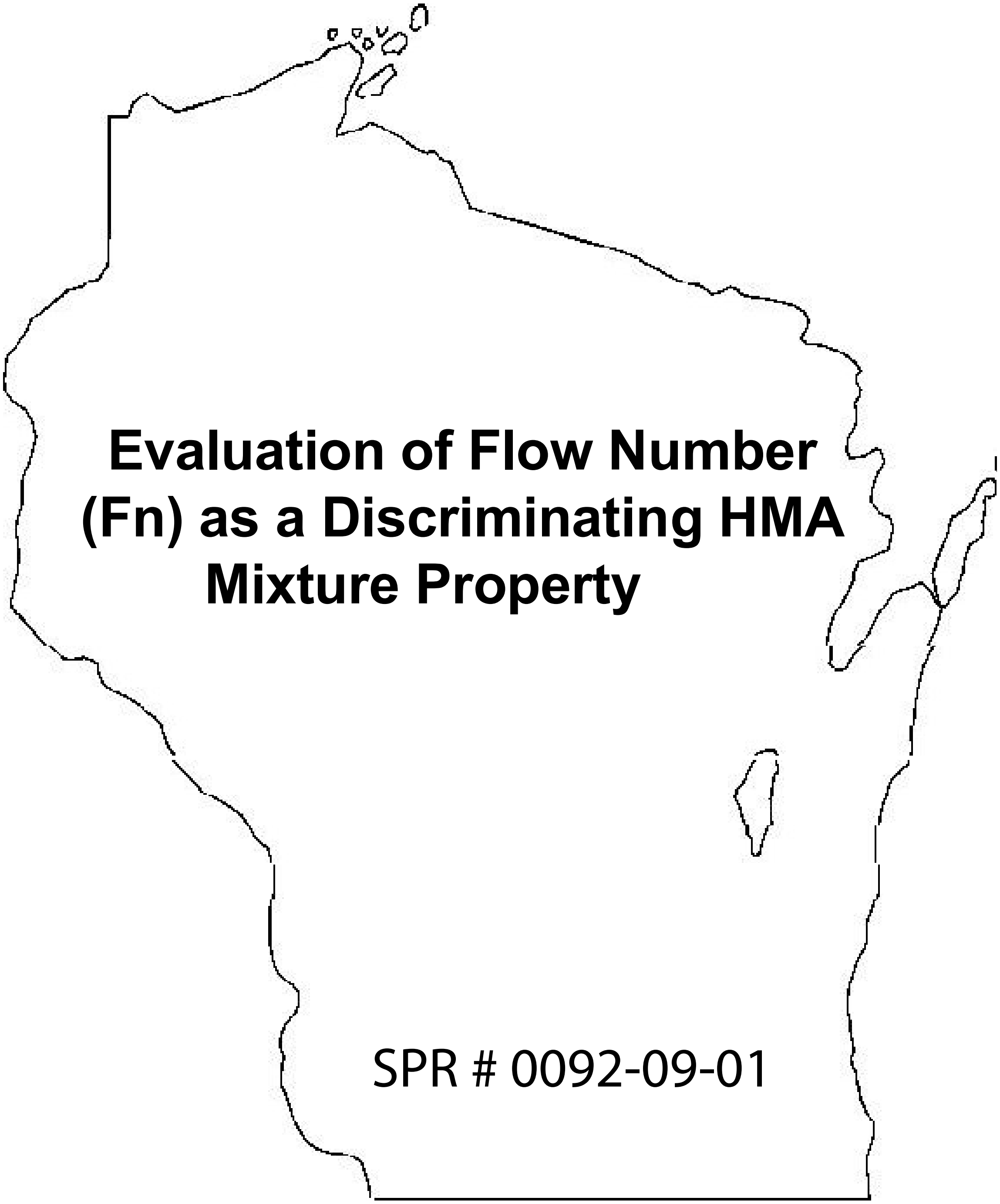
Wisconsin Highway Research Program



Evaluation of Flow Number (Fn) as a Discriminating HMA Mixture Property

SPR # 0092-09-01

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Disclaimer

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16. Abstract

This research investigated the use of the flow number in asphalt concrete mixture design and acceptance. It included: (1) a review of completed research concerning the flow number and the effect of mixture composition on rutting resistance, (2) an evaluation of Wisconsin Department of Transportation (WisDOT) criteria for mixture design and acceptance based on relationships between mixture composition and rutting resistance developed in National Cooperative Highway Research Program (NCHRP) Projects 9-25, 9-31, and 9-33, (3) a laboratory experiment to evaluate the effect of changes in asphalt content and filler content on rutting resistance as measured by the flow number, and (4) a laboratory experiment to develop flow number criteria for intersection mixtures. Recommendations and criteria for using the flow number test in mixture design and acceptance were developed.

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Executive Summary

Project Summary

Wisconsin Highway Research Program (WHRP) Project 0092-09-01 investigated the use of the flow number in asphalt concrete mixture design and acceptance. It included: (1) a review of completed research concerning the flow number and the effect of mixture composition on rutting resistance, (2) an evaluation of Wisconsin Department of Transportation (WisDOT) criteria for mixture design and acceptance based on relationships between mixture composition and rutting resistance developed in National Cooperative Highway Research Program (NCHRP) Projects 9-25, 9-31, and 9-33, (3) a laboratory experiment to evaluate the effect of changes in asphalt content and filler content on rutting resistance as measured by the flow number, and (4) a laboratory experiment to develop flow number criteria for intersection mixtures. Recommendations and criteria for using the flow number test in mixture design and acceptance were developed.

Background

The flow number is one of three tests that were identified in NCHRP Project 9-19 as simple performance tests related to the rutting resistance of asphalt concrete mixtures; the others being dynamic modulus and flow time. In NCHRP Project 9-33, tentative flow number criteria for mixture design were developed based on evaluation of a limited number of mixtures. These tentative criteria have been included the Mix Design Manual that was developed in that project.

Evaluation of the dynamic modulus and flow number tests in WHRP Project 0092-04-07: *Testing Wisconsin Mixtures for the AASHTO 2002 Mechanistic Design Procedure* concluded that the flow number appeared to be a more sensitive indicator of the rutting resistance of HMA than the dynamic modulus. Although this completed research supports the flow number as a general measure of rutting resistance, only limited data documenting the effect of mixture composition on the flow number have been reported. Additionally, the flow number criteria that were developed in NCHRP Project 9-33 were based on traffic moving at normal highway speeds. Mixtures placed at intersections are subjected to the effects of slow or standing traffic resulting in greater potential for rutting.

Current mixture design methods provide designers considerable freedom in selecting the composition of a mixture. With limited information available on the effects of mixture composition on the flow number, it may be difficult to develop mixtures that meet the flow number criteria. Additionally, acceptance criteria permit deviation from the design job mix formula during construction, which may result in a change in the flow number and rutting resistance of the mixture. WHRP Project 0092-09-01 was a structured study designed to evaluate the effect of changes in mixture composition on the flow number and to develop flow number criteria for mixtures used at intersections.

Process

WHRP Project 0092-09-01 started with a review of completed research concerning the flow number and the effect of mixture composition on rutting resistance. Based on this review two laboratory experiments were designed. The first experiment, called the primary flow number experiment, was designed to evaluate the effect of changes in asphalt content and filler content on the flow number. At total of 180 flow number tests were conducted on variation of six mixtures: three E-3 mixtures and three E-10 mixtures. The second experiment, called the intersection flow number experiment, was designed to evaluate differences in flow numbers for mixtures with good and poor performance at intersections. Eight different mixtures were evaluated in this experiment. The results of the two experiments and estimates of rutting resistance from a model developed in NCHRP Projects 9-25, 9-31, and 9-33 relating rutting resistance to mixture composition were used to evaluate current WisDOT criteria for mixture design and acceptance, and to establish recommended flow number criteria for use in mixture design and acceptance.

Findings and Conclusions

The evaluation of the WisDOT criteria for mixture design and acceptance found that the design criteria produce mixtures that are overdesigned for rutting for design traffic levels of E-3 and lower. Binder grade selection is critical for design traffic levels of E-10 and greater. For E-10 mixtures, PG 64 binders are needed to provide adequate rutting resistance. Neat PG 58 binders can be used with E-10 mixtures provided the dust to effective binder ratio exceeds 1.0.

Traffic levels E-30 and E-30x require polymer modified PG 70 binders to provide adequate rutting resistance.

Data from the primary flow number experiment confirmed that deviations in binder content and filler content significantly affect the rutting resistance of asphalt mixtures as measured by the flow number. Flow numbers consistently decreased with increasing binder content for all mixtures tested; however, the effect was mixture specific. At the WisDOT high warning limit of 0.3 percent, the flow number decreased from about 10 to 30 percent. For the more sensitive mixtures, this decrease is large enough to result in a one traffic level reduction in the rutting resistance of the mixture based on relationships between flow number and allowable traffic developed in WHRP Projects 0092-08-06 and 0092-09-01. The effect of filler content was mixed. Increasing the filler content above the design value generally improved rutting resistance, but for approximately one-half of the mixtures tested the rutting resistance also increased when the filler content was decreased.

It is well known that traffic speed has a significant effect on rutting in asphalt concrete mixtures. For the same traffic level, pavement areas subjected to slow speed and standing traffic require mixtures with greater rutting resistance to achieve the same rutting performance as mixtures subjected to high speed traffic. This was confirmed by the intersection experiment conducted in WHRP Project 0092-09-01. Intersection mixtures exhibiting good performance had flow numbers that were 4 to 26 times greater than those exhibiting poor performance. Based on evaluation of this data, it was determined that intersection mixtures should have flow numbers 6 times greater than those for normal traffic speed, 40 mph (64.4 km/hr). Based on this estimate and the speed relationship in the NCHRP rutting resistance model, flow number criteria for highway speed, 40 mph (64.4 km/hr) and greater, slow speed, 20 mph (32.2 km/hr), and intersections were developed. The criteria for the slow speed and intersection mixtures are 3 and 6 times that required for highway speed traffic.

A significant issue in flow number testing is an appropriate level of short-term oven conditioning for flow number specimens. Based on research completed in NCHRP Project 9-43, two hours of short-term conditioning at the compaction temperature was used in WHRP Project

0092-09-01 to represent the stiffness of the mixture at the time of construction. For the same mixtures tested in WHRP Projects 0092-08-06 using 4 hours of short-term conditioning at 135 ºC, 2 hours at the compaction temperature results in flow numbers that are approximately one-half of those measured using 4 hours of short-term conditioning at 135 ºC.

Recommendations

Several research studies including WHRP Projects 0092-04-07 and 0092-08-06 have recommended using the flow number during mixture design to evaluate asphalt concrete rutting resistance. The research completed in this project has shown that production deviations from the design binder and filler contents significantly affect rutting resistance. To account for the detrimental effect of increasing binder content on the flow number, flow number testing during mixture design should be conducted on specimens prepared at the high warning limit for asphalt content.

Flow number criteria for rutting resistance that were developed in WHRP Project 0092-08-06 were extended in this project to consider the effects of traffic speed and reduced short-term oven conditioning. This resulted in tentative flow number criteria as a function of design traffic level and traffic speed for two short-term oven conditioning protocols: 4 hours at 135 ºC, and 2 hours at the compaction temperature. WisDOT should consider conducting flow number testing on selected mixtures during the 2012 construction season to verify and improve these tentative criteria before considering their use in mixture design and acceptance.

The research completed in this project also showed that some mixtures could still provide adequate rutting resistance when produced outside of current WisDOT acceptance limits. The flow number test and the criteria developed in this project could be used to assign appropriate disincentives for mixtures produced outside of allowable production tolerances, where rutting is the primary distress that is expected based on the production deviations. This would include mixtures with high asphalt content and/or low filler content. When applying this approach to surface mixtures, consideration should be given to the potential of the mixture to lose skid resistance due to flushing, which is not considered by the flow number test.

When conducting flow number tests on plant produced mixtures, it is recommended that the criteria for two hours of short-term conditioning at the compaction temperature be used based on the findings in NCHRP Project 9-43 that showed that this level of conditioning reasonably reproduced the stiffness of HMA and WMA mixtures at the time of construction.

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Chapter 1 Introduction and Research Approach

1.1 Problem Statement

WHRP Project 0092-09-01, *Evaluation of Flow Number (F_n) as a Discriminating HMA Mixture Property*, addressed the use of the flow number in the design and acceptance of hot mix asphalt (HMA). The flow number is one of three tests that were identified in National Cooperative Highway Research Program (NCHRP) Project 9-19 as simple performance tests related to the rutting resistance of HMA mixtures (*1*); the others being dynamic modulus and flow time. In NCHRP Project 9-33, tentative flow number criteria for mixture design were developed based on evaluation of a limited number of mixtures (*2*). These tentative criteria were included the Mix Design Manual that was developed in that project.

Evaluation of the dynamic modulus and flow number tests in WHRP Project 0092-04-07, *Testing Wisconsin Mixtures for the AASHTO 2002 Mechanistic Design Procedure*, concluded that the flow number appeared to be a more sensitive indicator of the rutting resistance of HMA than the dynamic modulus (*3*). Although this completed research supports the flow number as a general measure of rutting resistance, only limited data documenting the effect of mixture composition on the flow number have been reported. Additionally, the flow number criteria that were developed in NCHRP Project 9-33 were based on traffic moving at normal highway speeds. Mixtures placed at intersections are subjected to the effects of slow or standing traffic resulting in greater potential for rutting.

Current mixture design methods provide designers considerable freedom in selecting the composition of a mixture. With limited information available on the effects of mixture composition on the flow number, it may be difficult to develop mixtures that meet the flow number criteria. Additionally, acceptance criteria permit deviation from the design job mix formula during construction, which may result in a change in the flow number and rutting resistance of the mixture. WHRP Project 0092-09-01 was designed as a structured study to evaluate the effect of changes in mixture composition on the flow number and rutting resistance of HMA and to develop flow number criteria for mixtures used at intersections. The findings of this study provide guidance to mix designers for meeting specified levels of rutting resistance. They also provide the Wisconsin Department of Transportation (WisDOT) information on appropriate flow number values for mixtures used in highway sections and intersections, and provide relationships to evaluate current mixture acceptance criteria and modify them if necessary.

1.2 Research Objectives

The objectives of WHRP Project 0092-09-01 were to: (1) investigate the effect of changes in mixture composition on the flow number and rutting resistance of HMA mixtures from Wisconsin, (2) evaluate the rutting resistance of mixtures used at intersections, and (3) recommend improved criteria for to the design and acceptance of HMA mixtures. The project served several purposes including:

- Provide a database of flow number properties for HMA mixtures used by WisDOT. The database includes a series of design mixtures classified by design traffic level, binder grade, and aggregate geology. The database also includes variations on these design mixtures based on the acceptance criteria used by WisDOT.

- Relationships between mixture composition and the flow number that can be used by engineers and technicians involved in the design and acceptance of HMA.

- Recommended flow number test methods and criteria for use in the design of HMA mixtures in Wisconsin. Criteria for various traffic levels for highway sections and intersections were recommended.

- Evaluation of current WisDOT acceptance criteria for HMA mixtures during construction. This evaluation was based on the relationships between mixture composition and the flow number generated from the data collected in this project.

1.3 Research Approach and Report Organization

WHRP Project 0092-09-01 was divided into seven tasks. These tasks are briefly described below:

Task 1: Literature Review. This task included a review of the literature and research in progress concerning the flow number and the effect of mixture composition on rutting resistance. Task 1 also included a detailed review of the WisDOT requirements for the design and acceptance of asphalt concrete and a review of acceptance requirements used by other agencies.

Task 2. Experimental Design. This task consisted of developing an experimental design for the flow number testing and analysis based on the findings from Task 1. Two experiments were developed: (1) primary flow number experiment addressing the effect of mixture composition on flow number and (2) intersection flow number experiment addressing appropriate flow numbers for intersection mixtures.

Task 3. Interim Report. The findings of the literature review and experimental design for the primary flow number study were documented in an Interim Report submitted to the Technical Oversight Committee (TOC). At this point the TOC requested that the study be expanded to address intersection mixtures. A separate experimental design for the intersection study was submitted. Both experimental designs were approved by the TOC prior to the start of laboratory testing in Task 4.

Task 4. Laboratory Testing. In Task 4, the laboratory portion of the research was completed. This task included: (1) material sampling, (2) fabrication of flow number test specimens, (3) flow number testing, (4) volumetric and binder testing, and (5) entering the test results into the project database.

Task 5. Data Analysis. The laboratory data collected in Task 4 was analyzed in Task 5. Data from the primary flow number experiment were analyzed to determine the effect of changes in asphalt content and mineral filler content on the rutting resistance as measured by the flow number. Analysis of data from the intersection flow number experiment focused on determining appropriate flow number criteria for mixtures used at intersections.

Task 6. Applications. In Task 6, potential applications of the flow number test in asphalt mixture design and acceptance were considered. Recommendations were made for using the flow number test in mixture design, quality verification, and pay factors for lots not meeting WisDOT production tolerances.

Task 7. Compile Final Report. The final task in the project was the preparation and submission of this Final Report for the project, documenting all significant work completed during the project.

Chapter 2 of this report presents the findings of the literature review. It includes a discussion of the development of the flow number test, variants of the flow number test that have been used in several projects, available criteria for using the flow number test in mixture design and analysis, and the effect of mixture composition on rutting resistance. Chapter 2 also includes a review of the WisDOT criteria for design and acceptance of asphalt mixtures and a general review of asphalt mixture design and acceptance practices in other states. The experimental designs for the primary flow number study and the intersection flow number study are discussed in Chapter 3 along with the materials, methods and analysis of the results. Chapter 4 describes potential applications for the flow number in mixture design and acceptance. Finally conclusions and recommendations based the work completed during the project are presented in Chapter 5.

Chapter 2 Literature Review

2.1 Asphalt Mixture Performance Tester

The Asphalt Mixture Performance Tester (AMPT) is a small servo-hydraulic testing device developed specifically for testing asphalt concrete mixtures. Figure 1 is a photograph of the AMPT. The AMPT was originally called the Simple Performance Test System when it was developed in National Cooperative Highway Research Program (NCHRP) Project 9-29. The Federal Highway Administration (FHWA) changed the name of the device to the AMPT when it took over implementation efforts for the equipment in 2008.

Figure 1. Photograph of the IPC Global Asphalt Mixture Performance Tester.

The AMPT was developed to conduct three performance related tests on asphalt concrete that were recommended in NCHRP Project 9-19 to compliment the Superpave volumetric mixture design method. These are dynamic modulus, flow number, and flow time. Data from all three tests were shown to correlate well with observed rutting in field pavements (*1*). The dynamic modulus is also the primary material input for asphalt concrete layer characterization in the American Association of State Highway and Transportation Officials (AASHTO) Mechanistic Empirical Pavement Design Guide (MEPDG). Thus, the AMPT can be used to obtain performance related properties of asphalt concrete for both mixture design and pavement structural design.

Substantial development and testing work for the AMPT was completed in NCHRP Project 9-29. (*4-7*). This included the development of a detailed equipment specification, the evaluation of three first article devices, ruggedness testing for the dynamic modulus and flow number tests, the preparation of three draft AASHTO standards for (1) specimen fabrication, (2) testing, and (3) data analysis, and an interlaboratory study to establish the precision of dynamic modulus and flow number tests. There are currently two manufacturers of the AMPT: Interlaken Technology Corporation, and IPC Global, Ltd. Approximately 30 units have been sold to highway agencies, research centers, and asphalt mixture producers in the United States.

2.2 Flow Number Test

2.2.1 Description

The flow number test is a variation on the repeated-load, permanent deformation test that has been used by researchers since the 1970's to measure the rutting potential of asphalt concrete mixtures (*8*). Figure 2 shows a schematic of the repeated loading used in this test. Haversine axial compressive-load pulses are applied to the specimen. The duration of the load pulse is 0.1 sec followed by a rest period of 0.9 sec. The permanent axial deformation measured at the end of the rest period is monitored during repeated loading and converted to strain by dividing by the original gauge length. The test may be conducted with or without confining pressure. If confining pressure is used, it remains constant during the test.

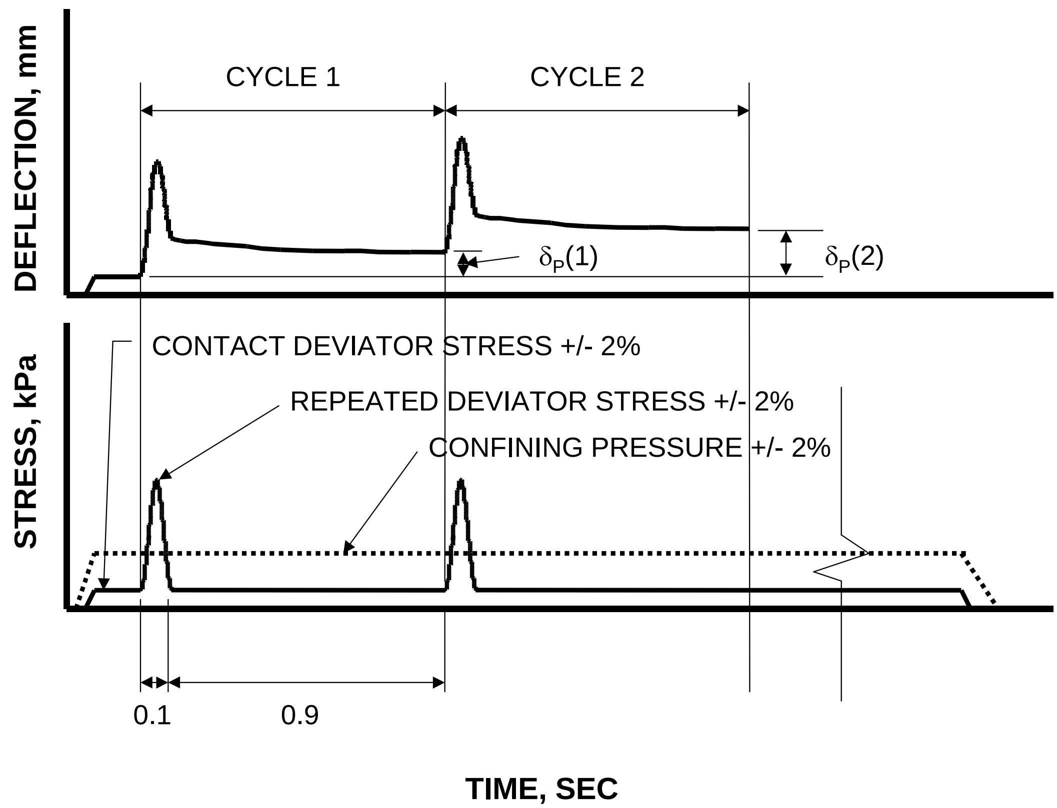


Figure 2. Loading in the Flow Number Test.

The variation introduced by the NCHRP Project 9-19 research is the concept of flow number, which is defined as the number of load pulses when the minimum rate of change in permanent strain occurs during the repeated-load test (*1*). It is determined by differentiation of the permanent strain versus number of load cycles curve. Figure 3 presents an example of a typical permanent axial strain response, and the computation of the flow number.

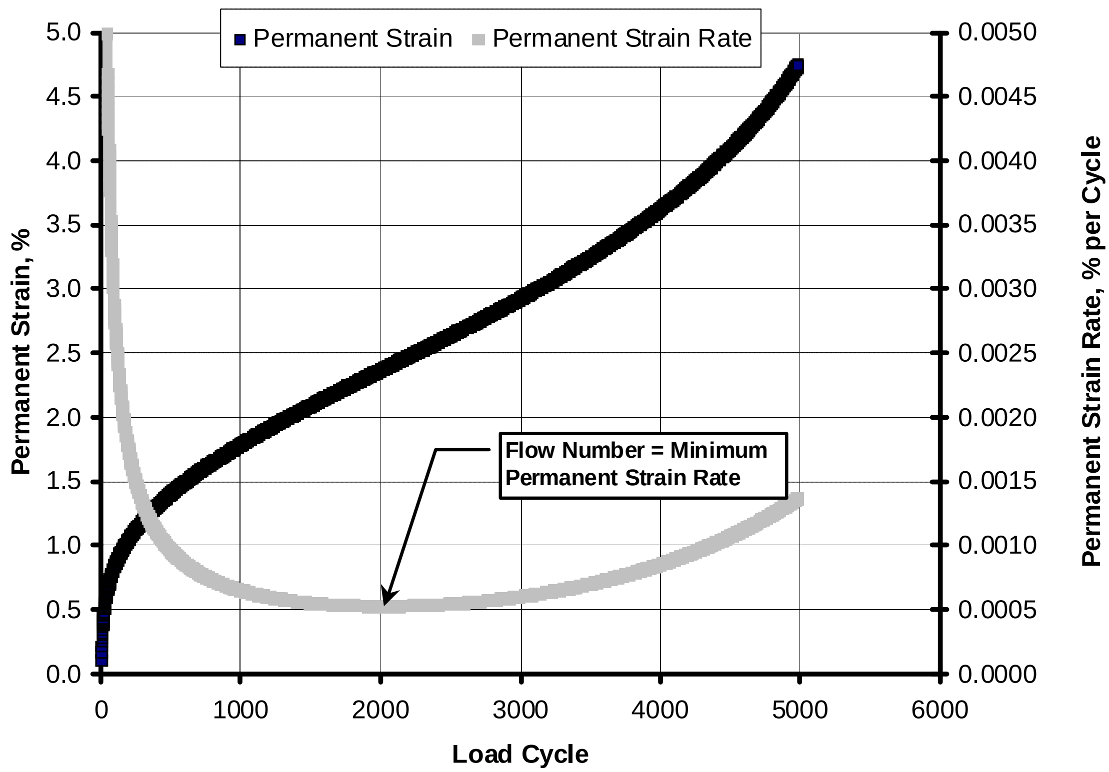


Figure 3. Example Flow Number Test Data.

Early flow number tests conducted in NCHRP Projects 9-19 and 9-29 showed the flow number to be highly variable with coefficients of variation ranging from 25 to 35 percent (*4,9*). The high variability was caused by the very flat trough in the derivative of the permanent strain curve making it difficult to accurately detect the flow number. In subsequent flow number work, researchers at the Arizona State University recommended using the Francken model (*10*) to fit the permanent strain versus number of loading cycles curve, and then performing the differentiation on the fitted curve (*11*). The Francken model algorithm has been recently introduced into the AMPT software. Equation 1 presents the Francken model, which in the AMPT flow number testing, is fit to the entire permanent strain curve using nonlinear least squares optimization. The flow number is then determined from the second derivative of the fitted curve. The flow number is the number of cycles were the second derivative, Equation 2, changes from negative to positive. In the ruggedness testing performed in NCHRP Project 9-29, the Francken model was been found to be a very repeatable method for determining the flow number (*6*).

$$\varepsilon_p = A(n^B) + C[e^{D*n} - 1] \tag{1}$$

where:

ε_p = permanent strain, %

n = number of cycles

A, B, C, and D = fitting parameters

$$\frac{d^2\varepsilon_p}{dn^2} = AB(B-1)n^{B-2} + CD^2e^{Dn} \tag{2}$$

where:

$\frac{d^2\varepsilon_p}{dn^2}$ = second derivative of permanent strain with respect to the number of loading cycles

n = number of cycles

A, B, C, and D = fitting parameters from Equation 1

2.2.2 Flow Number Test Variations

Unfortunately, the conditions for conducting the flow number test were not full standardized in NCHRP Project 9-19. The flow number test protocol developed in NCHRP Project 9-19 recommended testing at the effective pavement temperature using either unconfined tests with axial stress between 10 and 30 psi or confined tests with confining pressure between 5 and 30 psi and deviatoric stress between 70 and 140 psi. (*1*). The effective pavement temperature for permanent deformation is defined as the single test temperature at which the amount of permanent deformation would be equivalent to that which would be measured by considering the seasonal fluctuation in temperature throughout the year. Equation 3 is the equation for the effective pavement temperature for permanent deformation developed during the Strategic Highway Research Program (SHRP) (*12*).

$$T_{eff}(PD) = 30.8 - 0.12Z_{cr} + 0.92\left(MAAT_{average} + K_{\alpha}\sigma_{MAAT}\right) \quad (3)$$

where:

$T_{eff}(PD)$ = effective temperature for permanent deformation, °C

Z_{cr} = critical depth, mm

$MAAT$ = mean annual air temperature, °C

σ_{MAAT} = standard deviation of the mean annual air temperature, °C

K_{α} = value from standard normal table for the desired level of reliability

Table 1. Values of K_{α}.

Reliability Level, %	K_{α}
50	0.000
75	0.674
85	1.037
90	1.282
95	1.645
99	2.327

For a surface course mixture having a critical depth of 20 mm in Madison, WI (MAAT = 7.5 °C and σ_{MAAT} = 0.8 °C) using 95 percent reliability, the effective temperature for permanent deformation is 35.7 °C.

Using the effective pavement temperature and the range of stress levels recommended in NCHRP Project 9-19 resulted in many mixtures not exhibiting flow within 10,000 cycles, the recommended maximum number of load cycles. A 10,000 cycle test requires 2.8 hours; therefore, researchers using the flow number test arbitrarily increased either the temperature, deviatoric stress or both to ensure that flow would occur in the mixtures within 10,000 load cycles. Table 2 summarizes the stress and temperature conditions used in several documented flow number studies. Many researchers have followed the flow number guidance offered by the FHWA. In their early implementation efforts for the AASHTO MEPDG, the FHWA promoted conducting flow number tests at the 50 percent high pavement temperature from LTPPBind. They recommended the tests be conducted unconfined using an axial stress of 87 psi (600 kPa), the same vertical stress used in the gyratory compactor. Tentative criteria for using the flow number test in mixture design were developed in NCHRP Project 9-33 using data that the

FHWA collected in this manner (*2*). More recently, the FHWA has been collecting flow number test data using the confined testing conditions recommended in NCHRP Project 9-30A. These stress states were recommended based on an analysis of the stresses occurring in pavements under typical wheel loads. In WHRP Project 0092-08-06, the same mixtures were tested using both confined and unconfined tests. A significant finding from this study was that the variability in the unconfined tests was much lower (*13*).

Table 2. Temperature and Stress Conditions Used in Flow Number Studies.

Study	Stress State, psi		Temperature
	Confinement	Deviatoric	
NCHRP 9-19 (*1*)	Multiple	Multiple	Multiple
Texas Transportation Institute (*14*)	0	30	54.4 °C
FHWA Mobile Asphalt Lab (earlier)	0	87	50 % reliability high pavement temperature
Louisiana Transportation Research Center (*15*)	0	30	54 °C
WHRP 0092-04-07 (*3*)	0	87	Effective temperature
NCHRP 9-30A (*16*)	10	70	Multiple
FHWA Mobile Asphalt Lab (current)	10	70	Multiple
FHWA ALF (*17*)	5	120	64 °C
WHRP 0092-08-06 (*12*)	0	87	50 % reliability high pavement temperature
	10	70	

2.2.3 Flow Number and Rutting Resistance

In NCHRP Project 9-19, the flow number correlated well with the rutting resistance of mixtures used in experimental sections at the FHWA Pavement Testing Facility, MNRoad, and WesTrack (*1*). For tests at a given temperature, deviatoric stress, and confining stress, the rutting resistance of the mixture improved with increasing flow number. Figure 4 shows an example of the relationship between rutting and flow number obtained in the NCHRP Project 9-19 research for the FHWA Pavement Testing Facility sections. Recently, tentative criteria for the flow number test have been developed in NCHRP Project 9-33. The criteria are shown in Table 3. These are based on flow number test data collected by the FHWA on several field projects and a relationship between mixture volumetric properties and rutting resistance developed in NCHRP Projects 9-25 , 9-31, and 9-33 (*2*). The test is conducted at the 50 percent reliability performance grade temperature obtained from LTPPBind 3.1 at a depth of 20 mm without traffic volume or speed adjustments. The air void content of the specimens is 7.0 ±0.5 percent, and the flow number test is conducted without confinement using an axial stress of 87 psi (600 kPa). The criteria given in Table 3 are for an average rut depth of 7 mm which corresponds to 95 percent reliability that the rut depth will be less than 12 mm.

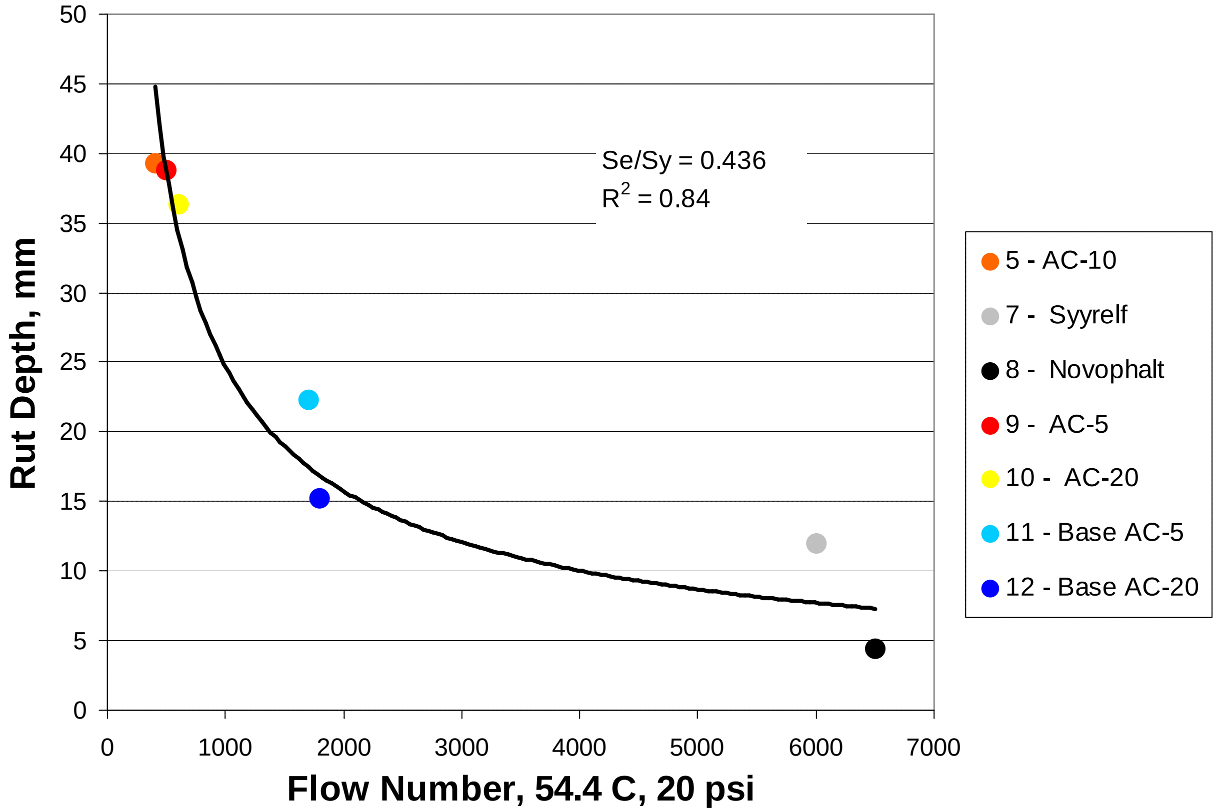


Figure 4. Relationship Between Flow Number and Rutting for the FHWA Pavement Testing Facility Sections *(1)*.

Table 3. NCHRP 9-33 Recommended Minimum Flow Number Requirements (*2*).

Traffic Level *Million ESALs*	**Minimum Flow Number** *Cycles*
< 3	---
3 to < 10	53
10 to < 30	190
≥ 30	740

Work completed in WHRP Project 00092-08-01, found the flow number criteria developed in NCHRP Project 9-33 to be overly conservative based on the reported field performance of the mixtures that were tested (*13)*. A likely reason for the discrepancy between the reported field performance and the NCHRP Project 9-33 criteria is the algorithm for computing the flow number has been changed since the NCHRP Project 9-33 were developed. The NCHRP Project 9-33 criteria were developed from flow number data collected using a forward finite difference algorithm (*4*). The flow number computed from this algorithm was found to be sensitive to the cycle interval used in the computations. During ruggedness testing of the AMPT, the finite difference algorithm was replaced with the Francken model as discussed earlier. Flow numbers based on the Francken model were used in WHRP Project 0092-08-06. Revised flow number criteria from WHRP Project 0092-08-06 are presented in Table 4. For these criteria, the flow number should be conducted using the same testing conditions described for the NCHRP Project 9-33 criteria.

Table 4. WHRP Project 0092-08-06 Minimum Flow Numbers for Various Traffic Levels (*13*).

Design Traffic Level, MESAL	Minimum Flow Number, Cycles
3	15
10	50
30	135
100	415

2.2.4 Effect of Mixture Composition on the Flow Number

Of the flow number studies that have been completed, only the two WHRP studies, WHRP projects 0092-04-07 and 0092-08-06, have included formal analysis of the effect of mixture composition on the flow number (*3,13*). NCHRP Project 9-19 included comparisons of flow number with observed rutting in accelerated pavement tests and test roads (*1*) but not with mixture composition. The FHWA has not completed an analysis of the confined test data that they are currently collecting; the unconfined data was analyzed in NCHRP Project 9-33 to develop criteria for flow number testing. The other studies included only comparisons of the ranking of rutting resistance based on the flow number and other tests like dynamic modulus, the Asphalt Pavement Analyzer, or the Hamburg wheel tracking test.

The statistical analysis of the flow number data completed in WHRP Project 0092-04-07 showed the flow number was significantly affected by: (1) design traffic level, (2) nominal maximum aggregate size, (3) dense-graded compared to SMA mixtures, and (4) air voids (*3*). The analysis further indicated that the flow number was not significantly affected by a 0.3 percent increase in binder content (*3*). The analysis of the flow number data completed in WHRP Project 0092-08-06 showed the flow number was significantly affected by: (1) binder grade, (2) fine aggregate angularity, and (3) design voids in the mineral aggregate (VMA) (*13*). In this project the air void content of the flow number specimens was held constant at 7.0 percent, where in WHRP Project 0092-04-07, the air void content was varied. Further analysis of the combined data from both of these projects is presented later in this Chapter.

2.2.5 Mixture Conditioning

In most of the flow number studies completed to date, laboratory prepared mixtures have been short-term conditioned for 4 hours at 135 °C in accordance with the performance property conditioning recommended in AASHTO R30, *Mixture Conditioning of Hot-Mix Asphalt (HMA)*. Short-term conditioning was first recommended by Von Quintus, et. al as part of the Asphalt-Aggregate Mixture Analysis System developed in NCHRP Project 9-6 (*18*). Von Quintus et. al. recommended 3 hours at 135 °C to simulate binder hardening and absorption that occurs during plant mixing (*18*). They noted that the temperature was selected to be the midpoint of the normal range of production temperature, 120 to 150 °C, and that the temperature and time may need to be revised if actual mixture production temperatures differ from 135 °C (*18*). Short-term conditioning was further evaluated during SHRP by comparing the resilient modulus of laboratory prepared mixtures conditioned in a forced draft oven with the resilient modulus of field cores that were less than two years old (*19*). One recommendation from this study based on analysis of only six projects was that 4 hours of oven conditioning at 135 °C provided a good estimate of the aging taking place during field mixing and up to 2 years in-service. The short-term oven conditioning of 4 hours at 135 °C was recommended at the end of SHRP for both volumetric design and performance testing, and was included in AASHTO PP2, *Practice of*

Short and Long Term Aging of Hot Mix Asphalt (HMA) which later became AASHTO R30 *Mixture Conditioning of Hot-Mix Asphalt (HMA)*. To expedite the mixture design process and reduce the amount of ovens required for mixture design, the FHWA Mixtures and Aggregates Expert Task Group (ETG) reviewed data concerning the effect of conditioning time and temperature on the volumetric properties of asphalt mixtures. The ETG ultimately recommended that the short-term oven conditioning for mixture design be changed to 2 hours at the compaction temperature for aggregates with water absorption less than 4.0 percent. For aggregates with greater water absorption and for performance testing, the short-term oven conditioning remained 4 hours at 135 °C. AASHTO R30 was eventually modified to reflect the ETG's recommendation.

With the growing popularity of warm mix asphalt (WMA), short-term conditioning has again become an important topic. NCHRP Project 9-43 included comparisons of properties of laboratory prepared mixtures conditioned for 2 and 4 hours at the compaction temperature and 4 hours at 135 °C with properties of plant produced mixtures taken from haul trucks (*20*). The properties that were evaluated included maximum specific gravity, dynamic modulus, and mixture tensile strength. Data were obtained for 8 mixtures from three projects and included 3 HMA control mixtures, and 5 WMA mixtures. Based on this experiment, 2 hours of oven conditioning at the compaction temperature best represented the volumetric, stiffness, and strength properties of the field mixtures at the time of construction. As a result, 2 hours of oven conditioning at the compaction temperature was tentatively recommended for both mixture design and performance testing in the mixture design procedure for WMA developed in NCHRP Project 9-43 (*20*). The data collected in NCHRP Project 9-43 also showed that 4 hours of oven conditioning at 135 °C significantly overestimated the stiffness and strength of the mixture at the time of construction, indicating that some adjustment of rutting resistance criteria may be necessary to accurately address the wider range of production temperatures anticipated in the future.

2.3 Effect of Mixture Composition on Rutting Resistance

In NCHRP Projects 9-25 and 9-31 a model was developed to estimate rutting resistance from mixture volumetric composition (*21*). This model was subsequently improved through additional research in NCHRP Project 9-33 (*2*) and Airfield Asphalt Pavement Technology Program Project 04-02 (*22*). Equation 4 presents the latest version of this model, which can be used to estimate the rutting resistance of a mixture from volumetric composition, in-place compaction and binder properties (*22*).

$$TR = 9.85 \times 10^{-5} \left(\mathrm{P} N_{design} K_s \right)^{1.373} V_d^{1.5185} V_{IP}^{-1.4727} M \tag{4}$$

where:

TR	=	allowable traffic in million ESALs to an average rut depth of 7.2 mm (50 % confidence level)
	=	allowable traffic in million ESALs to a maximum rut depth of 12 mm (95 % confidence level)
P	=	resistivity, s/nm
	=	$\dfrac{\left(\lvert G^* \rvert / \sin \delta \right) S_a^2 G_a^2}{49 VMA^3}$
$\lvert G^* \rvert / \sin \delta$	=	Estimated *aged* PG grading parameter at high temperatures, determined at 10 rad/s and at the yearly, 7-day average maximum pavement temperature at 20 mm below the pavement surface, as determined using LTPPBind, Version 3.1 (units of Pa/s); aged value can be estimated by multiplying the RTFOT value by 4.0 for long-term projects (10 to 20 year design life), and by 2.5 for short term projects of 1 to 2 years.
S_a	=	specific surface of aggregate in mixture, m^2/kg
	≅	the sum of the percent passing the 75, 150 and 300 micron sieves, divided by 5.0
G_a	=	the bulk specific gravity of the aggregate blend
VMA	=	design voids in the mineral aggregate for the mixture, volume
N_{design}	=	design gyrations

K_s	=	speed correction
	=	$(v/70)^{0.8}$, where v is the average traffic speed in km/hr
V_d	=	design air void content, volume %
V_{IP}	=	air void content, volume %, in-place
M	=	7.13 for mixtures containing typical polymer-modified binders, 1.00 otherwise

Note that aggregate angularity characteristics are not an explicit factor in this model. When using this model to predict allowable traffic, it is assumed that the aggregates in the mixture meet the angularity requirements given in AASHTO M323 for the design level gyration used.

To demonstrate the use of this model, a sensitivity analysis was conducted for a typical 12.5 mm surface course mixture with the characteristics given in Table 5, and assuming 7 percent in-place air voids and 70 km/hr traffic speed. This analysis yielded the following:

- Increasing VMA by 1.0 percent decreases the allowable traffic by 24 percent.
- Increasing the percent passing the 200 sieve by 1.0 percent increases the allowable traffic by 38 percent.
- Increasing the in-place air void content by 1.0 percent decreases the allowable traffic by 18 percent.
- Increasing the binder grade by one grade increases the allowable traffic by 159 percent.
- Decreasing the design gyrations and aggregate characteristics by one traffic level decreases the allowable traffic by 45 percent.
- Decreasing the design air void content by 0.5 percent, increases the allowable traffic by 18 percent.

Table 5. Summary of Typical 12.5 mm Mixture Design Properties.

Property		Value
	Sieve, mm	
Gradation, % passing	25	100.0
	19	100.0
	12.5	94.8
	9.5	84.3
	4.75	66.7
	2.36	47.7
	1.18	34.2
	0.6	21.9
	0.3	12.8
	0.15	7.1
	0.075	4.1
Binder content, wt %		5.0
Design Air Voids, vol %		4.0
Design VMA, vol %		15.1
Design VFA, vol %		73.5
Maximum Specific Gravity		2.534
Aggregate Bulk Specific Gravity		2.721
Effective binder content, vol %		11.1
Dust/Binder Ratio		0.9
Design Gyrations		75
PG 58-28 with aged $G^*/\sin\delta$, Pa		100,000

Analysis of the rutting resistance of the mixtures included in WHRP projects 0092-04-07 and 0092-08-06 using this model is presented in the next section. Analysis of the current WisDOT criteria for mixture design and acceptance using this model are presented in Section 2.6.

2.4 Analysis of Flow Number Data From WHRP Projects 0092-04-07 and 0092-08-06

Flow number tests were performed on a number of Wisconsin mixtures in WHRP Projects 0092-04-07 and 0092-08-06 (*3*,*13*). In both projects tests were conducted on mixtures having approved WisDOT mixture designs. Table 6 summarizes the mixtures that were tested in these two projects. A total of 33 mixtures were tested in these two projects at a target air void content of 7.0 percent. Of these 33 mixtures, 7 mixtures from WHRP Project 0092-04-07 were excluded from the analysis because they either had incomplete data or the air void content of the specimens tested were significantly different than 7.0 percent. The major difference in the data collected in these two projects was the temperature used in the flow number testing. In Project 0092-04-07, flow number tests were conducted at the effective pavement temperature computed for the location where the mixture was placed (*3*). In Project 0092-08-06 all mixtures were tested at 49.6 °C, the 50 percent reliability high pavement temperature computed from LTPPBind 3.1 for Madison, WI for a depth of 20 mm (*13*). The test temperature used in Project 0092-08-06 averaged approximately 12 °C higher than the test temperatures used in Project 0092-04-07.

The analysis that was conducted was to compute the allowable traffic for each mixture using Equation 4 and the properties of the specimens tested, then to develop relationships between flow number and allowable traffic. The computation of allowable traffic is summarized in Tables 7 and 8 for the mixtures from Projects 0092-04-07 and 0092-08-06, respectively. Comparisons of flow number and allowable traffic for the two data sets are shown in Figure 5. Both sets of data provide reasonable relationships between flow number and allowable traffic. Flow numbers for Project 0092-04-07, which were conducted at the effective pavement temperature are significantly higher than those conducted at the 7 day average maximum pavement temperature.

Table 6. Summary of Mixtures Tested for Flow Number in WHRP Projects 0092-04-07 and 0092-08-06.

No.	Project	Mixture	NMAS	Design Traffic Level	Binder Grade	Test Temperature, °C	Complete Data for Analysis	Comment
1	0092-04-07	Brule	19	E-0.3	PG 58-28	35.5	Yes	
2	0092-04-07	Baraboo	12.5	E-0.3	PG 58-28	36.6	Yes	
3	0092-04-07	Hurley	12.5	E-0.3	PG 58-28	35.7	Yes	
4	0092-04-07	Cascade	19	E-1	PG 58-28	37.7	No	Incomplete Binder Data
5	0092-04-07	Bloomville	19	E-1	PG 58-34	36.6	Yes	
6	0092-04-07	Medford	12.5	E-1	PG 58-28	35.7	No	Incomplete Binder Data
7	0092-04-07	Wautoma	12.5	E-1	PG 58-28	37.7	Yes	
8	0092-04-07	Waunakee	19	E-3	PG 58-28	37.9	Yes	
9	0092-04-07	Mosinee	19	E-3	PG 58-28	36.9	Yes	
10	0092-04-07	Cumberland	12.5	E-3	PG 58-28	35.2	Yes	
11	0092-04-07	Hayward	12.5	E-3	PG 58-28	36.1	Yes	
12	0092-04-07	Wausau	12.5	E-3	PG 64-28	36.9	Yes	
13	0092-04-07	Hurley	12.5	E-3	PG 64-34 P	35.7	No	Incomplete Binder Data
14	0092-04-07	Tomahawk	25	E-3	PG 58-28	35.6	No	Low Air Voids
15	0092-04-07	Antigo	19	E-10	PG 58-34 CRM	35.2	Yes	
16	0092-04-07	Antigo	12.5	E-10	PG 58-34 CRM	35.2	Yes	
17	0092-04-07	Plymouth	12.5	E-10	PG 64-22	37.3	Yes	
18	0092-04-07	Racine	12.5	E-10	PG 64-28 CRM	39.2	Yes	
19	0092-04-07	Wisconsin Rapids	19	E-10	NA	37.5	No	Incomplete Binder and Volumetric Data
20	0092-04-07	Northfield	12.5	E-10	PG 64-28	36.5	No	High Air Voids
21	0092-04-07	Northfield	19	E-30	PG 70-22	36.5	No	Low Air Voids
22	0096-08-06	Cisler	12.5	E-3	PG 58-28	49.6	Yes	
23	0096-08-06	Cisler	12.5	E-10	PG 58-28	49.6	Yes	
24	0096-08-06	Cisler	12.5	E-10	PG 70-28 P	49.6	Yes	
25	0096-08-06	Christian/Gade	12.5	E-3	PG 58-28	49.6	Yes	
26	0096-08-06	Christian/Gade	12.5	E-10	PG 58-28	49.6	Yes	
27	0096-08-06	Christian/Gade	12.5	E-10	PG 70-28 P	49.6	Yes	
28	0096-08-06	Glenmore	19	E-3	PG 58-28	49.6	Yes	
29	0096-08-06	Glenmore	19	E-10	PG 58-28	49.6	Yes	
30	0096-08-06	Glenmore	19	E-10	PG 70-28 P	49.6	Yes	
31	0096-08-06	Wimmie	12.5	E-3	PG 58-28	49.6	Yes	
32	0096-08-06	Wimmie	12.5	E-10	PG 58-28	49.6	Yes	
33	0096-08-06	Wimmie	12.5	E-10	PG 70-28 P	49.6	Yes	

Table 7. Summary of Estimated Rutting Resistance for WHRP Project 0092-04-07.

Mixture			Gradation				Aged Binder $G^*/\sin\delta$ Pa	Design Volumetrics				M	In-Place V_{ip} %	40 mph		Flow Number
Project	Design Traffic Level	Binder Grade	0.3 mm	0.15 mm	0.075 mm	Sa m/kg^2		Gsb	VMA %	N	V_d %			K	TR MESAL	
Baraboo	E-0.3	PG 58-28	18.6	6.7	4.4	5.94	119240	2.652	16.2	40	4	1	6.3	0.935	7.0	79
Brule	E-0.3	PG 58-28	17.7	6.7	3.5	5.58	95212	2.722	15.8	40	4	1	6.0	0.935	5.5	76
Hurley	E-0.3	PG 58-28	13.0	7.5	4.9	5.08	105948	2.689	16.5	40	4	1	6.0	0.935	4.0	102
Wautoma	E-1	PG 58-28	15.3	6.7	4.4	5.28	97080	2.713	14.5	60	4	1	7.0	0.935	9.6	84
Bloomville	E-1	PG 58-34	11.2	6.8	4.9	4.58	129620	2.696	13.9	60	4	1	6.3	0.935	13.2	149
Cumberland	E-3	PG 58-28	12.6	6.9	4.7	4.84	135640	2.738	13.5	75	4	1	6.3	0.935	26.1	254
Wausau	E-3	PG 64-28	9.6	4.8	3.8	3.64	196104	2.647	15.9	75	4	1	7.0	0.935	7.9	109
Mosinee	E-3	PG 58-58	8.8	4.4	3.4	3.32	91720	2.649	14.9	75	4	1	7.0	0.935	2.8	81
Waunakee	E-3	PG 58-58	16.0	7.3	3.8	5.42	88756	2.648	13.2	75	4	1	6.0	0.935	21.4	304
Hayward	E-3	PG 58-28	13.3	5.6	4.6	4.7	82520	2.728	15.0	75	4	1	6.0	0.935	8.4	47
Antigo	E-10	PG 58-34	10.3	5.4	3.9	3.92	61908	2.688	13.7	100	4	7.13	6.0	0.935	50.7	858
Racine	E-10	PG 64-28	8.4	5.2	4.1	3.54	146540	2.671	15.5	100	4	7.13	6.0	0.935	74.0	1624
Antigo	E-10	PG 58-34	11.6	6.0	4.1	4.34	61908	2.690	14.7	100	4	7.13	7.0	0.935	40.1	1249
Plymouth	E-10	PG 64-22	14.2	7.3	4.2	5.14	148580	2.768	14.5	100	4	1	6.0	0.935	42.7	960

Table 8. Summary of Estimated Rutting Resistance for WHRP Project 0092-08-06.

Mixture			Gradation				Aged Binder $G^*/\sin\delta$ Pa	Design Volumetrics				M	In-Place V_{ip} %	40 mph		Flow Number
Source	Design Traffic Level	Binder Grade	0.3 mm	0.15 mm	0.075 mm	Sa m/kg^2		Gsb	VMA %	N	V_d %			K	TR MESAL	
Cisler	E3	PG 58-28	11.0	5.2	3.7	3.98	99900	2.650	14.3	75	4	1	6.8	0.935	6.5	21
Cisler	E10	PG 58-28	10.6	5.6	3.8	4.00	99900	2.665	15.8	100	4	1	7.0	0.935	6.3	39
Cisler	E10	PG 70-28	10.6	5.6	3.8	4.00	153504	2.665	15.8	100	4	7.13	7.0	0.935	80.8	262
Christian/ Gade	E3	PG 58-28	11.6	5.5	3.5	4.12	99900	2.733	14.6	75	4	1	7.1	0.935	6.7	30
Christian/ Gade	E10	PG 58-28	11.1	5.5	3.4	4.00	99900	2.736	15.4	100	4	1	7.2	0.935	7.2	45
Christian/ Gade	E10	PG 70-28	11.1	5.5	3.4	4.00	153504	2.736	15.8	100	4	7.13	7.1	0.935	85.1	846
Glenmore	E3	PG 58-28	14.3	6.6	3.5	4.88	99900	2.747	13.5	75	4	1	6.7	0.935	16.2	96
Glenmore	E10	PG 58-28	12.8	5.9	3.2	4.38	99900	2.747	13.2	100	4	1	7.0	0.935	18.4	86
Glenmore	E10	PG 70-28	12.8	5.9	3.2	4.38	153504	2.747	13.2	100	4	7.13	7.1	0.935	231.4	1131
Wimmie	E3	PG 58-28	13.0	6.5	3.9	4.68	99900	2.713	14.6	75	4	1	6.9	0.935	9.7	32
Wimmie	E10	PG 58-28	12.8	6.9	4.2	4.78	99900	2.721	15.1	100	4	1	6.7	0.935	14.0	54
Wimmie	E10	PG 70-28	12.8	6.9	4.2	4.78	153504	2.721	15.1	100	4	7.13	6.8	0.935	175.5	324

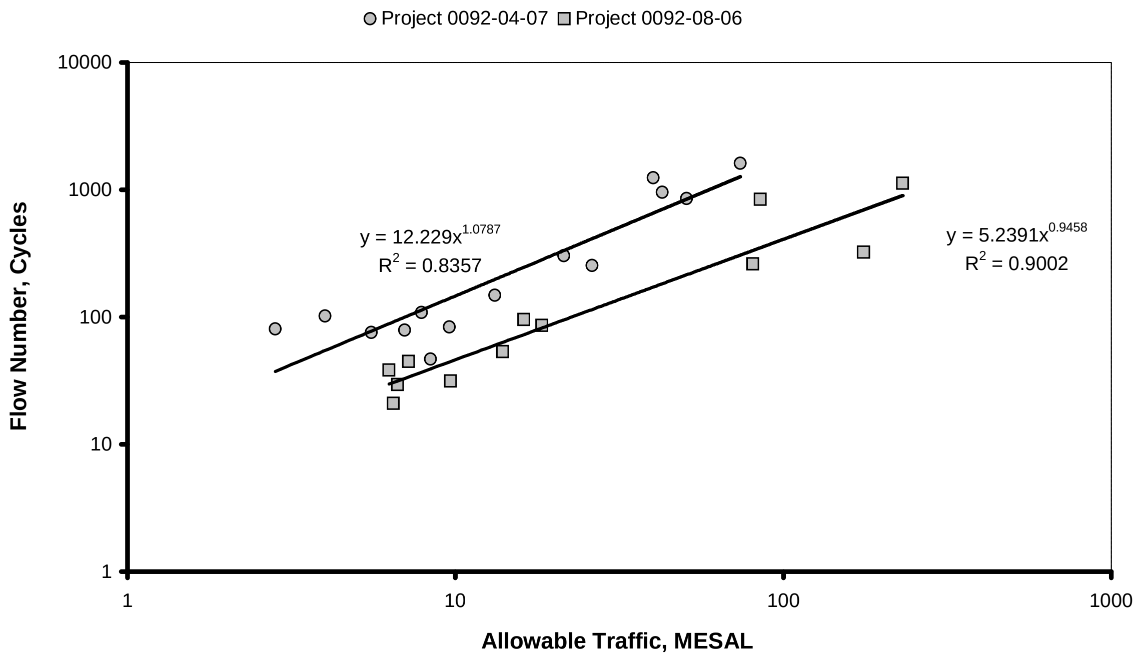


Figure 5. Relationship Between Flow Number and Allowable Traffic.

The relationships shown in Figure 5 show the flow number is approximately proportional to the allowable traffic computed using Equation 4; the exponents in the fitted relationships are approximately 1. From Equation 4, the allowable traffic is proportional to the binder stiffness G*/sinδ raised to the power 1.373. Combining these two suggests that the effect of temperature on the flow number can be accounted for by adjusting the flow number by the ratio of the binder G*/sinδ raised to the 1.373 power. Assuming that the binder stiffness doubles of each 6 °C decrease in temperature, Equation 5 presents the adjusted flow number for 49.6 °C.

$$FN_{49.6} = FN_T \times \left(e^{(0.1155\times(T-49.6))}\right)^{1.373} \quad (5)$$

where

$FN_{49.6}$ = adjusted flow number for 49.6 °C

FN = flow number at temperature T

T = flow number test temperature, °C

Figure 6 presents a plot of the combined flow number data from the two projects adjusted to the higher temperature used in Project 0092-04-07.

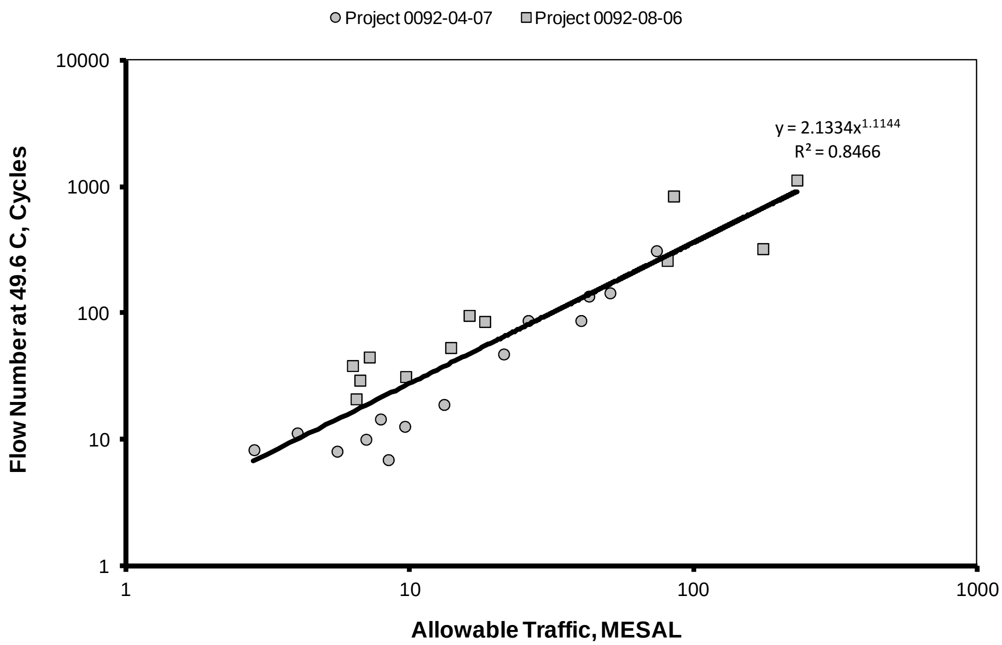


Figure 6. Relationship Between 49.6 °C Flow Number and Allowable Traffic.

Figure 7 compares the allowable traffic based on the rutting model developed in NCHRP Project 9-25, 9-31, and 9-33 with the design traffic level of the mixtures tested in WHRP Projects 0092-04-07 and 0092-08-06. This comparison indicates that Wisconsin mixtures are generally overdesigned based on rutting resistance.

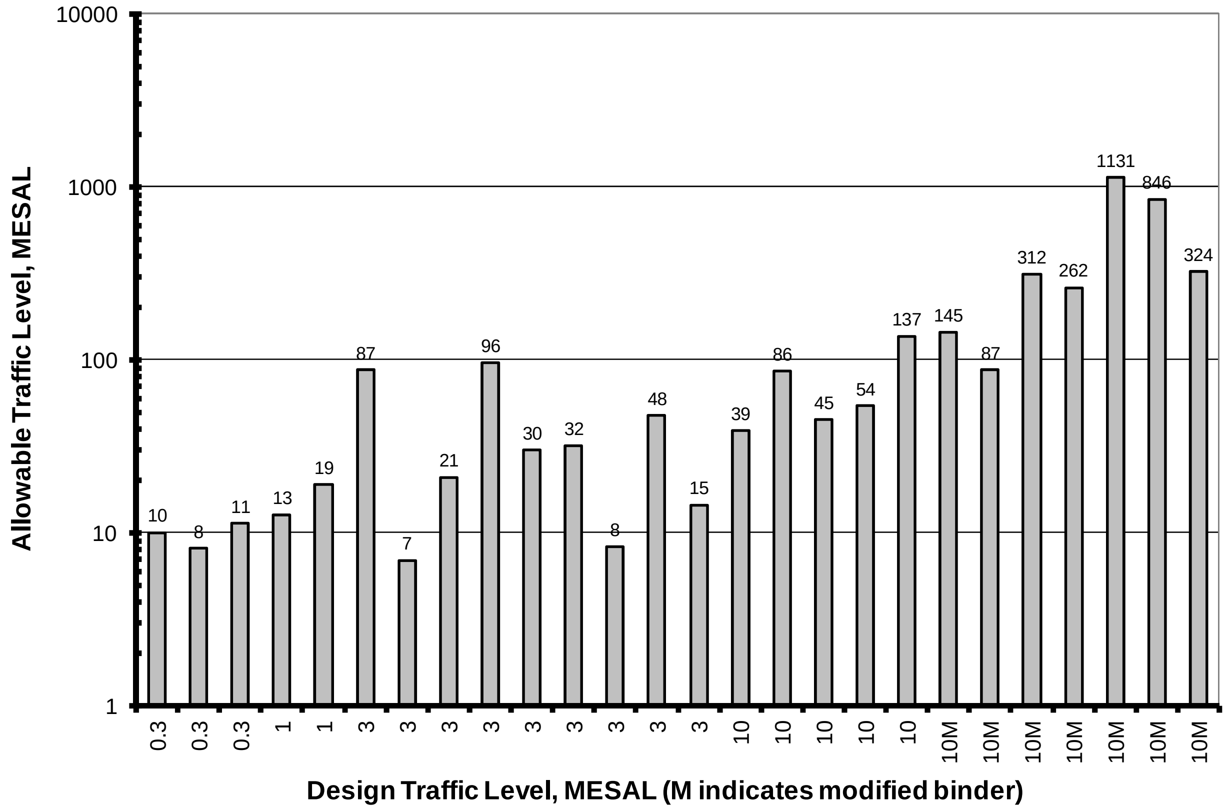


Figure 7. Comparison of Adjusted Allowable Traffic With Design Traffic Level.

This analysis of the flow number data collected in WHRP Projects 0092-04-07 and 0092-08-06 shows that the flow number test is sensitive to key mixture design and acceptance factors affecting the rutting resistance of asphalt concrete. These include:

- Aggregate gradation (percent passing 0.075 mm sieve),
- Binder grade,
- Binder modification,
- In-place air voids,
- Design compaction level, and
- Design VMA.

There is a good relationship between the flow number and the allowable traffic estimated by the rutting resistance model developed in NCHRP Projects 9-25, 9-31 and 9-33 which includes many of the key characteristics.

2.5 Intersection Mixtures

The flow number criteria shown in Figure 6 were developed for a traffic speed of 64.4 km/h (40 mi/h). Equation 6 presents these criteria:

$$F_n = 2.13 \times (TR_{64.4})^{1.11} \tag{6}$$

where:

F_n = minimum flow number

$TR_{64.4}$ = allowable traffic from Equation 4 for an assumed traffic speed of 64.4 km/h

Equations 4 and 6 can be used to establish flow number adjustment factors for different traffic speeds. Equation 4 can be reduced to a constant representing mixture factors times a speed adjustment factor:

$$TR = F\left(\frac{v}{70}\right)^{0.80} \tag{7}$$

where:

TR = allowable traffic

F = mixture factors

v = traffic speed

Substituting Equation 7 into Equation 6 yields an equation relating the flow number to traffic speed:

$$F_n = 2.13 \times F^{1.11\left(\frac{v}{70}\right)^{0.888}} \tag{8}$$

The ratio of the flow number at the standard traffic speed to the flow number at any other traffic speed is given by Equation 9:

$$\frac{F_{n_{64.4}}}{F_{n_X}} = \frac{2.13F^{1.11\left(\frac{64.4}{70}\right)^{0.888}}}{2.13F^{1.11\left(\frac{X}{70}\right)^{0.888}}} \tag{9}$$

Solving Equation 9 for the flow number at the standard traffic speed yields:

$$F_{n64.4} = \left(\frac{64.4}{X}\right)^{0.888} \times F_{n_x} \tag{10}$$

where:

X = traffic speed in km/h

F_{nX} = flow number for traffic speed X

$F_{n64.4}$ = flow number for traffic speed of 64.4 km/h

The first term in Equation 10 is a traffic speed adjustment factor for the flow number. Table 9 summarizes the traffic speed adjustment factor for speeds below 64.4 km/h (40 mi/h). For the AASHTO definition of standing traffic (speed of 20 km/h) the flow number for mixtures in areas with standing traffic should be 2.8 times that for mixtures in areas where the traffic speed is 64.4 km/h (40 mph) to have equivalent rutting resistance. The intersection flow number experiment described in Chapter 3 was developed to verify these flow number traffic speed adjustment factors.

Table 9. Flow Number Speed Adjustment Factors.

Traffic Speed		Flow Number Speed Correction Factor
mi/h	km/h	
40.0	64.4	1.0
35.0	56.4	1.1
30.0	48.3	1.3
25.0	40.3	1.5
20.0	32.2	1.9
15.0	24.2	2.4
12.4	20.0	2.8
10.0	16.1	3.4
5.0	8.1	6.3
1.0	1.6	26.6

2.6 Analysis of WisDOT Criteria for Mixture Design and Acceptance

2.6.1 WisDOT Criteria for Mixture Design and Acceptance

Tables 10 through 13, taken from the WisDOT 2010 Standard Specifications, present WisDOT mixture design requirements, production tolerances, and in-place pavement density requirements. In general the mixture design requirements in Tables 10 and 11 conform to those in AASHTO M323 for dense graded mixtures and AASHTO M325 for stone matrix asphalt (SMA) mixtures with the following exceptions:

- The 2.36 mm sieve control points for 9.5 mm mixtures provide a wider design gradation range that those in AASHTO M323.
- The gradation bands for SMA mixtures are more restrictive than those in AASHTO M325.
- The minimum VMA for 12.5 mm SMA mixtures is less than specified in AASHTO M325.
- Coarse aggregate fractured faces requirements are more stringent than AASHTO M323 for the E-0.3, E-1, and E-30 design traffic levels.
- The requirements for flat and elongated particles are more restrictive than AASHTO M323.
- Fine aggregate angularity requirements are more stringent than AASHTO M323 for design traffic levels of E-0.3 and E-3.

- The design gyration level for the E-0.3 and E-1 design traffic levels are less than specified by AASHTO M323. The design gyration level for SMA mixtures is less than specified by AASHTO M325.
- The upper VFA limit for the E-3 design traffic level is lower than specified in AASHTO M323.
- AASHTO M325 does not include ranges for dust to binder ratio or VFA.
- Tensile strength ratio requirements are less stringent than AASHTO M323 and AASHTO M325.

Table 10. WisDOT Gradation and VMA Requirements for Mixture Design. (Table 460-1 in WisDOT 2010 Standard Specifications).

SIEVE	PERCENTS PASSING DESIGNATED SIEVES						
	NOMINAL SIZE						
	37.5 mm	25.0 mm	19.0 mm	12.5 mm	9.5 mm	SMA 12.5 mm	SMA 9.5 mm
50.0-mm	100						
37.5-mm	90 – 100	100					
25.0-mm	90 max	90 -100	100				
19.0-mm	—	90 max	90 -100	100		100	
12.5-mm	—	—	90 max	90 -100	100	90 - 97	100
9.5-mm	—	—	—	90 max	90 -100	58 - 72	90 - 100
4.75-mm	—	—	—	—	90 max	25 - 35	35 - 45
2.36-mm	15 – 41	19 - 45	23 - 49	28 - 58	20 - 65	15 - 25	18 - 28
75-µm	0 – 6.0	1.0 - 7.0	2.0 - 8.0	2.0 - 10.0	2.0 - 10.0	8.0 - 12.0	10.0 - 14.0
% MINIMUM VMA	11.0	12.0	13.0	14.0	15.0	16.0	17.0

Table 11. WisDOT Mixture Design Requirements (Table 460-2 in WisDOT 2010 Standard Specifications).

Mixture type	E - 0.3	E - 1	E - 3	E - 10	E - 30	E - 30x	SMA
ESALs x 10^6 (20 yr design life)	< 0.3	0.3 - < 1	1 - < 3	3 - < 10	10 - < 30	>= 30	___
LA Wear (AASHTO T 96)							
100 revolutions(max % loss)	13	13	13	13	13	13	13
500 revolutions(max % loss)	50	50	45	45	45	45	40
Soundness (AASHTO T 104) (sodium sulfate, max % loss)	12	12	12	12	12	12	12
Freeze/Thaw (AASHTO T 103) (specified counties, max % loss)	18	18	18	18	18	18	18
Fractured Faces (ASTM 5821) (one face/2 face, % by count)	60 / __	65 / __	75 / 60	85 / 80	98 / 90	100/100	100/90
Flat & Elongated (ASTM D 4791) (max %, by weight)	5 (5:1 ratio)	5 (5:1 ratio)	5 (5:1 ratio)	5 (5:1 ratio)	5 (5:1 ratio)	5 (5:1 ratio)	20 (3:1ratio)
Fine Aggregate Angularity (AASHTO T304, method A, min)	40	40	43	45	45	45	45
Sand Equivalency (AASHTO T 176, min)	40	40	40	45	45	50	50
Gyratory Compaction							
Gyrations for N_{ini}	6	7	7	8	8	9	8
Gyrations for N_{des}	40	60	75	100	100	125	65
Gyrations for N_{max}	60	75	115	160	160	205	160
Air Voids, $\%V_a$ ($\%G_{mm}$ N_{des})	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)
% G_{mm} N_{ini}	<= 91.5[1]	<= 90.5[1]	<= 89.0[1]	<= 89.0	<= 89.0	<= 89.0	___
% G_{mm} N_{max}	<= 98.0	<= 98.0	<= 98.0	<= 98.0	<= 98.0	<= 98.0	___
Dust to Binder Ratio[2] (% passing $0.075/P_{be}$)	0.6 - 1.2	0.6 - 1.2	0.6 - 1.2	0.6 - 1.2	0.6 - 1.2	0.6 - 1.2	1.2 - 2.0
Voids filled with Binder (VFB or VFA, %)	70 - 80[4] [5]	65 - 78[4]	65 - 75[4]	65 - 75[3] [4]	65 - 75[3] [4]	65 - 75[3] [4]	70 - 80
Tensile Strength Ratio (TSR) (ASTM 4867)							
no antistripping additive	0.70	0.70	0.70	0.70	0.70	0.70	0.70
with antistripping additive	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Draindown at Production Temperature (%)	___	___	___	___	___	___	0.30

[1] The percent maximum density at initial compaction is only a guideline.

[2] For a gradation that passes below the boundaries of the caution zone(ref. AASHTO MP3), the dust to binder ratio limits are 0.6 - 1.6.

[3] For 9.5mm nominal maximum size mixtures, the specified VFB range is 73 - 76%.

[4] For 37.5mm nominal maximum size mixes, the specified VFB lower limit is 67%.

[5] For 25.0mm nominal maximum size mixes, the specified VFB lower limit is 67%.

The mixture production tolerances in Table 12 control the gradation and the asphalt content of the mixture, and the air void content and VMA of laboratory compacted specimens. Considering the WisDOT production limits are based on a sample size of 4, the JMF limits for gradation and asphalt content are less stringent than the single sample tolerances contained in ASTM D3515, *Standard Specifications for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures*. The WisDOT warning limits approximately correspond to the ASTM D3515 gradation and asphalt content tolerances for a sample size of 4. The warning limits for air void content and VMA correspond approximately to those recommended in NCHRP Report 409 (*23*) after adjustment for the difference in the sample size; 4 for WisDOT production tolerances compared to 5 for NCHRP Report 409. Since production penalties are assessed for materials produced between the warning and JMF limits, it is reasonable for the warning limits to correspond with the tolerances recommended in ASTM D3515 and NCHRP Report 409, and for the JMF limits to be broader.

Table 12. WisDOT Mixture Production Tolerances (From Section 460.2.8.2.1.5 of WisDOT 2010 Standard Specifications).

ITEM	JMF LIMITS	WARNING LIMITS
Percent passing given sieve:		
37.5-mm	+/- 6.0	+/- 4.5
25.0-mm	+/- 6.0	+/- 4.5
19.0-mm	+/- 5.5	+/- 4.0
12.5-mm	+/- 5.5	+/- 4.0
9.5-mm	+/- 5.5	+/- 4.0
2.36-mm	+/- 5.0	+/- 4.0
75-µm	+/- 2.0	+/- 1.5
Asphaltic content in percent	+/- 0.4	+/- 0.3
Air voids in percent	+/- 1.3	+/- 1.0
VMA in percent	- 1.5	- 1.2

The minimum in-place density requirements in Table 13 are somewhat less stringent than the percent within limits approach included in the AASHTO Quality Assurance Guide Specification (*24*). This guide specification recommends that 90 percent of each lot be within the limits of 91 to 96 percent of maximum density. Under this requirement less than 10 percent of the pavement area in a lot would have in-place density less than 91 percent of maximum density. The WisDOT in-place density requirement for traffic lanes with design traffic levels of E-10 and greater, is a lot average of 92.0 percent of maximum density with all individual tests above 87.0

percent of maximum density. This implies an allowable standard deviation of approximately 1.67 percent. For a lot average of 92.0 percent with a standard deviation of 1.67 percent, approximately 10 percent of the pavement area in the lot will have an in-place density below approximately 90 percent of maximum density.

Table 13. WisDOT In-Place Density Requirements (Table 460-3 in WisDOT 2010 Standard Specifications).

LOCATION	LAYER	PERCENT OF TARGET MAXIMUM DENSITY		
		MIXTURE TYPE		
		E-0.3, E-1, and E-3	E-10, E-30, and E-30x	SMA[4]
TRAFFIC LANES[2]	LOWER	91.5[3]	92.0[3]	___
	UPPER	91.5	92.0	___
SIDE ROADS, CROSSOVERS, TURN LANES, & RAMPS	LOWER	91.5[3]	92.0[3]	___
	UPPER	91.5	92.0	___
SHOULDERS & APPURTENANCES	LOWER	89.5	89.5	___
	UPPER	90.5	90.5	___

[1] The table values are for average lot density. If any individual density test result falls below 87% of the target maximum density, the engineer may investigate the acceptability of that material.

[2] Includes parking lanes as determined by the engineer.

[3] Minimum reduced by 2 percent for < 3 million ESALs and one percent for > 3 million ESALs, for that lower layer constructed directly on crushed aggregate or recycled base courses.

[4] The minimum required densities for SMA mixtures are specified in the contract special provisions.

2.6.2 Evaluation of WisDOT Criteria for Mixture Design Based on Rutting Resistance

The rutting resistance model developed in NCHRP Projects 9-25, 9-31, and 9-33 (Equation 4) can be used to evaluate many of the key WisDOT criteria for mixture design including:

- Binder grade and modification,
- Design gyration levels,
- Volumetric requirements (VMA, V_a ,VFA),
- Percent passing 0.075 mm sieve and dust to binder ratio.

Table 14 summarizes the input variables for Equation 4 and identifies where these inputs are obtained. For estimating the range of allowable volumetric properties based on the mixture design criteria, the following relationships are helpful:

Effective Volumetric Binder Content (VBE)

$$VBE = VMA - V_a \tag{11}$$

where:

VBE = effective binder content, vol %

VMA = voids in the mineral aggregate, vol %

V_a = air voids, vol %

Table 14. Input Variables for Estimating Mixture Rutting Resistance.

Input Variable	Description	Value Obtained From
$G^*/\sin\delta$	Estimated *aged* PG grading parameter at high temperatures, determined at 10 rad/s and at the yearly, 7-day average maximum pavement temperature at 20 mm below the pavement surface, as determined using LTPPBind, Version 3.1 (units of Pa); aged value can be estimated by multiplying the RTFOT value by 4.0 for long-term projects (10 to 20 year design life), and by 2.5 for short term projects of 1 to 2 years.	Typical value from Projects 0092-04-07 and 0092-08-06 for the binder grade used. PG 58 Neat = 100,000 Pa PG 64 Neat = 127,000 Pa PG 70 Polymer Modified = 155,000 Pa
M	Modification factor	PG 58 Neat = 1.00 PG 64 Neat = 1.00 PG 70 Modified = 7.13
G_a	Aggregate bulk specific gravity.	Typical value from Projects 0092-04-07 and 0092-08-06 for Wisconsin aggregates. G_a = 2.700
S_a	Aggregate specific surface.	Estimated from percent passing 0.075 mm sieve. See text for details.
VMA	Voids in the mineral aggregate for the as-produced mixture based on QC testing.	Estimated from design volumetric requirements. See text for details.
N_{design}	Design gyration level.	Mixture design requirements.
V_d	Design air void content	4.0 per design volumetric requirements
V_{IP}	In-place air void content.	Minimum average in-place density from specifications. V_{IP} = 8.5 for E-0.3, E-1, and E-3 V_{IP} = 8.0 for E-10, E30, and E-30x
K_s	Speed correction.	K_s = 0.935 for 40 mph traffic.

Voids Filled With Asphalt (VFA)

$$VFA = \frac{VBE}{VMA} \times 100 \qquad (12)$$

where:

VFA = voids filled with asphalt, vol %

VBE = effective binder content, vol %

VMA = voids in the mineral aggregate, vol %

Effective Binder Content by Weight

$$P_{be} \approx \frac{VBE}{(0.96)G_{mm}} \approx \frac{VBE}{2.45} \qquad (13)$$

where:

P_{be} = effective binder content by weight, wt %

VBE = effective binder content, vol %

G_{mm} = maximum specific gravity (assumed = 2.550)

Aggregate Surface Area (21)

$$S_a \approx 2.05 + (0.623 \times \% passing\ 0.075 mm\ sieve) \qquad (14)$$

where:

S_a = specific surface of aggregate in mixtures, m^2/kg

Using these relationships, the range of allowable design volumetric properties can be determined. First the minimum VMA is given by the design requirement. For a 12.5 mm mixture, the minimum VMA is 14.0 percent. The maximum VMA is given by the maximum VFA requirement. For E-3 and greater design traffic levels, the maximum VFA is 75 percent. Substituting Equation 11 into Equation 12, setting VFA = 75 percent and V_a = 4.0 percent, and solving for VMA, the maximum VMA is 16.0 percent. From Equation 11, the minimum and maximum design VBE for the 12.5 mm mixtures designed for E-3 or greater traffic are 10.0 and 12.0 percent respectively. From Equation 13, the approximate range of effective binder contents by weight is: 4.0 to 5.0 percent. The approximate range of allowable filler contents in the mixture is given by the dust proportion, which is specified as 0.6 to 1.2 yielding an approximate range for the percent passing the 0.075 sieve of 2.4 to 6.0 percent. Substituting this range into Equation 14 yields the approximate design range for the aggregate surface area of 3.5 to 6.0. Table 15 summarizes the approximate range of design volumetric properties for 12.5 mm mixtures.

Table 15. Approximate Range of Volumetric Properties for 12.5 mm Mixtures Based on WisDOT Design Criteria.

Property	E-0.3	E-1	E-3	E-10	E-30
Minimum VMA, vol %	14	14	14	14	14
Maximum VMA, vol %	20	18	16	16	16
Minimum S_a, m^2/kg	3.5	3.5	3.5	3.5	3.5
Maximum S_a, m^2/kg	7.0	6.5	6.0	6.0	6.0

Plots showing the effect of volumetric composition on the rutting resistance were developed for 12.5 mm mixtures for each design traffic level using Equation 4 and low, medium and high values for design VMA and dust to effective binder ratio. The applicable WisDOT design gyrations and minimum average lot in-place density from Tables 12 and 13 were used. The results are shown in Figures 8 through 14.

Figures 8, 9, and 10 show the results for the E-0.3, E-1, and E-3 design traffic levels. These figures show that the rutting resistance for these lower traffic level mixtures is acceptable considering current design criteria.

Figures 11 and 12 show the results for the E-10 design traffic level for neat PG 58 and neat PG 64 binders. These figures suggest that the rutting resistance offered by neat PG 58 binders may not be inadequate for the E-10 design traffic level except when the dust to effective binder ratio exceeds 1.0. Neat PG 64 binders provide improved rutting resistance; however, they may not be adequate for mixtures designed with high VMA and low dust to effective binder ratios. These analyses suggest that consideration should be given to specifying neat PG 64 binders for E-10 mixtures and increasing the minimum dust proportion.

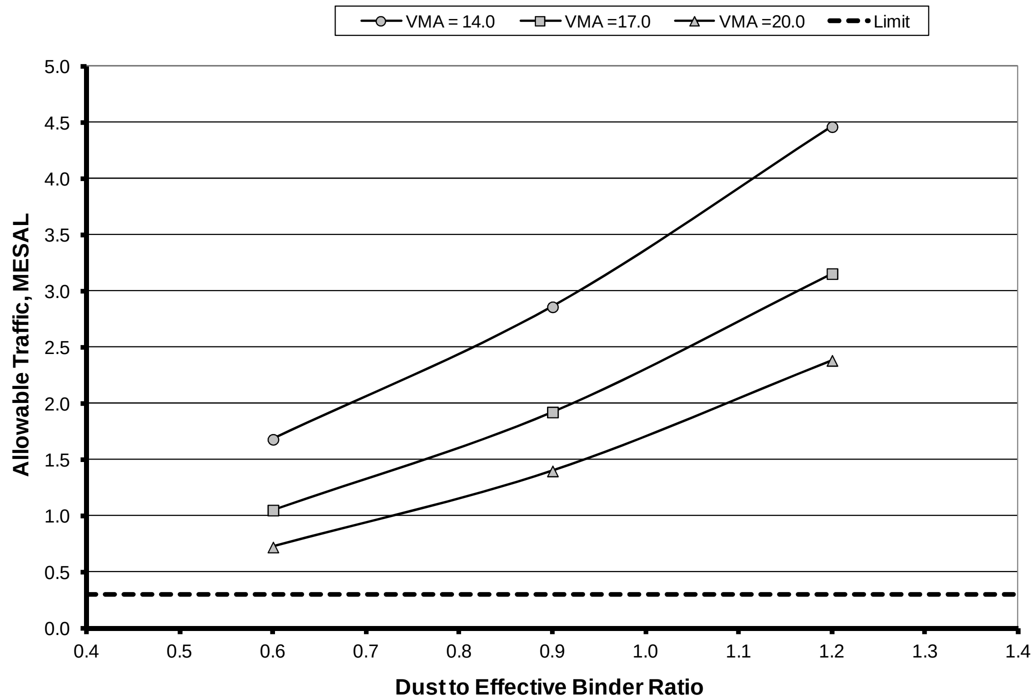


Figure 8. Effect of Design Volumetric Criteria on the Estimated Rutting Resistance of E-0.3 Mixtures with Neat PG 58 Binder.

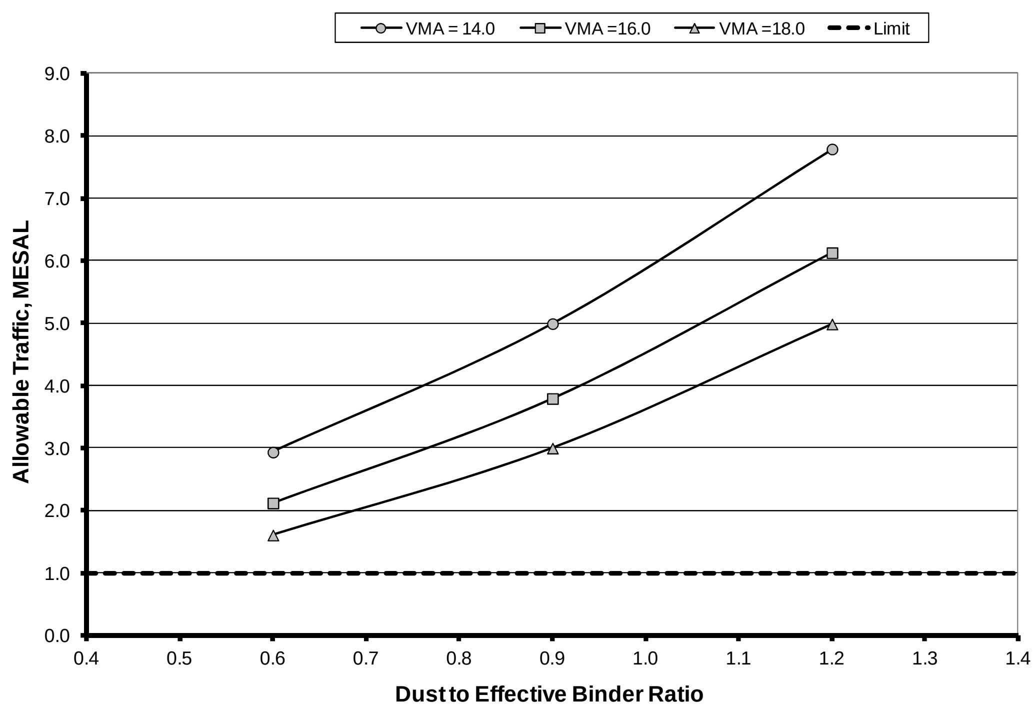


Figure 9. Effect of Design Volumetric Criteria on the Estimated Rutting Resistance of E-1 Mixtures with Neat PG 58 Binder.

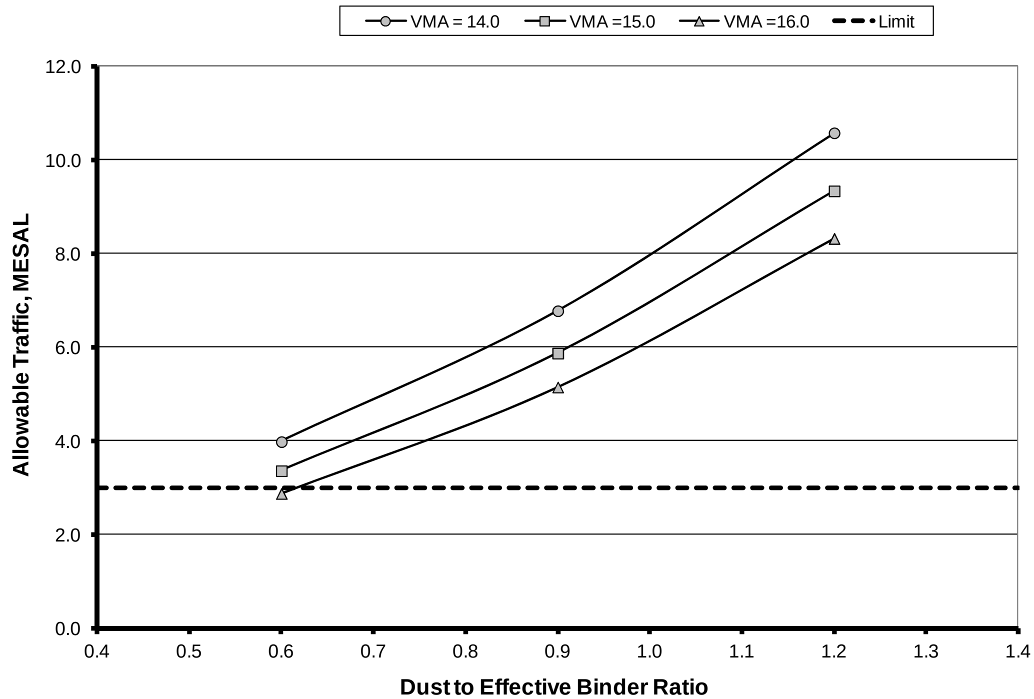


Figure 10. Effect of Design Volumetric Criteria on the Estimated Rutting Resistance of E-3 Mixtures with Neat PG 58 Binder.

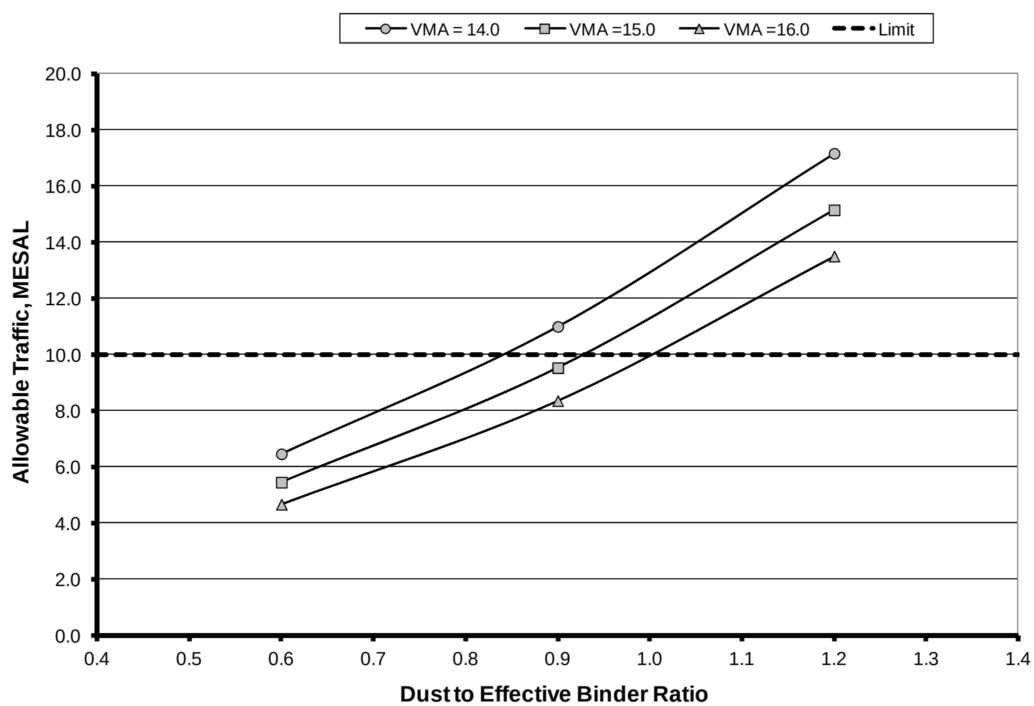


Figure 11. Effect of Design Volumetric Criteria on the Estimated Rutting Resistance of E-10 Mixtures with Neat PG 58 Binder.

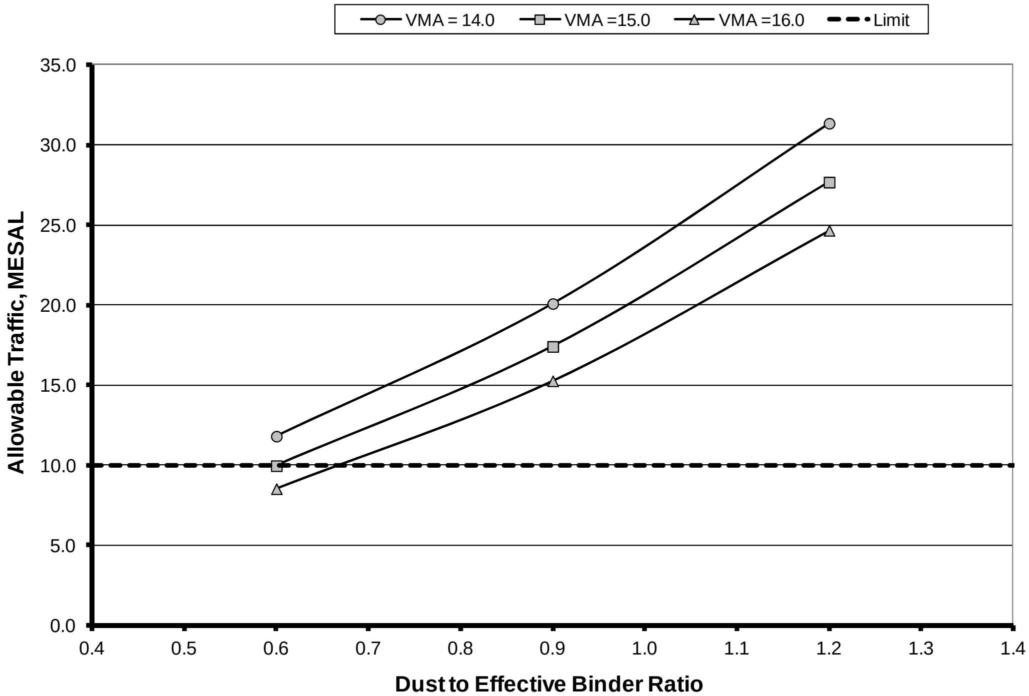


Figure 12. Effect of Design Volumetric Criteria on the Estimated Rutting Resistance of E-10 Mixtures with Neat PG 64 Binder.

Finally Figures 13 and 14 show the results for the E-30 design traffic level for neat PG 64 and polymer modified PG 70 binders. These figures indicate that adequate rutting resistance for the E-30 traffic level cannot be obtained with neat binders and that polymer modified binders should be used. When using polymer modified binders, the volumetric design criteria appear to be less important. From Figure 14, the rutting resistance of mixtures with polymer modified PG 70 binders is also adequate for the E-30x design traffic level.

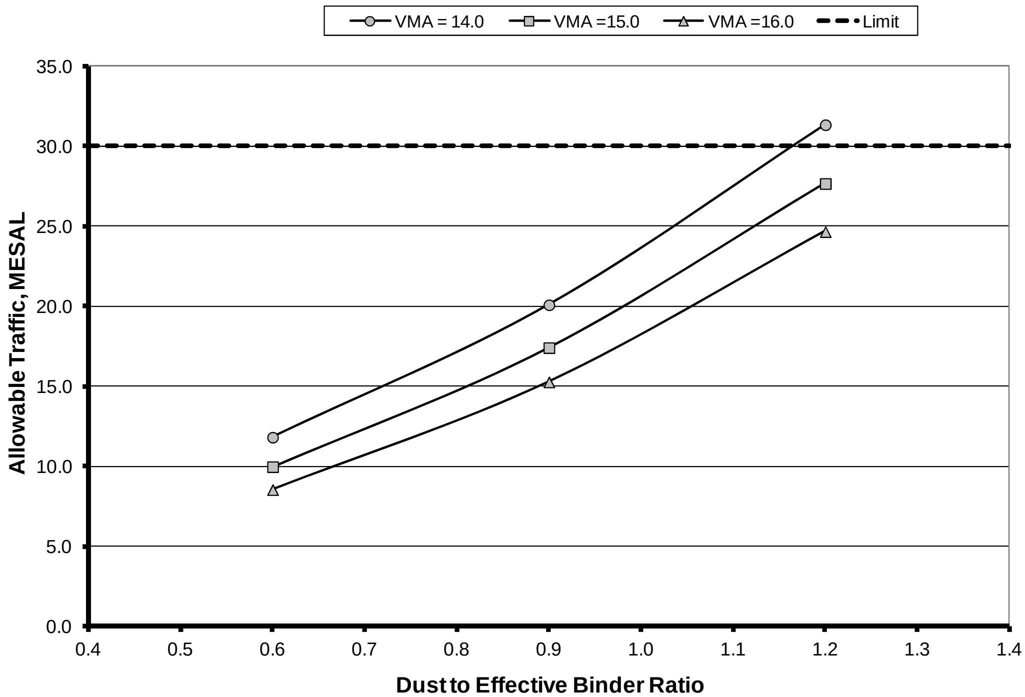


Figure 13. Effect of Design Volumetric Criteria on the Estimated Rutting Resistance of E-30 Mixtures with Neat PG 64 Binder.

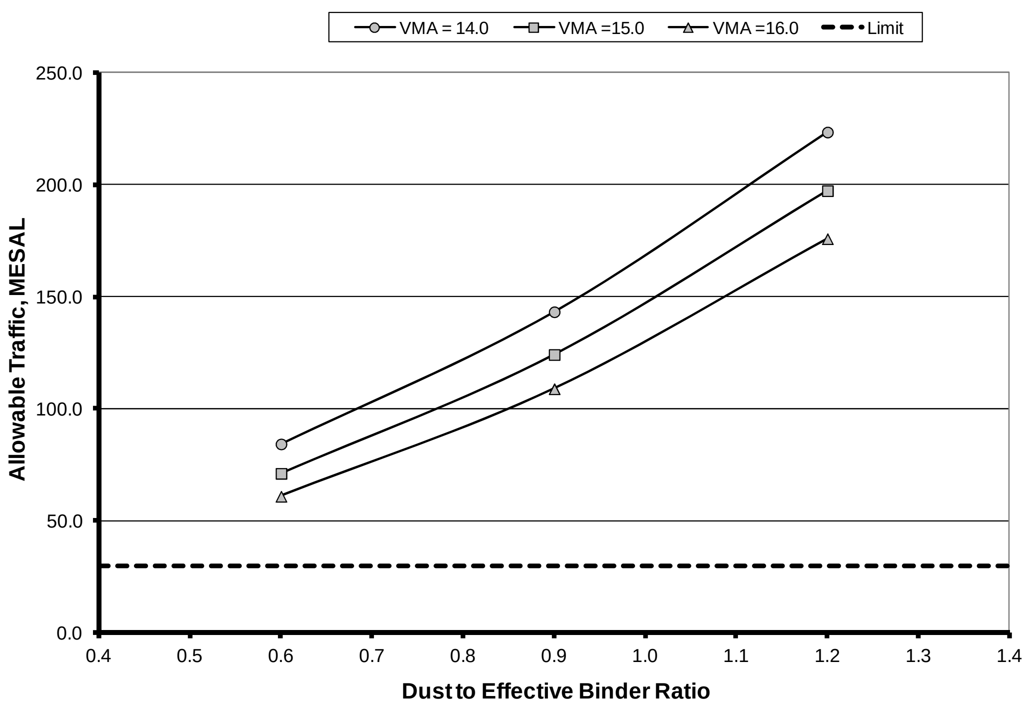


Figure 14. Effect of Design Volumetric Criteria on the Estimated Rutting Resistance of E-30 Mixtures with Polymer Modified PG 70 Binder.

2.6.3 Evaluation of WisDOT Criteria for Mixture Production Based on Rutting Resistance

Equation 4 can also be used to analyze the effect of mixture production tolerances on rutting resistance. When considering production variations, the usual interactions between asphalt content, percent passing the 0.075 mm sieve, VBE, V_a, and VMA must be considered.

2.6.3.1 Deviations from Target Binder Content

The WisDOT mixture production criteria permit the binder content to vary by ±0.3 percent for the warning limits and ±0.5 percent for the JMF limits. The general relationship between changes in binder content and changes in air voids of laboratory compacted specimens is a 1 percent increase in binder content produces a 2.5 percent decrease in air voids (*25*). Thus changes in V_a caused by changes in binder content will be approximately ±0.75 percent and ±1.25 percent for the warning and JMF limits, respectively. From Equation 10, changes in VBE caused by these allowable changes in binder content are approximately the same magnitude, but in the opposite direction. Thus, increasing the binder content by 0.3 percent decreases air voids by approximately 0.75 percent, but increases VBE by approximately 0.75 percent, resulting in essentially no change in VMA of the compacted laboratory specimen. The effect of changes in binder content on rutting resistance, assuming all other properties of the mixture remain constant, can then be estimated using Equation 4 where the only parameter that varies is V_d, which is 4.0 for the mixture as designed; lower for mixtures with higher binder contents, and higher for mixtures with lower binder contents. The change is given by Equation 15 and is plotted as a function of the change in binder content in Figure 15. Based on this analysis, the WisDOT warning limits result in approximately a 30 percent change in the rutting resistance of the mixture while the WisDOT JMF limits would result in approximately a 50 percent change in the rutting resistance. Considering the exponent in the relationship between flow number and allowable traffic is nearly one, a 0.3 percent increase in binder content would be expected to reduce the flow number by 30 percent. This reduction was not observed in the WHRP Project 0092-04-07 flow number data and was investigated further in the laboratory testing discussed in Chapter 3.

$$\Delta TR\% = 100\left(\frac{V_{QC}}{V_d}\right)^{1.5185} - 100 \quad (15)$$

where:

$\Delta TR\%$ = percent change in allowable traffic

V_{QC} = air void content of specimens compacted to N_{design} using the binder content of the as-produced mixture

V_d = air void content of specimens compacted to N_{design} using the design binder content

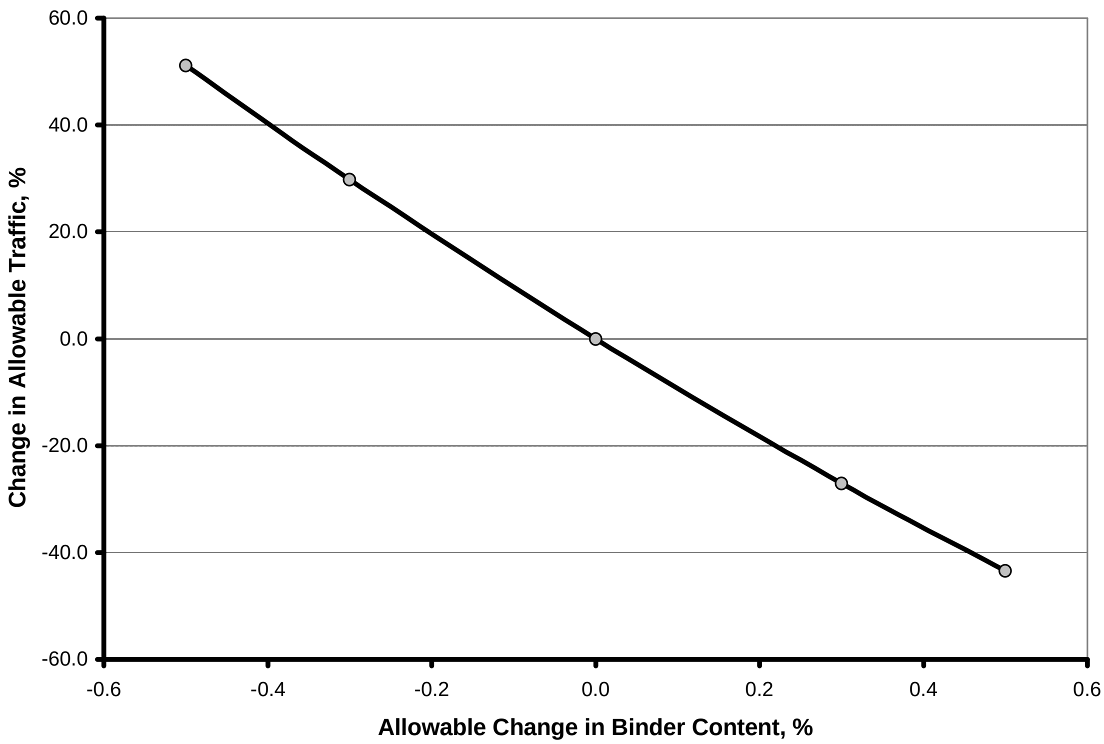


Figure 15. Effect of Deviations in Binder Content on Estimated Rutting Resistance.

2.6.3.2 Deviations from Target Filler Content

A similar analysis can be performed for deviations from the target filler content. Previous research on mineral fillers showed that a 1 percent increase in the filler content produced a 0.5 percent decrease in the air voids of laboratory compacted specimens (*26*). Thus changes in V_a

caused by changes in the percent passing the 0.075 mm sieve content will be approximately ±0.75 percent and ±1.00 percent for the warning and JMF limits, respectively. For mixtures with the same binder content, the VMA of the mixture will also change by these amounts. Additionally, the surface area of the mixture will change in accordance with Equation 14. The analysis of the effect of deviations in filler content is somewhat more complicated because two of the terms in Equation 4, (P and V_d) change as the filler content changes and the term, P, is affected by changes in both the surface area and VMA of the mixture. The analysis is best done using a spreadsheet. Figure 16 presents the results of this analysis for a 12.5 mm mixture with design VMA of 15 and a design dust to effective binder ratio of 0.9. Based on this analysis, the WisDOT warning limits result in approximately a 30 percent change in the rutting resistance of the mixture while the WisDOT JMF limits would result in approximately a 40 percent change in the rutting resistance. The change in rutting resistance resulting from deviations in filler content are similar in magnitude but opposite in sign to those caused by deviations in binder content. Increasing the filler content improves the rutting resistance of the mixture.

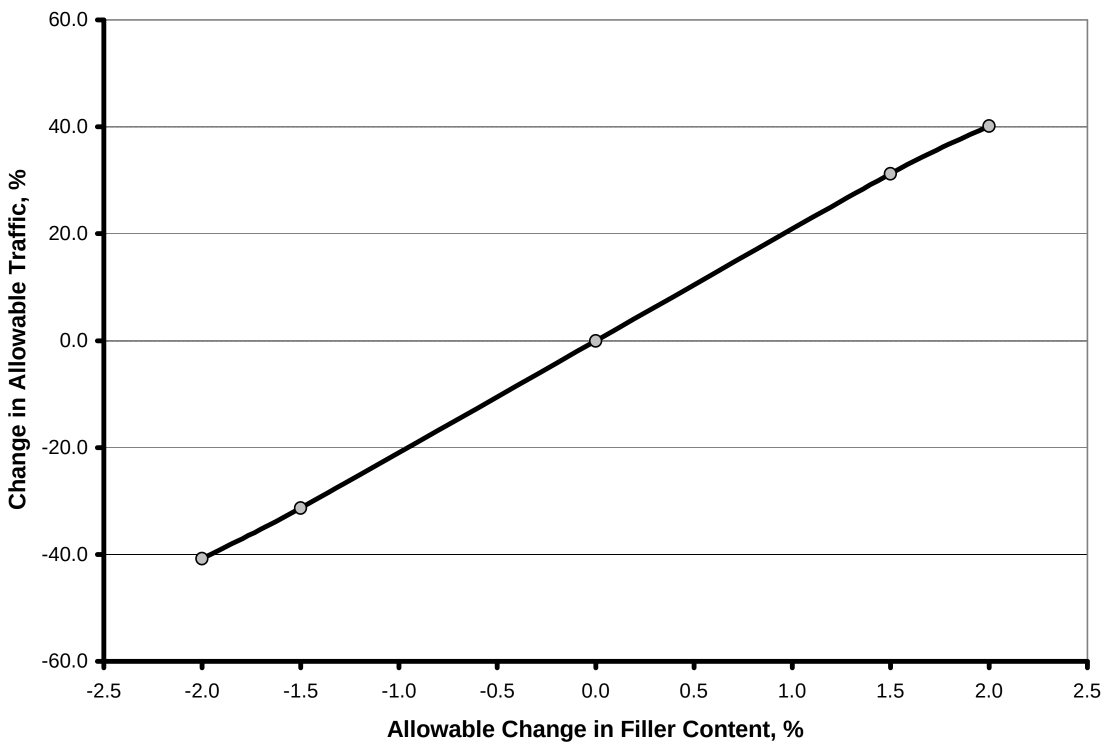


Figure 16. Effect of Deviations in Filler Content on Estimated Rutting Resistance.

2.6.4 Evaluation of WisDOT Criteria for In-Place Density Based on Rutting Resistance

The effect of in-place density on rutting resistance can also be evaluated using Equation 4. The WisDOT in-place density specification for traffic lanes, side roads, cross-overs, turn lanes, and ramps require minimum lot average densities of 91.5 percent of maximum density for traffic levels E-3 and less or 92.0 percent of maximum density for traffic levels E-10 and greater. Individual density test results may reach as low as 87 percent of maximum density. The effect of changes in in-place density on rutting resistance, assuming all other properties of the mixture remain constant, can be estimated using Equation 4 where the only parameter that varies is V_{ip}, the in-place air void content. The change relative to an arbitrary reference in-place air void content is given by Equation 16. Figure 17 is a plot of the analysis using 8 percent as the reference in-place air void content. From Figure 17, the effect of in-place density on rutting resistance is not as strong as the binder content and mineral filler effects. Improving in-place density by 1.0 percent improves rutting resistance by approximately 20 percent.

$$\Delta TR\% = 100\left(\frac{V_{IPR}}{V_{IP}}\right)^{1.4727} - 100 \qquad (16)$$

where:

$\Delta TR\%$ = percent change in allowable traffic

V_{IP} = in-place air void content

V_{IPR} = reference in-place air void content.

Considering the exponent in the relationship between flow number and allowable traffic is nearly one, a 1 percent increase in the air void content of laboratory specimens would be expected to reduce the flow number by 20 percent. In WHRP Project 0092-04-07 specimens were tested at nominal 7.0 and 10.0 percent air void contents. The average reduction in the flow number for the 10.0 percent specimens relative to the 7.0 percent specimens was 51 percent, which agrees reasonable well with that estimated using Equation 16 and a 3 percent change in air void content.

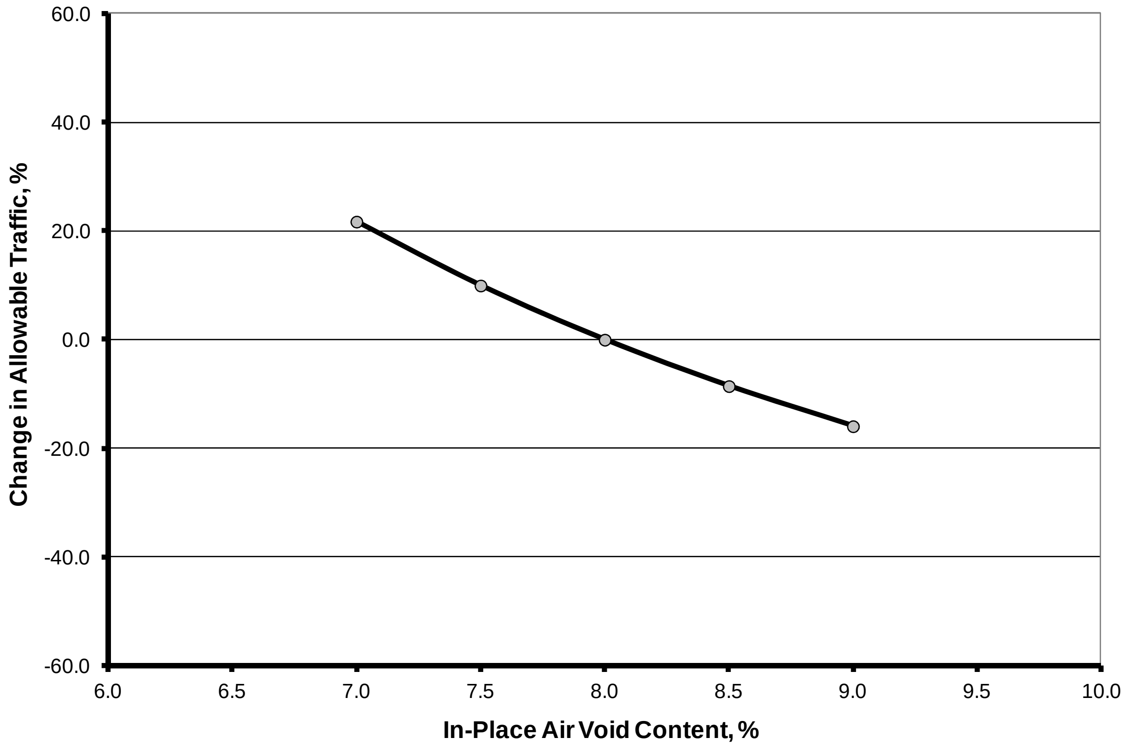


Figure 17. Effect of In-Place Density on Estimated Rutting Resistance.

2.7. Summary

The literature review included a review of the literature and research in progress concerning the flow number and the effect of mixture composition on rutting resistance. It also included a detailed review of the WisDOT requirements for the design and acceptance of asphalt concrete. The major findings of the literature review that were considered in the development of the laboratory testing plans are summarized below:

1. Several studies have shown the flow number to be a reasonable indicator of the rutting resistance of asphalt concrete.

2. Because the flow number testing and analysis was not fully standardized in NCHRP Project 9-19, a number of variations of the flow number test have been used in completed research studies. Flow number tests have been conducted with and

without confinement, and using various stress levels, temperatures, and specimen air void contents.

3. In WHRP Project 0092-08-06, 12 mixtures were evaluated using the most common unconfined and confined testing conditions. Data from the unconfined tests were found to be significantly less variable.

4. There is evidence that the standard laboratory short-term conditioning for performance property testing contained in AASHTO R30, 4 hours at 135 °C, represent the aging that occurs during construction and some time in-service. Consideration should be given to using a different short-term conditioning protocol based on the compaction temperature to allow consideration of warm mix asphalt in the future.

5. Tentative criteria for using the flow number test to evaluate rutting resistance were developed in NCHRP Project 9-33. These criteria are based on the following testing conditions:

    - Unconfined tests using an axial stress of 87 psi,
    - Testing at the 50 percent reliability high pavement temperature from LTPPBind 3.1,
    - Short-term conditioning of 4 hours at 135 °C,
    - Specimen air void content of 7.0 ± 0.5 percent

    Evaluation of these tentative criteria in WHRP Project 0092-08-06 concluded that they are overly conservative based on the reported field performance of typical Wisconsin mixtures. Revised criteria were developed in WRHP Project 0092-08-06.

6. To account for slower moving traffic at intersections, mixtures with higher flow numbers should be used. It appears that the flow criteria should be increased by a factor of 3 to 6 for intersection mixtures.

7. WHRP Projects 0092-04-07 and 0092-08-06 are the only research studies that included detailed evaluation of the effects of mixture composition on the flow number. Based on analysis of the data from these two projects, the flow number test is sensitive to key mixture design and acceptance factors affecting the rutting resistance of asphalt concrete. These include:

   - Aggregate gradation (percent passing 0.075 mm sieve),
   - Binder grade,
   - Binder modification,
   - In-place air voids,
   - Design compaction level, and
   - Design VMA.

8. An evaluation of the WisDOT mixture design requirements using the rutting model developed in NCHRP Projects 9-25, 9-31 and 9-33 indicated:

   - Current mixture design criteria result in mixtures that are overdesigned based on rutting resistance for design traffic levels of E-3 and lower.

   - Neat PG 58 binders are not adequate for the E-10 design traffic level except when the dust to effective binder ratio exceeds 1.0. Neat PG 64 binders provided improved rutting resistance; however, they may not be adequate for mixtures designed with very low dust to effective binder ratios.

   - For E-30 and E-30x design traffic levels neat PG 64 will not provide adequate rutting resistance. The rutting resistance of mixtures with polymer modified PG 70 binders substantially exceeds that required for both the E-30 and E-30x design traffic levels.

9. An evaluation of the WisDOT mixture acceptance requirements using the rutting model developed in NCHRP Projects 9-25, 9-31 and 9-33 suggested:

   - WisDOT warning limits for binder content, percent passing –0.075 mm sieve, VMA and air voids limit changes in rutting resistance to approximately 30 percent of the design value. Lower binder contents and higher filler contents result in improved rutting resistance.

   - A 0.5 percent decrease in the acceptable in-place air void content will improve rutting resistance by approximately 10 percent. In-place air voids likely have a greater effect on the fracture resistance and durability of mixtures compared to rutting resistance.

Chapter 3 Flow Number Testing and Analysis

3.1 Primary Flow Number Experiment

3.1.1 Experimental Design Factors

The purpose of the literature review and associated analyses presented in Chapter 2 was to guide the selection of factors to be included in the laboratory flow number experiments. Table 16 summarizes the factors that were considered for the experiment and the rationale for including selected factors in the experiment. Each factor is discussed in greater detail below.

3.1.1.1 Nominal Maximum Aggregate Size and Gradation

Based on the available budget, the primary flow number experiment included only the most common surface course mixtures used in Wisconsin. These are fine graded 12.5 mm nominal maximum aggregate size mixtures.

3.1.1.2 Design Traffic Levels and Gyrations

To include mixtures with a wide range of rutting resistance, the primary flow number experiment evaluated mixtures from three design traffic levels: E-3, E-10, and E-30. For mixtures in each design traffic level, the WisDOT design gyration levels was used.

3.1.1.3 Design VMA and VFA

As discussed earlier in this report, for a specified design air void content, the requirements on VMA and VFA control the effective binder content, VBE, of the mixture. The minimum VMA sets the minimum VBE and the maximum VFA sets the maximum VBE. For 12.5 mm mixtures and the design traffic levels selected, the minimum and maximum VBE are 10 and 12 percent, respectively corresponding to design VMA ranging from 14 to 16 percent. The effect of increasing VMA on the rutting resistance of asphalt mixtures was well established in NCHRP Projects 9-25 and 9-31 (*21*). Considering that most mixtures are designed approximately one percent above the minimum VMA value to account for changes that occur during production, the available range becomes too narrow to effectively select mixtures with different design VMA and VFA within an design traffic category. Therefore, design VMA and VFA were not

Table 16. Summary of Factors Considered for the Experiment.

Factor	Levels	Description	Comment
Nominal Maximum Aggregate Size	1	12.5 mm only	Limit to most often used surface courses in Wisconsin
Gradation	1	Fine graded only	Limit to most often used surface courses in Wisconsin
Design Traffic Levels	3	E-3, E-10, and E-30	Limit to traffic levels where rutting is a primary design consideration
Design Gyrations	2	75 for E-3, 100 for E-10 and E-30	Per WisDOT mixture design requirements
Design VMA and VFA	Not controlled	Within WisDOT mixture design requirements	Effect of design VMA on rutting resistance well established in NCHRP Project 9-25. Allowable range is too narrow to effectively select different mixtures.
Air Void Content	1	7.0 percent	Effect of air void content on rutting resistance and the flow number were well established in NCHRP Project 9-25 and WHRP Project 0092-04-07.
Aggregate Angularity	3	Low, medium, and high within E-3 and E-10 mixtures. E-10 high will also classify as E-30	Most flow number testing to date has evaluated only highly angular aggregates. Some Wisconsin E-3 and E-10 mixtures are produced using less angular aggregates and it is important to verify that the rutting resistance of these mixtures is acceptable for their design traffic level.
Filler content	3	Design, Design -2.0 percent, Design +2.0 percent	Filler content is both a design and acceptance criteria and has a major effect on the rutting resistance of asphalt concrete mixtures. Preliminary analyses suggest that low filler content mixtures may not have sufficient rutting resistance.
Binder content	3	Design, Design +0.2, Design +0.4	Binder content is both a design and acceptance criteria and has a major effect on the rutting resistance of asphalt concrete mixtures. WHRP Project 0092-04-07 test data indicates little effect on the flow number. NCHRP Project 9-25/9-31 rutting model indicates a major effect. This discrepancy requires further evaluation.
Binder Grade	4	For E-3, Neat PG 58-28 For E-10 Neat PG 58-28, Polymer Modified PG 64-28, and Polymer Modified PG 70-28. Only E-10 high angularity will be included PG 70-28.	Binder grade has a major effect on rutting resistance. Preliminary analyses suggest that neat PG 58-XX binders may not provide acceptable rutting resistance for E-10 mixtures, and that neat PG 64-XX binders may nor provide acceptable rutting resistance for E-30 mixtures.

included as controlled factors in the experiment. All mixtures were selected from accepted WisDOT designs meeting the volumetric requirements for the respective design traffic level.

3.1.1.4 Air Void Content

The effect of in-place air void content on rutting resistance and specimen air void content on flow number test results were well established in NCHRP Projects 9-25 and 9-31 and WHRP Project 0092-04-07, respectively and are in good agreement. Rutting resistance and the flow number decrease by approximately 18 percent for every 1 percent increase in air voids. Although the minimum in-place average air void content for Wisconsin mixtures is 8.5 and 8.0 percent, respectively for levels E-3 and lower and E-10 and greater, a specimen air void content of 7.0 percent was used in the primary flow number experiment. An air void content of 7.0 percent is typically used by many researchers to represent in-place air voids and was used in WHRP Projects 0092-04-07 and 0092-08-06. By performing the flow number tests at 7.0 percent air voids, the data from these earlier studies and other future national studies can be added to the database of flow number test results assembled for this project.

3.1.1.5 Aggregate Angularity

The effect of aggregate angularity on the flow number and rutting resistance has not been studied in great detail in past flow number research efforts. Consequently it was evaluated at multiple levels within the E-3 and E-10 design traffic levels. Aggregate angularity was included in the primary flow number experiment at three levels for the E-3 and E-10 mixtures based on the range of the aggregate angularity included in the WisDOT mixture design criteria. The high range of angularity for the E-10 mixtures was selected such that these mixtures will also qualify as E-30 designs.

3.1.1.6 Filler Content

The rutting model developed in NCHRP Projects 9-25, 9-31 and 9-33 indicates that the percent passing the 0.075 mm sieve has a major effect on the rutting resistance of asphalt mixtures. The analysis using this model that was presented in Chapter 2 indicates that rutting resistance improves with increasing dust to effective binder ratio. Additionally, filler content is a mixture acceptance factor. The NCHRP rutting model estimates a 30 percent improvement in rutting resistance for a 1.5 percent increase in filler content. Because filler content is an extremely important factor affecting rutting resistance it was included in the primary flow number experiment at three levels: design, design –2.0 percent, and design +2.0 percent. Both reductions and increases in filler content were evaluated because the analyses presented in Chapter 2 indicate that consideration should be given to increasing the minimum dust to effective binder content ratio. Based on review of the mixtures included in WHRP Projects 0092-04-07 and 0092-08-06, Wisconsin 12.5 mm mixtures are typically designed with dust to effective binder ratios of 0.9 to 1.0 and have effective binder contents of approximately 4.9 percent. The planned levels cover mixtures with dust to effective binder content ranges from approximately 0.5 to 1.4.

3.1.1.7 Binder Content

Like filler content, binder content is an acceptance factor in the WisDOT specifications. The rutting model developed in NCHRP Projects 9-25, 9-31 and 9-33 indicates the binder content of the mixture has a major effect on the rutting resistance. This model estimates that a 0.3 percent increase in binder content, which is the WisDOT warming limit, will decrease rutting resistance by approximately 30 percent. However, WHRP Project 0092-04-07 concluded that the flow number was not affected by a 0.3 percent increase in binder content. This discrepancy was evaluated in the primary flow number study by including binder content at three levels: design, design +0.2 percent and design +0.4 percent to cover the range of the WisDOT warning and JMF limits. Only increases in binder content were evaluated because rutting resistance decreases with increasing binder content.

3.1.1.8 Binder Grade

The last factor considered in the design of the experiment was binder grade. Binder grade is a major factor affecting rutting resistance. The analyses using the NCHRP rutting model presented in Chapter 2 suggest that neat PG 58-XX binders may not provide adequate rutting resistance for E-10 mixtures, and that neat PG 64-XX binders will not provide adequate rutting resistance for E-30 mixtures. Thus, the E-10 mixtures, for which the high angularity mixture will also meet E-30 requirements, included three binder grades: neat PG 58-28 and polymer modified PG 64-28 and PG 70-28 binders. Only the high angularity E-10 mixture were tested with the PG 70-28 binder. All E-3 mixtures used a neat PG 58-28 binder.

3.1.2 Detailed Experimental Design

Tables 17 and 18 present the detailed experimental design for the primary flow number experiment for E-3 and E-10 mixtures. These are full factorial designs for aggregate angularity, filler content, and binder content each at three levels. The E-10 design also is a full factorial for binder grade at two levels, and for the E-10 high angularity mixture, a full factorial for binder grade at three levels. Using two replicate specimens per cell, the entire experiment required the fabrication and testing of a total of 180 flow number specimens. Specimens were fabricated in accordance with AASHTO PP60, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor(SGC)*. The flow number tests were conducted in accordance with AASHTO TP79, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*, using the following testing conditions:

- Short-term oven conditioning of 2 hours at the compaction temperature. This conditioning was selected to represent the stiffness of the binder in the mixture upon completion of construction, and to allow the results to be extended to warm mix asphalt in the future.
- Target specimen air void content of 7.0 percent.
- Test temperature of 49.6 °C, which is the 50 percent reliability performance grade temperature at a depth of 20 mm for Madison, Wisconsin obtained from LTPPBind 3.1.
- Unconfined tests with an axial stress level of 87 psi (600 kPa) to match the stress levels used in WHRP Projects 0092-04-07 and 0092-08-06.

For these testing conditions, the anticipated range of flow numbers is from approximately 10 for the low angularity E-3 mixtures to approximately 1,000 for the high angularity E-10 mixtures with the modified binder.

Table 17. Experimental Design for E-3 Mixtures.

Binder Grade	Angularity	Filler Content	Binder Content	Replicates
PG 58-28	Low	Design +2.0	Design	2
			Design +0.2	2
			Design +0.4	2
		Design	Design	2
			Design +0.2	2
			Design +0.4	2
		Design -2.0	Design	2
			Design +0.2	2
			Design +0.4	2
	Medium	Design +2.0	Design	2
			Design +0.2	2
			Design +0.4	2
		Design	Design	2
			Design +0.2	2
			Design +0.4	2
		Design -2.0	Design	2
			Design +0.2	2
			Design +0.4	2
	High	Design +2.0	Design	2
			Design +0.2	2
			Design +0.4	2
		Design	Design	2
			Design +0.2	2
			Design +0.4	2
		Design -2.0	Design	2
			Design +0.2	2
			Design +0.4	2
Total Number of Flow Number Specimens and Tests				54

Table 18. Experimental Design for E-10 and E-30 Mixtures (Note High Angularity Will Meet E-30 Requirements).

Binder Grade	Angularity	Filler Content	Binder Content	Replicates
PG 58-28	Low	Design +2.0	Design	2
			Design +0.2	2
			Design +0.4	2
		Design	Design	2
			Design +0.2	2
			Design +0.4	2
		Design -2.0	Design	2
			Design +0.2	2
			Design +0.4	2
	Medium	Design +2.0	Design	2
			Design +0.2	2
			Design +0.4	2
		Design	Design	2
			Design +0.2	2
			Design +0.4	2
		Design -2.0	Design	2
			Design +0.2	2
			Design +0.4	2
	High	Design +2.0	Design	2
			Design +0.2	2
			Design +0.4	2
		Design	Design	2
			Design +0.2	2
			Design +0.4	2
		Design -2.0	Design	2
			Design +0.2	2
			Design +0.4	2
PG 64-28	Low	Design +2.0	Design	2
			Design +0.2	2
			Design +0.4	2
		Design	Design	2
			Design +0.2	2
			Design +0.4	2
		Design -2.0	Design	2
			Design +0.2	2
			Design +0.4	2
	Medium	Design +2.0	Design	2
			Design +0.2	2
			Design +0.4	2
		Design	Design	2
			Design +0.2	2
			Design +0.4	2
		Design -2.0	Design	2
			Design +0.2	2
			Design +0.4	2
	High	Design +2.0	Design	2
			Design +0.2	2
			Design +0.4	2
		Design	Design	2
			Design +0.2	2
			Design +0.4	2
		Design -2.0	Design	2
			Design +0.2	2
			Design +0.4	2
PG 70-28	High	Design +2.0	Design	2
			Design +0.2	2
			Design +0.4	2
		Design	Design	2
			Design +0.2	2
			Design +0.4	2
		Design -2.0	Design	2
			Design +0.2	2
			Design +0.4	2
Total Number of Flow Number Specimens and Tests				126

For the PG 58-28 cells in Tables 17 and 18, replicate specimens were compacted to N_{design} gyrations and the theoretical maximum specific gravity was measured to determine volumetric properties for use in the data analysis and for comparison to the WisDOT volumetric requirements. Some of the combinations resulted in air voids and VMA values exceeding the WisDOT volumetric requirements.

3.1.3 Materials

3.1.3.1 Mixtures

The experimental design presented in Tables 17 and 18 include a number of variations on six mixtures selected to cover the range of aggregate angularities permitted by the WisDOT specifications for the E-3 and E-10 traffic levels. Mix design data for these mixtures are summarized in Tables 19 and 20 for the E-3 and E-10 mixtures, respectively. Three of the six mixtures, Cisler E-3, Wimmie E-10, and Cisler E-10 were the same mixtures tested in WHRP Project 0092-08-06. The Glenmore E-3 mixture is a 12.5 mm mixture based on the 19 mm mixture tested in WHRP Project 0092-08-06. The low angularity mixtures were designed by the research team.

Figures 18 and 19 compare the gradation of the E-3 and E-10 mixtures, respectively. These figures show the control points and 0.45 maximum density line for 12.5 mm mixtures. All mixtures classify as fine-graded based on the AASHTO M323 classification system. Figure 20 compares the percent passing the 2.36 mm sieve which is the control sieve for 12.5 mm mixtures. All mixtures have more that 39 percent passing the 2.36 mm sieve; therefore, they classify as fine-graded. The low angularity Hollatz E-3 mixture is somewhat finer than the other mixtures. The gradation of the other mixtures are very similar. Figure 21 compares the estimated surface area of the aggregates in each of the mixtures. The surface area of the aggregates was estimated by summing the percent passing the 0.30, 0.15, and 0.075 mm sieves and dividing the result by 5 (*21*). The surface area of the low angularity Hollatz mixtures is somewhat higher than the other mixtures.

Table 19. Summary of E-3 Mixture Design Properties.

Angularity		Low	Medium	High
Coarse Aggregate		Hollatz	Cisler	Glenmore
Manufactured Fine Aggregate			Cisler	Glenmore
Natural Fine Aggregate		Hollatz	River	Van Handel
Gradation, % passing	Sieve size, mm			
	25	100.0	100.0	100.0
	19	100.0	100.0	100.0
	12.5	96.5	93.8	89.0
	9.5	89.1	83.7	76.0
	4.75	68.5	61.1	62.6
	2.36	54.3	47.8	44.5
	1.18	42.7	38.2	30.5
	0.6	34.0	26.7	21.8
	0.3	19.4	11.0	13.7
	0.15	6.4	5.2	6.8
	0.075	3.7	3.7	3.7
Binder content, wt %		5.8	5.3	5.2
Design Air Voids, vol %		4.0	4.0	4.2
Design VMA, vol %		15.7	14.9	15.1
Design VFA, vol %		74.2	73.2	72.3
Maximum Specific Gravity		2.512	2.479	2.574
Aggregate Bulk Specific Gravity		2.692	2.650	2.753
Effective binder content, vol %		11.7	10.9	10.9
Dust/Binder Ratio		0.8	0.8	0.9
Design Gyrations		75	75	75
Fractured Faces, 1 face, wt %		78.9	92.9	100.0
Fractured Faces, 2 faces, wt %		75.8	92.6	100.0
Sand Equivalent, %		85	83	80
Flat and Elongated, wt %		0.3	2.2	0.8
Fine Aggregate Angularity, %		41.7	44.0	46.8

Table 20. Summary of E-10 Mixture Design Properties.

Angularity		Low	Medium	High
Coarse Aggregate		Hollatz	Wimmie	Cisler
Manufactured Fine Aggregate		Morris Gade	Wimmie	Cisler
Natural Fine Aggregate		Hollatz	Wimmie	River
Gradation, % passing	Sieve size, mm			
	25	100.0	100.0	100.0
	19	100.0	100.0	100.0
	12.5	96.5	94.8	95.1
	9.5	89.1	84.3	83.3
	4.75	67.9	64.4	64.7
	2.36	45.6	45.6	46.3
	1.18	29.2	31.2	32.4
	0.6	19.6	22.0	22.7
	0.3	12.5	12.8	11.2
	0.15	7.9	6.9	5.6
	0.075	5.7	4.2	3.7
Binder content, wt %		5.4	5.0	5.5
Design Air Voids, vol %		4.0	3.8	4.0
Design VMA, vol %		14.2	14.9	15.8
Design VFA, vol %		71.9	74.6	74.7
Maximum Specific Gravity		2.555	2.533	2.472
Aggregate Bulk Specific Gravity		2.705	2.721	2.664
Effective binder content, vol %		10.2	11.1	11.8
Dust/Binder Ratio		1.3	0.9	0.7
Design Gyrations		100	100	100
Fractured Faces, 1 face, wt %		78.9	93.9	98.1
Fractured Faces, 2 faces, wt %		75.8	92.4	98.0
Sand Equivalent, %		85	84.0	85.0
Flat and Elongated, wt %		0.3	3.2	2.1
Fine Aggregate Angularity, %		46.4	46.0	46.4

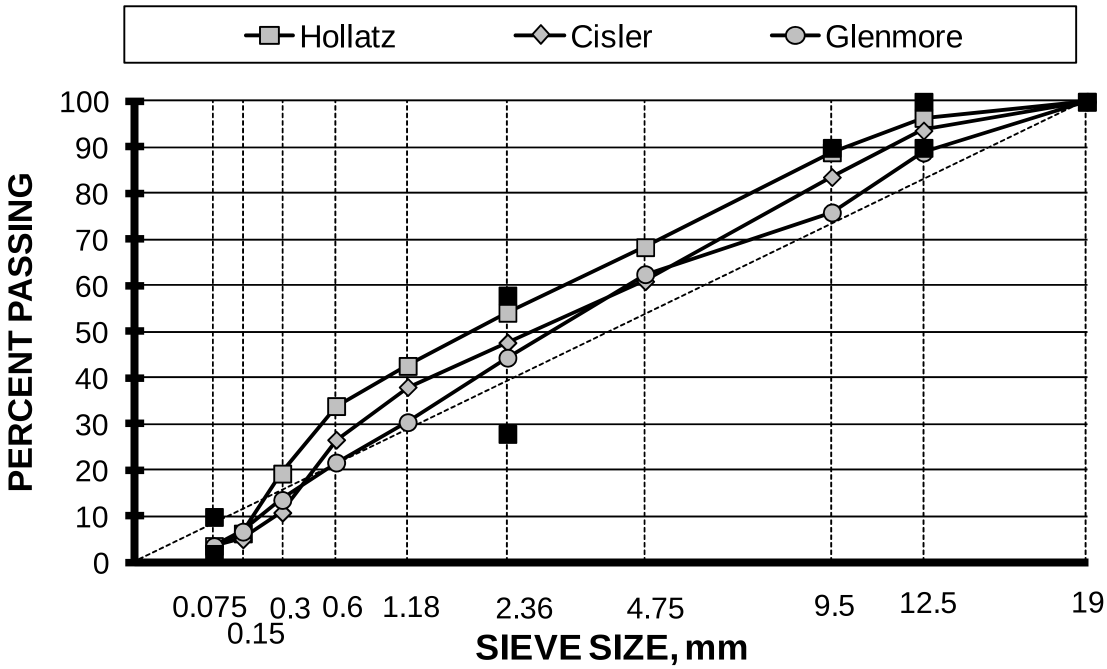


Figure 18. Gradation of E-3 Mixtures.

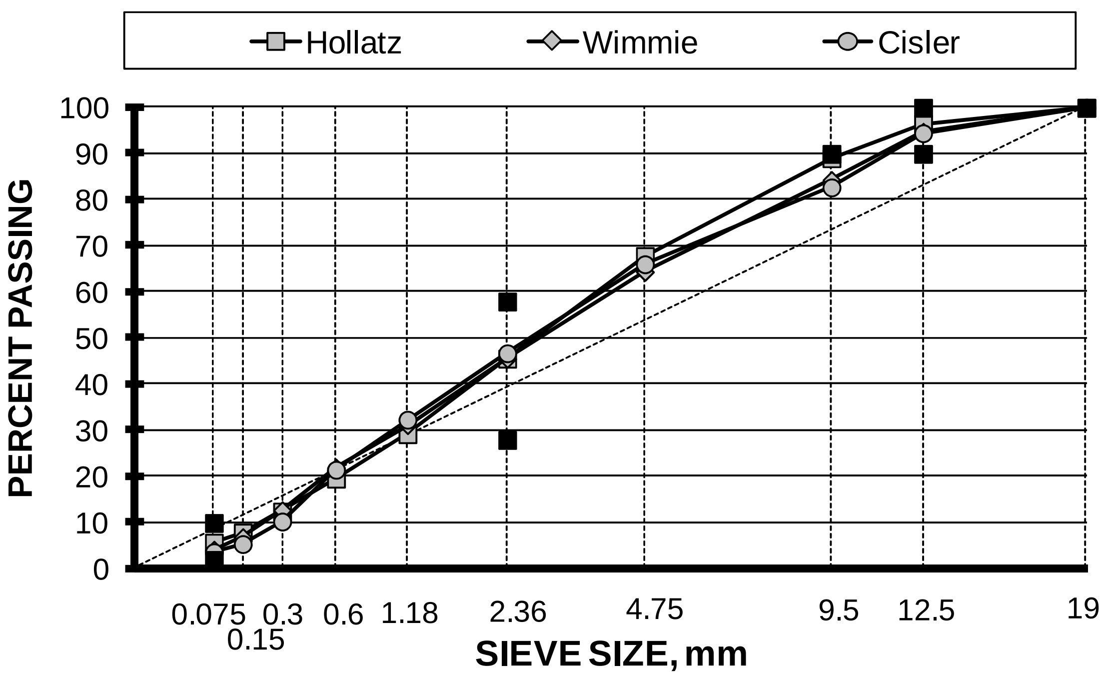


Figure 19. Gradation of E-10 Mixtures.

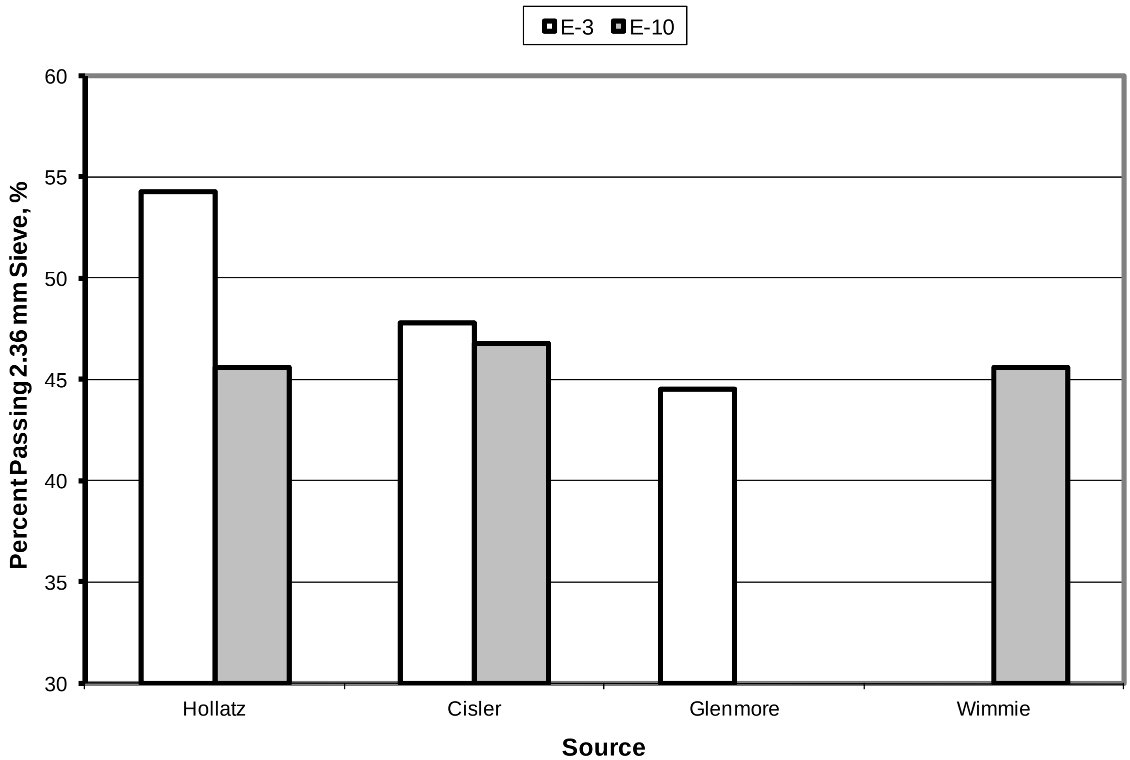


Figure 20. Percent Passing 2.36 mm Sieve (Control Sieve for 12.5 mm Mixtures).

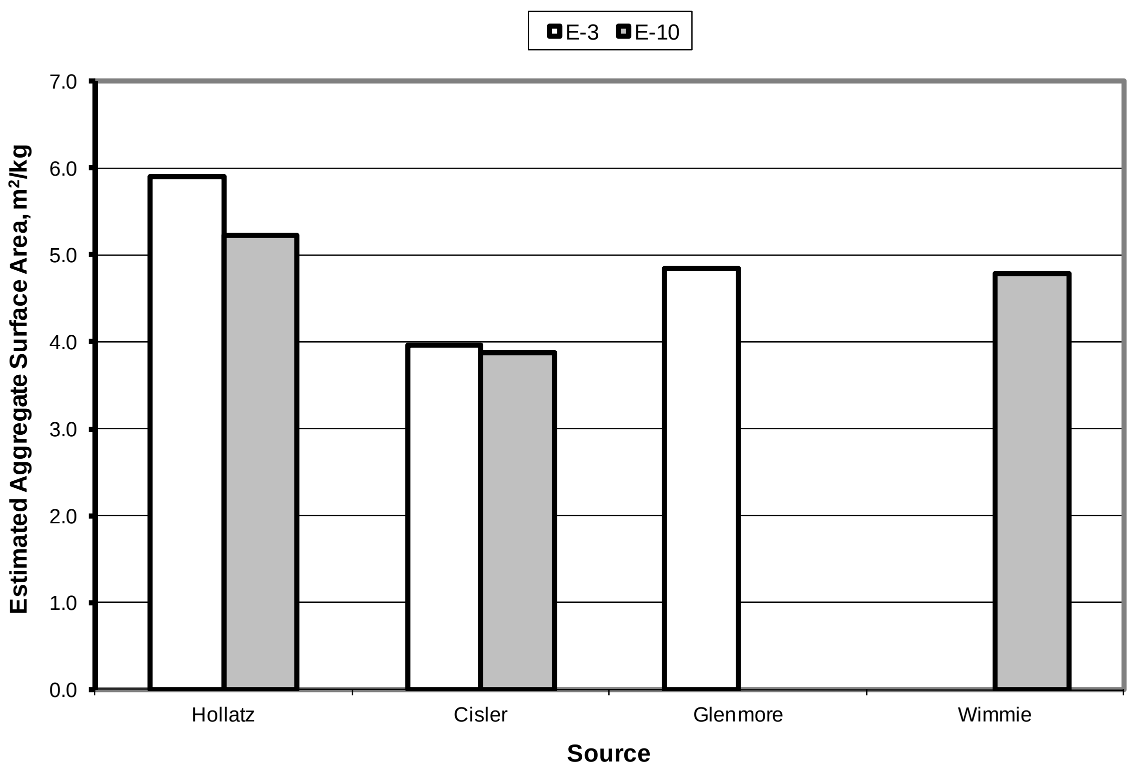


Figure 21. Estimated Aggregate Surface Area.

The angularity of the aggregates are compared in Figures 22 and 23. Figure 22 compares the coarse aggregate fractured faces for each of the mixtures. The coarse aggregates in the low angularity Hollatz mixtures have much lower angularity compared to the other mixtures. The fine aggregate angularity shown in Figure 23 is similar for all of the E-10 mixtures. The fine aggregate angularity varies significantly for the E-3 mixtures, ranging from a low of 41.7 to a high of 46.8.

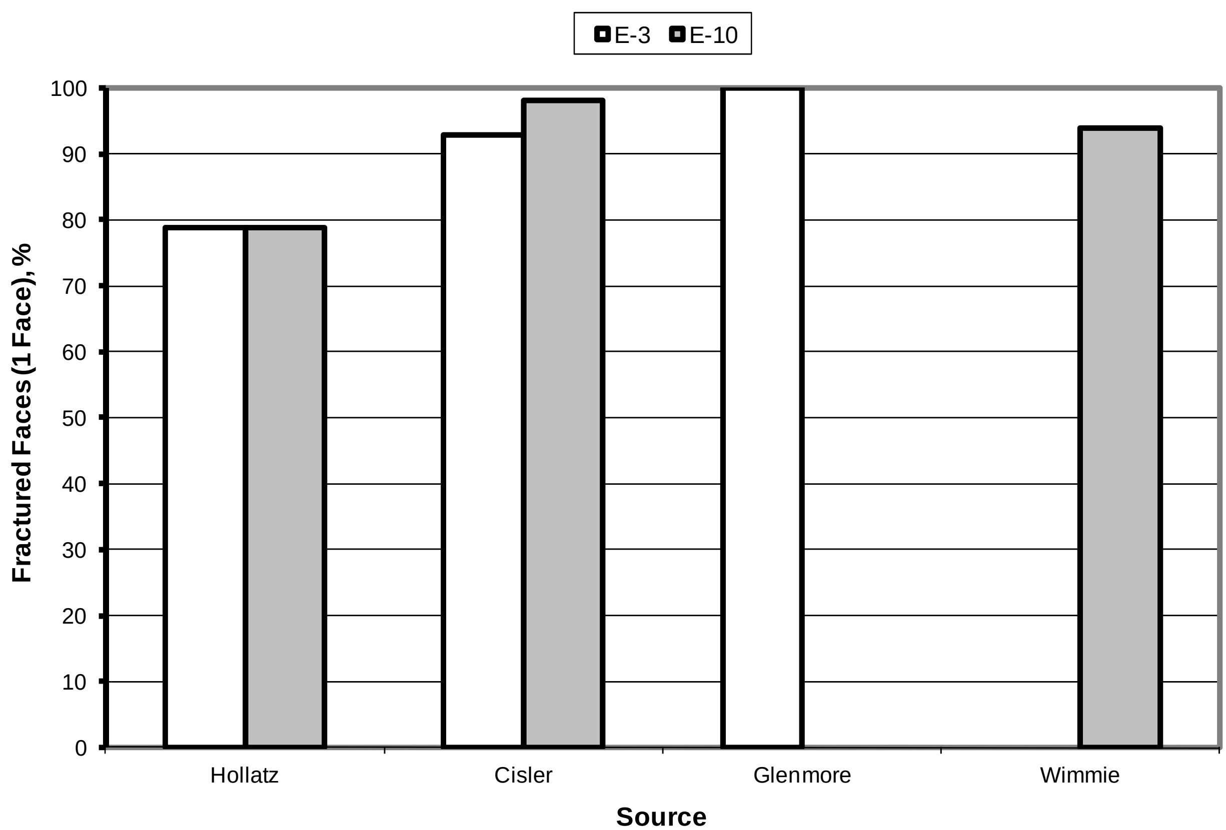


Figure 22. Coarse Aggregate Fractured Faces.

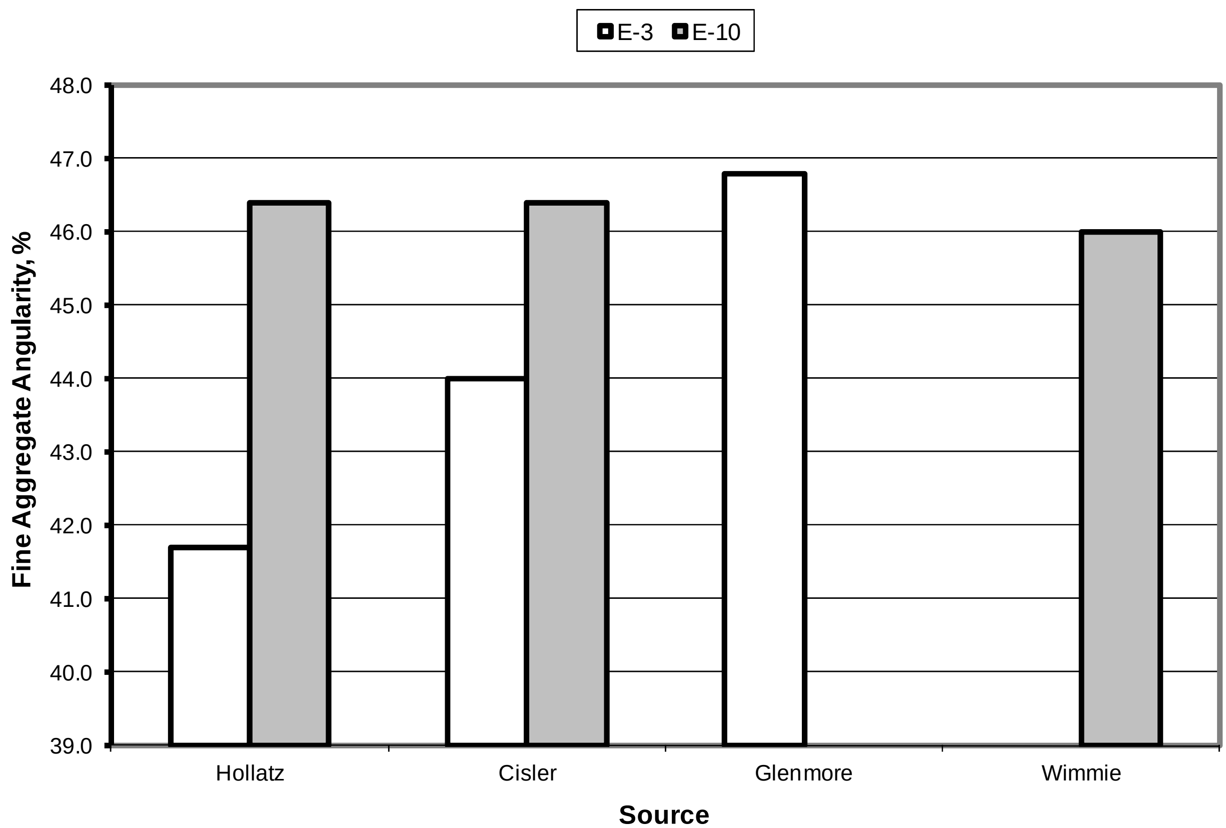


Figure 23. Fine Aggregate Angularity.

Figures 24 through 26 compare selected volumetric properties for the mixtures. Figure 24 compares the design VMA for the mixtures. The design VMA for the Hollatz low angularity E-3 and the Cisler high angularity E-10 mixtures are somewhat high exceeding 1.5 percent above the minimum specified for 12.5 mm mixtures. The design VMA for the Hollatz low angularity E-3 mixture at 14.2 percent is somewhat low for 12.5 mm mixtures. The design VMA for the other mixtures are about 1 percent higher than the minimum specified for 12.5 mm mixtures. Figure 24 shows the effective volumetric binder content of the mixtures, which is equal to the VMA minus the design air voids. Since the design air voids for all of the mixtures was approximately 4 percent, the effective volumetric binder content of the mixtures mirrors the design VMA. The Hollatz E-3 and the Cisler E-10 mixtures have higher effective volumetric binder content of approximately 11.8 percent while the Hollatz E-10 mixture has the lowest effective volumetric binder content of 10.2 percent. The other mixtures have effective volumetric binder content of approximately 11 percent.

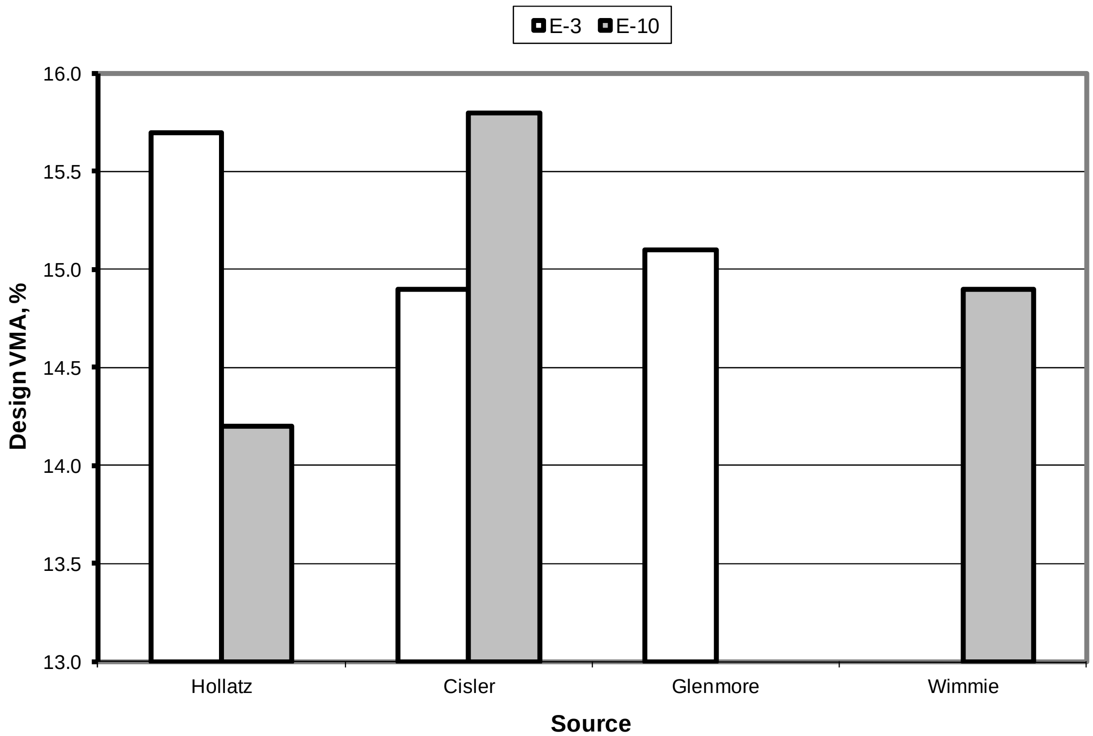


Figure 24. Design VMA.

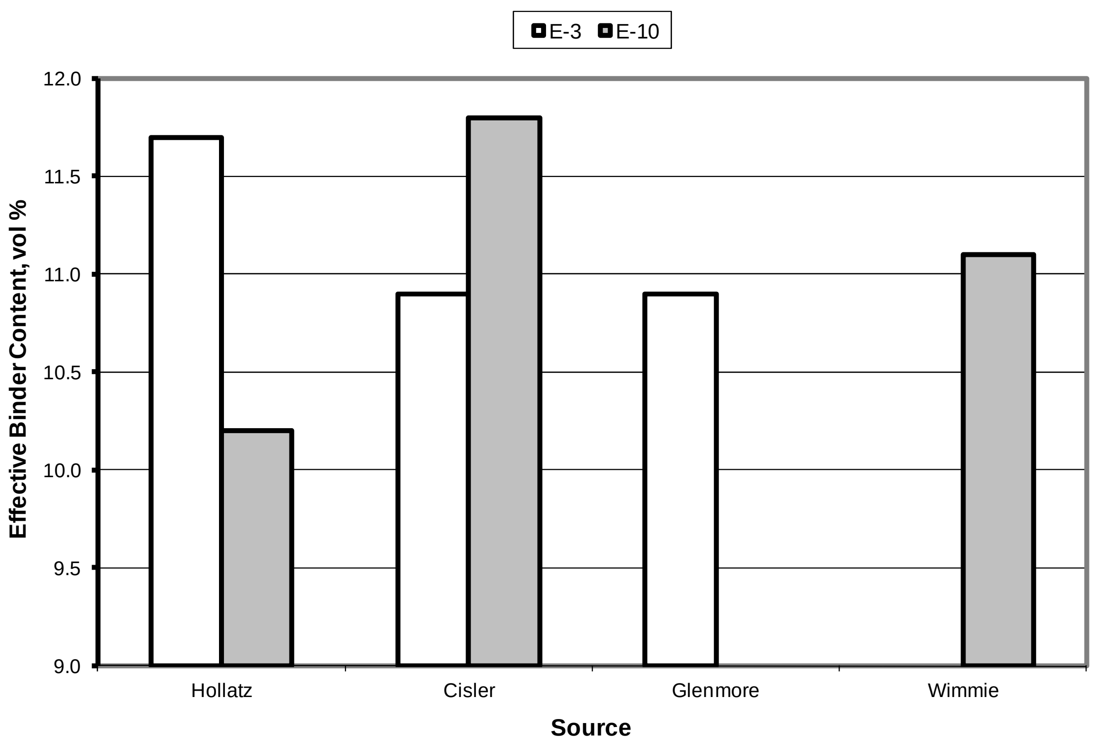


Figure 25. Effective Volumetric Binder Content.

Figure 26 compares the design binder content for the six mixtures. The design binder content ranges from 5.0 percent for the medium angularity Wimmie E-10 mixture to 5.8 percent of the low angularity Hollatz E-3 mixture. The other four mixtures have design binder contents ranging from 5.2 to 5.5 percent.

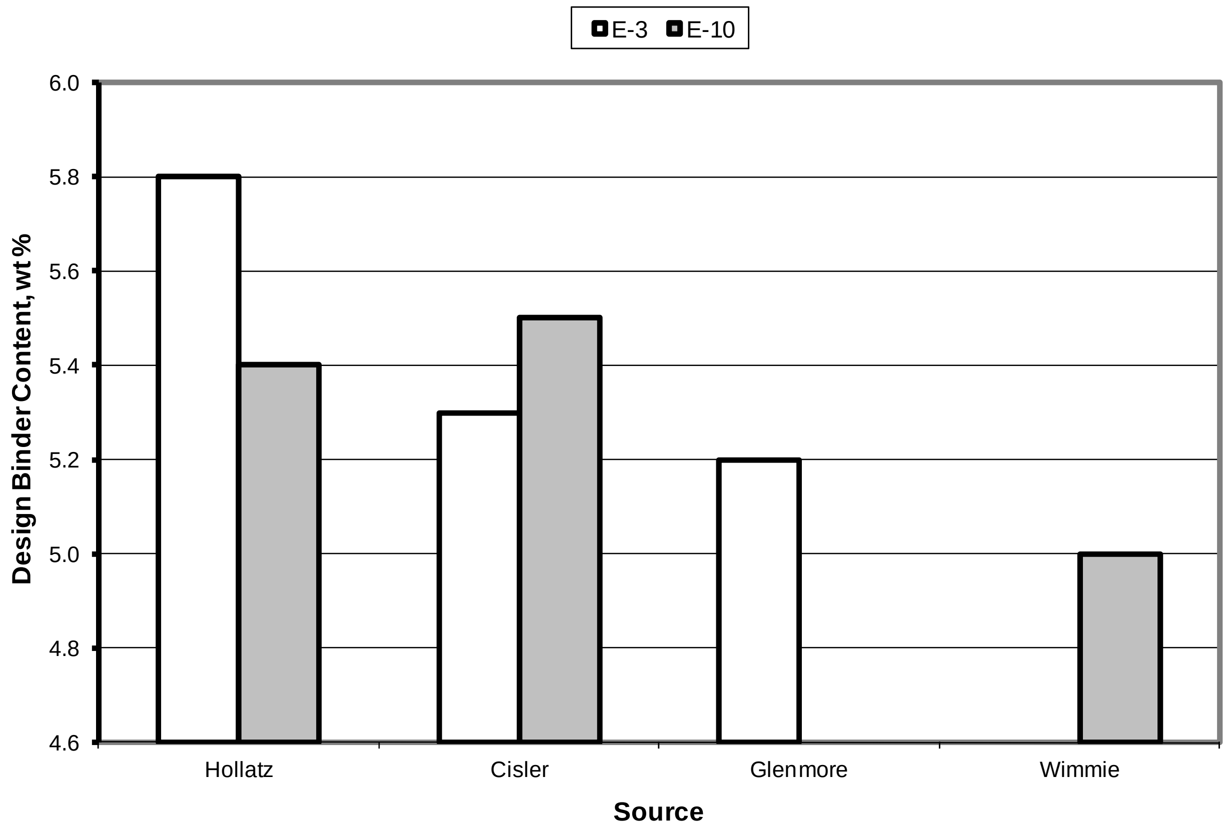


Figure 26. Design Binder Content.

3.1.3.2 Binders

The proposed experimental design also includes three different binders: a neat PG 58-28, and polymer modified PG 64-28, and PG 70-28. Table 21 summarizes performance grading properties and multiple stress creep recovery (MSCR) results for the three binders. The three binders have very similar low temperature properties. The RTFOT stiffness of the PG 64-28 binder is somewhat greater than that for the PG 70-28 binder. Based on the RTFOT stiffness, the continuous high temperature grades are PG 72.7 for the PG 64-28 compared to PG 70.5 for the PG 70-28.

Table 21. Binder Performance Grading Properties and Multiple Stress Creep Recovery Results.

Condition	Test	Temp, °C	PG 58-28	PG 64-28	PG 70-28
Tank	G*/sinδ, kPa AASHTO T 315	58	1.48		
		64	0.73	1.66	
		70		0.78	1.53
		76			0.97
Rolling Thin Film Residue	G*/sinδ, kPa AASHTO T 315	58	3.92		
		64	1.85		
		70		2.82	2.29
		76		1.64	1.45
Pressure Aging Vessel Residue	G*sinδ, kPa AASHTO T 315	13			6512
		16		5270	4533
		19	5680	3600	
		22	3802		
	Creep Stiffness (MPa) / m AASHTO T 313	-24	460 / 0.249	472 / 0.264	491 / 0.245
		-18	212 / 0.343	224 / 0.324	225 / 0.331
Grade	AASHTO M320	NA	PG 58-28	PG 64-28	PG 70-28
Continuous Grade	NA	NA	61.2 (17.0) –30.5	69.1 (16.4) -30.3	70.5 (15.2) –30.0
Rolling Thin Film Oven Residue	J_{NR}, /kPa AASHTO TP 70	58.0	1.90	0.22	0.14
	Recovery, % AASHTO TP 70	58.0	1.8	61.1	71.1
	J_{NR}, /kPa AASHTO TP 70	49.6	0.42	0.07	0.03
	Recovery, % AASHTO TP 70	49.6	22.1	70.0	78.0

The MSCR testing was conducted at two temperatures: (1) 58 °C, the 98 percent reliability performance grade temperature for Madison, WI, and (2) 49.6 °C, the temperature used in the flow number testing. Based on the MSCR testing the PG 70-28 binder has somewhat greater resistance to permanent deformation compared to the PG 64-28. Both of these binders have high temperature classifications of PG 58 V based on AASHTO MP 19. The PG 58-28 classifies as a PG 58 H based on AASHTO MP 19.

3.1.4 Results and Analysis

The results of the primary flow number experiment are summarized in Table 22 for the E-3 mixtures and Table 23 for the E-10 mixtures. These tables include the measured flow numbers, the air void content of the flow number test specimens, and the air void content of normal quality control test specimens compacted to the design gyration level. For the E-10 mixtures, quality control air voids were only measured for the PG 58-28 binder. Separate analyses were conducted on the nine design mixtures and the production variations as discussed below.

3.1.4.1 Design Mixtures

As discussed in Chapter 2, a number of factors affect the rutting resistance and flow number of asphalt concrete mixtures. WHRP Project 0092-08-06 found a good relationship between the flow number and rutting resistance estimated from the rutting resistance equation (Equation 4) developed in NCHRP Projects 9-25, 9-31, and 9-33 (*2*). Figure 27 presents a similar comparison for the nine design mixtures from the primary flow number experiment. The relationship between flow number and rutting resistance is poorer than that found earlier in WHRP Project 0092-08-06. It is also significantly lower due to the reduced short-term conditioning of 2 hours at the compaction temperature compared to 4 hours at 135 °C used in WHRP Project0092-08-06. Comparison of the two relationships shows that the flow number for short-term conditioning of 2 hours at the compaction temperature is one-half to one-quarter of that for the 4 hours at 135 °C.

Table 22. Flow Number Test Results for E-3 Mixtures.

Binder Grade	Angularity /Source	Filler Content %	Binder Content %	Specimen 1		Specimen 2		Average		QC Air Voids, %		
				FN	Air Voids, %	FN	Air Voids, %	FN	Air Voids, %	1	2	Avg
PG 58-28	Low Hollatz	+2.0	Design	9	6.9	9	7.1	9	7.0	3.0	2.4	2.7
			+0.2	10	6.5	10	6.5	10	6.5	1.8	2.0	1.9
			+0.4	8	6.6	8	6.7	8	6.7	1.8	0.8	1.3
		Design	Design	8	7.8	9	7.5	9	7.7	4.1	4.0	4.0
			+0.2	8	7.5	8	7.7	8	7.6	3.5	3.8	3.6
			+0.4	7	7.3	8	7.8	8	7.6	3.4	2.9	3.2
		-2.0	Design	3	7.9	3	7.3	3	7.6	6.1	6.1	6.1
			+0.2	3	7.2	3	6.9	3	7.1	5.1	5.5	5.3
			+0.4	3	7.3	3	7.1	3	7.2	5.1	4.7	4.9
	Medium Cisler	+2.0	Design	13	7.1	12	6.7	13	6.9	2.2	2.1	2.2
			+0.2	10	6.8	12	6.4	11	6.6	1.5	1.9	1.7
			+0.4	7	6.5	8	6.9	8	6.7	1.7	1.2	1.4
		Design	Design	7	7.5	6	7.4	7	7.5	4.2	3.8	4.0
			+0.2	6	7.4	7	7.4	7	7.4	2.9	3.6	3.3
			+0.4	6	7.4	7	7.1	7	7.3	3.0	2.6	2.8
		-2.0	Design	7	7.1	7	6.7	7	6.9	6.6	6.3	6.4
			+0.2	8	6.6	8	6.7	8	6.7	4.9	5.3	5.1
			+0.4	6	7.2	6	6.9	6	7.1	4.5	4.9	4.7
	High Glenmore	+2.0	Design	57	6.9	65	7.0	61	7.0	2.5	2.6	2.5
			+0.2	52	7.0	54	6.9	53	7.0	2.2	2.2	2.2
			+0.4	53	6.9	43	7.0	48	7.0	1.4	1.4	1.4
		Design	Design	59	6.5	67	6.8	63	6.7	4.1	4.2	4.2
			+0.2	63	6.5	59	6.7	61	6.6	3.3	2.9	3.1
			+0.4	55	6.7	47	6.9	51	6.8	2.9	3.0	3.0
		-2.0	Design	66	6.8	58	7.0	62	6.9	5.3	5.9	5.6
			+0.2	51	6.7	41	6.9	46	6.8	4.9	4.9	4.9
			+0.4	42	6.7	37	6.4	40	6.6	4.7	4.6	4.7

Table 23. Flow Number Test Results for E-10 Mixtures.

Binder Grade	Angularity /Source	Filler Content	Binder Content	Specimen 1		Specimen 2		Average		QC Air Voids		
				FN	Air Voids, %	FN	Air Voids, %	FN	AV	1	2	Avg
PG 58-28	Low Hollatz	+2.0	Design	80	6.8	94	6.9	87	6.9	3.1	3.1	3.1
			+0.2	76	6.8	76	7.1	76	7.0	2.6	2.4	2.5
			+0.4	68	6.7	68	7.2	68	7.0	2.1	2.3	2.2
		Design	Design	80	6.6	97	6.4	89	6.5	3.8	4.2	4.0
			+0.2	90	6.6	82	6.2	86	6.4	3.0	3.4	3.2
			+0.4	78	6.2	69	6.4	74	6.3	2.6	3.0	2.8
		-2.0	Design	70	7.3	76	7.3	73	7.3	5.1	4.9	5.0
			+0.2	70	7.5	60	7.5	65	7.5	4.9	5.3	5.1
			+0.4	53	7.7	56	7.4	55	7.6	4.3	4.0	4.2
	Medium Wimmie	+2.0	Design	30	6.9	28	6.8	29	6.9	1.6	1.4	1.5
			+0.2	30	6.9	33	7.0	32	7.0	0.3	0.6	0.4
			+0.4	21	7.0	21	6.8	21	6.9	0.2	0.0	0.1
		Design	Design	21	7.2	23	7.3	22	7.3	3.6	3.9	3.8
			+0.2	22	6.9	24	7.1	23	7.0	3.2	2.7	3.0
			+0.4	20	7.1	18	7.5	19	7.3	2.5	2.5	2.5
		-2.0	Design	21	7.4	18	7.3	20	7.4	6.3	6.0	6.2
			+0.2	15	7.9	16	7.4	16	7.7	6.2	6.2	6.2
			+0.4	17	7.6	22	7.0	20	7.3	6.1	5.7	5.9
	High Cisler	+2.0	Design	22	7.1	25	7.5	24	7.3	1.6	1.9	1.8
			+0.2	26	7.4	22	6.8	24	7.1	1.3	1.0	1.1
			+0.4	20	6.7	20	7.2	20	7.0	1.2	1.1	1.2
		Design	Design	19	7.4	19	7.5	19	7.5	4.0	4.1	4.1
			+0.2	16	7.4	15	7.4	16	7.4	3.3	3.3	3.3
			+0.4	14	7.1	13	7.4	14	7.3	2.7	2.4	2.6
		-2.0	Design	20	7.4	18	6.8	19	7.1	6.8	7.3	7.1
			+0.2	21	6.5	17	7.0	19	6.8	6.8	6.6	6.7
			+0.4	17	6.5	15	6.9	16	6.7	5.3	4.8	5.1

Table 23 (continued). Flow Number Test Results for E-10 Mixtures.

Binder Grade	Angularity /Source	Filler Content	Binder Content	Specimen 1		Specimen 2		Average		QC Air Voids		
				FN	Air Voids, %	FN	Air Voids, %	FN	AV	1	2	Avg
PG 64-28	Low Hollatz	+2.0	Design	427	6.8	484	6.6	456	6.7	NT	NT	NT
			+0.2	320	6.9	278	6.8	299	6.9	NT	NT	NT
			+0.4	239	6.9	259	6.8	249	6.9	NT	NT	NT
		Design	Design	372	6.7	439	6.8	406	6.8	NT	NT	NT
			+0.2	342	6.8	337	6.6	340	6.7	NT	NT	NT
			+0.4	232	6.7	242	6.5	237	6.6	NT	NT	NT
		-2.0	Design	415	6.4	484	6.5	450	6.5	NT	NT	NT
			+0.2	401	6.4	581	6.2	491	6.3	NT	NT	NT
			+0.4	294	6.4	340	6.5	317	6.5	NT	NT	NT
	Medium Wimmie	+2.0	Design	84	7.1	80	7.0	82	7.1	NT	NT	NT
			+0.2	72	6.7	72	6.8	72	6.8	NT	NT	NT
			+0.4	67	6.3	61	6.8	64	6.6	NT	NT	NT
		Design	Design	72	6.5	71	6.6	72	6.6	NT	NT	NT
			+0.2	63	6.8	59	6.5	61	6.7	NT	NT	NT
			+0.4	45	7.3	40	7.0	43	7.2	NT	NT	NT
		-2.0	Design	102	7.4	132	7.1	117	7.3	NT	NT	NT
			+0.2	85	6.8	82	6.7	84	6.8	NT	NT	NT
			+0.4	76	6.8	81	6.6	79	6.7	NT	NT	NT
	High Cisler	+2.0	Design	61	8.0	61	6.2	61	7.1	NT	NT	NT
			+0.2	57	8.2	54	6.1	56	7.2	NT	NT	NT
			+0.4	76	8.0	75	8.1	76	8.1	NT	NT	NT
		Design	Design	29	7.0	37	7.0	33	7.0	NT	NT	NT
			+0.2	37	6.6	26	6.8	32	6.7	NT	NT	NT
			+0.4	22	6.8	18	6.6	20	6.7	NT	NT	NT
		-2.0	Design	31	6.8	37	7.1	34	7.0	NT	NT	NT
			+0.2	21	7.0	32	6.8	27	6.9	NT	NT	NT
			+0.4	31	6.7	24	6.9	28	6.8	NT	NT	NT
PG 70-28	High Cisler	+2.0	Design	87	7.4	94	7.3	91	7.4	NT	NT	NT
			+0.2	66	7.5	79	7.2	73	7.4	NT	NT	NT
			+0.4	51	7.7	45	7.9	48	7.8	NT	NT	NT
		Design	Design	75	7.3	67	6.0	71	6.7	NT	NT	NT
			+0.2	61	7.7	64	7.3	63	7.5	NT	NT	NT
			+0.4	45	7.6	44	7.6	45	7.6	NT	NT	NT
		-2.0	Design	219	7.4	174	7.4	197	7.4	NT	NT	NT
			+0.2	106	7.0	107	6.9	107	7.0	NT	NT	NT
			+0.4	55	7.2	26	6.7	41	7.0	NT	NT	NT

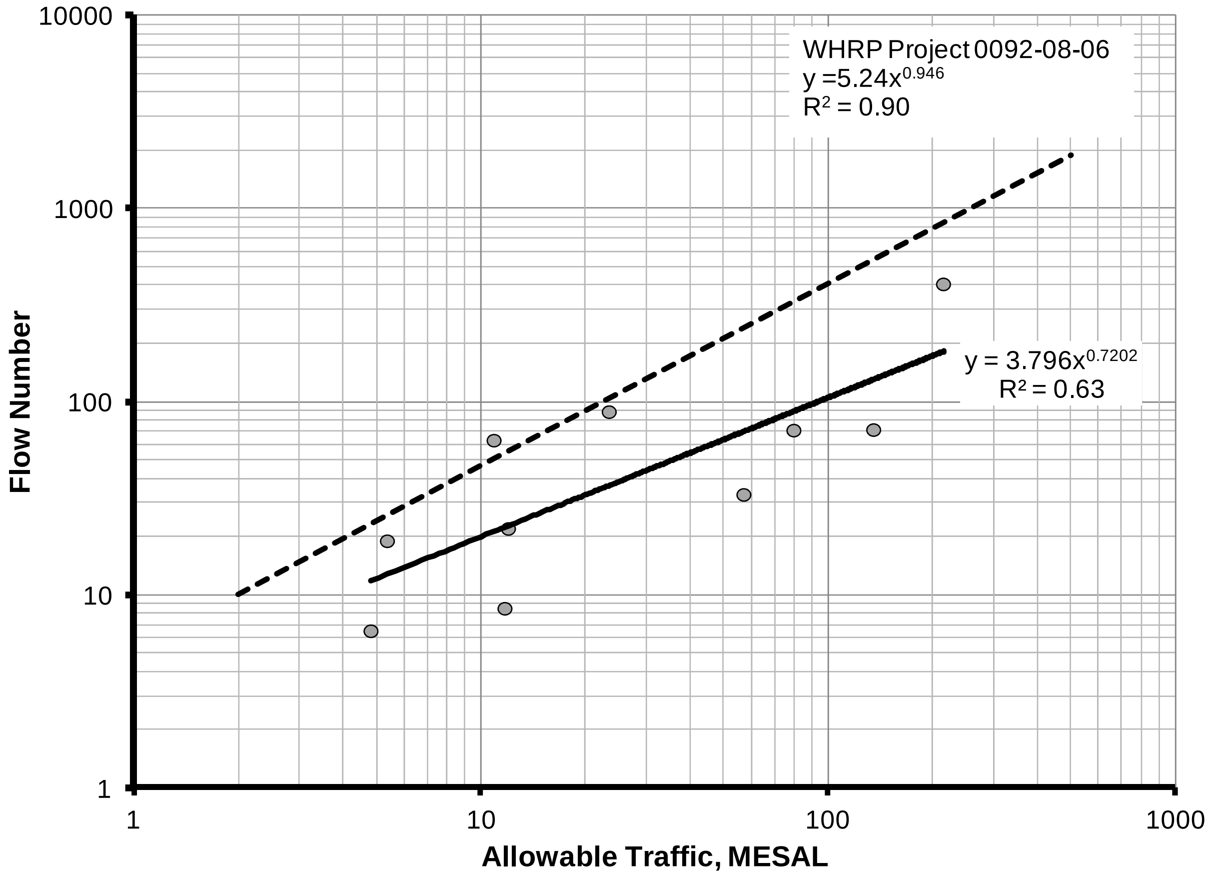


Figure 27. Relationship Between Estimated Allowable Traffic and Flow Number for the Design Mixtures.

The major factor not addressed by the estimated rutting resistance equation developed in NCHRP Projects 9-25, 9-31 and 9-33 is the angularity of the aggregates. The primary flow number experiment included mixtures with different levels of aggregate angularity. Figure 28 compares the measured flow numbers for PG 58-28 mixtures with different angularity levels. These data show that aggregate angularity, as it is currently measured, is not a good indicator of rutting resistance. For the E-3 mixtures, all mixtures have similar flow numbers. For the E-10 mixture, the low angularity mixture had the highest flow number.

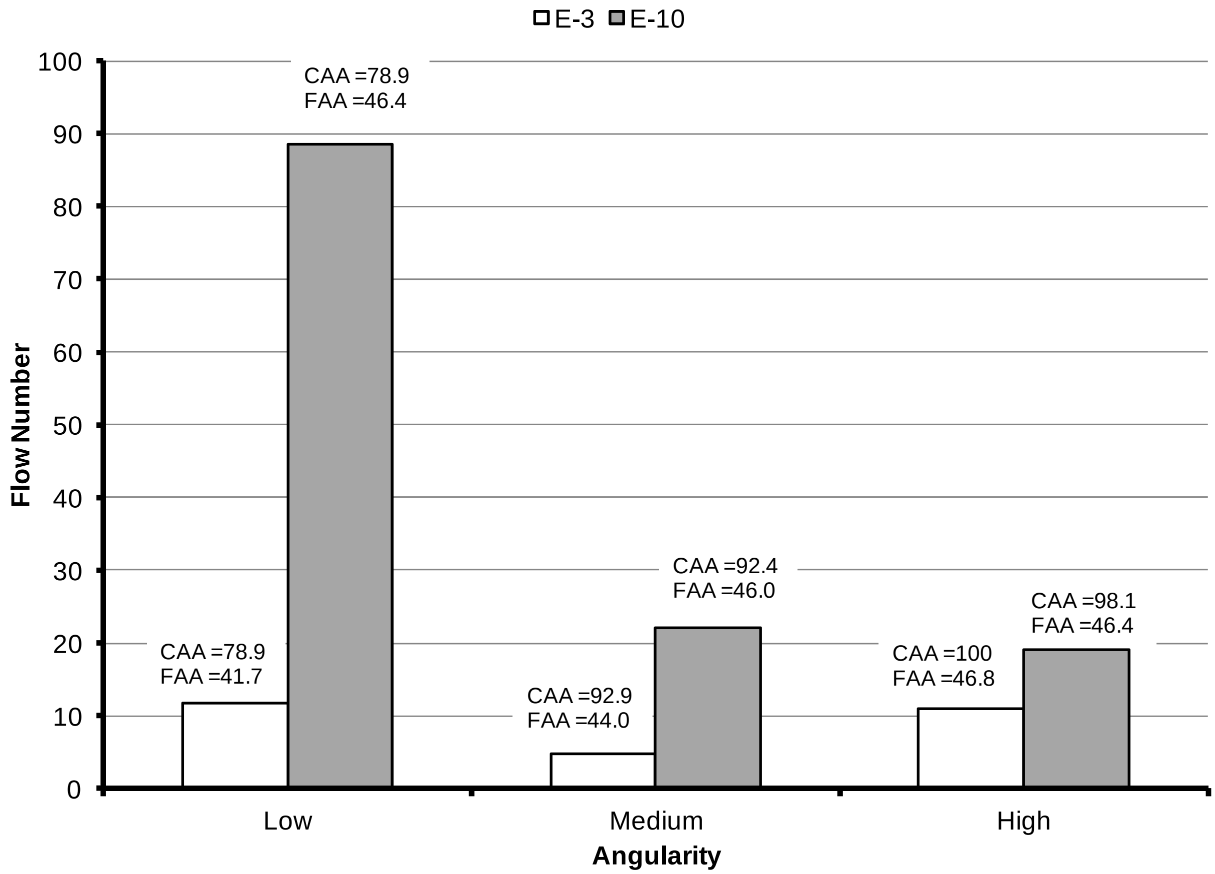
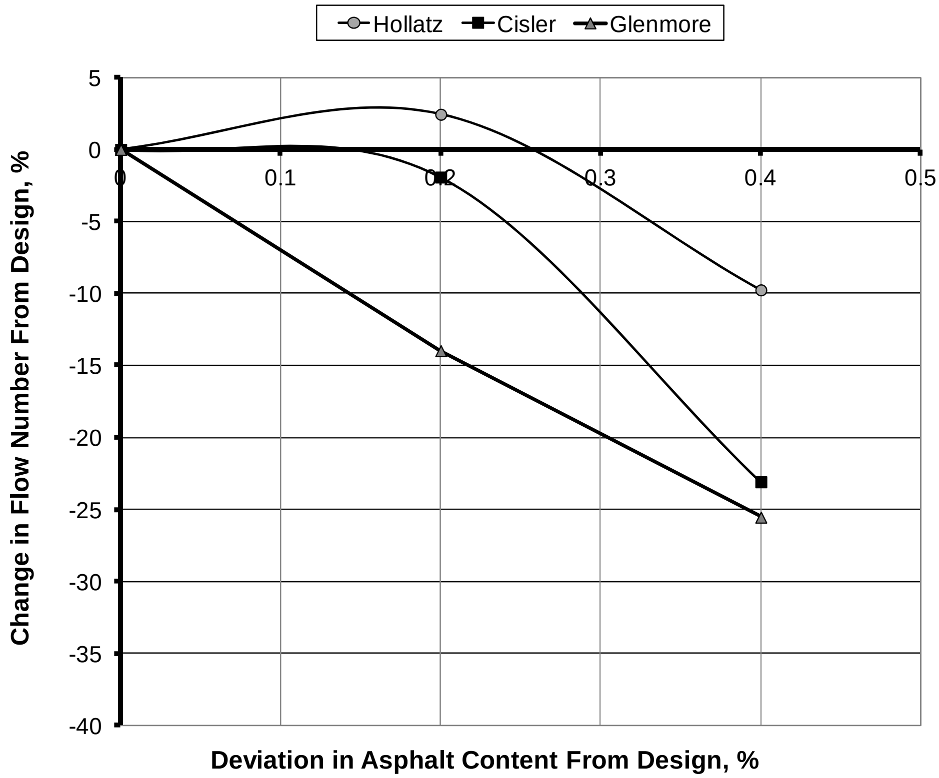


Figure 28. Effect of Aggregate Angularity on Flow Number for Mixtures With PG 58-28 Binder.

3.1.4.2 Production Variations

This analysis focused on the effect of variations in asphalt content and filler content on the rutting resistance as measured by the flow number, and whether these effects are accurately predicted by changes in air void content as monitored during mixture quality control and acceptance. Each of the nine mixtures was analyzed separately using graphical and analysis of variance techniques. Recall that all flow number specimens were compacted to a target air void content of 7.0 percent. The effects of asphalt content and filler content are shown graphically in Figures 29 through 32. Each of these figures shows the change in flow number associated with changing the asphalt content and filler content from the design value. Figure 29 shows the results for the E-3 mixtures. Figure 30, 31, and 32 show the results for the E-10 mixtures from the Hollatz, Wimmie, and Cisler sources.



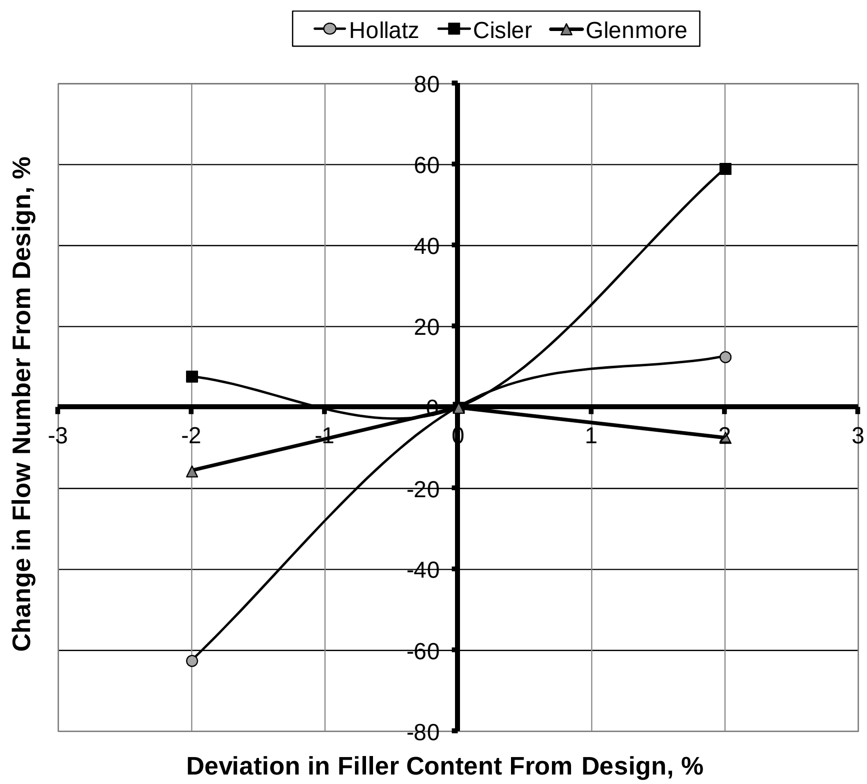


Figure 29. Effect of Asphalt Content and Filler Content on the Flow Number for the E-3 Mixtures.

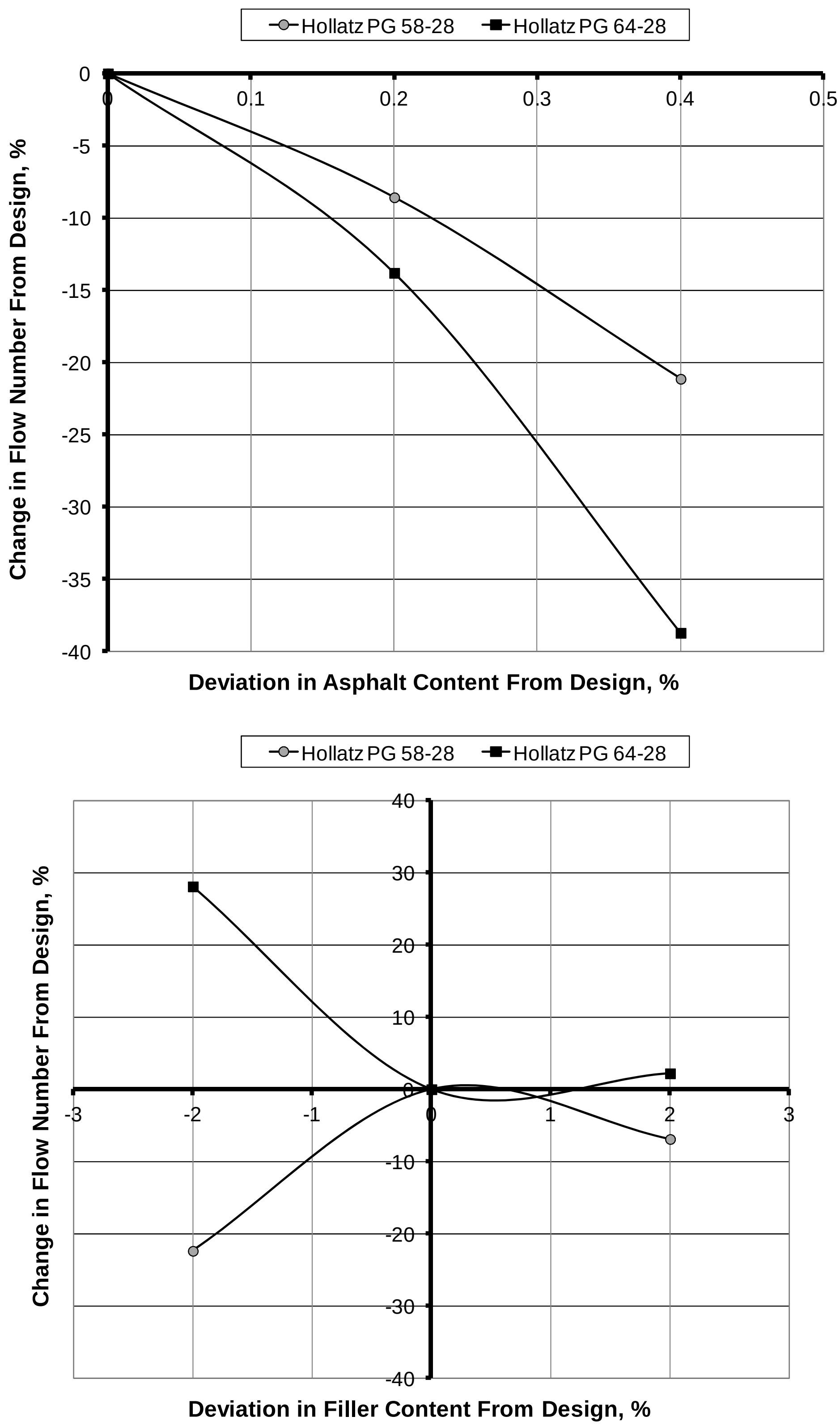


Figure 30. Effect of Asphalt Content and Filler Content on the Flow Number for the Hollatz E-10 Mixtures.

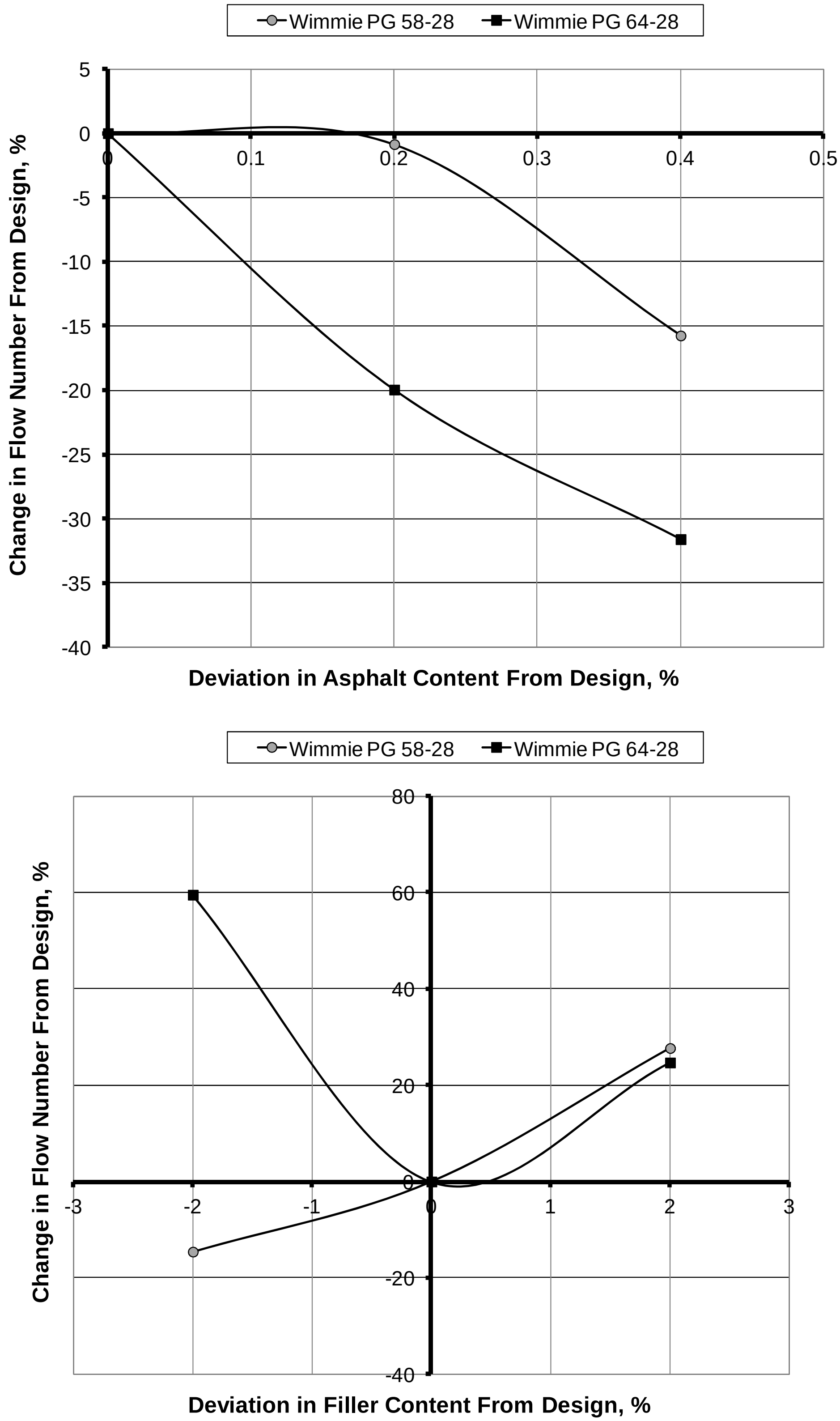


Figure 31. Effect of Asphalt Content and Filler Content on the Flow Number for the Wimmie E-10 Mixtures.

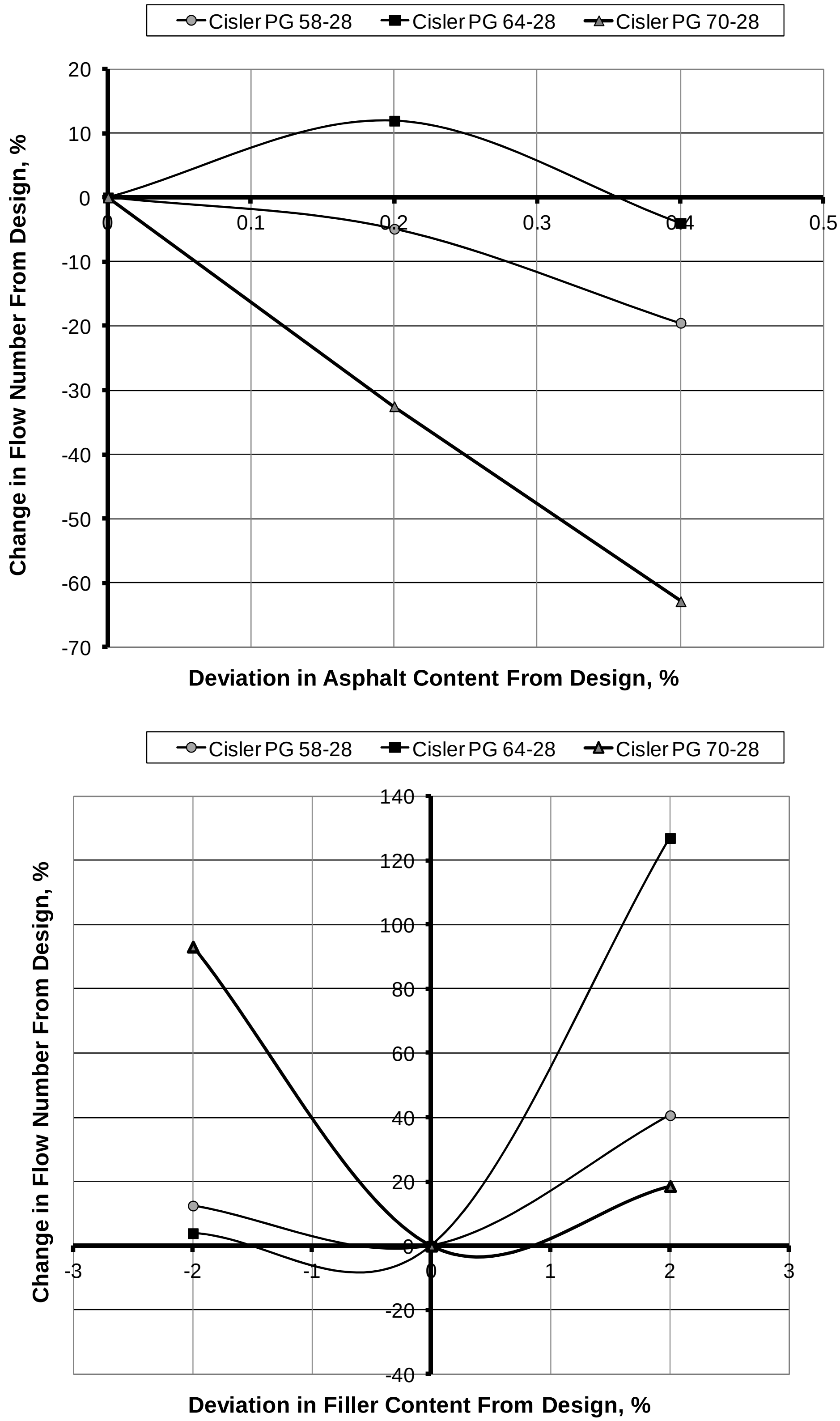


Figure 32. Effect of Asphalt Content and Filler Content on the Flow Number for the Cisler E-10 Mixtures.

This graphical analysis revealed the following trends for deviations in the asphalt content and filler content from the design values:

1. There is a rational, consistent effect of asphalt content on the flow number. The rutting resistance as measured by the flow number generally decreases with increasing asphalt content above the optimum asphalt content obtained from normal Superpave volumetric design.

2. The effect of filler content is mixed. In most cases, increasing the filler content above the design value resulted in an increase in the rutting resistance as measured by the flow number. However, for approximately one-half of the mixtures the flow number also increased when the filler content decreased below the design value, indicating that the design filler content for these mixtures produces a minimum level of rutting resistance.

3. For the E-10 mixtures, the effects of changes in asphalt content and filler content are more pronounced for the mixtures with the modified binders.

The trends from the graphical analysis were confirmed by analysis of variance performed on the data from each of the mixtures. The analysis of variance tested whether the flow number was affected by asphalt content and filler content. When a factor was found to be significant for a particular mixture, Fisher's least significant difference test was used to determine which factor levels resulted in significant differences (*27*). The results of this analysis are summarized in Table 24. The analysis of variance shows that the flow number is sensitive to changes in asphalt content and filler content. The effects, however, are mixture dependent.

Table 24. Summary of Analysis of Variance for Effect of Asphalt Content and Filler Content on Flow Number.

<table>
<tr><th rowspan="3">Design Traffic Level</th><th rowspan="3">Source</th><th rowspan="3">Binder Grade</th><th colspan="4">Analysis of Variance 0.5 percent Significance Level</th></tr>
<tr><th colspan="2">Filler Content</th><th colspan="2">Asphalt content</th></tr>
<tr><th>Significant Difference</th><th>Specific Effects</th><th>Significant Difference</th><th>Specific Effects</th></tr>
<tr><td rowspan="3">E-3</td><td>Hollatz</td><td>PG 58-28</td><td>Yes</td><td>-2 lower
+2 higher</td><td>No</td><td>NA</td></tr>
<tr><td>Cisler</td><td>PG 58-28</td><td>Yes</td><td>-2 no difference
+2 higher</td><td>No</td><td>NA</td></tr>
<tr><td>Glenmore</td><td>PG 58-28</td><td>Yes</td><td>-2 lower
+2 no difference</td><td>Yes</td><td>+0.2 lower
+0.4 lower</td></tr>
<tr><td rowspan="7">E-10</td><td rowspan="2">Hollatz</td><td>PG 58-28</td><td>Yes</td><td>-2 lower
+2 no difference</td><td>Yes</td><td>+ 0.2 no difference
+ 0.4 lower</td></tr>
<tr><td>PG 64-28</td><td>Yes</td><td>-2 higher
+2 no difference</td><td>Yes</td><td>+ 0.2 no difference
+ 0.4 lower</td></tr>
<tr><td rowspan="2">Wimmie</td><td>PG 58-28</td><td>Yes</td><td>-2 no difference
+2 higher</td><td>No</td><td>NA</td></tr>
<tr><td>PG 64-28</td><td>Yes</td><td>-2 higher
+2 higher</td><td>Yes</td><td>+ 0.2 lower
+0.4 lower</td></tr>
<tr><td rowspan="3">Cisler</td><td>PG 58-28</td><td>Yes</td><td>-2 no difference
+2 higher</td><td>Yes</td><td>+ 0.2 no difference
+ 0.4 lower</td></tr>
<tr><td>PG 64-28</td><td>Yes</td><td>-2 no difference
+ 2 higher</td><td>No</td><td>NA</td></tr>
<tr><td>PG 70-28</td><td>No</td><td>NA</td><td>Yes</td><td>+0.2 no difference
-0.2 lower</td></tr>
</table>

The final analysis that was conducted was a comparison of the change in flow number and the change in air voids at the design gyration level for deviations in filler and asphalt content from the design level. This analysis investigated the correlation between the change in flow number and the change in air voids for deviations from the design mixture for the mixtures made with PG 58-28 binder. Figure 33 presents a graphical analysis of the correlations. This analysis shows that the flow number generally decreases with increasing air voids, but the correlation for most mixtures is very poor. Table 25 summarizes the Pearson correlation coefficient between the change in air voids at the design gyration level and the change in flow number. The negative Pearson correlation coefficients confirm that flow number generally decreases with increasing quality control air voids, but only two of the correlation coefficients are significant at the 0.5 percent level of significance, confirming the generally poor relationship between quality control air voids and flow number.

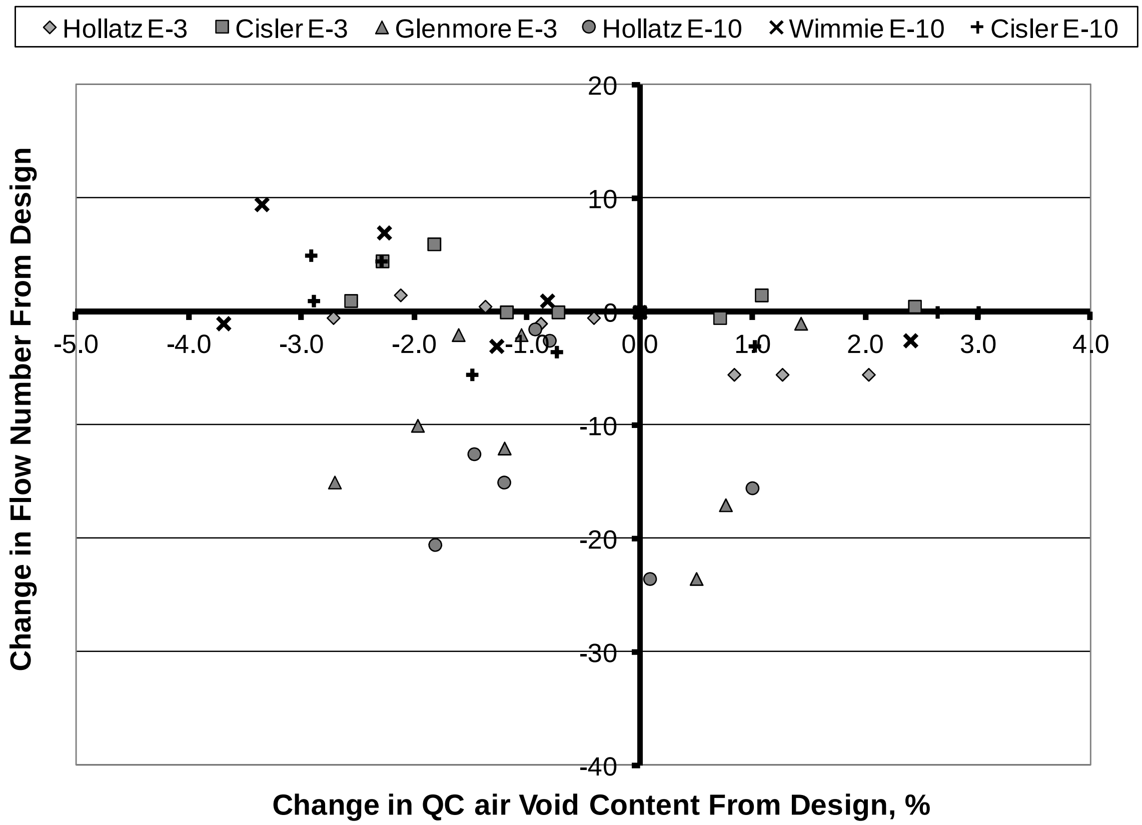


Figure 33. Correlation Between Change in QC Air Voids and Change in Flow Number.

Table 25. Summary of Correlation Analysis for Changes in Air Voids and Flow Number.

Design Traffic Level	Source	Binder Grade	Pearson Correlation Coefficient	Significant
E-3	Hollatz	PG 58-28	-0.85	Yes
	Cisler	PG 58-28	-0.49	No
	Glenmore	PG 58-28	0.02	No
E-10	Hollatz	PG 58-28	-0.18	No
	Wimmie	PG 58-28	-0.69	Yes
	Cisler	PG 58-28	-0.33	No

3.2 Intersection Flow Number Experiment

Chapter 2 included a rational approach for generating preliminary flow number criteria for intersections. As the traffic speed decreases, the rutting resistance as measured by the flow number must increase to provide pavements with approximately equal rutting performance.

Depending on the average vehicle speed through an intersection, the analysis in Chapter 2 found that the flow number for intersections mixtures should be 3 to 6 times that required for mixtures subjected to an average traffic speed of 64.4 km/h (40 mi/h). To select a reasonable flow number speed adjustment factor for intersections, flow numbers for mixtures with documented good and poor rutting performance at intersections were measured and compared.

For this experiment, the Technical Oversight Committee identified mixtures from four sources having poor performance at intersections. They also identified mixtures from these same sources expected to have good performance at intersections. For the poor performing mixtures, component materials were provided. For the good performing mixtures, plant mix was provided. The mixtures included in the intersection flow number experiment are summarized in Table 26. The mix designs for the poor performing mixtures are included in Appendix A.

Table 26. Mixtures Used in Intersection Flow Number Experiment.

Source	Component Materials for Poor Performing Intersection Mixture	Loose Mix for Good Performing Intersection Mixture
Honey Creek	X	X
Storrs	X	X
Sturgeon Bay	X	X
Tower	X	X

Triplicate specimens were prepared for each of the 8 mixtures. Specimens were fabricated in accordance with AASHTO PP60, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor(SGC)*. The flow number tests were conducted in accordance with AASHTO TP79, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*, using the following testing conditions:

- Short-term oven conditioning of 2 hours at the compaction temperature for the specimens fabricated from component materials. No short-term oven conditioning was used with the specimens fabricated from loose mix.

- Target specimen air void content of 7.0 percent.
- Test temperature of 49.6 °C, which is the 50 percent reliability performance grade temperature at a depth of 20 mm for Madison, Wisconsin obtained from LTPPBind 3.1.
- Unconfined tests with an axial stress level of 87 psi (600 kPa) to match the stress levels used in WHRP Projects 0092-04-07 and 0092-08-06.

Since the component materials collected for the poor performing mixtures were from a different construction season than the observed performance, specimens were compacted at the design gyration level to confirm the mixture design. A tolerance of ± 1.5 percent was considered reasonable based on the between laboratory standard deviation of approximately one percent from the latest AASHTO Materials Reference Laboratory gyratory proficiency samples (*28*). Table 27 summarizes the results from the mix verification.

Table 27. Intersection Mix Verification Results.

Source	Binder Grade	N_{design}	JMF Air Voids	Verification Air Voids
Honey Creek	PG 64-22	60	4.0	5.1
Storrs	PG 58-28	100	4.0	5.2
Sturgeon Bay	PG 58-28	40	4.0	3.2
Tower	PG 58-28	75	4.0	4.9

The results of the flow number tests are summarized in Table 28. The flow numbers for the poor performing mixtures are reasonable for the design traffic level considering a traffic speed of 64.4 km/h (40 mi/h). Table 29 compares the measured flow numbers with the relationship between allowable traffic and flow number shown earlier in Figure 27. The measured flow numbers are reasonable considering these criteria. The measured flow number for the Honey Creek mixture far exceeds the criterion for an E-1 mixture because a PG 64-22 binder was used. Table 29 also summarizes the ratio of the flow numbers for the good to poor performing intersection mixtures. The ratio ranges from about 4 for three of the sources to over 26 for the Honey Creek mixture.

Table 28. Intersection Mixture Flow Number Test Results.

Source	Intersection Performance	Specimen 1		Specimen 2		Specimen 3		Average	
		FN	Air Voids, %	FN	Air Voids, %	FN	Air Voids, %	FN	Air Voids, %
Honey Creek	Poor	44	6.9	37	7.1	40	7.2	40	7.1
	Good	1116	6.7	1005	7.3	1050	6.9	1057	7.0
Storrs	Poor	54	6.8	45	7	52	7.1	50	7.0
	Good	183	6.4	208	6.4	205	6.8	199	6.5
Sturgeon Bay	Poor	11	6	11	6.7	12	6.6	11	6.4
	Good	35	7.1	49	7.3	59	6.9	48	7.1
Tower	Poor	7	6.9	7	7.3	10	6.6	8	6.9
	Good	25	6.5	21	6.5	38	6.4	28	6.5

Table 29. Poor Performing Intersection Mixture Flow Numbers Compared to Normal Traffic Design Criteria.

Source	Binder Grade	N_{design}	Design Traffic	Measured Flow Number	2 hour Aging Flow Number Criteria	FN_{good}/FN_{poor} Intersection Mixtures
Honey Creek	PG 64-22	60	E-1	40	4	26.4
Storrs	PG 58-28	100	E-10	50	20	4.0
Sturgeon Bay	PG 58-28	40	E-0.3	11	2	4.4
Tower	PG 58-28	75	E-3	8	8	3.5

The intersection developmental work completed in Chapter 2 suggested that the required flow number for an intersection mixture should be 3 to 6 times that required for mixtures subjected to an average traffic speed of 64.4 km/h (40 mi/h). Using the 2 hour conditioning criteria from Figure 27 various multipliers were used and the predicted performance was compared to the observed performance. Using a multiplier of 6 with the 2 hour conditioning criteria resulted in the most balanced predictions as shown in Figure 34. The performance of 6 of the 8 mixtures was correctly predicted. The incorrect predictions were for the poor performing mixture from the Honey Creek source and the good performing mixture from the Tower source. For the

Honey Creek source, the criteria predict good performance for the poor performing mixture. For the Tower source, the criteria predict poor performance for the good performing mixture.

		Actual	
		Good	**Poor**
Predicted 6 x	**Good**	3	1
	Poor	1	3

Figure 34. Comparison of Predicted and Observed Performance for Intersection Flow Number Multiplier of 6.

Chapter 4. Applications in Mixture Design and Acceptance

This chapter discusses applications of the flow number test in mixture design and acceptance. It includes a summary of the major findings from WHRP Project 0092-09-01, followed by potential applications .

4.1 Major Findings

The literature review, testing, and analysis completed in WRHP Project 0092-09-01 produced a number of important findings about the flow number test and the rutting resistance of asphalt concrete mixtures. These findings are summarized below.

1. Several studies have shown the flow number to be a reasonable indicator of the rutting resistance of asphalt concrete. For the Wisconsin mixtures tested in WHRP Projects 0092-04-07, 0092-08-06 and 0092-09-01, the flow number generally increased with increasing design traffic level. The largest increases in flow number were observed for mixtures produced with modified binders.

2. Laboratory conditioning has a major effect on the flow number. For the same mixtures tested in WHRP Project 0092-08-06 using short-term conditioning of 4 hours at 135 °C and in WHRP Project 0092-09-01 using short-term conditioning of 2 hours at the compaction temperature, the 2 hours of conditioning at the compaction produced flow numbers that were approximately one-half of that obtained using 4 hours of conditioning at 135 °C.

3. For Wisconsin mixtures meeting current WisDOT volumetric design requirements, reasonable relationships between the flow number and estimated rutting resistance from the NCHRP Project 9-33 mixture composition model (Equation 4) were found in WHRP Projects 0092-08-06 and 0092-09-01. These relationships were used to develop tentative flow number criteria as a function of traffic level. The relationship was somewhat better when 4 hours of short-term conditioning at 135 °C was used. The flow number testing conditions for these criteria are:

- Unconfined tests using a repeated deviatoric stress of 87 psi (600 kPa),
- Testing at the 50 percent reliability high pavement temperature from LTPPBind 3.1,
- Specimen air void content of 7.0 ± 0.5 percent

4. The flow number was significantly affected by changes in binder content and filler content within current WisDOT acceptance levels. The rutting resistance as measured by the flow number generally decreases with increasing asphalt content above the optimum asphalt content obtained from normal Superpave volumetric design. Flow number reductions up to 30 percent for a 0.2 percent increase in binder content and 60 percent of a 0.4 percent increase in binder content were observed. The effect of filler content was mixed. In most cases, increasing the filler content above the design value resulted in an increase in the rutting resistance as measured by the flow number. However, for approximately one-half of the mixtures the flow number also increased when the filler content was decreased below the design value.

5. The effects of production variations in asphalt content and filler content are mixture specific and are not correlated with changes in air void content measured during quality control and acceptance testing. These changes can be large enough to reduce the rutting resistance of a mixture one traffic level based on the relationship between flow number and allowable traffic shown in Figure 27. The combination of low filler and high asphalt content produced the least rut resistant mixtures based on the flow number test.

6. Current measures of coarse and fine aggregate angularity do not appear to be good indicators of rutting resistance. Of the E-10 mixtures tested in WHRP Project 0092-09-01, the low angularity Hollatz E-10 mixture had the highest flow number, and the high angularity Cisler E-10 mixture had the lowest flow number.

7. The intersection study found the good performing intersection mixtures to have significantly higher flow numbers compared to the poor performing mixtures. The poor performing mixtures had acceptable rutting resistance for normal speed traffic for their

design traffic level. Flow number criteria for intersections that are 6 times higher than that required for normal speed traffic were developed.

4.2 Applications

Based on the findings of WHRP Project 0092-09-01, the primary application of flow number testing is during asphalt mixture design to ensure adequate rutting resistance. This testing would normally be performed by the producer or a testing laboratory working for the producer, and the results would be submitted as part of the mixture design submittal. To consider the possible negative effects of production variation on rutting resistance, the flow number test should be conducted after the volumetric design has been completed using an asphalt content corresponding to the high production warning limit (+0.3 percent). Tentative criteria for the flow number test are given in Table 30 for normal highway speed (assumed to be 40 mph (64.4 km/h) or greater), slow moving traffic (assumed to be 20 mph (32.2 km/h), and intersections. Criteria are given for mixtures that are short-term oven conditioned 2 hours at the compaction temperature as recommended for warm mix asphalt and the AASHTO R30 standard 4 hours at 135 °C. Intersection criteria were not provided for the two highest traffic levels because it is unlikely that the volume of traffic required for those design traffic levels can pass through intersections.

Table 30. Tentative Criteria for the Flow Number Test.

Design Traffic Level, MESAL	**Normal Traffic Speed >= 40 mph (64.4 km/hr)**		**Slow Traffic Speed 20 mph (32.2 km/hr)**		**Intersections 5 mph (8.1 km/hr) or less**	
	2 hr Conditioning at Compaction Temperature	4 hr Conditioning at 135 °C	2 hr Conditioning at Compaction Temperature	4 hr Conditioning at 135 °C	2 hr Conditioning at Compaction Temperature	4 hr Conditioning at 135 °C
1	5	5	10	10	30	30
3	10	15	20	30	60	90
10	20	45	40	90	120	270
30	45	135	90	270	NA	NA
30x	105	420	210	840	NA	NA

Notes:

1. Flow number testing per AASHTO TP79 using 0 confining stress, 87 psi (600 kPa) repeated deviatoric stress, and 4.4 psi (30 kPa) contact deviatoric stress
2. Test temperature equal to the 50 percent reliability high pavement design temperature from LTPPBind 3.1 at a depth of 20 mm for surface courses, the top of the layer for lower layers.
3. Specimen air void content 7.0 ±0.5 percent

A second application for flow number testing is in Quality Verification. This testing is conducted by WisDOT on reheated, plant produced mixtures. Flow number testing of random samples of plant mixture could be used to verify the rutting resistance of mixtures. These data can also be used to improve the tentative criteria shown in Table 30. Specimens for Quality Verification flow number testing should be prepared by reheating the mixture to an appropriate compaction temperature and compacting test specimens without further oven conditioning. Based on recent research on short-term conditioning (*20*), the Quality Verification flow number test results should be compared to the 2 hour conditioning criteria in Table 30.

The last application for flow number testing is in assigning appropriate disincentives, based on rutting resistance, for mixtures produced outside of allowable production tolerances, where rutting is the primary distress that is expected based on the production deviations. Based on the research completed in WHRP Project 0092-09-01, mixtures with high asphalt content will have lower rutting resistance. Additionally, some mixtures with low filler content may have lower rutting resistance. The research completed in WHRP Project 0092-09-01 also shows that mixtures that fail current WisDOT acceptance requirements may still have acceptable rutting resistance, particularly when they are overdesigned based on rutting resistance. Flow number testing on random samples from non-conforming lots could be used to establish the rutting resistance of the as-produced mixture. Test specimen fabrication and testing would be as described above for Quality Verification testing. Based on the measured flow number, the design traffic speed, and the relationship between allowable traffic and flow number shown in Figure 27, the allowable traffic for the as-produced mixture could be determined and compared to the design traffic for the project. Pay factors for rutting, based on the ratio of the allowable traffic for the as-produced mixture to the design traffic would be used to determine the payment for the nonconforming lot.

Chapter 5. Conclusions and Recommendations

5.1 Conclusions

WHRP Project 0092-09-01 included: (1) a review of completed research concerning the flow number and the effect of mixture composition on rutting resistance, (2) an evaluation of WisDOT criteria for mixture design and acceptance based on relationships between mixture composition and rutting resistance developed in NCHRP Projects 9-25, 9-31, and 9-33, (3) a laboratory experiment to evaluate the effect of changes in asphalt content and filler content on rutting resistance as measured by the flow number, and (4) a laboratory experiment to develop flow number criteria for intersection mixtures. Major conclusions drawn from the research completed in WHRP Project 0092-09-01 are summarized below.

5.1.1 Evaluation of WisDOT Mixture Design and Acceptance Criteria

The relationship between mixture composition and rutting resistance developed in NCHRP Projects 9-25, 9-31, and 9-33 (Equation 4) was used to evaluate the WisDOT mixture design and acceptance criteria. Based on this evaluation the WisDOT mixture design criteria produce mixtures that are overdesigned for rutting for design traffic levels of E-3 and lower. Binder grade selection is critical for design traffic levels of E-10 and greater. For E-10 mixtures, PG 64 binders are needed to provide adequate rutting resistance. Neat PG 58 binders can be used with E-10 mixtures provided the dust to effective binder ratio exceeds 1.0. Traffic levels E-30 and E-30x require polymer modified PG 70 binders to provide adequate rutting resistance.

The NCHRP relationship between mixture composition and rutting resistance was also used to evaluate WisDOT mixture acceptance requirements. The WisDOT warning limits for binder content, percent passing –0.075 mm sieve, VMA and air voids limit changes in rutting resistance to approximately 30 percent of the design value. Higher binder contents and lower filler contents result in reduced rutting resistance. The effect of in-place density on rutting resistance is much lower. A 0.5 percent increase in in-place density improves rutting resistance by about 10 percent.

Analysis of the data from the primary flow number experiment confirmed that deviations in binder content and filler content significantly affect the rutting resistance of asphalt mixtures as measured by the flow number. Flow numbers consistently decreased with increasing binder content for all mixtures tested; however, the effect was mixture specific. At the WisDOT high warning limit of 0.3 percent, the flow number decreased from about 10 to 30 percent. For the more sensitive mixtures, this decrease is large enough to result in a one traffic level reduction in the rutting resistance of the mixture based on relationships between flow number and allowable traffic developed in WHRP Projects 0092-08-06 and 0092-09-01. The effect of filler content was mixed. Increasing the filler content above the design value generally improved rutting resistance, but for approximately one-half of the mixtures tested the rutting resistance also increased when the filler content was decreased.

5.1.2 Flow Number Criteria for Intersection Mixtures

It is well known that traffic speed has a significant effect on rutting in asphalt concrete mixtures. For the same traffic level, pavement areas subjected to slow speed and standing traffic require mixtures with greater rutting resistance to achieve the same rutting performance as mixtures subjected to high speed traffic. Traffic speed is considered in the NCHRP rutting resistance equation (Equation 4). Based on this equation, decreasing the traffic speed from 40 to 10 mph (64.4 to 16.1 km/hr) decreases the allowable traffic to a rut depth of 0.5 in (12.5 mm) by a factor of about 3.4. The intersection experiment conducted in WHRP Project 0092-09-01 confirmed the reasonableness of this estimate. Intersection mixtures exhibiting good performance had flow numbers that were 4 to 26 times greater than those exhibiting poor performance. Based on evaluation of this data, it was determined that intersection mixtures should have flow numbers 6 times greater than those for normal traffic speed, 40 mph (64.4 km/hr). This corresponds to an effective speed at intersections of approximately 5 mph (8.1 km/hr). Based on this estimate and the speed relationship in the NCHRP rutting resistance model, flow number criteria for highway speed, 40 mph (64.4 km/hr) and greater, slow speed, 20 mph (32.2 km/hr), and intersections were developed. The criteria for the slow speed and intersection mixtures are 2 and 6 times that required for highway speed traffic.

5.1.3 Flow Number Testing

A significant issue in flow number testing is an appropriate level of short-term oven conditioning for flow number specimens. Based on research completed in NCHRP Project 9-43 (*20*), two hours of short-term conditioning at the compaction temperature was used in WHRP Project 0092-09-01 to represent the stiffness of the mixture at the time of construction. For the same mixtures tested in WHRP Projects 0092-08-06 using 4 hours of short-term conditioning at 135 ºC, 2 hours at the compaction temperature results in flow numbers that are approximately one-half of those measured using 4 hours of short-term conditioning at 135 ºC.

5.2 Recommendations

Several recommendations are appropriate based on the testing and analysis completed in WHRP Project 0092-09-01. These recommendations are listed below.

1. Several research studies including WHRP Projects 0092-04-07 and 0092-08-06 have recommended using the flow number during mixture design to evaluate asphalt concrete rutting resistance. The research completed in this project has shown that production deviations from the design binder and filler contents significantly affect rutting resistance. To account for the detrimental effect of increasing binder content on the flow number, flow number testing during mixture design should be conducted on specimens prepared at the high warning limit for asphalt content.

2. Flow number criteria for rutting resistance that were developed in WHRP Project 0092-08-06 were extended in this project to consider the effects of traffic speed and reduced short-term oven aging. This resulted in tentative flow number criteria as a function of design traffic level and traffic speed for two short-term oven aging conditions: 4 hours at 135 ºC, and 2 hours at the compaction temperature. WisDOT should consider conducting flow number testing on selected mixtures during the 2012 construction season to verify and improve these tentative criteria before considering their use in mixture design and acceptance.

3. The research completed in this project also showed that some mixtures could still provide adequate rutting resistance when produced outside of current WisDOT acceptance limits. The flow number test and the criteria developed in this project could be used to assign appropriate disincentives for mixtures produced outside of allowable production tolerances, where rutting is the primary distress that is expected based on the production deviations. This would include mixtures with high asphalt content and/or low filler content. When applying this approach to surface mixtures, consideration should be given to the potential of the mixture to lose skid resistance due to flushing, which is not considered by the flow number test.

4. When conducting flow number tests on plant produced mixtures, it is recommended that the criteria for two hours of short-term conditioning at the compaction temperature be used based on the findings in NCHRP Project 9-43 that showed that this level of conditioning reasonably reproduced the stiffness of HMA and WMA mixtures at the time of construction (*20*).

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Appendix A. Intersection Study Mix Designs for Poor Performing Mixtures

Payne & Dolan, Inc.
N3 W23650 Badinger Road
Waukesha, WI 53187
262/524-1731

REPORT OF SUPERPAVE VOLUMETRIC MIX DESIGN
(AASHTO MP-2, PP-28, T312 & ASTM D-4867)

Issued Date: 10/3/2007
Amended Date: 7/2/2009

DESIGN NUMBER: 507307 — JOB: 1090-16-60 (33034)
PLANT: Portable — MIX TYPE: E-1 — MIX TEMPERATURE: 135°C - 149°C
MIX SIZE: 12.5 mm — Design ESAL Range (mil.): 0.3 to < 1

Compactive Effort: (Gyrations) — Ni: 7 — Nd: 60 — Nm: 75

Binder Data: GRADE: PG 64-22 — SOURCE: CRM, Milwaukee — Gb: 1.036 — RAP Pb: 3.09

AGGREGATE SOURCE DATA

AGG	AGGREGATE	SOURCE	TEST#	LOCATION
AGG #1	RAP	33034	84-B-07	
AGG #2	5/8" Chip	Honey Creek Pit	160-A-07	NW1/4 S6 T3N R19E, Racine Co.
AGG #3	3/8" Chip	Honey Creek Pit	161-A-07	NW1/4 S6 T3N R19E, Racine Co.
AGG #4	MFG'D Sand	Honey Creek Pit	163-A-07	NW1/4 S6 T3N R19E, Racine Co.
AGG #5	N. Sand	Honey Creek Pit	164-A-07	NW1/4 S6 T3N R19E, Racine Co.

AGGREGATE GRADATION

		Agg #1	Agg #2	Agg #3	Agg #4	Agg #5	JMF	SPECIFICATION MIN	SPECIFICATION MAX
% BLEND		15.0	15.0	15.0	20.0	35.0			
2	50.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
1-1/2	37.5 mm	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
1	25.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
3/4	19.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2	12.5 mm	100.0	79.7	100.0	100.0	100.0	97.0	90.0	100.0
3/8	9.5 mm	93.6	21.9	92.4	100.0	100.0	86.2	0.0	90.0
#4	4.75 mm	75.5	4.5	16.2	93.3	89.1	64.3	0.0	0.0
#8	2.36 mm	60.1	3.5	4.2	62.5	75.8	49.2	28.0	58.0
#16	1.18 mm	47.4	3.0	3.4	39.5	63.0	38.0	0.0	0.0
#30	0.60 mm	35.9	2.8	3.1	25.8	48.0	28.2	0.0	0.0
#50	0.30 mm	21.7	2.7	3.0	15.7	19.1	13.9	0.0	0.0
#100	0.15 mm	14.4	2.5	2.9	8.4	5.7	6.6	0.0	0.0
#200	0.075 mm	11.2	2.3	2.7	4.7	3.5	4.6	2.0	10.0
FAA		42.5	0.0	0.0	46.0	40.8	42.7		
Gsb		2.644	2.681	2.684	2.699	2.662	2.673		

AGGREGATE DATA FOR BLENDED DESIGN JMF

CRUSH 1F/2F: 93.1 / 86.3 — Gsb: 2.673 — Moist. Absorption: 1.3 — L.A. WEAR: 0.0 (100) — ELONGATED: 0.6 (5/1)
FAA: 42.7 — Gsa: 2.765 — Dust Proportion: 1.1 — 0.0 (500)
SE: 89 — Gse: 2.738 — Soundness: 0.0 — Freeze-Thaw: 0.0

VOLUMETRIC DATA

Point	Added Pb	Total Pb	Gmm	Gmb	Va	VMA	VFB	Unit Wt.	%Gmm Ni	%Gmm Nm	TSR
A	3.7	4.2	2.561	2.385	6.9	14.5	52.4	2379			
B	4.2	4.7	2.542	2.407	5.3	14.2	62.7	2401			
C	4.7	5.2	2.523	2.426	3.8	14.0	72.9	2419			
JMF	4.7	5.2	2.523	2.422	4.0	14.1	71.6	2416	90.6	96.4	79.1
		Corr. Factor	0.000								TSR N = 17
SPECIFICATION					4.0	14.0	65 - 78		90.5	98.0	

Comments: WisDOT Aggregate Test Number: 225-218-2008 WisDOT Verification Number
A change in binder grade or source is recognized without the need for additional mix design testing. (per WisDOT 1559)

M. Noel Fortier

M. Noel Fortier
Wisconsin Certified Hot Mix Asphalt Technician IIIS

THE TEST DATA SHOWN ON THIS REPORT PERTAIN ONLY TO THE MATERIAL SUBMITTED FOR DESIGN.
AASHTO MP2 MODIFIED TO MEET CUSTOMER REQUIREMENTS.

Materials Laboratory Testing System Tests On:
Asphalt mix design
Type: DR - DESIGN REVIEW

Wisconsin Department of Transportation
Bureau of Technical Services-Central Lab
Truax Center, 3502 Kinsman Blvd.
Madison, WI 53704

Main Project ID: 1206-06-80
SOUTH MADISON BELTLINE
SEMINOLE HWY ENTRANCE RAMP
USH 12

Quantity:

Date Sampled: 04/05/05
By: KIM J. LEWIS

Date Received:

Date Tested:

Source: STORR'S

Legal Description: E, SW, Section: 25, T: 4 N, R: 13, E

County: ROCK

Design Lab: FRANK BROTHERS
Design ID: 20060

Mix Type: E-10 - 12.5 mm
Last Field Change Test Number:
Date:

	Material Description	Aggregate Source	Pit/Quarry	Location	Test Number
1	RAP	RAP	QRY	11, T: 14 N, R: 17,	0 - 162 - 53 - 2001
2	1/2" STONE	STORR'S	Pit	E, SW, Section: 25, T: 4 N, R: 13, E	0 - 225 - 73 - 2006
3	3/8" STONE	STORR'S	Pit	E, SW, Section: 25, T: 4 N, R: 13, E	0 - 225 - 73 - 2006
4	5/16" STONE	STORR'S	Pit	E, SW, Section: 25, T: 4 N, R: 13, E	0 - 225 - 73 - 2006
5	NATURAL SAND	STORR'S	Pit	E, SW, Section: 25, T: 4 N, R: 13, E	0 - 225 - 73 - 2006
6	WASHED CRUSHED SAND	STORR'S	Pit	E, SW, Section: 25, T: 4 N, R: 13, E	0 - 225 - 73 - 2006
7	WASHED FINE CRUSHED SAN	STORR'S	Pit	E, SW, Section: 25, T: 4 N, R: 13, E	0 - 225 - 73 - 2006

Sieve Sizes	1	2	3	4	5	6	7	JMF Blend
25.0 (1")	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0 (3/4")	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5 (1/2")	100.0	97.6	100.0	100.0	100.0	100.0	100.0	99.6
9.5 (3/8")	95.5	33.8	98.7	100.0	100.0	10.0	100.0	87.2
4.75 (#4)	70.3	1.1	7.7	83.7	99.2	99.3	100.0	65.3
2.36 (#8)	52.9	1.1	1.9	17.9	86.6	96.4	99.8	52.7
1.18 (#16)	42.8	1.1	1.6	3.0	73.2	57.3	90.4	38.0
0.600 (#30)	33.5	1.1	1.6	2.9	54.8	35.3	70.4	27.4
0.300 (#50)	19.3	1.0	1.5	2.7	21.0	22.0	48.3	17.0
0.150 (#100)	11.6	1.0	1.4	2.6	4.1	13.1	24.0	9.0
75 μm (#200)	7.8	0.8	1.2	3.1	1.3	7.9	8.6	4.8
Agg Blend %	9.0	16.0	15.0	13.0	7.0	24.0	16.0	100.0
Gsb:	2.642	2.651	2.651	2.652	2.626	2.692	2.695	2.665

% AC (Total): 5.2 4.7 Added
Grade: PG 58-28
Source: BP WHITING-AMOI
AC Sp. Gr: 1.031 @ 25/25°C
RAP % AC: 3.8
%VMA: 14.0
% VFB: 71.4
Sand Equiv. (%): 60.0

% Air Voids: 4.01%
Gmm: 2.519
Gmb: 2.418
Gse: 2.736
Nini: 8
Ndes: 100
Nmax: 160

FAA: 45.4
Gmm Corr:
Unit Wt (PCF): 150.50
% Gmm: 88.5
% Gmm: 96.7

Mixing Temp (°C): 275-300 F
Compaction Temp (°C):
Moisture Absorption: 1.47
Dust Proportion: 1.20
Fracture: 95.0 1F 93.0 2F
Thin/Elong: 1.8
TSR: 80.8 **Comp. Effort:** 37.0 N
Anitstrip: NONE

Volumetric Data

Point	% AC Total	% AC Added	Gmm	Gmb	Va	VMA	VFB
A	4.5		2.546	2.385	6.3	14.5	56.6
B	5.0		2.527	2.405	4.8	14.3	66.4
C	5.5		2.508	2.434	3.0	13.7	78.1
D	6.0		2.489	2.450	1.6	13.6	88.2

Verified Date: **Verified By:**

TOTAL P.02

Materials Laboratory Testing System Tests On:
Asphalt mix design
Type: DR - DESIGN REVIEW

Wisconsin Department of Transportation
Bureau of Technical Services-Central Lab
Truax Center, 3502 Kinsman Blvd.
Madison, WI 53704

Main Project ID: 1480-08-74
GREEN BAY - STURGEON BAY ROAD
CTH H - STH 42
STH 57

Quantity:

Date Sampled:
05/18/06
By: KARL RUNSTROM

Date Received:

Date Tested:

Source: STURGEON BAY - MM **Legal Description:** SE, NW, Section: 21, T: 27 N, R: 25, E **County:** DOOR

Design Lab: NORTHEAST ASPHALT
Design ID: 801106

Mix Type: E-0.3 - 12.5 mm
Last Field Change Test Number:
Date:

	Material Description	Aggregate Source	Pit/Quarry	Location	Test Number
1	RAP	RAP	QRY	11, T: 14 N, R: 17,	0 - 162 - 53 - 2001
2	5/8" X 1/2" CHIP	STURGEON BAY - MM	QRY	SE, NW, Section: 21, T: 27 N, R: 25, E	0 - 225 - 25 - 2005
3	1/2" X 1/4" CHIP	STURGEON BAY - MM	QRY	SE, NW, Section: 21, T: 27 N, R: 25, E	0 - 225 - 25 - 2005
4	MFG'D SAND	STURGEON BAY - MM	QRY	SE, NW, Section: 21, T: 27 N, R: 25, E	0 - 225 - 25 - 2005
5	NATURAL SAND	MURRAY	Pit	NE, SE, Section: 26, T: 26 N, R: 23, E	0 - 217 - 31 - 2005

Sieve Sizes	1	2	3	4	5	JMF Blend
25.0 (1")	100.0	100.0	100.0	100.0	100.0	100.0
19.0 (3/4")	100.0	100.0	100.0	100.0	100.0	100.0
12.5 (1/2")	95.9	71.9	100.0	100.0	100.0	95.6
9.5 (3/8")	94.9	19.1	90.1	100.0	100.0	85.6
4.75 (#4)	75.2	3.0	11.7	95.0	97.6	66.5
2.36 (#8)	57.5	2.3	4.5	63.3	84.3	50.8
1.18 (#16)	45.6	2.2	3.4	38.7	67.9	37.7
0.600 (#30)	36.5	2.1	3.1	22.7	50.3	27.0
0.300 (#50)	25.7	2.0	2.9	12.6	25.3	15.3
0.150 (#100)	15.6	2.0	2.7	6.7	5.2	6.3
75 µm (#200)	10.7	1.8	2.3	4.2	1.9	3.9
Agg Blend %	15.0	15.0	15.0	25.0	30.0	100.0
Gsb:	2.880	2.763	2.758	2.779	2.663	2.726

% AC (Total): 5.3 4.7 Added
Grade: PG 58-28
Source: CRM, GREEN BAY
AC Sp. Gr: 1.030 @ 25/25°C
RAP % AC:
%VMA: 15.0
% VFB: 73.4
Sand Equiv. (%): 84.0

% Air Voids: 4.00%
Gmm: 2.550
Gmb: 2.448
Gse: 2.780
Nini: 6
Ndes: 40
Nmax: 60

FAA: 43.0
Gmm Corr:
Unit Wt (PCF): 152.36
% Gmm: 90.3
% Gmm: 97.1

Mixing Temp (°C): 135-147
Compaction Temp (°C):
Moisture Absorption: 1.10
Dust Proportion: 0.90
Fracture: 97.1 1F 96.6 2F
Thin/Elong:
TSR: **Comp. Effort:** N
Antistrip:

Volumetric Data

Point	% AC Total	% AC Added	Gmm	Gmb	Va	VMA	VFB
A	4.8	4.20	2.570	2.431	5.4	15.1	64.2
B	5.3	4.70	2.550	2.444	4.2	15.1	72.2
C	5.8	5.20	2.530	2.471	2.3	14.6	84.2
D							

Verified Date: **Verified By:**

REPORT OF SUPERPAVE VOLUMETRIC MIX DESIGN
(AASHTO MP-2, PP-28, T312 & ASTM D-4867)

Issued Date: 4/11/2008
Amended Date: 4/11/2008

DESIGN NUMBER: 804807
PLANT: Tower
MIX SIZE: 12.5 mm
JOB: 1154-01-71 (608651)
MIX TYPE: E-3
Design ESAL Range (mil.): 1 to < 3
MIX TEMPERATURE: 135°C - 149°C

Compactive Effort: (Gyrations) Ni: 7 Nd: 75 Nm: 115

Binder Data: GRADE: PG 58-28 SOURCE: CRM Green Bay PG 58-28 Gb: 1.032 RAP Pb: 3.65

AGGREGATE SOURCE DATA

GG	AGGREGATE	SOURCE	TEST#	LOCATION
GG #1	Crushed Rap	Tower	118-B-07	SW1/4 SW1/4 S34 T31N R20E Marinette County
GG #2	5/8" x 1/2" Chip	Tower	64-A-07	SW1/4 SW1/4 S34 T31N R20E Marinette County
GG #3	1/2" x 1/4" Chip	Tower	65-A-07	SW1/4 SW1/4 S34 T31N R20E Marinette County
GG #4	MFD Sand	Tower	67-A-07	SW1/4 SW1/4 S34 T31N R20E Marinette County
GG #5	Washed Natural Sand	Tower	68-A-07	SW1/4 SW1/4 S34 T31N R20E Marinette County

AGGREGATE GRADATION

		Agg #1	Agg #2	Agg #3	Agg #4	Agg #5	JMF	SPECIFICATION MIN	SPECIFICATION MAX
% BLEND		10.0	13.0	18.0	20.0	39.0			
2	50.0 mm	100.0	100.0	100.0	100.0	100.0			
1-1/2	37.5 mm	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
1	25.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
3/4	19.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
1/2	12.5 mm	99.0	68.9	99.5	100.0	100.0	100.0	100.0	100.0
3/8	9.5 mm	92.7	10.3	88.4	100.0	100.0	95.8	90.0	100.0
#4	4.75 mm	71.0	3.1	8.0	95.0	96.1	85.5	0.0	90.0
#8	2.36 mm	54.9	2.9	4.3	42.5	79.0	65.4	0.0	0.0
#16	1.18 mm	45.1	2.8	3.5	18.6	65.5	46.0	28.0	58.0
#30	0.60 mm	37.3	2.7	3.2	10.2	48.7	34.8	0.0	0.0
#50	0.30 mm	26.1	2.6	2.9	6.5	23.1	25.7	0.0	0.0
#100	0.15 mm	15.6	2.4	2.6	4.6	4.0	13.8	0.0	0.0
#200	0.075 mm	10.9	2.0	2.1	3.4	1.5	4.8	0.0	0.0
	FAA	41.1	0.0	0.0	46.0	41.2	3.0	2.0	10.0
	Gsb	2.680	2.703	2.703	2.671	2.697	42.6		
							2.692		

AGGREGATE DATA FOR BLENDED DESIGN JMF

CRUSH 1F/2F: 81.4 / 79.6
FAA: 42.6
SE: 94
Gsb: 2.692
Gsa: 2.776
Gse: 2.744
Moist. Absorption: 1.1
Dust Proportion: 0.7
Soundness: 0.0
L.A. WEAR: 0.0 (100) 0.0 (500)
Freeze-Thaw: 0.0
ELONGATED: 0.6 (5/1)

VOLUMETRIC DATA

Point	Added Pb	Total Pb	Gmm	Gmb	Va	VMA	VFB	Unit Wt.	% Gmm Ni	% Gmm Nm	TSR
A	3.9	4.3	2.561	2.388	6.8	15.1	55.0	2382			
B	4.4	4.8	2.542	2.405	5.4	14.9	63.8	2399			
C	4.9	5.3	2.522	2.436	3.4	14.3	76.2	2429			
JMF	4.8	5.2	2.526	2.425	4.0	14.6	72.6	2418	96.5	97.3	82.5
		Corr. Factor:	0.000								TSR N = 15
SPECIFICATION					4.0	14.0	65 - 75		89.0	98.0	

Comments: WisDot Aggregate Test Number:225-04-2006 WisDOT Verification Number:
A change in binder grade or source is recognized without the need for additional mix design testing if the same binder (modified or unmodified) is used in the design. (per WisDOT 1559)

Michelle M. Colling

Wisconsin Certified Hot Mix Asphalt Mix Designer

THE TEST DATA SHOWN ON THIS REPORT PERTAIN ONLY TO THE MATERIAL SUBMITTED FOR DESIGN.

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