

NCAT Report 04-04

EVALUATION OF THE ASPHALT PAVEMENT ANALYZER FOR MOISTURE SENSITIVITY TESTING

By

Randy C. West
Jingna Zhang
Allen Cooley, Jr.

July 2004



277 Technology Parkway Auburn, AL 36830

EVALUATION OF THE ASPHALT PAVEMENT ANALYZER FOR MOISTURE SENSITIVITY TESTING

By:

Randy C. West
Assistant Director
National Center for Asphalt Technology
Auburn University, Auburn, Alabama

Jingna Zhang
Research Engineer
National Center for Asphalt Technology
Auburn University, Auburn, Alabama

Allen Cooley, Jr.
Burns, Cooley, Dennis, Inc.
Ridgeland, Mississippi

NCAT Report 04-04

July 2004

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the National Center for Asphalt Technology or Auburn University. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

ABSTRACT	iii
INTRODUCTION	1
PURPOSE OF THE STUDY	1
LITERATURE REVIEW	2
EXPERIMENTAL PLAN	5
Materials and Mixtures	5
Specimen Preparation	5
Specimen Conditioning.....	6
APA Stripping Procedure	6
ANALYSIS OF DATA.....	7
Deformation	7
Ratio of Deformation for Conditioned to Unconditioned Samples (C/U DR)	14
Wet/Dry Deformation Ratio (W/D DR)	15
Conditioned-Wet / Unconditioned-Dry Deformation Ratio (CW/UD DR).....	15
Deformation Slope	16
Ratio of Deformation Slope for Conditioned to Unconditioned Samples (C/U SR).....	19
Ratio of Deformation Slope for Samples Tested Wet Versus Samples Tested Dry (W/D SR)	20
Ratio of Conditioned-Wet/Unconditioned-Dry Deformation Slopes (CW/UD SR)	20
Stripping Inflection Point (SIP)	20
SUMMARY	21
CONCLUSIONS.....	22
RECOMMENDATIONS	23
REFERENCES	24
APPENDIX A: Mix Designs and Materials Information	27
APPENDIX B: Analysis of Secondary Deformation Slopes.....	30

ABSTRACT

This research study was designed to evaluate several options for using the Asphalt Pavement Analyzer (APA) to assess the moisture damage potential of HMA mixtures. The options which were of interest in this study were specimen type (beams or cylinders), load application type (direct contact with steel wheels or loading through pneumatic hoses), conditioning of samples prior to testing (saturation & freeze/thaw or no conditioning) and testing condition (dry or submerged in water). Several response variables were also considered for assessing mixture stripping including specimen deformation (rut depth), the secondary deformation slope, stripping inflection point and a variety of ratios of wet to dry and/or conditioned to unconditioned companion sets.

Tests were performed on two mixtures with known field stripping performance. One mixture used a granite aggregate which has a history of poor performance with regard to stripping; the other mixture used a limestone aggregate that has had no problems with stripping in actual pavements. Test responses from each test option combination were analyzed to determine if the conditions yielded results consistent with the field performance of these two mixtures.

Several different test set ups appeared to provide reasonable results. However, no single set of conditions was universally acceptable for all response variables. Each response variable had unique conditions which provided the correct ranking of the two mixtures. It was evident that the use of steel wheel loading was much more severe than loading through the pressurize hoses. Pre-conditioning of the samples by saturation with water and a freeze thaw cycle also appears to be a key factor. These conditions may help provide better distinction between good and poor performance, but they also increase variability of the results. More research is needed with a greater range of materials with known performance to conclusively establish a reliable test procedure and stripping criteria.

EVALUATION OF THE ASPHALT PAVEMENT ANALYZER FOR MOISTURE SENSITIVITY TESTING

Randy C. West, Jingna Zhang, and Allen Cooley, Jr.

INTRODUCTION

In the Southeast U.S., many of the conditions that affect moisture damage (a.k.a stripping) of asphalt pavements are prevalent. The climactic conditions of warm temperatures and high annual rainfall often combine with certain mixture characteristics, traffic loading, and pavement conditions to cause stripping damage.

However, it is believed by many asphalt pavement technologists that AASHTO T283, the most common test specified for evaluating moisture damage potential of hot mix asphalt (HMA), is poorly correlated to actual field performance (1). Over the past two decades, several researchers have studied other laboratory procedures for predicting whether or not a mixture, or a combination of aggregate and asphalt binder, is susceptible to a loss of cohesion in the presence of water (2). A better stripping test that can be applied to laboratory mix design and plant produced HMA quality control has yet to be identified.

One of the stripping tests that seems to have good success in mix design evaluation is the Hamburg Wheel Tracking Device (HWTM). This test is now used for evaluating asphalt mixes by several state highway agencies including Texas, Colorado, and Utah.

Another device, known as the Asphalt Pavement Analyzer (APA), can be used to perform wheel tracking tests on HMA specimens under a variety of conditions including the conditions which are similar to the Hamburg test. A growing number of highway agencies, contractors, and commercial testing laboratories now have and use the APA for HMA testing. Its most common use, however, is for testing and assessing the rutting potential of HMA mixtures. Although a few researchers have conducted limited studies on using the APA to evaluate stripping potential (3,4), the optimum conditions for the stripping test still need to be established.

PURPOSE OF THE STUDY

The purpose of this research was to identify the test conditions (factors) and response variable(s) using the APA that would provide the best indication of the moisture damage potential of HMA mixtures.

The APA is capable of testing HMA samples in a wide variety of conditions. The conditions which were of interest in this study included:

1. Beam or cylindrical HMA test specimens,
2. Loading the specimens through a linear hose (mimics a pneumatic tire) or direct contact with steel wheels as in the HWTM,
3. Preconditioning of specimens by vacuum saturation followed by a freeze and thaw cycle or unconditioned,

4. Testing of the HMA samples while submerged in water (i.e. wet) or dry. This limited scope project was an exploratory study intended only to evaluate certain test conditions. Only two mixtures were tested in this research. Further evaluations with a wide range of mixtures and possible refinements in the method would be necessary prior to the development of standard and/or test criterion.

LITERATURE REVIEW

Moisture damage has been a significant problem that has resulted in premature pavement failure. Environmental factors such as temperature and moisture can have a profound effect on the durability of hot mix asphalt pavements. When critical environmental conditions are coupled with poor materials and traffic, premature failure may result as a result of stripping of the asphalt binder from the aggregate particles.

A significant amount of research effort has been directed at this problem in the past and more is anticipated in the future. Numerous test methods, both qualitative and quantitative, have been developed and used in the past to assess the moisture susceptibility of HMA mixes (5-7).

Boiling Water Test (ASTM D3625) and **Static-Immersion Test** (AASHTO T182) are conducted on loose mixtures. Both of these tests are subjective (or qualitative) methods and do not involve any strength analysis. Since the tests are subjective the observed variability in test results within and between laboratories is very high (8).

Lottman Test was developed by Lottman (9,10) under the National Cooperative Highway Research Program (NCHRP) 246. The tensile strength ratio (TSR) was calculated as $TSR = (\text{indirect tensile strength (ITS) of conditioned specimens}) / (\text{ITS of control specimens})$. A minimum TSR of 0.70 is recommended by Lottman and Maupin (11,12) who reported values between 0.70 and 0.75 differentiated between stripping and nonstripping HMA mixtures. It has been argued that the Lottman procedures are too severe because the warm water soak of vacuum saturated and frozen specimens can develop internal water pressure. However, Stuart (13) and Parker and Gharaybeh (14) generally found a good correlation between the laboratory and field results. Oregon has successfully used this test with modulus ratio in lieu of tensile strength ratio (TSR) (15).

Tunncliffe and Root Conditioning (ASTM D4867) was proposed by Tunncliffe and Root under NCHRP Project 274 (16). A minimum TSR of 0.7 or 0.8 is usually specified. The use of a freeze-thaw cycle is not mandated in ASTM D4867. The primary emphasis is on saturation of the specimen which for a short duration of about 24 hours has been reported to be sufficient to induce moisture-related damage (17).

Modified Lottman Test (AASHTO T 283) was proposed by Kandhal and was adopted by AASHTO in 1985 (18). It combines the good features of Lottman test (NCHRP 246) and the Tunncliffe and Root test (NCHRP 274). This test has gained wide acceptance by the specifying agencies, and is also included in the Superpave specification. However, this test method has been inconsistent (19). Through their study, Bahia and Ahmad (1)

have found that it was difficult to establish any relationship between lab prepared mixes and the field recovered mixes. Khosla et. al. (20) stated that specification range of test variables needs to be tightened to evaluate the moisture susceptibility of the mix since they found that samples conditioned with air voids and saturation levels at the high limits of the acceptable ranges often failed the criteria; and the same mixes conditioned at lower levels of air voids and saturation passed the specification limits.

Immersion-Compression Test (AASHTO T 165 and ASTM D1075) was among the first tests to evaluate moisture susceptibility. Many agencies specify at least 70 percent retained strength. This test has produced retained strengths near 100 percent even when stripping is evident. Stuart (21) has attributed this to the internal pore water pressure and the insensitivity of the compressive test to measure the moisture-induced damage properly. Lack of satisfactory precision has been a major problem with this test.

The **Strategic Highway Research Program** (SHRP) had two research contracts dealing with moisture susceptibility of HMA mixes. SHRP project A-003A “Performance Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures” attempted to develop an improved test method to evaluate moisture susceptibility. SHRP project A-003B “Fundamental Properties of Asphalt-Aggregate Interactions Including Adhesion and Adsorption” studied the fundamental aspects of asphalt-aggregate bond. An Environmental Conditioning System (ECS) was developed in SHRP Project A-003A (22) in which HMA samples are exposed to wetting and accelerated hot-cold cycling to represent actual field exposure, including repeated loading to simulate traffic. The ECS system is relatively expensive but versatile. Sufficient information is not yet available to adopt this test method. Aschenbrener et. al. (23) reported that the ESC did not do an adequate job of identifying mixtures susceptible to moisture damage. A Net Adsorption Test (NAT) was developed under SHRP Project A-003B. It is a preliminary screening test for matching mineral aggregates and asphalt cement (24) and is based on the principles of adsorption and desorption. This test is an interesting one, however, additional validation data are needed for the NAT before it can be recommended as a proposed procedure.

Other Tests, such as moisture-vapor susceptibility, swell test, and a film stripping test are used by the California DOT to help evaluate moisture sensitivity. Retained Marshall stability has been used in Puerto Rico and some other states (15). Khosla et. al. (20) proposed an axial test to evaluate moisture susceptibility of asphalt mixtures. This test measures cohesion and angle of friction. It has been found that angle of friction did not change for conditioned and unconditioned samples and cohesion is sensitive to this change. They also used Superpave Shear Tester (SST) shear test for moisture damage study.

The **Hamburg Wheel Testing Device** (HWTD) was developed by Helmut-Wind Incorporated of Hamburg, Germany (25). It is used as a specification requirement for some of the most traveled roadways in Germany to evaluate rutting and stripping. Results obtained from the HWTD consist of rut depth, creep slope, stripping inflection point, and stripping slopes. The stripping inflection point is the number of wheel passes

corresponding to the intersection of the creep slope and the stripping slope. This value is used to estimate the relative resistance of the HMA sample to moisture-induced damage (26). A mixture that survives the HWTD test should be rut resistant in the field; however mixtures that do not survive the test may also perform well in the field. Use of this device in mixture pass/fail situations can result in the rejection of acceptable mixtures. However, if the criteria are set correctly this should be a reasonable test to evaluate rutting and/or stripping. Potential user agencies need to develop their own evaluation of test results using local conditions (25). Izzo and Tahmoressi (27) evaluated the laboratory repeatability of the HWTDs among different laboratories throughout the US. Their results indicated that the device has good repeatability when testing a gravel mixture, but it has poor repeatability when testing a limestone slab compacted mixture. Currently, the Texas DOT and Utah DOT use the HWTD to evaluate mix design or plant produced mix (28).

A similar device, named **Evaluator of Rutting and Stripping in Asphalt** (ERSA), was used by the University of Arkansas to evaluate rutting and stripping of HMA (29). A series of ERSA tests were conducted on the specimens using testing specifications similar to the HWTD. Their results indicated that cored cylindrical specimens and beams specimens had similar wheel-tracking test. Gyrotory compacted specimens had significantly lower rut depths than field compacted specimens. The authors stated that additional testing was needed to establish and validate the relationship between the performance of gyrotory compacted and field compacted specimens.

Purdue University laboratory wheel tracking device, **PURWheel**, was designed to evaluate rutting potential and/or moisture sensitivity of HMA (30). Test samples can be tested in either dry or wet conditions. Moisture sensitivity is defined as the ratio of the number of cycles to 12.7 mm of rutting in a wet condition to the number of cycles to 12.7 mm rutting in the dry condition. The 12.7-mm rut depth is used to differentiate between good and bad performing mixes with respect to rutting (30). Pan and White (31) have found that PURWheel test showed the abilities to evaluate the rutting/stripping of asphalt mixtures under various temperature/moisture conditions.

The **Asphalt Pavement Analyzer** (APA) was first manufactured in 1996 by Pavement Technology, Inc. The APA has been used in an attempt to evaluate rutting, fatigue, and moisture resistance of HMA mixtures. Test specimens for the APA can be either beam or cylindrical. Tests can also be performed on cores or slabs taken from an actual pavement. Test configurations for cylinders include 4% air voids, standard PG temperature, and standard hose and test configurations for beams include 5% air voids, standard PG temperature and standard hose were recommended in NCHRP Project 9-17 (Accelerated Laboratory Rutting Tests: Asphalt Pavement Analyzer) (32) to develop the APA rut test. Recently, various agencies have utilized APA to evaluate moisture damage of asphalt mixes. Cross and Voth (3, 33) evaluated anti-stripping agents using APA as an alternative test method. Samples were tested at 40°C using four different preconditioning procedures: dry, soaked, saturated, and saturated with a freeze cycle. The results indicated that only dry and soaked conditioning appeared to be adequate and saturation and saturation with a freeze cycle did not result in increased wet rut depths. As a conclusion,

it was found that the APA can be utilized to evaluate the moisture susceptibility of asphalt mixes.

A wide variety of test methods are being used by various agencies. However, no test has proven to be “superior” to other tests and no test can correctly identify a moisture-susceptible mix in all cases. This means that many HMA mixes which might otherwise perform satisfactorily in the field, are likely to be rendered unacceptable if these tests and criteria are used. It may also mean that poor mixes are accepted for use in some cases. The use of these tests has resulted in the increased use of antistripping agents in many states (34).

As stated previously, this study is aimed at identifying the best test condition and response variables using the APA to evaluate moisture sensitivity of HMA mixtures.

EXPERIMENTAL PLAN

The approach to the study was to evaluate and compare the APA performance of two mixtures; one mixture contained aggregates with good historical field performance related to stripping and the other mixture containing aggregates with poor field performance. Sixteen individual test condition (factors) comparisons were analyzed, eight condition ratios were analyzed, and four analyses were made with combinations of the study conditions. The test matrix was set up as a full-factorial experiment which allowed for traditional statistical analyses of the factors and responses. However, the results of the statistical analyses were generally not helpful in determining which combination of factors and which response variables provided the correct performance prediction for the mixtures.

Materials and Mixtures

Two dense-graded 19.0 mm nominal maximum aggregate size (NMAS) mixtures representing high and low stripping potential were selected for the testing. A mixture containing granite aggregate from Blue Circle Aggregates, Inc., Lithonia, Georgia which has had known field stripping problems was used for the high stripping potential mixture. A mixture containing limestone aggregate from Vulcan Materials Co. in Calera, Alabama which has excellent field performance was used as the low stripping potential mixture. No anti-stripping additive was used in the study mixtures. Both mixtures were tested to determine the tensile strength ratio (TSR) in accordance with AASHTO T283 including the freeze-thaw cycle. The TSR results for the mixtures were Granite = 41 percent, and Limestone = 71 percent. The complete mix designs, TSR data, and materials properties are included in Appendix A.

Specimen Preparation

All samples were prepared by grading and blending the aggregates and then mixing with the asphalt binder as commonly done in laboratory mix designs. Mixtures were aged for

2 hours at the compaction temperature prior to compaction as required for Superpave mix designs.

All beam specimens were compacted with the Asphalt Vibratory Compactor (AVC) from Pavement Technologies, Inc. Beam specimen dimensions were five inches wide, twelve inches long, and three inches in height. The air void range for the test specimens was 7.0 to 8.0 percent. Specimens outside of this range were discarded. All cylindrical specimens were compacted with a Superpave Gyrotory Compactor model AFG1 from Pine Instruments Co. Cylinders were 150 mm diameter and 75 mm in height. As with the beams, the air void range for the cylinders used in the testing was 7.0 to 8.0 percent. Specimens outside of this range were discarded.

The bulk specific gravity of the compacted specimens was determined with AASHTO T166. As is common practice for making lab specimens with high target air void contents, the stipulation in T166 regarding moisture absorption was disregarded.

Prior to testing specimens in the APA, the cylindrical specimens were cut to remove a small arc off the perimeter so that two specimens could be butted together. The flat portion of the cylindrical specimens was approximately 115 mm. This cut surface was sealed with a light coat of hot PG64-22 binder to avoid creating an artificial path for moisture intrusion. This asphalt binder seal also provided a bond between the butted specimens.

Specimen Conditioning

The procedure for conditioning selected specimens was similar to the method used for conditioning in AASHTO T283. However, vacuum saturation was not targeted for a specific percentage of saturation, but rather a given duration (6 minutes) and vacuum pressure (28 mm Hg). The resulting degree of void saturation from this procedure was generally between 90 to 100 percent. Immediately after the SSD weights were determined, the specimens were tightly wrapped with plastic wrap and placed in large freezer bags with 10 ml of water. The sealed specimens were then placed in a freezer at -18°C for sixteen hours, followed by a 60°C water bath for 24 hours and then a 25°C water bath for two hours. All conditioned specimens were dried at 50°C to remove residual moisture prior to testing.

APA Stripping Procedure

The APA tests three positions simultaneously. When testing cylindrical specimens, each position consisted of a butted pair of cylinders. The wheel loads on the device were calibrated to produce a 100 pound-force on the specimens. For tests conducted with the linear hose assembly, the hose pressure was set to 100 psi. Although the APA was programmed for 20,000 cycles for each test, many of the samples failed before 20,000 cycles were completed.

Rut depths (deformation of the specimen in the wheel path) were measured automatically. Manual measurements were also made at zero and 8000 cycles and the end of the test. For specimens which experienced greater deformation than the automatic cut off limit, the load on that position was released and the measurements ended at that point.

The test temperature was initially set at 64°C for all tests. However, after only a few tests it was realized that this temperature was too severe for the tests using the steel wheels. Therefore, all tests with steel wheels were conducted at 50°C. This is the temperature at which most agencies run the Hamburg WTD. Samples were preheated to the respective test temperature for four hours in an adjacent oven prior to the start of the test.

ANALYSIS OF DATA

There are several possible response variables that could be used to evaluate stripping potential of HMA mixtures with the APA stripping test.

- Deformation at 8000 cycles or other designated number of cycles
- Ratio of deformation of conditioned to unconditioned samples
- Ratio of deformation of samples tested wet versus samples tested dry
- Deformation rate (slope of secondary deformation)
- Ratio of deformation slope of conditioned to unconditioned samples
- Ratio of deformation slope for samples tested wet versus samples tested dry
- Stripping inflection point (number of cycles)
- Some combination of the above.

Each of these response variables have been explored to the degree possible using the data generated in this study and are further discussed in the following sections.

Deformation

Deformation of the test specimens in the wheel path (i.e. rut depth) as the response variable is perhaps the simplest to measure and evaluate. Although deformation is measured in the same manner as rut depths in the APA rutting test, the term “deformation” is used in this report to avoid confusion with “rut depth” since this term is considered synonymous with permanent deformation of HMA mixtures

For a stripping test in the APA, it is desirable to identify the conditions which cause moisture damage in mixtures prone to stripping and also result in low deformations for mixtures not susceptible to stripping. If this is possible, then a simple deformation criterion would be relatively quick and easy.

A disadvantage of using deformation as a criterion for stripping is that some mixtures may deform (rut) due to a weak aggregate structure and/or soft binder but may not have a problem with moisture damage. This would be what is called a false positive.

Since many of the tests failed prior to 20,000 cycles, it was decided to analyze the performance of the mixtures at 8,000 cycles because both manual and automatic results were available at this point. For just a few tests, the specimens failed even before 8,000 cycles, so measurements were extrapolated to this point.

The individual deformation measurements for the three test replicates are shown in Tables 1 and 2. The table also shows the coefficient of variation (C.V.) for each test set. The average coefficient of variation for deformation measurements for the two mixtures was 19%. The outlier evaluation procedure described in ASTM E 178 was used to determine if any individual replicate data should be eliminated from the average results. No outlier rut depth data were identified with this procedure.

The data in Table 3 was organized to compare the average deformations for the limestone and granite mixtures for each unique set of conditions. Based on known field performance, the limestone mixture should perform better than the granite mixture in a stripping test. The four rows that are shaded are tests in which none of the conditions are expected to cause stripping. These “unconditioned-dry” tests were used for two purposes: first as a check on the expectation that the granite mixture should perform better (have less rutting) than the limestone mixture when the conditions for stripping are not present, and second, to have a result baseline for both mixtures to demonstrate how much specimen deformation was due to stripping rather than just rutting.

Overall, only six of the twelve test conditions resulted in more stripping (using deformation as the response variable) for the granite mixture relative to the limestone mixture. Of those six test conditions, the differences between the granite mix and the limestone mix were practically insignificant (less than 2 mm) in four cases. The test that provided the correct rank and greatest difference between the two mixtures was Steel Wheel / Beam specimens / Pre-conditioning / Dry. The other test that had significantly greater deformation with the granite mixture than the limestone mixture was Steel Wheel /Cylindrical specimens/Pre-conditioning/Dry.

Table 1. Results for the Limestone Mixture

Deformation (mm) @ 8000 cycles

Test Number	Date Tested	Mix	Load Type	Specimen Type	Pre-Condition	Test Condition	Left	Center	Right	Avg.	C.V.(%)
1	5/23/02	Limestone	Hose	Cylinder	No	Dry	5.3	5.4	5.4	5.4	1
2	9/11/02	Limestone	Hose	Cylinder	No	Wet	4.6	6.0	4.4	5.0	17
3	8/26/02	Limestone	Hose	Cylinder	Yes	Dry	6.7	4.0	4.8	5.1	27
4	8/15/02	Limestone	Hose	Cylinder	Yes	Wet	5.3	4.2	3.6	4.4	20
5	5/22/02	Limestone	Hose	Beam	No	Dry	6.4	6.1	5.6	6.0	7
6	9/13/02	Limestone	Hose	Beam	No	Wet	7.5	4.5	5.6	5.9	26
7	12/27/02	Limestone	Hose	Beam	Yes	Dry	5.8	12.0	6.6	8.1	41
8	9/30/02	Limestone	Hose	Beam	Yes	Wet	6.2	6.1	6.3	6.2	2
9	4/2/03	Limestone	Steel Wheel	Cylinder	No	Dry	9.8	11.7	32.2	17.9	69
10	4/1/03	Limestone	Steel Wheel	Cylinder	No	Wet	11.7	11.0	9.8	10.9	9
11	4/17/03	Limestone	Steel Wheel	Cylinder	Yes	Dry	6.3	7.3	8.1	7.2	12
12	6/10/03	Limestone	Steel Wheel	Cylinder	Yes	Wet	10.4	12.8	9.6	10.9	15
13	3/21/03	Limestone	Steel Wheel	Beam	No	Dry	8.0	10.0	9.7	9.2	12
14	6/20/03	Limestone	Steel Wheel	Beam	No	Wet	9.9	15.0	20.6	15.2	35
15	6/19/03	Limestone	Steel Wheel	Beam	Yes	Dry	10.7	7.0	18.8	12.2	50
16	7/1/03	Limestone	Steel Wheel	Beam	Yes	Wet	19.8	13.0	15.4	16.1	21

Table 2. Results for the Granite Mixture

Deformation (mm) @ 8000 cycles

Test Number	Date Tested	Mix	Load Type	Specimen Type	Pre-Condition	Test Condition	Left	Center	Right	Avg.	C.V. (%)
17	9/20/02	Granite	Hose	Cylinder	No	Dry	3.5	4.3	3.7	3.8	11
18	8/29/02	Granite	Hose	Cylinder	No	Wet	3.7	3.4	4.1	3.7	9
19	3/10/03	Granite	Hose	Cylinder	Yes	Dry	6.3	8.0	6.6	7.0	13
20	5/22/03	Granite	Hose	Cylinder	Yes	Wet	5.6	5.9	3.6	5.0	25
21	5/28/02	Granite	Hose	Beam	No	Dry	4.4	4.0	5.4	4.6	16
22	8/27/02	Granite	Hose	Beam	No	Wet	6.2	5.7	6.3	6.1	5
23	3/5/03	Granite	Hose	Beam	Yes	Dry	5.5	6.1	6.7	6.1	10
24	3/7/03	Granite	Hose	Beam	Yes	Wet	7.0	8.0	7.2	7.4	7
25	3/24/03	Granite	Steel Wheel	Cylinder	No	Dry	7.8	8.0	8.6	8.1	5
26	4/3/03	Granite	Steel Wheel	Cylinder	No	Wet	6.4	8.0	10.9	8.5	27
27	6/6/03	Granite	Steel Wheel	Cylinder	Yes	Dry	12.3	8.1	8.8	9.7	23
28	7/17/03	Granite	Steel Wheel	Cylinder	Yes	Wet	8.2	13.1	10.2	13.3	23
29	10/12/02	Granite	Steel Wheel	Beam	No	Dry	8.6	8.5	10.4	9.2	12
30	4/15/03	Granite	Steel Wheel	Beam	No	Wet	8.3	8.1	6.6	7.7	12
31	1/6/03	Granite	Steel Wheel	Beam	Yes	Dry	15.6	10.8	26.7	17.7	46
32	7/3/03	Granite	Steel Wheel	Beam	Yes	Wet	10.3	11.1	NA	10.7	5

Table 3. Average Deformation (mm) for each Test Condition

Conditions ¹	Test Pair	Limestone	Granite
Hose/Cylinder/No/Dry	1:17	5.4	3.8
Hose/Cylinder/No/Wet	2:18	5.0	3.7
Hose/Cylinder/Yes/Dry	3:19	5.2	7.0
Hose/Cylinder/Yes/Wet	4:20	4.4	5.0
Hose/Beam/No/Dry	5:21	6.0	4.6
Hose/Beam/No/Wet	6:22	5.9	6.1
Hose/Beam/Yes/Dry	7:23	8.1	6.1
Hose/Beam/Yes/Wet	8:24	6.2	7.4
Wheel/Cylinder/No/Dry	9:25	17.9	8.1
Wheel/Cylinder/No/Wet	10:26	10.8	8.4
Wheel/Cylinder/Yes/Dry	11:27	7.2	9.7
Wheel/Cylinder/Yes/Wet	12:28	10.9	10.5
Wheel/Beam/No/Dry	13:29	9.2	9.2
Wheel/Beam/No/Wet	14:30	15.2	7.7
Wheel/Beam/Yes/Dry	15:31	12.2	17.7
Wheel/Beam/Yes/Wet	16:32	16.1	10.7

1. Conditions are listed as Load Type/Specimen Type/Pre-Conditioning/Test Wet or Dry

The analysis of variance (ANOVA) for “deformation” as the response variable is shown in Table 4. This analysis indicates that deformation over all conditions was not significantly different for the two mixtures. However, this statistical conclusion is the result of including the data from the four non-stripping conditions highlighted above as shaded. The factor with the highest level of significance was the type of load (wheel>hose). This effect is remarkable considering that the test temperature for the steel wheel tests was 14°C below the test temperature using the pneumatic hose. Other significant factors were specimen type, and the interaction of mix type and pre-conditioning, the interaction of specimen type and pre-conditioning, and the three-way interaction of mix type, specimen type and test condition.

The interaction box-plots, shown in Figures 1 and 2, illustrate the effects of several factors. These plots are constructed using the MINITAB statistical software program. The top of the boxes is the third quartile (Q3) and the bottom of the box is the first quartile (Q1). The median value is shown by the horizontal line within the box. The upper whisker extends to the highest data value within the upper limit of $Q3+1.5(Q3-Q1)$. The lower whisker, likewise, extends to the lowest data value within the lower limit of $Q1-1.5(Q3-Q1)$. Any data points outside this range are outliers and are shown as asterisks. These are the default settings for MINITAB box-plot graphs.

Table 4. Analysis of Variance for Deformation, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Mix	1	40.78	36.92	36.92	3.35	0.072
Load	1	781.82	777.90	777.90	70.49	0.000
Specimen	1	59.28	57.69	57.69	5.23	0.026
PreCondition	1	29.19	27.52	27.52	2.49	0.119
Water	1	0.93	1.20	1.20	0.11	0.743
Mix*Load	1	20.65	21.33	21.33	1.93	0.169
Mix*Specimen	1	0.17	0.11	0.11	0.01	0.923
Mix*PreCondition	1	74.47	71.00	71.00	6.43	0.014
Mix*Water	1	8.01	8.87	8.87	0.80	0.374
Load*Specimen	1	1.26	0.91	0.91	0.08	0.775
Load*PreCondition	1	0.00	0.02	0.02	0.00	0.966
Load*Water	1	0.39	0.20	0.20	0.02	0.894
Specimen*PreCondition	1	57.61	53.47	53.47	4.84	0.031
Specimen*Water	1	6.81	5.33	5.33	0.48	0.490
PreCondition*Water	1	0.03	0.01	0.01	0.00	0.971
Mix*Load*Specimen	1	2.89	1.90	1.90	0.17	0.680
Mix*Load*PreCondition	1	28.93	24.83	24.83	2.25	0.139
Mix*Load*Water	1	25.92	29.25	29.25	2.65	0.109
Mix*Specimen*PreCondition	1	10.28	12.14	12.14	1.10	0.298
Mix*Specimen*Water	1	24.95	27.10	27.10	2.46	0.122
Mix*PreCondition*Water	1	15.95	17.24	17.24	1.56	0.216
Load*Specimen*PreCondition	1	42.99	39.68	39.68	3.60	0.063
Load*Specimen*Water	1	0.05	0.00	0.00	0.00	0.990
Load*PreCondition*Water	1	7.42	5.91	5.91	0.54	0.467
Specimen*PreCondition*Water	1	29.36	31.71	31.71	2.87	0.095
Mix*Load*Specimen*PreCondition	1	0.10	0.28	0.28	0.03	0.875
Mix*Load*Specimen*Water	1	74.07	75.50	75.50	6.84	0.011
Mix*Load*PreCondition*Water	1	18.07	18.27	18.27	1.66	0.203
Mix*Specimen*PreCondition*Water	1	9.54	9.11	9.11	0.83	0.367
Load*Specimen*PreCondition*Water	1	34.25	34.03	34.03	3.08	0.084
Mix*Load*Specimen*PreCondition*Water	1	1.43	1.43	1.43	0.13	0.720
Error	63	695.27	695.27	11.04		
Total	94	2102.86				

From Figure 1, it can be seen that pre-conditioning of the samples increased the deformations measured on the granite mixture but had no effect or resulted in slightly less deformations for the limestone mixture. Also, the measured deformations using steel wheel loading were greater than with the pneumatic hose. However, using the steel wheel loading also appears to increase variability. From Figure 2, it can be seen that on average, neither the test condition (wet or dry) or specimen type (beam or cylinder) have a large effect on measured deformation. It is apparent, however, that tests conducted in water (wet) are more variable.

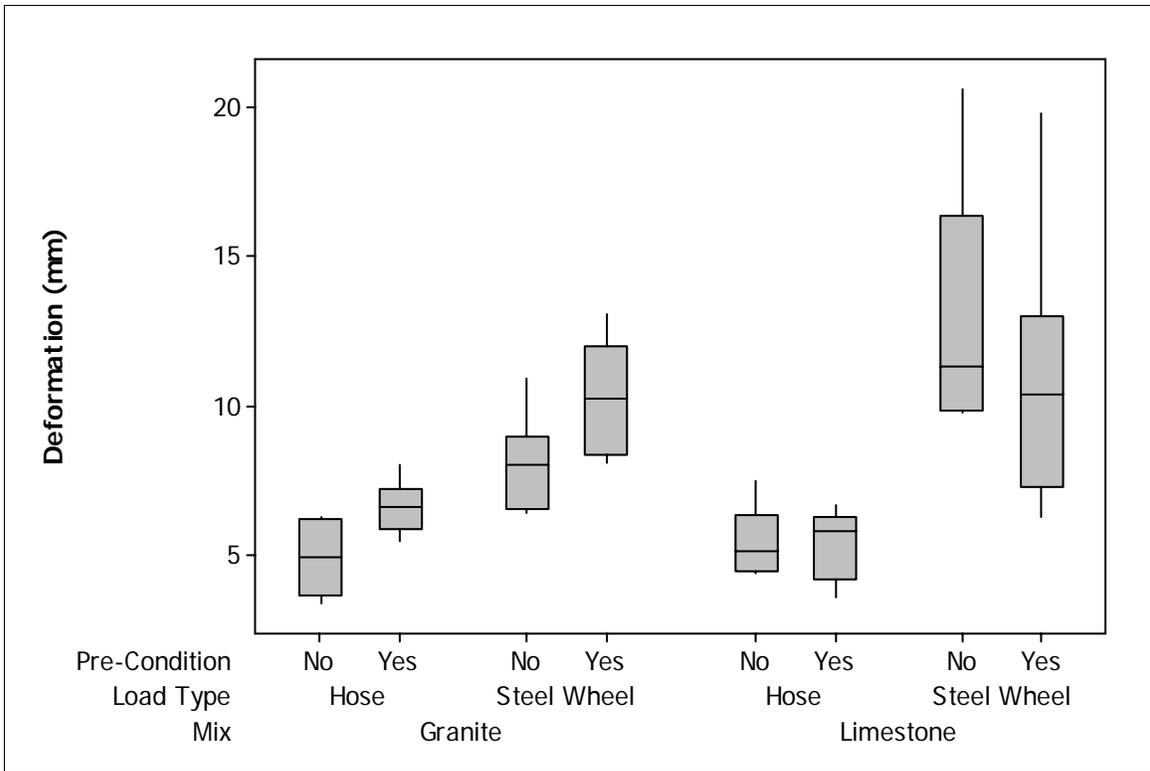


Figure 1. Interaction Box Plot of Mix Type, Load Type, and Pre-Conditioning

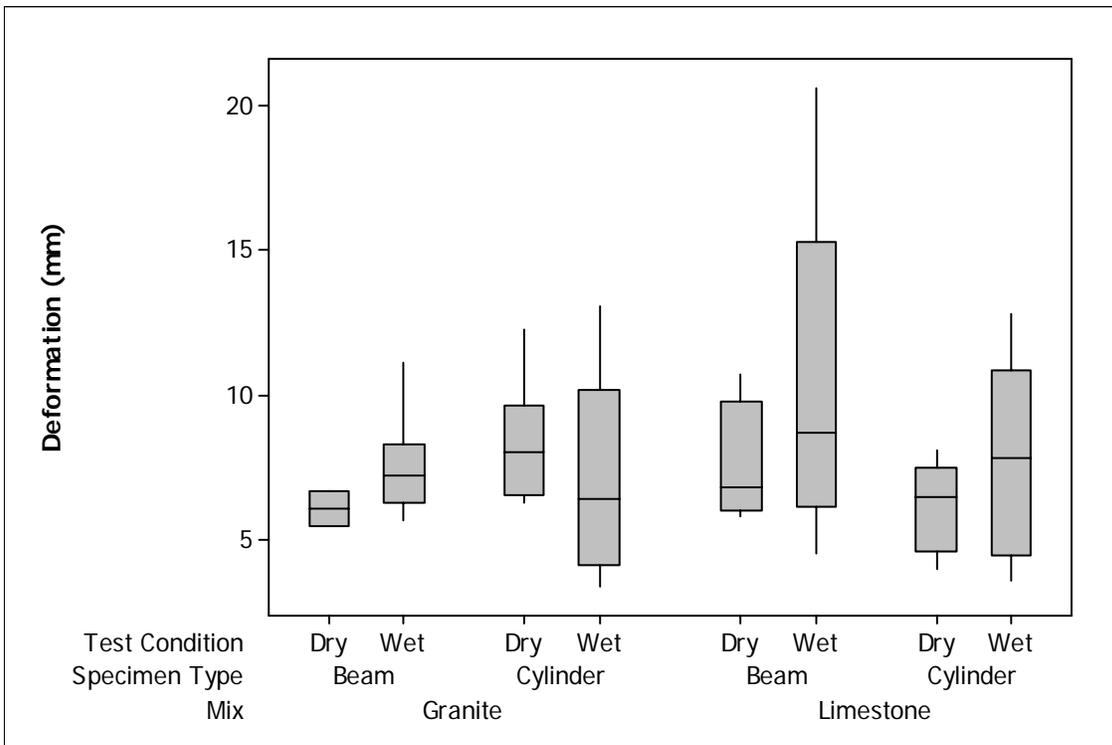


Figure 2. Interaction Box Plot of Mix Type, Specimen Type, and Wet or Dry Test

Ratio of Deformation for Conditioned to Unconditioned Samples (C/U DR)

A ratio of conditioned to unconditioned deformations, similar to a ratio of conditioned to unconditioned tensile strengths (i.e. TSR), is a plausible response variable because it is easy to understand. For example, let's say that the unconditioned sample deformation was 6.0 mm, and the conditioned deformation was 10.0 mm, then the ratio would be 1.67 or 167%. Note that a ratio greater than 1.0 (100%) indicates a loss of mixture strength due to the conditioning, which is the opposite of TSR. In other words, the larger the percentage then the greater the stripping potential.

The advantage of using a ratio as a criterion is that the response to the condition is normalized by the individual mixture. This allows for easier comparison of how the "conditioning" affects different mixtures.

A disadvantage of ratios, however, is that for small numbers, a ratio can be misleading. To illustrate this point, consider an unconditioned result of 2.0 mm and conditioned deformation of 3.0 mm. The ratio would also be 1.50 or 150%. However, a conditioned result of only 3.0 mm could hardly be considered a stripping failure. Therefore, as a possible specification, a criterion for stripping ratio should be combined with another criterion such as a maximum conditioned deformation.

Another disadvantage of using ratios as criteria is that two sets of specimens must be made, conditioned, and tested which significantly increases the expense and time of conducting the test.

The Conditioned/Unconditioned Deformation Ratios (C/U DR) for the each of the factor combinations are shown in Table 5. The expectation is that for the limestone mixture, the ratio would be close to 100%. Considering the average coefficient of variation of 19%, it is reasonable to have ratios between 80% to 120% for the limestone mixture. The stripping prone granite mixture should have much higher ratios than the limestone mixture. As seen from this data, the test combinations that correctly rated the two mixtures were Hose loading/Cylindrical specimens/Dry testing, Hose loading/Cylindrical specimens/Wet testing, and Steel Wheel loading/Beam specimens/Wet testing. The combination of Steel Wheel loading/Beam specimens/Dry testing may also be considered viable even though the ratio for the limestone mixture was 132.

Table 5. Conditioned / Unconditioned Deformation Ratio

Factors	Granite	Limestone	Difference
Hose/Cylinder/Dry	182	89	93
Hose/Cylinder/Wet	135	87	48
Hose/Beam/Dry	133	135	-2
Hose/Beam/Wet	122	106	16
Wheel/Cylinder/Dry	120	40	79
Wheel/Cylinder/Wet	125	101	24
Wheel/Beam/Dry	193	132	61
Wheel/Beam/Wet	140	106	34

Wet/Dry Deformation Ratio (W/D DR)

Another ratio that can be evaluated is wet versus dry deformation. In this comparison, sample pairs are conditioned the same, but one set is tested while submerged in water and the other set is tested dry. The advantages and disadvantages of ratios is the same for this response variable as stated above.

The Wet/Dry Deformation Ratios (W/D DR) for each factor combination are shown in Table 6. For this ratio, only one test combination rated and ranked the mixtures correctly: Hose loading / Beam specimens/No Pre-conditioning.

Table 6. Wet / Dry Deformation Ratios

Factors	Granite	Limestone	Difference
Hose/Cylinder/No Conditioning	97	93	4
Hose/Cylinder/Conditioning	72	85	-13
Hose/Beam/No Conditioning	132	97	35
Hose/Beam/Conditioning	121	76	45
Wheel/Cylinder/No Conditioning	104	61	43
Wheel/Cylinder/Conditioning	108	151	-43
Wheel/Beam/No Conditioning	84	164	-80
Wheel/Beam/Conditioning	60	132	-62

Conditioned-Wet/Unconditioned-Dry Deformation Ratio (CW/UD DR)

This combination of conditions combines the expected worst-case test scenario of pre-conditioning of samples and testing them while submerged. The deformation of samples tested with this most severe combination are divided by the results of unconditioned specimens tested in a dry state. Mixtures with potential moisture susceptibility would be expected to have a high ratio, whereas mixtures with low propensity to stripping would be expected to have a ratio near 100%.

The specimen preparation and testing protocol necessary for this combination of conditions would be the most time consuming and technician labor intensive.

Ratios for the two mixtures tested with these conditions are shown in Table 7. Only one combination of conditions appeared to correctly rate and rank the mixtures: Hose loading / Beam specimens.

Table 7. Conditioned-Wet / Unconditioned-Dry Deformation Ratios

Factors	Granite	Limestone	Difference
Hose/Cylinder	131	81	50
Hose/Beam	161	103	58
Wheel/Cylinder	129	61	68
Wheel/Beam	117	174	-57

Deformation Slope

The typical graph of deformation versus cycles as shown in Figure 3 includes two or three phases. The first part of the graph, usually within the first 1000 to 2000 cycles, most often follows a growth curve and is thought to be deformation primarily from consolidation of the specimen beneath the loaded wheel passes. The second part of the graph is typically a linear rate of deformation which may be referred to as the secondary deformation slope (S_{SD}). Many samples only have graphs which include these first two parts. For other samples, the rate of deformation increases as the test progresses. In a permanent deformation test, this part of the graph is referred to as tertiary flow and represents failure of the sample due to a loss of shear strength within the HMA sample. For a stripping test, the loss of shear strength may be due to the loss of cohesion with the HMA and the point at which (number of cycles) this failure begins is called the stripping inflection point. This is one of the parameters used to assess stripping with the Hamburg WTD. The stripping inflection point can be determined by plotting a tangent to the tertiary flow and intersecting this line with the secondary deformation slope.

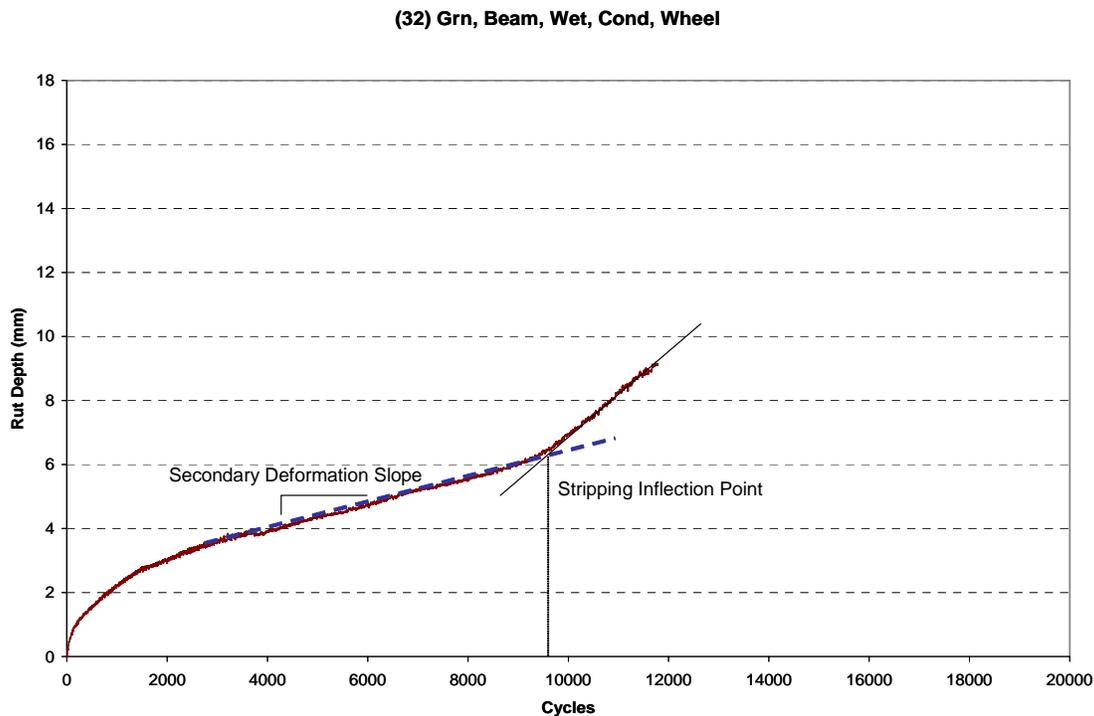


Figure 3. Example Plot of Results for an APA Stripping Test

Determining precise transition points between the consolidation part, the linear deformation part and the tertiary flow part of a test graph is an iterative process and requires some judgment. For this research, the least-squares curve-fitting feature from Microsoft Excel was used to evaluate three types of best-fit equations: polynomial equations, power equations, and linear equations.

- Polynomial equation form: $y = ax^2 + bx + c$
- Power equation form: $y = x^a$
- Linear equation form: $y = mx + b$

In each of the above equations, “x” represents the number of cycles.

Slopes for the polynomial equations were taken as the first order coefficient “b”. To simplify the analysis, the polynomial equations were fit to the entire data for the test. Although for some tests, the polynomial equation did not approximate the actual data in the first 2000 cycles, the part of the equation that was most important for determining the secondary deformation slope was quite close to the actual data. Slopes for the power equation were taken as the exponent “a”. As with the polynomial best fit equations, the power equations were based on the entire set of data for each test. The linear equations were fit only to range of data from 2000 to 8000 cycles. The slope for a linear equation is the coefficient “m”.

Data from each sample location (left, center, right) in each test was fitted with equations of the three forms above to provide replications for statistical analysis. The best fit equations for all test results are shown in Appendix B. Each form of the regression equations had very good fit with the measurements from the automated data as evident by correlation coefficients (R^2) of greater than 0.9. ANOVA results for the deformation slopes determined with the three equation forms, also included in Appendix B, indicated different factors and interactions as statistically significant. As with the ANOVA for deformation as the response variable, the ANOVA results for each of the deformation rates do not show significant differences between the mix types. As discussed before, this is largely due to the inclusion of data from tests which specimens were not pre-conditioned or tested with water. As expected, those tests generally show that the granite mixture had less deformation and rates of deformation than the limestone mixture.

To further analyze deformation slopes as a response variable, as well as ratios of certain conditions, the slope determined from the power equations was used since this slope had the lowest average coefficient of variation among replicates. Table 8 provides a comparison of the average deformation slopes of the two mixtures for each set of conditions.

Figures 4 and 5 show the interaction box plots for the main factors on the slopes of the deformations. From Figure 4 it can be seen that pre-conditioning of samples before testing appeared to only have an effect on the granite mixture tested with the steel wheel loading. This combination of factors also resulted in the greatest variability. Also, as evident from Figure 1, the steel wheel loading causes more damage to the samples compared to the pneumatic hose despite the test temperature with the steel wheels was 14°C lower. Figure 5 shows that tests performed with the samples under water resulted in slightly lower average slopes. However these differences are negligible considering the variability of the results. Also, no conclusions can be drawn from the comparison of specimen types.

Table 8. Average Deformation Slopes (mm/1000 cycles) for each Test Condition

Conditions ¹	Test Pair	Limestone	Granite
Hose/Cylinder/No/Dry	1:17	5.3	7.7
Hose/Cylinder/No/Wet	2:18	4.3	4.3
Hose/Cylinder/Yes/Dry	3:19	5.3	6.0
Hose/Cylinder/Yes/Wet	4:20	3.3	4.0
Hose/Beam/No/Dry	5:21	6.3	5.0
Hose/Beam/No/Wet	6:22	6.7	5.7
Hose/Beam/Yes/Dry	7:23	11.3	5.0
Hose/Beam/Yes/Wet	8:24	6.3	8.0
Wheel/Cylinder/No/Dry	9:25	24.7	13.0
Wheel/Cylinder/No/Wet	10:26	12.7	10.0
Wheel/Cylinder/Yes/Dry	11:27	9.0	10.7
Wheel/Cylinder/Yes/Wet	12:28	15.3	21.0
Wheel/Beam/No/Dry	13:29	10.7	9.3
Wheel/Beam/No/Wet	14:30	14.3	7.0
Wheel/Beam/Yes/Dry	15:31	11.3	22.7
Wheel/Beam/Yes/Wet	16:32	14.0	6.0

1. Conditions are listed as Load Type/Specimen Type/Pre-Conditioning/Test Wet or Dry

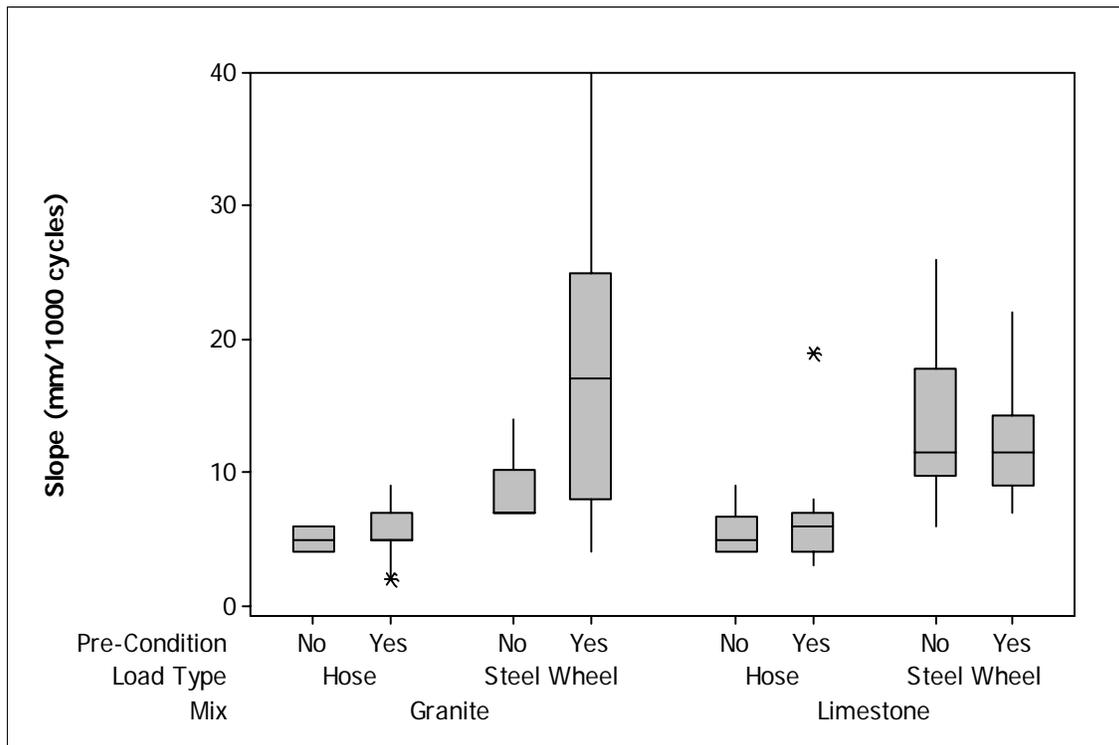


Figure 4. Interaction Box Plot of Mix Type, Load Type, and Pre-Conditioning on Slope. (* denotes outlier observations)

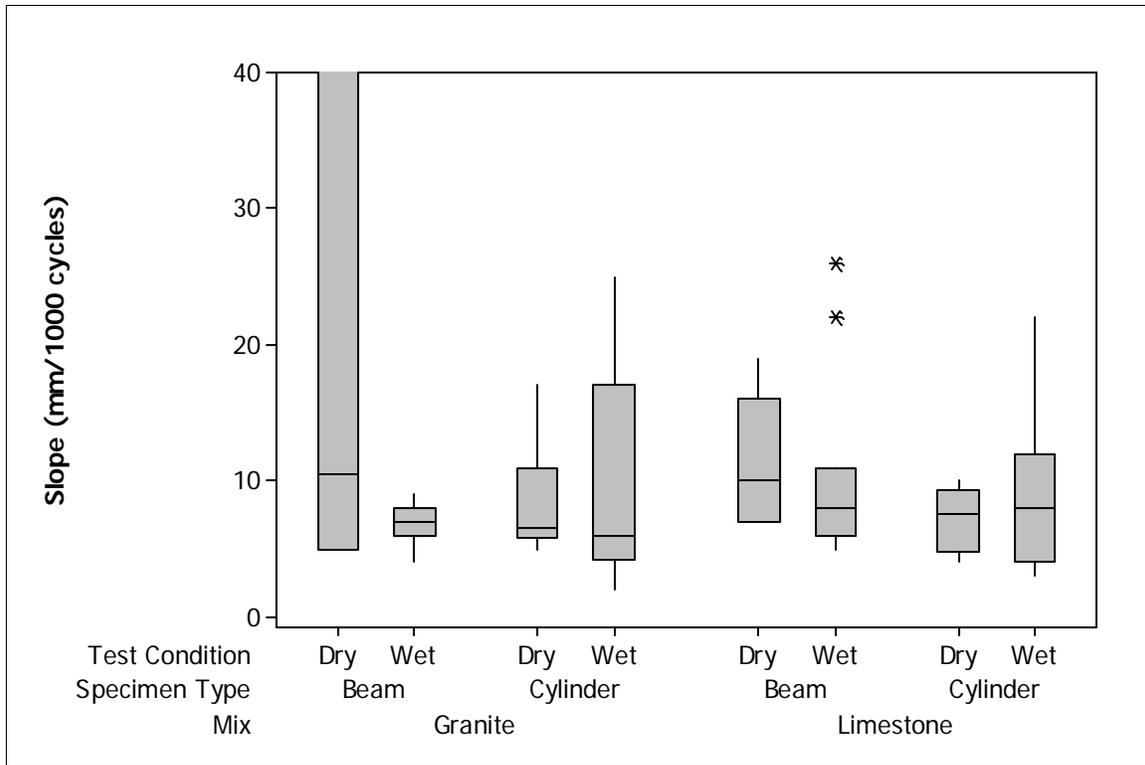


Figure 5. Interaction Box Plot of Mix Type, Specimen Type, and Test Condition (Wet or Dry) on Slope. (* denotes outlier observations)

Ratio of Deformation Slope for Conditioned to Unconditioned Samples (C/U SR)

The ratios of deformation slopes for conditioned to unconditioned samples for both mixtures are provided in Table 9. The factor combinations which provided the correct rating and rank for the two mixtures were: Hose loading/Beam specimens/Wet testing, and Steel Wheel loading/Beam specimens/Dry testing.

Table 9. Ratios of Conditioned / Unconditioned Deformation Slopes

Factors	Granite	Limestone	Difference
Hose/Cylinder/Dry	78	100	-22
Hose/Cylinder/Wet	92	77	15
Hose/Beam/Dry	100	179	-79
Hose/Beam/Wet	141	95	46
Wheel/Cylinder/Dry	82	36	46
Wheel/Cylinder/Wet	210	121	89
Wheel/Beam/Dry	243	106	137
Wheel/Beam/Wet	86	98	-12

Ratio of Deformation Slope for Samples Tested Wet Versus Samples Tested Dry (W/D SR)

The Wet/Dry Slope Ratios for the factor combinations are shown in Table 10. As can be seen, there was no set of conditions which provided correct rating and rank of the two mixtures.

Table 10. Ratios of Wet / Dry Deformation Slopes

Factors	Granite	Limestone	Difference
Hose/Cylinder/No Conditioning	57	81	-26
Hose/Cylinder/Conditioning	67	63	4
Hose/Beam/No Conditioning	113	105	8
Hose/Beam/Conditioning	160	56	104
Wheel/Cylinder/No Conditioning	77	51	26
Wheel/Cylinder/Conditioning	197	170	27
Wheel/Beam/No Conditioning	75	134	-59
Wheel/Beam/Conditioning	26	124	-98

Ratio of Conditioned-Wet / Unconditioned-Dry Deformation Slopes (CW/UD SR)

The ratios for conditioned-wet to unconditioned-dry deformation slopes are shown in Table 11. The only factor combination that gave the correct rating and rank for the two mixtures was Hose loading / Beam specimens.

Table 11. Ratios of Conditioned-Wet / Unconditioned Dry Deformation Slopes

Factors	Granite	Limestone	Difference
Hose/Cylinder	52	63	-11
Hose/Beam	160	100	60
Wheel/Cylinder	162	62	99
Wheel/Beam	64	131	-67

Stripping Inflection Point (SIP)

Graphs of deformation versus cycles were examined for each test to determine if a Stripping Inflection Point (SIP) existed and if so the approximate number of cycles where it occurred. This data is shown in Table 12. This analysis was not highly productive because determining the point at which the deformation accelerated was somewhat arbitrary for some data and also because the occurrence of an SIP was inconsistent within the test replicates. However, the one test set up that appears to show an SIP for the granite mixture and no SIP for the limestone mixture was Steel wheel / Cylindrical specimens / Pre-conditioned / Dry test. It is also evident that no tests using the pneumatic hoses had SIP's which clearly indicates that this type of load transfer is not as severe as using direct contact with steel wheels.

Table 12. Stripping Inflection Point Data for All Replicates

Conditions	Granite			Limestone		
	Left	Center	Right	Left	Center	Right
Hose/Cylinder/No/Dry	none	none	none	none	none	none
Hose/Cylinder/No/Wet	none	none	none	none	none	none
Hose/Cylinder/Yes/Dry	none	none	none	none	none	none
Hose/Cylinder/Yes/Wet	none	none	none	none	none	none
Hose/Beam/No/Dry	none	none	none	none	none	none
Hose/Beam/No/Wet	none	none	none	none	none	none
Hose/Beam/Yes/Dry	none	none	none	none	none	none
Hose/Beam/Yes/Wet	none	none	none	none	none	none
Wheel/Cylinder/No/Dry	none	none	none	9200	7900	2720
Wheel/Cylinder/No/Wet	none	none	none	9900	7800	8500
Wheel/Cylinder/Yes/Dry	5350	none	6500	none	none	none
Wheel/Cylinder/Yes/Wet	none	2560	none	none	none	none
Wheel/Beam/No/Dry	none	none	none	none	none	8100
Wheel/Beam/No/Wet	4850	9100	none	7080	5100	2600
Wheel/Beam/Yes/Dry	none	none	1360	none	none	5450
Wheel/Beam/Yes/Wet	NA	4630	9450	4500	5170	3900

SUMMARY

Table 13 shows a summary of the best factor combinations for each response variable. These are the factor combinations which yielded the correct rating and rank of the two mixtures. The various combinations listed suggest that there are several test options that may be used to assess stripping potential. The only primary factor that is consistently listed (explicitly or by inference in C/U ratios) is pre-conditioning of samples prior to testing.

From the simple-is-best point of view, the most preferred test set up from this list would probably be to use pre-conditioned cylindrical samples tested dry with steel wheel loading. This protocol features the simplicity of using cylindrical specimens and testing of only one set of samples. Possible criteria could be established for maximum deformation, maximum secondary deformation slope, and stripping inflection point. However, as discussed before, some mixtures may perform poorly in this test due to a weak aggregate structure and/or soft binder even though it is not stripping. Therefore, a better test for assessing only stripping potential is to use a ratio of wet/dry or conditioned/unconditioned data. Based on the combination of conditions listed in the above table, and using a preference of cylindrical specimens, a good test set up using a ratio as the response variable appears to be C/U DR with hose loading in a dry condition on cylindrical specimens. The test variability for this combination of conditions appears to be less than for the other sample preparation and testing protocols.

Table 13. Summary of Factors That Gave Correct Rank and Ratings

Response Variable	Best Factor Combinations			
	Load Type	Specimen Type	Pre-Conditioned	Wet/Dry
Deformation	Steel Wheel	Cylinder	Yes	Dry
	Steel Wheel	Beam	Yes	Dry
C/U DR	Hose	Cylinder	-	Dry
	Hose	Cylinder	-	Wet
	Steel Wheel	Beam	-	Wet
W/D DR	Hose	Beam	No	-
CW/UD DR	Hose	Beam	-	-
Slope	Steel Wheel	Cylinder	Yes	Wet
	Steel Wheel	Beam	Yes	Dry
C/U SR	Hose	Beam	-	Wet
	Steel Wheel	Beam	-	Dry
CW/UD SR	Hose	Beam	-	-
SIP	Steel Wheel	Cylinder	Yes	Dry

CONCLUSIONS

Based on this work involving two mixtures with known histories of good and bad stripping performance, it appears that certain conditions can be used to induce moisture damage in HMA mixtures in the APA. The selection of the best APA conditions for evaluating the stripping potential of HMA mixtures appears to be dependent on which response variable is used.

Use of the steel wheels for specimen loading is much more severe than using air filled hoses. The harsh condition of loading by steel wheels appeared to accelerate failure for the mixture which was susceptible to stripping and therefore possibly help distinguish good versus bad mix performance. However, the use of steel wheel loading appears to significantly increase variability among replicates in the test.

Pre-conditioning of specimens using a prescribed vacuum level (28 mm of Hg) and time (6 minutes) followed by a single freeze/thaw cycle appears to help distinguish a stripping prone mixture from a non-stripping prone mixture.

The research indicates that testing of unconditioned specimens in a submerged (wet) condition does not cause stripping to occur. Other researchers have theorized that water filled pores in the HMA specimens supports some of the wheel load similar to the pore pressure component of the effective strength in saturated soils.

The analyses did not indicate a significant difference between beam specimens compacted with an AVC and cylindrical specimens compacted with an SGC. Although interactions with other factors clearly favors the use of beam specimens, it is much more practical to use an SGC for compacting specimens.

Since no test replications were included in this study, it was not possible to provide an indication of repeatability. From the large variations of some results among test replicates, repeatability and reproducibility of these APA moisture tests is probably a concern.

RECOMENDATIONS

Much more information is needed before the reliability of any APA test can be established as a good indicator of stripping potential. Further research, if warranted, should include a more complete range of mixtures and performance so that possible failure criteria could be established. Replicate tests should be performed to address repeatability.

For future work with the APA for moisture damage assessments, it is recommended that automated measurements be used to track specimen deformations so that analysis can be made of total deformation, the secondary deformation slope, and possible stripping inflection points.

REFERENCES

1. Bahia, H, and S. Ahmad. "Evaluation and Correlation of Lab and Field Tensile Strength Ratio (TSR) Procedures and Values in Assessing the Stripping Potential of Asphalt Mixes." WisDOT Study #95-04, Final Report. December, 1999.
2. "Moisture Sensitivity of Asphalt Pavement." A National Seminar, February 4-6, 2003. San Diego, California. Transportation Research Board.
3. Cross, S.A., M.D Voth, and G.A. Fager. "Effects of Sample Preconditioning on Asphalt Pavement Analyzer Wet Rut Depths." Mid-Continent Transportation Symposium 2000, Ames, Iowa.
4. "APA User's Group Meeting Minutes.", September 26-27, 2000, Jackson, MS.
5. Kandhal, P.S. "Field and Laboratory Investigation of Stripping in Asphalt Pavements: State of the Art Report." Transportation Research Board, Transportation Research Record 1454, 1994.
6. Hicks, R.G. "Moisture Damage in Asphalt Concrete." NCHRP Synthesis of Highway Practices No. 175, October 1991.
7. Kandhal, P.S. "Moisture Susceptibility of HMA Mixes: Identification of Problem and Recommended Solutions." National Asphalt Pavement Association Quality Improvement Publication (QIP) 119, December 1992.
8. Ronald L. Terrel, Saleh Al-Swailmi. "Water Sensitivity of Asphalt-Aggregate Mixes: Test Selection." SHRP-A-403. National Research Council. Washington, DC. 1994.
9. Lottman, R.P. "Predicting Moisture-induced Damage to Asphalt Concrete." NCHRP Report 192, 1978.
10. Lottman, R.P. "Laboratory Test Methods for Predicting Moisture-Induced Damage to Asphalt Concrete." Transportation Research Board, Transportation Research Record 843, 1982.
11. Lottman, R.P. "Predicting Moisture – Induced Damage to Asphaltic Concrete – Field Evaluation." Transportation Research Board, NCHRP Report 246, 1982.
12. Maupin, G.W. "The Use of Antistripping Additives in Virginia." Proceeding of the Association of Asphalt Paving Technologists, Volume 51. 1982.
13. Stuart, K.D. "Evaluation of Procedures Used to Predict Moisture Damage in Asphalt Mixtures." FHWA Report FHWA/RD-86/091, 1986.
14. Parker, F. and F. Gharaybeh. "Evaluation of Indirect Tensile Tests for Assessing Stripping of Alabama Asphalt Concrete Mixtures." Transportation Research Board, Transportation Research Record 1115, 1987.
15. Freddy L. Roberts, Prithvi S. Kandhal, E. Ray Brown, Dah-Yinn Lee, and Thomas W. Kennedy. "Hot Mix Asphalt Materials, Mixture Design, and Construction." NAPA Education Foundation, Second Edition 1996.
16. Tunnicliff, D.G. and R.E. Root. "Use of Antistripping Additives in Asphaltic Concrete Mixtures." Transportation Research Board, NCHRP Report 174, 1984.
17. Coplantz, J.S. and D.E. Newcomb. "Water Sensitivity Test Methods for Asphalt Concrete Mixtures – A Laboratory Comparison." Transportation Research Board, Transportation Research Record 1171, 1988.

18. "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage." Test Method T 283-85. AASHTO, Part II – Methods of Sampling and Testing, August 1986.
19. Aschenbrener, T. "Evaluation of Hamburg Wheel-Tracking Device to Predict Moisture Damage in Hot Mix Asphalt." Transportation Research Board, Transportation Research Record 1492, 1995.
20. Khosla, N.P., B.G. Birdsall, and S. Kawaguchi, "Evaluation of Moisture Susceptibility of Asphalt Mixtures: Conventional and New Methods." Transportation Research Board, Transportation Research Record 1728, 2000.
21. Stuart, K.D. "Moisture Damage in Asphalt Mixtures – A State-of-the Art Report." FHWA, Report FHWA-RD-90—19, August 1990.
22. Al-Swailmi, S. and R.L. Terrel. "Evaluation of Water Damage of Asphalt Concrete Mixtures Using the Environmental Conditioning System (ECS)." Proceeding of the Association of Asphalt Paving Technologists, Volume 61. 1992.
23. Aschenbrener T., R.B. McGennis, and R.L. Terrel. "Comparison of Several Moisture Susceptibility Tests to Pavements of Known Field Performance." Proceeding of the Association of Asphalt Paving Technologists, Volume 64. 1995.
24. Curtis, C.W., K. Ensley, and J. Epps. "Fundamental Properties of Asphalt – Aggregate Interactions Including Adhesion and Absorption." Final Report SHRP A-003B, 1991.
25. Buchanan, M.S. "An Evaluation of Laboratory Wheel-Tracking Devices." Report Prepared for National Asphalt Pavement Association, National Center for Asphalt Technology. August 1997.
26. WesTrack Forensic Team. "Performance of Coarse-graded Mixes at WesTrack – Premature Rutting." Final Report. June 1998.
27. Izzo, R.P., and M. Tahmoressi, "Testing Repeatability of the Hamburg Wheel-Tracking Device and Replicating Wheel-Tracking Devices Among different Laboratories." Journal of Association of Asphalt Paving Technologists, Volume 68, 1999.
28. Hicks, R. Gray, L. Santucci, and T. Aschenbrener. "Introduction and Seminar Objectives.", Moisture Sensitivity of Asphalt Pavement, A National Seminar, February 4-6, 2003. San Diego, California. Transportation Research Board.
29. Hall, K.D., and S.G. Williams, "Acquisition and Evaluation of Hamburg Wheel-Tracking Device." Technical memo. (Final) Jan 93-Aug 94.
30. Pan, C. and T.D. White. "Conditions for Stripping Using Accelerated Testing." Report No. FHWA/IN/JTRP-97/13. Joint Transportation Research Program. Purdue University. West Lafayette, Indiana. February 1999.
31. Pan, C, and T.D. White. "Conditions for stripping Using Accelerated Testing." FHWA/IN/JTRP-97/13. February 1999.
32. Kandhal, P.S. and L.A. Cooley, Jr. "Accelerated Laboratory Rutting Tests: Evaluation of the Asphalt Pavement Analyzer." National Cooperative Highway Research Program, NCHRP Report 508, 2003.
33. Cross, S.A., and M.D. Voth. "Evaluation of Anti-stripping Agents using the Asphalt Pavement Analyzer." K-Tran Final Report, June 2001.

34. Brown, E.R., P.S. Kandhal, and J. Zhang. "Performance Testing for Hot Mix Asphalt." National Center for Asphalt Technology Report No. 01-05, November 2001.

APPENDIX A: Mix Designs and Materials Information

Limestone Mixture

Component Materials	Source	Approx. Percentage
Pre-graded lab stock limestone	Vulcan Matls., Calera AL	93.2
PG 67-22 asphalt binder	Ergon, Jackson, MS	4.8%

Verified Batch Gradation

Sieve	Percent Passing
25.0 mm	100
19.0 mm	97
12.5 mm	77
9.5 mm	65
4.75 mm	47
2.36 mm	26
1.18 mm	16
0.60 mm	11
0.30 mm	9
0.15 mm	7
0.075 mm	3.8

Optimum Pb 4.8%

Ndesign 100

Air Voids 4.0%

VMA 14.9%

VFA 73.1%

%Gmm @ Nini 84.8%

P₂₀₀/P_{be} 0.84

Mixing Temperature 160°C

Compaction Temperature 149°C

AASHTO T 283

Unconditioned Tensile Strength 109.4 psi

Conditioned Tensile Strength 77.3 psi

Tensile Strength Ratio 71 %

Granite Mixture

Component Materials	Source	Approx. Percentage
W-67	Blue Circle, Lithonia, GA	38%
W-78	Blue Circle, Lithonia, GA	28%
M-10	Blue Circle, Lithonia, GA	28%
PG 67-22 asphalt binder	Ergon, Jackson, MS	5.4%

Verified Batch Gradation

Sieve	Percent Passing
25.0 mm	100
19.0 mm	96
12.5 mm	81
9.5 mm	72
4.75 mm	50
2.36 mm	37
1.18 mm	24
0.60 mm	17
0.30 mm	12
0.15 mm	7
0.075 mm	3.5

Optimum Pb 5.4 %

Ndesign	100
Air Voids	4.0%
VMA	15.3%
VFA	73.9%
%Gmm @ Nini	85.6%
P ₂₀₀ /P _{be}	0.71

Mixing Temperature 160°C

Compaction Temperature 149°C

AASHTO T 283

Unconditioned Tensile Strength	134.0 psi
Conditioned Tensile Strength	54.6 psi
Tensile Strength Ratio	41 %

APPENDIX B: Analysis of Secondary Deformation Slopes

Table B-1A. Best Fit Equations for Tests 1-8

Test Number	L,C,R	Polynomial Equation	Slope 1	R ²	Exponential Equation	Slope 2	R ²	Linear Equation (2k-8k)	Slope 3	R ²
1	Left	$y = -1E-08x^2 + 0.0005x + 2.1858$	0.0005	0.9721	$y = 0.1431x^{0.4037}$	0.4037	0.9795	$y = 0.0003x + 2.8001$	0.0003	0.9805
1	Center	$y = -2E-08x^2 + 0.0006x + 1.6881$	0.0006	0.9843	$y = 0.119x^{0.419}$	0.4190	0.9811	$y = 0.0004x + 2.1837$	0.0004	0.9876
1	Right	$y = -1E-08x^2 + 0.0005x + 1.8562$	0.0005	0.9852	$y = 0.1279x^{0.4139}$	0.4139	0.9852	$y = 0.0004x + 2.4996$	0.0004	0.9841
2	Left	$y = -1E-08x^2 + 0.0004x + 1.7954$	0.0004	0.9637	$y = 0.1868x^{0.3493}$	0.3493	0.9822	$y = 0.0003x + 2.1027$	0.0003	0.9813
2	Center	$y = -2E-08x^2 + 0.0005x + 2.5925$	0.0005	0.9541	$y = 0.289x^{0.3324}$	0.3324	0.9497	$y = 0.0004x + 3.2613$	0.0004	0.9744
2	Right	$y = -9E-09x^2 + 0.0004x + 1.7379$	0.0004	0.9896	$y = 0.1394x^{0.3873}$	0.3873	0.9810	$y = 0.0003x + 2.1122$	0.0003	0.9844
3	Left	$y = -2E-08x^2 + 0.0007x + 2.768$	0.0007	0.9818	$y = 0.2703x^{0.364}$	0.3640	0.9725	$y = 0.0005x + 3.26$	0.0005	0.9901
3	Center	$y = -9E-09x^2 + 0.0004x + 1.7218$	0.0004	0.9816	$y = 0.139x^{0.387}$	0.3870	0.9665	$y = 0.0003x + 2.0964$	0.0003	0.9876
3	Right	$y = -2E-08x^2 + 0.0005x + 2.2193$	0.0005	0.9545	$y = 0.2396x^{0.3433}$	0.3433	0.9513	$y = 0.0003x + 3.1448$	0.0003	0.9699
4	Left	$y = -1E-08x^2 + 0.0004x + 2.7701$	0.0004	0.9435	$y = 0.4458x^{0.2737}$	0.2737	0.9549	$y = 0.0003x + 3.3977$	0.0003	0.9403
4	Center	$y = -8E-09x^2 + 0.0003x + 2.4681$	0.0003	0.9028	$y = 0.4431x^{0.249}$	0.2490	0.9050	$y = 0.0002x + 2.9089$	0.0002	0.9562
4	Right	$y = -1E-08x^2 + 0.0003x + 1.5272$	0.0003	0.9566	$y = 0.1617x^{0.3418}$	0.3418	0.9607	$y = 0.0002x + 1.894$	0.0002	0.8847
5	Left	$y = -1E-08x^2 + 0.0007x + 1.9538$	0.0007	0.9945	$y = 0.1029x^{0.4613}$	0.4613	0.9904	$y = 0.0005x + 2.5936$	0.0005	0.9967
5	Center	$y = -2E-08x^2 + 0.0006x + 2.0328$	0.0006	0.9916	$y = 0.1411x^{0.4199}$	0.4199	0.9856	$y = 0.0004x + 2.827$	0.0004	0.9953
5	Right	$y = -1E-08x^2 + 0.0006x + 1.9744$	0.0006	0.9875	$y = 0.1332x^{0.4156}$	0.4156	0.9898	$y = 0.0004x + 2.641$	0.0004	0.9903
6	Left	$y = -3E-08x^2 + 0.0009x + 1.7101$	0.0009	0.9937	$y = 0.0954x^{0.4793}$	0.4793	0.9900	$y = 0.0007x + 2.3094$	0.0007	0.9986
6	Center	$y = -1E-08x^2 + 0.0005x + 1.3662$	0.0005	0.9900	$y = 0.0853x^{0.4403}$	0.4403	0.9924	$y = 0.0004x + 1.8167$	0.0004	0.9884
6	Right	$y = -2E-08x^2 + 0.0006x + 1.7001$	0.0006	0.9825	$y = 0.1054x^{0.4361}$	0.4361	0.9811	$y = 0.0004x + 2.3885$	0.0004	0.9890
7	Left	$y = -2E-08x^2 + 0.0007x + 1.3437$	0.0007	0.9936	$y = 0.0949x^{0.4533}$	0.4533	0.9784	$y = 0.0005x + 1.8436$	0.0005	0.9978
7	Center	$y = -9E-08x^2 + 0.0019x + 1.949$	0.0019	0.9932	$y = 0.0954x^{0.539}$	0.5390	0.9966	$y = 0.001x + 4.097$	0.0010	0.9951
7	Right	$y = -2E-08x^2 + 0.0008x + 1.574$	0.0008	0.9846	$y = 0.0936x^{0.4713}$	0.4713	0.9871	$y = 0.0005x + 2.2928$	0.0005	0.9959
8	Left	$y = -2E-08x^2 + 0.0007x + 2.1427$	0.0007	0.9644	$y = 0.1418x^{0.4158}$	0.4158	0.9627	$y = 0.0004x + 3.124$	0.0004	0.9603
8	Center	$y = -2E-08x^2 + 0.0006x + 2.7738$	0.0006	0.9553	$y = 0.2733x^{0.346}$	0.3460	0.9526	$y = 0.0003x + 3.7443$	0.0003	0.9692
8	Right	$y = -2E-08x^2 + 0.0006x + 2.3236$	0.0006	0.9756	$y = 0.1829x^{0.3899}$	0.3899	0.9842	$y = 0.0004x + 2.9567$	0.0004	0.9755

Table B-1B. Best Fit Equations for Tests 9-16

Test Number	L,C,R	Polynomial Equation	Slope 1	R ²	Exponential Equation	Slope 2	R ²	Linear Equation (2k-8k)	Slope 3	R ²
9	Left	$y = -4E-08x^2 + 0.0012x + 3.1728$	0.0012	0.9613	$y = 0.2998x^{0.386}$	0.3860	0.9731	$y = 0.0007x + 4.4602$	0.0007	0.9936
9	Center	$y = -9E-08x^2 + 0.0018x + 2.8945$	0.0018	0.9776	$y = 0.2152x^{0.4454}$	0.4454	0.9867	$y = 0.0008x + 5.3472$	0.0008	0.9931
9	Right	$y = -2E-07x^2 + 0.0044x + 2.4366$	0.0044	0.9926	$y = 0.1718x^{0.5398}$	0.5398	0.9810	$y = 0.0035x + 3.0812$	0.0035	0.9906
10	Left	$y = -4E-08x^2 + 0.0015x + 2.429$	0.0015	0.9892	$y = 0.1252x^{0.5012}$	0.5012	0.9915	$y = 0.001x + 3.7139$	0.0010	0.9983
10	Center	$y = -2E-08x^2 + 0.0012x + 2.5403$	0.0012	0.9813	$y = 0.1255x^{0.493}$	0.4930	0.9866	$y = 0.0009x + 3.6636$	0.0009	0.9962
10	Right	$y = -3E-08x^2 + 0.0011x + 3.1574$	0.0011	0.9651	$y = 0.2695x^{0.398}$	0.3980	0.9736	$y = 0.0006x + 4.4495$	0.0006	0.9946
11	Left	$y = -5E-08x^2 + 0.0008x + 2.8086$	0.0008	0.9197	$y = 0.4356x^{0.3016}$	0.3016	0.9183	$y = 0.0003x + 4.5138$	0.0003	0.9403
11	Center	$y = -5E-08x^2 + 0.001x + 2.5283$	0.0010	0.9602	$y = 0.2642x^{0.3719}$	0.3719	0.9681	$y = 0.0004x + 4.3598$	0.0004	0.9669
11	Right	$y = -4E-08x^2 + 0.0009x + 3.4059$	0.0009	0.9466	$y = 0.4177x^{0.3328}$	0.3328	0.9625	$y = 0.0004x + 5.0086$	0.0004	0.9820
12	Left	$y = -6E-08x^2 + 0.0012x + 4.2489$	0.0012	0.9320	$y = 0.4926x^{0.3395}$	0.3395	0.9130	$y = 0.0005x + 6.1476$	0.0005	0.9803
12	Center	$y = -1E-07x^2 + 0.0022x + 2.5749$	0.0022	0.9882	$y = 0.1968x^{0.4654}$	0.4654	0.9839	$y = 0.0011x + 4.5922$	0.0011	0.9757
12	Right	$y = -6E-08x^2 + 0.0012x + 4.0715$	0.0012	0.9291	$y = 0.563x^{0.3175}$	0.3175	0.9263	$y = 0.0004x + 6.2107$	0.0004	0.9477
13	Left	$y = -2E-08x^2 + 0.001x + 1.3342$	0.0010	0.9967	$y = 0.0516x^{0.5579}$	0.5579	0.9891	$y = 0.0008x + 1.8171$	0.0008	0.9976
13	Center	$y = -2E-08x^2 + 0.0012x + 2.0764$	0.0012	0.9906	$y = 0.086x^{0.5288}$	0.5288	0.9914	$y = 0.0008x + 3.3152$	0.0008	0.9948
13	Right	$y = 8E-09x^2 + 0.001x + 1.8506$	0.0010	0.9906	$y = 0.0469x^{0.5938}$	0.5938	0.9829	$y = 0.0009x + 2.2481$	0.0009	0.9989
14	Left	$y = -3E-08x^2 + 0.0011x + 2.2485$	0.0011	0.9835	$y = 0.1318x^{0.4739}$	0.4739	0.9857	$y = 0.0008x + 3.1752$	0.0008	0.9960
14	Center	$y = 1E-07x^2 + 0.0006x + 2.5601$	0.0006	0.9877	$y = 0.0574x^{0.5917}$	0.5917	0.9415	$y = 0.0016x + 0.6423$	0.0016	0.9654
14	Right	$y = -1E-08x^2 + 0.0026x + 1.1076$	0.0026	0.9750	$y = 0.0429x^{0.677}$	0.6770	0.9451	$y = 0.0029x - 0.6286$	0.0029	0.9771
15	Left	$y = -1E-09x^2 + 0.0012x + 1.1997$	0.0012	0.9963	$y = 0.0349x^{0.6294}$	0.6294	0.9618	$y = 0.0012x + 0.7205$	0.0012	0.9952
15	Center	$y = -6E-09x^2 + 0.0007x + 1.7602$	0.0007	0.9880	$y = 0.0688x^{0.5177}$	0.5177	0.9852	$y = 0.0006x + 2.3357$	0.0006	0.9943
15	Right	$y = -5E-09x^2 + 0.0015x + 2.3767$	0.0015	0.9879	$y = 0.1049x^{0.5302}$	0.5302	0.9816	$y = 0.0014x + 2.5272$	0.0014	0.9882
16	Left	$y = 2E-08x^2 + 0.0022x + 0.8051$	0.0022	0.9833	$y = 0.0235x^{0.7335}$	0.7335	0.9534	$y = 0.0027x - 1.4303$	0.0027	0.9846
16	Center	$y = 4E-08x^2 + 0.0011x + 1.4811$	0.0011	0.9972	$y = 0.0275x^{0.6717}$	0.6717	0.9680	$y = 0.0014x + 0.8892$	0.0014	0.9947
16	Right	$y = 1E-07x^2 + 0.0009x + 1.5018$	0.0009	0.9952	$y = 0.0211x^{0.7106}$	0.7106	0.9348	$y = 0.002x - 1.2483$	0.0020	0.9794

Table B-1C. Best Fit Equations for Tests 17-24

Test Number	L,C,R	Polynomial Equation	Slope 1	R ²	Exponential Equation	Slope 2	R ²	Linear Equation (2k-8k)	Slope 3	R ²
17	Left	$y = -5E-08x^2 + 0.0008x + 1.1684$	0.0008	0.9786	$y = 0.1169x^{0.4076}$	0.4076	0.9834	$y = 0.0003x + 2.1168$	0.0003	0.9812
17	Center	$y = -5E-08x^2 + 0.0008x + 1.4094$	0.0008	0.9645	$y = 0.1788x^{0.3608}$	0.3608	0.9528	$y = 0.0002x + 2.5247$	0.0002	0.9635
17	Right	$y = -6E-08x^2 + 0.0007x + 1.3379$	0.0007	0.9283	$y = 0.1717x^{0.3567}$	0.3567	0.9397	$y = 0.0002x + 2.5011$	0.0002	0.8856
18	Left	$y = -2E-09x^2 + 0.0004x + 0.7438$	0.0004	0.9941	$y = 0.0325x^{0.5221}$	0.5221	0.9626	$y = 0.0004x + 0.8239$	0.0004	0.9926
18	Center	$y = -8E-09x^2 + 0.0004x + 0.8054$	0.0004	0.9841	$y = 0.0419x^{0.4853}$	0.4853	0.9757	$y = 0.0003x + 1.0104$	0.0003	0.9717
18	Right	$y = -1E-08x^2 + 0.0005x + 0.7953$	0.0005	0.9928	$y = 0.0434x^{0.5015}$	0.5015	0.9748	$y = 0.0004x + 0.9809$	0.0004	0.9906
19	Left	$y = -2E-08x^2 + 0.0006x + 2.7936$	0.0006	0.9654	$y = 0.3329x^{0.3245}$	0.3245	0.9708	$y = 0.0004x + 3.6242$	0.0004	0.9764
19	Center	$y = -2E-08x^2 + 0.0007x + 3.8894$	0.0007	0.9360	$y = 0.4915x^{0.3073}$	0.3073	0.9395	$y = 0.0004x + 5.0684$	0.0004	0.9799
19	Right	$y = -2E-08x^2 + 0.0006x + 2.773$	0.0005	0.9635	$y = 0.2908x^{0.3441}$	0.3441	0.9634	$y = 0.0004x + 3.6514$	0.0004	0.9777
20	Left	$y = -7E-09x^2 + 0.0005x + 2.301$	0.0005	0.9914	$y = 0.1587x^{0.4061}$	0.4061	0.9739	$y = 0.0004x + 2.9137$	0.0004	0.9944
20	Center	$y = -7E-09x^2 + 0.0005x + 2.4488$	0.0005	0.9873	$y = 0.1522x^{0.415}$	0.4150	0.9640	$y = 0.0003x + 3.1888$	0.0003	0.9696
20	Right	$y = -3E-09x^2 + 0.0002x + 2.3762$	0.0002	0.8391	$y = 0.3756x^{0.259}$	0.2590	0.8700	$y = 9E-05x + 3.1074$	0.0001	0.4803
21	Left	$y = -6E-09x^2 + 0.0005x + 0.9783$	0.0005	0.9982	$y = 0.0269x^{0.5723}$	0.5723	0.9869	$y = 0.0004x + 1.3249$	0.0004	0.9965
21	Center	$y = -5E-09x^2 + 0.0004x + 0.9562$	0.0004	0.9975	$y = 0.025x^{0.5703}$	0.5703	0.9832	$y = 0.0003x + 1.2816$	0.0003	0.9959
21	Right	$y = -2E-08x^2 + 0.0006x + 1.359$	0.0006	0.9934	$y = 0.0679x^{0.4828}$	0.4828	0.9957	$y = 0.0005x + 1.8565$	0.0005	0.9909
22	Left	$y = -1E-08x^2 + 0.0006x + 2.5409$	0.0006	0.9803	$y = 0.1785x^{0.3972}$	0.3972	0.9690	$y = 0.0004x + 3.1505$	0.0004	0.9757
22	Center	$y = -1E-08x^2 + 0.0005x + 2.097$	0.0005	0.9889	$y = 0.1265x^{0.4269}$	0.4269	0.9761	$y = 0.0004x + 2.783$	0.0004	0.9947
22	Right	$y = -1E-08x^2 + 0.0006x + 2.3341$	0.0006	0.9728	$y = 0.128x^{0.4318}$	0.4318	0.9736	$y = 0.0004x + 3.1784$	0.0004	0.9818
23	Left	$y = -1E-08x^2 + 0.0005x + 2.6128$	0.0005	0.9433	$y = 0.3027x^{0.3212}$	0.3212	0.9467	$y = 0.0003x + 3.4057$	0.0003	0.9555
23	Center	$y = -2E-08x^2 + 0.0005x + 2.8317$	0.0005	0.9551	$y = 0.3167x^{0.3276}$	0.3276	0.9498	$y = 0.0003x + 3.5964$	0.0003	0.9730
23	Right	$y = -1E-08x^2 + 0.0005x + 3.4481$	0.0005	0.9561	$y = 0.4724x^{0.2957}$	0.2957	0.9596	$y = 0.0003x + 4.3582$	0.0003	0.9771
24	Left	$y = -3E-09x^2 + 0.0007x + 1.8552$	0.0007	0.9939	$y = 0.0415x^{0.5839}$	0.5839	0.9799	$y = 0.0006x + 2.5726$	0.0006	0.9951
24	Center	$y = -2E-08x^2 + 0.0009x + 1.8138$	0.0009	0.9954	$y = 0.0548x^{0.556}$	0.5560	0.9967	$y = 0.0007x + 2.7617$	0.0007	0.9976
24	Right	$y = -7E-09x^2 + 0.0008x + 1.545$	0.0008	0.9969	$y = 0.0306x^{0.6133}$	0.6133	0.9924	$y = 0.0006x + 2.0699$	0.0006	0.9970

Table B-1D. Best Fit Equations for Tests 25-32

Test Number	L,C,R	Polynomial Equation	Slope 1	R ²	Exponential Equation	Slope 2	R ²	Linear Equation (2k-8k)	Slope 3	R ²
25	Left	$y = -6E-08x^2 + 0.0012x + 1.9866$	0.0012	0.9858	$y = 0.1697x^{0.4278}$	0.4278	0.9876	$y = 0.0005x + 3.6775$	0.0005	0.9794
25	Center	$y = -9E-08x^2 + 0.0014x + 2.6955$	0.0014	0.9420	$y = 0.2629x^{0.3875}$	0.3875	0.9268	$y = 0.0004x + 5.2415$	0.0004	0.9588
25	Right	$y = -7E-08x^2 + 0.0013x + 2.5795$	0.0013	0.9802	$y = 0.2748x^{0.3843}$	0.3843	0.9764	$y = 0.0005x + 4.5062$	0.0005	0.9692
26	Left	$y = -2E-08x^2 + 0.0007x + 1.7809$	0.0007	0.9799	$y = 0.1054x^{0.456}$	0.4560	0.9881	$y = 0.0005x + 2.6239$	0.0005	0.9899
26	Center	$y = -3E-08x^2 + 0.0009x + 2.5715$	0.0009	0.9772	$y = 0.2179x^{0.3992}$	0.3992	0.9839	$y = 0.0005x + 3.6281$	0.0005	0.9926
26	Right	$y = -4E-08x^2 + 0.0014x + 2.4303$	0.0014	0.9879	$y = 0.1157x^{0.505}$	0.5050	0.9940	$y = 0.0009x + 3.9937$	0.0009	0.9977
27	Left	$y = -8E-08x^2 + 0.0017x + 3.5686$	0.0017	0.9511	$y = 0.303x^{0.4095}$	0.4095	0.9621	$y = 0.0008x + 5.488$	0.0008	0.9695
27	Center	$y = -4E-08x^2 + 0.0009x + 3.7497$	0.0009	0.9321	$y = 0.6078x^{0.2902}$	0.2902	0.9250	$y = 0.0004x + 5.0726$	0.0004	0.9601
27	Right	$y = 1E-08x^2 + 0.0006x + 3.8604$	0.0006	0.9432	$y = 0.297x^{0.381}$	0.3810	0.9348	$y = 0.0005x + 4.6127$	0.0005	0.9792
28	Left	$y = -1E-07x^2 + 0.0018x + 1.762$	0.0018	0.9831	$y = 0.1176x^{0.4964}$	0.4964	0.9836	$y = 0.0011x + 2.9113$	0.0011	0.9958
28	Center	$y = 4E-08x^2 + 0.002x + 2.0969$	0.0020	0.9676	$y = 0.098x^{0.5623}$	0.5623	0.9487	$y = 0.0025x + 0.765$	0.0025	0.9297
28	Right	$y = -2E-07x^2 + 0.0025x + 1.8294$	0.0025	0.9862	$y = 0.1001x^{0.5427}$	0.5427	0.9763	$y = 0.0013x + 3.7801$	0.0013	0.9927
29	Left	$y = -4E-08x^2 + 0.0009x + 4.5475$	0.0009	0.8952	$y = 0.8655x^{0.2584}$	0.2584	0.9002	$y = 0.0003x + 6.3908$	0.0003	0.9714
29	Center	$y = -4E-08x^2 + 0.0009x + 4.1711$	0.0009	0.9136	$y = 0.7151x^{0.277}$	0.2770	0.9152	$y = 0.0003x + 6.0359$	0.0003	0.9705
29	Right	$y = -4E-08x^2 + 0.001x + 5.4976$	0.0010	0.9058	$y = 0.9403x^{0.2704}$	0.2704	0.9191	$y = 0.0004x + 7.5346$	0.0004	0.9804
30	Left	$y = 5E-09x^2 + 0.0007x + 2.4036$	0.0007	0.9872	$y = 0.0789x^{0.5225}$	0.5225	0.9761	$y = 0.0007x + 2.9401$	0.0007	0.9959
30	Center	$y = 9E-10x^2 + 0.0007x + 2.7148$	0.0007	0.9705	$y = 0.0937x^{0.5036}$	0.5036	0.9696	$y = 0.0005x + 3.7978$	0.0005	0.9951
30	Right	$y = -1E-08x^2 + 0.0007x + 1.8952$	0.0007	0.9891	$y = 0.0857x^{0.4852}$	0.4852	0.9757	$y = 0.0005x + 2.4535$	0.0005	0.9972
31	Left	$y = -8E-07x^2 + 0.007x - 0.3981$	0.0070	0.9915	$y = 0.0267x^{0.7712}$	0.7712	0.9841	$y = 0.0014x + 9.0958$	0.0014	0.8933
31	Center	$y = -5E-07x^2 + 0.0045x - 0.0201$	0.0045	0.9961	$y = 0.0138x^{0.8029}$	0.8029	0.9734	$y = 0.001x + 5.5332$	0.0010	0.9772
31	Right	$y = 4E-07x^2 + 0.0016x + 0.9205$	0.0016	0.9958	$y = 0.0096x^{0.8566}$	0.8566	0.9648	$y = 0.0043x - 3.3806$	0.0043	0.9968
32	Left									
32	Center	$y = 3E-08x^2 + 0.0008x + 2.0055$	0.0008	0.9683	$y = 0.0475x^{0.595}$	0.5950	0.9301	$y = 0.001x + 1.6369$	0.0010	0.9193
32	Right	$y = 1E-08x^2 + 0.0004x + 1.8503$	0.0004	0.9619	$y = 0.0671x^{0.4982}$	0.4982	0.9704	$y = 0.0004x + 2.3197$	0.0004	0.9951

Table B-2. Analysis of Variance for Slope 1 , Polynomial Equation Form ($y=ax^2+bx+c$)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Mix	1	0.0000000	0.0000000	0.0000000	0.06	0.806
Load Type	1	0.0000184	0.0000176	0.0000176	40.82	0.000
Specimen	1	0.0000003	0.0000002	0.0000002	0.42	0.519
Pre-Cond	1	0.0000013	0.0000010	0.0000010	2.38	0.128
TestCond	1	0.0000014	0.0000016	0.0000016	3.66	0.060
Mix*Load Type	1	0.0000002	0.0000001	0.0000001	0.31	0.580
Mix*Specimen	1	0.0000002	0.0000001	0.0000001	0.31	0.580
Mix*Pre-Cond	1	0.0000029	0.0000024	0.0000024	5.65	0.021
Mix*TestCond	1	0.0000005	0.0000007	0.0000007	1.60	0.210
Load Type*Specimen	1	0.0000001	0.0000002	0.0000002	0.42	0.519
Load Type*Pre-Cond	1	0.0000008	0.0000006	0.0000006	1.38	0.245
Load Type*TestCond	1	0.0000003	0.0000005	0.0000005	1.10	0.298
Specimen*Pre-Cond	1	0.0000026	0.0000021	0.0000021	4.94	0.030
Specimen*TestCond	1	0.0000005	0.0000007	0.0000007	1.68	0.200
Pre-Cond*TestCond	1	0.0000000	0.0000000	0.0000000	0.12	0.735
Mix*Load Type*Specimen	1	0.0000013	0.0000010	0.0000010	2.38	0.128
Mix*Load Type*Pre-Cond	1	0.0000037	0.0000031	0.0000031	7.21	0.009
Mix*Load Type*TestCond	1	0.0000011	0.0000014	0.0000014	3.32	0.073
Mix*Specimen*Pre-Cond	1	0.0000002	0.0000001	0.0000001	0.21	0.645
Mix*Specimen*TestCond	1	0.0000018	0.0000022	0.0000022	5.08	0.028
Mix*Pre-Cond*TestCond	1	0.0000006	0.0000008	0.0000008	1.84	0.179
Load Type*Specimen*Pre-Cond	1	0.0000010	0.0000007	0.0000007	1.68	0.200
Load Type*Specimen*TestCond	1	0.0000014	0.0000017	0.0000017	3.90	0.053
Load Type*Pre-Cond*TestCond	1	0.0000000	0.0000000	0.0000000	0.01	0.927
Specimen*Pre-Cond*TestCond	1	0.0000043	0.0000047	0.0000047	10.91	0.002
Mix*Load Type*Specimen*Pre-Cond	1	0.0000002	0.0000001	0.0000001	0.34	0.560
Mix*Load Type*Specimen*TestCond	1	0.0000042	0.0000045	0.0000045	10.50	0.002
Mix*Load Type*Pre-Cond*TestCond	1	0.0000021	0.0000022	0.0000022	5.22	0.026
Mix*Specimen*Pre-Cond*TestCond	1	0.0000005	0.0000005	0.0000005	1.23	0.271
Load Type*Specimen*Pre-Cond*TestCond	1	0.0000038	0.0000039	0.0000039	8.96	0.004
Mix*Load Type*Specimen*Pre-Cond*TestCond	1	0.0000011	0.0000011	0.0000011	2.58	0.114
Error	63	0.0000271	0.0000271	0.0000004		
Total	94	0.0000839				

Table B-3. Analysis of Variance for Slope 2, Power Equation Form ($a, y=x^a$)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Mix	1	0.0002830	0.0006830	0.0006830	0.32	0.574
Load Type	1	0.1555990	0.1589420	0.1589420	74.16	0.000
Specimen	1	0.2970400	0.2949050	0.2949050	137.60	0.000
Pre-Cond	1	0.0023480	0.0022220	0.0022220	1.04	0.313
TestCond	1	0.0244090	0.0233980	0.0233980	10.92	0.002
Mix*Load Type	1	0.0148350	0.0151560	0.0151560	7.07	0.010
Mix*Specimen	1	0.0171870	0.0171420	0.0171420	8.00	0.006
Mix*Pre-Cond	1	0.0327790	0.0318710	0.0318710	14.87	0.000
Mix*TestCond	1	0.0255490	0.0241920	0.0241920	11.29	0.001
Load Type*Specimen	1	0.0275500	0.0255200	0.0255200	11.91	0.001
Load Type*Pre-Cond	1	0.0835280	0.0779370	0.0779370	36.36	0.000
Load Type*TestCond	1	0.0115950	0.0093890	0.0093890	4.38	0.040
Specimen*Pre-Cond	1	0.1250870	0.1144030	0.1144030	53.38	0.000
Specimen*TestCond	1	0.0002730	0.0009700	0.0009700	0.45	0.503
Pre-Cond*TestCond	1	0.0000310	0.0004070	0.0004070	0.19	0.664
Mix*Load Type*Specimen	1	0.0089300	0.0116110	0.0116110	5.42	0.023
Mix*Load Type*Pre-Cond	1	0.0741030	0.0650290	0.0650290	30.34	0.000
Mix*Load Type*TestCond	1	0.0222830	0.0268970	0.0268970	12.55	0.001
Mix*Specimen*Pre-Cond	1	0.0077790	0.0051880	0.0051880	2.42	0.125
Mix*Specimen*TestCond	1	0.0143200	0.0179630	0.0179630	8.38	0.005
Mix*Pre-Cond*TestCond	1	0.0001870	0.0007820	0.0007820	0.37	0.548
Load Type*Specimen*Pre-Cond	1	0.0453830	0.0382750	0.0382750	17.86	0.000
Load Type*Specimen*TestCond	1	0.0011440	0.0025520	0.0025520	1.19	0.279
Load Type*Pre-Cond*TestCond	1	0.0098420	0.0131060	0.0131060	6.11	0.016
Specimen*Pre-Cond*TestCond	1	0.0007960	0.0018610	0.0018610	0.87	0.355
Mix*Load Type*Specimen*Pre-Cond	1	0.0050200	0.0030090	0.0030090	1.40	0.241
Mix*Load Type*Specimen*TestCond	1	0.0064200	0.0090050	0.0090050	4.20	0.045
Mix*Load Type*Pre-Cond*TestCond	1	0.0824850	0.0886160	0.0886160	41.35	0.000
Mix*Specimen*Pre-Cond*TestCond	1	0.0007530	0.0014150	0.0014150	0.66	0.420
Load Type*Specimen*Pre-Cond*TestCond	1	0.0728240	0.0761270	0.0761270	35.52	0.000
Mix*Load Type*Specimen*Pre-Cond*TestCond	1	0.1563360	0.1563360	0.1563360	72.94	0.000
Error	63	0.1350220	0.1350220	0.0021430		
Total	94	1.4617220				

Table B-4. Analysis of Variance for Slope 3 ($k, y=kx+b$) (2000-8000 cycles)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Mix	1	0.0000005	0.0000005	0.0000005	1.89	0.174
Load Type	1	0.0000096	0.0000094	0.0000094	34.32	0.000
Specimen	1	0.0000015	0.0000014	0.0000014	4.95	0.030
Pre-Cond	1	0.0000006	0.0000005	0.0000005	1.88	0.175
TestCond	1	0.0000002	0.0000001	0.0000001	0.51	0.478
Mix*Load Type	1	0.0000003	0.0000003	0.0000003	1.13	0.293
Mix*Specimen	1	0.0000003	0.0000003	0.0000003	1.13	0.293
Mix*Pre-Cond	1	0.0000019	0.0000017	0.0000017	6.21	0.015
Mix*TestCond	1	0.0000000	0.0000000	0.0000000	0.17	0.685
Load Type*Specimen	1	0.0000003	0.0000002	0.0000002	0.82	0.368
Load Type*Pre-Cond	1	0.0000004	0.0000004	0.0000004	1.30	0.258
Load Type*TestCond	1	0.0000002	0.0000002	0.0000002	0.63	0.430
Specimen*Pre-Cond	1	0.0000011	0.0000009	0.0000009	3.38	0.071
Specimen*TestCond	1	0.0000000	0.0000000	0.0000000	0.01	0.922
Pre-Cond*TestCond	1	0.0000000	0.0000000	0.0000000	0.00	0.952
Mix*Load Type*Specimen	1	0.0000001	0.0000002	0.0000002	0.69	0.408
Mix*Load Type*Pre-Cond	1	0.0000017	0.0000014	0.0000014	5.12	0.027
Mix*Load Type*TestCond	1	0.0000003	0.0000004	0.0000004	1.57	0.214
Mix*Specimen*Pre-Cond	1	0.0000001	0.0000001	0.0000001	0.46	0.502
Mix*Specimen*TestCond	1	0.0000017	0.0000019	0.0000019	7.00	0.010
Mix*Pre-Cond*TestCond	1	0.0000002	0.0000002	0.0000002	0.76	0.387
Load Type*Specimen*Pre-Cond	1	0.0000008	0.0000006	0.0000006	2.33	0.132
Load Type*Specimen*TestCond	1	0.0000000	0.0000000	0.0000000	0.05	0.831
Load Type*Pre-Cond*TestCond	1	0.0000001	0.0000000	0.0000000	0.17	0.685
Specimen*Pre-Cond*TestCond	1	0.0000009	0.0000011	0.0000011	3.96	0.051
Mix*Load Type*Specimen*Pre-Cond	1	0.0000000	0.0000001	0.0000001	0.27	0.602
Mix*Load Type*Specimen*TestCond	1	0.0000025	0.0000027	0.0000027	9.70	0.003
Mix*Load Type*Pre-Cond*TestCond	1	0.0000006	0.0000006	0.0000006	2.21	0.142
Mix*Specimen*Pre-Cond*TestCond	1	0.0000000	0.0000000	0.0000000	0.16	0.688
Load Type*Specimen*Pre-Cond*TestCond	1	0.0000015	0.0000016	0.0000016	5.66	0.020
Mix*Load Type*Specimen*Pre-Cond*TestCond	1	0.0000005	0.0000005	0.0000005	2.00	0.163
Error	63	0.0000173	0.0000173	0.0000003		
Total	94	0.0000453				