ABSTRACT

CHEN, CHUN. Quantify Antitrip Additives in Asphalt Binders and Mixes. (Under the direction of Dr. Akhtarhusein A. Tayebali and Dr. Detlef Knappe).

In this study, litmus and colorimetric tests were developed to quantify the contents of amine-based antistrip additives in asphalt binders and mixes. In addition, the effect of prolonged heating on antistrip additive content was evaluated for both asphalt binders and mixes. Results of this study indicate that both litmus and colorimetric tests are capable of detecting and quantifying amine-based antistrip additives in asphalt binders and mixes. Also, both test methods were able to validate the antistrip additive contents in field samples with known additive contents.

When subjected to prolonged heating periods, the antistrip additive content decreased substantially for both asphalt binders and mixes. For asphalt binders, no antistrip additive content was detectable after 24 to 48 hours of extended heating; for mixes, the measured antistrip additive content approached non-detectable level after 6 to 12 hours of extended heating.

Tensile Strength Ratio test was conducted in this research to evaluate the effect of prolonged heating on the asphalt-aggregate bond strength of hot mix asphalt (HMA) containing liquid antistrip additives. Improvement of moisture sensitivity by use of amine-based antistrip additive was observed to be lost to a great extent after prolonged heating. It shows that the remaining part of antistrip additive after prolonged heating has reduced effect on adhesion between asphalt and aggregate. The volatilization and/or chemical change that occur during the heating process of amine-based antistrip additive affect the improvement of asphalt-aggregate adhesion and ultimately the moisture susceptibility of mixes.

Quantify Antistrip Additives in Asphalt Binders and Mixes

by

Chun Chen

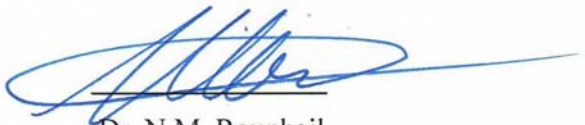
A dissertation submitted to the Graduate Faculty of
North Carolina State University
In partial fulfillment of the
Requirements for the degree of
Doctor of Philosophy

CIVIL ENGINEERING

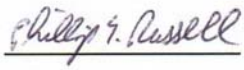
Raleigh, NC

2007

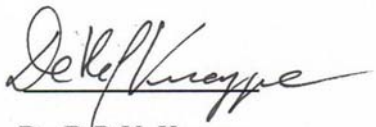
APPROVED BY:



Dr. N.M. Rouphail



Dr. P.E. Russell



Dr. D.R.U. Knappe
(Co-Chair of Advisory Committee)



Dr. A.A. Tayebali
(Co-Chair of Advisory Committee)

DEDICATION

To my parents and sister

BIOGRAPHY

Chun Chen was born in Mianyang City, Sichuan province, China, in 1978. He received his Bachelor of Science degree in Civil and Transportation engineering from Chang'an University, Xi'an, China, in 2000. He received his Master of Science degree in Highway and Transportation Engineering from Tongji University, Shanghai, China, in March, 2003. He worked as highway engineer in Shanghai Pudong New Area Highway Administration from April, 2003 to August, 2003. In August, 2003, he went to North Carolina State University, Raleigh, North Carolina, USA to study for his Ph.D. in Civil Engineering.

ACKNOWLEDGEMENTS

Many people offered their help and support to me in the completion of this dissertation. First of all, my grateful words are not enough to express my sincerest appreciation to my advisor, Dr. Akhtarhusein A. Tayebali, for providing me such a wonderful opportunity to study at NCSU. Without his support, guidance, understanding and encouragement, it would never be possible for me to complete this research. As a Chinese saying goes: “once be a teacher for me, always be my father for life”. In the past four years, I not only improved my academic accomplishments under his guidance, but learned the philosophy of life and received fatherly care from him.

I would like to thank Dr. Detlef R.U. Knappe, Dr. Nagui M. Rouphail, and Dr. Phillip E. Russell for serving on my advisory committee. I am grateful to Dr. Knappe for his constructive comments, suggestions and effort, which benefited this dissertation. I greatly appreciate the always warm help and beneficial advice from Dr. Rouphail. My thanks go to my advisory committee member and graduate school representative, Dr. Russell, for his taking time from Appalachian State University to attend my final defenses.

I want to acknowledge my gratitude to the North Carolina Department of Transportation, the sponsor of this research, the North Carolina State University Department of Civil Engineering and Southeastern Transportation Center for their support. I want to express my sincere thanks to those people and agencies for their help and provisions of specimen and data for this research.

Finally, I would like to give my deepest love and thanks to my parents and elder sister, who provide selfless and unconditional love, endless support and absolute faith in me. Being with them, I always have courage and strength to live in the hard time through my life. I have received so much from them and hope to repay them some day.

TABLE OF CONTENTS

LIST OF TABLES vii

LIST OF FIGURES ix

1. INTRODUCTION 1

1.1 Background 1

1.2 Literature Review of Asphalt-Aggregate Adhesion 4

1.3 Objectives and Scope of the Study 9

2. QUANTIFY ANTISTRIP ADDITIVE USING LITMUS TEST METHOD 13

2.1 Litmus Test Overview 13

2.2 Objectives and Tasks 14

2.3 Materials 14

2.4 Procedure to Quantify Antistrip Additives in Asphalt Binders and Mixes 15

2.5 Test Results and Discussion 19

3. QUANTIFY ORGANIC ANTISTRIP ADDITIVE USING COLORIMETRIC TEST METHOD 36

3.1 Colorimetric Test Overview 36

3.2 Extraction Technique of Antistrip Additives from Asphalt Binders and Mixes 37

3.3 Procedure to Quantify Antistrip Additives in Asphalt Binders and Mixes Using Colorimetric Test 39

3.4 Test Results and Discussion 42

4. EFFECT OF PROLONGED HEATING ON ANTISTRIP ADDITIVE CONTENTS IN ASPHALT BINDERS AND MIXES USING LITMUS AND COLORIMETRIC TEST METHODS 58

4.1 Introduction 58

4.2 Thermogravimetric Analysis of Pure Antistrip Additives 58

4.3 Changes in Antistrip Additive Contents in Asphalt Binders and Mixes after Prolonged Heating 59

4.4 Discussion of Test Results *62*

4.5 Conclusion *63*

4.6 Recommendation *63*

5. EVALUATION OF THE EFFECT OF PROLONGED HEATING ON THE ASPHALT-AGGREGATE ADHESION USING TENSILE STRENGTH RATIO TEST 78

5.1 Introduction *78*

5.2 Job-Mix-Formula Evaluation and Revision *78*

5.3 Tensile Strength Ratio Testing *80*

5.4 Discussion of Test Results *83*

6. FUTURE RESEARCH NEED FOR EVALUATING ADHESIVE BOND STRENGTH BETWEEN ASPHALT AND AGGREGATE AFTER PROLONGED HEATING 95

6.1 Theoretical background of Contact angle method *95*

6.2 Contact Angle Test Overview and Preliminary Test Results *97*

6.3 Introduction of Other Test Methods *98*

7. SUMMARY AND CONCLUSIONS 106

REFERENCES 109

APPENDIX A DATA FOR LOF 6500 AND MORLIFE 2200 IN ASPHALT BINDERS AND MIXES USING LITMUS TEST 113

APPENDIX B DATA FOR LOF 6500 AND MORLIFE 2200 IN ASPHALT BINDERS AND MIXES USING COLORIMETRIC ANALYSIS 126

APPENDIX C JOB-MIX-FORMULA AND TENSILE STRENGTH RATIO TEST DATA FOR ASPHALT MIXES WITH 0.8% LOF 6500 AND MORLIFE 2200 ANTISTRIP ADDITIVES IN ASPHALT BINDERS AFTER PROLONGED HEATING 133

LIST OF TABLES

TABLE 2-1 PHYSICAL PROPERTY OF ANTISTRIP ADDITIVES 24
TABLE 2-2 BLEND PERCENTAGES, MATERIAL TYPE I 24
TABLE 2-3 GRADATION, MATERIAL TYPE I 24
TABLE 2-4 BLEND PERCENTAGES, MATERIAL TYPE II 25
TABLE 2-5 GRADATION, MATERIAL TYPE II 25
TABLE 2-6 DATA FOR LOF 6500 ADDITIVE IN PG 64-22 CITGO WILMINGTON ASPHALT BINDER, COLOR INDEX 26
TABLE 2-7 DATA FOR MORLIFE 2200 ADDITIVE IN PG 64-22 CITGO WILMINGTON ASPHALT BINDER, COLOR INDEX 26
TABLE 2-8 DATA FOR LOF 6500 ADDITIVE IN ASPHALT MIX I, COLOR INDEX ... 27
TABLE 2-9 DATA FOR MORLIFE 2200 ADDITIVE IN ASPHALT MIX I, COLOR INDEX 27
TABLE 2-10 DATA FOR LOF 6500 ADDITIVE IN ASPHALT MIX II, COLOR INDEX .. 27
TABLE 2-11 DATA FOR MORLIFE 2200 ADDITIVE IN ASPHALT MIX II, COLOR INDEX 28
TABLE 2-12 RESULTS FOR LOF 6500 ADDITIVE IN MIX I, FIELD SAMPLES 29
TABLE 3-1 DATA FOR LOF 6500 ADDITIVE IN PG 64-22 CITGO WILMINGTON ASPHALT BINDER, ABSORBANCE 47
TABLE 3-2 DATA FOR MORLIFE 2200 ADDITIVE IN PG 64-22 CITGO WILMINGTON ASPHALT BINDER, ABSORBANCE 47
TABLE 3-3 DATA FOR LOF 6500 ADDITIVE IN ASPHALT MIX I, ABSORBANCE.... 47
TABLE 3-4 DATA FOR MORLIFE 2200 ADDITIVE IN ASPHALT MIX I, ABSORBANCE. 48
TABLE 3-5 DATA FOR LOF 6500 ADDITIVE IN ASPHALT MIX II, ABSORBANCE .. 48
TABLE 3-6 DATA FOR MORLIFE 2200 ADDITIVE IN ASPHALT MIX II, ABSORBANCE 48
TABLE 3-7 RESULTS FOR LOF 6500 ADDITIVE IN MIX I, FIELD SAMPLES 49
TABLE 5-1 GRADATIONS FOR ORIGINAL JMF AND REVISED LAB TEST 85
TABLE 5-2 AIR VOIDS DATA OF NON-ADDITIVE SAMPLES 85
TABLE 5-3 AIR VOIDS DATA OF LOF 6500 ADDITIVE SAMPLES..... 86
TABLE 5-4 AIR VOIDS DATA OF MORLIFE 2200 ADDITIVE SAMPLES..... 87
TABLE 5-5 TSR TEST RESULTS: NONE ADDITIVE IN ASPHALT WITH 2-HOUR HEATING 88
TABLE 5-6 TSR TEST RESULTS: 0.8% LOF ADDITIVE IN ASPHALT WITHOUT PROLONGED HEATING..... 88
TABLE 5-7 TSR TEST RESULTS: 0.8% LOF ADDITIVE IN ASPHALT WITH 2-HOUR HEATING 88
TABLE 5-8 TSR TEST RESULTS: 0.8% LOF ADDITIVE IN ASPHALT WITH 6-HOUR HEATING 89

TABLE 5-9 TSR TEST RESULTS: 0.8% LOF ADDITIVE IN ASPHALT WITH 12-HOUR HEATING 89
TABLE 5-10 TSR TEST RESULTS: 0.8% LOF ADDITIVE IN ASPHALT WITH 24-HOUR HEATING 89
TABLE 5-11 TSR TEST RESULTS: 0.8% MORLIFE ADDITIVE IN ASPHALT WITHOUT PROLONGED HEATING 90
TABLE 5-12 TSR TEST RESULTS: 0.8% MORLIFE ADDITIVE IN ASPHALT WITH 2-HOUR HEATING 90
TABLE 5-13 TSR TEST RESULTS: 0.8% MORLIFE ADDITIVE IN ASPHALT WITH 6-HOUR HEATING 90
TABLE 5-14 TSR TEST RESULTS: 0.8% MORLIFE ADDITIVE IN ASPHALT WITH 12-HOUR HEATING 91
TABLE 5-15 TSR TEST RESULTS: 0.8% MORLIFE ADDITIVE IN ASPHALT WITH 24-HOUR HEATING 91

LIST OF FIGURES

FIGURE 1-1 SUMMARY OF RESEARCH APPROACH AND METHODOLOGY 12
FIGURE 2-1 AN ASPHALT BINDER AND MIX HEATING DEVICE AND A SPECTROPHOTOMETER 30
FIGURE 2-2 STRIPSCAN DEVICE FOR MEASURING ANTISTRIP ADDITIVES IN ASPHALT BINDERS AND MIXES 30
FIGURE 2-3 SAMPLE HEATING CAN AND LITMUS STRIPS 31
FIGURE 2-4 CALIBRATION CURVE FOR LOF 6500 ADDITIVE IN PG 64-22 CITGO WILMINGTON ASPHALT BINDER, PERCENT ADDITIVE VS. COLOR INDEX 32
FIGURE 2-5 CALIBRATION CURVE FOR MORLIFE 2200 ADDITIVE IN PG 64-22 CITGO WILMINGTON ASPHALT BINDER, PERCENT ADDITIVE VS. COLOR INDEX 32
FIGURE 2-6 CALIBRATION CURVE FOR LOF 6500 ANTISTRIP ADDITIVE IN MIX I, PERCENT ADDITIVE VS. COLOR INDEX 33
FIGURE 2-7 CALIBRATION CURVE FOR MORLIFE 2200 ANTISTRIP ADDITIVE IN MIX I, PERCENT ADDITIVE VS. COLOR INDEX 33
FIGURE 2-8 CALIBRATION CURVE FOR LOF 6500 ANTISTRIP ADDITIVE IN MIX II, PERCENT ADDITIVE VS. COLOR INDEX 34
FIGURE 2-9 CALIBRATION CURVE FOR MORLIFE 2200 ANTISTRIP ADDITIVE IN MIX II, PERCENT ADDITIVE VS. COLOR INDEX 34
FIGURE 2-10 COMPARISON OF CALIBRATION CURVES FOR MIX I AND MIX II CONTAINING LOF 6500 ANTISTRIP ADDITIVE 35
FIGURE 2-11 COMPARISON OF CALIBRATION CURVES FOR MIX I AND MIX II CONTAINING MORLIFE 2200 ANTISTRIP ADDITIVE 35
FIGURE 3-1 SCHEMATIC OF AMINE TRAPPING SYSTEM 50
FIGURE 3-2 FLOW METER USED TO CONTROL N_2 GAS FLOW RATE 50
FIGURE 3-3 EXTRACTION DEVICE FOR TRANSFERRING ANTISTRIP ADDITIVE FROM ASPHALT BINDER TO THE AQUEOUS PHASE 51
FIGURE 3-4 EXTRACTION DEVICE FOR TRANSFERRING ANTISTRIP ADDITIVE FROM ASPHALT MIX TO THE AQUEOUS PHASE 51
FIGURE 3-5 CHEMICAL REACTION OF AQUEOUS EXTRACT WITH DYE AND EXTRACTION OF SOLVENT 52
FIGURE 3-6 SPECTROMETER FOR MEASUREMENT OF ABSORBANCE OF ETHYLENE DICHLORIDE EXTRACTS 53
FIGURE 3-7 CALIBRATION CURVE FOR LOF 6500 ADDITIVE IN PG 64-22 CITGO WILMINGTON ASPHALT BINDER, PERCENT ADDITIVE VS. ABSORBANCE 54
FIGURE 3-8 CALIBRATION CURVE FOR MORLIFE 2200 ADDITIVE IN PG 64-22 CITGO WILMINGTON ASPHALT BINDER, PERCENT ADDITIVE VS. ABSORBANCE 54
FIGURE 3-9 CALIBRATION CURVE FOR LOF 6500 ANTISTRIP ADDITIVE IN MIX I, PERCENT ADDITIVE VS. ABSORBANCE 55
FIGURE 3-10 CALIBRATION CURVE FOR MORLIFE 2200 ANTISTRIP ADDITIVE IN MIX I, PERCENT ADDITIVE VS. ABSORBANCE 55

FIGURE 3-11 CALIBRATION CURVE FOR LOF 6500 ANTISTRIP ADDITIVE IN MIX II, PERCENT ADDITIVE VS. ABSORBANCE 56
FIGURE 3-12 CALIBRATION CURVE FOR MORLIFE 2200 ANTISTRIP ADDITIVE IN MIX II, PERCENT ADDITIVE VS. ABSORBANCE 56
FIGURE 3-13 COMPARISON OF CALIBRATION CURVES FOR MIX I AND MIX II CONTAINING LOF 6500 ANTISTRIP ADDITIVE 57
FIGURE 3-14 COMPARISON OF CALIBRATION CURVES FOR MIX I AND MIX II CONTAINING MORLIFE 2200 ANTISTRIP ADDITIVE 57
FIGURE 4-1 MASS LOSS OF PURE ANTISTRIP ADDITIVES AS FUNCTION OF HEATING TIME 65
FIGURE 4-2 EFFECT OF PROLONGED HEATING ON LOF 6500 ANTISTRIP ADDITIVE.. 65
FIGURE 4-3 MEASURED LOF 6500 ADDITIVE CONTENT IN ASPHALT BINDER AS FUNCTION OF TIME USING LITMUS TEST, MEASURED ADDITIVE CONTENT VS. ACTUAL ADDITIVE CONTENT 66
FIGURE 4-4 DECLINE OF LOF 6500 ADDITIVE CONTENT IN ASPHALT BINDER DURING PROLONGED HEATING PROCESS USING LITMUS TEST 66
FIGURE 4-5 DECLINE OF MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT BINDER DURING PROLONGED HEATING PROCESS USING LITMUS TEST 67
FIGURE 4-6 MEASURED LOF 6500 ADDITIVE CONTENT IN ASPHALT MIX I AS FUNCTION OF TIME USING LITMUS TEST, MEASURED ADDITIVE CONTENT VS. ACTUAL ADDITIVE CONTENT 67
FIGURE 4-7 DECLINE OF LOF 6500 ADDITIVE CONTENT IN ASPHALT MIX I DURING PROLONGED HEATING PROCESS USING LITMUS TEST 68
FIGURE 4-8 MEASURED MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT MIX I AS FUNCTION OF TIME USING LITMUS TEST, MEASURED ADDITIVE CONTENT VS. ACTUAL ADDITIVE CONTENT 68
FIGURE 4-9 DECLINE OF MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT MIX I DURING PROLONGED HEATING PROCESS USING LITMUS TEST 69
FIGURE 4-10 MEASURED LOF 6500 ADDITIVE CONTENT IN ASPHALT MIX II AS FUNCTION OF TIME USING LITMUS TEST, MEASURED ADDITIVE CONTENT VS. ACTUAL ADDITIVE CONTENT 69
FIGURE 4-11 DECLINE OF LOF 6500 ADDITIVE CONTENT IN ASPHALT MIX II DURING PROLONGED HEATING PROCESS USING LITMUS TEST 70
FIGURE 4-12 MEASURED MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT MIX II AS FUNCTION OF TIME USING LITMUS TEST, MEASURED ADDITIVE CONTENT VS. ACTUAL ADDITIVE CONTENT 70
FIGURE 4-13 DECLINE OF MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT MIX II DURING PROLONGED HEATING PROCESS USING LITMUS TEST 71
FIGURE 4-14 MEASURED LOF 6500 ADDITIVE CONTENT IN ASPHALT BINDER AS FUNCTION OF TIME USING COLORIMETRIC TEST, ABSORBANCE VS. ORIGINAL ADDITIVE CONTENT 71
FIGURE 4-15 DECLINE OF LOF 6500 ADDITIVE CONTENT IN ASPHALT BINDER DURING PROLONGED HEATING PROCESS USING COLORIMETRIC TEST 72

FIGURE 4-16 MEASURED MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT BINDER AS FUNCTION OF TIME USING COLORIMETRIC TEST, MEASURED ADDITIVE CONTENT VS. ORIGINAL ADDITIVE CONTENT 72
FIGURE 4-17 DECLINE OF MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT BINDER DURING PROLONGED HEATING PROCESS USING COLORIMETRIC TEST 73
FIGURE 4-18 MEASURED LOF 6500 ADDITIVE CONTENT IN ASPHALT MIX I AS FUNCTION OF TIME USING COLORIMETRIC TEST, MEASURED ADDITIVE CONTENT VS. ORIGINAL ADDITIVE CONTENT 73
FIGURE 4-19 DECLINE OF LOF 6500 ADDITIVE CONTENT IN ASPHALT MIX I DURING PROLONGED HEATING PROCESS USING COLORIMETRIC TEST 74
FIGURE 4-20 MEASURED MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT MIX I AS FUNCTION OF TIME USING COLORIMETRIC TEST, MEASURED ADDITIVE CONTENT VS. ORIGINAL ADDITIVE CONTENT 74
FIGURE 4-21 DECLINE OF MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT MIX I DURING PROLONGED HEATING PROCESS USING COLORIMETRIC TEST 75
FIGURE 4-22 MEASURED LOF 6500 ADDITIVE CONTENT IN ASPHALT MIX II AS FUNCTION OF TIME USING COLORIMETRIC TEST, MEASURED ADDITIVE CONTENT VS. ORIGINAL ADDITIVE CONTENT 75
FIGURE 4-23 DECLINE OF LOF 6500 ADDITIVE CONTENT IN ASPHALT MIX II DURING PROLONGED HEATING PROCESS USING COLORIMETRIC TEST 76
FIGURE 4-24 MEASURED MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT MIX II AS FUNCTION OF TIME USING COLORIMETRIC TEST, MEASURED ADDITIVE CONTENT VS. ORIGINAL ADDITIVE CONTENT 76
FIGURE 4-25 DECLINE OF MORLIFE 2200 ADDITIVE CONTENT IN ASPHALT MIX II DURING PROLONGED HEATING PROCESS USING COLORIMETRIC TEST 77
FIGURE 5-1 GRADATION CURVES FOR ORIGINAL JMF AND REVISED LAB TEST ... 92
FIGURE 5-2 TSR VALUES OF NON-ADDITIVE AND 0.8% LOF ADDITIVE 92
FIGURE 5-3 TSR VALUES OF NON-ADDITIVE AND 0.8% MORLIFE ADDITIVE 93
FIGURE 5-4 DECLINATION OF TSR RESULTS WITH PROLONGED HEATING 93
FIGURE 6-1 CONTACT ANGLE FORMATION ON A SOLID SURFACE 101
FIGURE 6-2 A SKETCH OF CONTACT ANGLE GONIOMETER 101
FIGURE 6-3 CONTACT ANGLE GONIOMETER 102
FIGURE 6-4 CAPTURED PICTURE OF WATER DROPLET ON THE MICROSCOPE QUARTZ SLIDE AT 25°C 102
FIGURE 6-5 CAPTURED PICTURE OF WATER DROPLET ON THE MICROSCOPE GLASS SLIDE AT 25°C 103
FIGURE 6-6 CAPTURED PICTURE OF ASPHALT DROPLET ON THE MICROSCOPE QUARTZ SLIDE AT 135°C 103
FIGURE 6-7 CAPTURED PICTURE OF ASPHALT DROPLET ON THE MICROSCOPE GLASS SLIDE AT 135°C 104
FIGURE 6-8 A SCHEMATIC OF MODIFIED PATTI 104
FIGURE 6-9 A SCHEMATIC OF AN ATOMIC FORCE MICROSCOPE 105

1. Introduction

1.1 Background

The surface course of highways must be tough enough to resist distortion under traffic and provide a smooth and skid-resistant riding surface; meanwhile, it must be waterproof to protect the entire pavement and subgrade from the weakening effect of water [1]. Pavement performance in terms of moisture sensitivity is determined by the strength of the adhesive bond between the asphalt binder and the aggregate [2]. Loss of adhesion at the asphalt-aggregate interface due to the invasion of water, commonly called stripping, is one of the principal events that leads to the failure of asphalt pavements [3]. Once initiated, stripping usually progresses rapidly. Widespread stripping can lead to strength loss, which causes cracking and raveling with the eventual formation of potholes. This results in shorter pavement life and many millions of dollars in pavement damage each year. A survey of state highway and other agencies found that stripping problems were widespread and influenced by a large number of factors including aggregate type, asphalt binder grade and source, mix design, construction, and climate [4]. Antistrip additives are commonly required for improving adhesion between the asphalt binder and the aggregate surface and, thus, the resistance of asphalt pavement to stripping damage. Antistrip additives include lime, fatty amines, and styrene-butadiene [5].

Amine-based antistrip additives are commonly required by state highway agencies for improving adhesion between the asphalt binder and the aggregate surface to increase the resistance of asphalt pavement to stripping damage. Just as the content of asphalt binder is a control index for asphalt mix design, the content of amine-based antistrip additive is important. However, the detection and quantification of the content of amine-based antistrip additive in hot-mix-asphalt (HMA) remains a practical problem. In addition there are concerns in the asphalt industry regarding the volatilization of these additives once they have been incorporated into the binders and mixes. Because a quick and convenient way of checking the amount of antistrip additives is lacking, the asphalt pavement material is not checked for the level of antistrip additive as often as it should be. As a result, the potential absence or variability in the dosage of antistrip additive, or volatilization of additive due to prolonged heating creates uncertainty in the quality of asphalt pavements.

One of the most commonly used procedures to control stripping is the Tensile Strength Ratio (TSR) test, which is an indirect method to determine the presence of additives through measuring the performance of the asphalt mix. However, the TSR test method generally takes days for test results to be available, and in many instances it is unreliable. Tarrer et al. [6] has proposed a procedure that is a modified version of ASTM Test Method D 2073 Standard Test Methods for total, primary, secondary, and tertiary amine values of fatty amines, amidoamines, and diamines by referee potentiometric method [7] that allows direct measurement of the amount of amine-based antistrip additives in asphalt binder using a titration test. Ulrich et al. [8] further developed the titration test method so that it can be used for both asphalt binders and mixes. In this

study, litmus and colorimetric test methods are presented. These methods are relatively quick, simple, and reliable for quantifying amine-based antistrip additive contents in asphalt binders and mixes.

NCDOT requires antistrip additives in all asphalt mixes in order to increase the resistance of the mixes to moisture-induced damage. Absence or non-uniform use of the antistrip additive can lead to severe reduction in pavement life. Two such detrimental effects were noted recently in North Carolina—1) failure to use antistrip additive in Rutherford County in 1998 [9] led NCDOT to require the contractor to put 1-inch additional surface mix over an asphalt pavement in which 25,000 tons of material had already been placed and compacted; 2) results of two NCDOT studies [10, 11] show that the severe delamination problems in Buncombe County are directly attributable to the moisture sensitivity of asphalt mixes containing baghouse fines.

In order to develop a reliable test procedure, two methodologies were evaluated in this study. These include 1) a litmus test using the StripScan device and 2) a colorimetric test following the extraction of organic antistrip additive from asphalt binders and mixes.

The effect of prolonged heating on the loss of antistrip additives was explored in this study. Once the standard procedures of litmus and colorimetric tests are developed, the use of litmus and colorimetric tests offered a viable method to study the effect of prolonged heating on the loss of amine-based antistrip additives in both asphalt binders and mixes. In order to explore the loss of additive due to prolonged heating, the litmus and colorimetric test procedures were repeated for asphalt binder samples containing different levels of antistrip additive after 2, 6, 24, and 48 hours of prolonged heating. For asphalt

mix samples containing different levels of antistrip additive, tests were repeated after 1, 2, 4, 6, and 12 hours of prolonged heating.

Tensile Strength Ratio (TSR) and other test methods were used in this study to evaluate the adhesive bond strength between asphalt binder containing antistrip additive and aggregate. The literature review of asphalt-aggregate adhesion is presented in the next section to show the important phenomenon explained by different theories and methodologies. TSR test values were used to observe the effectiveness of antistrip additive on adhesion between asphalt and aggregate due to prolonged heating period.

1.2 Literature Review of Asphalt-Aggregate Adhesion

The interaction between asphalt binder and aggregate has been of concern and proven to be a very important area of research since the 1930s. Many researchers looked into adhesive bond between asphalt binder and aggregate to explain loss of adhesion due to presence of moisture in the asphalt pavement. Many methodologies and theories have been developed to explain and analyze the asphalt-aggregate adhesion.

1.2.1 Test methods used to measure adhesion between asphalt binder and aggregate

The most common test methods to measure the surface tension of liquids are Wilhelmy plate method, DuNouy ring method, maximum pull force method, pendant drop method, spring drop method and bubble pressure method.

Traditional tests that have been used to measure asphalt-aggregate adhesion include the cyclic stress tests, Texas boiling water tests, indirect tensile strength, Marshall Stability and heats of immersion. The effectiveness of the tests for correlating with field performance appears to vary with the particular asphalt-aggregate mix. Perhaps through a more thorough understanding of the effect of antistripping agents on the chemistry and mechanisms of adhesion a more predictive test can be developed to evaluate the efficacy of a combination of antistripping in asphalt and aggregate mixtures [12].

In recent years, some researchers have used new devices to evaluate asphalt-aggregate interaction with the development of new technologies. Vergasselt [13] found that the various bitumen fractions are distinguished by their absorption coefficients and by the relative values of their absorption coefficients at different wavelengths, and the colorimetric method examined makes it possible to assess binder-aggregate interactions. Williams et. al [14, 15] used environmental scanning electron microscope (ESEM) to observe the asphalt-aggregate interface of lime-treated aggregate, amine-treated asphalt and styrene-butadiene rubber-treated aggregate before and after freeze-thaw cycles, and concluded that the polymer treatment was more effective than the amine treatment, which was more effective than the lime treatment. Ramanathan et. al [16] developed ultrasonic technique to measure the adhesion of asphalt to aggregate. The observation is in general agreement with trends in measured heats of bonding of asphalts with aggregates, which show a significant variation with aggregate for a given asphalt but not much variation with asphalt for a given aggregate. Miknis et. al [17] described a nuclear magnetic resonance (NMR) imaging method that allows for direct calculation of interfacial surface tensions of asphalts. The behavior of a water drop on the surfaces of eight SHRP core asphalts as a

function of time was studied using this method. Abraham et. al [18] used an atomic force microscope (AFM) to directly measure the interaction between asphaltenes and silica surfaces in aqueous solutions. The electrokinetic properties of these surfaces were determined to establish a link between conventional electrokinetic studies and AFM results. Hussein et. al [19] introduced a simple mechanistic approach that desribes the response of the asphalt-aggregate system to temperature and the observations were associated with asphalt concrete low-temperature performance and its resistance to stripping. Nguyen et. al [20] developed a nondestructive, sensitive spectroscopic method for measuring water stripping resistance at the molecular level of asphalt/siliceous aggregates exposed to water. Fourier transform infrared spectroscopy in the multiple internal reflection mode (FTIR-MIR) was developed to quantify the water layer at the asphalt/siliceous aggregate interface and a method based on a pneumatic adhesion tester and a porous stub was investigated for measuring the adhesion loss of asphalt/ siliceous aggregate system exposed to water.

1.2.2 Theories used to explain mechanism of asphalt-aggregate interaction

Many theories and associated mechanisms such as weak boundary layers, mechanical theory, electrostatic theory, chemical bonding theory, and thermodynamic theory etc. have been developed to explain and analyze the asphalt-aggregate adhesion.

Weak boundary layer

This theory does not explain why materials adhere to one another but rather adhesive bonds fail in either the adhesive or substrate due to the presence of an interphase

region of low cohesive strength [21]. The theory suggests that rupture always takes place at the weakest link found at the interface between materials. These defects at the interface are possible because of poor wetting, the presence of voids and dust at the interface. Tarrar and Wagh [22] report that dust on aggregates have a tendency to trap air when mixed with bitumen and consequently weaken the bitumen-aggregate bond. This theory explains that the initial stage of moisture damage usually happens at the weak interaction between aggregate and asphalt binder.

Mechanical interlock theory

Mechanical theory describes the most intuitive adhesion phenomenon and traditionally involves mechanical gripping of the adhesive into the cavities, pores and asperities of the solid surface on a macroscopic scale [21]. After an initial rapid wetting, the filling of microvoids by the liquid takes place, followed by its solidification [23]. The resulting interlocking combines the cohesive strength of both individual solids to form an interface that acts as a composite material with properties intermediate to those of each material surface. Such a lock and key mechanism of bonding can explain the good resistance of some bonds to water damage. Aggregate properties are much more influential in determining adsorption and stripping behavior than are asphalt properties. [24] In addition to aggregate surface texture, aggregate porosity and pore structure are also known to affect stripping [22]

Electrostatic theory

This theory postulates that adhesion arises from the interaction of electropositive and electronegative, on either side of an interface, where on one side there is a solid, and on the other an electric double layer composed of solvated ions and counter-ions [25]. This model finds much application in colloid science, but it has found little practical use in engineering because of the large number of parameters it requires for predicting adhesion. In an early use of this theory, Sherwood [26] could not successfully predict the strength of the bitumen-aggregate bond. A variation of the model was used by Ensley [27] in an attempt to explain the interaction of bitumen around aggregates, but such ordering was later disproved [28]. The electrostatic theory has been disputed by others in the past.

Chemical bonding theory

Chemical reaction between two materials coming into contact is responsible for adhesion to produce new compounds upon formation [29]. Molecular species in bitumen primarily consist of long carbon chains and rings saturated with hydrogen, which are essentially nonpolar in character [30]. These non-polar molecules interact mainly through van der Waals forces. Because van der Waals forces are additive, their contribution in these large molecules is significant. While active chemical sites on aggregate surfaces promote bonding of particularly polar species in bitumen, covering of these sites by non-polar hydrocarbons can completely mask their activity [31]. During mixing at high temperatures, however, more polar species should equilibrate with the surface and displace the more weakly adsorbed and non-polar components on the aggregate surface

[32]. This theory explains the bonding interaction by different chemical constitute of asphalt and aggregate.

Adsorption theory

The theory can be applied to the vast majority of adhesion and adsorption phenomena of liquids onto solids. Thermodynamic theory is based on the concept that an adhesive will adhere to a substrate due to established intermolecular forces at the interface provided intimate contact is achieved. The magnitude of these fundamental forces can generally be related to thermodynamic quantities, such as surface free energies of the materials involved in the adhesive bond. [33] It describes wetting phenomena and is based on the measurement of the contact angle between a liquid and a solid. The details of this theory are stated in Chapter 6.

Some other theories such as acid-base theory [34, 35] and diffusion theory [36, 37] have been used to explain interaction between asphalt and aggregate, but they have not attracted much attention by other researchers.

1.3 Objectives and Scope of the Study

The first objective of this study was to develop a standardized, reproducible and quantifiable test procedure to detect organic antistrip additives in asphalt binders and asphalt mixes. A reliable and standardized test procedure would allow highway agencies to determine if the specified level of organic antistrip additive has been added to the asphalt binder or mix and hence, reduce the amount of substandard asphalt mix being placed in the field. It also allows highway agencies and contractors to have a quality

control test to inspect asphalt binders and hot mix samples. In this study, two methodologies were explored – 1) litmus test method, and 2) colorimetric analysis method. For the colorimetric analyses, it was necessary to extract amines in asphalt binders or mixes through heating and to trap the emitted vapors in water to obtain an aqueous solution containing the fatty amines. The next objective of this research was to study the effect of prolonged heating on the contents of the amine-based antistrip additives in asphalt binders and mixes using a reliable test method that accurately quantifies the antistrip additive content. The final objective of this research task was to evaluate the effect of prolonged heating on adhesive bond strength between asphalt and aggregate of HMA containing amine-based antistrip additives. TSR test values were used to evaluate whether the loss of additive content due to prolonged heating affects bond strength between asphalt and aggregate. In particular, the objectives of this study were to:

1) Determine the ability of litmus and colorimetric tests to reliably quantify amine-based antistrip additives in binders and mixes;
2) Develop a procedure to extract volatiles containing antistrip additives from asphalt binders and mixes and to dissolve emitted compounds in a water trap;
3) Determine if litmus and colorimetric tests can quantify antistrip additives in field samples;
4) Determine the effect of prolonged heating on antistrip additive contents in asphalt binders and mixes using litmus and colorimetric tests; and
5) Evaluate the effect of prolonged heating on adhesive bond strength between asphalt and aggregate.

The scope of this research is limited to the quantification of amine-based antistrip additives. Detection of inorganic additives, particularly lime, was not considered in this study. Figure 1-1 provides the work plan for the study.

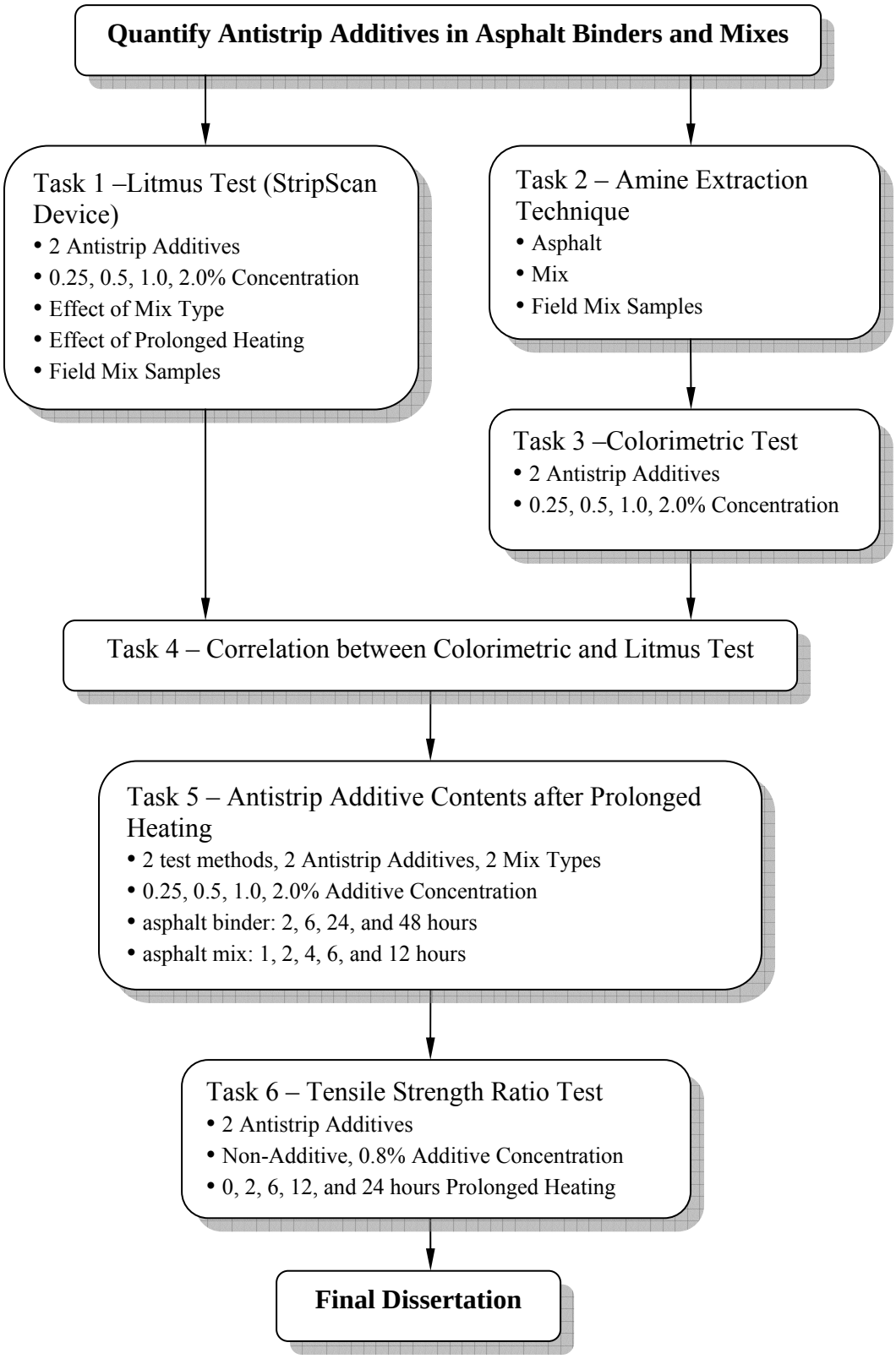


Figure 1-1 Summary of Research Approach and Methodology

2. Quantify Antistrip Additive Using Litmus Test Method

2.1 Litmus Test Overview

The litmus test is a simple method of detecting anti-strip additive in asphalt binders and mixes and requires a three-step procedure. In the first step, the organic antistrip additive is volatilized by heating asphalt binders or mixes. In the second step, a litmus paper is exposed to the vapors containing the volatilized antistrip additive for a prescribed time period. In the third step, a spectrophotometer is used to measure the color change of the litmus paper that is brought about by the exposure to the antistrip additive. The difference in spectrophotometer readings of the litmus paper before and after vapor exposure is the color index that is used to quantify the amount of antistrip additive.

The litmus test is an intuitively simple procedure that at a minimum requires a device that can control the sample temperature at a desired level, and a spectrophotometer that can read the change in color (color index) of the litmus paper that results from exposure to the chemical vapors. Figure 2-1 shows an example of such a rudimentary device that was initially used for the measurement of the antistrip additive. However, operator-related variables affect the reproducibility of the test results and, therefore, it was imperative to standardize and fully automate the testing procedure. Figure 2-2 shows an example of an automated device, StripScan device (InstroTek, Inc, Raleigh, NC) that was used to measure the quantity of antistrip additives in asphalt binders and mixes.

2.2 Objectives and Tasks

The principal work tasks for litmus test were as follows:

1 Determine the ability and degree of complexity of the litmus test using StripScan to detect the presence and concentration of antistrip additives in asphalt binders and mixes.
2 Investigate the accuracy and repeatability of the litmus test.
3 Determine if litmus test can quantify antistrip additives in field samples.

Based on the results, recommend a standardized test procedure that can be adopted and followed by NCDOT.

2.3 Materials

Most of the organic antistrip additives are proprietary chemical mixtures, and detailed characterizations are not usually available. Typically, organic antistrip additives contain fatty amines such as long-chain, primary, secondary and tertiary amines, diamines, amidoamines and imidoazolines [38]. Two types of additives were used in this research. LOF 6500 is a modified fatty amidoamine and Morlife 2200 is polyamine and mixed polycycloaliphatic polyamine, their physical properties are shown in Table 2-1. Both of these antistrip additives were tested with PG64-22 asphalt binder from the Citgo Wilmington refinery. Two types of field mixes were also tested. For both the field mixes, the job-mix-formula (JMF) required only LOF 6500 antistrip additive. However, during lab testing of the materials obtained from the field, both LOF 6500 and Morlife 2200 were used as antistrip additives. Details of the field mixes are as follows:

Material Type I:

Blend Percentages and Gradation are shown in Table 2-2 and Table 2-3.

Total Binder Content: 4.50%

Binder Grade: PG 64-22 Citgo Wilmington asphalt

Mix Temperature: 300°F

Antistrip Additive: LOF 6500 antistrip additive in the amount of 0.5%.

Material Type II:

Blend Percentages and Gradation are shown in Table 2-4 and Table 2-5.

Total Binder Content: 5.10%

Binder Grade: PG 64-22 Trumbull asphalt

Mix Temperature: 300°F

Antistrip Additive: LOF 6500 antistrip additive in the amount of 0.5%.

2.4 Procedure to Quantify Antistrip Additives in Asphalt Binders and Mixes

To determine the presence and amount of a given antistrip additive in the binder or mix, the spectrophotometer readings must initially be calibrated with asphalt binders or mixes of interest that contain known amounts of antistrip additive. Based on considerable experience developed during this study, it is suggested that 100-g asphalt binder samples or 2000-g asphalt mix samples be used for calibration and analysis of unknown samples.

2.4.1 Calibration procedure to determine antistrip additive content in asphalt binder

Initially, several tests were conducted to gain experience in using the StripScan device. The final test method used for producing the asphalt cement with antistrip additive was to take 500-g of the asphalt sample, adding to it a given additive percentage and mixing thoroughly so that the additive was uniformly dispersed. Immediately after mixing, the asphalt sample was divided into five 100-g batches to prevent segregation of the antistrip additive from the asphalt cement.

Based on the experience obtained in using the StripScan device, the following procedure was developed and followed for testing.

1. Based on the desired quantity of asphalt binder, weigh out the required mass of antistrip additive and place into a large metal can. For example, to obtain a 0.25% additive content in 500-g of asphalt binder, 1.25-g additive is weighed out. Subsequently, pour 500-g heated asphalt into the can containing the measured additive content.
2. Mix thoroughly for at least 3 min. to ensure that the additive is uniformly distributed in the asphalt binder. A low-shear mixer of the type used for producing modified asphalt binders may be used.
3. Immediately after mixing, pour 100-g samples into individual test cans and close the can lid. In this study, 150-mm diameter cans were used as shown in Figure 2-3. It should be noted here that the can lid required for the litmus device has a 25-mm diameter opening in the middle to facilitate litmus testing. This hole

should be sealed with a cork or rubber stopper during sample preparation to prevent vapor loss. At this point, the individual cans containing 100-g of asphalt binder with additive may be stored temporarily at room temperature.

4. Using steps 1 to 3, prepare samples with different levels of antistrip additive contents. In this study, five levels of antistrip additive content were evaluated—0, 0.25, 0.5, 1.0 and 2.0% by weight of asphalt binder.
5. Immediately prior to testing, heat the sample in a forced draft oven at 150°C for 15 min. It should be noted that for multiple sample testing, the samples should not all be heated simultaneously. The sample heating process should be staggered based on operator efficiency such that while a given sample is being analyzed with the litmus test, the other samples are not being over-conditioned by heating them for more than 15 min.
6. Transfer the heated sample to the litmus device. A heating plate in the device maintains the sample temperature at 150°C as verified with a thermocouple introduced through a small hole in the can lid. At this point, the 25-mm diameter opening in the can lid is unplugged.
7. A litmus test strip is brought into contact with the vapors escaping through the lid opening for a period of 3 min. It should be noted that before exposing the litmus strip to vapors, it has to be scanned with the spectrophotometer to establish a baseline reading.
8. After 3 min. of exposure to the vapors, the litmus strip is removed and immediately scanned with the spectrophotometer. The difference in

spectrophotometer readings before and after vapor exposure is the color index that corresponds to the amount of antistrip additive present in the binder.

9. Repeat the procedure for replicate samples and for samples containing different levels of antistrip additive contents.
10. Establish a calibration curve (regression equation) between the additive content and the color index determined by the spectrophotometer.

In this study, steps 7 to 10 were fully automated in the litmus test using StripScan device shown in Figure 2-2. Figures 2-4 and 2-5 show the calibration curves for asphalt binder containing the LOF 6500 and Morlife 2200 antistrip additives, respectively. It should be noted that the calibration curves for the two anti-strip additives differ because of the different chemical composition of the two additives. Once established, these calibration curves can be used for quality control and quality assurance of field samples.

2.4.2 Calibration procedure to determine antistrip additive content in asphalt mixes

1. Incorporate the required amount of antistrip additive in asphalt binder. This process is the same as that presented above.
2. Prepare asphalt mix samples containing different antistrip additive contents. In this study, three 2000-g mix samples were prepared for each level of antistrip additive content.
3. Before testing, preheat the sample for 1-h. Leave the lid open when heating and stir (agitate) the sample every 15-30 min.
4. Follow steps 6 to 10 outlined above for the asphalt binder.

2.5 Test Results and Discussion

2.5.1 Test results for antistrip additive in asphalt binder

For the litmus test, PG 64-22 Citgo Wilmington asphalt binder samples were prepared using LOF 6500 and Morlife 2200 antistrip additives at levels of 0, 0.25, 0.5, 1.0 and 2.0% by asphalt binder weight. For each level of antistrip additive content, five replicate samples, each weighing 100-g, were prepared. Each sample was tested three times using different litmus strips. Tables 2-6 and 2-7 show the color index obtained using the StripScan device for PG 64-22 Citgo Wilmington asphalt binder containing the two antistrip additives LOF 6500 and Morlife 2200, respectively.

Figure 2-4 shows the correlation between the LOF 6500 additive content and the color index; the coefficient of determination (R^2) was 0.92. It can be seen from these data that the StripScan is fairly effective in detecting not only the presence of the antistrip additive LOF 6500 but also the amount (percentage) of the additive in the binder. That is, the StripScan is able to detect qualitatively as well as quantitatively the presence of the antistrip additive. Similarly, Figure 2-5 shows Morlife 2200 antistrip additive content as a function of color index. It should be noted that in Figures 2-4 and 2-5, for a given additive content, there is a fair amount of scatter in the measurement of color index. This scatter is accounted for in the regression R^2 values and will inherently affect the accuracy of predicted additive content values.

One difficulty that was encountered with the measurement of the Morlife 2200 antistrip additive was that the additive content could only be measured quantitatively up

to a level of 0.5%. Beyond this limit the color index did not change measurably as is evident in Table 2-7. This behavior is attributed to saturation of the litmus paper. However, up to the 0.5%-level of antistrip additive content, the presented relationship has an R^2 value of 0.99. It needs to be noted that the exposure time of the litmus paper to the vapors was 3 min. in this study. For some antistrip additives such as Morlife 2200 that tend to saturate the litmus paper more quickly, a testing agency may need to reduce the exposure time, testing temperature, or both if high levels of antistrip additive need to be quantified in asphalt binders.

Once developed, the regression equations (calibration curves) shown in Figures 2-4 and 2-5 can be used to detect the presence and amount of antistrip additive in field asphalt binder samples for quality control and quality assurance purposes with a reasonable degree of certainty as indicated by the R^2 values (> 0.9). Although the quantitative determination of higher percentages of antistrip additive may be difficult for some additive types, the data show that the procedure developed herein can detect the presence of antistrip additive in a qualitative manner in such instances.

2.5.2 Test results for antistrip additives in asphalt mixes

Although the JMF requires the use of LOF 6500 antistrip additive for mixes I and II, testing was also conducted on mixes with Morlife 2200 antistrip additive.

Two types of asphalt mix samples were prepared using LOF 6500 and Morlife 2200 antistrip additives at levels of 0, 0.25, 0.5, 1.0 and 2.0% by asphalt binder weight. It should be noted that these two types of asphalt mix differ not only in gradation but also in

asphalt type. The PG 64-22 Citgo Wilmington asphalt was used for asphalt mix I, whereas PG 64-22 Trumbull asphalt was used for asphalt mix II. For each level of antistrip additive content, three replicate samples, each weighing 2000-g, were prepared. Each sample was tested twice using different litmus strips. Tables 2-8 and 2-9 show the color index obtained from the StripScan device for asphalt mix I containing the two antistrip additives LOF 6500 and Morlife 2200, respectively. Similarly, Tables 2-10 and 2-11 show color index data for asphalt mix II containing the two antistrip additives.

It should be noted that the calibration curves presented in Figures 2-6 to 2-9 for the two antistrip additives differ because of the different chemical composition of the two additives, different mix gradation and different asphalt types. The R^2 values for these calibration curves are all higher than 0.96. However, the calibration curves are very steep, especially, at additive contents higher than 1%. Therefore, it may be difficult to accurately evaluate higher additive contents in unknown mix samples. The litmus strip saturation problem that was encountered with Morlife 2200 in PG 64-22 Citgo Wilmington asphalt binder was not encountered with the respective mixes, perhaps because the additive adhered more strongly to the aggregate.

Figures 2-10 and 2-11 show the effect of mix type for each antistrip additive, respectively. These comparisons suggest that different mixes (combination of aggregate source and gradation, asphalt binder source and content) require individual calibration curves.

2.5.3 Validation of the litmus test procedure using field samples

To validate the litmus test procedure, field samples of mix I were obtained from the job site. The hot mix was sampled from the back of the truck just before lay-down operation and immediately placed into testing cans that were sealed with masking tape. The JMF requires that field mix I contains 0.5% antistrip additive LOF 6500 by asphalt binder weight.

Twenty field samples were analyzed in the laboratory according to the litmus test procedure outlined for mix testing. The color index was obtained and the antistrip additive LOF 6500 content was computed using the regression equation shown in Figure 2-6. That is,

$$C = 1.89 \times 10^{-7} i^3 - 2.70 \times 10^{-4} i^2 + 1.34 \times 10^{-1} i - 22.28 \qquad \text{Eq. (2.1)}$$

where, C is calculated additive content (%), i is color index value.

The predicted values are shown in Table 2-12.

The field sample test results show that antistrip additive in mix I ranged from 0.49% to 0.58%, with a mean value of 0.55% and a coefficient of variation of 4.83%. The test results indicate that the litmus procedure is able to qualitatively detect the presence of antistrip additive in the field mix as well as to quantify the amount in the field mix that was tested in this study. However, to confirm these results, further verification is needed using more mixes, different antistrip additives and dosages.

2.4.3 Summary and conclusion

This study presents a relatively simple method for detecting and quantifying amine-based antistrip additives in asphalt binders and mixes. The developed procedure was based on a litmus test that produced results that are quantifiable and repeatable with low coefficients of variation. The conclusions based on the results of this study are:

- The litmus test appears to be capable of detecting and quantifying organic antistrip additives (at least those used in this study).
- For both asphalt binders and mixes, the color index was strongly correlated with antistrip additive content ($R^2 > 0.92$). The relationships were particularly strong for asphalt mixes, with R^2 values greater than 0.96.
- The relationship between color index and antistrip additive content is unique for each asphalt binder and mix containing a given additive type.
- The litmus test method was capable of correctly determining the amount of antistrip additive in a field mix.
- The repeatability of the test based on the analysis of 20 replicate field samples had a coefficient of variation of less than 5%. However, these results are based on one field mix, with tests conducted by a single operator. It is anticipated that the coefficient of variation will be higher when testing is conducted by multiple operators in multiple laboratories. Therefore, further verification is needed using more mixes, different antistrip additives and dosages.

Table 2-1 Physical Property of Antistrip Additives

Physical Parameter	LOF 6500	Morlife 2200
Boiling Point	>500ºF	716ºF
Solubility in Water	Slight	Miscible
Vapor Pressure (mmHg at 25ºC)	<1	Not Established
Vapor Density (Air= 1)	>1	Not Established
Appearance	Dark brown liquid	Brown dark liquid
Odor	Mild	Slight
Specific Gravity (at 25ºC)	0.96-0.98	1.06

Table 2-2 Blend Percentages, Material Type I

Material	Blend %
Coarse Aggregate,#78M	15.0
Coarse Aggregate,#67	47.0
Recycled Asphalt Pavement (RAP), Coarse	15.0
Screenings, Regular	16.0
Sand, Natural	7.0
Total	100.0

Table 2-3 Gradation, Material Type I

Sieve Size (mm)	Passing %
50.0	100
37.5	100
25.0	100
19.0	98
12.5	77
9.5	64
4.75	39
2.36	27
1.18	22
0.6	13
0.3	8.0
0.15	6.0
0.075	4.1

Table 2-4 Blend Percentages, Material Type II

Material	Blend %
Coarse Aggregate,#57	15.7
Coarse Aggregate,#78M	31.0
Recycled Asphalt Pavement (RAP), Coarse	14.9
Screenings, Asphalt	7.0
Screenings, Concrete	26.2
Sand, Pit	5.2
Total	100.0

Table 2-5 Gradation, Material Type II

Sieve Size (mm)	Passing %
50.0	100
37.5	100
25.0	100
19.0	98
12.5	90
9.5	84
4.75	60
2.36	44
1.18	31
0.6	26
0.3	16
0.15	8
0.075	4.1

Table 2-6 Data for LOF 6500 Additive in PG 64-22 Citgo Wilmington Asphalt Binder, Color Index

Antistrip Additive Content (%)	Color Index														
	Test 1			Test 2			Test 3			Test 4			Test 5		
0	448	429	431	428	434	423	433	434	423	419	425	429	419	437	444
0.25	731	720	717	663	681	675	713	700	692	612	622	620	612	600	592
0.5	728	739	730	787	796	806	702	697	691	769	754	752	860	861	854
1	920	931	926	901	892	890	956	967	966	942	929	940	899	909	887
2	1005	989	995	1020	1040	1021	992	989	990	1002	1009	999	1042	1060	1062

Table 2-7 Data for Morlife 2200 Additive in PG 64-22 Citgo Wilmington Asphalt Binder, Color Index

Antistrip Additive Content (%)	Color Index														
	Test 1			Test 2			Test 3			Test 4			Test 5		
0	448	429	431	428	434	423	433	434	423	419	425	429	419	437	444
0.25	712	707	690	649	630	654	615	595	598	677	668	659	622	631	610
0.5	1017	1027	1012	1000	1019	1026	983	977	969	1001	989	1011	988	976	970
1	1042	1029	1037	1031	1028	1033	1048	1034	1029	1033	1026	1031	1040	1038	1033
2	1008	998	992	995	997	1006	996	998	1000	1003	991	991	997	992	994

Table 2-8 Data for LOF 6500 Additive in Asphalt Mix I, Color Index

Antistrip Additive Content (%)	Color Index					
	Test 1		Test 2		Test 3	
0	388	386	383	384	382	381
0.25	394	401	406	399	404	405
0.5	432	441	440	449	452	458
1	534	542	537	534	535	540
2	612	628	629	610	626	622

Table 2-9 Data for Morlife 2200 Additive in Asphalt Mix I, Color Index

Antistrip Additive Content (%)	Color Index					
	Test 1		Test 2		Test 3	
0	388	386	383	384	382	381
0.25	468	461	474	472	469	448
0.5	502	498	539	542	488	490
1	562	553	543	545	550	533
2	598	600	602	588	537	540

Table 2-10 Data for LOF 6500 Additive in Asphalt Mix II, Color Index

Antistrip Additive Content (%)	Color Index					
	Test 1		Test 2		Test 3	
0	428	423	418	419	422	424
0.25	438	441	444	449	432	430
0.5	474	480	501	510	520	512
1	598	605	627	630	619	617
2	714	715	685	690	739	732

Table 2-11 Data for Morlife 2200 Additive in Asphalt Mix II, Color Index

Antistrip Additive Content (%)	Color Index					
	Test 1		Test 2		Test 3	
0	428	423	418	419	422	424
0.25	433	437	445	440	435	439
0.5	498	495	468	474	482	486
1	604	597	569	576	592	583
2	865	862	854	857	859	860

Table 2-12 Results for LOF 6500 Additive in Mix I, Field Samples

Specimen	Color Index	Additive Content (%)
1	451	0.57
2	446	0.54
3	447	0.55
4	451	0.57
5	437	0.49
6	439	0.50
7	449	0.56
8	453	0.58
9	451	0.57
10	446	0.54
11	448	0.56
12	452	0.58
13	452	0.58
14	449	0.56
15	444	0.53
16	441	0.51
17	450	0.57
18	444	0.53
19	447	0.55
20	445	0.54
Average	447	0.55
Standard Deviation (*s*)	4.45	0.027
Coefficient of Variation (*cv*) (%)	1.00	4.83



Figure 2-1 An Asphalt Binder and Mix Heating Device and a Spectrophotometer



Figure 2-2 StripScan Device for Measuring Antistrip Additives in Asphalt Binders and Mixes

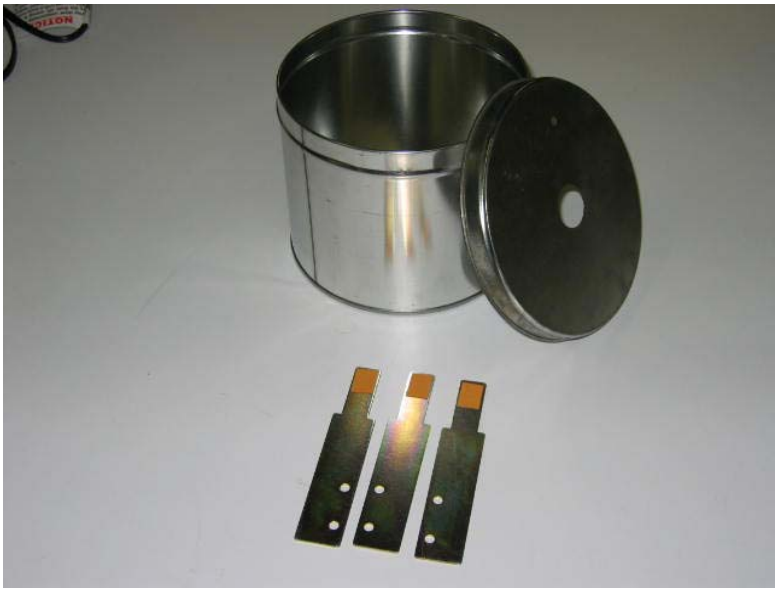


Figure 2-3 Sample Heating Can and Litmus Strips

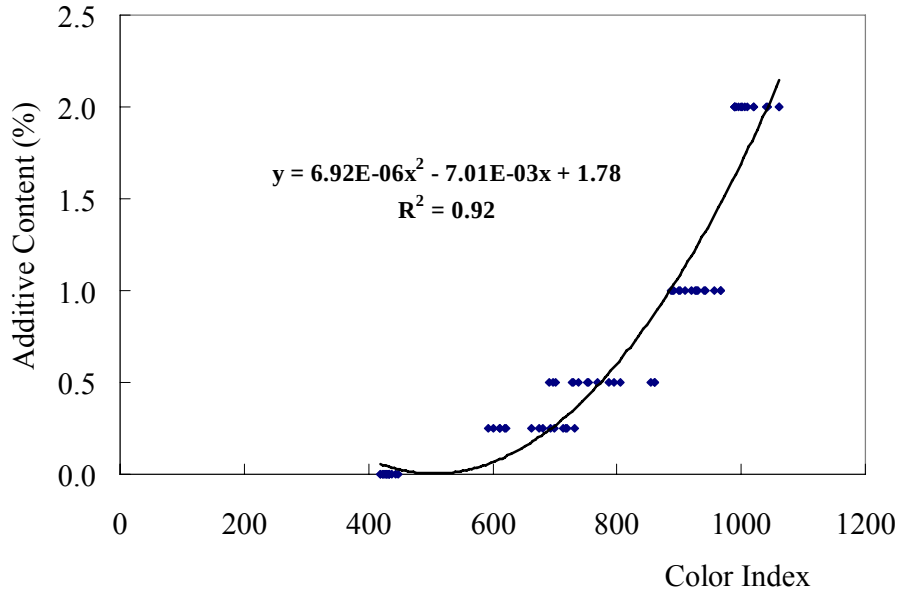


Figure 2-4 Calibration Curve for LOF 6500 Additive in PG 64-22 Citgo Wilmington Asphalt Binder, Percent Additive vs. Color Index

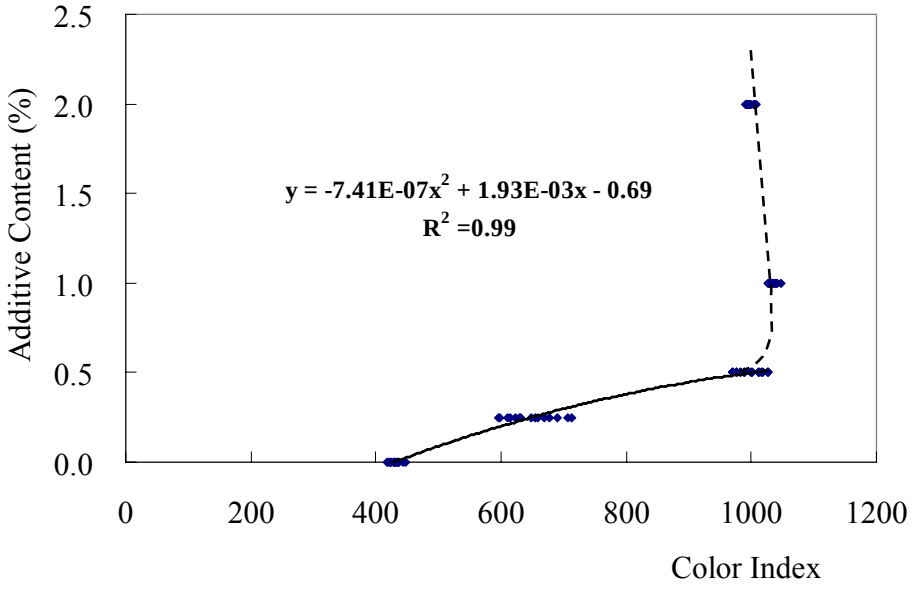


Figure 2-5 Calibration Curve for Morlife 2200 Additive in PG 64-22 Citgo Wilmington Asphalt Binder, Percent Additive vs. Color Index

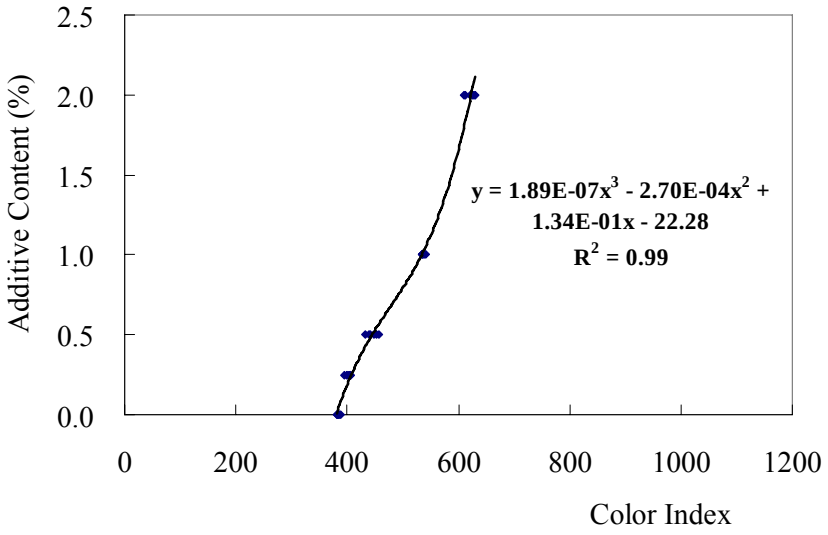


Figure 2-6 Calibration Curve for LOF 6500 Antistrip Additive in Mix I, Percent Additive vs. Color Index

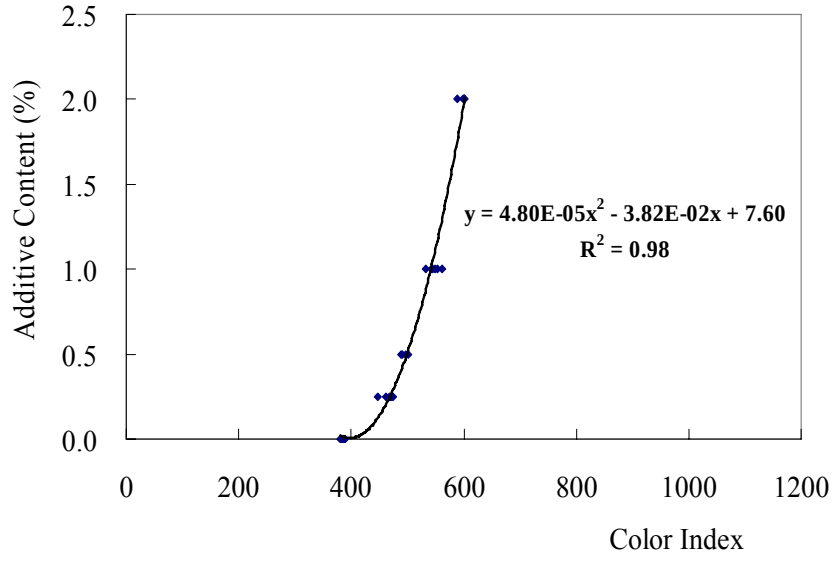


Figure 2-7 Calibration Curve for Morlife 2200 Antistrip Additive in Mix I, Percent Additive vs. Color Index

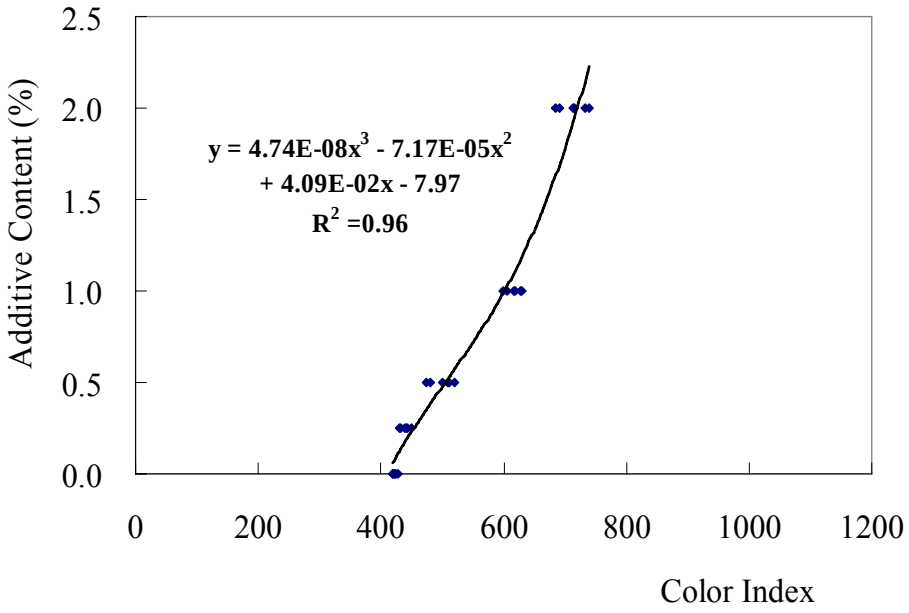


Figure 2-8 Calibration Curve for LOF 6500 Antistrip Additive in Mix II, Percent Additive vs. Color Index

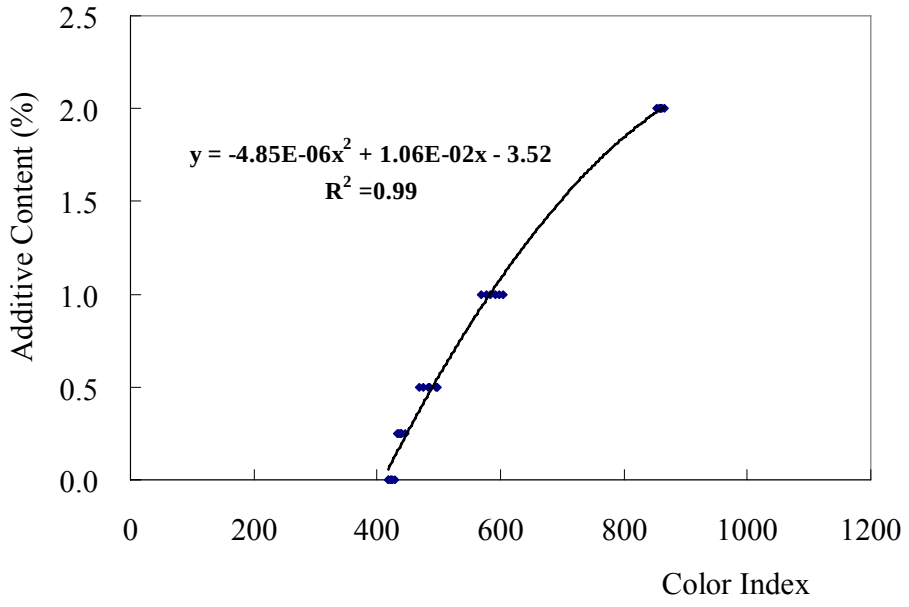


Figure 2-9 Calibration Curve for Morlife 2200 Antistrip Additive in Mix II, Percent Additive vs. Color Index

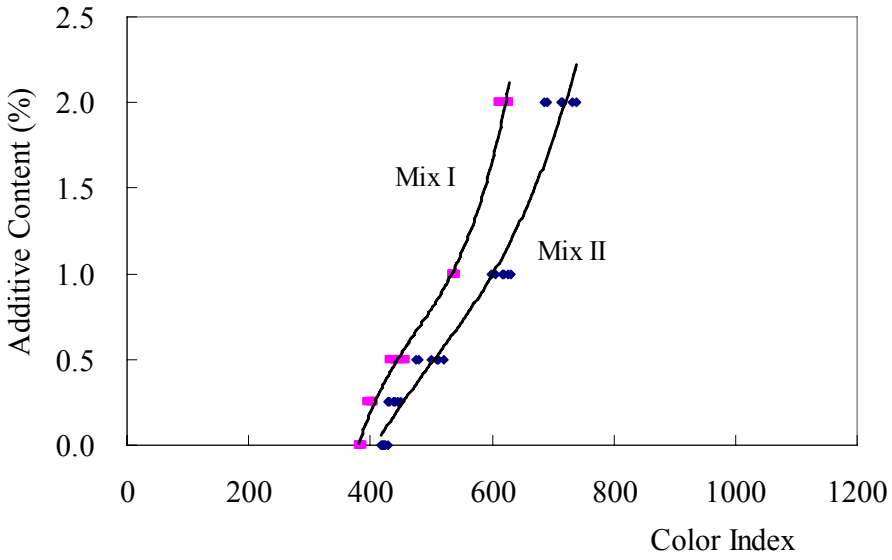


Figure 2-10 Comparison of Calibration Curves for Mix I and Mix II Containing LOF 6500 Antistrip Additive

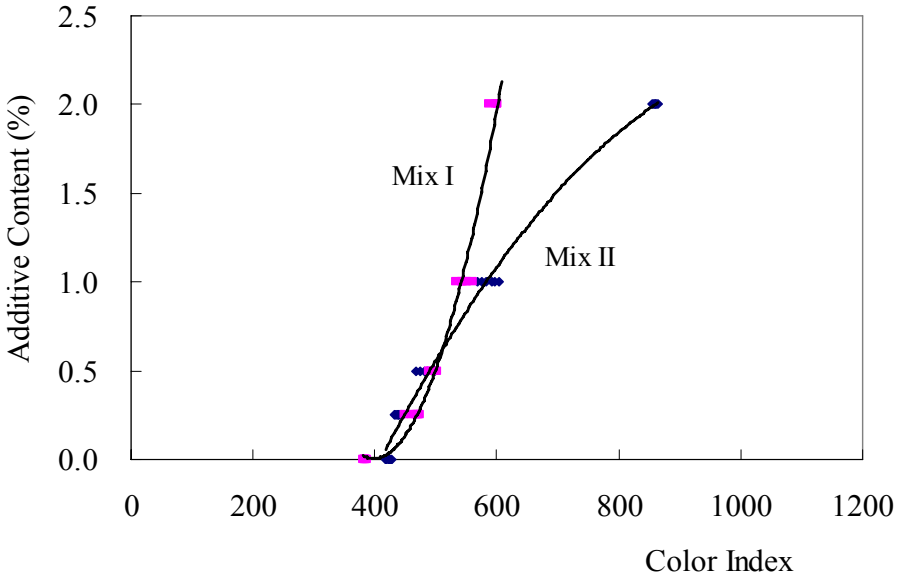


Figure 2-11 Comparison of Calibration Curves for Mix I and Mix II Containing Morlife 2200 Antistrip Additive

3. Quantify Organic Antistrip Additive Using Colorimetric Test Method

3.1 Colorimetric Test Overview

Various methods for the spectrophotometric determination of amines in aqueous solution have been developed since the 1960s [39-41]. Silverstein [40] established a spectrophotometric method for quantifying the aqueous concentrations of fatty amines. To determine the total amine concentration in water, methyl orange was allowed to react with the amines in the presence of an acetate buffer, and the resulting yellow complex was extracted into ethylene dichloride. The method was effective for amine analyses in the parts per million (ppm) concentration range. Larrick [41] improved on Silverstein's spectrophotometric analysis method by combining the buffer and dye reagents into a combination reagent. In this study, the aqueous solution of amines was produced by dissolving volatiles emitted during heating of asphalt binders and mixes in a water trap. Details of the procedure and the device for trapping amine vapors into solution are outlined below.

The colorimetric test for quantifying amine-based antistrip additives in asphalt binders and mixes was developed as a three-step process consisting of (1) amine extraction and trapping, (2) chemical reaction with color reagent, and (3) absorbance measurement. First, during the extraction and trapping process, a preheated sample of asphalt binder or mix was transferred to a hot plate and maintained at a temperature of

170°C. For a period of 10 minutes, emitted gases were transported with the N_2 carrier gas to a gas washing bottle containing 100 mL of ultrapure water. The time measurement was started when air bubbles first appeared in the water. Second, in the chemical reaction process, 5 mL of Larrick's combined reagent [41] was added to 100 mL deionized water taken from the gas washing bottle and allowed to react for a period of 10 min. Following the addition of 20 mL of ethylene dichloride, the colored complex formed in step 2 was extracted into the organic solvent by shaking the sample for 5 min. Upon phase separation, an ethylene dichloride sample was removed, and the absorbance of the ethylene dichloride extract was measured in a 1-cm path length glass cuvette at a wavelength of 420 nm using a spectrophotometer (UV1, Spectronic Unicam, England). An ethylene dichloride extract obtained using asphalt binder or mix without antistrip additive was used to establish a baseline reading for absorbance measurements. The absorbance values of the ethylene dichloride extracts obtained from samples containing different levels of antistrip additive contents were compared with the baseline absorbance value, and the difference between the sample and baseline values was used to quantify the amount of antistrip additive in asphalt binders or mixes.

3.2 Extraction Technique of Antistrip Additives from Asphalt Binders and Mixes

The colorimetric technique requires that amines are present in aqueous solution. Therefore, an amine trapping system was developed during the course of this study. A schematic representation is shown in Figure 3-1. This device consisted of a nitrogen gas cylinder, valve, tube, heating tape, flow meter, sample container, heater, and a gas

washing bottle containing deionized water. The functions of individual components are stated in detail as follows:

a. Nitrogen tank: Inert N_2 gas under pressure was used to facilitate the transport of volatiles from the sample container into the gas washing bottle (Fisher Scientific, Hampton, NH) containing deionized water.
b. Valve: Start or stop N_2 gas flow from the gas tank.
c. Stainless steel tube: Transfer N_2 gas from tank to sample container and deionized water.
d. Heating tape: Heat N_2 gas flowing in stainless steel tubes to avoid condensation of asphalt fumes.
e. Flow meter: N_2 gas flow rate was controlled by the flow meter at 50 cm^3/min. (shown in Figure 3-2)
f. Sample container: Two sizes of sealed metal cans were used to heat samples: A quarter-gallon can was used for asphalt binders, and a gallon-can was used for mixes (Figures 3-3 and 3-4 show asphalt binder and asphalt mix sample containers, respectively). For analyses, 100-g asphalt binder and 2000-g asphalt mix samples were used. The operator needs to asure that the sample container is fully sealed when testing; otherwise, air leakage will prevent transport of the emitted gas from the sample container to the water trap.
g. Heater: The test sample temperature was maintained at 170°C during the extraction process.
h. Gas washing bottle: A gas washing bottle containing deionized water was used to transfer amines from the gaseous to the aqueous phase.

3.3 Procedure to Quantify Antistrip Additives in Asphalt Binders and Mixes Using Colorimetric Test

Using the above stated components, the following test conditions were used to extract antistrip additives from asphalt binders and mixes: (1) samples were maintained at a temperature of 170ºC, (2) the N_2 gas flow rate was 50 cm^3/min, and (3) the extraction time (time that N_2 flowed through the extraction system) was 10 min.

The preparation procedure of asphalt binder and asphalt mix samples for colorimetric test is similar to the litmus test outlined previously.

3.3.1 Calibration procedure to determine antistrip additive content in asphalt binder

Based on the experience obtained with the litmus test, the following experimental procedure was developed and followed for the colorimetric method:

1. Based on the desired quantity of asphalt binder, weigh out the required mass of antistrip additive and place into a large metal can. For example, to obtain a 0.25% additive content in 300-g of asphalt binder, 1.25-g additive is weighed out. Subsequently, pour 300-g heated asphalt into the can containing the measured additive content.
2. Mix thoroughly for at least 3 minutes to ensure that the additive is uniformly distributed in the asphalt binder. A low-shear mixer of the type used for producing modified asphalt binders may be used.
3. Immediately after mixing, pour 100-g samples into individual test cans and close

the can lid. In this study, quarter gallon can size was used as shown in Figure 3-3. The individual cans containing 100-g of asphalt binder with additive may be stored temporarily at room temperature.

4. Using steps 1 to 3, prepare samples with different levels of antistrip additive contents. In this study, five levels of antistrip additive content were evaluated—0, 0.25, 0.5, 1.0 and 2.0% by weight of asphalt binder.
5. Prior to testing, heat the sample in a forced draft oven at 170°C for 15 minutes. It should be noted that for multiple sample testing, the samples should not all be heated simultaneously. The sample heating process should be staggered based on operator efficiency such that while a given sample is being analyzed with the colorimetric test, the other samples are not being over conditioned by heating them for more than 15 minutes.
6. Prior to testing, prepare 500 mL color reagent (see Figure 3-5a). The procedure for preparing color reagent is as follows: Dissolve 0.1 g of methyl orange in 100 mL deionized water; dissolve 29.6-g of sodium acetate trihydrate and 50-g of potassium chloride in separate 100 mL deionized water. Combine these two 100 mL solutions and add 100 mL of glacial acetic acid to it. Finally dilute this 300 mL solution to 500 mL with deionized water. [15].
7. Immediately prior to starting the extraction procedure, turn on the heater and heating tape such that the temperature of the sample and the vapor transfer lines are maintained at 170°C, then open the valves of the N_2 gas tank.
8. Transfer the heated sample to the amine trapping device and allow the vapors to pass through 100 mL deionized water for 10 min. Stopwatch is started when air

bubbles begin to appear in the water of the gas washing bottle. Nitrogen gas at a flow rate of 50 cm^3/min is used to facilitate the transfer of vapors from the can containing the asphalt sample to the wash bottle containing deionized water.

9. Add 5 mL of the color reagent to the acidified water in the wash bottle (from step 8) and set aside for 10 min (see Figure 3-5b). Add 20 mL of ethylene dichloride and shake for 5 min. Allow the layers to separate for 5 min (see Figure 3-5c) [15].
10. Extract 1-2 mL of the ethylene dichloride phase (lower layer) and place into glass vial (see Figure 3-5d).
11. Repeat the procedure steps 5, 8, 9, 10 for samples containing different levels of antistrip additive contents.
12. Measure absorbance of the ethylene dichloride sample immediately at 420 nm using a spectrophotometer. The ethylene dichloride extract abtained from an asphalt sample without added antistrip additive is used as the baseline absorbance value measured with the spectrophotometer (UV1, Spectronic Unicam, England, shown in Figure 3-6), that is, use this extract to zero the spectrophotometer.
13. Establish a calibration curve (regression equation) between the additive content and the absorbance values determined by the spectrophotometer.

3.3.2 Calibration procedure to determine antistrip additive content in asphalt mixes

The preparation procedure of asphalt mix sample is the same as that for litmus test and the colorimetric test procedure is similar to that described for asphalt binder.

1. Incorporate the required amount of antistrip in asphalt binder. This process is the

same as that presented above.

2. Prepare asphalt mix samples containing different antistrip additive contents. In this study, three 2000-g mix samples were prepared for each level of antistrip additive content. Note that the sample container needs to be replaced with a larger 1 gal. can, as shown in Figure 3-4.
3. Before testing, preheat the sample for 1 hour at 170°C. Leave the lid open when heating and stir (agitate) the sample every 15-30 minutes.
4. Follow steps 8 to 13 outlined above for the asphalt binder.

3.4 Test Results and Discussion

3.4.1 Test results for antistrip additive in asphalt binder

For the colorimetric test, two antistrip additives (LOF 6500 and Morlife 2200) were added to PG64-22 Citgo Wilmington asphalt binder at levels of 0, 0.25, 0.5, 1.0 and 2.0% as previously described. Antistrip additive was heat-extracted from the asphalt binder and trapped in water. Following reaction with a color reagent, the aqueous reaction product was extracted into a small volume of organic solvent and the color intensity (absorbance) of the solvent extract was quantified by spectrophotometry. The absorbance of the ethylene dichloride extract from an asphalt binder sample without antistrip additive was used as the baseline.

The raw absorbance data obtained for asphalt binder samples, prepared in triplicate at each of five tested additive levels, are shown in Tables 3-1 and 3-2 for LOF 6500 and Morlife 2200, respectively. Calibration curves for the two antistrip additives in

PG64-22 Citgo Wilmington asphalt binders were developed from the data of Tables 3-1 and 3-2 and are shown in Figures 3-7 and 3-8 for LOF 6500 and Morlife 2200, respectively. Figures 3-7 and 3-8 show the relationship between absorbance and antistrip additive content is approximately linear ($R^2 > 0.95$). It is reasonable that the concentration of colored antistrip additive reaction product extracted into ethylene dichloride is proportional to the amount of antistrip additive in asphalt binder. The steeper slope obtained with the Morlife 2200 antistrip additive suggests that Morlife 2200 is either evaporated more easily from asphalt binder or more reactive with the color reagent than LOF 6500. As a consequence, different types of antistrip additive have unique chemical properties and require the development of individual calibration curves. Overall, Figures 3-7 and 3-8 illustrate that the colorimetric test method is effective in detecting not only the presence of antistrip additive but also the amount of antistrip additive in asphalt binder.

3.4.2 Test results for antistrip additives in asphalt mixes

In this study testing was conducted on mixes I and II containing both LOF 6500 and Morlife 2200 antistrip additive.

The two types of asphalt mix samples were prepared using LOF 6500 and Morlife 2200 antistrip additives at levels of 0, 0.25, 0.5, 1.0 and 2.0% by asphalt binder weight. For each level of antistrip additive content, three replicate samples, each weighing 2000g, were prepared. Tables 3-3 and 3-4 show the absorbance data obtained at 420nm wavelength for asphalt mix I containing the two antistrip additives LOF 6500 and Morlife 2200, respectively. Similarly, Tables 3-5 and 3-6 show the absorbance data obtained for

asphalt mix II containing the two antistrip additives LOF 6500 and Morlife 2200, respectively.

It should be noted that the calibration curves presented in Figures 3-9 to 3-12 for the two antistrip additives differ because of the different chemical composition of the two antitrip additives, different mix gradation and different asphalt types. The R^2 values for these calibration curves are all higher than 0.94. Unlike the linear calibration equations of antistrip additive in asphalt binder, the calibration regression equations of antistrip additive in asphalt mix are quadratic. In addition, these figures show that the calibration equations derived by data of antistrip additive in asphalt mix using colorimetric test are not very accurate for samples containing antistrip additive contents of 0.25% or below.

Figures 3-13 and 3-14 show the effect of mix type for each antistrip additive, respectively. As was the case with litmus testing, these comparisons suggest that different mixes (combination of aggregate source and gradation, asphalt binder source and content) require individual calibration curves.

3.4.3 Validation of the colorimetric test procedure using field samples

As with the litmus test, field samples corresponding to mix I were obtained from the job site to validate the colorimetric test procedure. The hot mix was sampled from the back of the truck just before lay-down operation and immediately placed into testing cans that were sealed with masking tape. The JMF required field mix I to contain 0.5% LOF 6500 antistrip additive by asphalt binder weight.

Ten field samples were tested in the laboratory according to the colorimetric test procedure outlined for mix testing. The absorbance at 420nm was obtained and the LOF 6500 antistrip additive content was computed using the regression equation shown in Figure 3-10. That is,

$$C=751.9681a^2+12.0664a+0.0928 \quad \text{Eq. (3-1)}$$

where, C is calculated additive content (%), *a* is absorbance value.

The predicted values are shown in Table 3-7.

The field sample tests results show that antistrip additive in mix I ranged from 0.38% to 0.66%, with a mean value of 0.49% and a coefficient of variation of 18%. The test results indicate that the colorimetric procedure is able to qualitatively detect the presence of antistrip additive in the field mix as well as to quantify the amount.

3.4.4 Summary and Conclusion

In this study, an amine trapping system was developed and used to extract organic antistrip additive from asphalt binders and mixes into aqueous solution. The developed procedure was based on a colorimetric test that produced results that are quantifiable and repeatable. The conclusions based on the results of this study are:

- The designed extraction device can successfully extract organic antistrip additive from asphalt binders and mixes into deionized water, which makes possible the detection of antistrip additive in asphalt by a colorimetric method.
- For both asphalt binders and mixes, the absorbance at 420nm was strongly correlated with antistrip additive content ($R^2 > 0.94$).

- The colorimetric test is capable of detecting and quantifying organic antistrip additive (at least those used in this study).
- The relationship between absorbance and antistrip additive content is unique for each asphalt binder and mix containing a given additive type.
- The colorimetric test method was capable of determining the amount of antistrip additive in a field mix.
- The repeatability of the test based on the analysis of 10 replicate field samples was acceptable with a coefficient of variation of approximately 18%.

Table 3-1 Data for LOF 6500 Additive in PG 64-22 Citgo Wilmington Asphalt Binder, Absorbance

Antistrip Additive Content (%)	Absorbance		
	Test 1	Test 2	Test 3
0	0	0	0
0.25	0.0030	0.0022	0.0018
0.5	0.0103	0.0089	0.0078
1	0.0124	0.0146	0.0174
2	0.0329	0.0297	0.0273

Table 3-2 Data for Morlife 2200 Additive in PG 64-22 Citgo Wilmington Asphalt Binder, Absorbance

Antistrip Additive Content (%)	Absorbance		
	Test 1	Test 2	Test 3
0	0	0	0
0.25	0.0018	0.0032	0.0041
0.5	0.0122	0.0096	0.0137
1	0.0287	0.0252	0.0273
2	0.0405	0.0422	0.0373

Table 3-3 Data for LOF 6500 Additive in Asphalt Mix I, Absorbance

Antistrip Additive Content (%)	Absorbance		
	Test 1	Test 2	Test 3
0	0	0	0
0.25	0.0030	0.0038	0.0024
0.5	0.0145	0.0206	0.0171
1	0.0285	0.0257	0.0290
2	0.0410	0.0429	0.0441

Table 3-4 Data for Morlife 2200 Additive in Asphalt Mix I, Absorbance

Antistrip Additive Content (%)	Absorbance		
	Test 1	Test 2	Test 3
0	0	0	0
0.25	0.0054	0.0067	0.0062
0.5	0.0282	0.0257	0.0245
1	0.0401	0.0393	0.0457
2	0.0509	0.0556	0.0602

Table 3-5 Data for LOF 6500 Additive in Asphalt Mix II, Absorbance

Antistrip Additive Content (%)	Absorbance		
	Test 1	Test 2	Test 3
0	0	0	0
0.25	0.0027	0.0024	0.0019
0.5	0.0223	0.0247	0.0212
1	0.0363	0.0380	0.0404
2	0.0542	0.0510	0.0483

Table 3-6 Data for Morlife 2200 Additive in Asphalt Mix II, Absorbance

Antistrip Additive Content (%)	Absorbance		
	Test 1	Test 2	Test 3
0	0	0	0
0.25	0.0043	0.0052	0.0029
0.5	0.0379	0.0357	0.0342
1	0.0569	0.0579	0.0552
2	0.0789	0.0756	0.0744

Table 3-7 Results for LOF 6500 Additive in Mix I, Field Samples

Specimen NO.	Absorbance	Additive Content (%)
1	0.0154	0.46
2	0.0192	0.60
3	0.0137	0.40
4	0.0178	0.55
5	0.0165	0.50
6	0.0142	0.42
7	0.0171	0.52
8	0.0206	0.66
9	0.0131	0.38
10	0.0151	0.45
Average	0.0163	0.49
Standard Deviation (s)	0.0024	0.09
Coefficient of Variation (cv) (%)	14.9827	18.47

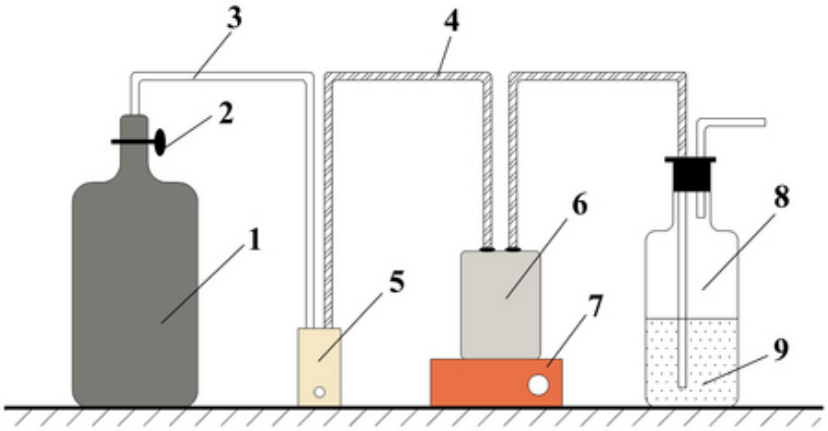


Figure 3-1 Schematic of Amine Trapping System



Figure 3-2 Flow Meter used to Control N_2 Gas Flow Rate



Figure 3-3 Extraction Device for Transferring Antistrip Additive from Asphalt Binder to the Aqueous Phase



Figure 3-4 Extraction Device for Transferring Antistrip Additive from Asphalt Mix to the Aqueous Phase



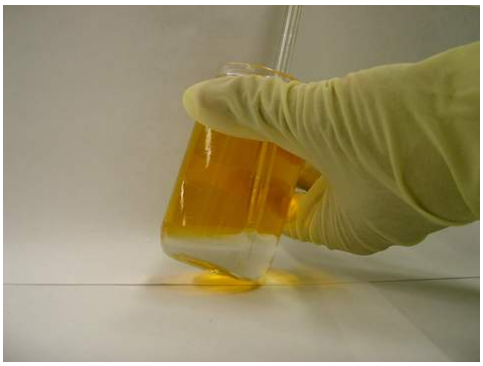
a) Preparation of color reagent



b) Add color reagent to acidified water and set aside



c) Phase separation



d) Extraction of ethylene dichloride phase

Figure 3-5 Chemical Reaction of Aqueous Extract with Dye and Extraction of Solvent

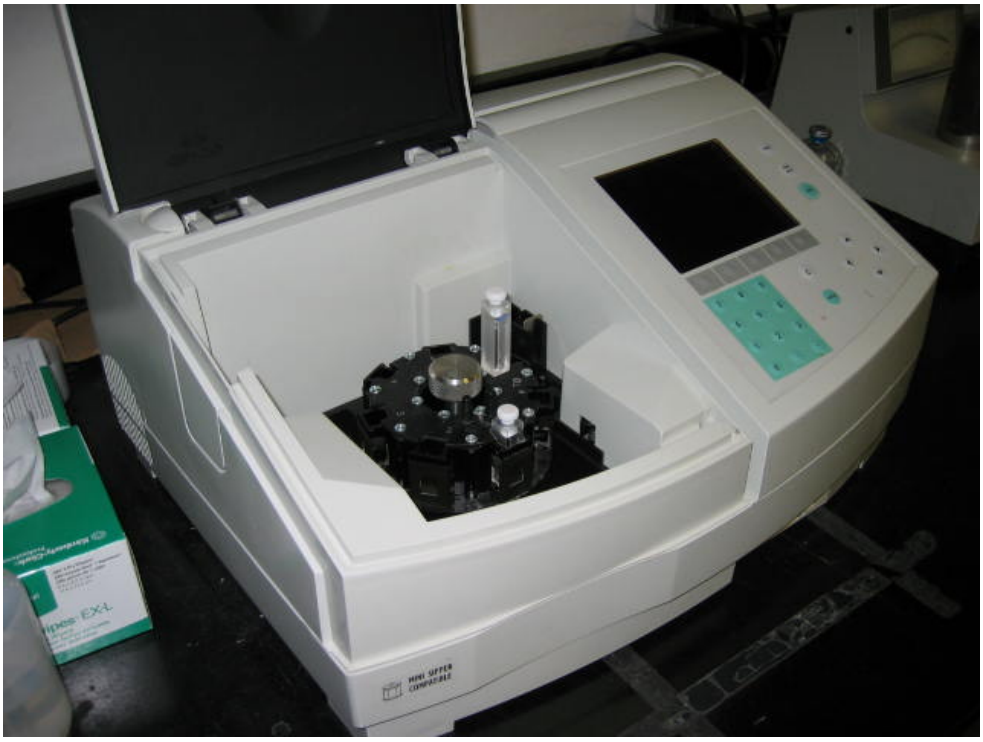


Figure 3-6 Spectrometer for Measurement of Absorbance of Ethylene Dichloride Extracts

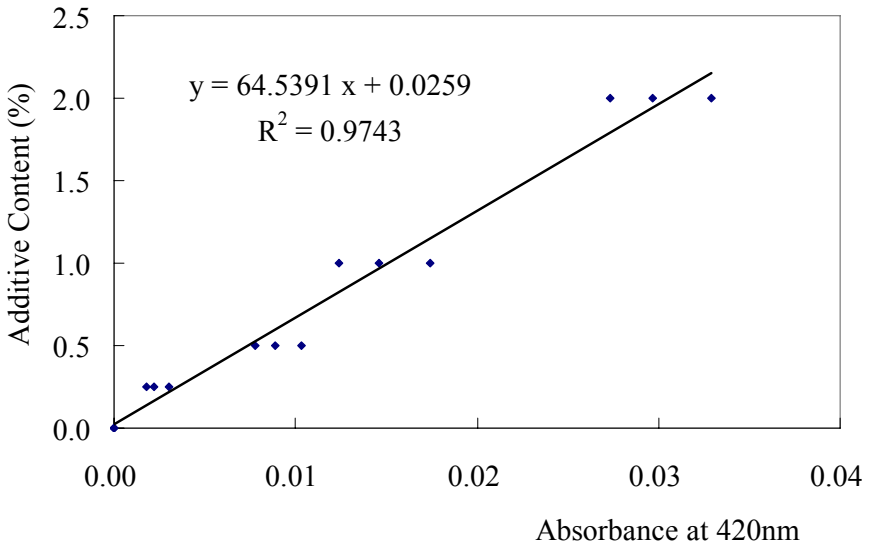


Figure 3-7 Calibration Curve for LOF 6500 Additive in PG 64-22 Citgo Wilmington Asphalt Binder, Percent Additive vs. Absorbance

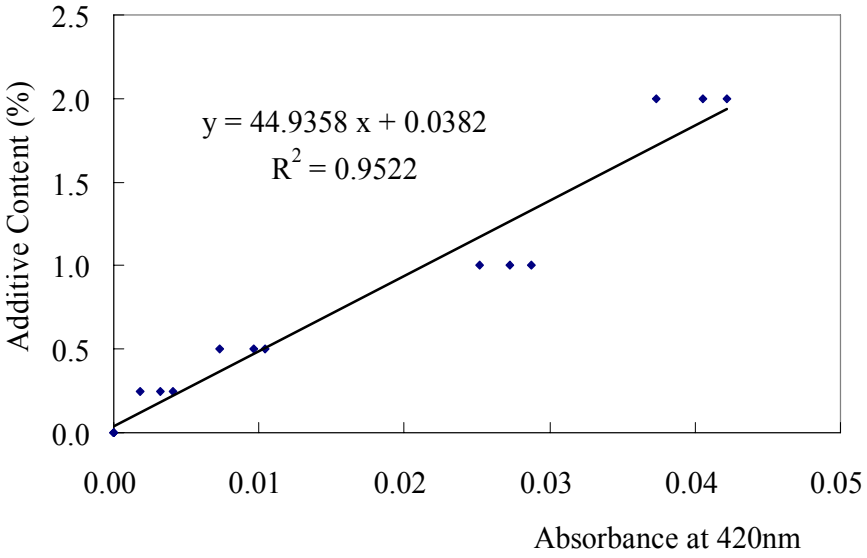


Figure 3-8 Calibration Curve for Morlife 2200 Additive in PG 64-22 Citgo Wilmington Asphalt Binder, Percent Additive vs. Absorbance

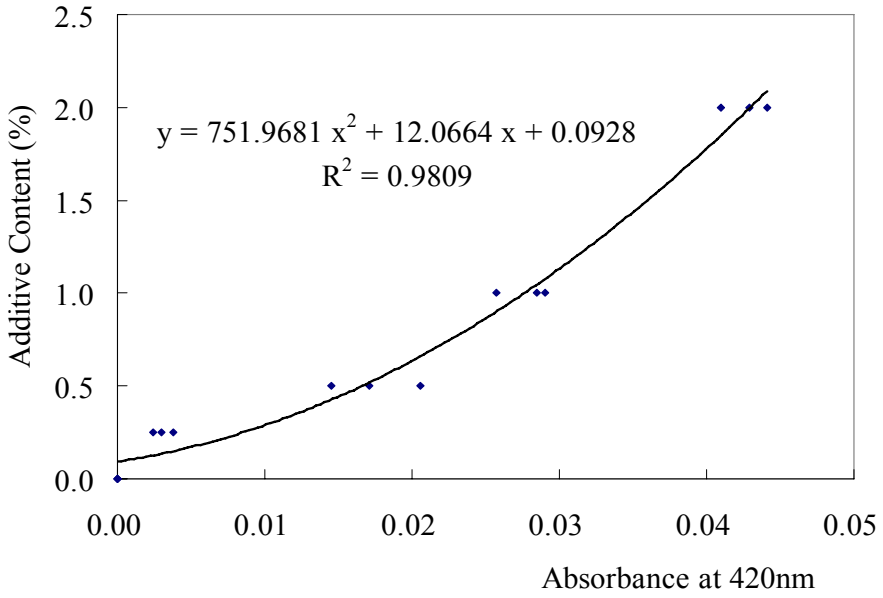


Figure 3-9 Calibration Curve for LOF 6500 Antistrip Additive in Mix I, Percent Additive vs. Absorbance

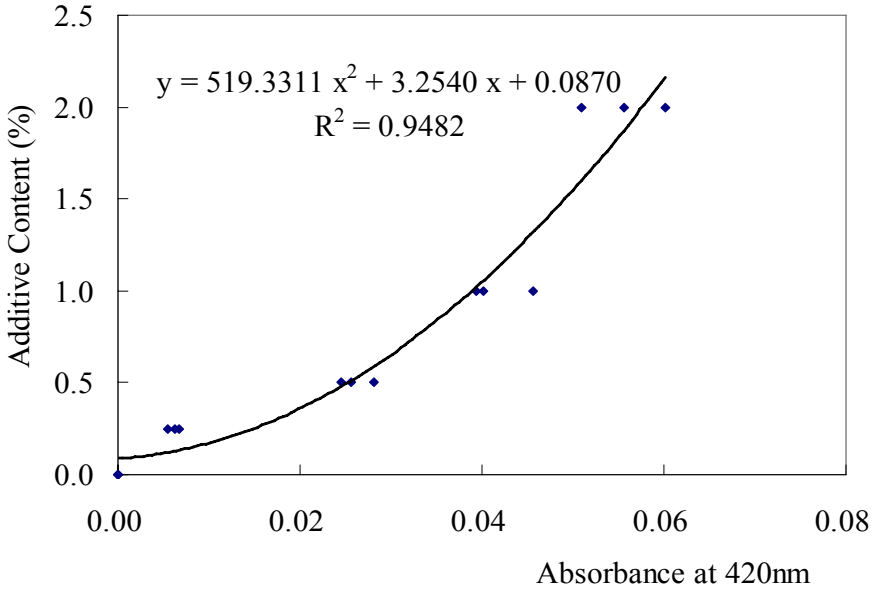


Figure 3-10 Calibration Curve for Morlife 2200 Antistrip Additive in Mix I, Percent Additive vs. Absorbance

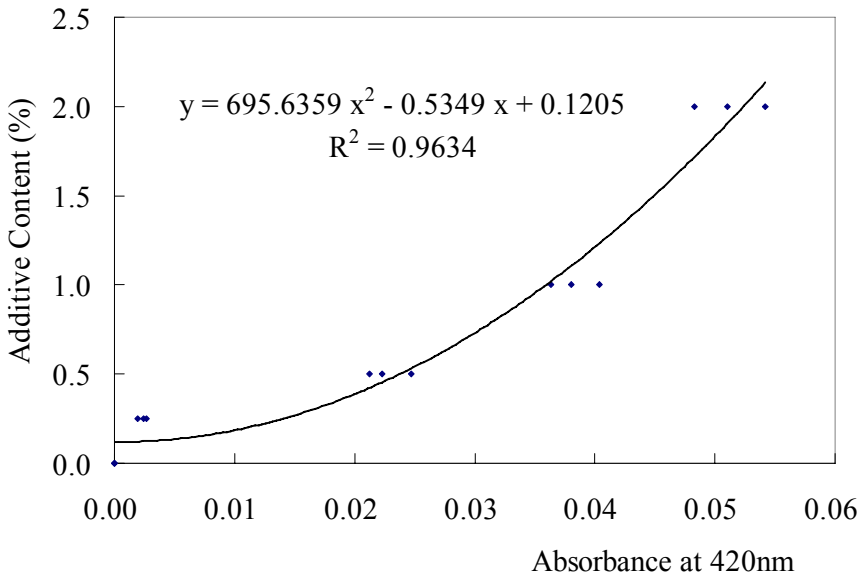


Figure 3-11 Calibration Curve for LOF 6500 Antistrip Additive in Mix II, Percent Additive vs. Absorbance

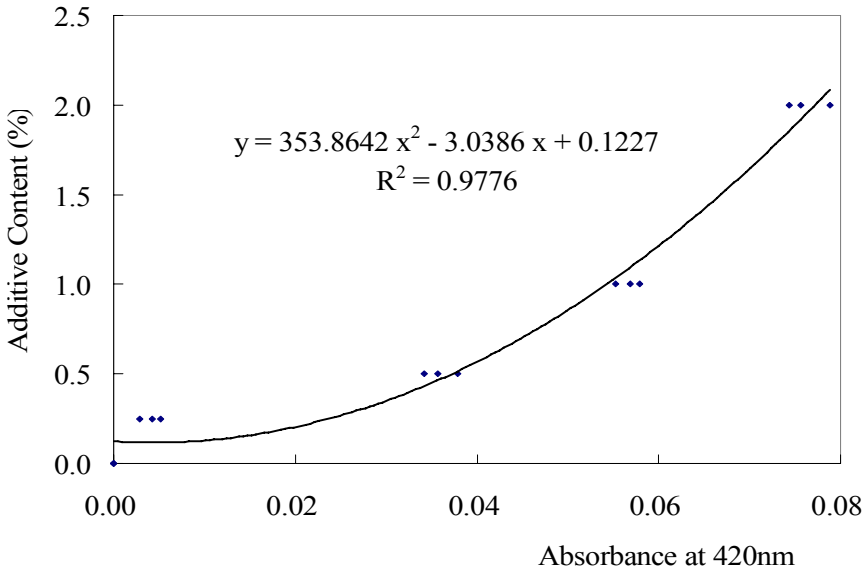


Figure 3-12 Calibration Curve for Morlife 2200 Antistrip Additive in Mix II, Percent Additive vs. Absorbance

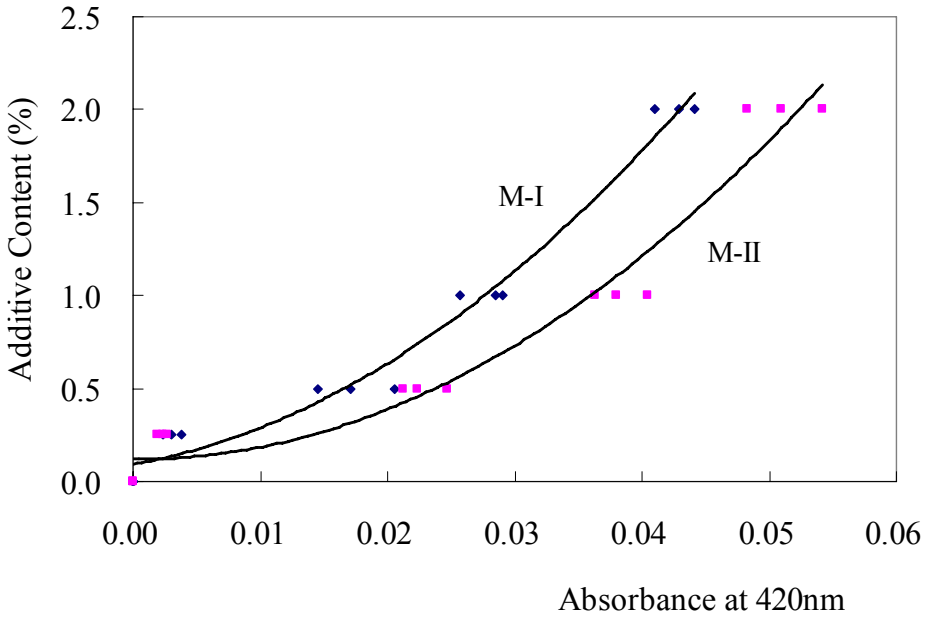


Figure 3-13 Comparison of Calibration Curves for Mix I and Mix II Containing LOF 6500 Antistrip Additive

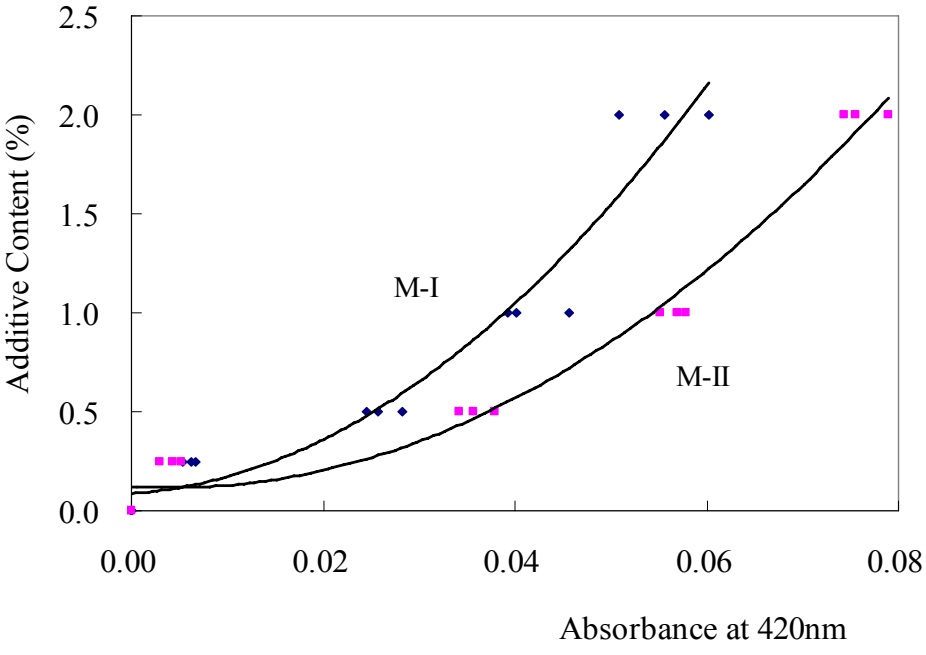


Figure 3-14 Comparison of Calibration Curves for Mix I and Mix II Containing Morlife 2200 Antistrip Additive

4. Effect of Prolonged Heating on Antistrip Additive Contents in Asphalt Binders and Mixes Using Litmus and Colorimetric Test Methods

4.1 Introduction

The loss of amine-based antistrip additives from asphalt binders and mixes through volatilization has long been suspected in the asphalt industry. Due to this reason, many highway agencies now require the use of lime as antistrip additive in mixes. The use of litmus and colorimetric tests offers a viable method to study the effect of prolonged heating on the loss of amine-based antistrip additives in both asphalt binders and mixes. The effect of prolonged heating on the loss of antistrip additives is explored in the following sections.

4.2 Thermogravimetric Analysis of Pure Antistrip Additives

Both antistrip additives LOF 6500 and Morlife 2200 were subjected to thermal analysis to evaluate the effect of prolonged heating on the mass loss. Figure 4-1 shows the mass loss in percent as a function of time at 150°C temperature for both antistrip additives. Based on Figure 4-1, Morlife 2200 antistrip additive is more volatile as compared to LOF 6500 antistrip additive. The mass loss is rapid in the first 6 to 8 hours of heating and tapers off after about 24 hours of heating. In 48 hours, the mass loss for antistrip additives LOF 6500 and Morlife 2200 is roughly 30 and 50 percent, respectively.

Based on Figure 4-1, it is apparent that the higher molecular weight fraction in both antistrip additives does not volatilize easily. However, visual inspection of the antistrip additive LOF 6500 sample shown in Figure 4-2 indicates a distinct color change as function of heating time. After approximately 12 hours of heating, the clear liquid turns to black sticky mass probably indicating decomposition of the non-volatile fraction. The sticky mass was observed to solidify upon cooling. Similar observations were also made for the Morlife 2200 antistrip additive.

4.3 Changes in Antistrip Additive Contents in Asphalt Binders and Mixes after Prolonged Heating

In order to explore the loss of additive due to prolonged heating, the litmus and colorimetric test procedures presented in Chapters 2 and 3 were repeated for asphalt binder samples containing different levels of antistrip additive after 2, 6, 24, and 48 hours of prolonged heating. For asphalt mix samples containing different levels of antistrip additive, tests were repeated after 1, 2, 4, 6, and 12 hours of prolonged heating.

4.3.1 Change of measured antistrip additive content in asphalt binders and mixes after prolonged heating using litmus test

To measure the change in antistrip additive content in asphalt binders and mixes after prolonged heating, the litmus test procedure was used on samples obtained after prolonged heating (2, 6, 24, and 48 hours). Litmus test data are presented in Appendix A. Based on the color index obtained, additive contents were computed from the regression

equation presented in Figure 2-3 shown in the chapter 2. Figures 4-3 and 4-4 show the trend in the data graphically for asphalt binder containing LOF 6500 additive.

An important observation from the data obtained can be seen in Figure 4-4 that represents the decline of additive content as a function of prolonged heating. The data shows that after 24 to 48 hours of heating, there is practically no additive left in the asphalt binder. This poses a serious question regarding the effectiveness of the antistrip additives in field mixes – especially, mixes prepared using terminally blended asphalt binders that may be stored at high temperatures for up to 24 hours and sometimes even longer.

Figure 4-5 shows the data for the antistrip additive Morlife 2200. It should be noted from this figure and as discussed previously in chapter 2, that the StripScan is not able to quantitatively detect very high percentages of the Morlife 2200 antistrip additive (beyond 0.5 to 1.0 percent) due to the over saturation of the litmus strip in the StripScan. For this reason Table A-4 in appendix A shows no data entries related to the samples containing 1 and 2% Morlife 2200 antistrip additive. However, up to 0.5-percent, the antistrip additive could be measured accurately. Similar to the LOF 6500 antistrip additive, Figure 4-5 also shows that after extended heating the Morlife 2200 is also evaporating from the asphalt binder. After 24 to 48 hours of extended heating, there is practically no antistrip additive left in the binder.

Figures 4-6 through 4-9 show the effect of prolonged heating on antistrip additive contents in Mix I for LOF 6500 and Morlife 2200 additives. The trend for the loss of antistrip additive (both LOF 6500 and Morlife 2200) in asphalt Mix I is very similar to

that obtained for the asphalt binder. A notable difference, however, is that the measured additive content in asphalt mix decreases rapidly in the first 6 hours and the additive content approaches zero in a much shorter time frame than that observed for asphalt binder.

Similar to Mix I, Figures 4-10 through 4-13 show the effect of prolonged heating on antistrip additive contents for Mix II. The observations are the same as for Mix I, that is, after 6 hours of prolonged heating, practically no antistrip additive could be detected.

4.3.2 Change of measured antistrip additive content in asphalt binders and mixes after prolonged heating process using colorimetric test

In order to validate the ability of the litmus test to evaluate the effect of prolonged heating on antistrip additive contents in asphalt binders and mixes, the tests conducted using the litmus test were repeated using the colorimetric analysis.

The colorimetric analysis data are presented in Appendix B. The results are summarized in Figures 4-14 and 4-15; and Figures 4-16 and 4-17 for LOF 6500 and Morlife 2200 additives, respectively. The results of colorimetric analysis validate the results obtained using the litmus test. That is, upon prolonged heating both LOF 6500 and Morlife 2200 antistrip additive contents approach zero after 24 to 48 hours.

Figures 4-18 to 4-25 shows the results for antistrip additive loss in Mixes I and II. The mix test results also validate the litmus test observations of drastic decline in antistrip additive contents in 6 to 12 hours of prolonged heating at nominal storage and compaction temperatures.

4.4 Discussion of Test Results

The test results presented above raise some interesting questions. First, it is not unreasonable to assume that in many instances, especially for terminally blended asphalt binders, that the binders will be subjected to elevated temperatures for 24 to 48 hours during storage and transport. Second, it is also not unreasonable that mixes in many instances will be subjected to elevated temperatures for 6 to 12 hours during storage and transport. The question is how does the loss of amine-based antistrip additive through volatilization affect the mix performance? Are the DOTs getting more moisture-susceptible mixes and does it translate into inferior pavement performance?

The question of terminally blended asphalt binders is easier to tackle. Based on the results of this study, loss of antistrip additive content is expected by the time terminally blended binder is used at the plant for mix production. The magnitude of the loss will depend on the temperature at which the binder is stored and transported as well as the duration between production and its ultimate use. It is also possible to blend the virgin binder with antistrip additive at the plant just before use, which is preferable but raises the question of antistrip additive segregation. During the course of this study, some issues with segregation were noted; however, this issue was not pursued further and was bypassed by blending smaller batches of binder and immediately pouring the binder into cans using 100-g samples.

In terms of mixes, assuming that a correct dosage of antistrip additive is contained in the mix, does the loss of additive content due to storage and transport at elevated temperatures affect mix performance in terms of moisture sensitivity? This

question poses a serious conundrum. Without further research, it is not possible to conclude that the mix will be inferior and more moisture-sensitive. The antistrip additive supposedly facilitates the stronger bond between the asphalt binder and the aggregate. It can be argued that once the antistrip additive has facilitated the bonding process during mixing, volatilization of any excess antistrip additive in the mix may not be of any consequence. Therefore, further research is needed to investigate the effect of extended heating on the bond strength between asphalt and aggregate in relation to loss of antistrip additive content.

4.5 Conclusion

Based on the litmus test and colorimetric analysis, it is evident that there is a loss of antistrip additive content in both asphalt binders and mixes when the asphalt binder or mix is subjected to prolonged heating. However, it is neither clear nor possible at this time to conclude what effect if any, does the loss of antistrip additive have on the moisture sensitivity of mixes if the loss occurs after mix production assuming that the specified dosage of antistrip was used during production.

4.6 Recommendation

As stated previously, litmus and colorimetric tests can detect the presence of the antistrip additive qualitatively as well as quantitatively, also, the decline trend of additive content as a function of prolonged heating is observed by using litmus and colorimetric test methods. However, litmus and colorimetric test methods have a limitation to evaluate the effect of loss of antistrip in prolonged heating on moisture sensitivity of asphalt mixes.

In the next chapters, TSR and other test methods are recommended to evaluate the effect of prolonged heating on adhesive bond strength between asphalt and aggregate.

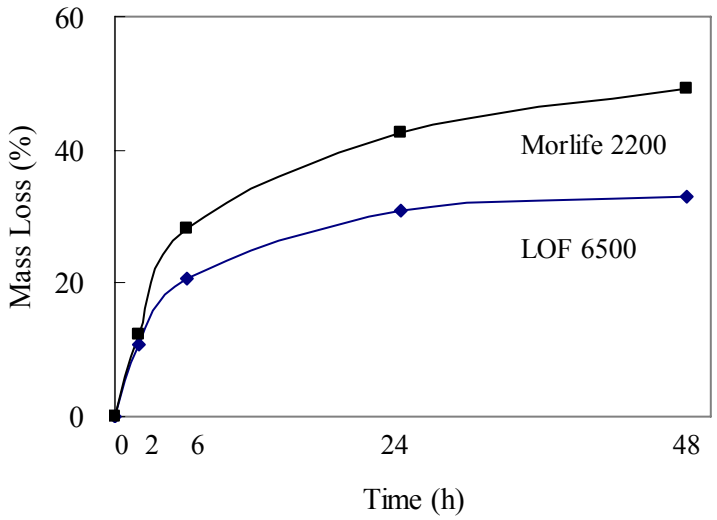


Figure 4-1 Mass Loss of Pure Antistrip Additives as Function of Heating Time

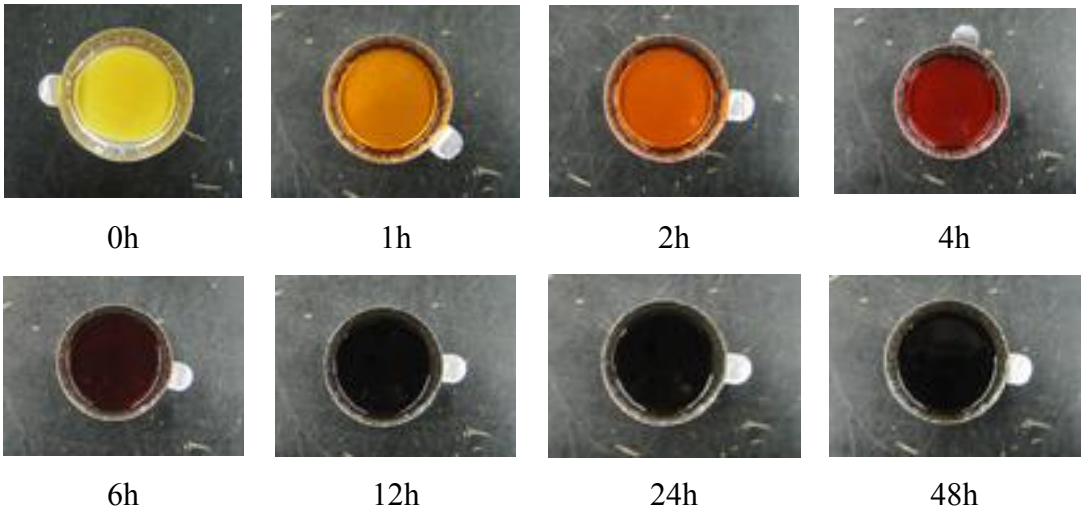


Figure 4-2 Effect of Prolonged Heating on LOF 6500 Antistrip Additive

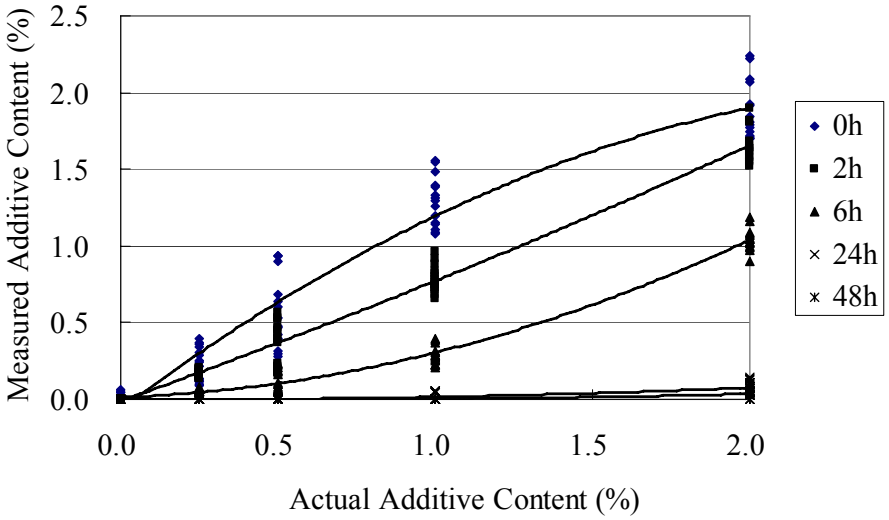


Figure 4-3 Measured LOF 6500 Additive Content in Asphalt Binder as Function of Time using Litmus Test, Measured Additive Content vs. Actual Additive Content

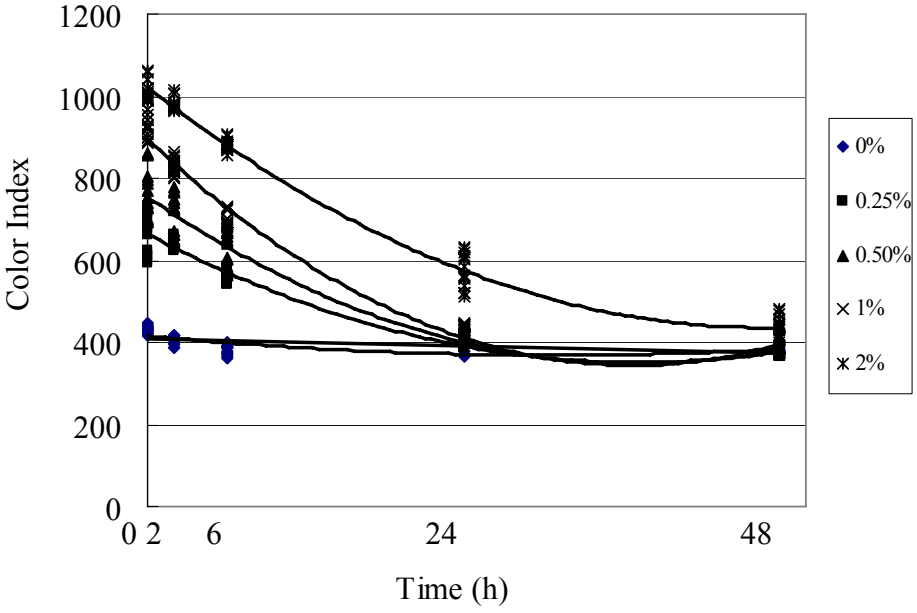


Figure 4-4 Decline of LOF 6500 Additive Content in Asphalt Binder during Prolonged Heating Process using Litmus Test

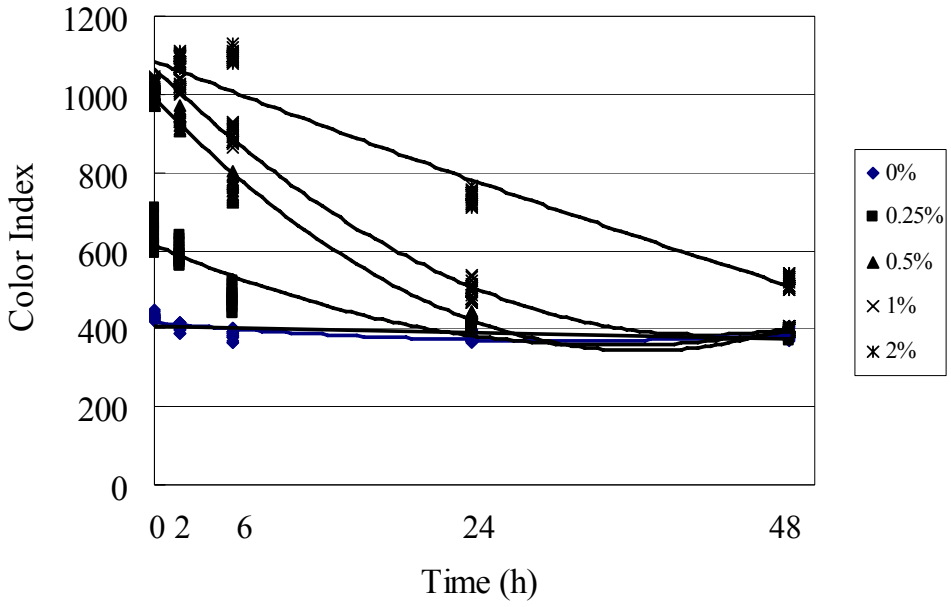


Figure 4-5 Decline of Morlife 2200 Additive Content in Asphalt Binder during Prolonged Heating Process using Litmus Test

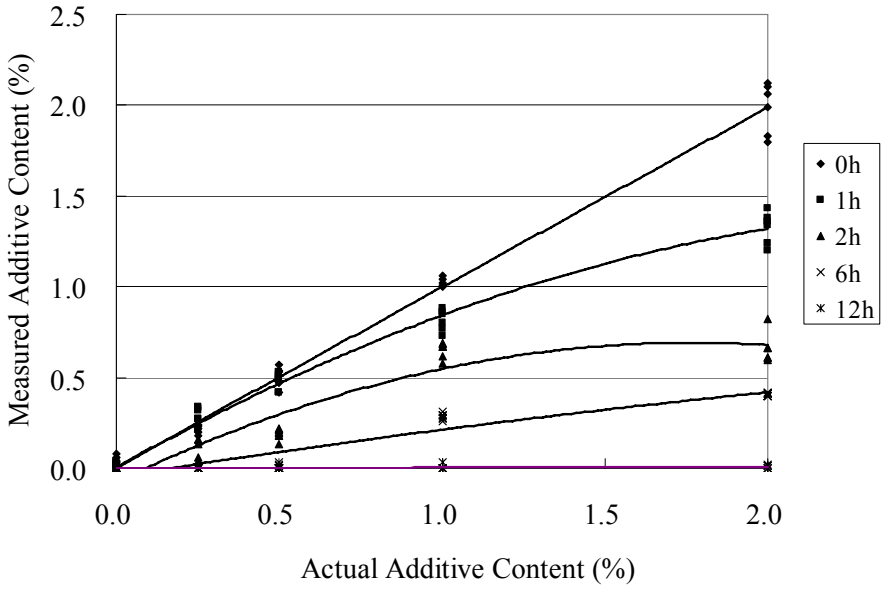


Figure 4-6 Measured LOF 6500 Additive Content in Asphalt Mix I as Function of Time using Litmus Test, Measured Additive Content vs. Actual Additive Content

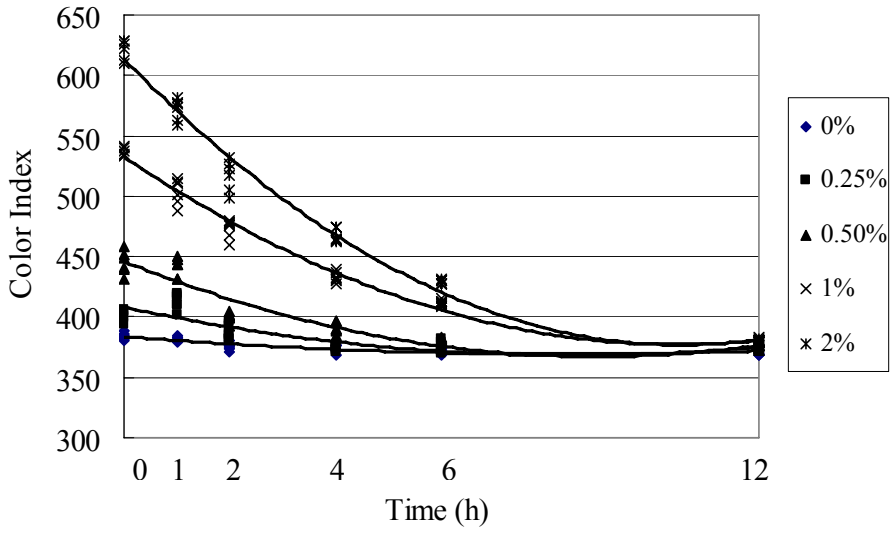


Figure 4-7 Decline of LOF 6500 Additive Content in Asphalt Mix I during Prolonged Heating Process using Litmus Test

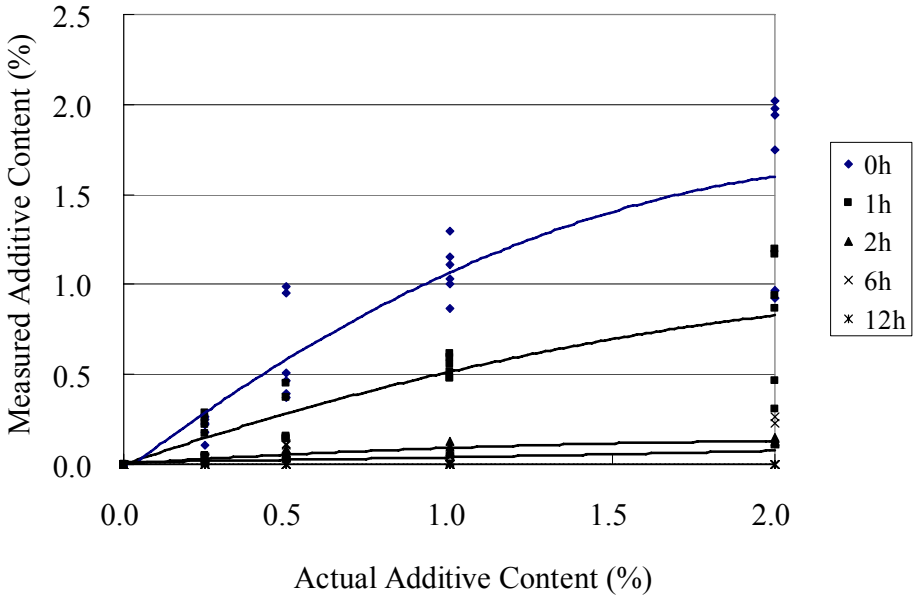


Figure 4-8 Measured Morlife 2200 Additive Content in Asphalt Mix I as Function of Time using Litmus Test, Measured Additive Content vs. Actual Additive Content

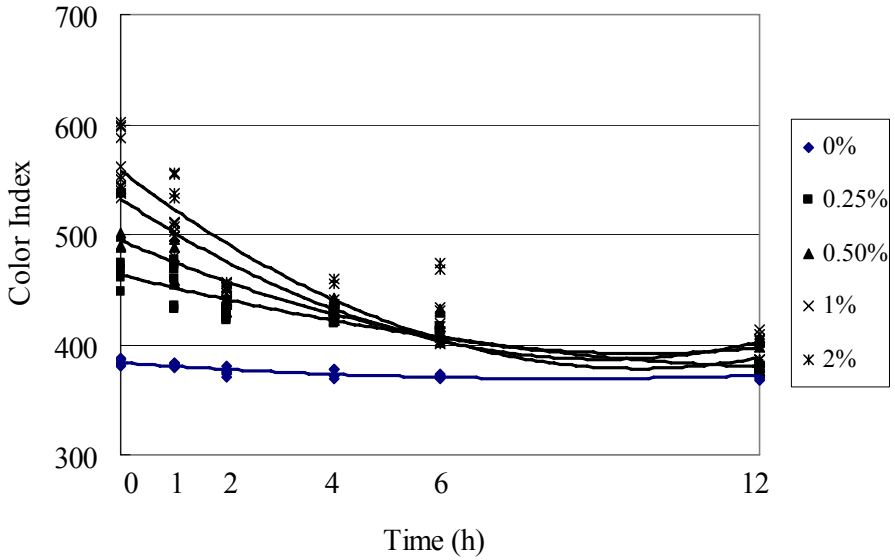


Figure 4-9 Decline of Morlife 2200 Additive Content in Asphalt Mix I during Prolonged Heating Process using Litmus Test

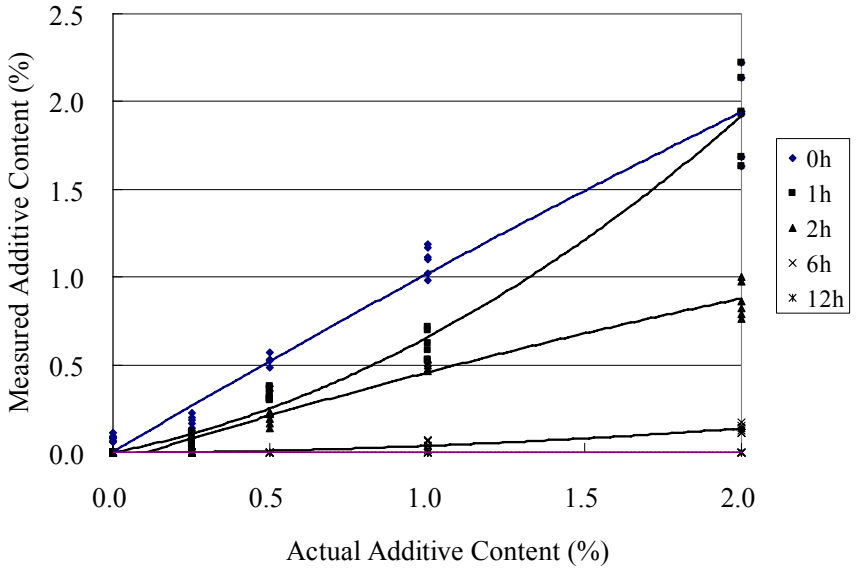


Figure 4-10 Measured LOF 6500 Additive Content in Asphalt Mix II as Function of Time using Litmus Test, Measured Additive Content vs. Actual Additive Content

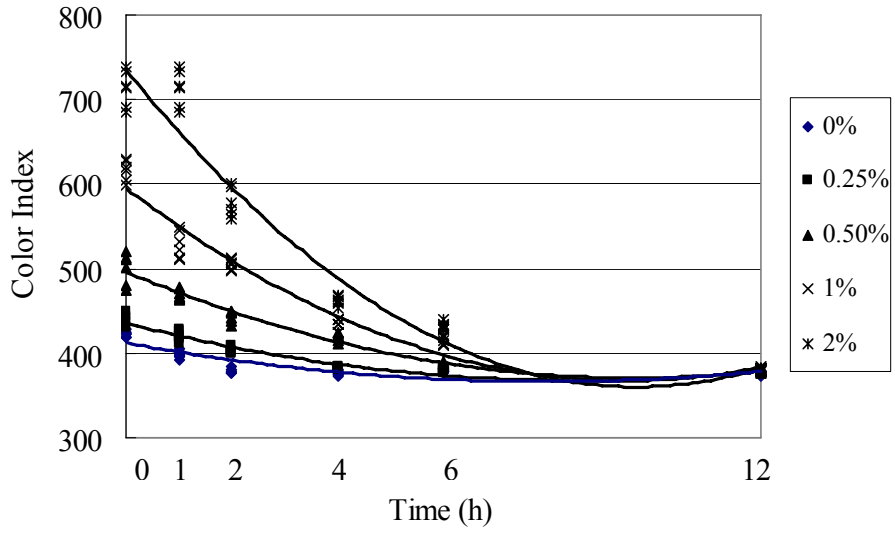


Figure 4-11 Decline of LOF 6500 Additive Content in Asphalt Mix II during Prolonged Heating Process using Litmus Test

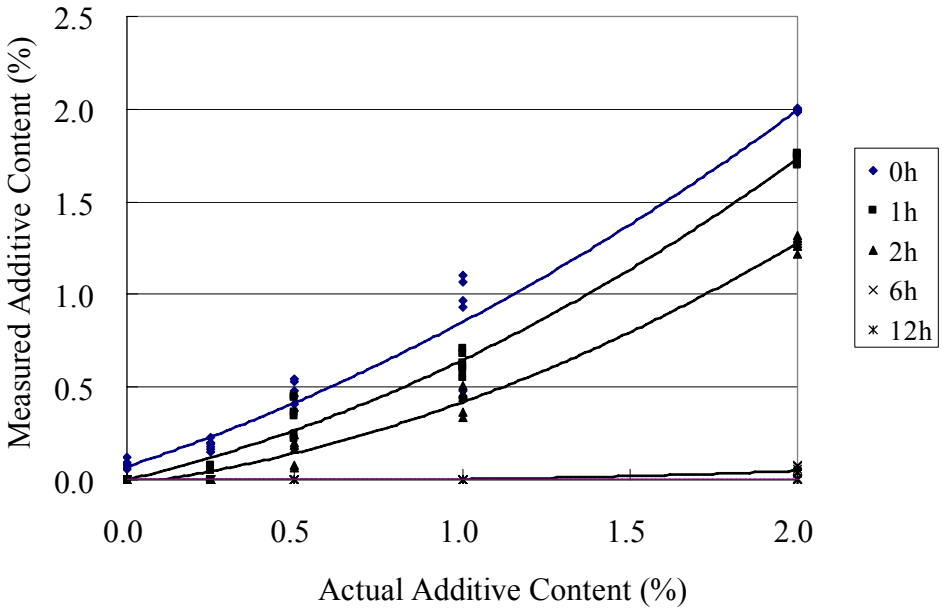


Figure 4-12 Measured Morlife 2200 Additive Content in Asphalt Mix II as Function of Time using Litmus Test, Measured Additive Content vs. Actual Additive Content

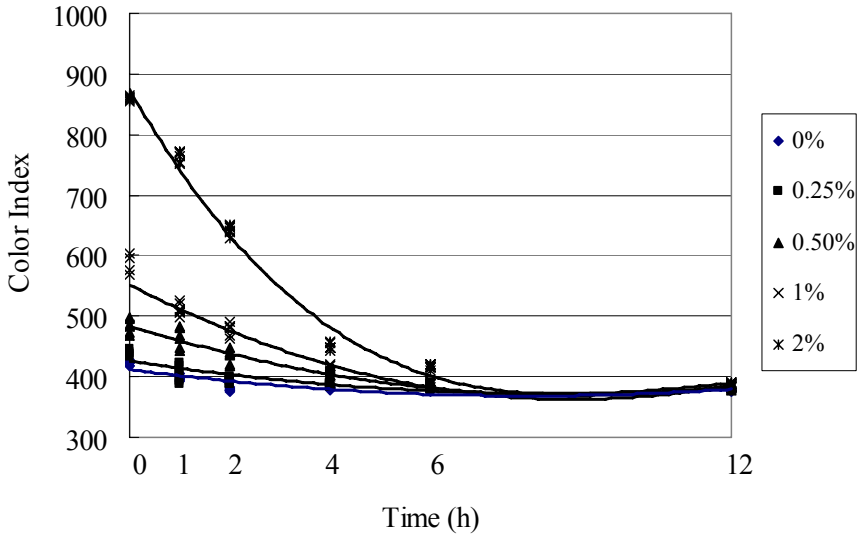


Figure 4-13 Decline of Morlife 2200 Additive Content in Asphalt Mix II during Prolonged Heating Process using Litmus Test

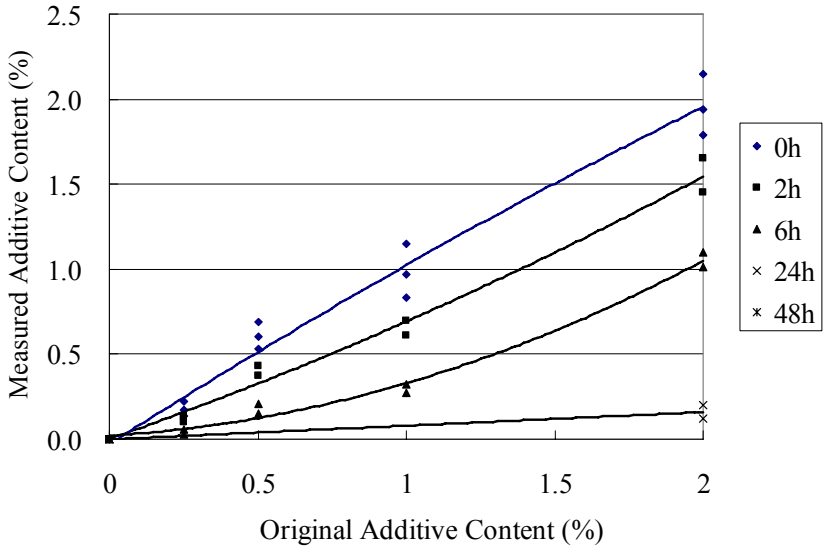


Figure 4-14 Measured LOF 6500 Additive Content in Asphalt Binder as Function of Time using Colorimetric Test, Absorbance vs. Original Additive Content

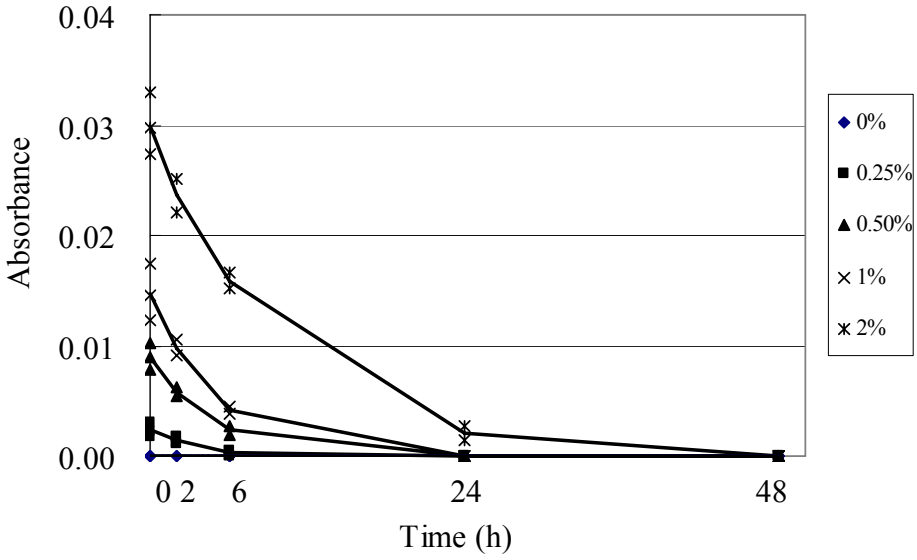


Figure 4-15 Decline of LOF 6500 Additive Content in Asphalt Binder during Prolonged Heating Process using Colorimetric Test

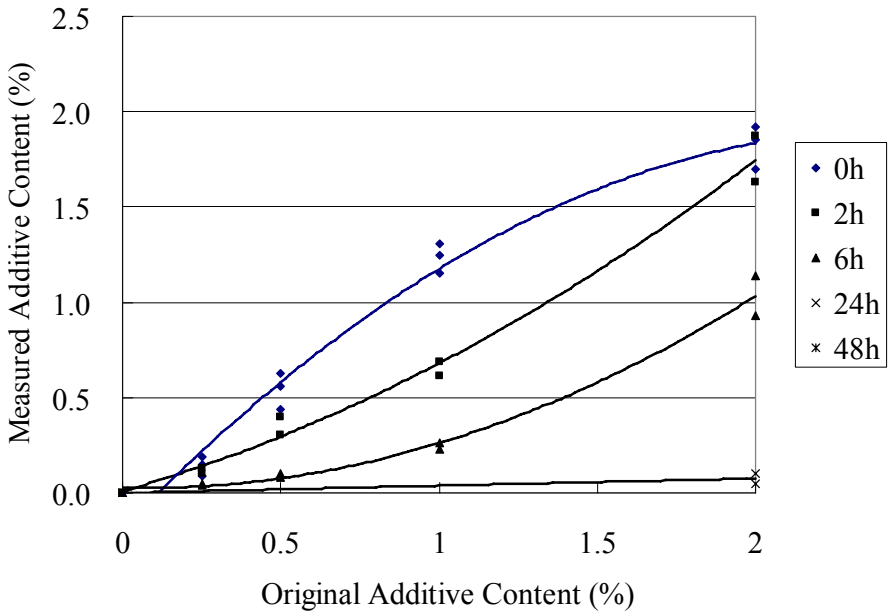


Figure 4-16 Measured Morlife 2200 Additive Content in Asphalt Binder as Function of Time using Colorimetric Test, Measured Additive Content vs. Original Additive Content

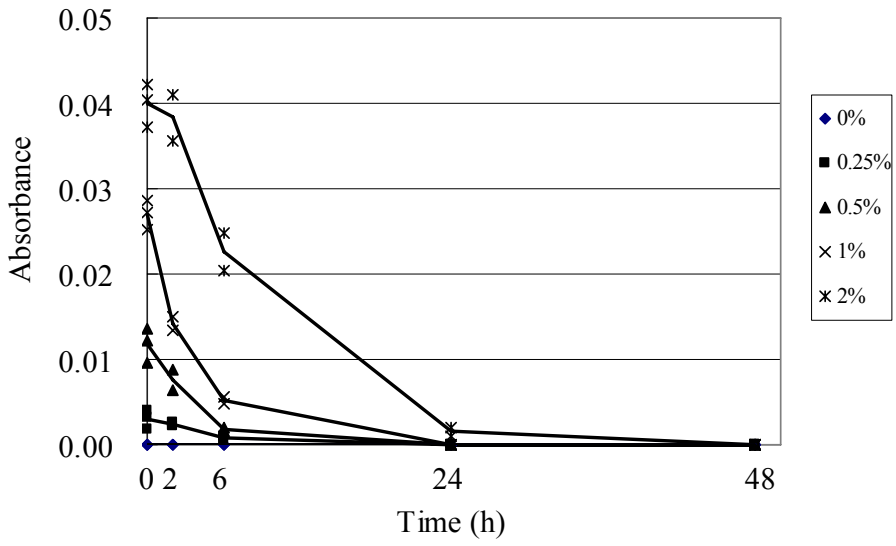


Figure 4-17 Decline of Morlife 2200 Additive Content in Asphalt Binder during Prolonged Heating Process using Colorimetric Test

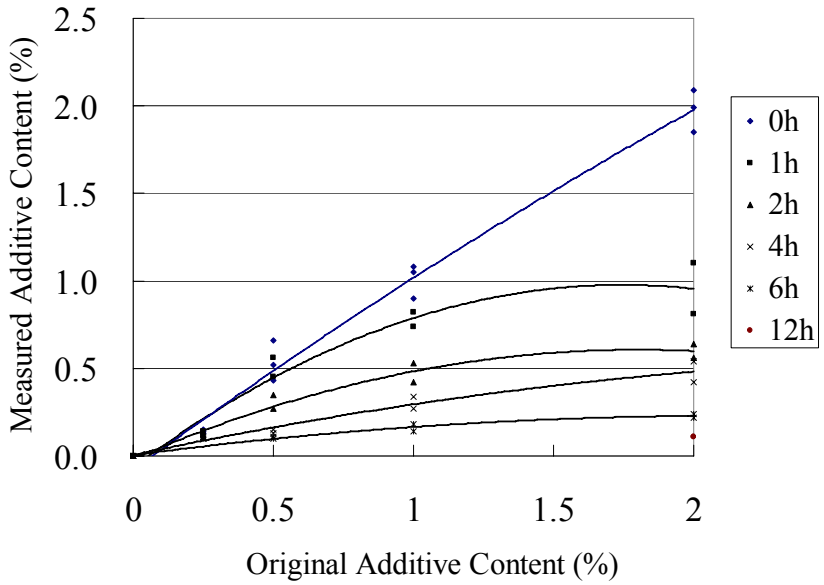


Figure 4-18 Measured LOF 6500 Additive Content in Asphalt Mix I as Function of Time using Colorimetric Test, Measured Additive Content vs. Original Additive Content

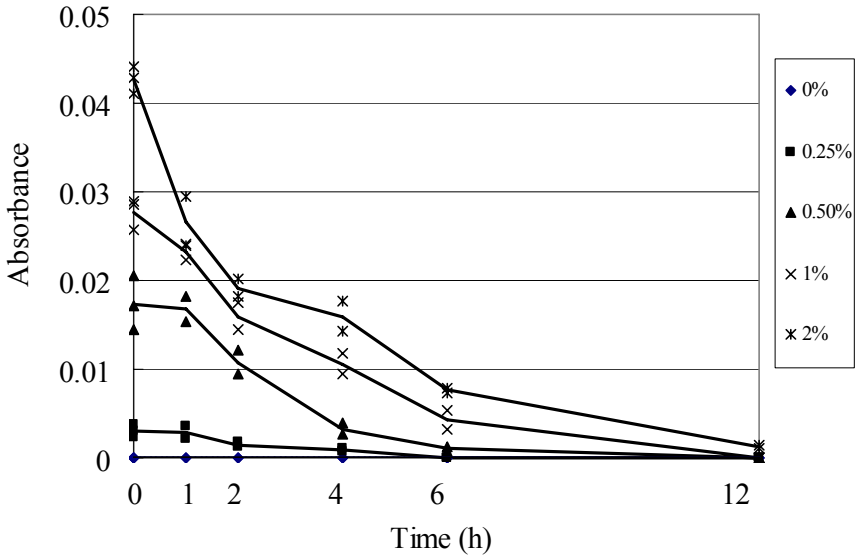


Figure 4-19 Decline of LOF 6500 Additive Content in Asphalt Mix I during Prolonged Heating Process using Colorimetric Test

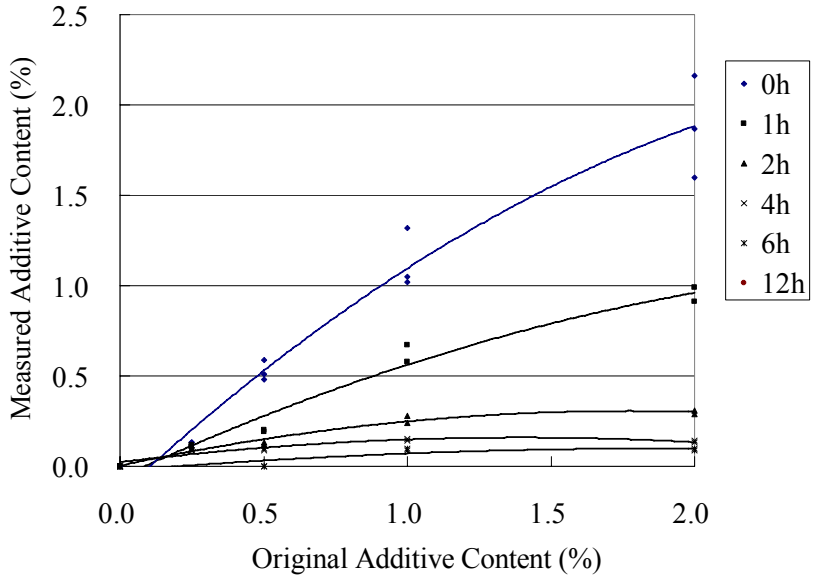


Figure 4-20 Measured Morlife 2200 Additive Content in Asphalt Mix I as Function of Time using Colorimetric Test, Measured Additive Content vs. Original Additive Content

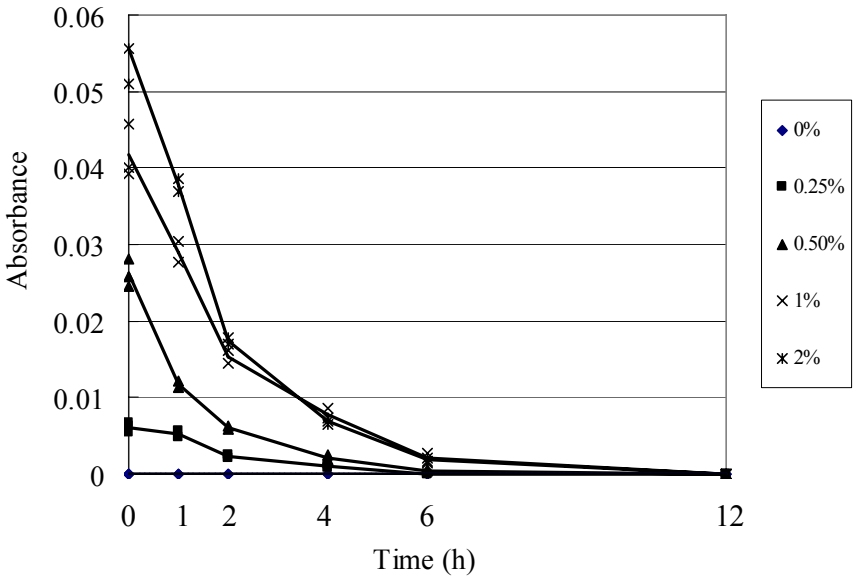


Figure 4-21 Decline of Morlife 2200 Additive Content in Asphalt Mix I during Prolonged Heating Process using Colorimetric Test

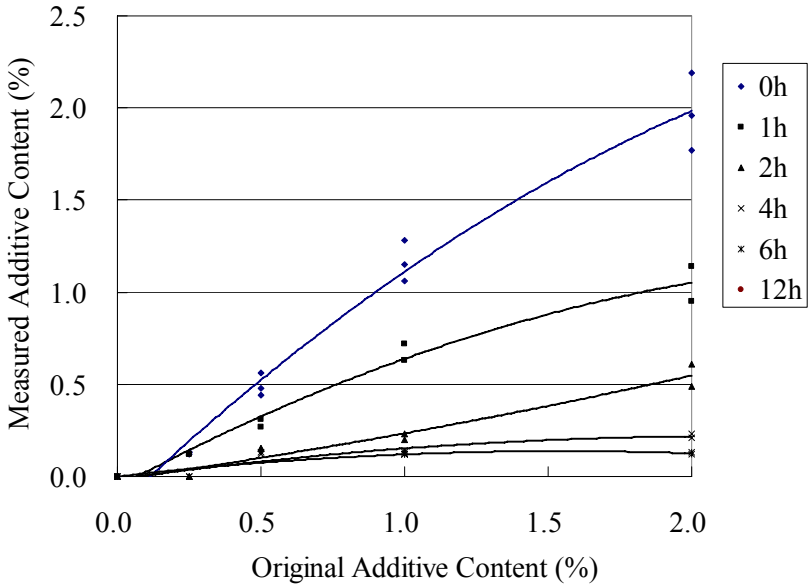


Figure 4-22 Measured LOF 6500 Additive Content in Asphalt Mix II as Function of Time using Colorimetric Test, Measured Additive Content vs. Original Additive Content

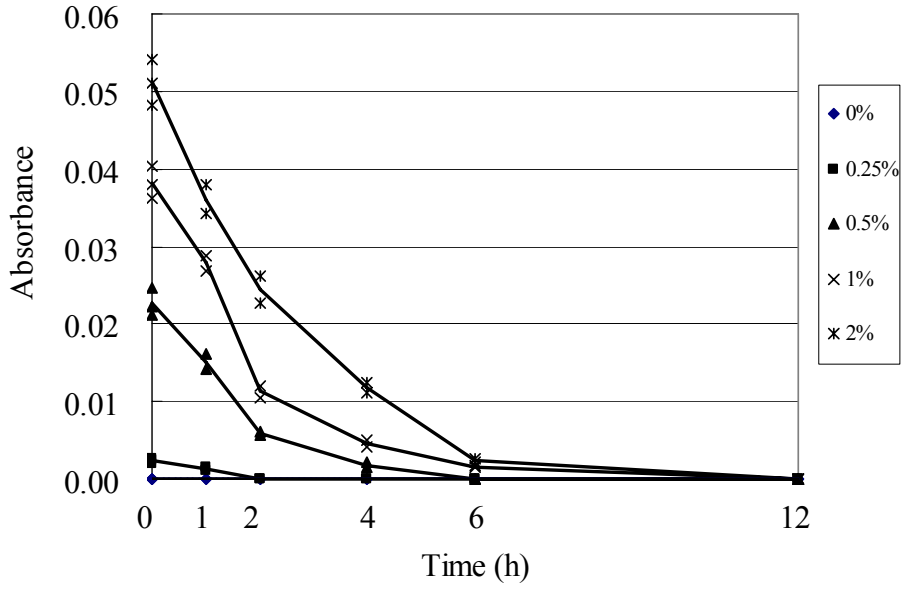


Figure 4-23 Decline of LOF 6500 Additive Content in Asphalt Mix II during Prolonged Heating Process using Colorimetric Test

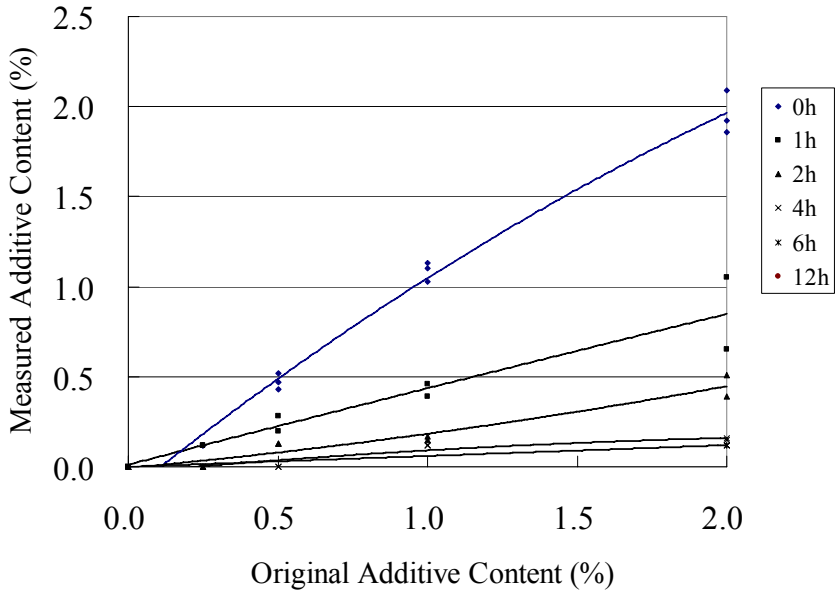


Figure 4-24 Measured Morlife 2200 Additive Content in Asphalt Mix II as Function of Time using Colorimetric Test, Measured Additive Content vs. Original Additive Content

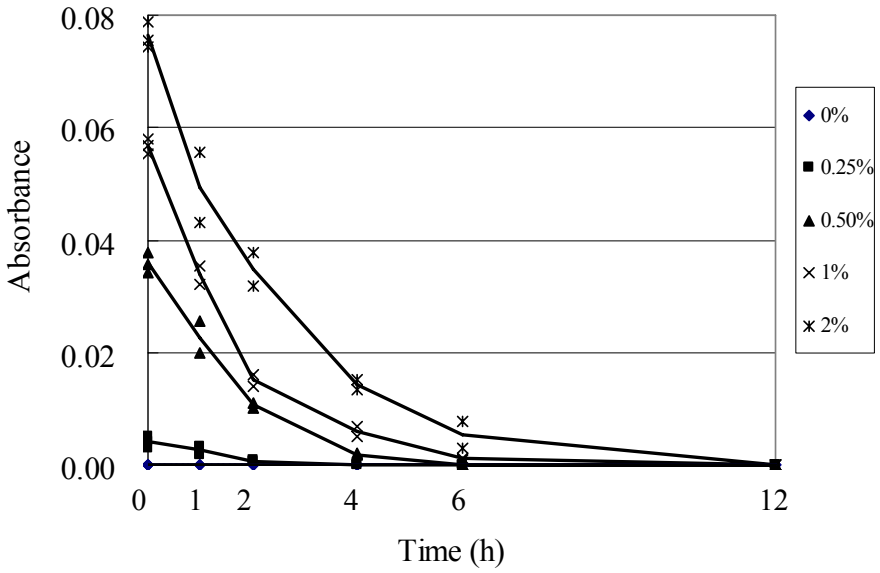


Figure 4-25 Decline of Morlife 2200 Additive Content in Asphalt Mix II during Prolonged Heating Process using Colorimetric Test

5. Evaluation of the Effect of Prolonged Heating on the Asphalt-Aggregate Adhesion Using Tensile Strength Ratio Test

5.1 Introduction

The adhesive bond strength between asphalt binder containing antistrip additive and aggregate was evaluated in this study using Tensile Strength Ratio (TSR) test method. On account of the substantial decrease of antistrip additive contents for both asphalt binders and mixes when subjected to prolonged heating, whether the loss of additive content due to storage and transport at elevated temperatures affects mix performance in terms of moisture sensitivity or not was evaluated in this study.

In this study, specimens were divided into two equal batches containing 0.8% LOF 6500 antistrip additive and Morlife 2200 antistrip additive in the asphalt respectively. Eight mixes of each batch were heated for 0, 2, 6, 12, 24 hours. Samples without antistrip additive were also produced to determine the effectiveness of the antistrip additive in preventing moisture damage.

5.2 Job-Mix-Formula Evaluation and Revision

5.2.1 Gradation revision

The asphalt binders and mixes used in this study were obtained from the NCDOT. A PG 76-22 asphalt binder was used for all mixes, which is different from previous mixes

used for litmus and colorimetric tests which used PG 64-22. A copy of the original JMF provided by NCDOT is attached as Appendix C.

The JMF had batching percentages for the three aggregate constituents, baghouse fines, asphalt and antistrip additive. The aggregate fractions were 34 percent 78-M stone, 18 percent #67 stone, and 48 percent washed screenings. For these three aggregate constituents, the material passing the #200 sieve was removed. The proportions of aggregate constituents and baghouse fines were adjusted a little to increase the #200 sieve percent passing from 4.8% to 6.5%, which would increase the moisture susceptibility of mixtures. The gradation data are shown in Table 5-1 and graduation curves are plotted in Figure 5-1.

5.2.2 Evaluation of volumetric properties

The volumetric properties of the laboratory mix were evaluated once the graduation was determined. The asphalt used in this JMF was a PG 76-22 produced by Conoco in Knoxville, TN. The design asphalt content was determined to be 5.6 percent by weight of the mix. The LOF 6500 antistrip additive was added to the asphalt cement at 0.8 percent by weight of the asphalt. The asphalt concrete was mixed in the laboratory at 163ºC and the maximum specific gravity was determined. Using AASHTO T 209 (Maximum Specific Gravity of Bituminous Paving Mixtures), the maximum specific gravity, G_{mm}, was found to be 2.530 compared to the G_{mm} of 2.520 for the JMF.

$$G_{mm} = \frac{A}{A - C}$$

Where:

A = mass of dry sample in air in grams

C = mass of water displaced by sample at 25ºC in grams

The quantity of each Superpave gyratory compactor (SGC) samples was calculated by use of experimental G_{mm} value. The target air voids of samples are 7% and compacted at 143ºC for testing.

5.3 Tensile Strength Ratio Testing

5.3.1 Sample preparation

The moisture susceptibility testing performed in this study followed the NCDOT modified AASHTO T 283 standard. This standard calls for sets of 6 to 8 specimens with a 150 mm diameter and a height of 95 mm. These specimens were compacted to a 7±1 percent air-void level; otherwise the sample would be discarded. The specimens were then divided into subsets with half being dry and the other half being moisture conditioned. The samples were conditioned in a 60ºC water bath until saturated between 50 and 80 percent. Once saturated, a Marshall indirect tensile test is performed on each specimen. The average tensile strength for each subset is then used to calculate the TSR value as shown below:

$$TSR = \frac{S_2}{S_1}$$

Where:

TSR=tensile strength ratio

S_1=average dry sample tensile strength

S_2=average conditioned sample tensile strength

After the TSR is calculated, it is compared to a minimum value to determine the level of moisture damage. The NCDOT acceptable minimum retained strength is 85 percent. Any mix that falls below this value is unsatisfactory and action must be taken to inhibit moisture damage. Two notable differences between the T-283 standard and the test performed by NCDOT is the number of specimens and the freeze-thaw cycle. NCDOT uses eight specimens per subset while T-283 requires six. The freeze-thaw cycle, which is optional in T-283, is not used by NCDOT.

Each specimen was mixed at 163ºC and subsequently aged for four hours at 65ºC following the NCDOT specifications. The mixes were then heated for two hours at 143ºC, after which they were compacted using a Superpave Gyratory Compactor. The compaction of each specimen was controlled by height of 95 mm. After the samples fully cool down to room temperature, the bulk specific gravity of specimen was measured by AASHTO T 166 Saturated Surface Dry (SSD) method (Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens).

$$G_{mb} = \frac{A}{B - C}$$

Where:

A = dry weight

B = SSD weight

C = submerged weight

Then air voids of samples were calculated.

$$Percent\ Air\ Voids = 100\ (G_{mm} - G_{mb})/G_{mm}$$

5.3.2 Test results and analysis

Total of 88 specimens were prepared and delivered to NCDOT for conditioning and testing. Out off the 88 specimens, 8 specimens were prepared based on the TSR sample procedure. The samples were prepared with pure asphalt (without adding antistrip additive). Following the NCDOT specifications the samples were mixed at 163ºC and subsequently aged for four hours at 65ºC. These mixes were then heated for two hours at 143ºC, after which they were compacted using a Superpave Gyratory Compactor. The air voids data of these eight samples are shown in Table 5-2. The remaining 80 specimens divided into two equal batches containing 0.8% LOF 6500 and Morlife 2200 antistrip additives in the asphalt binders respectively. Eight specimens of each batch were heated for 0, 2, 6, 12, 24 hours at 143ºC respectively. The air voids data of LOF 6500 samples and Morlife 2200 samples are shown in Table 5-3 and Table 5-4.

The TSR test results of these 88 specimens are tabulated in Table 5-5 through Table 5-15. Table 5-5 shows the TSR test results for specimens prepared with asphalt without any antistrip additive, using NCDOT modified T283 method. The TSR value is obtained to be 71.1%. Table 5-6 to Table 5-10 show TSR test results of asphalt mixes containing 0.8% of LOF 6500 (8 samples each), heated for the duration of 0, 2, 6, 12, 24 hours respectively. The TSR values are 84.1%, 90.9%, 83.1%, 77.2%, 76.3% respectively. Table 5-11 to Table 5-15 show TSR test results of asphalt mixes containing 0.8% of Morlife 2200 (8 samples each), heated for the duration of 0, 2, 6, 12, 24 hours respectively. The TSR values are 88.0%, 85.4%, 79.8%, 79.3%, 67.4% respectively. The TSR values of asphalt mixes increased from 71.1% to 90.9 and 85.4% for LOF 6500 and

Morlife 2200 antistrip additives respectively and are higher than NCDOT standard mixture TSR value. In the first 2-hour heating, the TSR values remained at a very high level but after that, the TSR values reduced. Based on the finding in Chapter 4, no antistrip additive content was detectable in asphalt mix after 6 to 12 hours of extended heating. In this test, after 12 hours of prolonged heating, the TSR values of mixes with LOF 6500 and Morlife 2200 antistrip additives are 77.2% and 79.3%, respectively. These values are slightly higher than TSR value of specimens with no additive, which is 71.1%. After 24-hour prolonged heating, the TSR values of mixes with LOF 6500 and Morlife 2200 antistrip additives are 76.3% and 67.4%, which are similar to or lower than TSR value obtained without additive.

The declining trend of the curve plotted between TSR test results vs. prolonged heating are shown in Figure 5-2 to Figure 5-4. The raw data of TSR test are shown in Appendix C.

5.4 Discussion of Test Results

From the TSR test results, the improvement of moisture sensitivity using amine based antistrip additive was lost to a great extent after prolonged heating. It is obvious that after only 6-hour heating, TSR values drop to about 80% for both LOF 6500 and Morlife 2200 antistrip additives, which are below the NCDOT standard value. Considering storage and transport as well as the duration between production and its ultimate paving in the field, this situation is very serious and needs due attention by NCDOT.

As shown in Figure 4-1 in the previous chapter, Morlife 2200 antistrip additive is more volatile as compared to LOF 6500 antistrip additive. After 24 hours, the mass loss for antistrip additives LOF 6500 and Morlife 2200 is roughly 25 and 45 percent, respectively. TSR test results show that the remained higher molecular weight fraction of antistrip additive after prolonged heating has reduced effect on adhesion between asphalt and aggregate. The chemical change that occurs during the heating process of amine based antistrip additive is a very important factor that affects the improvement of asphalt-aggregate adhesion.

It should be noted that two types of amine based antistrip additives, one level of antistrip additive content and one graduation of asphalt mix were used in this study. For further confirmation, more mixes, different organic antistrip additives and dosages are recommended for testing. Moreover, other test methods to evaluate moisture sensitivity of asphalt-aggregate mixes are recommended to verify the findings in future research.

Table 5-1 Gradations for Original JMF and Revised Lab Test

Sieves (mm)	Percent Passing		Control Points
	JMF Batching	Revision	
37.5	100.0	100.0	
25	99.8	99.9	
19	98.2	98.5	100.0
12.5	90.1	91.7	90.0-100.0
9.5	82.3	85.0	<90.0
4.75	59.3	63.3	
2.36	44.9	49.1	28.0-58.0
1.18	31.9	35.5	
0.6	22.4	25.4	
0.3	13.7	16.0	
0.15	7.6	9.7	
0.075	4.8	6.5	4.0-8.0

Table 5-2 Air Voids Data of Non-Additive Samples

Sample ID*	Weight in air (g)	Weight in water (g)	SSD (g)	BSG	Air Voids (%)	Water Absorbed (%)
N00-2-1	3932.4	2277.6	3952.7	2.348	7.2	1.2
N00-2-2	3941.0	2276.5	3955.4	2.347	7.2	0.9
N00-2-3	3941.2	2277.6	3956.4	2.348	7.2	0.9
N00-2-4	3942.3	2282.0	3958.3	2.352	7.0	1.0
N00-2-5	3942.0	2284.0	3959.6	2.353	7.0	1.1
N00-2-6	3929.6	2280.6	3950.8	2.353	7.0	1.3
N00-2-7	3943.4	2275.2	3953.8	2.349	7.1	0.6
N00-2-8	3941.2	2279.2	3957.2	2.349	7.2	1.0

Table 5-3 Air Voids Data of LOF 6500 Additive Samples

Sample ID	Weight in air (g)	Weight in water (g)	SSD (g)	BSG	Air Voids (%)	Water Absorbed (%)
L08-0-1	3911.5	2257.9	3928.2	2.342	7.4	1.0
L08-0-2	3929.5	2267.8	3949.0	2.337	7.6	1.2
L08-0-3	3924.7	2274.6	3946.8	2.347	7.2	1.3
L08-0-4	3938.9	2281.7	3955.7	2.353	7.0	1.0
L08-0-5	3940.5	2277.1	3956.5	2.346	7.3	1.0
L08-0-6	3942.9	2276.4	3962.1	2.339	7.5	1.1
L08-0-7	3939.5	2286.1	3958.5	2.356	6.9	1.1
L08-0-8	3934.4	2284.2	3961.2	2.346	7.3	1.6
L08-2-1	3928.3	2263.1	3945.7	2.335	7.7	1.0
L08-2-2	3942.9	2290.2	3954.3	2.369	6.3	0.7
L08-2-3	3942.7	2293.0	3955.7	2.371	6.3	0.8
L08-2-4	3913.2	2260.2	3927.4	2.347	7.2	0.9
L08-2-5	3905.1	2238.3	3913.3	2.331	7.8	0.5
L08-2-6	3933.0	2272.4	3949.4	2.345	7.3	1.0
L08-2-7	3930.5	2269.9	3940.2	2.353	7.0	0.6
L08-2-8	3919.0	2272.9	3944.5	2.344	7.3	1.5
L08-6-1	3933.7	2267.9	3945.9	2.344	7.3	0.7
L08-6-2	3928.9	2266.2	3942.1	2.344	7.3	0.8
L08-6-3	3943.6	2275.7	3955.6	2.348	7.2	0.7
L08-6-4	3939.1	2273.9	3954.1	2.344	7.3	0.9
L08-6-5	3941.7	2277.1	3954.8	2.349	7.1	0.8
L08-6-6	3936.8	2269.3	3946.8	2.347	7.2	0.6
L08-6-7	3934.9	2274.2	3952.5	2.345	7.3	1.0
L08-6-8	3933.1	2267.5	3946.1	2.343	7.4	0.8
L08-12-1	3908.4	2255.9	3919.8	2.349	7.2	0.7
L08-12-2	3913.0	2265.8	3930.2	2.351	7.1	1.0
L08-12-3	3929.0	2277.2	3936.5	2.368	6.4	0.5
L08-12-4	3949.8	2297.1	3962.1	2.372	6.2	0.7
L08-12-5	3927.7	2275.9	3936.3	2.366	6.5	0.5
L08-12-6	3935.9	2267.0	3946.0	2.344	7.3	0.6
L08-12-7	3934.5	2268.2	3941.7	2.351	7.1	0.4
L08-12-8	3941.6	2291.3	3965.7	2.354	7.0	1.4
L08-24-1	3934.7	2263.5	3946.3	2.338	7.6	0.7
L08-24-2	3934.5	2264.8	3947.6	2.338	7.6	0.8
L08-24-3	3935.1	2267.3	3949.2	2.340	7.5	0.8
L08-24-4	3944.9	2264.9	3952.5	2.338	7.6	0.5
L08-24-5	3940.3	2267.3	3953.4	2.337	7.6	0.8
L08-24-6	3946.3	2273.6	3957.3	2.344	7.4	0.7
L08-24-7	3939.6	2268.9	3952.1	2.341	7.5	0.7
L08-24-8	3938.3	2267.5	3950.8	2.340	7.5	0.7

Table 5-4 Air Voids Data of Morlife 2200 Additive Samples

Sample ID	Weight in air (g)	Weight in water (g)	SSD (g)	BSG	Air Voids (%)	Water Absorbed (%)
M08-0-1	3945.2	2277.7	3956.0	2.351	7.1	0.6
M08-0-2	3936.9	2269.4	3947.1	2.347	7.2	0.6
M08-0-3	3941.2	2267.5	3949.6	2.343	7.4	0.5
M08-0-4	3937.5	2266.7	3947.6	2.342	7.4	0.6
M08-0-5	3911.1	2244.5	3921.4	2.332	7.8	0.6
M08-0-6	3941.7	2275.1	3952.4	2.350	7.1	0.6
M08-0-7	3911.0	2249.4	3924.4	2.335	7.7	0.8
M08-0-8	3943.5	2273.8	3952.9	2.349	7.2	0.6
M08-2-1	3936.1	2273.4	3945.4	2.354	7.0	0.6
M08-2-2	3920.5	2259.1	3934.8	2.340	7.5	0.9
M08-2-3	3921.4	2260.9	3935.6	2.342	7.4	0.8
M08-2-4	3940.5	2281.3	3955.2	2.354	7.0	0.9
M08-2-5	3917.7	2252.2	3928.0	2.338	7.6	0.6
M08-2-6	3935.8	2282.4	3951.6	2.358	6.8	0.9
M08-2-7	3928.0	2274.3	3944.8	2.351	7.1	1.0
M08-2-8	3943.1	2278.3	3954.7	2.352	7.0	0.7
M08-6-1	3940.3	2270.6	3950.7	2.345	7.3	0.6
M08-6-2	3942.4	2266.5	3953.0	2.338	7.6	0.6
M08-6-3	3939.6	2267.4	3950.7	2.340	7.5	0.7
M08-6-4	3936.9	2266.6	3950.3	2.338	7.6	0.8
M08-6-5	3938.3	2266.5	3951.3	2.338	7.6	0.8
M08-6-6	3916.8	2249.4	3930.7	2.330	7.9	0.8
M08-6-7	3928.8	2258.5	3941.0	2.335	7.7	0.7
M08-6-8	3936.4	2268.9	3950.1	2.341	7.5	0.8
M08-12-1	3937.1	2274.1	3946.1	2.355	6.9	0.5
M08-12-2	3932.5	2262.3	3939.3	2.345	7.3	0.4
M08-12-3	3939.5	2273.8	3948.7	2.352	7.0	0.5
M08-12-4	3937.3	2271.2	3945.5	2.352	7.1	0.5
M08-12-5	3939.8	2272.8	3946.3	2.354	6.9	0.4
M08-12-6	3928.9	2269.7	3942.4	2.349	7.2	0.8
M08-12-7	3934.6	2277.8	3947.2	2.357	6.8	0.8
M08-12-8	3934.7	2269.0	3940.1	2.355	6.9	0.3
M08-24-1	3937.4	2258.7	3946.4	2.333	7.8	0.5
M08-24-2	3945.2	2262.5	3956.2	2.329	7.9	0.6
M08-24-3	3917.9	2247.6	3926.3	2.334	7.8	0.5
M08-24-4	3936.5	2264.6	3947.2	2.340	7.5	0.6
M08-24-5	3948.2	2268.7	3963.5	2.330	7.9	0.9
M08-24-6	3940.6	2256.3	3948.6	2.329	8.0	0.5
M08-24-7	3924.6	2252.3	3935.7	2.331	7.9	0.7
M08-24-8	3934.9	2257.9	3942.8	2.335	7.7	0.5

Table 5-5 TSR Test Results: None Additive in Asphalt with 2-Hour Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
N00-2-4	7.0	1397.0	1509.3	N00-2-1	7.2	1052.2	1072.6
N00-2-5	7.0	1522.4		N00-2-2	7.2	1069.9	
N00-2-6	7.0	1516.7		N00-2-3	7.2	1075.4	
N00-2-7	7.1	1501.8		N00-2-8	7.2	1131.8	
Tensile Strength Ratio (%)				**71.1**			

Table 5-6 TSR Test Results: 0.8% LOF Additive in Asphalt without Prolonged Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
L08-0-4	7.0	1023.5	991.8	L08-0-1	7.4	791.4	833.8
L08-0-5	7.3	1008.0		L08-0-2	7.6	819.6	
L08-0-6	7.5	937.8		L08-0-3	7.2	936.3	
L08-0-8	7.3	975.7		L08-0-7	6.9	847.9	
Tensile Strength Ratio (%)				**84.1**			

Table 5-7 TSR Test Results: 0.8% LOF Additive in Asphalt with 2-Hour Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
L08-2-4	7.2	1370.4	1289.3	L08-2-1	7.7	1078.7	1171.4
L08-2-5	7.8	1208.2		L08-2-2	6.3	1210.1	
L08-2-7	7.0	1386.6		L08-2-3	6.3	1191.0	
L08-2-8	7.3	1204.4		L08-2-6	7.3	1151.8	
Tensile Strength Ratio (%)				**90.9**			

Table 5-8 TSR Test Results: 0.8% LOF Additive in Asphalt with 6-Hour Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
L08-6-4	7.2	1541.3	1544.3	L08-6-1	7.3	1285.2	1283.8
L08-6-5	7.1	1547.3		L08-6-2	7.3	1252.9	
L08-6-7	7.2	1551.3		L08-6-3	7.3	1323.2	
L08-6-8	7.4	1450.1		L08-6-6	7.3	1282.5	
Tensile Strength Ratio (%)				**83.1**			

Table 5-9 TSR Test Results: 0.8% LOF Additive in Asphalt with 12-Hour Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
L08-12-2	7.1	1975.3	1925.8	L08-12-1	7.2	1457.7	1487.7
L08-12-5	6.5	1981.5		L08-12-3	6.4	1478.5	
L08-12-7	7.1	1876.4		L08-12-4	6.2	1705.7	
L08-12-8	7.0	1818.9		L08-12-6	7.3	1496.9	
Tensile Strength Ratio (%)				**77.2**			

Table 5-10 TSR Test Results: 0.8% LOF Additive in Asphalt with 24-Hour Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
L08-24-5	7.6	1189.2	1212.7	L08-24-1	7.6	955.7	925.7
L08-24-6	7.4	1078.4		L08-24-2	7.6	899.5	
L08-24-7	7.5	1298.5		L08-24-3	7.5	839.3	
L08-24-8	7.5	1236.2		L08-24-4	7.6	915.9	
Tensile Strength Ratio (%)				**76.3**			

Table 5-11 TSR Test Results: 0.8% Morlife Additive in Asphalt without Prolonged Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
M08-0-2	7.2	884.2	882.4	M08-0-1	7.1	816.9	776.6
M08-0-3	7.4	880.5		M08-0-2	7.4	755.7	
M08-0-7	7.7	844.4		M08-0-5	7.8	739.1	
M08-0-8	7.2	884.2		M08-0-6	7.1	797.4	
Tensile Strength Ratio (%)				**88.0**			

Table 5-12 TSR Test Results: 0.8% Morlife Additive in Asphalt with 2-Hour Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
M08-2-5	7.6	1196.2	1255.7	M08-2-1	7.0	1083.1	1072.6
M08-2-6	6.8	1283.8		M08-2-2	7.5	1026.7	
M08-2-7	7.1	1265.2		M08-2-3	7.4	1062.1	
M08-2-8	7.0	1246.2		M08-2-4	7.0	1154.3	
Tensile Strength Ratio (%)				**85.4**			

Table 5-13 TSR Test Results: 0.8% Morlife Additive in Asphalt with 6-Hour Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
M08-6-5	7.6	1444.1	1461.1	M08-6-1	7.3	1232.7	1166.3
M08-6-6	7.9	1429.4		M08-6-2	7.6	1119.9	
M08-6-7	7.7	1521.1		M08-6-3	7.5	1136.4	
M08-6-8	7.5	1478.1		M08-6-4	7.6	1196.2	
Tensile Strength Ratio (%)				**79.8**			

Table 5-14 TSR Test Results: 0.8% Morlife Additive in Asphalt with 12-Hour Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
M08-12-4	7.1	1829.1	1813.2	M08-12-1	6.9	1366.1	1438.4
M08-12-6	7.2	1778.4		M08-12-2	7.3	1397.0	
M08-12-7	6.8	1826.5		M08-12-3	7.0	1479.7	
M08-12-8	6.9	1799.9		M08-12-5	6.9	1531.6	
Tensile Strength Ratio (%)				**79.3**			

Table 5-15 TSR Test Results: 0.8% Morlife Additive in Asphalt with 24-Hour Heating

Unconditioned Specimens				Conditioned Specimens			
Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)	Sample ID	Air Voids (%)	Tensile Strength	Mean Tensile Strength (lb)
M08-24-5	7.9	1346.7	884.6	M08-24-1	7.8	412.0	596.2
M08-24-6	8.0	938.4		M08-24-2	7.9	745.4	
M08-24-7	7.9	830.8		M08-24-3	7.8	447.0	
M08-24-8	7.7	714.4		M08-24-4	7.5	1021.4	
Tensile Strength Ratio (%)				**67.4**			

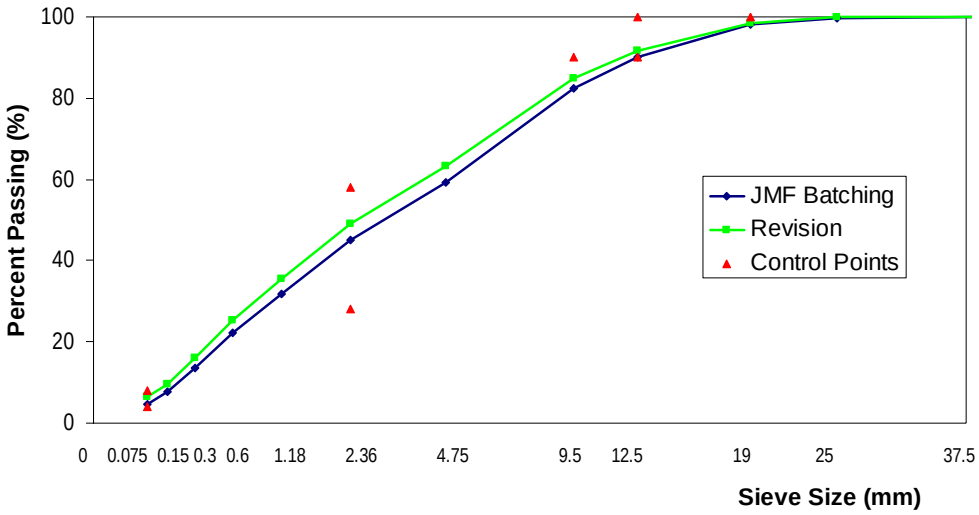


Figure 5-1 Gradation Curves for Original JMF and Revised Lab Test

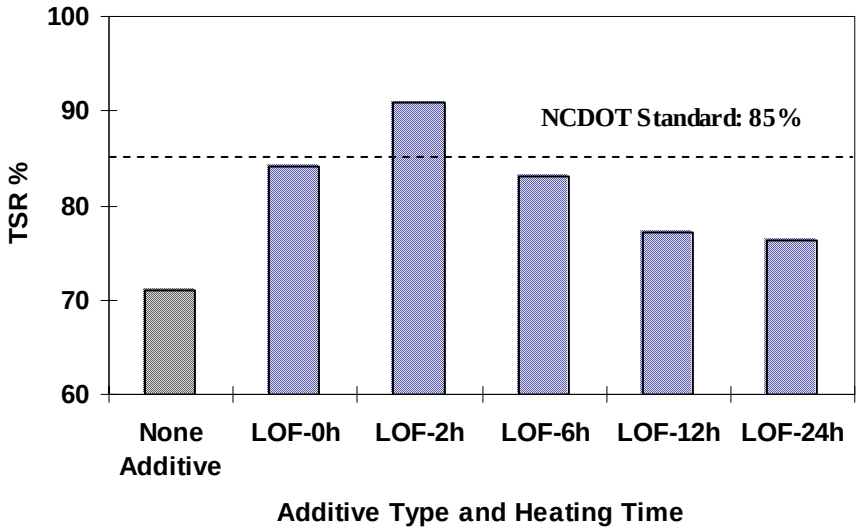


Figure 5-2 TSR Values of Non-Additive and 0.8% LOF Additive

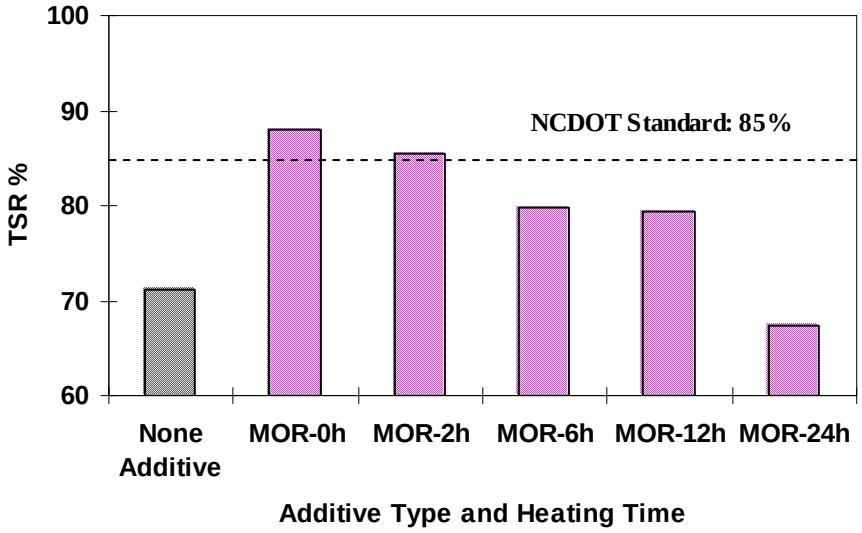


Figure 5-3 TSR Values of Non-Additive and 0.8% Morlife Additive

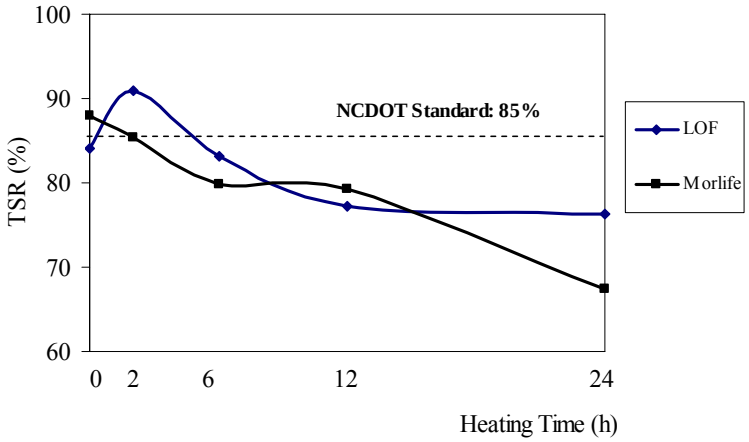


Figure 5-4 Declination of TSR Results with Prolonged Heating

*Specimen Nomenclature

In order to keep track of the large number of samples produced and tested throughout this study, the following specimen designation system was developed. The names of the subsets had 4 characters describing the type of antistrip additive, percentage of antistrip additive content, prolonged heating time and quantity of specimens. A list of the terms and meanings follows:

First Character – Testing type

L – LOF 6500 additive

M – Morlife 2200 additive

N – None additive

Second Character – Percentage of antistrip additive content

00 – none antistrip additive added to asphalt binder

08 – 0.8% antistrip additive added to asphalt binder

Third Character – Prolonged heating time

12 – 12 hours prolonged heating

Fourth Character – Quantity of specimens

6. Future Research Need for Evaluating Adhesive Bond Strength between Asphalt and Aggregate after Prolonged Heating

In previous chapter, TSR testing was conducted to evaluate asphalt-aggregate adhesion and the fact that the improvement of moisture sensitivity by use of amine based antistrip additive was lost to a great extent after prolonged heating was found. In this chapter, some other test methods are recommended to evaluate adhesive bond strength between asphalt and aggregate for further verification in the future research.

6.1 Theoretical background of Contact angle method

Contact angles (θ) offer an easy-to-measure indication of the chemical bonding of the uppermost surface layers of a solid. This bonding determines adhesion and also allows prediction of coating properties and detection of trace surface contaminants. In a theoretical approach, surface energy values can be calculated from contact angle data, or an empirical approach can be taken and dealt only with contact angles. Contact angle is a quantitative measure of the wetting of a solid by a liquid. It is the angle formed by the liquid at the three phase boundary where a liquid, gas and solid intersect. It is a direct measure of interactions taking place between the participating phases.

Contact angle technique has developed in recent years by combination use of other advanced devices. Chang [42] developed a combined acoustic emission/poker chip test to measure the mechanical behavior of, and cavitation in, asphalt thin films and developed a laser contact angle goniometry technique and a modified blister test to

characterize, respectively, the asphalt surfaces and the adhesive strength between asphalt and aggregate surfaces. Cheng et.al [43] used universal gas adsorption and the Wilhelmy plate methods to measure surface free energies of aggregate and asphalt respectively to predict moisture damage potential. Drelich et. al [44] measured surface tension values for toluene-extracted bitumens with the Wilhelmy plate and contact angle techniques. Jada et. al [45] analyse the acid-base interactions at the water-bitumen interface for substrates having various asphaltenes and resins contents by contact angles. Eustathopoulos et.al [46] reviewed measurement of contact angle and work of adhesion at high temperature.

The shape of the drop and the magnitude of the contact angle are controlled by three interaction forces of interfacial tension of each participating phase (gas, liquid and solid). In an ideal situation the relation between these forces and the contact angle can be described by the Young's equation: $\gamma_{LV} \cos\theta = \gamma_{SV} - \gamma_{SL}$ (see Figure 6-1) and is often also referred to as Young's contact angle. γ_{SV} and γ_{LV} describe the surface tension components of the two phases; symbol γ_{SL} represents the interfacial tension between the two phases, and θ stands for the contact angle corresponding to the angle between vectors γ_{LV} and γ_{SL}. The work of adhesion is expressed as Young - Dupree equation:

$$Wa = \gamma_{LV}(1+\cos\theta) \qquad \text{Eq. (6.1)}$$

In this contact angle test, in order to simplify studying the effect of antistrip additive on asphalt-aggregate interaction, the element of water immersion is not considered. The basic contact angles at high temperature are used to evaluate this performance. It should be noted that this contact angle value is static, which is different

with usually used Wilhelmy plate method. The development of contact angle goniometer and image identification technologies make small contact angle discernable.

6.2 Contact Angle Test Overview and Preliminary Test Results

Contact angle goniometer is installed in this semester and contact angle test was tried in this quarter. The contact angle goniometer consists of light source, camera, microscope, etc. A computer is used to dispose the captured image and calculate the contact angle value automatically. Contact angle goniometer should be revised so that it can measure contact angle at mixing temperature to simulate actual situation as possible. In this test, environmental chamber and elevated temperature syringe chamber are used to maintain the specific temperature. A glass or aggregate plate which can be heated and maintained at high temperature will be used as solid phase. The sketch and real contact angle goniometer are shown in Figure 6-2 and 6-3.

Various tests have been conducted to determine the contact angle of water, anti-strip additive (LOF 6500 and Morlife 2200) and asphalt with respect to the glass slide and quartz slide. A brief summary of the procedure followed in order to determine the contact angle is described as follows. It is noted that the contact angle of water is determined at 25° C and for asphalt and anti-strip additive the temperature of the environmental chamber was maintained at 135° C.

1) The designated temperature (as mentioned above) in the environmental chamber and the micro-syringe chamber are controlled during the test process.

2) The micro-syringe was used to place a drop over the slide (quartz/glass). The quantity of the droplet was controlled by the micro-syringe. The quantity of the asphalt droplet was 0.01 ml and the water and anti-strip additive droplet was 0.02 ml.
3) The slide was placed inside the environmental chamber. It was left for 15 minutes for the balance of temperature.
4) The platform was checked for the horizontality. To obtain this condition, the tilt of the platform was set to zero.
5) The contact angle of the liquid with respect to the slide was measured automatically with the help of the DROPimage software.

The captured pictures of water droplet on quartz and glass slides measured at 25°C are shown in Figure 6-4 and 6-5. The contact angle values are 36.2^{o} and 61.1^{o} respectively. The contact angle value for water-glass is in good correlation with the values observed in the published papers [46, 47]. The captured pictures of asphalt droplet on quartz and glass slides at 135°C are shown in Figure 6-6 and 6-7. The contact angle value is 8.2^{o} for asphalt droplet on glass slide, but it is too small to be measured for asphalt droplet on quartz slide.

6.3 Introduction of Other Test Methods

6.3.1 Pull-off Test

The pneumatic adhesion tensile testing instrument (PATTI) was developed by the National Institute of Standards and Technology (NIST) and its use has been standardized

as ASTM test method D4541 “Pull-off Strength of Coatings Using Portable Adhesion Tester.”[49] The main features of this device include a portable pneumatic adhesion tester, a pressure hose, a piston, and a metal wing-pull stub as a loading fixture. Youtcheff [50] has used PATTI device to evaluate moisture sensitivity of asphalt binders using adhesive loss of asphalt-aggregate systems exposed to water. The adhesion of asphalt binders has also been evaluated by Kanitpong and Bahia [51] using a modified PATTI device (schematic shown in Figure 6-8). The tensile and bonding strength of asphalt binder applied to a solid surface was measured as a function of duration of moisture conditioning. In this test asphalt binder is applied to a pull stub, which is then pressed onto the solid surface. The pressure required to pull the stub from the surface is the measured adhesive bond. The PATTI device is a low cost, simple, and well described test method. The PATTI is therefore considered as a good test for measuring adhesive characteristic before and after water conditioning.

6.3.2 Atomic Force Microscopy Test

Atomic force microscope (AFM) is an instrument used for studying surface properties of materials at the atomic to micron level. The AFM may be used to image surfaces at atomic resolution as well as to measure forces at nano-newton scale. Figure 6-9 shows a schematic of the AFM. Forces between the tip and the sample surface cause the cantilever to bend, or deflect. A detector in the AFM head measures the cantilever deflection as the tip scans the surface of the sample. The force commonly associated with AFM is the van der Waals' forces. A computer generates a map of the surface topography from the measured cantilever deflection. Information on atomic- and molecular-scale

interactions as well as nano-scale adhesive and elastic response is provided by AFM force measurements.

The Western Research Institute (WRI) has reported use of Atomic Force Microscopy to develop quantifiable images of asphalts and asphalt with additives [52] and their adhesive properties with aggregate at interfacial region. Loeber et. al [53] has reported that the structure of asphalts can be studied without any pre-preparation with AFM. Abraham et. al [18] has also reported use of AFM to directly measure the interaction between asphaltenes and silica surfaces in aqueous solutions. The electrokinetic properties of these surfaces were determined to establish a link between conventional electrokinetic studies and AFM results.

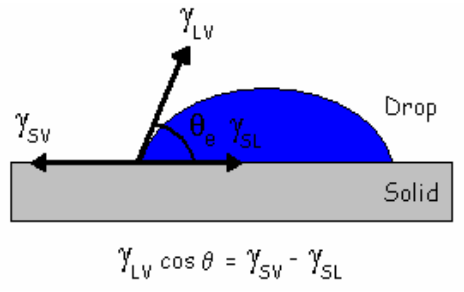
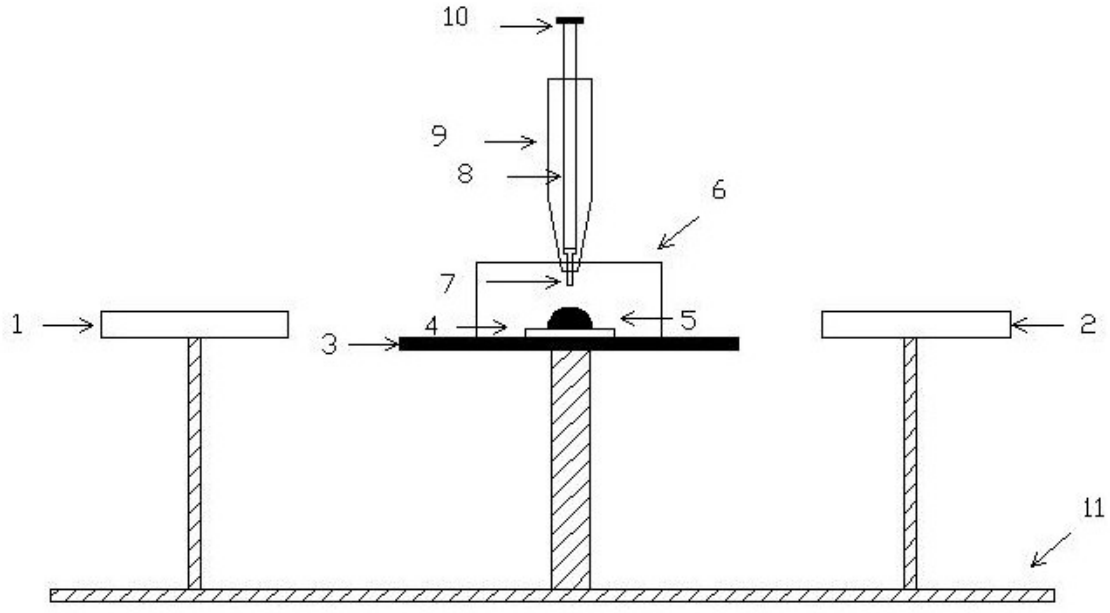


Figure 6-1 Contact Angle Formation on a Solid Surface



1. Light Source 2. Microscope Camera 3. Platform 4. Solid Plate 5. Liquid Droplet 6. Environmental Chamber 7. Metal Needle 8. Micro syringe (1cc) 9. Elevated Temperature Syringe Chamber 10. Piston 11. Base of Instrument

Figure 6-2 A Sketch of Contact Angle Goniometer

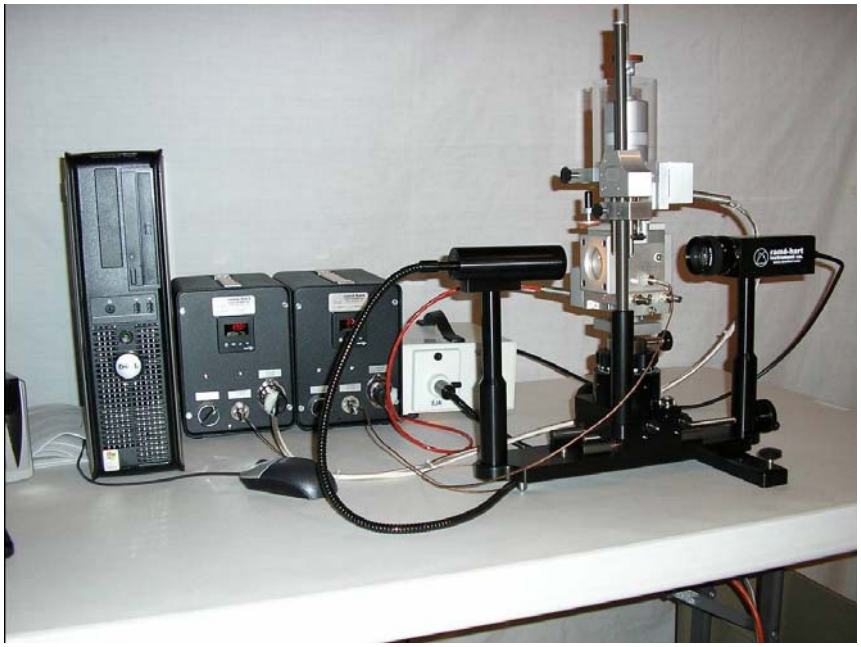


Figure 6-3 Contact Angle Goniometer

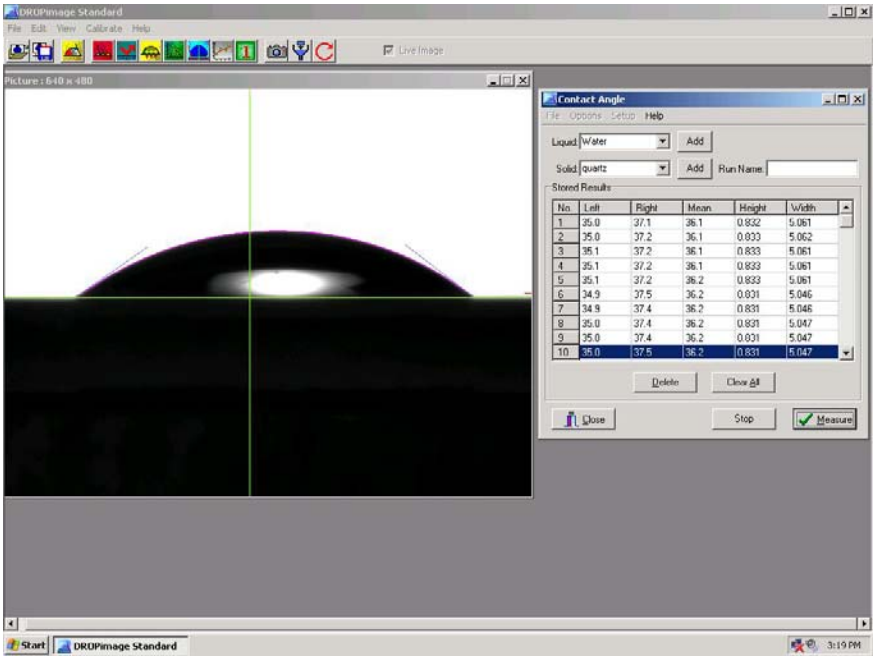


Figure 6-4 Captured Picture of Water Droplet on the Microscope Quartz Slide at 25°C

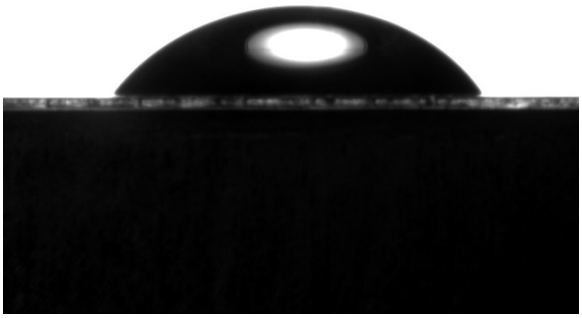


Figure 6-5 Captured Picture of Water Droplet on the Microscope Glass Slide at 25°C

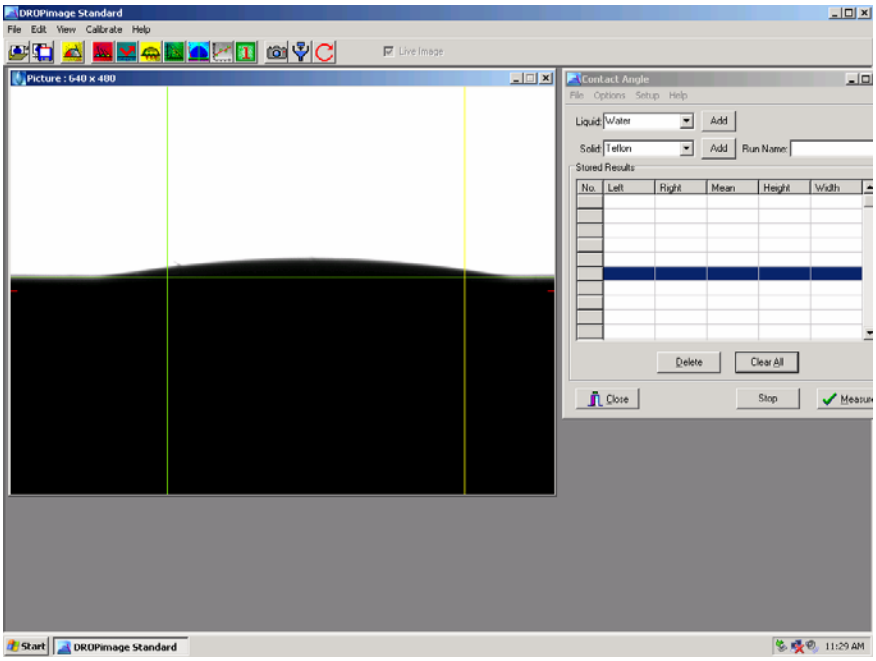


Figure 6-6 Captured Picture of Asphalt Droplet on the Microscope Quartz Slide at 135°C

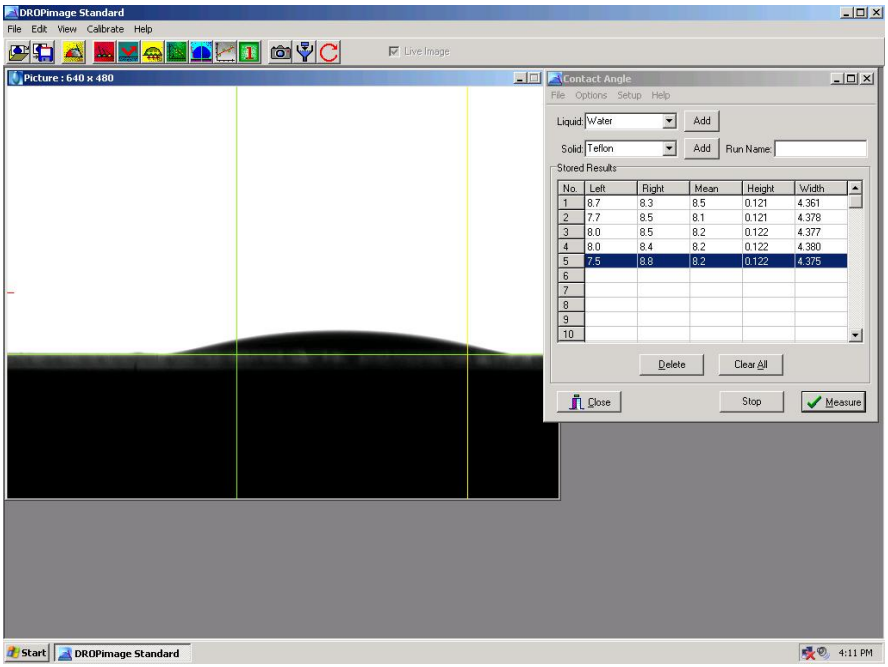


Figure 6-7 Captured Picture of Asphalt Droplet on the Microscope Glass Slide at 135°C

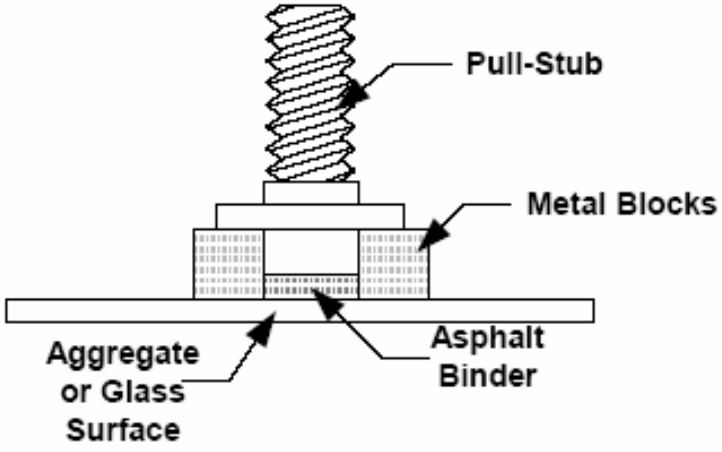


Figure 6-8 A Schematic of Modified PATTI

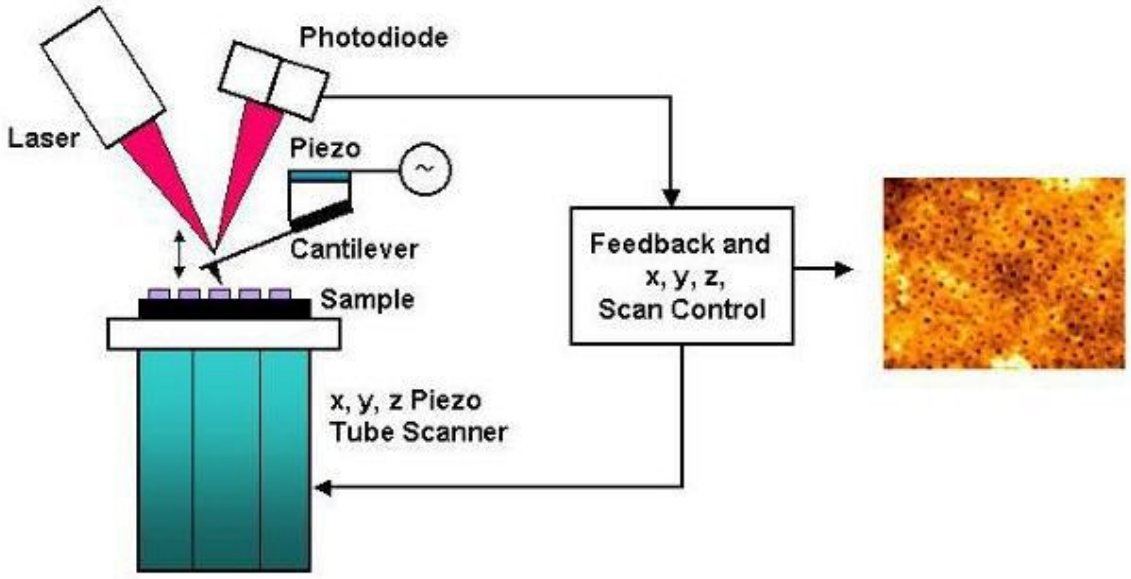


Figure 6-9 A Schematic of an Atomic Force Microscope

7. Summary and Conclusions

In this research study, litmus and colorimetric tests were developed to quantify amine-based antistrip additives in asphalt binders and mixes. The effect of prolonged heating on antistrip additive content was measured for both asphalt binders and mixes using litmus and colorimetric test methods. The effect of prolonged heating on adhesive bond strength between asphalt and aggregate was also evaluated by use of TSR and other test methods.

Based on the results of this study, the comparison and limitation of litmus and colorimetric test methods are stated as follows:

- Both test methodologies rely on the fact that amine-based antistrip additives will volatilize upon heating. If an antistrip additive is very stable at elevated temperatures and does not volatilize, both test methods are likely going to fail not only in determining the antistrip additive content but also in detecting the presence of antistrip additives.
- In both test methods, spectrophotometers were used and the antistrip additive content determination was based on changes in color intensity.
- The litmus test is simpler to conduct and results can be obtained relatively quickly compared to the colorimetric test that requires amines to be extracted into aqueous solution prior to analysis.

- For some antistrip additive types, saturation problems in litmus testing may be encountered at higher additive contents. For this reason it appears that the litmus test may be more suitable for detecting lower additive contents. However, it may be possible to reliably detect higher additive contents by varying the temperature and/or litmus paper exposure time to vapors.
- The colorimetric test seems to be more suitable for detecting higher additive contents and is less sensitive at lower additive content.

Specific conclusions are as follows:

- Both litmus and colorimetric tests are capable of detecting and quantifying amine-based antistrip additives in asphalt binders and mixes.
- The change in color intensity was highly correlated to the antistrip additive contents for both test methods.
- Both test methods provided reasonable results when the level of antistrip additive was determined for field samples. However, it needs to be noted that this conclusion is based on testing a single field mix I with LOF 6500 antistrip additive content of 0.5% by weight of asphalt binder. Additional verification using different mixes, different antistrip additives, and different dosages is needed.
- Based on limited testing conducted on measuring additive contents for field samples in this study, in general, the coefficient of variation (cv) of 5% for the litmus test was lower than the cv of 18.5% for the colorimetric tests. Testing in this study was conducted by a single operator. Testing by

multiple operators and in multiple laboratories may produce higher variability in test results.

- The antistrip additive content was found to decrease substantially for asphalt binders and mixes when subjected to prolonged heating periods. For asphalt binders, the measured antistrip additive content was practically zero after 24 to 48 hours of extended heating; for asphalt mixes, the measured antistrip additive content approached zero after 6 to 12 hours of extended heating.
- The improvement of moisture sensitivity by use of amine based antistrip additive lost to a great extent after prolonged heating. TSR values drop to less than 85% for both LOF 6500 and Morlife 2200 antistrip additives after only 6-hour heating. It shows that remaining part of antistrip additive after prolonged heating has reduced effect on adhesion between asphalt and aggregate. The volatilization and/or chemical change that occur during the heating process of amine based antistrip additive affect the improvement of asphalt-aggregate adhesion and ultimately the moisture susceptibility of mixes.

Based on the test results of this study, storage and transport as well as the duration between production and its ultimate paving in the field should be done as soon as possible. It is also recommended that highway agencies consider lime as a substitute to improve moisture susceptibility of asphalt mixes.

References

[1] Yang H, Huang. “Pavement Analysis and Design”, Prentice Hall, 1993

[2] M.E. Labib. “Asphalt-Aggregate Interactions and Mechanisms for Water Stripping”, Preprint American Chemical Society Division of Fuel Chemistry Volume37, NO.3, August 23-28, 1992

[3] R.P.L ottman. “Predicting Moisture-Induced Damage to Asphaltic Concrete, Field Evaluation”, NCHRP Report 246, Transportation Research Board, 1982

[4] D.G. Tunnicliff, R.E. Root. “Use of Antistripping Additives in Asphaltic Concrete Mix-Laboratory Phase”, NCHRP Report 274, Transportation Research Board, 1984

[5] Theresa M. Williams and Francis P. Miknis. “The Effect of Antistrip Treatments on Asphalt-Aggregate Systems: An Environmental Scanning Electron Microscope Study”, Journal of Elastomers and Plastics, Vol.30, October, 1998

[6] A.R. Tarrer, H.H. Yoon, B.M., Kiggundu, F.L. Roberts, and V.P. Wagh. "Detection of Amine-Based Antistripping Additives in Asphalt Cement", Transportation Research Record 1228, National Research Council, Washington D.C., pp.128-136, 1989

[7] ASTM D2073 Standard Test Methods for Total, Primary, Secondary, and Tertiary Amine Values of Fatty Amines, Amidoamines, and Diamines by Referee Potentiometric Method. American Society for Testing and Materials, Philadelphia, 1981

[8] R. Ulrich, P. Carroll, B. Krepps, S. Cantrell, and K.D. Hall, “A Titration Method for Measuring the Amount of Liquid Amine-Based Antistrip Additive in Asphalts and Pavements”, International Journal of Pavement Engineering, Vol. 2, Number 1, April 2001

[9] Tayebali, A. A., G. S. Natu, and M. Kulkarni. “Comparison of Material Properties and Life of Pavement Sections Containing Mixes with and without Non-Strip Additives,” Technical Assistance to NCDOT Report No. 98-03, Center for Transportation Engineering Studies, Department of Civil Engineering, North Carolina State University, June 1998

[10] Tayebali, A. A., M. Kulkarni, and H. F. Waller, “Delamination and Shoving of Asphalt Concrete Layers Containing Baghouse Fines, Final Report FHWA/NC2002-011, North Carolina Department of Transportation, May 2000

[11] Tayebali, A. A., W. K. Fischer, Y. X. Huang, and M. B. Kulkarni, “Effect of Percentage Baghouse Fines on the Amount and Type of Antistripping Agent Required to Control Moisture Sensitivity,” Final Report FHWA/NC/2003-04, North Carolina Department of Transportation, June 2003

[12] Christine W. Curtis, “A Literature Review of Liquid Antistripping And Tests for Measuring Stripping”, SHRP-A/UIR-90–016, Strategic Highway Research Program, National Research Council, Washington, D.C. 1990

[13] A.F. Verhasselt. “UV/VIS Spectrophotometry for the Evaluation of Binder-Aggregate Interactions”, Preprints - Division of Petroleum Chemistry, American Chemical Society, v 35, n 3, Jul, 1990

[14] Theresa M. Williams, Francis P. Miknis. “The Effect of Antistrip Treatments on Asphalt-Aggregate Systems: An Environmental Scanning Electron Microscope Study”, Journal of Elastomers and Plastics, v 30, n 4, Oct, 1998, p 282-295

[15] Theresa M. Williams, Francis P. Miknis. “Use of Environmental SEM to Study Asphalt-Water Interactions”, Journal of Materials in Civil Engineering, v 10, n 2, May, 1998, p 121-124

[16] K. Ramanathan, R.L. Stallings, J.R. Newsome. “An Ultrasonic Technique for the Measurement of Adhesion of Asphalt to Aggregate”, Journal of Adhesion Science and Technology, v 5, n 3, 1991

[17] F.P. Miknis, A.T. Pauli, A. Beemer, B. Wilde. “Use of NMR Imaging to Measure Interfacial Properties of Asphalts”, Fuel, v 84, n 9, June, 2005, p 1041-1051

[18] T. Abraham, D. Christendat, K. Karan, Z. Xu, J. Masliyah. “Asphaltene-Silica Interactions in Aqueous Solutions: Direct Force Measurements Combined with Electrokinetic Studies”, Industrial and Engineering Chemistry Research, v 41, n 9, May 1, 2002, p 2170-2177

[19] H. Mohamed El Hussein, A.O. Abd El Halim. “Differential Thermal Expansion and Contraction: a Mechanistic Approach to Adhesion in Asphalt Concrete”, Canadian Journal of Civil Engineering, v 20, n 3, Jun, 1993, p 366-373

[20] Tinh Nguyen, Eric Byrd, Dale Bentz, Jim Seiler. “Development of a Method for Measuring Water-Stripping Resistance of Asphalt/Siliceous Aggregate Mixtures”, Sponsor: Federal Highway Administration, Washington, DC.; American Association of State Highway and Transportation Officials, Washington, DC. Report: TRB/NCHRP-ID002, May 1996, 40p

[21] J. Schultz and M. Nardin, “Theories and Mechanisms of Adhesion”, Handbook of Adhesive Technology , New York: Marcell Dekker Inc.1994

[22] A.R. Tarrar and V.P. Wagh, “The Effect of the Physical and Chemical Characteristics of the Aggregate on Bonding,” Strategic Highway Research Program Report SHRP-A/ UIR-91-507, Washington, D.C.: National Research Council, 1992

[23] Vakula V.L. and Pritykin, L.M., “Polymer Adhesion: Basic Physico-Chemical Principles”, Ellis Horwood Ed., New York, 1991

[24] Christine W. Curtis, Keith Ensley, Jon Epps, "Fundamental Properties of Asphalt-Aggregate Interactions Including Adhesion and Absorption", Strategic Highway Research Program Report SHRP-A-341, National Research Council Washington, DC 1993

[25] Vold, R.D. and Vold. J.J., “Colloid and Interface Chemistry”, Addison-Wesley Reading, Massachusetts, USA, 1983

[26] Sherwood, W.C., “Determination of the Surface Charges of Certain Highway Aggregates by Streaming Potential Methods”, Report 24-1, Virginia Highway Research Council, Virginia, USA, 1967

[27] Ensley, K., "A study of asphalt-aggregate interactions and asphalt molecular interactions by microcalorimetric methods: postulated interaction mechanism", Journal of the Institute of Petroleum 59, 1973, p279-289

[28] Jennings, P.W., Pribanic, J.A., Fanconi, B. and VanderHart, D.L, "Binder characterization and evaluation by nuclear magnetic resonance spectroscopy", Strategic Highway Research Program Report SHRP-A-335, National Research Council, Washington, DC, 1993

[29] B.M. Kiggundu and F.L. Robberts, "Stripping in HMA Mixtures: State-of-the-Art and Critical Review of Test Methods," NCAT Report No.88-2, National Centre for Asphalt Technology, 1988

[30] D.N. Little and J.R. Jones, "Chemical and Mechanical Mechanisms of Moisture Damage in Hot Mix Asphalt Pavements," National Seminar in Moisture Sensitivity, San Diego, CA, 2003

[31] C.W. Curtis, "Investigation of Asphalt-Aggregate Interactions in Asphalt Pavements," American Chemical Society, Fuel, 37,1292-1297,1992

[32] J.C. Petersen, H. Plancher, E.K. Ensley, G. Miyake, and R.L.Venable, "Chemistry of Asphalt-Aggregate Interaction Relationship with Moisture Damage Prediction Test," Transportation Research Record 843,1982

[33] Arno W. Hefer, Dallas N. Little, Robert L. Lytton. "A Synthesis of Theories and Mechanisms of Bitumen-Aggregate Adhesion Including Recent Advances in Quantifying the Effects of Water", Jounal of the Association of Asphalt Paving Technologists, v 74, 2005

[34] Goodrich, J.L., Goodrich, J.E., and Kari, W.J., "Asphalt composition tests: Their application and relation to field performance", Transportation Research Record 1096, 1985 p146-167

[35] Petersen, J.C., "Quantitative functional groups analysis of asphalts using differential infrared spectrometry and selective chemical reactions: Theory and application", Transportation Research Record 1096, 1986 p1-11

[36] Masson, J.F. and Lacasse, M.A., "Effect of Hot-Air Lance on Crack Sealant Adhesion", Journal of Transportation Engineering 125, 1999, p357-363

[37] Knight, N.E., "Sealing cracks in bituminous overlays of rigid bases", Transportation Research Record 1041, 1985, p75-81

[38] L.D. Metcalfe. "The Analysis of Cationic Surfactants", Journal of the American Oil Chemists' Association 61:363-366, 1984

[39] A.S. Pearce. "Sulphonphthalein Method for the Colorimetric Determination of Low Concentrations of Amine in Water", Chemistry and Industry, 825, 1961

[40] Ronald M, Silverstein. "Spectrophotometric Determination of Primary, Secondary, and Tertiary Fatty Amines in Aqueous Solution." Analytical Chemistry 35: 154-157, 1963

[41] Larrick, M.A. "Spectrophotometric Determination of Fatty Amines in Aqueous Solution." Analytical Chemistry 35: 1760, 1963

[42] W.V. Chang. “Application of Acoustic Emission to Study the Cohesive and Adhesive Strength of Asphalt”, Sponsor: Strategic Highway Research Program, Washington, DC., Feb 1994, 298p

[43] DingXin Cheng, Dallas N. Little, Robert L. Lytton, James C. Holste. “Use of Surface Free Energy Properties of the Asphalt-Aggregate System to Predict Moisture Damage Potential”, Journal of the Association of Asphalt Paving Technologists, v 71, 2002, p 59-88

[44] Jaroslaw Drelich, Krishna Bukka, Jan D. Miller, Francis V. Hanson.“Surface Tension of Toluene-Extracted Bitumens from Utah Oil Sands as Determined by Wilhelmy Plate and Contact Angle Techniques”, Energy & Fuels, v 8, n 3, May-June, 1994, p 700-704

[45] A.Jada, M.Salou. “Effects of the Asphaltene and Resin Contents of the Bitumens on the Water-Bitumen Interface Properties”, Journal of Petroleum Science and Engineering v 33, 2002,185-193

[46] N. Eustathopoulos, N. Sobczak, A. Passerone, K. Nogi. “Measurement of contact angle and work of adhesion at high temperature”, Journal of Materials Science, v 40, n 9-10, May, 2005, p 2271-2280

[46]A. Sklodowska, M. Wozniak, R.Matlakowska. "The method of contact angle measurements and estimation of work of adhesion in bioleaching of metals", Biological Procedures Online, Vol. 1 No. 3, April, 1999

[47] Prokop, R. M., O. I. del Rio, N. Niyakan, A. W. Neuman. 1996. Interfacial tension from the height and diameter of sessile drops from the height and diameter of sessile drops and captive bubbles with an arbitrary contact angle. Can. J. Chem. Engineering 74:534-541

[49] ASTM D4541. “Pull-Off Strength of Coatings Using Portable Adhesion Testers.” Annual Book of ASTM Standards, Vol. 06.01, American Society for Testing and Materials, Philadephia, PA 1995

[50] J. Youtcheff and V. Aurilio. “Moisture Sensitivity of asphalt Binders: Evaluation and Modeling of the Pneumatic Adhesion test Results.” Canadian Technical Asphalt Association proceedings, 1997

[51] K.Kanitpong, and H.U.Bahia. "Roles of Adhesion and Thin Film Tackiness of Asphalt Binders in Moisture Damage of HMA," Journal of the Association of Asphalt Paving Technologists, Vol. 72, 2003, pp. 502-528

[52] Huang, S,Turner, TF, Pauli, AT, Miknis, FP, Branthaver, JF,Robertson, RE. "Evaluation of Different Techniques for Adhesive Properties of Asphalt-Filler Systems at Interfacial Region" Journal of ASTM International, Volume 2, May 2005

[53] Loeber, L., Sutton, O., Morel, J., Valleton, J.-M. & Muller, G. “New direct observations of asphalts and asphalt binders by scanning electron microscopy and atomic force microscopy.” Journal of Microscopy 182 (1), 32-39, 1996.

Appendix A Data for LOF 6500 and Morlife 2200 in Asphalt Binders and Mixes Using Litmus Test

Table A-1 Data for LOF 6500 Antistrip Additive in Asphalt Binder using Litmus Test, Color Index

Test 1

Content (%)	2h			6h			24h			48h		
0	408	414	416	391	400	401	389	387	392	378	379	384
0.25	662	658	647	568	570	570	396	401	392	370	379	380
0.5	672	663	661	603	605	601	403	406	406	372	376	375
1	801	812	806	659	668	670	420	411	416	380	379	382
2	979	980	972	868	870	854	587	562	559	431	437	433

Test 2

Content (%)	2h			6h			24h			48h		
0	402	397	407	388	378	390	371	370	370	371	372	373
0.25	630	642	633	542	547	543	390	388	391	370	371	370
0.5	741	747	750	651	647	641	411	409	407	374	376	377
1	821	817	825	689	692	687	429	427	429	388	386	386
2	970	968	962	877	872	881	606	603	609	447	454	444

Test 3

Content (%)	2h			6h			24h			48h		
0	409	409	416	376	389	385	397	392	399	405	400	392
0.25	631	622	627	541	552	550	391	388	392	380	381	380
0.5	645	650	651	570	566	562	399	398	399	388	389	389
1	829	821	817	668	679	682	417	415	415	386	388	388
2	977	975	966	882	878	876	521	512	521	412	411	411

Test 4

Content (%)	2h			6h			24h			48h		
0	389	395	387	364	362	370	371	377	369	379	378	376
0.25	657	644	641	579	586	570	410	406	407	380	378	378
0.5	727	721	729	617	609	611	401	403	407	381	387	385
1	833	837	841	700	703	692	436	439	440	401	399	387
2	1017	1006	1005	902	907	886	554	537	560	411	417	419

Test 5

Content (%)	2h			6h			24h			48h		
0	417	411	408	385	376	390	365	369	371	384	377	382
0.25	642	630	637	563	559	555	394	386	388	377	372	378
0.5	767	769	777	669	672	660	422	429	426	382	379	380
1	866	856	850	731	721	726	441	444	447	410	408	407
2	982	986	979	887	881	889	626	631	620	467	478	480

Table A-2 Data for LOF 6500 Antistrip Additive in Asphalt Binder using Litmus Test, Measured Antistrip Additive (%)

Test 1

Content (%)	2h			6h			24h			48h		
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.21	0.20	0.18	0.06	0.06	0.06	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.23	0.21	0.21	0.10	0.10	0.10	0.00	0.00	0.00	0.00	0.00	0.00
1	0.66	0.71	0.68	0.20	0.22	0.23	0.00	0.00	0.00	0.00	0.00	0.00
2	1.63	1.64	1.59	0.97	0.98	0.90	0.08	0.05	0.05	0.06	0.05	0.06

Test 2

Content (%)	2h			6h			24h			48h		
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.14	0.17	0.15	0.04	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.43	0.45	0.46	0.19	0.18	0.17	0.00	0.00	0.00	0.00	0.00	0.00
1	0.75	0.73	0.77	0.28	0.28	0.27	0.00	0.00	0.00	0.00	0.00	0.00
2	1.57	1.56	1.52	1.02	1.00	1.04	0.11	0.10	0.11	0.05	0.04	0.05

Test 3

Content (%)	2h			6h			24h			48h		
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.15	0.13	0.14	0.04	0.05	0.04	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.17	0.18	0.19	0.06	0.06	0.05	0.00	0.00	0.00	0.00	0.00	0.00
1	0.78	0.75	0.73	0.22	0.25	0.26	0.00	0.00	0.00	0.00	0.00	0.00
2	1.62	1.61	1.55	1.05	1.03	1.02	0.03	0.03	0.03	0.00	0.00	0.00

Test 4

Content (%)	2h			6h			24h			48h		
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.20	0.17	0.17	0.07	0.08	0.06	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.39	0.37	0.39	0.12	0.11	0.11	0.00	0.00	0.00	0.00	0.00	0.00
1	0.80	0.82	0.84	0.31	0.31	0.28	0.00	0.00	0.00	0.00	0.00	0.00
2	1.90	1.82	1.81	1.16	1.19	1.07	0.05	0.04	0.05	0.00	0.00	0.00

Test 5

Content (%)	2h			6h			24h			48h		
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.17	0.14	0.16	0.05	0.05	0.05	0.11	0.00	0.00	0.00	0.00	0.00
0.5	0.53	0.53	0.56	0.23	0.23	0.21	0.07	0.00	0.00	0.00	0.00	0.00
1	0.96	0.91	0.88	0.40	0.37	0.38	0.05	0.05	0.05	0.00	0.00	0.00
2	1.65	1.68	1.63	1.07	1.04	1.09	0.14	0.15	0.13	0.03	0.03	0.03

Table A-3 Data for Morlife 2200 Antistrip Additive in Asphalt Binder using Litmus Test, Color Index

Test 1

Content (%)	2h			6h			24h			48h		
0	408	414	416	391	400	401	389	387	392	378	379	384
0.25	620	631	639	501	512	521	414	415	414	397	392	394
0.5	961	959	972	801	787	792	437	440	444	401	403	406
1	1041	1019	1020	898	905	892	512	505	509	396	399	401
2	1108	1098	1097	1085	1082	1079	737	720	725	531	520	527

Test 2

Content (%)	2h			6h			24h			48h		
0	402	397	407	388	378	390	371	370	370	371	372	373
0.25	587	576	592	462	475	458	403	410	406	394	392	391
0.5	931	942	944	782	776	769	428	437	431	391	395	395
1	1000	1009	1003	865	878	872	466	468	475	406	401	405
2	1103	1109	1103	1132	1121	1109	749	728	734	524	531	529

Test 3

Content (%)	2h			6h			24h			48h		
0	409	409	416	376	389	385	397	392	399	405	400	392
0.25	578	562	559	473	487	491	397	401	405	370	377	381
0.5	942	933	927	743	752	739	445	441	439	406	404	401
1	1063	1042	1039	927	916	921	538	521	533	400	404	399
2	1085	1065	1070	1092	1090	1087	714	710	721	503	498	507

Test 4

Content (%)	2h			6h			24h			48h		
0	389	395	387	364	362	370	371	377	369	379	378	376
0.25	601	592	607	488	476	469	411	403	405	400	402	391
0.5	939	941	953	762	772	764	431	429	433	397	392	400
1	1022	1019	1010	881	879	876	487	472	476	398	402	401
2	1083	1072	1096	1097	1092	1100	767	741	756	539	540	542

Test 5

Content (%)	2h			6h			24h			48h		
0	417	411	408	385	376	390	365	369	371	384	377	382
0.25	568	571	576	439	441	452	404	406	404	388	381	379
0.5	912	908	922	722	731	729	429	430	430	394	398	401
1	1041	1037	1026	911	909	924	501	497	506	401	407	406
2	1080	1092	1078	1107	1098	1096	742	746	751	511	506	500

Table A-4 Data for Morlife 2200 Antistrip Additive in Asphalt Binder using Litmus Test, Measured Antistrip Additive (%)

Test 1

Content (%)	2h			6h			24h			48h		
0	0.02	0.03	0.03	0.01	0.02	0.02	0.01	0.01	0.01	0.00	0.00	0.00
0.25	0.22	0.23	0.23	0.11	0.12	0.13	0.03	0.03	0.03	0.01	0.01	0.01
0.5	0.52	0.52	0.53	0.38	0.37	0.37	0.05	0.05	0.06	0.02	0.02	0.02
1												
2												

Test 2

Content (%)	2h			6h			24h			48h		
0	0.02	0.01	0.02	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.19	0.18	0.19	0.07	0.08	0.07	0.02	0.03	0.02	0.01	0.01	0.01
0.5	0.50	0.51	0.51	0.36	0.36	0.35	0.04	0.05	0.05	0.01	0.01	0.01
1												
2												

Test 3

Content (%)	2h			6h			24h			48h		
0	0.03	0.03	0.03	0.00	0.01	0.00	0.01	0.01	0.02	0.02	0.02	0.01
0.25	0.18	0.16	0.16	0.08	0.10	0.10	0.01	0.02	0.02	0.00	0.00	0.00
0.5	0.51	0.50	0.49	0.33	0.33	0.32	0.06	0.05	0.05	0.02	0.02	0.02
1												
2												

Test 4

Content (%)	2h			6h			24h			48h		
0	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.20	0.19	0.20	0.10	0.09	0.08	0.03	0.02	0.02	0.02	0.02	0.01
0.5	0.50	0.50	0.52	0.34	0.35	0.35	0.05	0.04	0.05	0.01	0.01	0.02
1												
2												

Test 5

Content (%)	2h			6h			24h			48h		
0	0.03	0.03	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.17	0.17	0.18	0.05	0.05	0.06	0.02	0.02	0.02	0.01	0.00	0.00
0.5	0.48	0.47	0.49	0.31	0.32	0.31	0.04	0.04	0.04	0.01	0.02	0.02
1												
2												

Table A-5 Data for LOF 6500 Antistrip Additive in Asphalt Mix I using Litmus Test, Color Index

Test 1

Content (%)	1h		2h		4h		6h		12h	
0	384	380	374	377	377	372	374	372	372	369
0.25	402	410	397	393	376	374	371	373	373	373
0.5	432	444	393	401	390	384	380	379	372	373
1	501	510	476	477	428	430	411	409	383	380
2	582	574	505	498	462	463	430	431	381	382

Test 2

Content (%)	1h		2h		4h		6h		12h	
0	383	382	371	376	369	372	370	372	375	377
0.25	410	416	386	382	371	375	382	379	376	378
0.5	447	450	399	404	396	397	383	380	376	380
1	515	512	480	479	440	437	413	412	379	377
2	559	563	517	522	474	474	428	428	378	380

Test 3

Content (%)	1h		2h		4h		6h		12h	
0	381	379	380	375	377	372	370	369	368	370
0.25	418	420	384	382	376	373	370	372	377	373
0.5	443	431	400	402	388	390	381	382	375	377
1	488	496	459	467	432	433	415	410	379	379
2	576	577	527	532	464	465	428	430	381	377

Table A-6 Data for LOF 6500 Antistrip Additive in Asphalt Mix I using Litmus Test, Measured Antistrip Additive (%)

Test 1

Content (%)	1h		2h		4h		6h		12h	
0	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.21	0.27	0.16	0.13	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.42	0.50	0.13	0.20	0.10	0.04	0.00	0.00	0.00	0.00
1	0.80	0.85	0.67	0.67	0.40	0.41	0.28	0.26	0.03	0.00
2	1.43	1.34	0.82	0.78	0.60	0.60	0.41	0.42	0.01	0.02

Test 2

Content (%)	1h		2h		4h		6h		12h	
0	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.27	0.32	0.06	0.02	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.51	0.53	0.18	0.22	0.16	0.16	0.03	0.00	0.00	0.00
1	0.88	0.86	0.69	0.68	0.47	0.46	0.29	0.29	0.00	0.00
2	1.20	1.24	0.89	0.92	0.66	0.66	0.40	0.40	0.00	0.00

Test 3

Content (%)	1h		2h		4h		6h		12h	
0	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.33	0.34	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.49	0.42	0.19	0.21	0.08	0.10	0.01	0.02	0.00	0.00
1	0.73	0.77	0.58	0.62	0.42	0.43	0.31	0.27	0.00	0.00
2	1.36	1.38	0.95	0.99	0.61	0.61	0.40	0.41	0.01	0.00

Table A-7 Data for Morlife 2200 Antistrip Additive in Asphalt Mix I using Litmus Test, Color Index

Test 1

Content (%)	1h		2h		4h		6h		12h	
0	384	380	374	377	377	372	374	372	372	369
0.25	468	460	434	430	430	432	431	430	376	380
0.5	456	455	439	437	440	442	450	448	402	406
1	507	499	441	440	433	431	420	416	414	405
2	554	556	452	457	431	429	406	412	387	379

Test 2

Content (%)	1h		2h		4h		6h		12h	
0	383	382	371	376	369	372	370	372	375	377
0.25	473	477	424	422	426	424	427	430	379	382
0.5	496	488	443	439	439	435	430	432	398	406
1	512	510	453	447	441	437	434	431	404	410
2	538	533	455	450	459	456	474	469	398	386

Test 3

Content (%)	1h		2h		4h		6h		12h	
0	381	379	380	375	377	372	370	369	368	370
0.25	435	432	427	430	428	420	417	412	380	377
0.5	458	455	436	429	428	422	410	402	384	376
1	503	499	440	438	430	422	408	411	379	381
2	498	480	451	452	428	426	401	404	376	376

Table A-7 Data for Morlife 2200 Antistrip Additive in Asphalt Mix I using Litmus Test, Measured Antistrip Additive (%)

Test 1

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.22	0.17	0.05	0.04	0.04	0.04	0.04	0.04	0.00	0.00
0.5	0.15	0.14	0.07	0.06	0.07	0.08	0.12	0.11	0.00	0.00
1	0.56	0.48	0.08	0.07	0.05	0.04	0.01	0.01	0.00	0.00
2	1.17	1.20	0.13	0.15	0.04	0.03	0.00	0.00	0.00	0.00

Test 2

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.26	0.29	0.02	0.02	0.03	0.02	0.03	0.04	0.00	0.00
0.5	0.45	0.38	0.08	0.07	0.07	0.05	0.04	0.04	0.00	0.00
1	0.61	0.59	0.13	0.10	0.08	0.06	0.05	0.04	0.00	0.00
2	0.94	0.87	0.14	0.12	0.16	0.15	0.26	0.23	0.00	0.00

Test 3

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.05	0.04	0.03	0.04	0.03	0.01	0.01	0.00	0.00	0.00
0.5	0.16	0.14	0.06	0.03	0.03	0.02	0.00	0.00	0.00	0.00
1	0.52	0.48	0.07	0.06	0.04	0.02	0.00	0.00	0.00	0.00
2	0.47	0.31	0.12	0.13	0.03	0.03	0.00	0.00	0.00	0.00

Table A-8 Data for LOF 6500 Antistrip Additive in Asphalt Mix II using Litmus Test, Color Index

Test 1

Content (%)	1h		2h		4h		6h		12h	
0	401	397	377	377	376	375	380	376	376	379
0.25	418	420	399	400	380	382	377	379	377	377
0.5	466	463	437	432	411	415	385	389	379	378
1	522	531	498	500	425	424	410	412	380	384
2	679	695	570	577	467	459	428	430	382	379

Test 2

Content (%)	1h		2h		4h		6h		12h	
0	406	398	376	379	379	374	379	382	379	376
0.25	429	427	401	404	381	384	384	377	377	379
0.5	470	465	442	449	421	419	389	390	378	377
1	545	550	507	512	439	435	415	419	380	381
2	665	657	559	564	453	460	439	435	381	380

Test 3

Content (%)	1h		2h		4h		6h		12h	
0	395	392	380	384	381	372	378	379	378	372
0.25	416	412	401	409	385	384	380	384	377	379
0.5	477	479	448	450	422	424	387	385	382	377
1	512	510	511	505	440	434	420	421	380	378
2	701	699	601	597	469	462	432	428	383	381

Table A-9 Data for LOF 6500 Antistrip Additive in Asphalt Mix II using Litmus Test, Measured Antistrip Additive (%)

Test 1

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.06	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.31	0.30	0.16	0.14	0.02	0.04	0.00	0.00	0.00	0.00
1	0.58	0.62	0.47	0.48	0.10	0.09	0.01	0.02	0.00	0.00
2	1.58	1.73	0.82	0.86	0.32	0.28	0.11	0.13	0.00	0.00

Test 2

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.12	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.33	0.31	0.19	0.23	0.07	0.06	0.00	0.00	0.00	0.00
1	0.69	0.72	0.51	0.53	0.17	0.15	0.04	0.06	0.00	0.00
2	1.46	1.39	0.76	0.79	0.25	0.28	0.17	0.15	0.00	0.00

Test 3

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.05	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.37	0.38	0.22	0.23	0.08	0.09	0.00	0.00	0.00	0.00
1	0.53	0.52	0.53	0.50	0.18	0.15	0.07	0.07	0.00	0.00
2	1.79	1.77	1.00	0.97	0.33	0.29	0.14	0.11	0.00	0.00

Table A-10 Data for Morlife 2200 Antistrip Additive in Asphalt Mix II using Litmus Test, Color Index

Test 1

Content (%)	1h		2h		4h		6h		12h	
0	401	397	377	377	384	379	381	378	379	379
0.25	422	417	401	398	390	382	388	390	381	380
0.5	447	444	421	419	389	391	382	386	382	384
1	509	512	483	480	402	400	393	389	388	385
2	768	771	641	645	458	449	416	411	391	389

Test 2

Content (%)	1h		2h		4h		6h		12h	
0	406	398	376	379	381	382	377	379	381	377
0.25	389	392	387	388	388	385	379	382	380	384
0.5	482	480	441	447	403	395	384	389	379	381
1	506	499	467	462	411	408	389	391	385	384
2	754	751	638	629	448	444	421	418	391	383

Test 3

Content (%)	1h		2h		4h		6h		12h	
0	395	392	380	384	380	383	375	378	375	377
0.25	405	409	392	395	389	390	381	388	380	381
0.5	467	464	438	435	414	409	385	389	383	382
1	522	527	491	484	417	420	392	384	391	382
2	772	764	651	648	448	456	415	420	385	389

Table A-11 Data for Morlife 2200 Antistrip Additive in Asphalt Mix II using Litmus Test, Measured Antistrip Additive (%)

Test 1

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.08	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.24	0.22	0.08	0.06	0.00	0.00	0.00	0.00	0.00	0.00
1	0.61	0.63	0.46	0.44	0.00	0.00	0.00	0.00	0.00	0.00
2	1.75	1.76	1.27	1.29	0.31	0.25	0.04	0.01	0.00	0.00

Test 2

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.45	0.44	0.20	0.24	0.00	0.00	0.00	0.00	0.00	0.00
1	0.59	0.55	0.36	0.33	0.01	0.00	0.00	0.00	0.00	0.00
2	1.70	1.69	1.26	1.22	0.25	0.22	0.08	0.06	0.00	0.00

Test 3

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.36	0.35	0.18	0.17	0.03	0.00	0.00	0.00	0.00	0.00
1	0.68	0.71	0.51	0.47	0.05	0.07	0.00	0.00	0.00	0.00
2	1.76	1.74	1.32	1.30	0.25	0.30	0.04	0.07	0.00	0.00

Appendix B Data for LOF 6500 and Morlife 2200 in Asphalt Binders and Mixes Using Colorimetric Analysis

Table B-1 Data for LOF 6500 Antistrip Additive in Asphalt Binder using Colorimetric Test, Absorbance

Content (%)	2h		6h		24h		48h	
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.25	0.0017	0.0012	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000
0.5	0.0062	0.0054	0.0028	0.0020	0.0000	0.0000	0.0000	0.0000
1	0.0091	0.0105	0.0038	0.0045	0.0000	0.0000	0.0000	0.0000
2	0.0251	0.0221	0.0166	0.0152	0.0027	0.0015	0.0000	0.0000

Table B- 1

Table B-2 Data for LOF 6500 Additive in Asphalt Binder using Colorimetric Test, Measured Antistrip Additive (%)

Content (%)	2h		6h		24h		48h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.14	0.10	0.06	0.03	0.00	0.00	0.00	0.00
0.5	0.43	0.37	0.21	0.15	0.00	0.00	0.00	0.00
1	0.61	0.70	0.27	0.32	0.00	0.00	0.00	0.00
2	1.65	1.45	1.10	1.01	0.20	0.12	0.00	0.00

Table B- 2

Table B-3 Data for Morlife 2200 Antistrip Additive in Asphalt Binder using Colorimetric Test, Absorbance

Content (%)	2h		6h		24h		48h	
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.25	0.0022	0.0027	0.0011	0.0007	0.0000	0.0000	0.0000	0.0000
0.5	0.0088	0.0064	0.0021	0.0016	0.0000	0.0000	0.0000	0.0000
1	0.0134	0.0150	0.0049	0.0057	0.0000	0.0000	0.0000	0.0000
2	0.0357	0.0411	0.0204	0.0249	0.0021	0.0011	0.0000	0.0000

Table B-4 Data for Morlife 2200 Additive in Asphalt Binder using Colorimetric Test, Measured Antistrip Additive (%)

Content (%)	2h		6h		24h		48h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.10	0.13	0.05	0.04	0.00	0.00	0.00	0.00
0.5	0.40	0.30	0.10	0.08	0.00	0.00	0.00	0.00
1	0.61	0.69	0.23	0.26	0.00	0.00	0.00	0.00
2	1.63	1.87	0.93	1.14	0.10	0.05	0.00	0.00

Table B-5 Data for LOF 6500 Antistrip Additive in Asphalt Mix I using Colorimetric Test, Absorbance

Content (%)	1h		2h		4h		6h		12h	
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.25	0.0035	0.0022	0.0017	0.0012	0.0010	0.0007	0.0000	0.0000	0.0000	0.0000
0.5	0.0153	0.0182	0.0121	0.0094	0.0039	0.0027	0.0012	0.0008	0.0000	0.0000
1	0.0223	0.0241	0.0175	0.0144	0.0117	0.0094	0.0054	0.0032	0.0000	0.0000
2	0.0294	0.0239	0.0182	0.0201	0.0142	0.0177	0.0074	0.0079	0.0015	0.0010

Table B-6 Data for LOF 6500 Additive in Asphalt Mix I using Colorimetric Test, Measured Antistrip Additive (%)

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.14	0.12	0.12	0.11	0.11	0.10	0.00	0.00	0.00	0.00
0.5	0.45	0.56	0.35	0.27	0.15	0.13	0.11	0.10	0.00	0.00
1	0.74	0.82	0.53	0.42	0.34	0.27	0.18	0.14	0.00	0.00
2	1.10	0.81	0.56	0.64	0.42	0.54	0.22	0.24	0.11	0.11

Table B-7 Data for Morlife 2200 Antistrip Additive in Asphalt Mix I using Colorimetric Test, Absorbance

Content (%)	1h		2h		4h		6h		12h	
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.25	0.0048	0.0056	0.0020	0.0025	0.0009	0.0012	0.0000	0.0000	0.0000	0.0000
0.5	0.0121	0.0114	0.0062	0.0058	0.0026	0.0018	0.0004	0.0006	0.0000	0.0000
1	0.0277	0.0304	0.0144	0.0162	0.0070	0.0087	0.0027	0.0016	0.0000	0.0000
2	0.0386	0.0369	0.0178	0.0169	0.0074	0.0064	0.0022	0.0014	0.0000	0.0000

Table B-8 Data for Morlife 2200 Additive in Asphalt Mix I using Colorimetric Test, Measured Antistrip Additive (%)

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.11	0.12	0.10	0.10	0.09	0.09	0.00	0.00	0.00	0.00
0.5	0.20	0.19	0.13	0.12	0.10	0.09	0.00	0.00	0.00	0.00
1	0.58	0.67	0.24	0.28	0.14	0.15	0.10	0.09	0.00	0.00
2	0.99	0.91	0.31	0.29	0.14	0.13	0.10	0.09	0.00	0.00

Table B-9 Data for LOF 6500 Antistrip Additive in Asphalt Mix II using Colorimetric Test, Absorbance

Content (%)	1h		2h		4h		6h		12h	
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.25	0.0016	0.0011	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.5	0.0161	0.0142	0.0061	0.0057	0.0022	0.0015	0.0000	0.0000	0.0000	0.0000
1	0.0268	0.0289	0.0105	0.0121	0.0041	0.0050	0.0017	0.0015	0.0000	0.0000
2	0.0379	0.0342	0.0262	0.0227	0.0124	0.0111	0.0026	0.0021	0.0000	0.0000

Table B-10 Data for LOF 6500 Additive in Asphalt Mix II using Colorimetric Test, Measured Antistrip Additive (%)

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.12	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.31	0.27	0.15	0.15	0.13	0.12	0.00	0.00	0.00	0.00
1	0.63	0.72	0.20	0.23	0.13	0.14	0.12	0.12	0.00	0.00
2	1.14	0.95	0.61	0.49	0.23	0.21	0.13	0.12	0.00	0.00

Table B-11 Data for Morlife 2200 Antistrip Additive in Asphalt Mix II using Colorimetric Test, Absorbance

Content (%)	1h		2h		4h		6h		12h	
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.25	0.0033	0.0019	0.0009	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.5	0.0256	0.0198	0.0102	0.0111	0.0021	0.0017	0.0000	0.0000	0.0000	0.0000
1	0.0322	0.0355	0.0141	0.0162	0.0052	0.0068	0.0009	0.0012	0.0000	0.0000
2	0.0557	0.0431	0.0378	0.0319	0.0151	0.0134	0.0078	0.0029	0.0000	0.0000

Table B-12 Data for Morlife 2200 Additive in Asphalt Mix II using Colorimetric Test, Measured Antistrip Additive (%)

Content (%)	1h		2h		4h		6h		12h	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.12	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.28	0.20	0.13	0.13	0.00	0.00	0.00	0.00	0.00	0.00
1	0.39	0.46	0.15	0.17	0.12	0.12	0.00	0.00	0.00	0.00
2	1.05	0.65	0.51	0.39	0.16	0.15	0.12	0.12	0.00	0.00

Appendix C Job-Mix-Formula and Tensile Strength Ratio Test Data for Asphalt Mixes with 0.8% LOF 6500 and Morlife 2200 Antistrip Additives in Asphalt Binders after Prolonged Heating

Table C- 1 Original JMF Provided by NCDOT

13

REVISED November 2003 — MAT FORM 661 (3/P)

REPORT ON SUPERPAVE MIX DESIGN

MD# 06-222

DATE SUBMITTED:		DATE APPROVED:	04-20-06
PROJECT NO.:		BINDER:	CONOCO Knoxville AT29 PG 76-22
COUNTY:		ADDITIVE:	ARR-MAZ Ad-Here 6500 LOF (.8 %)
CONTRACTOR:	APAC Atlantic	Vulcan Materials	Enka CA69 Washed Scrgs.
PLANT & NO.:	APAC Enka AS16	Vulcan Materials	Enka CA69 78-M Stone
DESIGNED BY:	SANDRA CLAYTON SDT 50670	Vulcan Materials	Enka CA69 # 67 Stone
SPECIFICATION:	S 12.5 D Surface Mix		
GYRATIONS:	9/125/ 150 mm 157 °C		
TRAFFIC LEVEL:	>30.0 Million ESALs		
BINDER SPECIFIC GRAVITY:	1.030		Baghouse Fines
COMPACTOR TYPE:	Troxler		

GRADATION OF MATERIALS USED

MATERIAL	Washed Scrgs	78-M Stone	# 67 Stone				BgHsFines	Rap	BLEND	CONTROL
PERCENT (MD)	45.8	34.0	18.0				2.2		100.0	POINTS
PERCENT (JMF)	48.0	34.0	18.0						100.0	
Sieves(mm) 50.0	100.0	100.0	100.0				100.0		100	
37.5	100.0	100.0	100.0				100.0		100	
25.0	100.0	100.0	99.0				100.0		100	
19.0	100.0	100.0	90.0				100.0		98	100.0
12.5	100.0	99.0	47.0				100.0		90	90.0 - 100.0
9.5	100.0	92.0	17.0				100.0		82	< 90.0
4.75	97.0	33.0	8.0				100.0		59	
2.36	85.0	9.0	4.0				100.0		45	28.0 - 58.0
1.18	60.0	5.0	3.0				100.0		32	
0.600	41.0	3.0	2.0				100.0		22	
0.300	22.0	3.0	2.0				100.0		14	
0.150	10.0	2.0	1.0				100.0		8	
0.075	4.7	1.4	0.9				90.0		4.8	4.0 - 8.0
Ign.Furn. Corr.Factor										
Agg. Bulk Dry S.G.	2.734	2.690	2.697				2.734		2.712	
							Agg. Effective S.G.:		2.757	
Agg. Apparent S.G.	2.774	2.752	2.743				2.774		2.761	

Mix Properties at N design

		Opt. Pb	5.0	5.5	6.0	6.5
% Asphalt Binder-Total Mix			5.0	5.5	6.0	6.5
Gmb @ Ndes (or Nmax)		#DIV/0!	2.398	2.415	2.433	2.447
Max. Specific Gravity(Gmm)			2.544	2.524	2.505	2.486
% Voids-Total Mix (VTM)		#DIV/0!	5.7	4.3	2.9	1.6
% Solids-Total Mix		#DIV/0!	94.3	95.7	97.1	98.4
% Effective Binder Content (Pbe)		-0.6	4.4	4.9	5.4	5.9
Dust to Pbe Ratio (Pb.0#S/Pbe)		-8.00	1.09	0.98	0.89	0.81
By Volume of Effective Pb		#DIV/0!	10.2	11.5	12.8	14.0
% Solids by Vol. of Agg. Only		#DIV/0!	84.1	84.2	84.3	84.4
% Voids in Mineral Agg. (VMA)		#DIV/0!	16.0	15.8	15.7	15.6
% Voids Filled w/Binder (VFA)		#DIV/0!	63.8	72.8	81.5	89.7
% Gmm @ Nini	9	#DIV/0!	87.9	89.2	90.4	91.6
% Gmm @ Ndes	125	#DIV/0!	94.3	95.7	97.2	98.4
% Gmm @ Nmax		#DIV/0!				

% RAP / % Virgin:	0/100
Pb in RAP:	
Pb from RAP:	
Pb Absorption:	0.6
% ASH:	
TSR % Retained :	108.5
Ignition Furn. Calibr.:	
Pb (Design):	5.6
Rice Specific Gravity:	2.525
Lab Specific Gravity:	2.419
Percent Air Voids:	4.0
Percent VMA:	15.8
Percent VFA:	74.7
DUST/AC Ratio:	0.95
% Gmm @ Nini	89.4
% Gmm @ Nmax	—
Pb ADDED:	5.6
Pb from RAP:	—
Pb TOTAL:	5.6

Uncomp. Void Cont.*	NA
Sand Equivalent:	78.5
C. Agg. Angularity	100/100
F. Agg. Angularity:	51.3
Flat & Elongated:	8.7

COMMENTS: Rut depth = 1.6 mm

DESIGNED BY: Sandra Clayton SDT 50670

APPROVAL: C. A. Clippard, Jr.

Table C-2 TSR Test Data for None Antistrip Additives in Asphalt Mixes with 2-Hour Heating

Revised 11-29-99

NCDOT

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Marshall Compactive Method

M&T 612 (QMS-2)

Date Mix Produced:	Mix Type: N00-2	JMF No.:
Contractor: NCSU	Plant Location:	Plant Cert. No.:
Additive Supplier:	Additive Grade:	Additive Dosage:
Date Compacted:	No. Gyrations: to height	Date Test Completed: 2/27/2007

SPECIMEN NUMBER			1	2	3	4	5	6	7	8
DIAMETER(in)		(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(in.)		(b)	96.000	96.000	95.900	96.000	95.900	95.700	95.800	96.000
DRY MASS IN AIR		(c)	3932.4	3941.0	3941.2	3942.3	3942.0	3929.6	3943.4	3941.2
SSD MASS IN AIR		(d)	3952.7	3955.4	3956.4	3958.3	3959.6	3950.8	3953.8	3957.2
MASS IN WATER		(e)	2277.6	2276.5	2277.6	2282.0	2284.0	2280.6	2275.2	2279.2
VOLUME	(d-e)	(f)	1675.1	1678.9	1678.8	1676.3	1675.6	1670.2	1678.6	1678.0
BULK SP. GR.	(c ÷ f)	(g)	2.348	2.347	2.348	2.352	2.353	2.353	2.349	2.349
MAX. SP.GR.	(From Actual Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS	(100 X (h - g) ÷ h)	(i)	7.2	7.2	7.2	7.0	7.0	7.0	7.1	7.2
VOLUME AIR VOIDS	(i X f) ÷ 100	(j)	120.6	120.9	120.9	117.3	117.3	116.9	119.2	120.8
PEAK LOAD (psi)		(k)				31600	34400	34200	33900	
DRY TS	(2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**********	**********	**1397.0**	**1522.4**	**1516.7**	**1501.8**	**********
CALC. SSD AT 70% SAT.	(0.70 X j) + c		4016.8	4025.6	4025.8	4024.4	4024.1	4011.4	4026.8	4025.8
CALC. SSD AT 80% SAT.	(0.80 X j) + c		4028.9	4037.7	4037.9	4036.2	4035.8	4023.1	4038.7	4037.9

SATURATED	MINUTES @		"Hg							
Date and Time in:	01/16/02 9.15AM			Date and Time out:						
SSD MASS		(m)	4018.4	4030.3	4033.0					4028.9
MASS IN WATER		(n)	2347.0	2354.4	2358.0					2354.1
VOLUME	(m - n)	(o)	1671.4	1675.9	1675.0	**********	**********	**********	**********	1674.8
VOL. ABS. H2O	(m - c)	(p)	86.0	89.3	91.8	**********	**********	**********	**********	87.7
% SATURATION	100 X (p ÷ j)		71.3	73.9	75.9	**********	**********	**********	**********	72.6

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS		(q)	4019.0	4033.0	4037.5					4033.5
MASS IN WATER		(r)	2347.7	2352.0	2355.6					2352.9
VOLUME	(q - r)	(s)	1671.3	1681.0	1681.9	**********	**********	**********	**********	1680.6
VOLUME ABS. H2O	(q - c)	(t)	86.6	92.0	96.3	**********	**********	**********	**********	92.3
% SATURATION	100 X (t ÷ j)		71.8	76.1	79.7	**********	**********	**********	**********	76.4
PEAK LOAD (psi)		(u)	23800	24200	24300					25600
WET TS	(2 X u) ÷ (a X b X 3.1416)	(v)	**1052.2**	**1069.9**	**1075.4**	**********	**********	**********	**********	**1131.8**
INTERNAL SPECIMEN TEMPERATURE (°F .)			77.00	76.00	76.50	76.00	76.50	76.50	76.50	76.50

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS	QA/QC Joint Test?
Dry Subset	7.1		76.4	**1509.3**	
Wet Subset	7.2	73.4	76.5	**1072.6**	Circle One
TENSILE STRENGTH RATIO				**71.1**	**Yes** **No**
QA/QC COMPARATIVE TSR					

TESTED BY: Clippard/Massey

CERT. NO.:

TESTED BY:

CERT. NO.:

LAB LOCATION:

LAB CERT NO.:

Visual Stripping:(Circle one)

None **Minor** **Moderate** **Severe**

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA

Table C-3 TSR Test Data for 0.8% LOF 6500 Antistrip Additives without Prolonged Heating

Revised August 2006

NCDOT M&T 612 (QMS-2)

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Gyratory Compactive Method

Date Mix Produced:	Mix Type:	JMF No.:	LO8-0-1-8
Contractor: NC STATE	Plant Location:	Plant Cert. No.:	
Additive Supplier:	Additive Grade: LOF 6500	Additive Dosage:	(%)
Date Compacted:	No. Gyrations: To height	Date Test Completed:	5/18/2007

SPECIMEN NUMBER			1	2	3	4	5	6	7	8
DIAMETER(mm)		(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(mm)		(b)	96.000	95.800	96.100	96.200	96.000	96.400	96.100	95.700
DRY MASS IN AIR		(c)	3911.5	3929.5	3924.7	3938.9	3940.5	3942.9	3939.5	3934.4
SSD MASS IN AIR		(d)	3928.2	3949.0	3946.8	3955.7	3956.5	3962.1	3958.5	3961.2
MASS IN WATER		(e)	2257.9	2267.8	2274.6	2281.7	2277.1	2276.4	2286.1	2284.2
VOLUME	(d-e)	(f)	1670.3	1681.2	1672.2	1674.0	1679.4	1685.7	1672.4	1677.0
BULK SP. GR.	(c ÷ f)	(g)	2.342	2.337	2.347	2.353	2.346	2.339	2.356	2.346
MAX. SP.GR.	(Optimum Binder Content Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS	(100 X (h - g) ÷ h)	(i)	7.4	7.6	7.2	7.0	7.3	7.5	6.9	7.3
VOLUME AIR VOIDS	(i X f) ÷ 100	(j)	124.3	128.0	120.9	117.1	121.9	127.2	115.3	121.9
PEAK LOAD (Newton's)		(k)				23200	22800	21300		22000
DRY TS(kPa)	(2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**********	**********	**1023.5**	**1008.0**	**937.8**	**********	**975.7**
CALC. SSD AT 70% SAT.	(0.70 X j) + c		3998.5	4019.1	4009.4	4020.9	4025.8	4032.0	4020.2	4019.7
CALC. SSD AT 80% SAT.	(0.80 X j) + c		4010.9	4031.9	4021.4	4032.6	4038.0	4044.7	4031.7	4031.9

SATURATED	MINUTES @	"Hg							
Date and Time in:	11/16/99 1:00 PM		Date and Time out:		11/17/99 1:00 PM				
SSD MASS	(m)	4010.9	4020.6	4013.1				4030.9	
MASS IN WATER	(n)	2331.1	2342.9	2343.3				2351.0	
VOLUME	(m - n) (o)	1679.8	1677.7	1669.8	**********	**********	**********	1679.9	**********
VOL. ABS. H2O	(m - c) (p)	99.4	91.1	88.4	**********	**********	**********	91.4	**********
% SATURATION	100 X (p ÷ j)	80.0	71.2	73.1	**********	**********	**********	79.3	**********

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS		(q)	4025.3	4032.7	4019.6				4041.4	
MASS IN WATER		(r)	2348.4	2356.1	2354.0				2363.5	
VOLUME	(q - r)	(s)	1676.9	1676.6	1665.6	**********	**********	**********	1677.9	**********
VOLUME ABS. H2O	(q - c)	(t)	113.8	103.2	94.9	**********	**********	**********	101.9	**********
% SATURATION	100 X (t ÷ j)		91.6	80.6	78.5	**********	**********	**********	88.4	**********
PEAK LOAD (Newton's)		(u)	17900	18500	21200				19200	
WET TS(kPa)	(2000 X u) ÷ (a X b X 3.1416)	(v)	**791.4**	**819.6**	**936.3**	**********	**********	**********	**847.9**	**********
INTERNAL SPECIMEN TEMPERATURE (°F .)			78.00	78.00	78.00	79.00	78.00	79.00	77.00	78.00

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS	QA/QC Joint Test?
Dry Subset	7.3		78.5	**991.8**	
Wet Subset	7.3	74.7	77.8	**833.6**	Circle One
TENSILE STRENGTH RATIO				**84.1**	***(Yes)*** No
QA/QC COMPARATIVE TSR					

Visual Stripping:place x in appropriate box

None	Minor	Moderate	Severe

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA

TESTED BY: JASON THOMPSON

CERT. NO.: 51972

TESTED BY:

CERT. NO.:

LAB LOCATION:

LAB CERT NO.:

Comments:

Table C-4 TSR Test Data for 0.8% LOF 6500 Antistrip Additives with 2-Hour Prolonged Heating

Revised 11-29-99

NCDOT

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Marshall Compactive Method

M&T 612 (QMS-2)

Date Mix Produced:	Mix Type: L08-2	JMF No.:	
Contractor: NCSU	Plant Location:	Plant Cert. No.:	
Additive Supplier:	Additive Grade:	Additive Dosage:	
Date Compacted:	No. Gyrations: to height	Date Test Completed: 2/20/2007	

SPECIMEN NUMBER		1	2	3	4	5	6	7	8
DIAMETER(in)	(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(in.)	(b)	96.000	95.400	95.500	95.700	95.900	95.800	95.500	96.200
DRY MASS IN AIR	(c)	3928.3	3942.9	3942.7	3913.2	3905.1	3933.0	3930.5	3919.0
SSD MASS IN AIR	(d)	3945.7	3954.3	3955.7	3927.4	3913.3	3949.4	3940.2	3944.5
MASS IN WATER	(e)	2263.1	2290.2	2293.0	2260.2	2238.3	2272.4	2269.9	2272.9
VOLUME (d-e)	(f)	1682.6	1664.1	1662.7	1667.2	1675.0	1677.0	1670.3	1671.6
BULK SP. GR. (c ÷ f)	(g)	2.335	2.369	2.371	2.347	2.331	2.345	2.353	2.344
MAX. SP.GR. (From Actual Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS (100 X (h - g) ÷ h)	(i)	7.7	6.3	6.3	7.2	7.8	7.3	7.0	7.3
VOLUME AIR VOIDS (i X f) ÷ 100	(j)	129.6	104.8	104.8	120.0	130.7	122.4	116.9	122.0
PEAK LOAD (psi)	(k)				30900	27300		31200	27300
DRY TS (2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**********	**********	**1370.4**	**1208.2**	**********	**1386.6**	**1204.4**
CALC. SSD AT 70% SAT. (0.70 X j) + c		4019.0	4016.3	4016.0	3997.2	3996.6	4018.7	4012.3	4004.4
CALC. SSD AT 80% SAT. (0.80 X j) + c		4031.9	4026.8	4026.5	4009.2	4009.6	4030.9	4024.0	4016.6

SATURATED MINUTES @		"Hg							
Date and Time in: 01/16/02 9.15AM			Date and Time out:						
SSD MASS	(m)	4026.9	4020.3	4017.2			4019.2		
MASS IN WATER	(n)	2348.5	2358.7	2357.1			2346.6		
VOLUME (m - n)	(o)	1678.4	1661.6	1660.1	**********	**********	1672.6	**********	**********
VOL. ABS. H2O (m - c)	(p)	98.6	77.4	74.5	**********	**********	86.2	**********	**********
% SATURATION 100 X (p ÷ j)		76.1	73.8	71.1	**********	**********	70.4	**********	**********

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS	(q)	4034.9	4029.0	4026.0			4029.9		
MASS IN WATER	(r)	2355.7	2366.0	2364.3			2355.6		
VOLUME (q - r)	(s)	1679.2	1663.0	1661.7	**********	**********	1674.3	**********	**********
VOLUME ABS. H2O (q - c)	(t)	106.6	86.1	83.3	**********	**********	96.9	**********	**********
% SATURATION 100 X (t ÷ j)		82.3	82.1	79.5	**********	**********	79.2	**********	**********
PEAK LOAD (psi)	(u)	24400	27200	26800			26000		
WET TS (2 X u) ÷ (a X b X 3.1416)	(v)	**1078.7**	**1210.1**	**1191.0**	**********	**********	**1151.8**	**********	**********
INTERNAL SPECIMEN TEMPERATURE (°F .)		77.50	77.50	77.00	76.50	76.00	77.00	77.00	77.00

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS	QA/QC Joint Test?
Dry Subset	7.4		76.6	**1289.3**	
Wet Subset	6.9	72.9	77.3	**1171.4**	Circle One
TENSILE STRENGTH RATIO				**90.9**	**Yes** **No**
QA/QC COMPARATIVE TSR					

TESTED BY: Clippard/Massey
CERT. NO.:
TESTED BY:
CERT. NO.:
LAB LOCATION:
LAB CERT NO.:

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA

Visual Stripping:(Circle one)

None **Minor** **Moderate** **Severe**

Table C- 5 TSR Test Data for 0.8% LOF 6500 Antistrip Additives with 6-Hour Prolonged Heating

Revised August 2006

NCDOT M&T 612 (QMS-2)

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Gyratory Compactive Method

Date Mix Produced:		Mix Type:				JMF No.:		LO8-6-1-8	
Contractor:	NC STATE	Plant Location:				Plant Cert. No.:			
Additive Supplier:		Additive Grade:	LOF6500			Additive Dosage:		(%)	
Date Compacted:		No. Gyrations:	To height			Date Test Completed:		5/24/2007	

SPECIMEN NUMBER			1	2	3	4	5	6	7	8
DIAMETER(mm)		(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(mm)		(b)	96.100	96.200	96.100	95.900	96.000	96.300	96.300	96.000
DRY MASS IN AIR		(c)	3933.7	3928.9	3943.6	3939.1	3941.7	3936.8	3934.9	3933.1
SSD MASS IN AIR		(d)	3945.9	3942.1	3955.6	3954.1	3954.8	3946.8	3952.5	3946.1
MASS IN WATER		(e)	2267.9	2266.2	2275.7	2273.9	2277.1	2269.3	2274.2	2267.5
VOLUME	(d-e)	(f)	1678.0	1675.9	1679.9	1680.2	1677.7	1677.5	1678.3	1678.6
BULK SP. GR.	(c ÷ f)	(g)	2.344	2.344	2.348	2.344	2.349	2.347	2.345	2.343
MAX. SP.GR.	(Optimum Binder Content Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS	(100 X (h - g) ÷ h)	(i)	7.3	7.3	7.2	7.3	7.1	7.2	7.3	7.4
VOLUME AIR VOIDS	(i X f) ÷ 100	(j)	123.2	123.0	121.2	123.2	119.7	121.5	123.0	124.0
PEAK LOAD (Newton's)		(k)			34900		35000	35200		32800
DRY TS(kPa)	(2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**********	**1541.3**	**********	**1547.3**	**1551.3**	**********	**1450.1**
CALC. SSD AT 70% SAT.	(0.70 X j) + c		4019.9	4015.0	4028.4	4025.4	4025.5	4021.8	4021.0	4019.9
CALC. SSD AT 80% SAT.	(0.80 X j) + c		4032.2	4027.3	4040.5	4037.7	4037.5	4034.0	4033.3	4032.3

SATURATED	MINUTES @	"Hg							
Date and Time in:	11/16/99 1:00 PM		Date and Time out:			11/17/99 1:00 PM			
SSD MASS	(m)	4028.8	4025.6		4026.2			4029.0	
MASS IN WATER	(n)	2348.5	2344.7		2348.6			2352.0	
VOLUME	(m - n) (o)	1680.3	1680.9	**********	1677.6	**********	**********	1677.0	**********
VOL. ABS. H2O	(m - c) (p)	95.1	96.7	**********	87.1	**********	**********	94.1	**********
% SATURATION	100 X (p ÷ j)	77.2	78.6	**********	70.7	**********	**********	76.5	**********

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS	(q)	4044.6	4042.4		4039.9			4043.1	
MASS IN WATER	(r)	2361.5	2359.7		2360.9			2363.1	
VOLUME	(q - r) (s)	1683.1	1682.7	**********	1679.0	**********	**********	1680.0	**********
VOLUME ABS. H2O	(q - c) (t)	110.9	113.5	**********	100.8	**********	**********	108.2	**********
% SATURATION	100 X (t ÷ j)	90.0	92.3	**********	81.8	**********	**********	88.0	**********
PEAK LOAD (Newton's)	(u)	29100	28400		29900			29100	
WET TS(kPa)	(2000 X u) ÷ (a X b X 3.1416) (v)	**1285.2**	**1252.9**	**********	**1323.2**	**********	**********	**1282.5**	**********
INTERNAL SPECIMEN TEMPERATURE (°F .)		79.00	79.00	79.00	79.00	80.00	80.00	79.00	80.00

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS	QA/QC Joint Test?
Dry Subset	7.2		79.8	**1544.3**	
Wet Subset	7.3	75.5	79.0	**1283.8**	Circle One
TENSILE STRENGTH RATIO				**83.1**	***(Yes)*** **No**
QA/QC COMPARATIVE TSR					

Visual Stripping:place x in appropriate box

None	Minor	Moderate	Severe

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA

TESTED BY: JASON THOPMSON

CERT. NO.: 51972

TESTED BY:

CERT. NO.:

LAB LOCATION:

LAB CERT NO.:

Comments:

Table C- 6 TSR Test Data for 0.8% LOF 6500 Antistrip Additives with 12-Hour Prolonged Heating

Revised 11-29-99

NCDOT

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Marshall Compactive Method

M&T 612 (QMS-2)

Date Mix Produced:		Mix Type: L08-12	JMF No.:
Contractor:	NCSU	Plant Location:	Plant Cert. No.:
Additive Supplier:		Additive Grade:	Additive Dosage:
Date Compacted:		No. Gyrations: to height	Date Test Completed: 2/22/2007

SPECIMEN NUMBER			1	2	3	4	5	6	7	8
DIAMETER(in)		(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(in.)		(b)	95.500	95.400	95.300	95.300	95.100	96.400	95.900	95.900
DRY MASS IN AIR		(c)	3908.4	3913.0	3929.0	3949.8	3927.7	3935.9	3934.5	3941.6
SSD MASS IN AIR		(d)	3919.8	3930.2	3936.5	3962.1	3936.3	3946.0	3941.7	3965.7
MASS IN WATER		(e)	2255.9	2265.8	2277.2	2297.1	2275.9	2267.0	2268.2	2291.3
VOLUME	(d-e)	(f)	1663.9	1664.4	1659.3	1665.0	1660.4	1679.0	1673.5	1674.4
BULK SP. GR.	(c ÷ f)	(g)	2.349	2.351	2.368	2.372	2.366	2.344	2.351	2.354
MAX. SP.GR.	(From Actual Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS	(100 X (h - g) ÷ h)	(i)	7.2	7.1	6.4	6.2	6.5	7.3	7.1	7.0
VOLUME AIR VOIDS	(i X f) ÷ 100	(j)	119.8	118.2	106.2	103.2	107.9	122.6	118.8	117.2
PEAK LOAD (psi)		(k)		44400			44400		42400	41100
DRY TS	(2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**1975.3**	**********	**********	**1981.5**	**********	**1876.4**	**1818.9**
CALC. SSD AT 70% SAT.	(0.70 X j) + c		3992.3	3995.7	4003.3	4022.1	4003.2	4021.7	4017.7	4023.6
CALC. SSD AT 80% SAT.	(0.80 X j) + c		4004.2	4007.5	4014.0	4032.4	4014.0	4034.0	4029.6	4035.4

SATURATED	MINUTES @	"Hg							
Date and Time in:	01/16/02 9.15AM		Date and Time out:						
SSD MASS	(m)	3994.5		4003.4	4023.2		4025.9		
MASS IN WATER	(n)	2332.3		2345.5	2361.5		2352.3		
VOLUME	(m - n)	(o)	1662.2	**********	1657.9	1661.7	**********	1673.6	**********	**********
VOL. ABS. H2O	(m - c)	(p)	86.1	**********	74.4	73.4	**********	90.0	**********	**********
% SATURATION	100 X (p ÷ j)		71.9	**********	70.1	71.1	**********	73.4	**********	**********

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS	(q)	4013.2		4020.3	4036.4		4043.8		
MASS IN WATER	(r)	2342.9		2357.6	2369.2		2362.3		
VOLUME	(q - r)	(s)	1670.3	**********	1662.7	1667.2	**********	1681.5	**********	**********
VOLUME ABS. H2O	(q - c)	(t)	104.8	**********	91.3	86.6	**********	107.9	**********	**********
% SATURATION	100 X (t ÷ j)		87.5	**********	86.0	83.9	**********	88.0	**********	**********
PEAK LOAD (psi)		(u)	32800		33200	38300		34000		
WET TS	(2 X u) ÷ (a X b X 3.1416)	(v)	**1457.7**	**********	**1478.5**	**1705.7**	**********	**1496.9**	**********	**********
INTERNAL SPECIMEN TEMPERATURE (°F .)			78.00	77.50	78.00	77.50	77.00	77.50	77.50	77.00

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS
Dry Subset	6.9		77.3	**1925.8**
Wet Subset	6.8	71.6	77.8	**1487.7**
TENSILE STRENGTH RATIO				**77.2**
QA/QC COMPARATIVE TSR				

QA/QC Joint Test?	
Circle One	
Yes	**No**

TESTED BY: Clippard/Massey
CERT. NO.:
TESTED BY:
CERT. NO.:
LAB LOCATION:
LAB CERT NO.:

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA

Visual Stripping:(Circle one)

None	Minor	Moderate	Severe

Table C- 7 TSR Test Data for 0.8% LOF 6500 Antistrip Additives with 24-Hour Prolonged Heating

Revised August 2006

NCDOT M&T 612 (QMS-2)

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Gyratory Compactive Method

L08-24-1THRU-8

Date Mix Produced:		Mix Type:		JMF No.:	Pending
Contractor:	NC STATE	Plant Location:		Plant Cert. No.:	
Additive Supplier:	MORELIFE	Additive Grade:		Additive Dosage:	(%)
Date Compacted:		No. Gyrations:	To height	Date Test Completed:	5/10/2007

SPECIMEN NUMBER			1	2	3	4	5	6	7	8
DIAMETER(mm)		(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(mm)		(b)	97.700	97.200	97.600	97.200	98.500	97.600	97.400	97.500
DRY MASS IN AIR		(c)	3934.7	3934.5	3935.1	3944.9	3940.3	3946.3	3939.6	3938.3
SSD MASS IN AIR		(d)	3946.3	3947.6	3949.2	3952.5	3953.4	3957.3	3952.1	3950.8
MASS IN WATER		(e)	2263.5	2264.8	2267.3	2264.9	2267.3	2273.6	2268.9	2267.5
VOLUME	(d-e)	(f)	1682.8	1682.8	1681.9	1687.6	1686.1	1683.7	1683.2	1683.3
BULK SP. GR.	(c ÷ f)	(g)	2.338	2.338	2.340	2.338	2.337	2.344	2.341	2.340
MAX. SP.GR.	(Optimum Binder Content Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS	(100 X (h - g) ÷ h)	(i)	7.6	7.6	7.5	7.6	7.6	7.4	7.5	7.5
VOLUME AIR VOIDS	(i X f) ÷ 100	(j)	127.6	127.7	126.5	128.4	128.7	123.9	126.0	126.7
PEAK LOAD (Newton's)		(k)					27600	24800	29800	28400
DRY TS(kPa)	(2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**********	**********	**********	**1189.2**	**1078.4**	**1298.5**	**1236.2**
CALC. SSD AT 70% SAT.	(0.70 X j) + c		4024.0	4023.9	4023.7	4034.7	4030.4	4033.0	4027.8	4027.0
CALC. SSD AT 80% SAT.	(0.80 X j) + c		4036.8	4036.6	4036.3	4047.6	4043.2	4045.4	4040.4	4039.6

SATURATED	MINUTES @	"Hg							
Date and Time in:	11/16/99 1:00 PM		Date and Time out:			11/17/99 1:00 PM			
SSD MASS		(m)	4040.0	4039.4	4013.9	4029.9			
MASS IN WATER		(n)	2342.9	2347.5	2317.2	2337.9			
VOLUME	(m - n)	(o)	1697.1	1691.9	1696.7	1692.0	**********	**********	**********	**********
VOL. ABS. H2O	(m - c)	(p)	105.3	104.9	78.8	85.0	**********	**********	**********	**********
% SATURATION	100 X (p ÷ j)		82.5	82.2	62.3	66.2	**********	**********	**********	**********

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS		(q)	4065.8	4067.7	4067.2	4069.0				
MASS IN WATER		(r)	2357.6	2363.8	2355.2	2364.2				
VOLUME	(q - r)	(s)	1708.2	1703.9	1712.0	1704.8	**********	**********	**********	**********
VOLUME ABS. H2O	(q - c)	(t)	131.1	133.2	132.1	124.1	**********	**********	**********	**********
% SATURATION	100 X (t ÷ j)		102.8	104.3	104.4	96.7	**********	**********	**********	**********
PEAK LOAD (Newton's)		(u)	22000	20600	19300	21800				
WET TS(kPa)	(2000 X u) ÷ (a X b X 3.1416)	(v)	**955.7**	**899.5**	**839.3**	**951.9**	**********	**********	**********	**********
INTERNAL SPECIMEN TEMPERATURE (°F .)			78.00	78.00	78.00	78.00	79.00	79.00	79.00	79.00

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS	QA/QC Joint Test?
Dry Subset	7.5		79.0	**1212.7**	Circle One
Wet Subset	7.6	73.3	78.0	**925.7**	
TENSILE STRENGTH RATIO				**76.3**	*(Yes)* No
QA/QC COMPARATIVE TSR					

Visual Stripping:place x in appropriate box

None	Minor	Moderate	Severe

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA

TESTED BY: JASON THOMPSON

CERT. NO.: 51972

TESTED BY:

CERT. NO.:

LAB LOCATION:

LAB CERT NO.:

Comments:

Table C- 8 TSR Test Data for 0.8% Morlife 2200 Antistrip Additives without Prolonged Heating

Revised August 2006

NCDOT M&T 612 (QMS-2)

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Gyratory Compactive Method

Date Mix Produced:	Mix Type:	JMF No.:	MO6-00-1-8
Contractor: NC STATE	Plant Location:	Plant Cert. No.:	
Additive Supplier:	Additive Grade: MORLIFE	Additive Dosage:	(%)
Date Compacted:	No. Gyrations: To height	Date Test Completed:	5/17/2007

SPECIMEN NUMBER			1	2	3	4	5	6	7	8
DIAMETER(mm)		(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(mm)		(b)	95.600	96.000	96.400	96.600	95.900	95.800	96.000	96.000
DRY MASS IN AIR		(c)	3945.2	3936.9	3941.2	3937.5	3911.1	3941.7	3911.0	3943.5
SSD MASS IN AIR		(d)	3956.0	3947.1	3949.6	3947.6	3921.4	3952.4	3924.4	3952.9
MASS IN WATER		(e)	2277.7	2269.4	2267.5	2266.7	2244.5	2275.1	2249.4	2273.8
VOLUME	(d-e)	(f)	1678.3	1677.7	1682.1	1680.9	1676.9	1677.3	1675.0	1679.1
BULK SP. GR.	(c ÷ f)	(g)	2.351	2.347	2.343	2.342	2.332	2.350	2.335	2.349
MAX. SP.GR.	(Optimum Binder Content Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS	(100 X (h - g) ÷ h)	(i)	7.1	7.2	7.4	7.4	7.8	7.1	7.7	7.2
VOLUME AIR VOIDS	(i X f) ÷ 100	(j)	118.9	121.6	124.3	124.6	131.0	119.3	129.2	120.4
PEAK LOAD (Newton's)		(k)		20000	20000				19100	20000
DRY TS(kPa)	(2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**884.2**	**880.5**	**********	**********	**********	**844.4**	**884.2**
CALC. SSD AT 70% SAT.	(0.70 X j) + c		4028.5	4022.0	4028.2	4024.7	4002.8	4025.2	4001.4	4027.8
CALC. SSD AT 80% SAT.	(0.80 X j) + c		4040.3	4034.2	4040.7	4037.2	4015.9	4037.2	4014.3	4039.8

SATURATED	MINUTES @	"Hg							
Date and Time in:	11/16/99 1:00 PM		Date and Time out:		11/17/99 1:00 PM				
SSD MASS	(m)	4028.6			4035.3	4014.3	4035.1		
MASS IN WATER	(n)	2351.0			2353.8	2334.9	2357.1		
VOLUME	(m - n)	(o)	1677.6	**********	**********	1681.5	1679.4	1678.0	**********	**********
VOL. ABS. H2O	(m - c)	(p)	83.4	**********	**********	97.8	103.2	93.4	**********	**********
% SATURATION	100 X (p ÷ j)		70.1	**********	**********	78.5	78.8	78.3	**********	**********

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS	(q)	4043.3			4050.8	4031.2	4048.3		
MASS IN WATER	(r)	2363.4			2365.0	2348.5	2367.9		
VOLUME	(q - r)	(s)	1679.9	**********	**********	1685.8	1682.7	1680.4	**********	**********
VOLUME ABS. H2O	(q - c)	(t)	98.1	**********	**********	113.3	120.1	106.6	**********	**********
% SATURATION	100 X (t ÷ j)		82.5	**********	**********	90.9	91.7	89.3	**********	**********
PEAK LOAD (Newton's)		(u)	18400			17200	16700	18000		
WET TS(kPa)	(2000 X u) ÷ (a X b X 3.1416)	(v)	**816.9**	**********	**********	**755.7**	**739.1**	**797.4**	**********	**********
INTERNAL SPECIMEN TEMPERATURE (°F .)			78.00	79.00	79.00	78.00	78.00	78.00	79.00	79.00

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS
Dry Subset	7.4		79.0	**882.4**
Wet Subset	7.4	76.4	78.0	**776.6**
TENSILE STRENGTH RATIO				**88.0**

QA/QC Joint Test? Circle One ***(Yes)*** No

QA/QC COMPARATIVE TSR

Visual Stripping:place x in appropriate box

None	Minor	Moderate	Severe

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA

TESTED BY: JASON THOMPSON

CERT. NO.: 51972

TESTED BY:

CERT. NO.:

LAB LOCATION:

LAB CERT NO.:

Comments:

Table C- 9 TSR Test Data for 0.8% Morlife 2200 Antistrip Additives with 2-Hour Prolonged Heating

Revised August 2006

NCDOT M&T 612 (QMS-2)

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Gyratory Compactive Method

Date Mix Produced:	Mix Type:		JMF No.: MO6-02-1-8
Contractor: NC STATE	Plant Location:		Plant Cert. No.:
Additive Supplier:	Additive Grade: MORELIFE		Additive Dosage: (%)
Date Compacted:	No. Gyrations: To height		Date Test Completed:

SPECIMEN NUMBER			1	2	3	4	5	6	7	8
DIAMETER(mm)		(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(mm)		(b)	96.000	95.900	95.900	95.600	95.800	96.200	95.600	95.700
DRY MASS IN AIR		(c)	3936.1	3920.5	3921.4	3940.5	3917.7	3935.8	3928.0	3943.1
SSD MASS IN AIR		(d)	3945.4	3934.8	3935.6	3955.2	3928.0	3951.6	3944.8	3954.7
MASS IN WATER		(e)	2273.4	2259.1	2260.9	2281.3	2252.2	2282.4	2274.3	2278.3
VOLUME	(d-e)	(f)	1672.0	1675.7	1674.7	1673.9	1675.8	1669.2	1670.5	1676.4
BULK SP. GR.	(c ÷ f)	(g)	2.354	2.340	2.342	2.354	2.338	2.358	2.351	2.352
MAX. SP.GR.	(Optimum Binder Content Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS	(100 X (h - g) ÷ h)	(i)	7.0	7.5	7.4	7.0	7.6	6.8	7.1	7.0
VOLUME AIR VOIDS	(i X f) ÷ 100	(j)	116.2	126.1	124.7	116.4	127.3	113.5	117.9	117.9
PEAK LOAD (Newton's)		(k)					27000	29100	28500	28100
DRY TS(kPa)	(2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**********	**********	**********	**1196.2**	**1283.8**	**1265.2**	**1246.2**
CALC. SSD AT 70% SAT.	(0.70 X j) + c		4017.5	4008.8	4008.7	4022.0	4006.8	4015.3	4010.6	4025.6
CALC. SSD AT 80% SAT.	(0.80 X j) + c		4029.1	4021.4	4021.2	4033.6	4019.5	4026.6	4022.3	4037.4

SATURATED	MINUTES @	"Hg							
Date and Time in:	11/16/99 1:00 PM		Date and Time out:		11/17/99 1:00 PM				
SSD MASS	(m)	4025.6	4015.1	4019.3	4024.3				
MASS IN WATER	(n)	2353.0	2336.7	2341.3	2349.3				
VOLUME	(m - n) (o)	1672.6	1678.4	1678.0	1675.0	**********	**********	**********	**********
VOL. ABS. H2O	(m - c) (p)	89.5	94.6	97.9	83.8	**********	**********	**********	**********
% SATURATION	100 X (p ÷ j)	77.0	75.0	78.5	72.0	**********	**********	**********	**********

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS	(q)	4038.1	4031.7	4030.9	4035.8				
MASS IN WATER	(r)	2363.1	2351.0	2353.6	2361.0				
VOLUME	(q - r) (s)	1675.0	1680.7	1677.3	1674.8	**********	**********	**********	**********
VOLUME ABS. H2O	(q - c) (t)	102.0	111.2	109.5	95.3	**********	**********	**********	**********
% SATURATION	100 X (t ÷ j)	87.8	88.2	87.8	81.9	**********	**********	**********	**********
PEAK LOAD (Newton's)	(u)	24500	23200	24000	26000				
WET TS(kPa)	(2000 X u) ÷ (a X b X 3.1416) (v)	**1083.1**	**1026.7**	**1062.1**	**1154.3**	**********	**********	**********	**********
INTERNAL SPECIMEN TEMPERATURE (°F .)		77.00	77.00	77.00	77.00	78.00	78.00	78.00	78.00

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS	QA/QC Joint Test?
Dry Subset	7.1		78.0	**1255.7**	Circle One
Wet Subset	7.2	75.6	77.0	**1072.6**	
TENSILE STRENGTH RATIO				**85.4**	*(Yes)* No
QA/QC COMPARATIVE TSR					

TESTED BY: JASON THOMPSON
CERT. NO.: 51972
TESTED BY:
CERT. NO.:
LAB LOCATION:
LAB CERT NO.:
Comments:

Visual Stripping:place x in appropriate box

None	Minor	Moderate	Severe

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA

Table C- 10 TSR Test Data for 0.8% Morlife 2200 Antistrip Additives with 6-Hour Prolonged Heating

Revised August 2006

NCDOT M&T 612 (QMS-2)

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Gyratory Compactive Method

MO8-6-1-THR

Date Mix Produced:		Mix Type:				JMF No.:	Pending		
Contractor:	NC STATE	Plant Location:				Plant Cert. No.:			
Additive Supplier:		Additive Grade:	MORELIFE			Additive Dosage:	(%)		
Date Compacted:		No. Gyrations:	To height			Date Test Completed:	5/11/2007		

SPECIMEN NUMBER		1	2	3	4	5	6	7	8
DIAMETER(mm)	(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(mm)	(b)	96.400	97.400	97.100	95.800	96.400	96.200	95.700	95.900
DRY MASS IN AIR	(c)	3940.3	3942.4	3939.6	3936.9	3938.3	3916.8	3928.8	3936.4
SSD MASS IN AIR	(d)	3950.7	3953.0	3950.7	3950.3	3951.3	3930.7	3941.0	3950.1
MASS IN WATER	(e)	2270.6	2266.5	2267.4	2266.6	2266.5	2249.4	2258.5	2268.9
VOLUME (d-e)	(f)	1680.1	1686.5	1683.3	1683.7	1684.8	1681.3	1682.5	1681.2
BULK SP. GR. (c ÷ f)	(g)	2.345	2.338	2.340	2.338	2.338	2.330	2.335	2.341
MAX. SP.GR. (Optimum Binder Content Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS (100 X (h - g) ÷ h)	(i)	7.3	7.6	7.5	7.6	7.6	7.9	7.7	7.5
VOLUME AIR VOIDS (i X f) ÷ 100	(j)	122.7	128.2	126.1	127.6	128.2	133.2	129.6	125.3
PEAK LOAD (Newton's)	(k)					32800	32400	34300	33400
DRY TS(kPa) (2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**********	**********	**********	**1444.1**	**1429.4**	**1521.1**	**1478.1**
CALC. SSD AT 70% SAT. (0.70 X j) + c		4026.2	4032.2	4027.9	4026.2	4028.0	4010.0	4019.5	4024.1
CALC. SSD AT 80% SAT. (0.80 X j) + c		4038.4	4045.0	4040.5	4039.0	4040.8	4023.3	4032.5	4036.6

SATURATED MINUTES @		"Hg							
Date and Time in: 11/16/99 1:00 PM			Date and Time out:			11/17/99 1:00 PM			
SSD MASS	(m)	4026.6	4041.9	4036.8	4030.4				
MASS IN WATER	(n)	2350.1	2359.2	2356.7	2352.1				
VOLUME (m - n)	(o)	1676.5	1682.7	1680.1	1678.3	**********	**********	**********	**********
VOL. ABS. H2O (m - c)	(p)	86.3	99.5	97.2	93.5	**********	**********	**********	**********
% SATURATION 100 X (p ÷ j)		70.4	77.6	77.1	73.3	**********	**********	**********	**********

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS	(q)	4042.2	4058.3	4051.7	4049.5				
MASS IN WATER	(r)	2360.2	2369.1	2365.5	2364.9				
VOLUME (q - r)	(s)	1682.0	1689.2	1686.2	1684.6	**********	**********	**********	**********
VOLUME ABS. H2O (q - c)	(t)	101.9	115.9	112.1	112.6	**********	**********	**********	**********
% SATURATION 100 X (t ÷ j)		83.1	90.4	88.9	88.2	**********	**********	**********	**********
PEAK LOAD (Newton's)	(u)	28000	25700	26000	27000				
WET TS(kPa) (2000 X u) ÷ (a X b X 3.1416)	(v)	**1232.7**	**1119.9**	**1136.4**	**1196.2**	**********	**********	**********	**********
INTERNAL SPECIMEN TEMPERATURE (°F .)		79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS	QA/QC Joint Test?
Dry Subset	7.7		79.0	**1461.1**	
Wet Subset	7.5	74.6	79.0	**1166.3**	Circle One
TENSILE STRENGTH RATIO				**79.8**	***(Yes)*** **No**
QA/QC COMPARATIVE TSR					

Visual Stripping:place x in appropriate box

None	Minor	Moderate	Severe

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA

TESTED BY: JASON THOMPSON 51972

CERT. NO.:

TESTED BY:

CERT. NO.:

LAB LOCATION:

LAB CERT NO.:

Comments:

Table C- 11 TSR Test Data for 0.8% Morlife 2200 Antistrip Additives with 12-Hour Prolonged Heating

Revised August 2006

NCDOT M&T 612 (QMS-2)

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Gyratory Compactive Method

MO6-12-1-E

Date Mix Produced:	Mix Type:	JMF No.:	Pending
Contractor: NC STATE	Plant Location:	Plant Cert. No.:	
Additive Supplier:	Additive Grade: MORELIFE	Additive Dosage:	(%)
Date Compacted:	No. Gyrations: To height	Date Test Completed:	5/15/2007

SPECIMEN NUMBER			1	2	3	4	5	6	7	8
DIAMETER(mm)		(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(mm)		(b)	96.000	96.000	95.800	95.600	95.600	95.700	96.200	95.500
DRY MASS IN AIR		(c)	3937.1	3932.5	3939.5	3937.3	3939.8	3928.9	3934.6	3934.7
SSD MASS IN AIR		(d)	3946.1	3939.3	3948.7	3945.5	3946.3	3942.4	3947.2	3940.1
MASS IN WATER		(e)	2274.1	2262.3	2273.8	2271.2	2272.8	2269.7	2277.8	2269.0
VOLUME	(d-e)	(f)	1672.0	1677.0	1674.9	1674.3	1673.5	1672.7	1669.4	1671.1
BULK SP. GR.	(c ÷ f)	(g)	2.355	2.345	2.352	2.352	2.354	2.349	2.357	2.355
MAX. SP.GR.	(Optimum Binder Content Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS	(100 X (h - g) ÷ h)	(i)	6.9	7.3	7.0	7.1	6.9	7.2	6.8	6.9
VOLUME AIR VOIDS	(i X f) ÷ 100	(j)	115.8	122.7	117.8	118.1	116.3	119.8	114.2	115.9
PEAK LOAD (Newton's)		(k)				41200		40100	41400	40500
DRY TS(kPa)	(2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**********	**********	**1829.1**	**********	**1778.4**	**1826.5**	**1799.9**
CALC. SSD AT 70% SAT.	(0.70 X j) + c		4018.2	4018.4	4021.9	4019.9	4021.2	4012.7	4014.6	4015.8
CALC. SSD AT 80% SAT.	(0.80 X j) + c		4029.8	4030.6	4033.7	4031.7	4032.8	4024.7	4026.0	4027.4

SATURATED	MINUTES @	"Hg							
Date and Time in:	11/16/99 1:00 PM		Date and Time out:		11/17/99 1:00 PM				
SSD MASS	(m)	4024.8	4022.9	4026.7		4024.6			
MASS IN WATER	(n)	2352.6	2345.7	2353.1		2351.9			
VOLUME	(m - n)	(o)	1672.2	1677.2	1673.6	**********	1672.7	**********	**********	**********
VOL. ABS. H2O	(m - c)	(p)	87.7	90.4	87.2	**********	84.8	**********	**********	**********
% SATURATION	100 X (p ÷ j)		75.7	73.7	74.0	**********	72.9	**********	**********	**********

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS		(q)	4042.8	4042.6	4044.3		4044.1			
MASS IN WATER		(r)	2364.4	2358.7	2364.2		2364.4			
VOLUME	(q - r)	(s)	1678.4	1683.9	1680.1	**********	1679.7	**********	**********	**********
VOLUME ABS. H2O	(q - c)	(t)	105.7	110.1	104.8	**********	104.3	**********	**********	**********
% SATURATION	100 X (t ÷ j)		91.3	89.8	89.0	**********	89.7	**********	**********	**********
PEAK LOAD (Newton's)		(u)	30900	31600	33400		34500			
WET TS(kPa)	(2000 X u) ÷ (a X b X 3.1416)	(v)	**1366.1**	**1397.0**	**1479.7**	**********	**1531.6**	**********	**********	**********
INTERNAL SPECIMEN TEMPERATURE (°F .)			79.00	79.00	79.00	78.00	79.00	78.00	79.00	79.00

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS	QA/QC Joint Test?
Dry Subset	7.0		78.5	**1813.2**	
Wet Subset	7.1	74.1	79.0	**1438.4**	Circle One
TENSILE STRENGTH RATIO				**79.3**	*(Yes)* No
QA/QC COMPARATIVE TSR					

TESTED BY: JASON THOMPSON

CERT. NO.: 51972

TESTED BY:

CERT. NO.:

LAB LOCATION:

LAB CERT NO.:

Comments:

Visual Stripping:place x in appropriate box

None	Minor	Moderate	Severe

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA

Table C- 12 TSR Test Data for 0.8% Morlife 2200 Antistrip Additives with 24-Hour Prolonged Heating

Revised August 2006

NCDOT M&T 612 (QMS-2)

TENSILE STRENGTH RATIO (TSR) TEST WORKSHEET

Gyratory Compactive Method

MO8-24-1-THR

Date Mix Produced:	Mix Type:	JMF No.:	Pending
Contractor: NC STATE	Plant Location:	Plant Cert. No.:	
Additive Supplier:	Additive Grade: MORELIFE	Additive Dosage:	(%)
Date Compacted:	No. Gyrations: To height	Date Test Completed:	5/11/2007

SPECIMEN NUMBER			1	2	3	4	5	6	7	8
DIAMETER(mm)		(a)	150.000	150.000	150.000	150.000	150.000	150.000	150.000	150.000
THICKNESS(mm)		(b)	98.900	98.500	97.800	96.400	97.700	98.600	99.100	99.800
DRY MASS IN AIR		(c)	3937.4	3945.2	3917.9	3936.5	3948.2	3940.6	3924.6	3934.9
SSD MASS IN AIR		(d)	3946.4	3956.2	3926.3	3947.2	3963.5	3948.6	3935.7	3942.8
MASS IN WATER		(e)	2258.7	2262.5	2247.6	2264.6	2268.7	2256.3	2252.3	2257.9
VOLUME	(d-e)	(f)	1687.7	1693.7	1678.7	1682.6	1694.8	1692.3	1683.4	1684.9
BULK SP. GR.	(c ÷ f)	(g)	2.333	2.329	2.334	2.340	2.330	2.329	2.331	2.335
MAX. SP.GR.	(Optimum Binder Content Rice Test)	(h)	2.530	2.530	2.530	2.530	2.530	2.530	2.530	2.530
% AIR VOIDS	(100 X (h - g) ÷ h)	(i)	7.8	7.9	7.8	7.5	7.9	8.0	7.9	7.7
VOLUME AIR VOIDS	(i X f) ÷ 100	(j)	131.4	134.3	130.1	126.7	134.2	134.8	132.2	129.6
PEAK LOAD (Newton's)		(k)					31000	21800	19400	16800
DRY TS(kPa)	(2000 X k) ÷ (a X b X 3.1416)	(l)	**********	**********	**********	**********	**1346.7**	**938.4**	**830.8**	**714.4**
CALC. SSD AT 70% SAT.	(0.70 X j) + c		4029.4	4039.2	4009.0	4025.2	4042.2	4034.9	4017.1	4025.6
CALC. SSD AT 80% SAT.	(0.80 X j) + c		4042.5	4052.7	4022.0	4037.8	4055.6	4048.4	4030.3	4038.6

SATURATED	MINUTES @		"Hg							
Date and Time in:	11/16/99 1:00 PM			Date and Time out:		11/17/99 1:00 PM				
SSD MASS		(m)	4040.6	4051.0	4021.0	4025.4				
MASS IN WATER		(n)	2329.8	2344.1	2323.6	2346.7				
VOLUME	(m - n)	(o)	1710.8	1706.9	1697.4	1678.7	**********	**********	**********	**********
VOL. ABS. H2O	(m - c)	(p)	103.2	105.8	103.1	88.9	**********	**********	**********	**********
% SATURATION	100 X (p ÷ j)		78.5	78.8	79.2	70.2	**********	**********	**********	**********

CONDITIONED 24 HOURS IN 140 DEGREE WATER

SSD MASS		(q)	4091.9	4082.6	4062.5	4051.7				
MASS IN WATER		(r)	2360.9	2361.6	2347.6	2358.7				
VOLUME	(q - r)	(s)	1731.0	1721.0	1714.9	1693.0	**********	**********	**********	**********
VOLUME ABS. H2O	(q - c)	(t)	154.5	137.4	144.6	115.2	**********	**********	**********	**********
% SATURATION	100 X (t ÷ j)		117.6	102.3	111.1	90.9	**********	**********	**********	**********
PEAK LOAD (Newton's)		(u)	9600	17300	10300	23200				
WET TS(kPa)	(2000 X u) ÷ (a X b X 3.1416)	(v)	**412.0**	**745.4**	**447.0**	**1021.4**	**********	**********	**********	**********
INTERNAL SPECIMEN TEMPERATURE (°F .)			79.00	79.00	79.00	79.00	79.00	79.00	79.00	79.00

	Aver. VTM	Aver. Saturation	Aver. Temp.	Median TS
Dry Subset	7.9		79.0	**884.6**
Wet Subset	7.7	76.7	79.0	**596.2**
TENSILE STRENGTH RATIO				**67.4**
QA/QC COMPARATIVE TSR				

QA/QC Joint Test? Circle One (Yes) No

TESTED BY: JASON THOMPSON
CERT. NO.: 51972
TESTED BY:
CERT. NO.:
LAB LOCATION:
LAB CERT NO.:
Comments:

Visual Stripping:place x in appropriate box

None	Minor	Moderate	Severe

Note: Attach proposed M&T 601 form when TSR specimens are being submitted to QA