 64 -28 | 51 | < 14,000 | < 16,000 | > 30 | > 22 |
| B | 64 -28 | 52 | < 11,000 | < 11,000 | > 30 | > 24 |
| B | 64 -28 | 54 | < 8,000 | < 12,000 | > 30 | > 20 |
| | | | | | | |
| B | 58 - 28 | 45 | < 16,000 | No Stripping | > 30 | < 8 |
| B | 58 -28 | 47 | < 12,000 | < 16,000 | > 30 | > 20 |
| B | 58 -28 | 49 | < 14,000 | < 16,000 | > 30 | > 18 |

## 5.0 Analysis

The first observation, as seen in table 2, is that there is not a clear trend between the number of passes to the stripping inflection point and the test temperature. There is either enough energy in the temperature of the water to cause the slab to strip and fail, or there is not. Failure can occur within a range of less than 8,000 passes to less than 18,000 passes and does so independent of temperature or binder grade as long as that temperature is above the critical stripping temperature (CST). In other words, once all of the conditions for stripping are present, the material will fail.

This apparent random behavior in the number of cycles to reach the stripping point is likely due to the material undergoing internal changes as the flaws grow and coalescence, eventually resulting in total material failure. As it is often seen in tests were the material is taken to failure (e.g., strength), the response is dependent on the random location of internal flaws. Thus, complex statistical distributions are needed to predict the material's behavior [Weibull, 1951; Tvergaard, 1989]. As mentioned in the previous section, once the material fails the test, it is an indication that this combination of asphalt and aggregates are not compatible and should not be used in that environment.

From tables 1 and 2, the temperature 'CST' was determined for each performance grade and binder source. This is the temperature below which no stripping was observed and above which there was stripping.

## 6.0 Discussion

Table 3 shows that there is a general trend in that the higher the performance grade of the binder, the higher the CST. This relation is further explored in figure 8. The figure shows both performance grade based on UDOT specs versus the CST and the Continuous Grade (temperature at which $G^*/\sin\delta$ equals 2.2 kPa on RTFOT residue material) versus the CST. As the trendline shows, there is a fair relation, with an R-squared of 0.81, between the CST and the continuous binder grade. If the UDOT binder grade (i.e., discrete values of 58, 64, and 70) is used, the R-squared between the CST and binder grade drops to 0.72. This indicates that binder grade contributes to some, but not all, of the performance of a mixture tested in the HWTD.

**Table 3: Critical stripping temperature**

| Binder Performance Grade Based on Utah Specs | Critical Stripping Temperature. ºC | |
|---|---|---|
| | Binder A | Binder B |
| 70 -28 | 55 (PG - 15*) | 54 (PG - 16) |
| 64 -28 | 54 (PG - 10) | 49 (PG - 15) |
| 58 -28 | 49 (PG - 9) | <45 (PG - 14) |

***The number in parenthesis represents the difference between the UT PG and the CST**

One notable exception to the relation between binder grade and CST is the mixture prepared with Binder A where there is no significant difference, in terms of the CST, between the modified binders PG 70-28 and PG 64-28. This was not seen in Binder B where the CST varied almost linearly with the binder grade. Furthermore, Binder A 64-28 and Binder B 64-28 had significantly different CST even though they are expected to perform the same. It is hypothesize that the temperature difference between the CST of Binder A PG 70-28/64-28 and Binder B PG 64-28 is probably due to the temperature stiffness relation of each binder. The temperature-stiffness relation of the modified binders was studied as part of this work and is discussed on the next section.

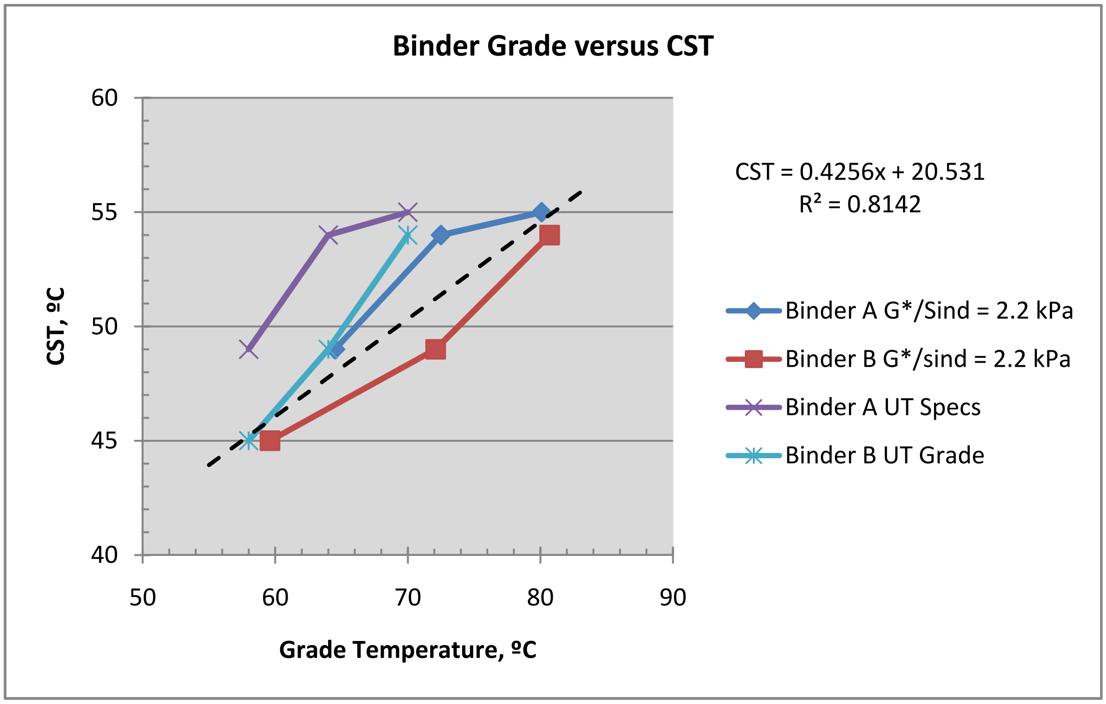


**Figure 8: Relation between CST and Binder Grade**
**The trendline and relation shown is for continuous grade and CST**.

## 6.1 Binder Temperature-Stiffness Relation

In the Superpave performance grading system the binders are tested at a specific temperature that represents the maximum temperature for a given environment. In other words, the PG 64-28 was tested only at 64 ºC and 70 ºC. These temperatures are about 14 ºC higher than the temperature used for the HWTD tests. As shown in figure 8, the stiffness of the binder contributes to some, but not all, of the observed performance. To verify the extent to which the results are affected by the stiffness of the binder, temperature sweeps were run on the modified binders to measure $G^*/\sin\delta$ and non-recoverable creep compliance, Jnr, from the Multiple Stress Creep Recovery (MSCR) test. The results of these tests are summarized in table 4. Complete results are shown in Appendix C.

Figure 9 shows the temperature-stiffness relation in terms of $G^*/\sin\delta$ for the modified binders along with the CST. This figure shows that Binder A PG 70-28 has a higher stiffness, at any temperature, when compared to the rest of the binders. This explains why it has the highest CST. At temperatures above 56 ºC, Binder B PG 70-28 has higher stiffness than Binder A 64-28 (as it should since there is a grade difference between them) but this relation reverses at the lower temperatures where HWTD tests are conducted. This reversal in stiffness helps explain why there was no difference in performance between both binders and both had similar CSTs.

**Table 4: Binder properties at the Critical Stripping Temperature**

| Binder | Performance Grade | $G^*/\sin\delta$ at CST(1) kPa | % Recovered strain (100 Pa) at CST(1) |
|---|---|---|---|
| A | 70-28 | 23.9 | 60.0 |
| | 64-28 | 15.3 | 43.4 |
| B | 70-28 | 14.9 | 56.6 |
| | 64-28 | 21.4 | 44.0 |

**(1) CST from Table 3**

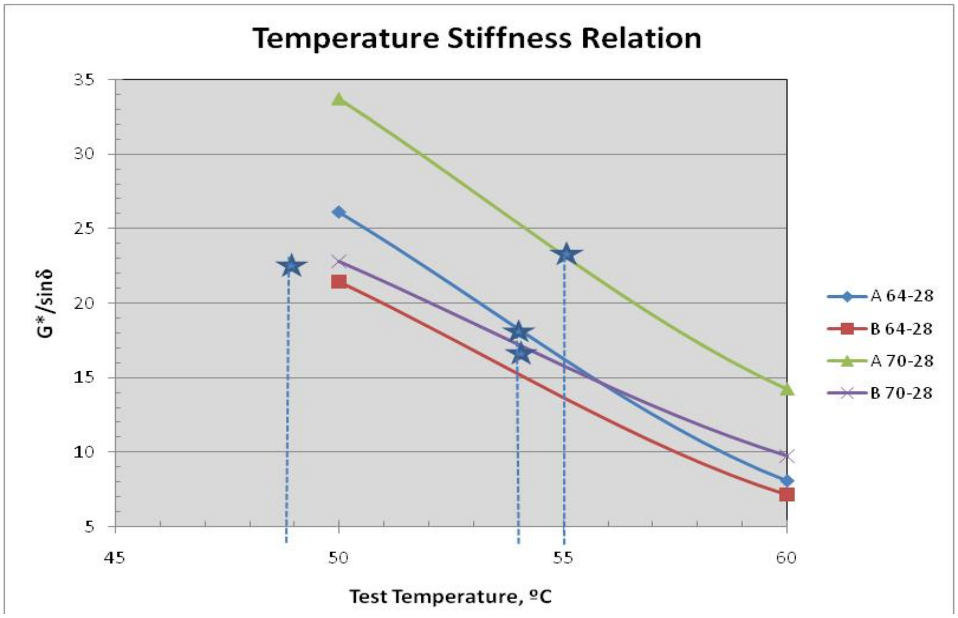


**Figure 9: Temperature-stiffness relation for the modified binders.**
**The dotted lines with stars represent the CST of each binder.**

It is also clear from figure 9 that binder stiffness alone cannot explain the results from the HWTD. Binder B 64-28 has a higher stiffness at the CST than both Binder A 64-28 and Binder B 70-28 (23 kPa versus 18 kPa). In other words, binder stiffness is not enough to predict moisture susceptibility of the mixtures tested in the HWTD. This reinforces the belief that moisture susceptibility results from a lack of compatibility between binders and aggregates. It is believed that the chemistry involved in the modification also plays a role in the binder-aggregate bond. Unfortunately, the proprietary nature of the modification process did not allow the research team to further evaluate the chemistry of each binder tested.

## 6.2 PolyPhosphoric Acid

There is evidence in the literature that PolyPhosphoric Acid (PPA) can increase the bonding energy between binder and aggregate on certain systems [Kodraft, et al., 2007]; some literature shows that values of PPA above 0.2% are sufficient to increase this bond [Orange et al., 2004]. As shown in table 5, it was determined that both binder sources used in this study contained phosphorous, some of it in the form of PPA. If indeed the PPA increases the bonding between binder and aggregate, it might influence some of the results from this research.

**Table 5: Percentage of Phosphorus by weight**

| Binder Performance Grade Based on UDOT Specs | Phosphorus by weight (%) | |
|---|---|---|
| | Binder A | Binder B |
| 70 -28 | 0.51 | 0.68 |
| 64 -28 | 0.29 | 0.49 |
| 58 -28 | 0.01 | 0.01 |

To verify the effect of PPA on the results, new mixtures were prepared using PG 70-28 binders from both sources but manufactured without phosphorous –and thus no PPA-. Slabs were prepared with the no-PPA binders from both suppliers and the CST was determined. The results, shown in table 6, indicate that there is only about a one degree difference in terms of CST between the binder containing PPA and the one without PPA. It is not believed that the HWTD test is sensitive enough to capture such small different in performance.

Figure 10 shows a comparison for Binder A PG 70-28 with and without PPA. The test temperature was 54 ºC, which is below the CST and no stripping is expected. As can be seen, the mixture with PPA shows less than 4-mm rut with a gradual inflection point around 17,000 passes. The mixture without PPA shows a final rut that is 2-mm deeper with a slightly steeper stripping slope. This is a small difference in performance believed to be the result of the PPA creating a slightly stiffer binder (see discussion on previous section). Unfortunately, the complex chemistry involved did not allow the research team to evaluate if the PPA created a stronger bond between aggregate and binder. Given that the amount of PPA exceeds the minimum values recommended in the literature it is believed that, for this aggregate-binder combination, the effects of PPA are too small to be evaluated using the HWTD. Thus, it is unclear what benefit, if any, PPA would have on mixture performance.

**Table 6: Critical stripping temperature for mixes prepared with PG 70-28 with and without phosphorous**

| | CST, ºC | |
|---|---|---|
| PG 70-28 | Binder A | Binder B |
| With Phosphorous | 55 | 54 |
| Without Phosphorous | 54 | 53 |

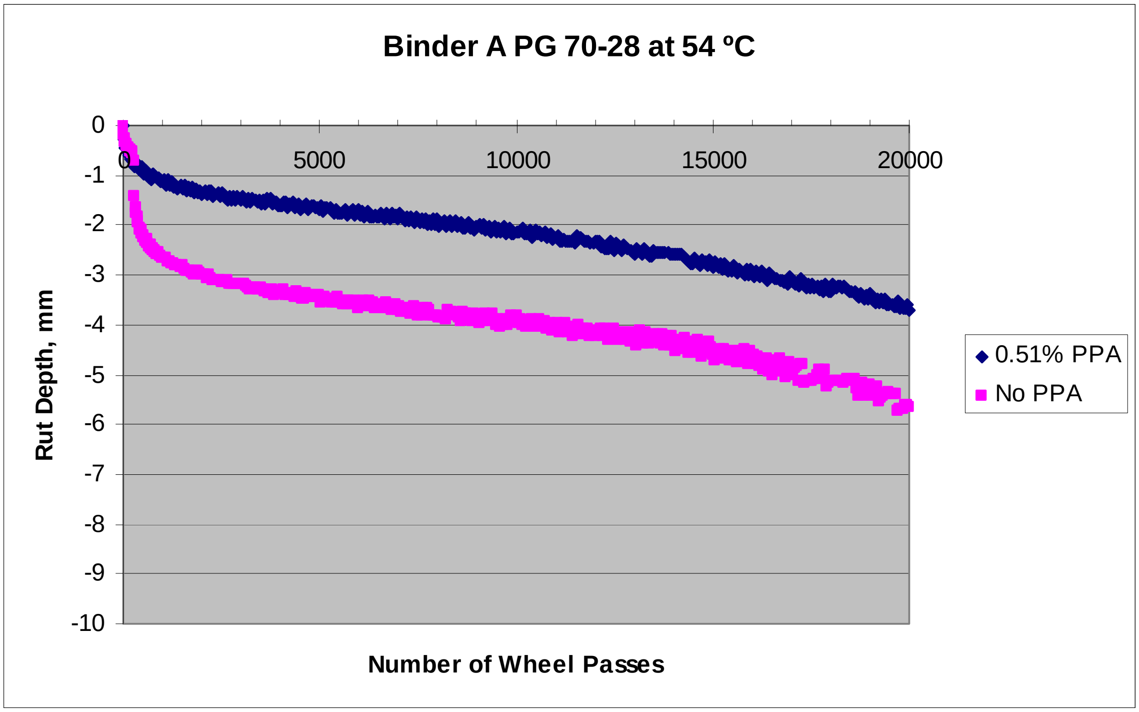


**Figure 10: Comparison between mixtures prepared with and without PPA.**

## 6.3 Determination of Testing Temperature

The data shown in figure 8 suggests that asphalt mixtures prepared with modified binders (PG 70-28 and PG 64-28) would show no moisture susceptibility when tested at the current temperature of 50 ºC yet they would strip if the temperature is increased by 5 ºC. The obvious question then becomes what is an appropriate test temperature for mixtures prepared with these binders?

There are many arguments that can be made to select an appropriate test temperature. One argument can be to select the test temperature based on the CST of the material. In such case the test temperature can be determined using the relations developed using the data in figure 8:

$$\text{HWTD Test Temp} = T_{G^*/\sin\delta=2.2kPa} * 0.42 + 20.5 \qquad \text{Equation 1}$$

$$\text{HWTD Test Temp} = \text{UT Grade} * 0.62 + 11 \qquad \text{Equation 2}$$

Where:

**Test Temp** is the recommended test temperature for the HWTD

$\mathbf{T_{G^*/\sin\delta=2.2kPa}}$ is the temperature at which G*/sind equals 2.2 kPa

**UT Grade** is the binder grade obtained using UDOT specifications

Using equations 1 and 2 the range in test temperature for each binder grade is shown in table 7.

**Table 7: Range of test temperature in the HWTD for different binder grades**

| Binder High Temperature Performance Grade Based on UDOT Specs | Range of Test Temperature ºC(1) |
|---|---|
| 58 | 44 – 47 |
| 64 | 50 – 51 |
| 70 | 54 |

**(1) Values from equations 1 and 2**

The range of test temperatures shown in table 7 is based on the performance grade of the binder only. It does not take into consideration the environment in which the mixture will be used. The research team believes that a better approach is to select a test temperature **<u>based on the environment for which the mixture is intended</u>**. A mixture intended for a 'hot' location should be tested at a higher temperature than a mixture intended for a 'cold' location regardless of the binder grade used.

Based on the data from LTPPBind [FHWA, 2005], pavement temperatures across the state of Utah often reach values above 50 ºC. For example, at Salt Lake City Airport the air temperature reaches 36.5 ºC and the pavement temperature reaches 57.4 ºC (7-day average high temperature); at this location the recommended binder grade, based on temperature, is PG 64-22. At the south end of the state, in St. George, the air temperature reaches 41.8 ºC and the pavement temperature reaches as high as 66.8 ºC; thus the recommended binder grade is PG 70-16.

A further consideration in selecting the test temperature is the historic data available. Significant testing has been done on mixtures using the HWTD at 50 ºC. As shown in figure 11, based on the environmental conditions in the state of Utah, the PG 64-XX is the most common binder grade used in the state. If a new test temperature is recommended, new performance relations would need to be developed and the old data would be of little or no use. Table 7 shows that the test temperature based on binder grade for a PG 64 is in the vicinity of 50 ºC. Therefore, it is reasonable to select 50 ºC as the test temperature for mixtures that will be placed on an environment for which PG 64-XX is recommended (i.e., most of the State). Maintaining the test temperature at 50 ºC takes advantage of the wealth of information available from many years of testing.

However, both the results from this research and pavement temperature data suggest that when a PG 70-XX binder is used, the test temperature should be increased. With CSTs of 55 ºC and 54 ºC for binders A and B, respectively, and a test temperature of 54.4 ºC based on equation 2; a test temperature of 54 ºC should be used in the HWTD. As shown in this report, tests have been performed at this temperature with successful results.

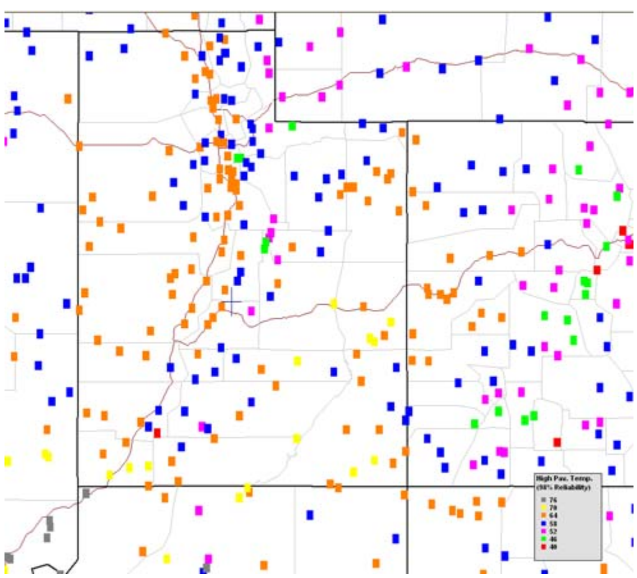


**Figure 11: High temperature binder grade distribution in Utah (>98% reliability)**

It is important to recognize that the selection of test temperature for the HWTD is based on the **<u>recommended binder for the environment</u>** and not the actual binder grade used in the mix. There might be some circumstances where a PG 58-XX is used in an environment where the recommended grade is PG 64-XX. In such cases the temperature for HWTD testing should be 50 ºC.  LTPPBind allows for the determination of pavement temperature at different depths; in cases where the mixture will be placed below the surface, the recommended temperature grade at the specific depth should be selected. This is critical given that stripping often occurs at intermediate layers.

## 7.0 Conclusions

Based on the data collected as part of this work, it is evident that failure caused by moisture damage in the HWTD is a function of the presence of water, the wheel load, the temperature, and the compatibility between the aggregate and the binder.  In other words, there is a mechanical component of the water displacing the binder and a bonding component between the aggregate and the binder.  These components are affected by the temperature of the test.  Specifically, the data shows that there is a critical stripping temperature (CST) below which the tests would indicate that there will be no stripping regardless of the actual stripping potential of the binder-aggregate combination.

For the testing of mixtures prepared with binders modified with polymers and with and without PPA, a test temperature of 50° C does not reach the CST.  Depending on how the CST is determined, the difference between the CST and the binder grade is between 10 to 16 ºC for modified binders.  Obviously, the specific numbers from this research are system dependent; different aggregates sources in combination with these binders will most likely have different CSTs.  Binders with different chemical formulation will most likely have different CSTs too.  However, the CSTs outlined here are believed to be the low limits based on the understanding that the aggregate used was prone to failure in the field and no lime or anti-stripping agent was used.  It is evident, nonetheless, that modified binders are intended for use in high temperature environments and so higher temperature testing is critical.

Under identical test conditions, mixtures made with binders of the same performance grade from two different manufacturers performed differently at every tested temperature.  It was shown that, while the binders had the same performance grade, their temperature-stiffness relation was different and what was believed to be a stiffer binder actually had a lower value of $G^*/\sin\delta$ at the mixture test temperature.  It is therefore concluded that testing of binders using current Superpave methods or even the Superpave plus methods used by UDOT cannot determine the moisture susceptibility of a mixture the way a HWTD test does.

Literature suggests that PPA creates a bond that is independent of binder grade and might improve performance. There was no evidence of such change in performance of the binders and aggregates used in this research. The issue of chemistry is a complex variable that affects all work related to mixture performance. More work is needed to confirm how the chemistry of a binder affects its performance in terms of rutting and moisture susceptibility and the possible benefits of lime or anti-stripping agents.

## 8.0 Recommendations

Based on the conclusions obtained from this work, it is recommended that standard protocols be revised and new HWTD tests at higher temperatures be adopted to ensure that future HMA projects do not contain aggregate-binder combinations that are susceptible to both rutting and moisture damage. The following recommendations are made:

- For mixtures intended to be used in a location where the recommended binder is PG 64-XX, a test temperature of 50 ºC is suggested. This recommendation is based on the premise that currently all HWTD tests are done at this temperature. By keeping this temperature, material engineers can take advantage of the wealth of data that has been collected over the years. PG 64-XX is perhaps the most common binder grade used in Utah.
- For mixtures intended to be used in a location where the recommended binder is PG 70-XX, the test temperature should be raised from 50° C to 54° C. By performing HWTD tests at 54 ºC, potentially poor performing mixtures can be identified.
- The data from this work shows that a mixture made with a PG 58-XX binder will most likely fail the test at 50 ºC so a lower temperature of 46 ºC is recommended.

The HWTD test temperatures discussed above are based on the <u>recommended binder grade</u> for the given environment regardless of the actual binder grade used in the mixtures. The recommended binder grade can be easily found using LTPPBind Software available at the following website:

http://www.fhwa.dot.gov/pavement/ltpp/product.cfm

Further testing on how chemistry affects the results of binder-aggregate interactions in the HWTD, including the addition of lime or anti-stripping agents, should be conducted. The relation between the recommended test temperature, the number of passes for evaluation, and the actual pavement performance should be monitored and adjusted once field data becomes available.

## 9.0 References

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# **Appendix A**

Binder Test Results

UDOT
CONNECTING COMMUNITIES

Materials Division - Asphalt Binder Lab
4501 South 2700 West
Salt Lake City, UT 84114-5950

Date Tested: **12/16/2007**
Sample ID: **74-W**
Technician(s): **K McKinney**
Algebraic Difference: **86**
Project Number:
Project Name: **UofU Hamburg Research 07**

Supplier: Binder B
Material Grade: **PG58,-28**
Date Sampled: **9/17/2007**
Date Received: **9/17/2007**

Notes, and Information: **Phosphorus content .01% Wt. %**

| | | PG58, | | | | PG64 | | | | PG70 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -22 | -28 | -34 | -40 | -22 | -28 | -34 | -40 | -22 | -28 | -34 |

## ORIGINAL BINDER

| ORIGINAL BINDER | PROCEDURE | PG58 | | PG64 | PG70 |
|---|---|---|---|---|---|
| **Flash Point Temp** Min. 230°C | AASHTO T48 | | | | |
| **Rotational Vis.** 3 Pa.s (3000 cP) Test Temp 135.0°C | AASHTO T316 | **276** | | | |
| **Specific Gravity** Temp 15.6°C | AASHTO T228 | | | | |
| | | 58.0°C | | 64.0°C | 70.0°C |
| **Dynamic Shear** | AASHTO T315 | | | | |
| Test Temp @10 rad/sec, °C | | | | | |
| Algebraic Difference less than 92°C | | | | | |
| G*/sin delta, 1.00 kPa min. | | **1.093** | | **0.5461** | |
| Algebraic Difference of 92°C | | | | | |
| G* (Complex Modulus), 1.30 kPa min. | | **1.092** | | **0.5460** | |
| Phase Angle (delta), 74 degrees max. | | **87.20** | | **89.10** | |
| G*/sin delta, 1.00 kPa min. | | **1.093** | | **0.5461** | |
| Algebraic Difference of 98°C | | | ***Tcrit = 59.02°C*** | | |
| G* (Complex Modulus), 1.30 kPa min. | | | | | |
| Phase Angle (delta), 71 degrees max. | | | | | |
| G*/sin delta, 1.00 kPa min. | | | | | |
| Algebraic Difference Greater Than 92°C | | | | | |
| **Toughness** 75 in-lbs min. | ASTM D5801 | | | | |
| **Tenacity** 50 in-lbs min. | ASTM D5801 | | | | |

## RTFO RESIDUE

| RTFO RESIDUE | AASHTO T240 | 58.0°C | | 64.0°C | 70.0°C |
|---|---|---|---|---|---|
| Mass Change, 1.00% max loss | | **-0.181%** | | | |
| **Dynamic Shear** | AASHTO T315 | | | | |
| Test Temp @10 rad/sec, °C | | **G* 2.530** | | **G* 1.249** | |
| G*/sin delta, 2.20 kPa min. | | **2.544** | | **1.252** | |
| Phase Angle (delta), Report | | **84.10** | | **86.30** | |
| **Multiple Stress Creep/Recovery** | | | ***Tcrit = 59.60°C*** | | |
| Percent Recovery, 100 Pa @ High Test Temp. | | **3.45%** | | | |
| Percent Recovery, 3200 Pa @ High Test Temp. | | **0.34%** | | | |
| Difference is Percent Recovery | | **3.11%** | | | |
| **Elastic Recovery** 65, or 70% @ 25.0°C, 20cm pull, then cut | AASHTO $T301_{mod}$ | cm | | cm | cm |

## PAV RESIDUE

PAV RESIDUE — AASHTO R28
20 hrs @ 2.10 Mpa — 100.0°C | 100.0°C | 100.0°C

**Dynamic Shear** — AASHTO T315

| | 22°C | 19°C | 16°C | 13°C | 25°C | 22°C | 19°C | 16°C | 28°C | 25°C | 22°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test Temp @10 rad/sec, °C | | | | | | | | | | | |
| G*sin delta, 5000 kPa max. | | **3896** | | | | | | | | | |
| Phase Angle (delta), Report | | **46.10** | | | | | | | | | |

**BBR, Creep Stiffness** — AASHTO T313

| Test Temp @ 60 sec, °C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stiffness, 300.0 Mpa max. | | **225** | | | | | | | | | |
| m-value, .300 min. | | **0.325** | | | | | | | | | |

**Direct Tension** — AASHTO T314
Algebraic Difference Greater Than 92°C

| Test Temp @ 1.0mm/min, °C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Failure Strain, 1.5% min. | | **1.510** | | | | | | | | | |
| Failure Stress, 4.0 MPa min. | | **4.53** | | | | | | | | | |

Tested By: K McKinney
Quality Assurance Technician

Reviewed By:
Materials Engineer

UDOT CONNECTING COMMUNITIES

Materials Division - Asphalt Binder Lab
4501 South 2700 West
Salt Lake City, UT 84114-5950

Date Tested: **1/3/2008**
Sample ID: **75-W**
Technician(s): **K McKinney**
Algebraic Difference: **92**
Project Number:
Project Name: **UofU Hamburg Research 07**

Supplier: Binder B
Material Grade: **PG64,-28**
Date Sampled: **9/17/2007**
Date Received: **9/17/2007**

Notes, and Information: **71.5%** Binder B **PG70,-28 (76-W) + 28.5%** Binder B **PG58,-28 (74-W)**

**10725g + 4275g = 15000g**

| | | PG58, | | | | PG64 | | | | PG70 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -22 | -28 | -34 | -40 | -22 | -28 | -34 | -40 | -22 | -28 | -34 |

**Phosphorus content .49% Wt. %**

| **ORIGINAL BINDER** | **PROCEDURE** | PG58 | PG64 | PG70 |
|---|---|---|---|---|
| **Flash Point Temp** Min. 230°C | AASHTO T48 | | | |
| **Rotational Vis.** 3 Pa.s (3000 cP) Test Temp 135.0°C | AASHTO T316 | | **842** | |
| **Specific Gravity** Temp 15.6°C | AASHTO T228 | | **1.02776** | |
| | | 58.0°C | 64.0°C | 70.0°C |
| **Dynamic Shear** Test Temp @10 rad/sec, °C | AASHTO T315 | | | |
| Algebraic Difference less than 92°C G*/sin delta, 1.00 kPa min. | | | | |
| Algebraic Difference of 92°C | | | | |
| G* (Complex Modulus), 1.30 kPa min. | | | **2.219** | **0.9693** |
| Phase Angle (delta), 74 degrees max. | | | **74.00** | **76.40** |
| G*/sin delta, 1.00 kPa min. | | | **2.307** | **0.9971** |
| | | | *Tcrit 69.99°C* | |
| Algebraic Difference of 98°C | | | | |
| G* (Complex Modulus), 1.30 kPa min. | | | | |
| Phase Angle (delta), 71 degrees max. | | | | |
| G*/sin delta, 1.00 kPa min. | | | | |
| Algebraic Difference Greater Than 92°C | | | | |
| **Toughness** 75 in-lbs min. | ASTM D5801 | | | |
| **Tenacity** 50 in-lbs min. | ASTM D5801 | | | |

| **RTFO RESIDUE** | AASHTO T240 | 58.0°C | 64.0°C | 70.0°C |
|---|---|---|---|---|
| Mass Change, 1.00% max loss | | | **-0.355%** | |
| **Dynamic Shear** Test Temp @10 rad/sec, °C | AASHTO T315 | | **G* 4.525** | **G* 2.724** |
| G*/sin delta, 2.20 kPa min. | | | **4.898** | **2.904** |
| Phase Angle (delta), Report | | | **67.50** | **69.70** |
| | | | *Tcrit 72.12°C* | |
| **Multiple Stress Creep/Recovery** | | | | |
| Percent Recovery, 100 Pa @ High Test Temp. | | | **49.41%** | |
| Percent Recovery, 3200 Pa @ High Test Temp. | | | **26.05%** | |
| Difference is Percent Recovery | | | **23.36%** | |
| **Elastic Recovery** | AASHTO T301 mod | cm | cm **4.00** | cm |
| 65, or 70% @ 25.0°C, 20cm pull, then cut | | | **80.00%** | |

**PAV RESIDUE** AASHTO R28
20 hrs @ 2.10 Mpa — 100.0°C | 100.0°C | 100.0°C

**Dynamic Shear** AASHTO T315

| | 22°C | 19°C | 16°C | 13°C | 25°C | 22°C | 19°C | 16°C | 28°C | 25°C | 22°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test Temp @10 rad/sec, °C G*sin delta, 5000 kPa max. | | | | | | **2205** | | | | | |
| Phase Angle (delta), Report | | | | | | **44.50** | | | | | |

**BBR, Creep Stiffness** AASHTO T313

| Test Temp @ 60 sec, °C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stiffness, 300.0 Mpa max. | | | | | | **168** | | | | | |
| m-value, .300 min. | | | | | | **0.331** | | | | | |

**Direct Tension** AASHTO T314
Algebraic Difference Greater Than 92°C

| Test Temp @ 1.0mm/min, °C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Failure Strain, 1.5% min. | | | | | | **3.42** | | | | | |
| Failure Stress, 4.0 MPa min. | | | | | | **4.750** | | | | | |

Tested By: K McKinney
Quality Assurance Technician

Reviewed By:
Materials Engineer

**UDOT** CONNECTING COMMUNITIES

Materials Division - Asphalt Binder Lab
4501 South 2700 West
Salt Lake City, UT 84114-5950

Date Tested: **1/3/2008**
Sample ID: **76-W**
Technician(s): **K McKinney**
Algebraic Difference: **92**
Project Number:
Project Name: **UofU Hamburg Research 07**

Supplier: Binder B
Material Grade: **PG70,-28**
Date Sampled: **9/17/2007**
Date Received: **9/17/2007**

Notes, and Information: **Phosphorus content .68% Wt. %**

| | | PG58, | | | | PG64 | | | | PG70 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -22 | -28 | -34 | -40 | -22 | -28 | -34 | -40 | -22 | -28 | -34 |

## ORIGINAL BINDER

| Test | PROCEDURE | PG58 | PG64 | PG70 | |
|---|---|---|---|---|---|
| **Flash Point Temp** Min. 230°C | AASHTO T48 | | | | |
| **Rotational Vis.** 3 Pa.s (3000 cP) Test Temp 135.0°C | AASHTO T316 | | | **1502** | |
| **Specific Gravity** Temp 15.6°C | AASHTO T228 | | | **1.02890** | |
| | | 58.0°C | 64.0°C | 70.0°C | |
| **Dynamic Shear** Test Temp @10 rad/sec, °C | AASHTO T315 | | | | |
| Algebraic Difference less than 92°C: G*/sin delta, 1.00 kPa min. | | | | | |
| Algebraic Difference of 92°C: G* (Complex Modulus), 1.30 kPa min. | | | | | |
| Phase Angle (delta), 74 degrees max. | | | | | |
| G*/sin delta, 1.00 kPa min. | | | | | |
| Algebraic Difference of 98°C | | | | | **@ 76.0°C** |
| G* (Complex Modulus), 1.30 kPa min. | | | | **1.781** | **1.1320** |
| Phase Angle (delta), 71 degrees max. | | | | **69.90** | **72.30** |
| G*/sin delta, 1.00 kPa min. | | | | **1.900** | **1.188** |
| Algebraic Difference Greater Than 92°C | | | | ***Tcrit = 77.58°C*** | |
| **Toughness** 75 in-lbs min. | ASTM D5801 | | | | |
| **Tenacity** 50 in-lbs min. | ASTM D5801 | | | | |

## RTFO RESIDUE

| Test | PROCEDURE | PG58 | PG64 | PG70 | |
|---|---|---|---|---|---|
| **RTFO RESIDUE** | AASHTO T240 | 58.0°C | 64.0°C | 70.0°C | |
| Mass Change, 1.00% max loss | | | | **-0.392%** | |
| **Dynamic Shear** Test Temp @10 rad/sec, °C | AASHTO T315 | | | **G* 2.979** | **G* 2.457** |
| G*/sin delta, 2.20 kPa min. | | | | **3.453** | **2.754** |
| Phase Angle (delta), Report | | | | **59.60** | **63.10** |
| | | | | ***Tcrit = 80.76°C*** | |
| **Multiple Stress Creep/Recovery** | | | | | |
| Percent Recovery, 100 Pa @ High Test Temp. | | | | | |
| Percent Recovery, 3200 Pa @ High Test Temp. | | | | | |
| Difference is Percent Recovery | | | | | |
| **Elastic Recovery** | AASHTO $T301_{mod}$ | cm | cm | cm 2.25 | |
| 65, or 70% @ 25.0°C, 20cm pull, then cut | | | | **88.75%** | |

## PAV RESIDUE

**PAV RESIDUE** AASHTO R28 — 20 hrs @ 2.10 Mpa — 100.0°C | 100.0°C | 100.0°C

**Dynamic Shear** AASHTO T315

| | 22°C | 19°C | 16°C | 13°C | 25°C | 22°C | 19°C | 16°C | 28°C | 25°C | 22°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test Temp @10 rad/sec, °C / G*sin delta, 5000 kPa max. | | | | | | | | | | **1181** | |
| Phase Angle (delta), Report | | | | | | | | | | **46.90** | |

**BBR, Creep Stiffness** AASHTO T313

| | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test Temp @ 60 sec, °C / Stiffness, 300.0 Mpa max. | | | | | | | | | | **144** | |
| m-value, .300 min. | | | | | | | | | | **0.336** | |

**Direct Tension** AASHTO T314
Algebraic Difference Greater Than 92°C

| | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test Temp @ 1.0mm/min, °C / Failure Strain, 1.5% min. | | | | | | | | | | **1.570** | |
| Failure Stress, 4.0 MPa min. | | | | | | | | | | **4.55** | |

Tested By: K McKinney
Quality Assurance Technician

Reviewed By:
Materials Engineer

UDOT CONNECTING COMMUNITIES

Materials Division - Asphalt Binder Lab
4501 South 2700 West
Salt Lake City, UT 84114-5950

Date Tested: **12/16/2007**
Sample ID: **71-W**
Technician(s): **K McKinney**
Algebraic Difference: **86**
Project Number:
Project Name: **UofU Hamburg Research 07**

Supplier: Binder A
Material Grade: **PG58,-28**
Date Sampled: **9/17/2007**
Date Received: **9/17/2007**

Notes, and Information: **Phosphorus content 0.01 Wt. %**

| | | PG58, | PG64 | PG70 |
|---|---|---|---|---|
| | | -22 / -28 / -34 / -40 | -22 / -28 / -34 / -40 | -22 / -28 / -34 |
| **ORIGINAL BINDER** | **PROCEDURE** | | | |
| **Flash Point Temp** Min. 230°C | AASHTO T48 | | | |
| **Rotational Vis.** 3 Pa.s (3000 cP) Test Temp 135.0°C | AASHTO T316 | **344** | | |
| **Specific Gravity** Temp 15.6°C | AASHTO T228 | **1.0277** | | |
| | | 58.0°C | 64.0°C | 70.0°C |
| **Dynamic Shear** Test Temp @10 rad/sec, °C | AASHTO T315 | | | |
| Algebraic Difference less than 92°C | | | | |
| G*/sin delta, 1.00 kPa min. | | | | |
| Algebraic Difference of 86°C | | | | |
| G* (Complex Modulus), 1.00 kPa min. | | **1.729** | **0.8337** | |
| Phase Angle (delta), Report | | **85.70** | **87.60** | |
| G*/sin delta, 1.00 kPa min. | | **1.773** | **0.8344** | |
| Algebraic Difference of 98°C | | ***Tcrit = 62.94°C*** | | |
| G* (Complex Modulus), 1.30 kPa min. | | | | |
| Phase Angle (delta), 71 degrees max. | | | | |
| G*/sin delta, 1.00 kPa min. | | | | |
| Algebraic Difference Greater Than 92°C | | | | |
| **Toughness** 75 in-lbs min. | ASTM D5801 | | | |
| **Tenacity** 50 in-lbs min. | ASTM D5801 | | | |
| **RTFO RESIDUE** | AASHTO T240 | 58.0°C | 64.0°C | 70.0°C |
| Mass Change, 1.00% max loss | | **-0.301%** | | |
| **Dynamic Shear** Test Temp @10 rad/sec, °C | AASHTO T315 | | | |
| G*/sin delta, 2.20 kPa min. | | **5.123** | **2.443** | |
| Phase Angle (delta), Report | | **81..40** | **84.00** | |
| **Multiple Stress Creep/Recovery** | | ***Tcrit = 64.54°C*** | | |
| Percent Recovery, 100 Pa @ High Test Temp. | | **5.69%** | | |
| Percent Recovery, 3200 Pa @ High Test Temp. | | **1.20%** | | |
| Difference is Percent Recovery | | **4.49%** | | |
| **Elastic Recovery** 65, or 70% @ 25.0°C, 20cm pull, then cut | AASHTO $T301_{mod}$ | cm | cm | cm |

| **PAV RESIDUE** 20 hrs @ 2.10 Mpa | AASHTO R28 | 100.0°C | | | | 100.0°C | | | | 100.0°C | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dynamic Shear** Test Temp @10 rad/sec, °C | AASHTO T315 | 22°C | 19°C | 16°C | 13°C | 25°C | 22°C | 19°C | 16°C | 28°C | 25°C | 22°C |
| G*sin delta, 5000 kPa max. | | | **5196** | | | | | | | | | |
| Phase Angle (delta), Report | | | **42.30** | | | | | | | | | |
| **BBR, Creep Stiffness** Test Temp @ 60 sec, °C | AASHTO T313 | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C |
| Stiffness, 300.0 Mpa max. | | | **277** | | | | | | | | | |
| m-value, .300 min. | | | **0.310** | | | | | | | | | |
| **Direct Tension** Algebraic Difference Greater Than 92°C Test Temp @ 1.0mm/min, °C | AASHTO T314 | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C |
| Failure Strain, 1.5% min. | | | **4.170** | | | | | | | | | |
| Failure Stress, 4.0 MPa min. | | | **4.17** | | | | | | | | | |

Tested By: K McKinney
Quality Assurance Technician

Reviewed By:
Materials Engineer

UDOT CONNECTING COMMUNITIES

Materials Division - Asphalt Binder Lab
4501 South 2700 West
Salt Lake City, UT 84114-5950

Date Tested: **1/3/2008**
Sample ID: **72-W**
Technician(s): **K McKinney**
Algebraic Difference: **92**
Project Number:
Project Name: **UofU Hamburg Research 07**

Supplier: Binder A
Material Grade: **PG64,-28**
Date Sampled: **9/17/2007**
Date Received: **9/17/2007**

Notes, and Information: **67.5%** A **PG70,-28 (73-W) + 32.5%** A **PG58,-28 (71-W)** **(Phosphorus .29% Wt.)**

**10125g + 4875g = 15000g**

| | | PG58, | | | | PG64 | | | | PG70 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -22 | -28 | -34 | -40 | -22 | -28 | -34 | -40 | -22 | -28 | -34 |

## ORIGINAL BINDER

| ORIGINAL BINDER | PROCEDURE | PG58 | PG64 | PG70 |
|---|---|---|---|---|
| **Flash Point Temp** Min. 230°C | AASHTO T48 | | | |
| **Rotational Vis.** 3 Pa.s (3000 cP) Test Temp 135.0°C | AASHTO T316 | | **735** | |
| **Specific Gravity** Temp 15.6°C | AASHTO T228 | | **1.02631** | |
| | | 58.0°C | 64.0°C | 70.0°C |
| **Dynamic Shear** Test Temp @10 rad/sec, °C | AASHTO T315 | | | |
| Algebraic Difference less than 92°C: G*/sin delta, 1.00 kPa min. | | | | |
| Algebraic Difference of 92°C: G* (Complex Modulus), 1.30 kPa min. | | | **2.496** | **0.9983** |
| Phase Angle (delta), 74 degrees max. | | | **73.50** | **74.80** |
| G*/sin delta, 1.00 kPa min. | | | **2.604** | **1.034** |
| | | | *Tcrit 70.13°C* | |
| Algebraic Difference of 98°C: G* (Complex Modulus), 1.30 kPa min. | | | | |
| Phase Angle (delta), 71 degrees max. | | | | |
| G*/sin delta, 1.00 kPa min. | | | | |
| Algebraic Difference Greater Than 92°C | | | | |
| **Toughness** 75 in-lbs min. | ASTM D5801 | | | |
| **Tenacity** 50 in-lbs min. | ASTM D5801 | | | |

## RTFO RESIDUE

| RTFO RESIDUE | AASHTO T240 | 58.0°C | 64.0°C | 70.0°C |
|---|---|---|---|---|
| Mass Change, 1.00% max loss | | | **-0.336%** | |
| **Dynamic Shear** Test Temp @10 rad/sec, °C | AASHTO T315 | | | |
| G*/sin delta, 2.20 kPa min. | | | **6.326** | **3.420** |
| Phase Angle (delta), Report | | | **66.80** | **68.40** |
| | | | *Tcrit 72.52°C* | |
| **Multiple Stress Creep/Recovery** Percent Recovery, 100 Pa @ High Test Temp. | | | **57.83%** | |
| Percent Recovery, 3200 Pa @ High Test Temp. | | | **35.87%** | |
| Difference is Percent Recovery | | | **21.96%** | |
| **Elastic Recovery** | AASHTO T301mod | cm | cm 3.75 | cm |
| 65, or 70% @ 25.0°C, 20cm pull, then cut | | | **81.25%** | |

## PAV RESIDUE

AASHTO R28 — 20 hrs @ 2.10 Mpa — 100.0°C / 100.0°C / 100.0°C

**Dynamic Shear** — AASHTO T315

| | PG58 22°C | 19°C | 16°C | 13°C | PG64 25°C | 22°C | 19°C | 16°C | PG70 28°C | 25°C | 22°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| G*sin delta, 5000 kPa max. | | | | | | **2949** | | | | | |
| Phase Angle (delta), Report | | | | | | **42.50** | | | | | |

**BBR, Creep Stiffness** — AASHTO T313 — Test Temp @ 60 sec, °C

| | PG58 -12°C | -18°C | -24°C | -30°C | PG64 -12°C | -18°C | -24°C | -30°C | PG70 -12°C | -18°C | -24°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stiffness, 300.0 Mpa max. | | | | | | **213** | | | | | |
| m-value, .300 min. | | | | | | **0.306** | | | | | |

**Direct Tension** — AASHTO T314 — Algebraic Difference Greater Than 92°C — Test Temp @ 1.0mm/min, °C

| | PG58 -12°C | -18°C | -24°C | -30°C | PG64 -12°C | -18°C | -24°C | -30°C | PG70 -12°C | -18°C | -24°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Failure Strain, 1.5% min. | | | | | | **2.63** | | | | | |
| Failure Stress, 4.0 MPa min. | | | | | | **5.460** | | | | | |

Tested By: K McKinney
Quality Assurance Technician

Reviewed By:
Materials Engineer

UDOT
CONNECTING COMMUNITIES

Materials Division - Asphalt Binder Lab
4501 South 2700 West
Salt Lake City, UT 84114-5950

Date Tested: **1/3/2008**
Sample ID: **73-W**
Technician(s): **K McKinney**
Algebraic Difference: **92**
Project Number:
Project Name: **UofU Hamburg Research 07**

Supplier: Binder A
Material Grade: **PG70,-28**
Date Sampled: **9/17/2007**
Date Received: **9/17/2007**

Notes, and Information: **Phosphorus content .51% Wt. %**

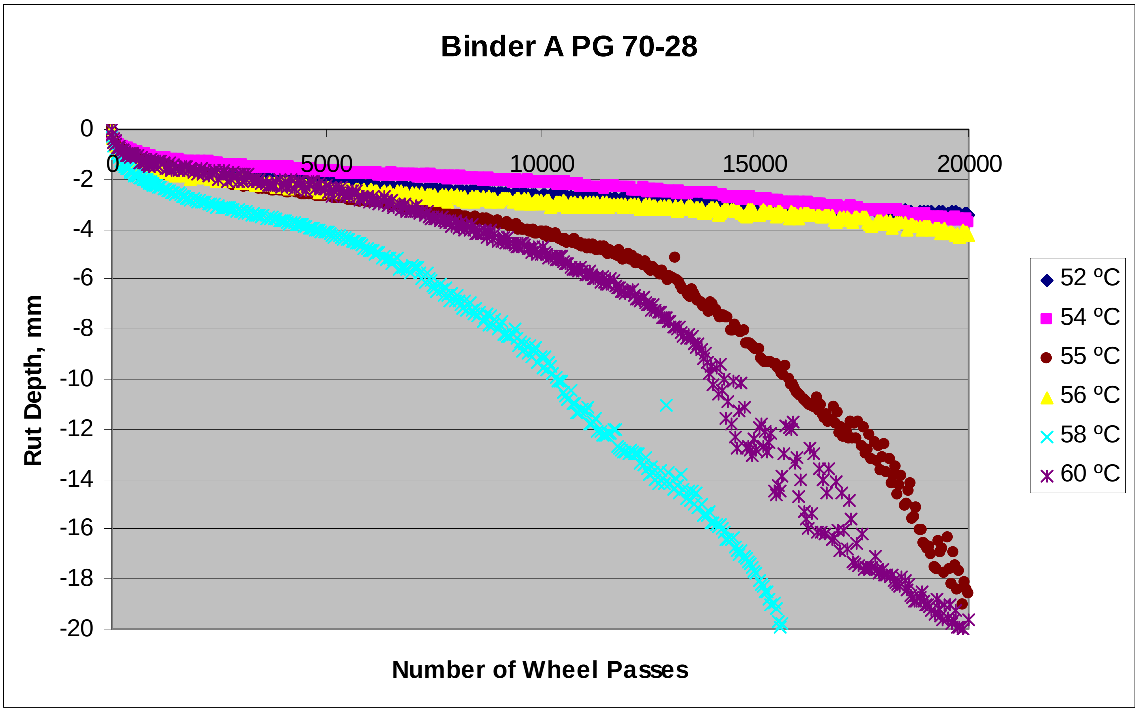
| | | PG58, | | | | PG64 | | | | PG70 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | -22 | -28 | -34 | -40 | -22 | -28 | -34 | -40 | -22 | -28 | -34 | |
| **ORIGINAL BINDER** | **PROCEDURE** | | | | | | | | | | | | |
| **Flash Point Temp** Min. 230°C | AASHTO T48 | | | | | | | | | | | | |
| **Rotational Vis.** 3 Pa.s (3000 cP) Test Temp 135.0°C | AASHTO T316 | | | | | | | | | | **1064** | | |
| **Specific Gravity** Temp 15.6°C | AASHTO T228 | | | | | | | | | | **1.03150** | | |
| | | 58.0°C | | | | 64.0°C | | | | 70.0°C | | | |
| **Dynamic Shear** | AASHTO T315 | | | | | | | | | | | | |
| Test Temp @10 rad/sec, °C | | | | | | | | | | | | | |
| Algebraic Difference less than 92°C | | | | | | | | | | | | | |
| G*/sin delta, 1.00 kPa min. | | | | | | | | | | | | | |
| Algebraic Difference of 92°C | | | | | | | | | | | | | |
| G* (Complex Modulus), 1.30 kPa min. | | | | | | | | | | | | | |
| Phase Angle (delta), 74 degrees max. | | | | | | | | | | | | | |
| G*/sin delta, 1.00 kPa min. | | | | | | | | | | | | | |
| Algebraic Difference of 98°C | | | | | | | | | | | | | @ 76.0°C |
| G* (Complex Modulus), 1.30 kPa min. | | | | | | | | | | | **1.601** | | **1.056** |
| Phase Angle (delta), 71 degrees max. | | | | | | | | | | | **66.60** | | **68.20** |
| G*/sin delta, 1.00 kPa min. | | | | | | | | | | | **1.744** | | **1.137** |
| Algebraic Difference Greater Than 92°C | | | | | | | | | | | ***Tcrit = 77.35°C*** | | |
| **Toughness** 75 in-lbs min. | ASTM D5801 | | | | | | | | | | | | |
| **Tenacity** 50 in-lbs min. | ASTM D5801 | | | | | | | | | | | | |
| **RTFO RESIDUE** | AASHTO T240 | 58.0°C | | | | 64.0°C | | | | 70.0°C | | | |
| Mass Change, 1.00% max loss | | | | | | | | | | | **-0.401%** | | |
| **Dynamic Shear** | AASHTO T315 | | | | | | | | | | | | |
| Test Temp @10 rad/sec, °C | | | | | | | | | | | **G* 4.060** | | **2.797** |
| G*/sin delta, 2.20 kPa min. | | | | | | | | | | | **4.723** | | **3.219** |
| Phase Angle (delta), Report | | | | | | | | | | | **59.30** | | **60.30** |
| **Multiple Stress Creep/Recovery** | | | | | | | | | | | ***Tcrit = 80.07°C*** | | |
| Percent Recovery, 100 Pa @ High Test Temp. | | | | | | | | | | | | | |
| Percent Recovery, 3200 Pa @ High Test Temp. | | | | | | | | | | | | | |
| Difference is Percent Recovery | | | | | | | | | | | | | |
| **Elastic Recovery** | AASHTO T301$_{mod}$ | cm | | | | cm | | | | cm 2.00 | | | |
| 65, or 70% @ 25.0°C, 20cm pull, then cut | | | | | | | | | | | **90.00%** | | |
| **PAV RESIDUE** | AASHTO R28 | | | | | | | | | | | | |
| 20 hrs @ 2.10 Mpa | | 100.0°C | | | | 100.0°C | | | | 100.0°C | | | |
| **Dynamic Shear** | AASHTO T315 | | | | | | | | | | | | |
| Test Temp @10 rad/sec, °C | | 22°C | 19°C | 16°C | 13°C | 25°C | 22°C | 19°C | 16°C | 28°C | 25°C | 22°C | |
| G*sin delta, 5000 kPa max. | | | | | | | | | | | **2014** | | |
| Phase Angle (delta), Report | | | | | | | | | | | **44.2** | | |
| **BBR, Creep Stiffness** | AASHTO T313 | | | | | | | | | | | | |
| Test Temp @ 60 sec, °C | | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | |
| Stiffness, 300.0 Mpa max. | | | | | | | | | | | **188** | | |
| m-value, .300 min. | | | | | | | | | | | **0.319** | | |
| **Direct Tension** | AASHTO T314 | | | | | | | | | | | | |
| Algebraic Difference Greater Than 92°C | | | | | | | | | | | | | |
| Test Temp @ 1.0mm/min, °C | | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | -30°C | -12°C | -18°C | -24°C | |
| Failure Strain, 1.5% min. | | | | | | | | | | | **3.450** | | |
| Failure Stress, 4.0 MPa min. | | | | | | | | | | | **5.30** | | |

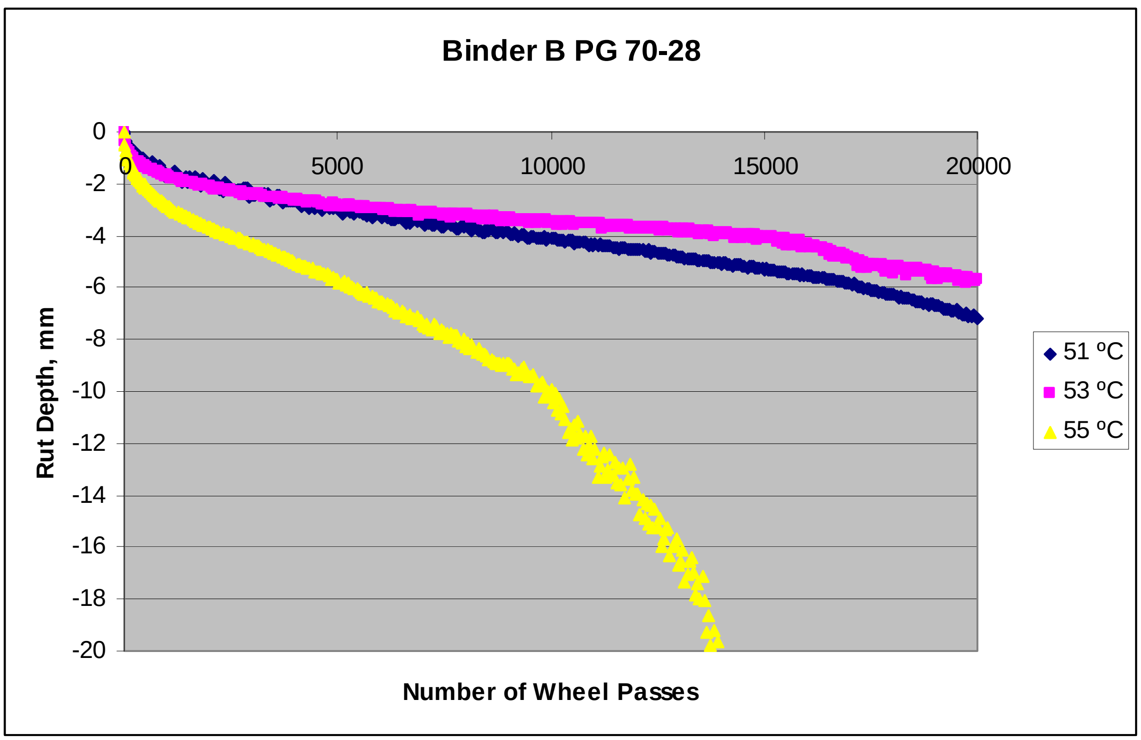
Tested By: K McKinney
Quality Assurance Technician

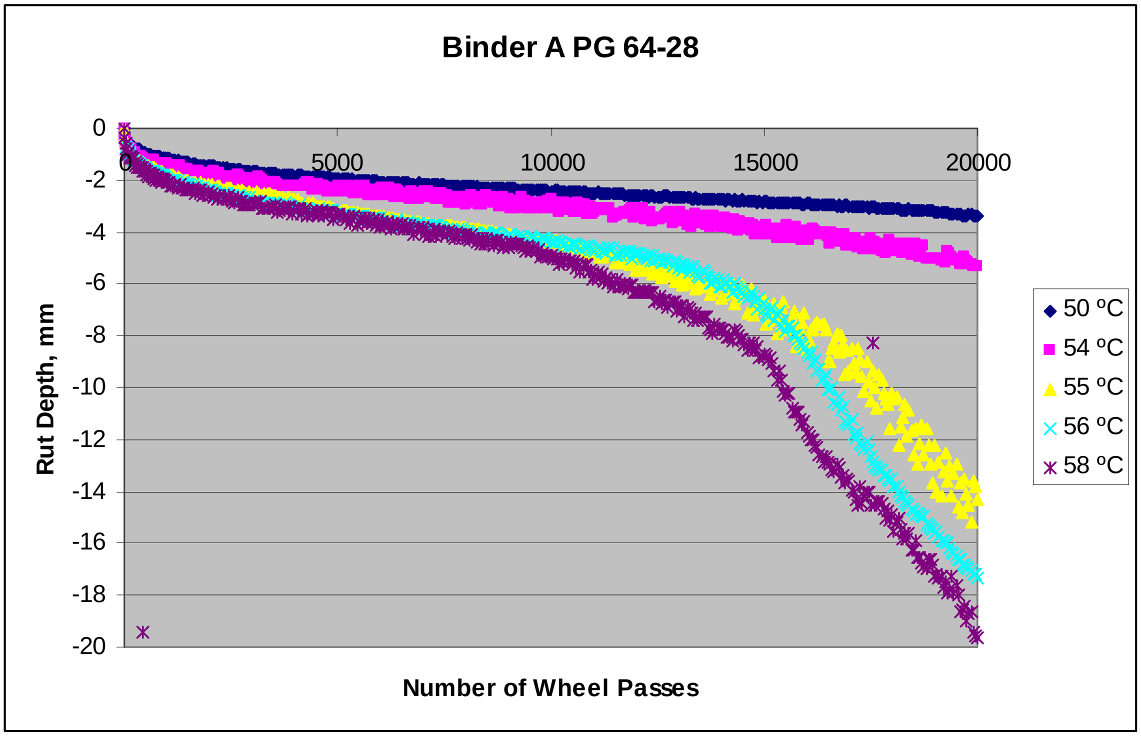
Reviewed By:
Materials Engineer

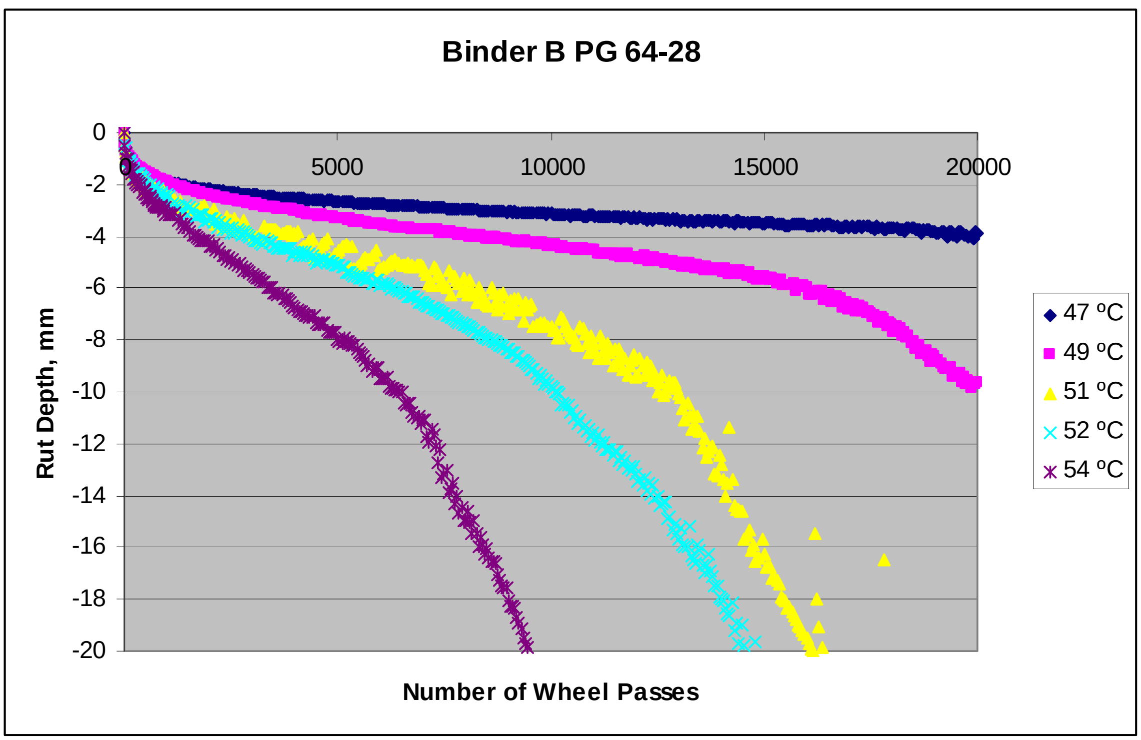
# Appendix B

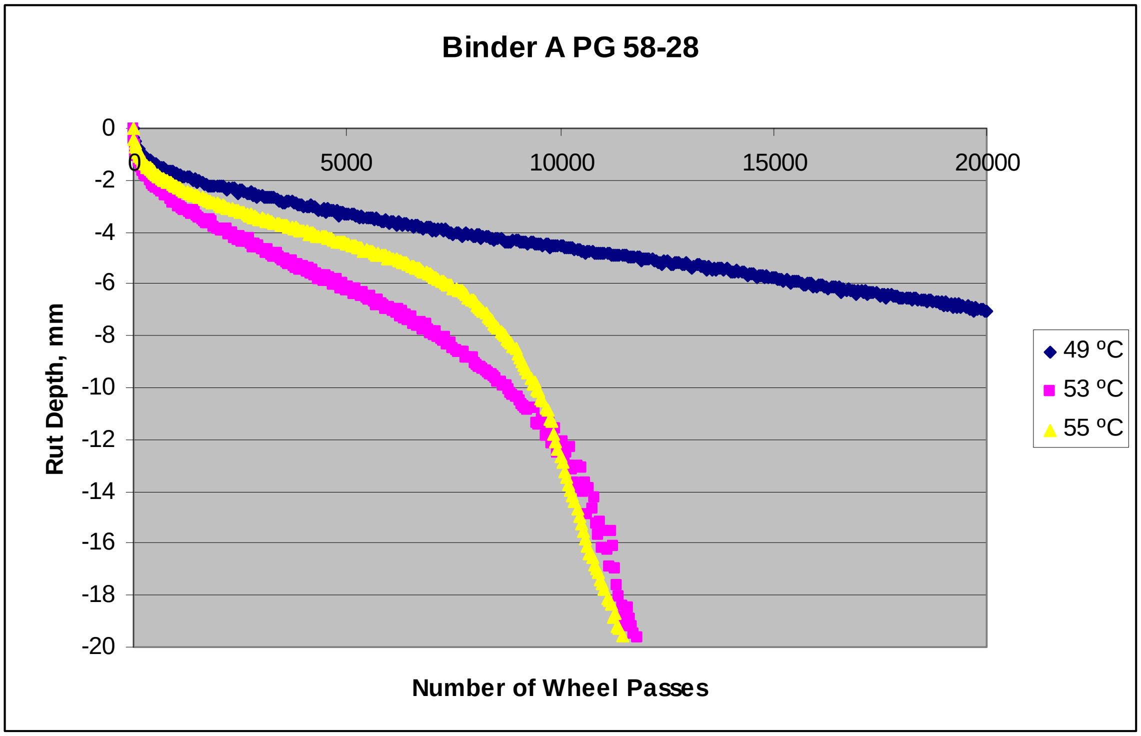
Test Results

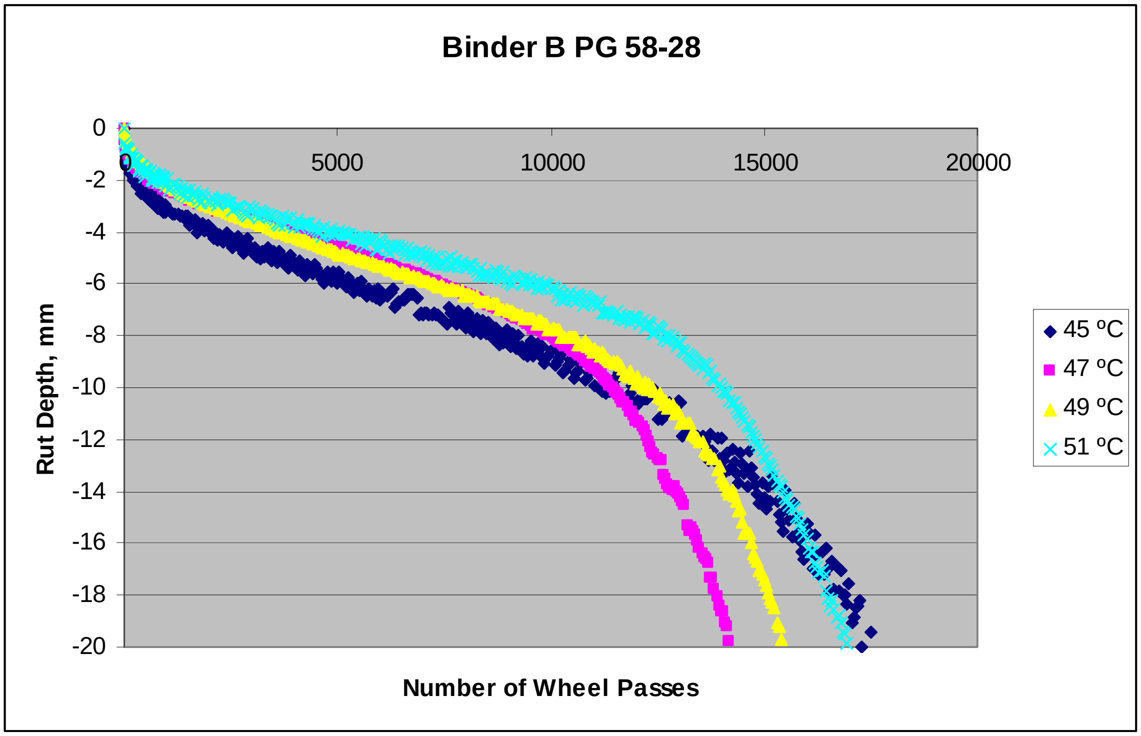

Binder A PG 70-28
Rut Depth, mm
Number of Wheel Passes
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
5000
10000
15000
20000
52 ºC
54 ºC
55 ºC
56 ºC
58 ºC
60 ºC

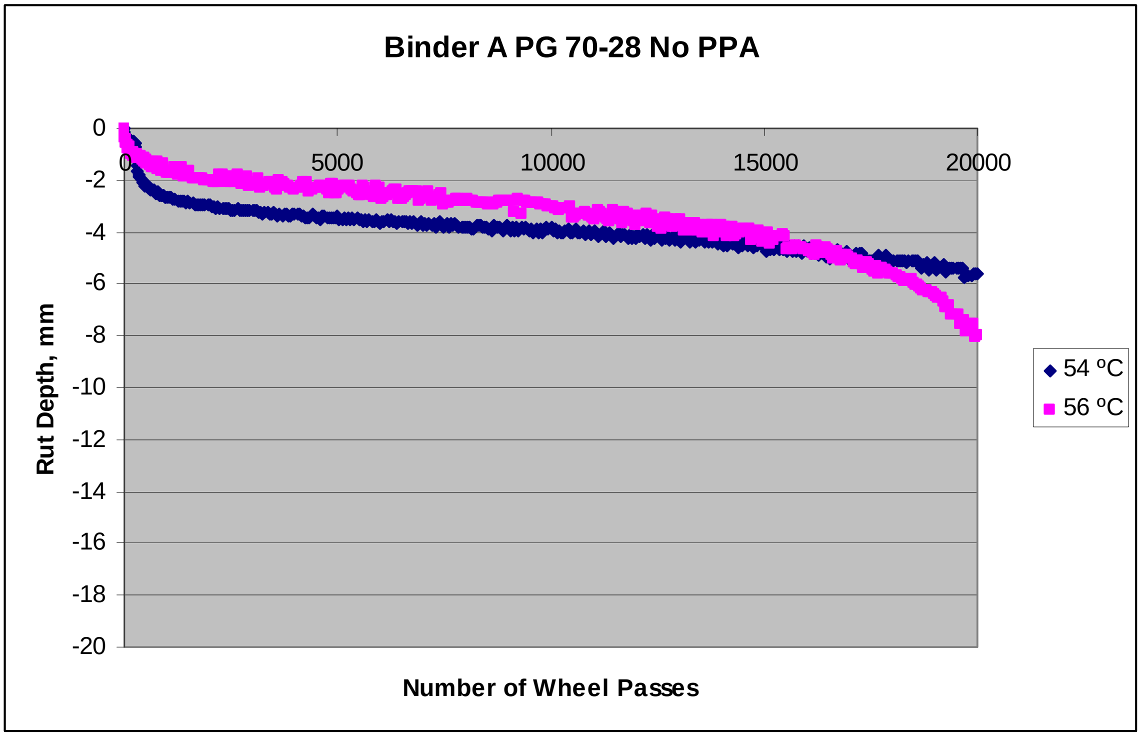

Binder B PG 70-28
Rut Depth, mm
Number of Wheel Passes
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
5000
10000
15000
20000
51 ºC
53 ºC
55 ºC

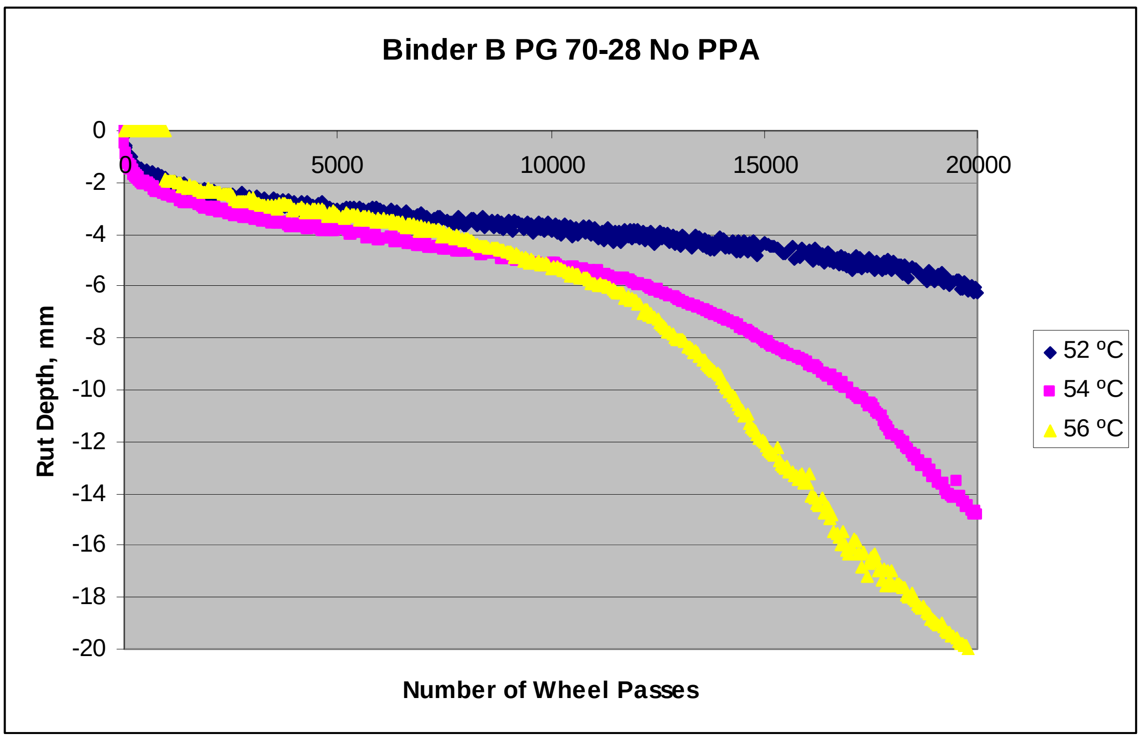

Binder A PG 64-28
Rut Depth, mm
Number of Wheel Passes
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
5000
10000
15000
20000
50 ºC
54 ºC
55 ºC
56 ºC
58 ºC


Binder B PG 64-28
Rut Depth, mm
Number of Wheel Passes
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
5000
10000
15000
20000
47 ºC
49 ºC
51 ºC
52 ºC
54 ºC


Binder A PG 58-28
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
5000
10000
15000
20000
Rut Depth, mm
Number of Wheel Passes
49 ºC
53 ºC
55 ºC


Binder B PG 58-28
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
5000
10000
15000
20000
Rut Depth, mm
Number of Wheel Passes
45 ºC
47 ºC
49 ºC
51 ºC


Binder A PG 70-28 No PPA
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
5000
10000
15000
20000
Rut Depth, mm
Number of Wheel Passes
54 ºC
56 ºC


Binder B PG 70-28 No PPA
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
5000
10000
15000
20000
Rut Depth, mm
Number of Wheel Passes
52 ºC
54 ºC
56 ºC

## Appendix C

Temperature Sweep for Modified Binders

# UTAH DEPARTMENT OF TRANSPORTATION

## Central Asphalt Laboratory

**Project: UofU Hamburg Research**

**RTFODSR**

| Sample ID/Product: | Temperature | G* | δ | G*/sinδ |
|---|---|---|---|---|
| Binder A PG64,-28 | 50.0°C | 23.420 | 63.78 | 26.106 |
| | 60.0°C | 7.338 | 65.16 | 8.086 |
| | 70.0°C | 2.746 | 67.60 | 2.971 |
| | 80.0°C | 1.075 | 71.13 | 1.136 |

**RTFODSR**

| Sample ID/Product: | Temperature | G* | δ | G*/sinδ |
|---|---|---|---|---|
| Binder A PG70,-28 | 50.0°C | 28.658 | 58.18 | 33.726 |
| | 60.0°C | 12.045 | 57.72 | 14.247 |
| | 70.0°C | 5.459 | 57.12 | 6.501 |
| | 80.0°C | 2.291 | 59.36 | 2.663 |

**RTFODSR**

| Sample ID/Product: | Temperature | G* | δ | G*/sinδ |
|---|---|---|---|---|
| Binder B PG64,-28 | 50.0°C | 19.131 | 62.93 | 21.484 |
| | 60.0°C | 6.516 | 64.93 | 7.193 |
| | 70.0°C | 2.471 | 68.35 | 2.658 |
| | 80.0°C | 0.9241 | 73.16 | 0.9655 |

**RTFODSR**

| Sample ID/Product: | Temperature | G* | δ | G*/sinδ |
|---|---|---|---|---|
| Binder B PG70,-28 | 50.0°C | 18.388 | 53.57 | 22.856 |
| | 60.0°C | 8.044 | 55.44 | 9.767 |
| | 70.0°C | 3.525 | 59.18 | 4.105 |
| | 80.0°C | 1.952 | 62.74 | 2.195 |

## UTAH DEPARTMENT OF TRANSPORTATION

### Central Asphalt Laboratory

**Project: UofU Hamburg Research**

## MSCR

| Sample ID/Product: | | Temperature | Percent Recovery | Difference in Percent Recovery | Non Recoverable Compliance (Jnr) (k/Pa) | Percent Difference in Jnr |
|---|---|---|---|---|---|---|
| Binder A PG64,-28 | 100 Pa | 50.0°C | 47.00% | | 0.08 | |
| | 3200 Pa | | 38.00% | 19.00% | 0.05 | -69.00% |
| | 100 Pa | 60.0°C | 41.00% | | 0.33 | |
| | 3200 Pa | | 35.00% | 16.00% | 0.37 | 11.00% |
| | 100 Pa | 70.0°C | 30.00% | | 1.09 | |
| | 3200 Pa | | 18.00% | 41.00% | 1.49 | 27.00% |
| | 100 Pa | 80.0°C | 18.00% | | 4.35 | |
| | 3200 Pa | | 4.00% | 79.00% | 6.35 | 32.00% |

| Sample ID/Product: | | Temperature | Percent Recovery | Difference in Percent Recovery | Non Recoverable Compliance (Jnr) (k/Pa) | Percent Difference in Jnr |
|---|---|---|---|---|---|---|
| Binder A PG70,-28 | 100 Pa | 50.0°C | 61.00% | | 0.04 | |
| | 3200 Pa | | 60.00% | 1.00% | ..04 | -7.00% |
| | 100 Pa | 60.0°C | 59.00% | | 0.11 | |
| | 3200 Pa | | 58.00% | 2.00% | 0.10 | -2.00% |
| | 100 Pa | 70.0°C | 55.00% | | 0.28 | |
| | 3200 Pa | | 53.00% | 4.00% | 0.28 | -2.00% |
| | 100 Pa | 80.0°C | 43.00% | | 0.93 | |
| | 3200 Pa | | 27.00% | 37.00% | 1.43 | 35.00% |

| Sample ID/Product: | | Temperature | Percent Recovery | Difference in Percent Recovery | Non Recoverable Compliance (Jnr) (k/Pa) | Percent Difference in Jnr |
|---|---|---|---|---|---|---|
| Binder B PG64,-28 | 100 Pa | 50.0°C | 44.00% | | 0.11 | |
| | 3200 Pa | | 41.00% | 7.00% | 0.12 | 6.00% |
| | 100 Pa | 60.0°C | 35.00% | | 0.46 | |
| | 3200 Pa | | 26.00% | 27.00% | 0.60 | 23.00% |
| | 100 Pa | 70.0°C | 26.00% | | 1.38 | |
| | 3200 Pa | | 11.00% | 57.00% | 2.64 | 48.00% |
| | 100 Pa | 80.0°C | 14.00% | | 6.11 | |
| | 3200 Pa | | 2.00% | 84.00% | 9.74 | 37.00% |

| Sample ID/Product: | | Temperature | Percent Recovery | Difference in Percent Recovery | Non Recoverable Compliance (Jnr) (k/Pa) | Percent Difference in Jnr |
|---|---|---|---|---|---|---|
| Binder B PG70,-28 | 100 Pa | 50.0°C | 62.00% | | 0.05 | |
| | 3200 Pa | | 60.00% | 3.00% | 0.06 | 5.00% |
| | 100 Pa | 60.0°C | 53.00% | | 0.18 | |
| | 3200 Pa | | 46.00% | 12.00% | 0.22 | 19.00% |
| | 100 Pa | 70.0°C | 41.00% | | 0.64 | |
| | 3200 Pa | | 23.00% | 43.00% | 1.21 | 47.00% |
| | 100 Pa | 80.0°C | 28.00% | | 1.63 | |
| | 3200 Pa | | 8.00% | 71.00% | 3.87 | 58.00% |