Regressing Air Voids for Balanced HMA Mix Design

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16. Abstract

This project evaluated the impact of the air voids regression approach on cracking, rutting, and moisture damage resistance of asphalt mixtures. The experimental plan included a total six mixes designed for low, medium, and high traffic levels, with various contents of RAP and RAS. Mixture performance tests included the Illinois Flexibility Index Test to evaluate intermediate temperature cracking resistance, the Disc-Shaped Compacted Tension for low-temperature cracking resistance, and the Hamburg Wheel Tracking Test for rutting and moisture resistance. The results indicate that the regressed air voids concept can improve mixture cracking resistance without compromising the rutting resistance of asphalt mixes. Recommendations to WisDOT include a strategy to be accomplished in three stages: (1) implementation of the 3.0% regressed air voids mix designs without performance tests; (2) continued use of the 3.0% regressed air voids mix designs with added Hamburg rutting criteria based on traffic levels; and (3) implementation of a Balanced Mix Design specification and eventually withdrawing the regressed air voids design requirement.

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Executive Summary

This research project evaluated the impact that regressed air void mix designs has on cracking, rutting, and moisture damage resistance of asphalt mixtures. A total of six mixes were designed for low, medium, and high traffic levels, with various contents of RAP and RAS. Mixture performance tests included the Illinois Flexibility Index Test (I-FIT) per AASHTO TP 124 to evaluate intermediate temperature cracking resistance, the Disc-Shaped Compacted Tension (DCT) Test per ASTM D 7313 to evaluate low temperature cracking resistance, and the Hamburg Wheel Tracking Test (HWTT) per AASHTO T 324 to evaluate rutting and moisture damage resistance.

Summary of Findings

I-FIT Results

For five of the six mixtures evaluated, regressing the design air voids increased the asphalt content by 0.3 to 0.4% and resulted in a clear improvement in the Flexibility Index. Based on these results, the regressed air voids approach to mix design will have a positive impact on the intermediate temperature cracking resistance of asphalt mixtures.

DCT Results

Although DCT Fracture Energy results increased for mixtures designed with regressed air voids, the improvement was not statistically significant. Based on these results, the regressed air voids approach is not expected to have a significant impact on thermal cracking.

HWTT Results

Hamburg results analyzed using the AASHTO procedure indicated that Mix 2 (Medium Traffic, PG 58-28, 20% RAP, 0% RAS) and Mix 3 (High Traffic, PG 58-28, 15% RAP, 0% RAS) are susceptible to stripping. However, field performance of these mixtures has not shown any indications of moisture damage. This could indicate that the Hamburg test can give false positive errors. None of the six mixtures exhibited Stripping Inflection Points in the first 10,000 passes of the test. The four mixes that had no signs of stripping completed the full 20,000 passes with rut depths less than 12.5 mm.

Corrected rut depths using the modified procedure proposed by Yin et al. were significantly lower than the common maximum rutting criterion of 12.5 mm (0.5”). All of the mixtures designed with air voids regressed to 3.0 percent met the rutting criterion indicating that the regressed air voids approach will not likely cause a future problem with increased rutting susceptibility of asphalt pavements.

Recommendations

Results from this project indicate that the regressed air voids concept can improve mixture cracking resistance without compromising the deformation resistance of asphalt mixes. Therefore, a three stage implementation strategy is recommended**:** (1) full implementation of 3.0% regressed

air voids without performance tests and informing contractors of plans to add Hamburg testing; (2) adding Hamburg rutting and stripping criteria based on traffic levels and informing contractors of plans to add IFIT; and (3) implementation of Balanced Mix Design and eventually withdrawing regressed air voids and other volumetric criteria for mix design approval.

Acknowledgement

The authors acknowledge the support from the Project Oversight Committee (POC) in refining the experimental plan, identifying the materials and mix designs to be used in this study, coordinating the collection and delivery of all the materials, evaluating project progress and reviewing and providing recommendations to improve this report.

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1. INTRODUCTION

This report documents the work completed for Wisconsin Highway Research Program (WHRP) Project 0092-16-06, Regressing Air Voids for Balanced HMA Mix Design. The objectives of this study were to assess the impacts of increasing asphalt binder contents of asphalt mixtures using the regressed air voids concept and to recommend whether not to proceed with implementation of this approach. To accomplish these objectives, NCAT worked with the project oversight committee (POC) to develop an experimental plan that included (a) the testing of mixtures from WisDOT's three mix categories (high, medium, and low traffic) at three asphalt contents corresponding to 4.0, 3.5, and 3.0 percent air voids; (b) evaluating the effects of air voids and mixture traffic level on laboratory measured performance properties to evaluate mixtures for resistance to rutting and cracking; and (c) making recommendations to WisDOT specifications regarding air void regression. In addition, the study provides useful information regarding the selection of mixture performance tests and preliminary criteria for those tests for use in a balanced mix design approach.

This evaluation included laboratory prepared mixtures containing reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS). Testing and evaluation of each mixture included: Hamburg Wheel Tracking Test (HWTT)-AASHTO T 324, Illinois Flexibility Index (I-FIT)-AASHTO TP 124, and Disc-Shaped Compacted Tension (DCT)-ASTM D 7313. The findings presented in this report are based on laboratory test results conducted at the National Center for Asphalt Technology (NCAT). This project included the following tasks:

Task 1. Synthesis of Current Practice and Research. This task encompassed a literature review to assess current practices and research of the effects of air void regression. This information helped the researchers refine the experimental plan.

Task 2. Work Plan and Laboratory Testing. In this task, a laboratory experiment was designed to evaluate the air void regression approach using mixes designed for low, medium, and high traffic levels.

Task 3. Interim Presentation and Project Memorandum. This task included the preparation of an interim web-meeting presentation with the POC and an interim report summarizing the results of Tasks 1 and 2. The presentation was made on February 24, 2017 and the interim report was submitted on April 10, 2017.

Task 4. Execution of Work Plan and Analysis of Results. Once approval from the POC was granted, the work plan was conducted and the results were analyzed.

Task 5. Final Report. This task includes a final report documenting the findings of the study and project closeout activities. Recommendations related to the regressed air voids approach were provided for WisDOT consideration.

2. LITERATURE REVIEW

2.1 Background

In the United States, asphalt paving mixtures are primarily designed using the Superpave system where proportioning of the components relies largely on volumetric properties. Early Superpave implementation focused primarily on rutting resistance. Mix designs for moderate and high traffic pavements were designed for improved rutting resistance by specifying a higher grade of asphalt binder and higher quality aggregates. Most highway agencies now report that rutting problems have been virtually eliminated. However, there have been growing concerns that the primary mode of distress for asphalt pavements is now cracking of various forms (West et al. 2018). There are several possible contributing factors to increased cracking, including issues with mix designs, increased use of recycled materials, problems with construction quality, and failing to adequately address underlying pavement distresses during pavement rehabilitation (Bonaquist et al, 2014). It is now well recognized that the current mix design system has some shortcomings (Zhou et al, 2016).

In response to pavement durability concerns, many state departments of transportation (DOTs) have modified their mix design and acceptance requirements to obtain higher asphalt contents. Some of these modifications include reduced compactive efforts (lowering design gyrations), air voids regression, increased minimum voids in the mineral aggregate (VMA) criteria, and setting more restrictive limits on reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) (West et al, 2018). In volumetric mix design, the effective asphalt content is controlled by the difference between the air voids and VMA. To increase the effective asphalt content in mixes, it is necessary to either target a lower air void content or increase the minimum VMA criteria (Mallick et al. 2000).

2.2 State of the Practice to Increase Asphalt Content of Asphalt Mixes

A number of highway agencies have started to either explore or adopt approaches to improve the cracking resistance of asphalt mixes by increasing the asphalt content. The following sections discuss some of these modifications.

2.2.1 *Air Voids Regression*

In this approach, a mix is designed using standard laboratory methods and criteria including a target air void content of 4.0%. The asphalt content is then increased to achieve a “regressed” target of 3.5% or 3.0% air voids. Once the job mix formula (JMF) and aggregate proportions are set, the binder content typically increases by 0.3 to 0.4% for a target of 3.0% air voids. Potential risks associated with this approach include: (1) even with the increased asphalt content, the mixture may still not have adequate cracking resistance, and (2) the added binder could make the mixture susceptible to rutting.

2.2.2 *Lowering Design Air Voids*

Lowering the target air void content during mix design will increase the asphalt content of the mixes only if VMA criteria are not reduced. However, mix design VMA results are challenging to validate because the reproducibility of aggregate and recycled material's bulk specific gravities is very poor. If air void content is also a quality assurance criteria during asphalt mix production, the as-produced air void target and associated tolerances must also be changed (Nicholls et al, 2008).

2.2.3 *Lowering Gyration Levels (N_{design})*

Lowering just the gyration levels (N_{design}) will not result in an increase in the asphalt content of a mix unless the gradation is fixed. However, since gradations are not fixed, the aggregate blend can be adjusted to obtain the same effective asphalt content as the higher gyration mix design. Lowering N_{design} can enable finer gradations, which are generally easier to compact than coarse graded mixes. Research conducted at NCAT as part of NCHRP Project 9-9 indicated that the compactive efforts recommended in AASHTO R 35 were too high. Data from numerous projects across the United States showed that pavements were not densifying under traffic to the levels achieved in the Superpave Gyratory Compactor (SGC). The recommendation was to reduce the N_{design} level by 20-25% depending on the design traffic (Prowell and Brown, 2007). Many agencies have decreased the N_{design} with successful field performance.

2.2.4 *Increasing Minimum VMA*

VMA represents the total volume of intergranular space between aggregate particles of a compacted mix. For a given air void content, increasing the VMA will yield a higher asphalt content. For a given compactive effort (N_{design}), VMA can only be altered by changing the aggregate blend. However, as noted above, VMA criteria are quite challenging to validate and enforce because of the poor reproducibility of bulk specific gravities of aggregates and recycled materials.

A survey for the AASHTO Subcommittee on Materials conducted in 2014 gathered information regarding state DOT modifications to the Superpave mix design standard, AASHTO R 35, related to design air voids, design gyrations, and minimum VMA (Aschenbrener, 2014). A total of 26 DOTs responded to this survey; the results are summarized in Figures 1-3. Based on this information, seven states had decreased target air voids, sixteen states use lower design gyrations, and eight states increased minimum VMA requirements. For some states, a combination of modifications were made.

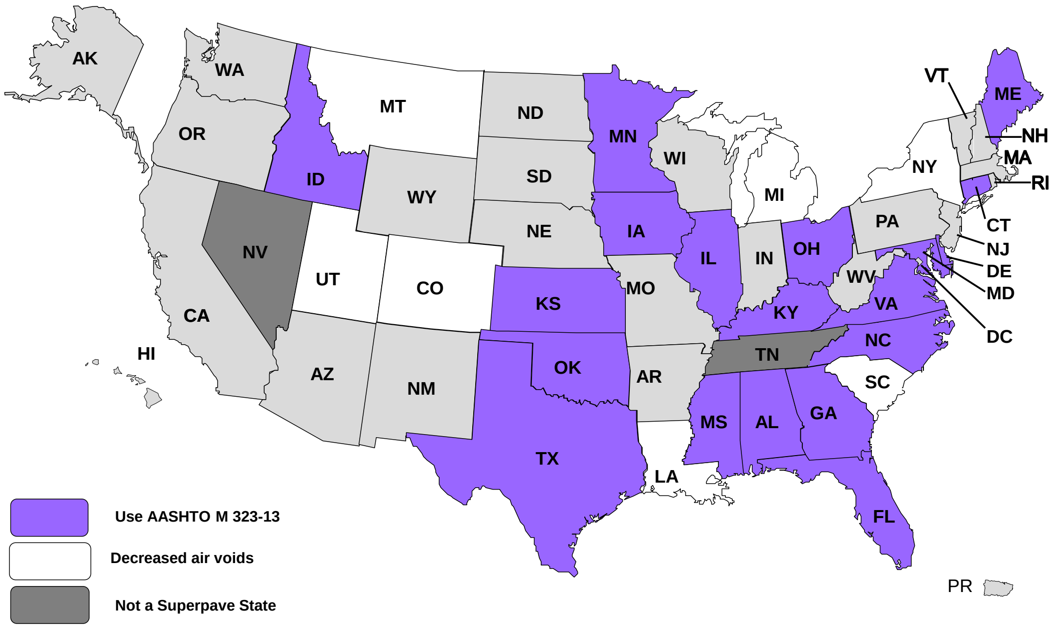


Figure 1 Design Target Air Voids (Aschenbrener, 2014)

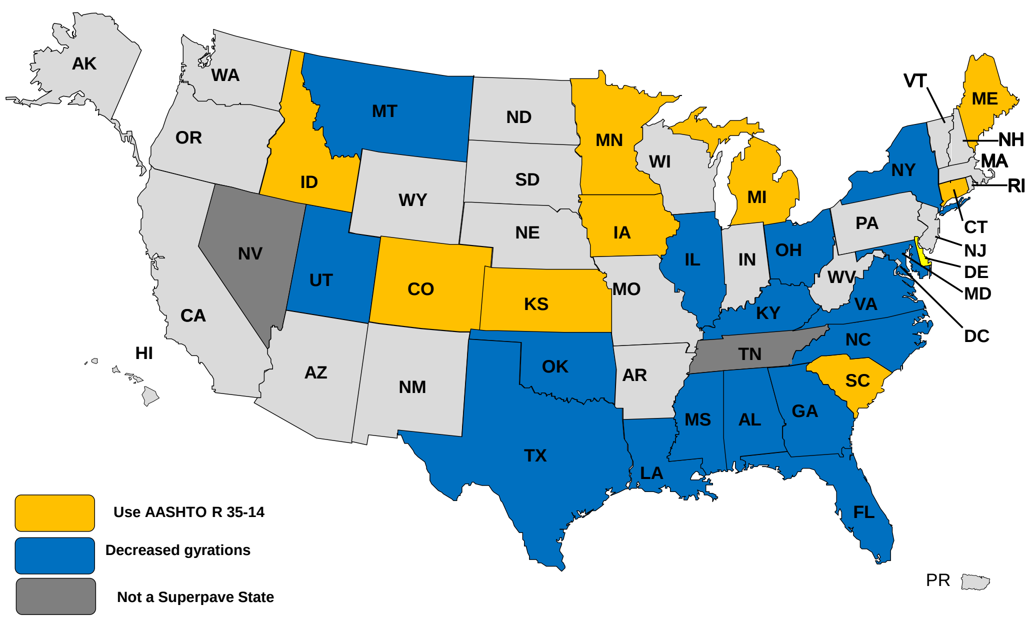


Figure 2 Design Gyrations (Aschenbrener, 2014)

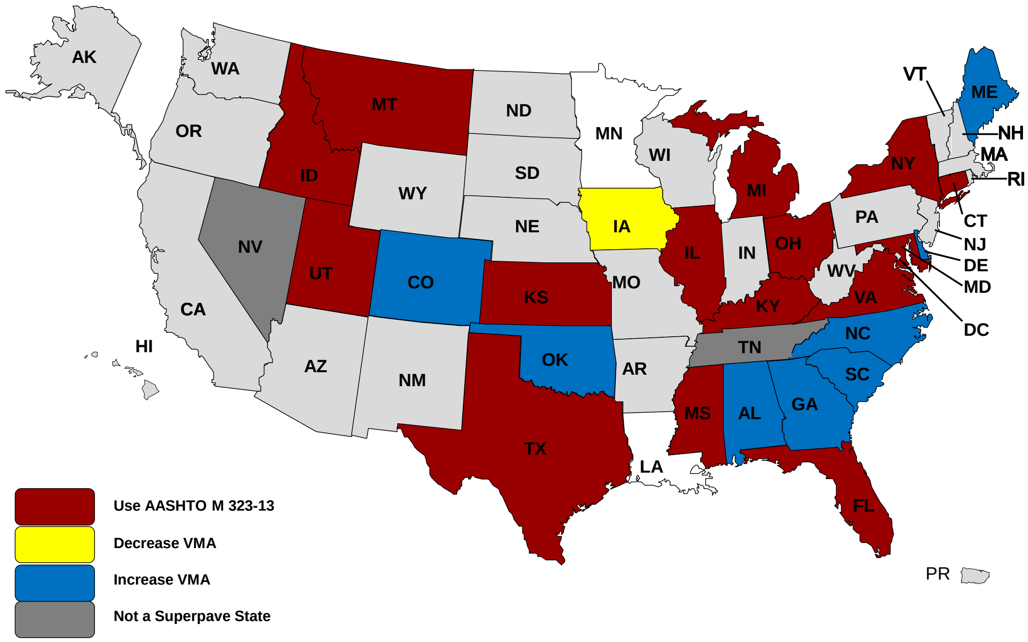


Figure 3 Minimum Design VMA (Aschenbrener, 2014)

2.2.5 *Specific DOT Approaches to Improve Mix Designs*

The following sections present state DOT approaches to increase asphalt content to improve durability of their asphalt mixtures. This information was collected from published journals, technical reports, articles, presentations, and personal communications.

Alabama. The Alabama DOT uses 60 gyrations for all Superpave mixtures and a design air voids content of 3.5% for mixes containing RAS and 4.0% for all other mixtures (Alabama DOT, 2012).

Illinois. The Illinois DOT (IDOT) has used the regressed air void concept for several years in the northeast part of the state with local agency contracts. They allow contractors to modify their lower traffic volume mixes (N_{design} = 50 at 4.0% air voids) during production by targeting 3.5% air voids and also re-proportioning IDOT verified mix designs within permitted specifications adjustments. This option is permitted through a special provision in contracts (Houston, 2017). Table 1 presents the asphalt mixture requirements included in this provision. In addition, when asphalt binder replacement (ABR) (also known as recycled binder ratio) exceeds 15%, the new binder in the mix shall be changed as shown in Table 1. ABR below 30% and RAS below 2% is allowed.

The feedback received by Illinois DOT regarding the implementation of this approach has been positive and indicates improved constructability and density, less segregation, and better finished appearance (Houston, 2017).

Table 1 IDOT Special Provision Asphalt Mixture Requirement (IDOT, 2016)

Item	AC Type		Air Voids
	Overlay	Full Depth	
Surface course, mix "C/D"	PG58-22/58-28[1]	PG58-22/46-34[1]	3.5% at N_{design} = 50
Leveling binder	PG 58-22/PG58-28[1]	PG 58-28/PG 46-34[1]	
Binder course, IL-19	PG 58-22/58-28[1]	PG 58-28/46-34[1], PG 58-28 when 4" below in depth	

[1] New asphalt when ABR exceeds 15%

Kansas. The Kansas DOT started exploring both air voids reduction and changes in gyration levels in 2007 (Leibrock, 2016). The first project was built in 2007 with a mixture designed with 3.5% air voids and 75 gyrations. In 2009, another project was designed at 3.5% air voids, but N_{design} was lowered to 60. Kansas began 3.0% air void projects in 2010, and they have constructed about 70 such projects throughout the state. A Hamburg criterion (max. 12.5 mm at 10,000 passes) is required of the 3.0% air void mix designs.

Louisiana. The Louisiana Department of Transportation and Development (LADOTD) proposed new specifications requirements in 2013 increasing the asphalt binder content of asphalt mixtures in order to address cracking potential while considering possible impacts to rutting. The new specification criteria included lower gyration levels and air void contents ranging from 2.5% to 4.5% (Cooper et al., 2016). These mix design criteria are based on the type of mixture and intended use (i.e., binder or wearing course, traffic level, etc.).

Michigan. After several years of trial projects using the regressed air voids approach, Michigan DOT began full implementation of the method in 2016. Mix designs must meet their standard aggregate quality requirements and volumetric criteria using a 4.0% air void target. However, the design asphalt content is increased to yield 3.0% air voids. During field production, the air void target is 3.0% with a single test acceptance limit of 2.0%.

Minnesota. In Minnesota, the wearing course (top 4" placed in two lifts) is designed at 4.0% air voids and the non-wear mixture (below 4" from the surface) is designed at 3.0% air voids. In addition, local agencies typically require mix designs at 3.0% air voids for lower volume facilities. The Minnesota DOT (MnDOT) used regressed air voids at their Minnesota Road Research Facility (MnROAD) on Cell 19 during the summer of 2016. The asphalt mixture was designed at 100 gyrations and 3.0% air voids. MnDOT will place another 3% regressed air void section in the summer of 2017 (Garrity, 2017).

Montana. In Montana, asphalt mixtures are designed following AASHTO R 35 and meeting AASHTO M 323. However, the optimum asphalt content is selected at the lowest air void value between 3.4 to 4.0% as long as all other criteria are met (Montana DOT, 2014). Montana DOT has also established a rutting criterion for mix acceptance and quality assurance. During production, when two consecutive HWTT samples do not meet the requirements, production is suspended and a revised mix design and samples for verification and Hamburg testing must be submitted.

Ohio. For the Ohio DOT, medium traffic level mixes are designed at 3.5% air voids. The quality control air voids tolerance is adjusted down 0.5% as well. Ohio has used this approach for a number of years. With this approach, 0.2-0.3% increase in asphalt is achieved for the 0.5% less air voids (Powers, 2017).

Utah. The Utah DOT allows mix designs to be performed with air void contents between 3.0% and 4.0%. The low air void mixtures are designed for low volume roads and mixtures used in regions with cold climates (Utah DOT, 2013).

Virginia. Virginia DOT researchers simply added 0.5 and 1.0% asphalt to certain existing mixture designs and conducted comparative tests on the mixtures (Maupin, 2003). They first determined the Superpave gyratory compactor (SGC) compactive effort that yielded the same air voids achieved in the field for each mix. Permeability, rutting resistance (APA), and fatigue properties (flexural beam) were determined to evaluate the effect of reduced air voids on performance. They reported tremendous benefit in reducing permeability when only 0.5 percent asphalt was added. Consequently, fatigue properties increased with the increased asphalt content. With lower permeability, the long-term benefits of fatigue may be further augmented. Rutting did not appear to be problematic, even with the addition of 1.0% asphalt.

Wisconsin. The Wisconsin DOT is currently working towards specifications to increase the asphalt binder content in asphalt pavements in order to improve performance. The approach under evaluation is the regressed air voids method, designing the mix to meet all standard criteria including 4.0% air voids and then determining the amount of binder needed to achieve 3.5% or 3.0% air voids. The approach was used on test sections on State Trunk Highway 21 in 2016. The impact that the approach has on pavement performance has yet to be determined.

2.3 Low Air Void Asphalt Mixture Risks

Low in-place air voids have historically been associated with distress types such as flushing/bleeding and rutting/shoving. In a study of in-place rutting, Brown and Cross (1989) looked at pavements that experienced premature rutting and at pavements that had no rutting after more than ten years of service. They used coring, trenching, and laboratory tests to assess the source and cause of the rutting. They concluded that a low air void content in situ or in re-compacted specimens was a good indicator for rutting and pointed to a previous study with similar results (Huber and Herman, 1987).

Another study was conducted to identify mix design parameters that may affect rutting. A total of 42 pavements were sampled from 14 different states. Similarly, based on coring, trenching, and laboratory tests, the following conclusions were made: (1) pavements that rutted had in-place air void content below 3%; and (2) most of the observed rutting was confined to the top 3” to 4” of the pavement (Brown and Cross, 1992).

Somewhat in contradiction to the above studies, good field performance has been reported for mixes designed and constructed with low air void contents. Davis (1988) reported that large-stone (maximum aggregate sizes of 50.0 mm or larger) dense-graded mixes performed extremely well with no rutting or cracking at an in-place air void content of 3% or less; these mixes also had very soft binders. It important to note that the previous studies were conducted prior to the implementation of Superpave and the widespread use of polymer modified asphalt binders for heavy traffic pavements. However, another example was documented in the Westrack experiment. The asphalt mixture in test section 43, a Nevada DOT mix, was designed to a target air void content of 1.7% (FHWA, 1998). After paving, the average in-place air voids of the corresponding test section were also very low, 1.6%. Despite this fact, this mix experienced minimal rutting/shoving compared to all other sections in the experiment. In addition, "rich-bottom" and "high modulus" low air void mixtures have been suggested in the context of perpetual pavements to provide increased fatigue resistance at the bottom of the asphalt course (Harvey et al., 1996). For example, researchers in California used a pavement reconstruction strategy that included a rich bottom layer, 50 to 75 mm (2 to 3 inches) thick, designed to 2% air voids (Harvey et al., 1999). Detailed reports on such mixture designs and ''rich-bottom'' construction can be found in Monismith et al. (2001), Scullion (2006), and Willis and Timm (2006), among others. It is important to keep in mind that most of these cases refer to mixes that were intentionally designed at low air void contents and usually refer to base mixtures.

2.4 Balanced Mix Design

Many asphalt technologists understand that only adjusting the air void target may not be sufficient to optimize mix designs and ensure that they will perform as desired. There are two major shortcomings of the volumetric mix design approach. The first limitation is due to the dependency of VMA on an accurate measure of aggregate bulk specific gravity. Determination of this property is time consuming and fraught with subjectivity, which results in poor repeatability and even worse reproducibility. Consequently, verification of mix design VMA between two labs is difficult. Furthermore, when the span of time between mix design and production increases, so does the probability of natural variations for many materials used in mix designs. The second weakness of volumetric mix design has to do with the inability to assess the effects of modified binders, additives, and recycled materials. Whether the mix design includes a polymer-modified binder, RAP, RAS, rejuvenator, or some combination of these materials, volumetric properties provide no indication as to whether the mix's composite binder helps or hurts its durability. Although recycled materials are now used in most mixes, there is no way to know if the recycled binders are truly activated and behave as a composite material with the other binder and/or rejuvenators.

Consequently, the concept of balanced mix design is gaining popularity as a way to better assess a mix design's resistance to major forms of distress, including rutting, cracking, and moisture damage. To date, only a few DOTs have implemented the balanced mix design concept, and each state has selected different tests for assessing cracking resistance. In 2015, the Federal Highway Administration (FHWA) Expert Task Group on Mixtures and Construction formed a task force on

Balanced Mix Design (BMD) that defined BMD as "asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate and location within the pavement structure." Balanced mix design infers that the mixture is designed to balance between rutting resistance and cracking resistance using appropriately selected mixture performance tests rather than relying solely on volumetric guidelines. The task force identified three potential approaches to the use of BMD; these approaches are illustrated on the flowchart in Figure 4 and are briefly discussed in the following sections (FHWA, 2016).

2.4.1 *Volumetric Design with Performance Verification (Approach 1)*

This approach starts with the current Superpave mix design method for determining optimum asphalt binder content. The completed mix design then undergoes selected performance testing to assess its resistance to rutting, cracking, and moisture damage. If the mix design meets the performance test criteria, the JMF is established and production begins; otherwise, the entire mix design process is repeated using different materials (e.g., aggregate or asphalt binder) or mix proportions until all of the performance criteria are satisfied. This is the most common approach currently used by state DOTs.

2.4.2 *Performance-Modified Volumetric Mix Design (Approach 2)*

This approach begins with the Superpave mix design method to establish a design aggregate structure and a preliminary binder content. The performance test results are then used to adjust either the binder content or component properties (such as asphalt binder grade or aggregate properties) until the performance criteria are satisfied. The final design is primarily focused on meeting performance test criteria and may not be required to meet all of the traditional mix design criteria.

2.4.3 *Performance Design (Approach 3)*

This approach establishes and adjusts mixture components and proportions based on performance analysis with limited or no requirements for volumetric properties. Requirements may be set for asphalt binder and aggregate properties. Once the laboratory test results meet the performance criteria, mixture volumetric properties may be determined for initial construction control. This approach is not currently used by SHAs but could be a viable option.

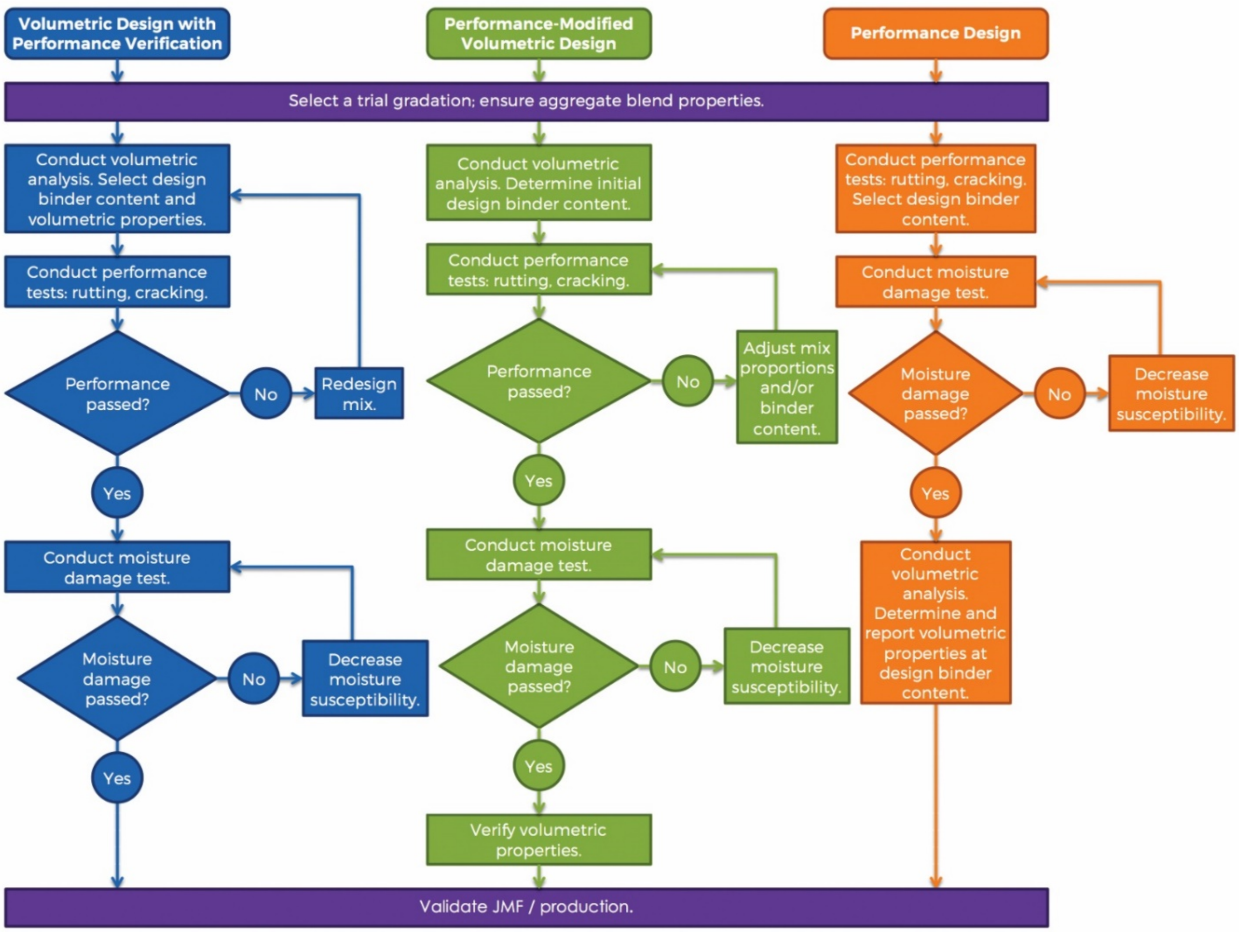


Figure 4 Schematic Illustrations of Three BMD Approaches (NCAT, 2017)

Some states have started to use BMD Approach 1 and 2. The task force identified Illinois, Louisiana, New Jersey, Texas, and Wisconsin as Approach 1 states. California is using Approach 2. Rutgers University has proposed Approach 3 for New Jersey, but it has not been implemented. Overall, the primary hurdle to overcome for BMD implementation is determining what performance tests work and what criteria should be used.

2.4.4 *Selection of Asphalt Mixture Performance Tests*

Over the past few decades, numerous mixture performance tests have been developed by different researchers to evaluate the rutting resistance, cracking resistance, and moisture susceptibility of asphalt mixtures. Considering the different mechanism in crack initiation and propagation, mixture cracking tests can be further categorized into thermal cracking, reflection cracking, bottom-up fatigue cracking, and top-down fatigue cracking. Table 2 provides a list of mixture performance tests that are commonly used in asphalt research and are being considered by highway agencies. The table also indicates if performance criteria have been established. Some of these performance tests are better suited for routine use in mix design and quality assurance testing, while others are more focused on characterizing the fundamental properties of asphalt mixtures and predicting pavement response.

Table 2 Commonly Used Asphalt Mixture Performance Tests

Mixture Distress	Laboratory Test	Test Standard	Test Parameter(s)	Criteria Available
Thermal Cracking	Disk-Shaped Compact Tension (DCT) Test	ASTM D7313-13	Fracture Energy	Yes
	Indirect Tensile (IDT) Test	AASHTO T 322-07	Creep Compliance, Tensile Strength	No
	Semi-Circular Bend (SCB) Test	AASHTO TP 105-13	Fracture Energy	Yes
	Thermal Stress Restrained Specimen Test	BS EN12697-4	Fracture Temperature, Fracture Strength	No
Reflection Cracking	Disk-Shaped Compact Tension Test	ASTM D7313-13	Fracture Energy	No
	Texas Overlay Test	TxDOT Tex-248-F, NJDOT B-10	Cycles to Failure, Fracture Properties	Yes
Bottom-Up Fatigue Cracking	Direct Tension Cyclic Fatigue Test	AASHTO TP 107-14	Damage Characteristic Curve, Fatigue Model	No
	Flexural Bending Beam Fatigue Test	AASHTO T 321, ASTM D7460	Cycles to Failure, Fatigue Equation	No
	IDT Test	N/A	Fracture Energy, N_{flex} Factor	No
	Illinois Flexibility Index Test	AASHTO TP 124-16	Flexibility Index	Yes
	SCB at Intermediate Temperature	LaDOTD TR 330-14, ASTM D8044-16	Strain Energy Release Rate	Yes
	Texas Overlay Test	TxDOT Tex-248-F	Cycles to Failure, Fracture Properties	Yes
Top-Down Fatigue Cracking	Direct Tension Test	N/A	Fracture Parameters	No
	IDT Energy Ratio Test	N/A	Dissipated Creep Strain Energy, Energy Ratio	Yes
Rutting	Asphalt Pavement Analyzer	AASHTO T 340	Rut Depth	Yes
	Flow Number	AASHTO TP 79-15	Flow Number	Yes
	Hamburg Wheel Tracking Test	AASHTO T 324	Rut Depth	Yes
	Superpave Shear Tester	AASHTO T 320-07	Permanent Shear Strain	No
	Triaxial Stress Sweep Test	AASHTO TP 116-15	Minimum Strain Rate	Yes
Moisture Susceptibility	Hamburg Wheel Tracking Test	AASHTO T 324	Rut Depth, Stripping Inflection Point	Yes
	IDT Strength Test	AASHTO T 283	Tensile Strength Ratio, Wet IDT Strength	Yes
Durability	Cantabro Test	AASHTO TP 108-14	Mass Loss	No

Table 3 shows a list of state agencies who have implemented performances tests in their current mix design specifications. This list was obtained from a survey of state agencies and asphalt contractors as part of NCHRP Project 20-07(406) (West et al. 2018).

Table 3 Implementation of Mixture Performance Tests by State Highway Agencies

Mixture Distress	Laboratory Test	Implemented by State Agency
Thermal Cracking	Disk-Shaped Compact Tension Test	IA, MN, MO
Reflection Cracking	Texas Overlay Test	NJ, TX
	Illinois Flexibility Index Test	IL
	Semi-Circular Bend (SCB) Test	LA
Bottom-Up Fatigue Cracking	Flexural Bending Beam Fatigue Test	IA, NJ, PA
	Illinois Flexibility Index Test	IL
	SCB at Intermediate Temperature	LA
	Texas Overlay Test	TX
Top-Down Cracking	Illinois Flexibility Index Test	IL
	Semi-Circular Bend (SCB) Test	LA
Rutting	Asphalt Pavement Analyzer	AL, AK, AR, GA, ID, NC, NJ, OR, SC, SD, VA
	Flow Number	DE
	Hamburg Wheel Tracking Test	CA, IA, IL, LA, MA, ME, MT, TX, UT, WA
Moisture Susceptibility	Hamburg Wheel Tracking Test	IA, LA, MA, ME, TX, UT, WA
	Tensile Strength Ratio	All 50 states minus the ones with HWTT

In order to include any of these mixture performance tests in a BMD procedure, criteria should first be established with good correlations to the corresponding pavement distress in the field. Considerations must also be given to practical issues such as testing time, data analysis complexity, test variability, equipment availability and cost, and sensitivity to mix design parameters. In addition, DOTs may consider the intended asphalt mix application (e.g. asphalt overlay, high traffic mixture), climate, and/or recycled materials contents.

2.4.5 *State of the Practice for BMD*

Many DOTs are evaluating different cracking tests for integration into mixture design. The next sections summarize examples from different agencies related to BMD approaches.

California. The California Department of Transportation (Caltrans) has a pavement design framework that includes performance-based specifications and the CalME (Caltrans' Mechanistic Empirical Design Program) to perform a mix design. Performance testing consists of repeated shear (AASHTO T 320) bending beam fatigue test (AASHTO T 321) including frequency sweep testing, and HWTT (AASHTO T 324). A short-term conditioning protocol is used for repeated shear and HWTT. The procedure for developing the specification limits was developed by Tsai et al. (2012). Specification limits were selected based on the 95% confidence interval for the given property based on replicate tests. Caltrans accepts 95% of the risk of laboratory test variability. The performance-based specifications must be applied to plant-produced mix. To date, seven interstate projects have been built using this approach. Caltrans is focusing on using these mixtures on very high-volume pavements. Table 4 summarizes the current requirements for HWTT.

Table 4 California Requirements for Hamburg Test (Caltrans, 2015)

High Temperature Binder Grade	Minimum Passes to 0.5 inch Rut Depth	Minimum Passes at the Inflection Point
PG 58	10,000	10,000
PG 64	15,000	10,000
PG 70	20,000	12,500
PG 76 or higher	25,000	15,000

Georgia. The Georgia DOT has included rutting and moisture susceptibility testing as part of mix design approval for many years. The APA test is used as a standard part of the mix design approval and field-produced mix design verification of all asphalt mixtures. The agency method Georgia Development Test (GDT) GDT-115 is followed for determining rutting susceptibility using the APA. The APA criteria are presented in the laboratory Standard Operating Procedure 2 and allow an additional ± 0.1 inch (2 mm) of tolerance for field-produced mix design verification (Georgia DOT, 2014). The agency has different test temperatures based on the mixture location in the pavement structure. The ¾-in. (19 mm) and 1-in. (25 mm) Superpave mixes are tested at 120°F (49°C) and the ⅜-in. (9.5 mm) and ½-in. (12.5 mm) Superpave mixes are tested at 147°F (64°C).

Moisture susceptibility testing is of importance in Georgia because of the stripping potential of aggregates routinely used in asphalt mixtures. The Georgia DOT method GDT-66 is a variation of the tensile strength ratio (TSR) test that compares the diametral tensile strength of mixtures on conditioned and unconditioned specimens (Georgia DOT, 2011). Stripping of particles is visually rated as none, slight, moderate, and severe. The HWTT may also be conducted for special cases following the AASHTO T 324 standard.

Illinois. The Illinois DOT balanced mix design approach consists of integrating two laboratory performance tests with the volumetric mix design process (Al-Qadi et al., 2015), integrating the Hamburg wheel tracking with short-term conditioning and the I-FIT method to assess rutting and cracking potential. IDOT has Hamburg specification requirements for mix design, quality control, and quality assurance. The initial cracking thresholds have been proposed based on the results of I-FIT tests conducted for varying types of asphalt mixes and their correlation to field cracking performance. To meet the performance criteria, the asphalt binder content can be increased, the asphalt binder source can be changed, or quantities of recycled materials can be reduced. Final volumetric properties are required to meet the Superpave mixture design system.

Louisiana. The Louisiana Department of Transportation and Development (LADOTD) has proposed the use of conventional volumetric criteria with the HWTT to evaluate rutting resistance and the semi-circular bend (SCB) test to evaluate intermediate temperature cracking. Louisiana mixtures have historically shown good rutting resistance, so the balanced mixture designs commonly result in increased asphalt content. In a recent publication, the Louisiana Transportation Research Center (LTRC) is proposing performance-based specifications for permanent deformation and cracking (Mohammad et al., 2016). Table 5 shows the proposed performance test criteria.

Table 5 Proposed Performance Test Criteria (Mohammad et al., 2016)

Performance-Based Tests	Level 1 Traffic	Level 2 Traffic
LWT RD at 50°C, mm	≤10.0	≤6.0
SCB Jc at 25°C, kJ/m^2	≥0.5	≥0.6

Michigan. Williams (2004) used characterization of materials, performance testing of asphalt specimens, and statistical analysis to develop a performance-based specification for the Michigan DOT. The objectives of the study were to obtain and characterize asphalt field samples throughout Michigan, develop performance testing criteria, and ultimately, to develop field specifications for acceptance. The main reason for the study was to move forward in testing and acceptance procedures to facilitate the eventual implementation of performance-related specifications. The research divided Michigan into six different regions to address the various climatic properties and material availability. Testing was conducted on asphalt sampled from each of the six regions. The research primarily used the IDT, the Superpave shear tester, the beam fatigue test, the uniaxial strain test, and the Asphalt Pavement Analyzer (APA). With this information, the accuracy of empirical models used in the past and the effect that asphalt content and air voids have on long-term performance were determined.

Minnesota. The Minnesota Department of Transportation (MnDOT) is in the process of implementing a low-temperature cracking performance specification for asphalt mixtures. The specification utilizes the disc-shaped compact tension (DCT) test (ASTM D7313) with fracture energy as performance criteria. A pilot implementation began in 2013 with five construction projects in Minnesota (Johanneck et al., 2015). The pilot projects required the mix design specimens to be tested as part of mix approval and verification testing conducted on production mix samples. The pilot study helped identify some challenges to full-scale implementation as well as recognize differences in DCT fracture energy results between laboratory-prepared mix design samples and plant-produced mix. Further research is underway to modify and finalize the DCT performance specifications. This study also confirmed traditional viewpoints on asphalt mix design such as increasing binder contents and/or the use of "colder" performance grade low-temperature binders to achieve higher fracture energies. Research is ongoing to further evaluate the effects of asphalt content, VMA, VFA, PG range, and percentage of recycled materials. Furthermore, the test sections with and without adjusted mixes from the pilot projects are being continually observed and their field cracking performance documented to establish relationships between DCT fracture energy and low-temperature cracking performance. Table 6 summarizes the recommended DCT fracture energy criteria for low, medium, and high traffic pavements. These criteria were determined through a national pooled fund study on low temperature cracking in asphalt pavements (Marasteanu et al., 2012).

Table 6 Recommended DCT Fracture Energy (G_f) Criteria (Marasteanu et al., 2012)

Criteria	Project Criticality/Traffic Level		
	High >30M ESALs	Moderate 10-30M ESALs	Low <10M ESALs
Fracture Energy, minimum (J/m^2), Low PG +10°C	690	460	400

Abbreviation: ESALs, equivalent single axle loads

New Jersey. The New Jersey DOT (NJDOT) established a mix design and acceptance program that contractors are required to follow for performance-based asphalt mixtures (Bennert et al., 2014). For this program, contractors perform a volumetric mix design using the proposed materials and mixture design specifications. Materials are then submitted to the NJDOT to prepare specimens for performance testing including the APA, the Overlay Test (OT), and bending beam fatigue (BBF) test. If the test results meet the specified criteria, the contractor is allowed to produce the mixture; otherwise, the mixture must be redesigned. Possible mix design adjustments include the incorporation of warm mix asphalt technology, rejuvenators, and polymers. During project construction, mixtures are sampled for performance testing to ensure that their properties meet required specifications. The NJDOT has been using this performance-based mixture design and acceptance program on several types of their asphalt mixtures. Table 7 presents the APA and OT criteria that must be met for high RAP mixtures. NJDOT also has performance testing requirements for testing in the APA and BBF for some specialized mixtures that include bottom rich base course (BRBC) and bridge deck water-proofing surface course (BDWSC). The performance requirements for these mixtures are summarized in Table 8.

Table 7 NJDOT Performance Testing Requirements and Test Methods for Design of High RAP Mixtures (NJDOT, 2007)

Test	Requirement			
	Surface Course		Intermediate Course	
	PG 64-22	PG 76-22	PG 64-22	PG 76-22
APA at 8,000 cycles	< 7 mm	< 4 mm	< 7 mm	< 4 mm
OT	>150 cycles	>175 cycles	>100 cycles	>125 cycles

Table 8 NJDOT Performance Testing Requirements for Specialized Paving Mixtures

Test	Requirement	
	BRBC	BDWSC
APA	< 5 mm at 8,000 loading cycles	< 3 mm at 8,000 loading cycles
BBF	>100,000 cycles at 100 microstrains	>100,000 cycles

In addition, Rutgers University recently proposed a performance-based balanced mix design procedure for the NJDOT (Bennert and Pezeshki, 2015). Different from the approach described above, the proposed method sets the asphalt content at the midpoint between the maximum asphalt content to meet the APA test criteria and the minimum asphalt content to satisfy the OT criteria. The criteria for both tests were established based on the field performance of existing NJDOT projects and are sensitive to different traffic levels and pavement locations. In addition to performance testing, the volumetric properties of the designed mixture will also be measured to ensure they meet the specification criteria.

Texas. The BMD concept was originally developed in Texas and uses volumetric design with performance verification with the HWTT to evaluate rutting resistance and the OT to evaluate cracking resistance. Volumetric criteria are used to select the asphalt binder content. HWTT and OT tests are conducted at three asphalt contents: optimum, optimum +0.5%, and optimum +1.0%. Compaction is conducted at two levels: one for volumetric properties and one for performance testing. The optimum asphalt content is selected within a range of binder contents where both the rutting and cracking requirements are met. For most mixes, there is a range where both rutting and cracking requirements are met, but if a binder and aggregate combination fails to pass performance testing criteria, a new volumetric design is required. This concept is illustrated in Figure 5. Mixtures that fail to pass performance testing criteria require a new volumetric design with adjustments that may include asphalt content, binder source, or aggregate source. (Zhou et al., 2014).

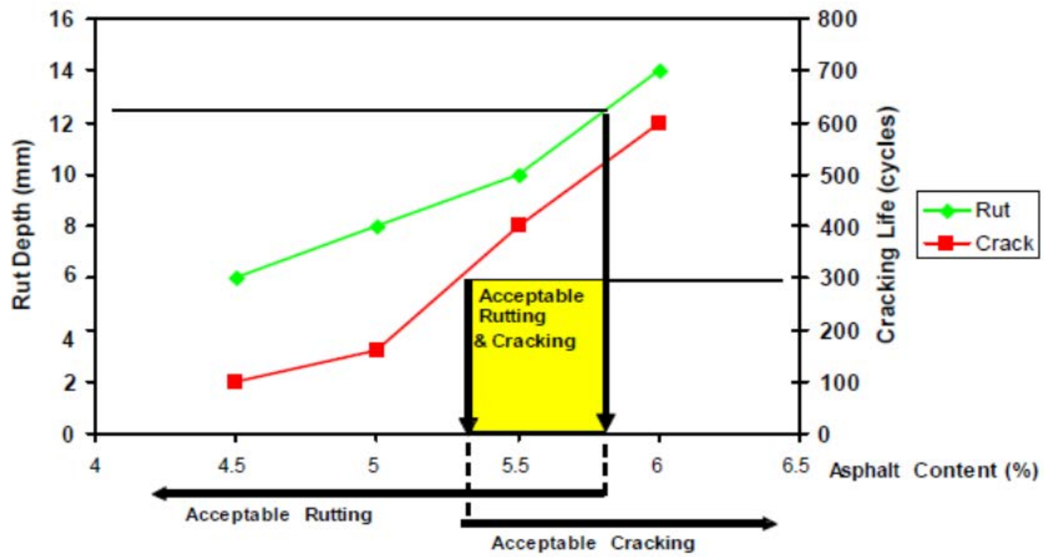


Figure 5 Balancing Rutting and Cracking Requirements (Zhou et al., 2014)

TXDOT specifications currently include requirements for HWTT and OT for stone matrix asphalt (SMA) and permeable friction course (PFC) mixes. For dense graded mixes, they only have a HWTT requirement since their normal dense graded mixes have not performed well in the OT (McCarthy et al., 2016). Table 9 presents the HWTT requirements for dense graded mixes. Table 10 summarizes the HWTT and OT requirements for SMA and PFC mixes in Texas.

Table 9 Texas DOT HWTT Requirement for Dense Graded Mixes (Superpave Mixes, Items 340 and 341)

High Temperature Binder Grade	Minimum Number of Passes at 12.5 mm Rut Depth at 50°C
PG 64 or lower	10,000
PG 70	15,000
PG 76 or higher	20,000

Table 10 Texas DOT HWTT and OT requirements for SMA and PFC Mixes (Items 342 and 346)

Mixture	HWTT	OT, Number of Cycles
Fine PFC (PG 76)	10,000 min passes at 12.5 mm rut depth at 50°C	200 min
SMA	12.5 mm maximum rut depth at 20,000 passes at 50°C	200 min

Ohio. The Ohio DOT (ODOT) has incorporated APA testing for rutting in the design mix for heavy traffic Superpave mixes. For medium and lighter traffic projects, ODOT uses the Marshall mixture design method. The agency also uses the HWTT and TSR tests for evaluating moisture damage potential. The Polisher test is a friction test used to qualify the mix. It uses the British Pendulum Number (ASTM E303) and a degradation curve. ODOT is currently using these performance tests as part of its standard specification requirements for its heavy mixes. In addition, the agency incorporates APA and BBF test criteria in its specification for bridge deck waterproofing HMA, which is a highly polymer-modified impermeable asphalt surface course (Ohio DOT, 2013). Table 11 summarizes the recommended criteria for these mixes.

Table 11 JMF Criteria for ODOT HMA Surface Course for Bridge Decks (Ohio DOT, 2013)

JMF Criteria	Specification
Total modified binder, %, min.	7.25
Gyrations, N_{des}/N_{max}	50/75
Air voids, %	1.5
VMA, %, min.	15.5
APA rutting (4.0% air voids, 64°C), mm, max.	4
Flexural beam fatigue (4.0% air voids, 10Hz, 1500 microstrain), cycles, min.	100,000

Wisconsin. The Wisconsin DOT (WisDOT) formed a specification development team with the Wisconsin Asphalt Producers Association to pilot the use of performance tests for mixtures containing more than 25% recycled materials (Paye, 2014). For these pilot projects, WisDOT requires the use of HWTT for moisture and rutting, DCT test for low temperature cracking, SCB test for fatigue cracking, and PG grading of the recovered asphalt binder.

At the local level, the City of Janesville has incorporated additional performance criteria for mix design verification and acceptance based on these same tests (City of Janesville, 2017). According to their current specifications, asphalt mix designs must meet the performance requirements in Table 12 for the DCT (ASTM D7313), SCB (ASTM D8044, only 25 mm notch depth, air voids on cut specimen and using I-FIT software to analyze the data), and Hamburg (AASHTO T 324). DCT and Hamburg testing follow the WisDOT modified procedures, however, no additional aging of the DCT and SCB specimens is required. Additionally, an ongoing study by the University of Wisconsin-Madison is examining analysis and feasibility of performance-based testing specifications to include the HWTT, confined Flow Number, and the SCB test at intermediate and low temperatures (WHRP Project 0092-15-04).

Table 12 Performance-Based specification for City of Janesville

Test	5 LT	5 MT	3 LT
DCT (minimum Fracture Energy) Tested at -18°C	375 J/m^2	400 J/m^2	350 J/m^2
SCB-LSU (minimum Flexibility Index) Tested at 19°C	6.0	9.0	6.0
Hamburg Wheel (maximum rut depth and passes to stripping inflection point (SIP)) Tested at 45°C	<12.5 mm at 7,500	<12.5 mm at 11,250	<12.5 mm at 7,500

2.5 Summary of State of the Practice

The implementation of Superpave mix designs significantly improved the rutting resistance of asphalt pavements by specifying higher quality aggregates and a higher grade of asphalt binders. However, many agencies have growing concerns that some Superpave mixes are experiencing cracking and other durability related distresses due to low asphalt content. In response to these concerns, several agencies have successfully modified their mix design and acceptance requirements to increase the asphalt contents of their mixes. Some of these approaches include air voids regression, lowering design gyrations, and increased minimum VMA criteria. For some agencies, a combination of approaches is currently followed.

Along with these successful changes, there are also cases where agencies have made changes that were not successful at increasing the optimum asphalt content. Simply designing at lower gyration or lower air voids is not effective. If aggregate gradations were held constant, these methods could work. However, in a low-bid environment, the contractors are making changes to gradations and dust content in which asphalt mixtures remain at low optimum asphalt contents.

There are two minor risks with mixtures designed with higher asphalt contents or lower air voids. Even with the increased asphalt content, the mix may still not have adequate cracking resistance, or conversely, the added binder could make the mixture susceptible to rutting.

SHAs and the asphalt paving industry have come to realize that simply adjusting the air void target or other mix design modification may not be sufficient to optimize mix designs and ensure that they will perform as desired. As a result, several state agencies are moving toward a balanced mix design approach that uses performance tests to design mixes with a balance between rutting resistance and cracking resistance instead of relying solely on volumetric guidelines. The need for such an approach becomes even more critical with the increased use of different binder and mixture modifiers, additives, RAP, and RAS materials since asphalt mixtures containing those additives are likely to have different mechanical properties that cannot be assessed in the current volumetric mix design practices.

3. EXPERIMENTAL PLAN

With the support of the project oversight committee (POC) and information gathered from the literature review, the test plan originally presented in the project proposal was modified and finalized. The following information summarizes the materials and test procedures that the research team and POC agreed upon.

A total of six mixes designed for low, medium, and high traffic levels were identified with the support of Wisconsin contractors. Table 13 summarizes the mix designs containing aggregates commonly used in the different regions of Wisconsin and different percentages of recycled materials.

Table 13 Test Variables for Wisconsin Field Projects

Mix #	Aggregate Source	Traffic Level	Recycled Content
1	Muskego	Low (<2 M ESALs)	Standard RAP Level (<25%)
2	King's Bluff	Medium (2-8 M ESALs)	Standard RAP Level (<25%)
3	King's Bluff	High (≥ 8 M ESALs)	Standard RAP Level (<25%)
4	Muskego	Medium (2-8 M ESALs)	High RAP Level (>25%)
5	Cisler	Medium (2-8 M ESALs)	High RAP and RAS
6	Muskego	High (≥ 8 M ESALs)	RAP and RAS

The evaluation of each mixture included the following performance tests:

- Illinois Flexibility Index Test (I-FIT) - Illinois Test Procedure 405 (AASHTO TP 124)
    - Intermediate Temperature Load Related Cracking Resistance
- Disc-Shaped Compact Tension (DCT) - ASTM D7313
    - Low Temperature Cracking Resistance
- Hamburg Wheel Tracking Test (HWTT) - AASHTO T 324
    - Rutting and Moisture Resistance

The performance tests were conducted for each mix at asphalt contents corresponding to three air void contents (4.0, 3.5, and 3.0 percent) to assess effects of using the air voids regression approach.

3.1 Materials and Mix Designs

Table 14 shows the blend gradations, materials, and cold feed percentages from each project JMF, and Table 15 shows the mix design parameters and volumetric results for each project. Mix 1 was a 9.5 mm nominal maximum aggregate size (NMAS) mixture and the rest were 12.5 mm NMAS mixtures. All mixtures met the AASHTO Superpave volumetric criteria shown in Table 16. Per WisDOT specifications, low traffic corresponds to less than two million ESALs, medium traffic from two to eight million ESALs, and high traffic as more than eight million ESALs. Three of the mixes were designed for medium traffic, two for high traffic, and one for low traffic level. RAP percentages ranged from 15% for Mix 3 to 37% for Mix 5. Mixes 5 and 6 included 3% RAS.

Table 14 JMF Gradations and Material Blending

Sieve (in.)	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
1.0"	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	100.0	100.0	100.0	100.0	99.6	100.0
1/2"	100.0	95.0	94.3	98.1	94.0	97.8
3/8"	97.8	89.0	87.8	89.4	86.1	85.7
#4	69.8	71.9	71.9	76.3	69.9	61.2
#8	47.0	53.7	49.8	56.8	46.6	42.4
#16	34.7	41.4	34.2	40.6	35.5	28.0
#30	22.2	28.1	23.9	26.7	25.0	17.5
#50	11.0	16.2	16.0	12.7	13.4	9.0
#100	5.8	7.7	8.7	7.0	7.6	5.6
#200	4.6	4.0	4.2	5.5	5.2	4.4
Materials - % Blend						
	3/8" Chips - 25%	3/4" Clean – 19%	3/4" Clean – 23%	3/8" Chips - 12%	5/8x3/8 Bit Agg – 13%	5/8" Chips – 17%
	Natural Sand – 36%	3/8 Washed Chip – 7%	3/8 Washed Chip – 5%	Natural Sand – 28%	3/8x1/8 Washed Chips – 8%	3/8" Chips – 19%
	MFG'D Sand – 10%	3/8" Washed Man Sand – 27%	3/8" Washed Man Sand – 40%	MFG'D Sand – 23%	3/8 Bit Agg – 18%	Natural Sand – 10.5
	DEG – 1.0%	5/8" Screened Sand – 27%	1/8" Washed Man Sand – 10%	DEG – 1.0%	3/16 Washed Man Sand – 13%	MFG'D Sand – 34%
			5/8" Screened Sand – 7%		5/8 River Sand – 8%	DEG – 0.5%
	P&D RAP – 28%	Plant 86 RAP – 20%	Hauser St. RAP – 15%	P&D RAP – 36%	Plant 22 ¾" RAP – 37%	P&D RAP – 16%
					Plant 22 RAS – 3%	P&D RAS – 3%

Table 15 JMF Design Parameters

Mix Designation	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Compactive Effort	40 gyr	75 gy	100 gyr	75 gyr	75 gyr	100 gyr
NMAS (mm)	9.5	12.5	12.5	12.5	12.5	12.5
Traffic Level	Low	Medium	High	Medium	Medium	High
AC (%)	5.9	5.4	5.3	5.4	5.4	5.4
Virgin AC (%)	4.7	4.3	4.5	3.8	3.0	4.0
Virgin Binder Grade	PG 58-28	PG 58-28	PG 58-28	PG 58-34	PG 58-34	PG 58-34
Percent RAP	28	20	15	36	37	16
Percent RAS	0	0	0	0	3	3
RAP AC%	4.65	5.50	5.50	4.65	4.60	4.65
RAS AC%	0	0	0	0	23.60	21.00
RAP Binder Ratio	0.22	0.20	0.16	0.31	0.32	0.14
RAS Binder Ratio	0	0	0	0	0.13	0.12
Design V_a (%)	4.0	4.0	4.0	4.0	4.0	4.0
Blend G_{sb}	2.678	2.660	2.658	2.683	2.654	2.660
G_{mm} at Optimum	2.488	2.494	2.496	2.525	2.474	2.508
G_{se} at Optimum	2.730	2.714	2.713	2.756	2.692	2.732
VMA	16.1	14.9	14.6	14.5	15.4	14.4
VFA	75.2	73.2	72.6	72.4	74.0	72.2
P_{ba}	0.7	0.8	0.8	1.0	0.5	1.0
P_{be}	5.2	4.7	4.5	4.4	4.9	4.4
Dust Proportion	0.9	0.8	0.9	1.2	1.1	1.0
TSR%	85.1	82	85.9	86.6	77	93.4

Table 16 AASHTO Superpave Mix Design Requirements

Design ESALs (Million) for 20 Yr. Design Life	VMA, % Minimum NMAS, mm		VFA Range (%)	Dust to Binder Ratio
	12.5	9.5		
<0.3	14.0	15.0	70-80	0.6-1.2
0.3 to <3			65-78	
3 to <10			65-75	
10 to <30			65-75	
≥30			65-75	

Mixes 1, 4, and 6 were validated using the contractor blend percentages at the optimum asphalt contents. For each mix, three specimens were compacted at N_{des} for G_{mb} and two G_{mm} samples were prepared and tested. For each of these mixes, the G_{mb} and G_{mm} results were within the acceptable range of two results (multi-laboratory precision) compared to the respective JMF values. All three mixes were designed to 4.0% air voids, and all of the verifications had average air voids within 1.0% of the target. Based on these findings, the research team moved forward with these mixes using the JMF blend percentages for the main testing plan.

A similar methodology was employed for Mixes 2, 3, and 5. However, for these mixes, there were significant differences in G_{mb} and G_{mm} from the JMF values, with the average air voids for the validation of each mix falling outside the 4.0 ± 1.0 percent air voids range. Based on these results, the research team verified the gradations of the received aggregate materials along with the asphalt contents of the received RAP and RAS by centrifuge extraction. For each mixture, the blend percentages were adjusted to match, as closely as possible, the blend gradation to the JMF gradation. The RAP and RAS asphalt contents tested at NCAT were also used to calculate the percentage of virgin binder required for each mix to match the optimum asphalt content from the JMF. For each mix, N_{des} samples were produced at the JMF optimum asphalt content and either plus or minus 0.5% asphalt from the JMF optimum content (depending whether the original verification was high or low on air void content). The asphalt content to yield 4.0% air voids for each mix with the modified blend was calculated, and this asphalt content was used for the remainder of the testing plan. It is important to note that the G_{sb} values reported on the JMFs were used to calculate VMAs for the mix verification testing.

3.2 Performance Testing

This section provides a summary of the test procedures and methodologies used to analyze the test results.

3.2.1 *Illinois Flexibility Index Test (I-FIT)*

Illinois Flexibility Index Testing (I-FIT) was performed for this project using a Test Quip® I-FIT testing device. Semi-circular asphalt specimens were prepared to a target air void content of 7.0 ± 0.5 percent after trimming. A minimum of four replicates were prepared and tested for each mixture and design air voids level tested, though up to eight replicates were tested if available. Each specimen was trimmed from a larger 160 mm tall by 150 mm diameter gyratory specimen. Four replicates could be obtained per gyratory specimen. A notch was then trimmed into each specimen at a target depth of 15 mm and width of 1.5 mm along the center axis of the specimen. Figure 6 shows the IFIT test setup. The specimens were tested at target test temperature of 25.0 ± 0.5°C after being conditioned in an environmental chamber for two hours. Specimens were loaded monotonically at a rate of 50 mm/min until the load dropped below 0.1 kN after the peak was recorded. Both force and actuator displacement were recorded at a rate of 50 Hz by the system. An example of the raw data collected is shown in Figure 7.

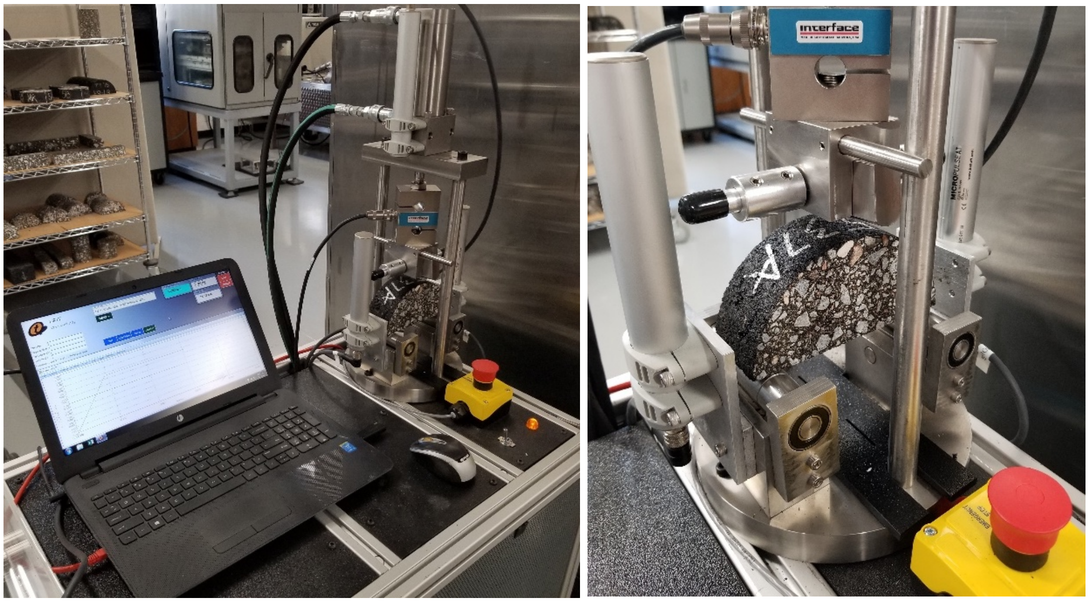


Figure 6 NCAT I-FIT Test Setup

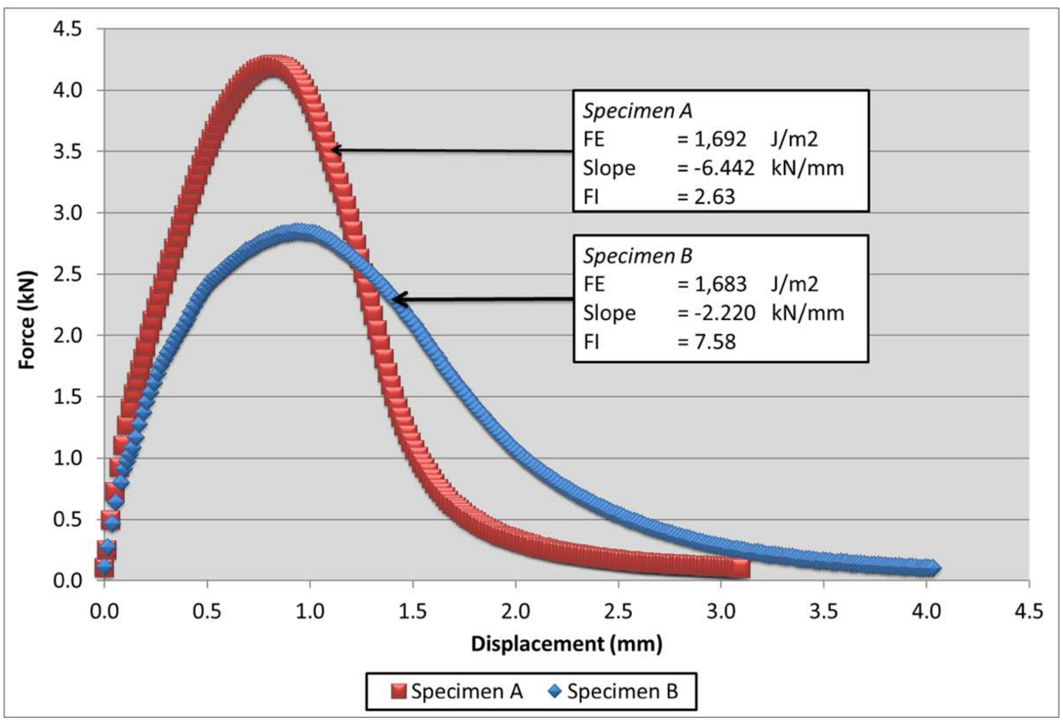


Figure 7 Example of Raw Data from I-FIT Test

The collected data were used to calculate two critical parameters for each tested specimen, the Fracture Energy (FE) and the Flexibility Index (FI). The Fracture Energy (Equation 1) represents the area under the load-displacement curve normalized for the specimen dimensions. It is calculated by integrating the area under the raw load-displacement curve and dividing it by the ligament area (the area of the semi-circular specimen through which the crack will propagate). To calculate the Flexibility Index (Equation 2), the slope of the post-peak portion of the curve must be determined. This is the slope of the load-displacement curve determined at the inflection point after the peak. The Flexibility Index is calculated by dividing the Fracture Energy by the post-peak slope and then multiplying that quotient by a scaling factor. A higher Flexibility Index is indicative of a mix exhibiting a more ductile failure while a lower Flexibility Index indicates a more brittle failure. Figure 7 compares two specimens with very similar Fracture Energies but different Flexibility Index values due to having different post-peak slope values. In this example, Specimen A has a steeper post-peak slope, and hence a lower FI, than Specimen B. Based on FI, Specimen A would be considered less resistant to cracking than Specimen B. Data analysis for this project was performed using software developed by TestQuip®.

$$G_f = \frac{w_f}{a_{lig}} \quad (1)$$

$$FI = \frac{G_f}{|m|} \, x \, A \quad (2)$$

Where:

- G_f = Fracture Energy (J/m^2);
- W_f = Work of Fracture (J);
- A_{lig} = Ligament Area (mm^2) = (Specimen Radius – Notch Length) x Specimen Width;
- FI = Flexibility Index;
- m = Post-Peak Slope (kN/mm); and
- A = Scaling Factor (0.01 for gyratory specimens).

The University of Illinois at Urbana-Champaign has conducted some lab to field comparisons between the FI and field cracking performance of asphalt mixtures (Al-Qadi et al., 2015). Comparison of FI results from loose mix samples and mixture performance at FHWA's accelerated loading facility (ALF) showed good agreement between the FI and load repetitions to failure of the accelerated sections. For the FHWA ALF, the three poor-performing sections had an FI of less than 2, whereas the control section (which was among the top performers) had an FI value of 10 (Al-Qadi et al., 2015). Additionally, some correlation was seen between the FI and cores obtained from nine different IDOT (Illinois DOT) districts. The FI clearly showed the effects of aging on these cores, with a clear reduction in FI for cores from pavements that were more than 10 years old. Sections with FI less than 4 to 5 on the field cores generally exhibited premature cracking (Al-Qadi et al., 2015). IDOT currently recommends a minimum design FI of 8 for AC surface mixes (Al-Qadi et al., 2017).

3.2.2 *Disk-Shaped Compact Tension (DCT)*

The Disk-Shaped Compact Tension (DCT) test assesses the low temperature fracture resistance of asphalt mixtures. This test is performed in accordance with ASTM D 7313-13. A minimum of four replicate specimens prepared to an air void content of 7.0 ± 1.0 percent were tested. The final DCT specimens are 50 ± 5 mm thick that have been cut from a larger gyratory sample initially compacted to 160 mm tall and 150 mm in diameter. The individual test specimens are then trimmed to meet the required dimensions in ASTM D 7313-13. The critical components are a flat edge on one side of the specimen for instrumentation gage points, a 62.5 ± 5.0 mm notch down the center of the specimen from the flat edge, and two 1-inch diameter holes on each side of the notch. A picture of a DCT specimen in the Materials Test System (MTS)® load frame used at NCAT is shown in Figure 6.

The recommended test temperature from ASTM D 7313-13 is the low PG grade of the binder plus 10°C. Since the virgin binders were a PG 58-28 and a PG 58-34, a test temperature of -18°C was selected for this study (-28°C plus 10°C). A single temperature was desired to effectively compare all of the mixtures under evaluation. DCT specimens are loaded in tension by metal rods that are inserted through the specimen core holes (see Figure 9). A clip gage is installed over the crack mouth prior to the start of the test to control and record the crack mouth opening displacement (CMOD). After the specimens are conditioned to the target test temperature, they are loaded into the DCT loading frame and the clip gage is installed. Initially, a seating load of 0.2 kN is applied to the specimen in tension. After the seating load is applied, the test is then performed in CMOD control with the clip gage opening at a constant rate of 0.017 mm/sec (0.00067 in/sec). Hence, each specimen is tested at a constant crack mouth opening rate. The test is performed until the load drops below 0.1 kN. An example of the load versus CMOD behavior is shown in Figure 7.

The material fracture energy (G_f) can be calculated using Equation 3 below. The area under the load vs. CMOD curve is determined through numerical integration using the trapezoid rule. The material fracture energy can then give an indication of the traffic level that the mixture should be able to withstand in the field. Table 6 (presented in previous section) summarizes the recommended DCT fracture energy threshold for low, medium, and high traffic pavements (Marasteanu et al., 2012).

$$G_f = \frac{AREA}{B*(W-a)} \quad (3)$$

Where:

G_f = Fracture Energy (J/m^2);
$AREA$ = Area under Load-CMOD curve;
B = Specimen Thickness (m); and
$W\text{-}a$ = Initial Ligament Length (m).

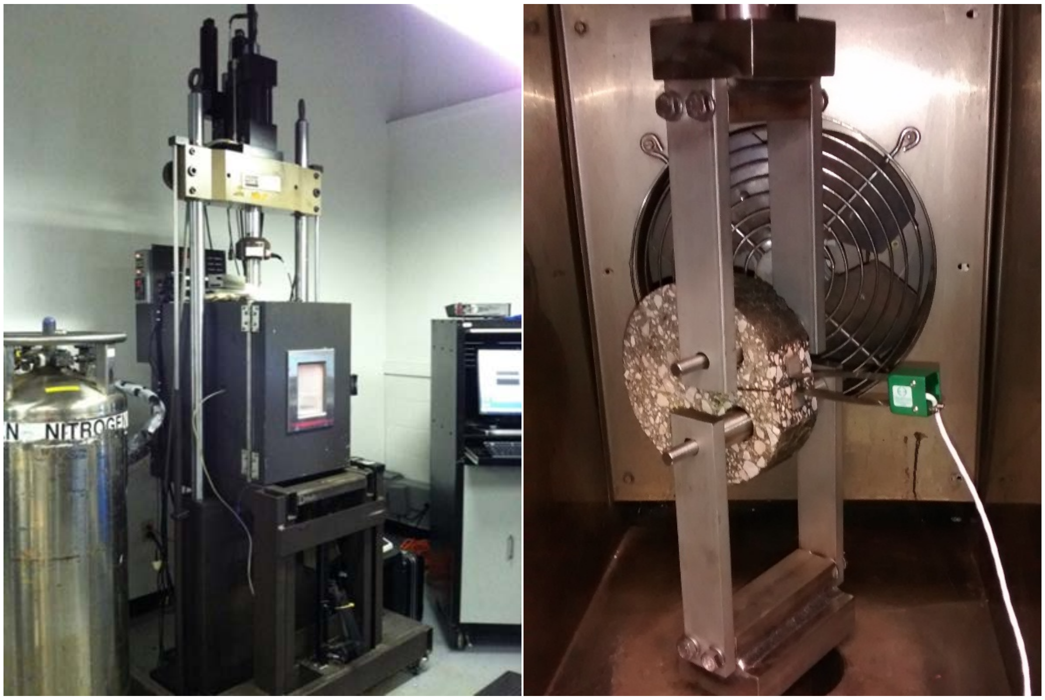


Figure 6 MTS® Load Frame at NCAT (left) and DCT Setup within MTS® (right)

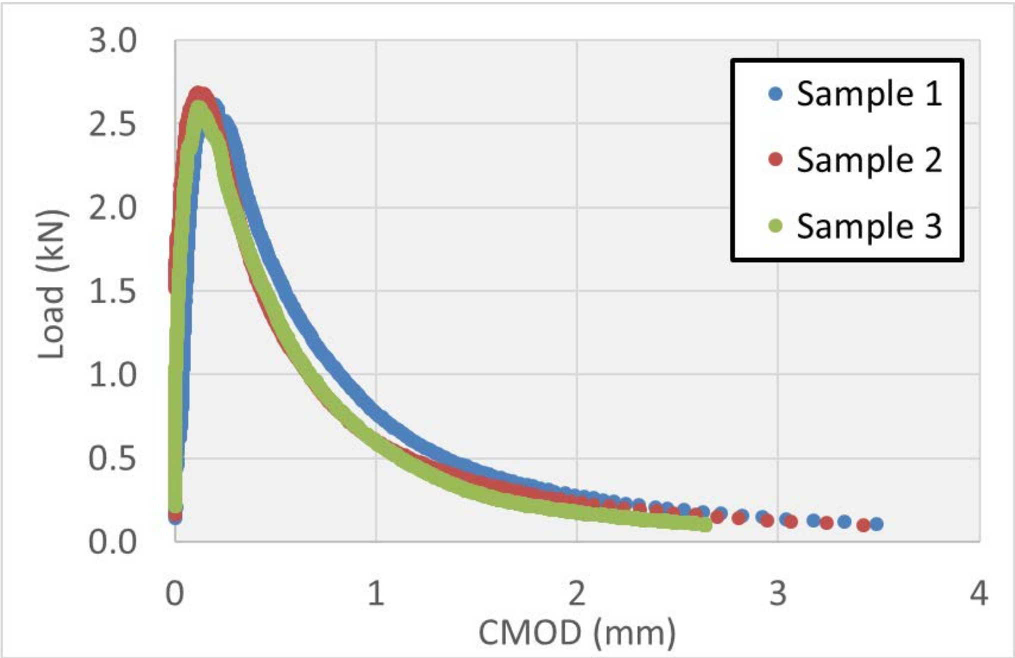


Figure 7 Example Load versus CMOD Data – DCT Test

3.2.3 *Hamburg Wheel-Tracking Test (HWTT)*

The Hamburg Wheel Tracking Device shown in Figure 8 was used to determine both the rutting and stripping susceptibility of the mixtures tested for this project. HWTT testing was performed in accordance with AASHTO T 324-16 with the exception that a lower test temperature of 46°C was used per the request of the POC. This was slightly different from the recommended HWTT test temperature of 45°C as recommended for Wisconsin by Bahia, et al (2016). Two replicates were tested per mix, with each replicate consisting of two trimmed specimens (four specimens total per mix). The specimens were originally compacted using an SGC to a diameter of 150 mm and a height of 60 mm. The specimen ends were then trimmed to fit in the Hamburg molds for testing. The target air voids on the Hamburg specimens was 7.0 ± 0.5 percent.

The specimens were tested under a 158 ± 1 pound wheel load for 10,000 cycles (20,000 passes) while submerged in a water bath maintained at a temperature of 46ºC. While being tested, rut depths were measured by an LVDT, which recorded the relative vertical position of the load wheel after each load cycle. After testing, these data were used to determine the point at which stripping occurred in the mixture under loading and the relative rutting susceptibility of those mixtures. Testing would be terminated early in the event of severe rutting (greater than 12.5 mm of rutting). Figure 9 illustrates a typical data output from the Hamburg device. These data show the progression of rut depth with number of cycles. Two tangents are evident from this curve: the steady-state rutting portion of the curve and the portion of the curve after stripping. The intersection of these two curve tangents defines the stripping inflection point of the mixture. The AASHTO defined stripping inflection point was calculated using a spreadsheet developed by the Iowa DOT (Iowa Department of Transportation, 2018). This spreadsheet was modified for compatibility with NCAT's Hamburg device.

A secondary method of Hamburg analysis was also employed for this study. This method was developed by Yin et al. (2014) to separate the data from the Hamburg curve into the steady-state (corrected) rut depth, as illustrated in Figure 10. This method isolates the rut depth due to permanent deformation within the mixture from that caused by the stripping of asphalt binders from the aggregates. As a result, the corrected rut depth proves a more accurate indication regarding the mixture resistance to rutting than the total rut depth. Note that the stripping number in this analysis represents the number of passes at which stripping occurs in the mixture and is determined as the inflection point of the rut depth curve. It is typically much lower than the AASHTO stripping inflection point.

Comparing the stripping inflection points and total rutting of the different mixtures gives a measure of the relative moisture and deformation susceptibility of these mixtures. A stripping inflection point of greater than 10,000 passes has been shown to be a good indicator of a moisture-resistant mix (Kvasnak et al., 2010). The Texas DOT uses the criteria in

Table 9 to evaluate the rutting resistance of their asphalt mixtures. These criteria specify the total allowable rut depth in the Hamburg test as a function of the mixture base binder grade. Several other states use variations of the Hamburg test and criteria as well (Mohamed et al., 2015).

Figure 8 Hamburg Wheel-Tracking Device

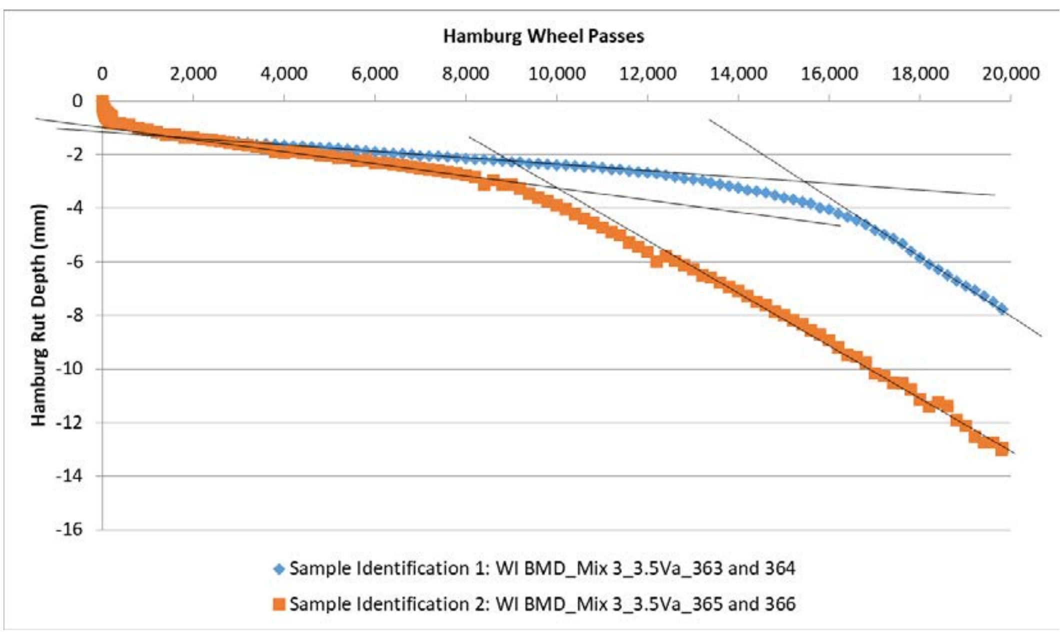


Figure 9 Example of Hamburg Raw Data

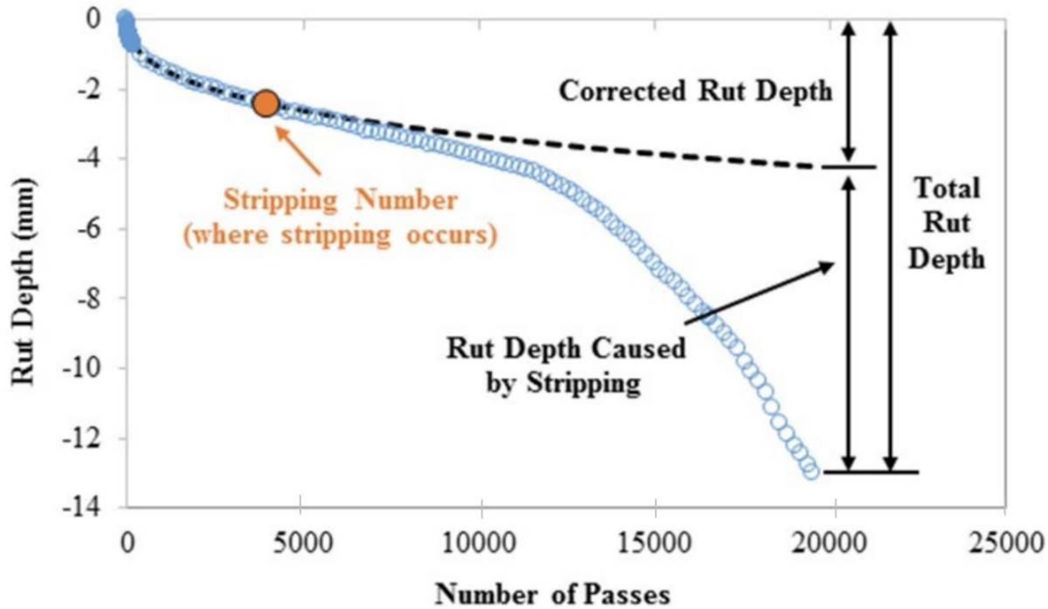


Figure 10 Example of Corrected Rut Depth Hamburg Analysis (Yin et al., 2014)

4. RESULTS AND ANALYSIS

The following sections present the results of the laboratory testing conducted at NCAT.

4.1 I-FIT Results and Analysis

A statistical summary of the I-FIT testing results is shown in Table 17. A database of the individual I-FIT replicate results is provided in Appendix A. Within a given mix and design air void content, the ASTM E178-16a procedure with a confidence level of 90% was used to identify FI values that were statistical outliers. For this study, 121 I-FIT replicates were tested and five were identified as outliers. These values are reported in Appendix A but were not included in the average values shown in this section. Of the 18 I-FIT sets tested in this study, the average FI coefficient of variation was 21.1%, which is consistent with values found in literature (Al-Qadi et al., 2015).

Figure 11 through Figure 13 show the average FI as a function of design air void content for the low, medium, and high design traffic levels. Except for Mix 3 at 3.0% air voids, regressing the air voids improved the average I-FIT FI values. Figure 14 shows a plot of the normalized FI (each mix normalized to its average FI at 4.0% design air voids) versus percent air void regression. The slope of this regression analysis is 0.73, indicating a 73% increase in the global average of FI with a 1% regression in design air voids.

Finally, a statistical analysis was conducted to determine whether the increase in FI values was statistically meaningful. An analysis if variance (ANOVA) with a Tukey's test for statistical groupings ($\alpha = 0.05$) was conducted on each of the six mixes (Montgomery, 1991). A summary of the statistical groupings from this analysis is presented in Table 18 while the complete ANOVA result is provided in Appendix A. This table shows that for four of the six mixes, air void regression statistically improved the I-FIT FI. Additionally, the set for each mix tested at 3.0% design air voids was always in the highest statistical grouping. Therefore, using the I-FIT FI and regressing the air voids of mixtures by 1.0% increased the design asphalt contents by 0.3-0.4% and had a significant and positive impact on the intermediate temperature cracking resistance of the mixtures in this study.

Table 17 Summary of I-FIT Flexibility Index Results

Mix ID	Design Air Voids (%)	Replicates	Air Voids (%)	Flexibility Index		
			Average	Avg.	Std. Dev.	CV (%)
Mix 1	4.0	6	7.3	8.0	1.49	18.8
	3.5	6	7.1	10.3	2.11	20.6
	3.0	5	7.3	12.2	1.49	12.2
Mix 2	4.0	6	7.0	6.0	1.63	27.2
	3.5	8	6.9	9.6	2.37	24.8
	3.0	7	7.1	13.0	2.49	19.2
Mix 3	4.0	8	6.9	4.5	1.26	27.7
	3.5	7	6.9	5.6	0.56	9.9
	3.0	7	6.9	5.7	0.92	16.2
Mix 4	4.0	4	7.4	6.1	1.31	21.5
	3.5	6	7.3	7.8	2.20	28.2
	3.0	6	7.2	13.0	2.90	22.4
Mix 5	4.0	8	7.0	4.5	1.42	31.5
	3.5	8	7.1	5.1	1.59	31.3
	3.0	8	6.9	6.5	1.74	26.7
Mix 6	4.0	7	6.8	5.2	0.52	9.9
	3.5	4	7.1	9.1	1.74	19.1
	3.0	5	6.8	9.8	1.24	12.6

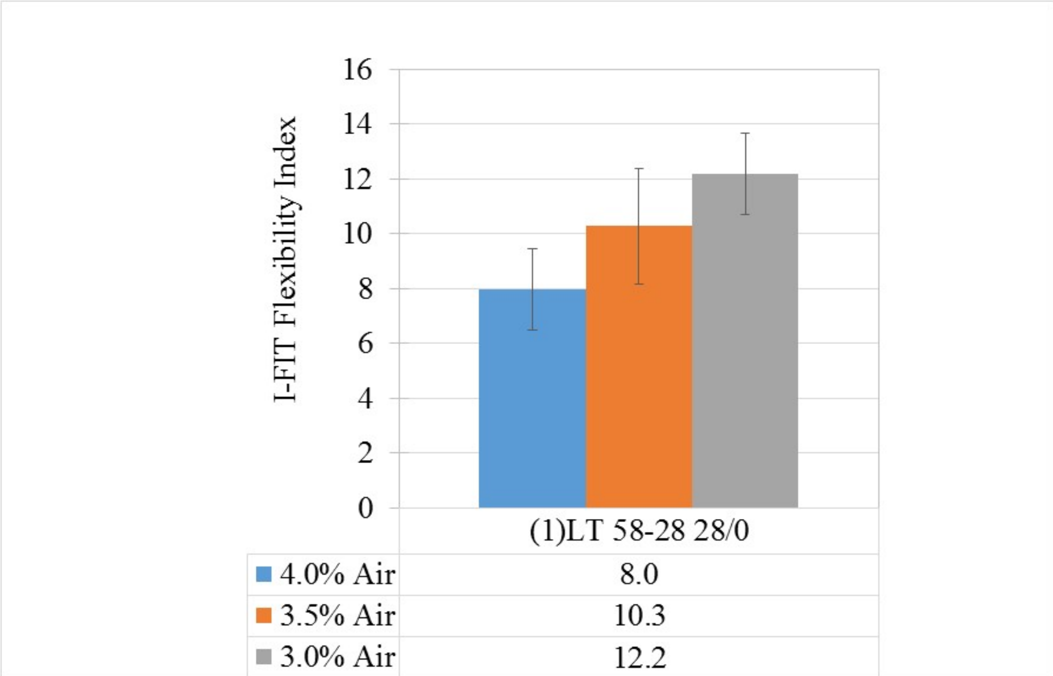
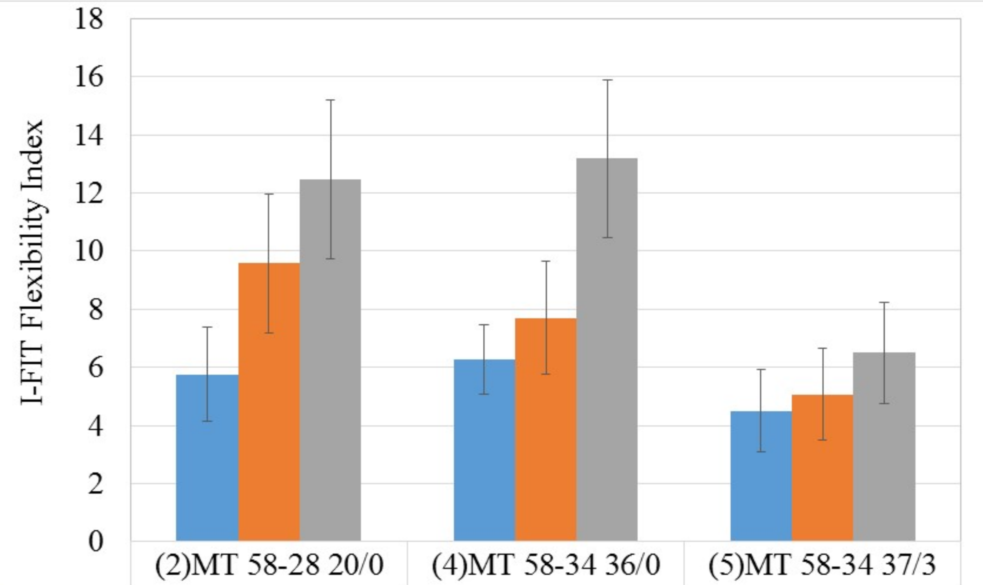
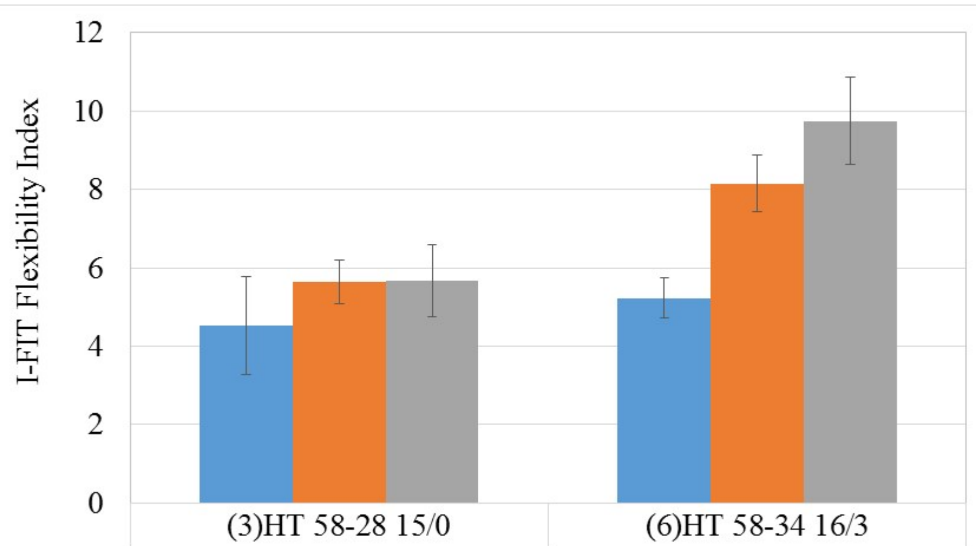


Figure 11 I-FIT Flexibility Index for Low Traffic Mixes



	(2)MT 58-28 20/0	(4)MT 58-34 36/0	(5)MT 58-34 37/3
4.0% Air	5.8	6.3	4.5
3.5% Air	9.6	7.7	5.1
3.0% Air	12.5	13.2	6.5

Figure 12 I-FIT Flexibility Index for Medium Traffic Mixes



	(3)HT 58-28 15/0	(6)HT 58-34 16/3
4.0% Air	4.5	5.2
3.5% Air	5.7	8.2
3.0% Air	5.7	9.7

Figure 13 I-FIT Flexibility Index for High Traffic Mixes

Table 18 Tukey's Test (α=0.05) Statistical Groupings for I-FIT FI, Within Mix

Mix ID	**Design Air Voids (%)**		
	4.0	*3.5*	*3.0*
Mix 1	B	A,B	A
Mix 2	C	B	A
Mix 3	A	A	A
Mix 4	B	B	A
Mix 5	A	A	A
Mix 6	B	A	A

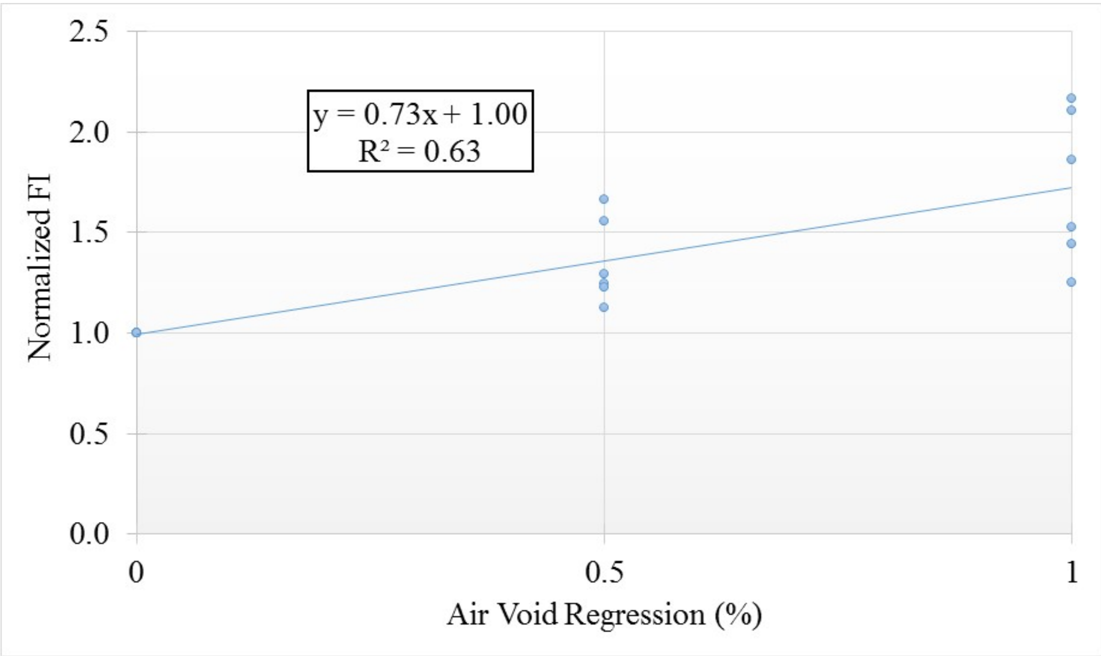


Figure 14 Normalized I-FIT Flexibility Index versus Regressed Air Void Level

4.2 DCT Test Results and Analysis

Table 19 shows a summary of the DCT Fracture Energy results for each combination of mixture and design air void content (18 unique sets). The individual replicate results are provided in Appendix B. ASTM E178-16a with a confidence level of 90% was used to identify statistical outliers for DCT Fracture Energy. Using this method, four outliers were identified out of 98 total specimens tested. These outliers are listed in Appendix B but are not included in the average values reported in this section. Post outlier removal, the average coefficient of variation for DCT Fracture Energy was 12.3 percent.

Figure 15 through Figure 17 show the DCT Fracture Energy as a function of air void regression for the low, medium, and high traffic mixes, respectively. Figure 18 shows a plot of normalized DCT Fracture Energy (normalized to the average Fracture Energy at the 4.0% design air void content for each mix) versus percent air void regression. The slope of this regression is 0.12, indicating that on average the DCT Fracture Energy of these mixtures increased 12% as the design air void content of these mixtures was regressed from 4.0 to 3.0 percent. This percent increase is significantly smaller than was seen for the I-FIT FI at the intermediate temperature of 25°C. However, it should be noted that this average 12% increase was enough to improve the average DCT Fracture Energy for four of the six mixes to above the common threshold value of 400 J/m^2.

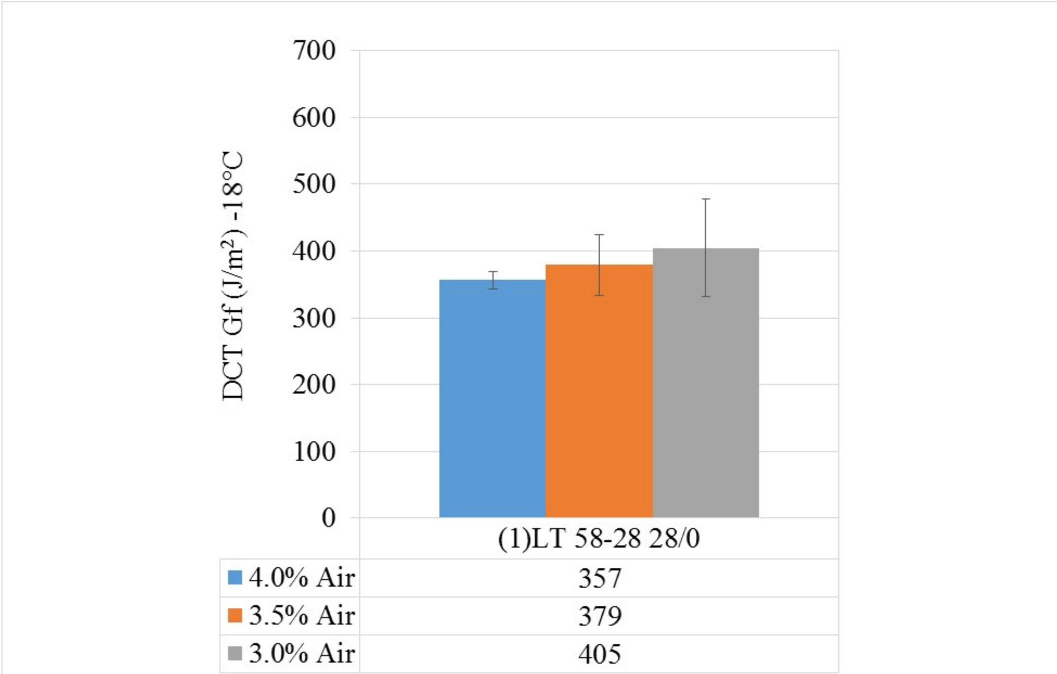
A statistical analysis was performed on each of the six unique mixes using an ANOVA (α = 0.05). For each of the six mixtures, regressing the air voids from 4.0 to 3.0 percent (and the corresponding 0.3-0.4 percent increase in total asphalt content) did not statistically improve the DCT Fracture Energy. A summary of the ANOVA p-values is shown in Table 20 with the complete ANOVA analysis for each mix provided in Appendix B.

Table 19 Summary of DCT Fracture Energy Results (-18°C)

Mix ID	Design Air Voids (%)	Replicates	Specimen Air Voids (%)	Fracture Energy, G_f (J/m^2)		
			Avg.	Avg.	St. Dev	CV (%)
Mix 1	4.0	5	7.4	357	12.9	3.6
	3.5	5	6.8	379	45.1	11.9
	3.0	6	7.0	405	72.8	18.0
Mix 2	4.0	6	7.5	366	54.3	14.8
	3.5	4	7.2	384	24.6	6.4
	3.0	4	7.1	425	97.7	23.0
Mix 3	4.0	6	7.1	387	42.2	10.9
	3.5	5	7.1	396	46.3	11.7
	3.0	5	7.0	437	77.0	17.6
Mix 4	4.0	6	7.1	368	49.4	13.4
	3.5	6	7.0	399	28.6	7.2
	3.0	6	7.3	432	81.9	19.0
Mix 5	4.0	4	7.1	566	24.4	4.3
	3.5	6	7.1	549	98.1	17.9
	3.0	5	7.1	605	16.2	2.7
Mix 6	4.0	6	7.2	500	103.6	20.7
	3.5	4	7.5	512	45.0	8.8
	3.0	5	7.3	534	47.2	8.8

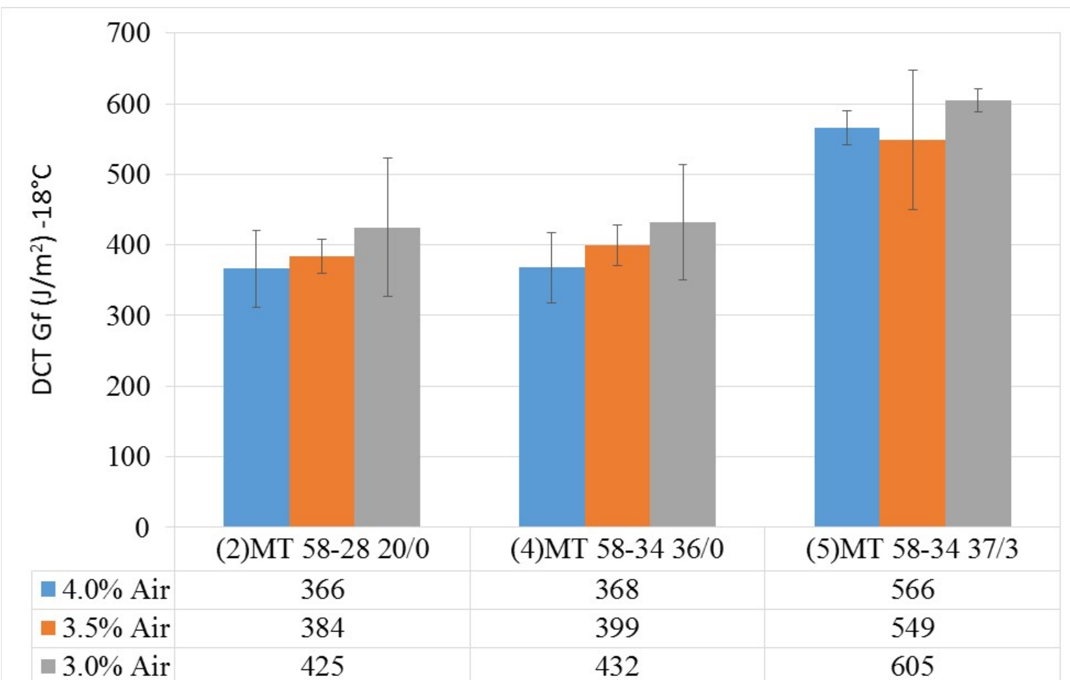
Table 20 ANOVA p-values (α = 0.05) for DCT Fracture Energy (-18°C)

Mix ID	ANOVA p-value
Mix 1	0.346
Mix 2	0.392
Mix 3	0.341
Mix 4	0.193
Mix 5	0.386
Mix 6	0.758



	(1)LT 58-28 28/0
4.0% Air	357
3.5% Air	379
3.0% Air	405

Figure 15 DCT Fracture Energy Results (-18°C) for Low Traffic Mix Designs



	(2)MT 58-28 20/0	(4)MT 58-34 36/0	(5)MT 58-34 37/3
4.0% Air	366	368	566
3.5% Air	384	399	549
3.0% Air	425	432	605

Figure 16 DCT Fracture Energy Results (-18°C) for Medium Traffic Mix Designs

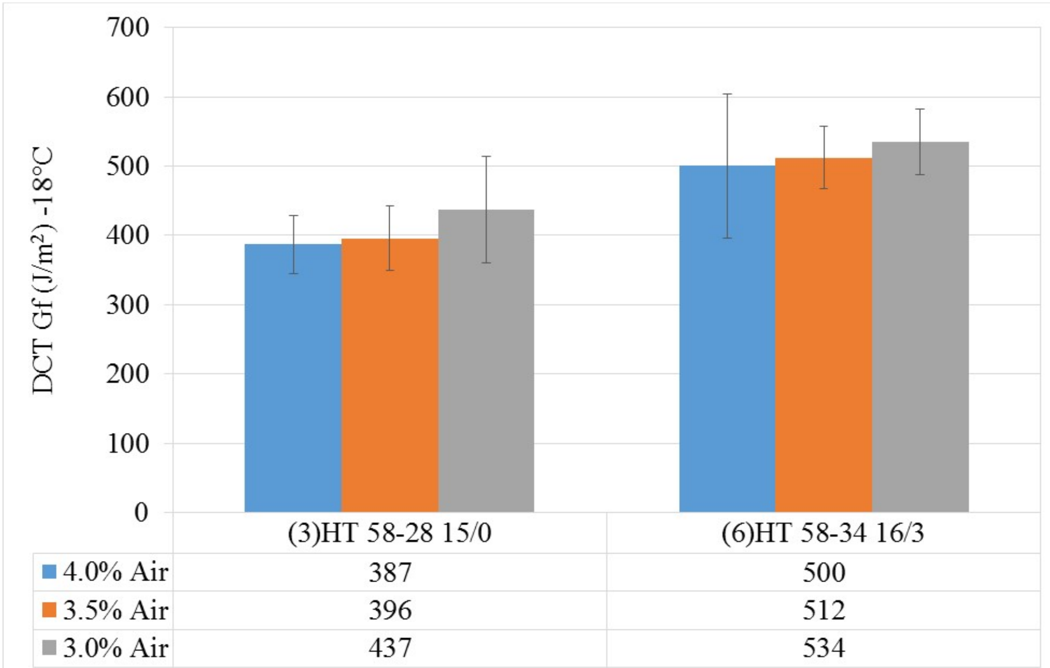


Figure 17 DCT Fracture Energy Results (-18°C) for High Traffic Mix Designs

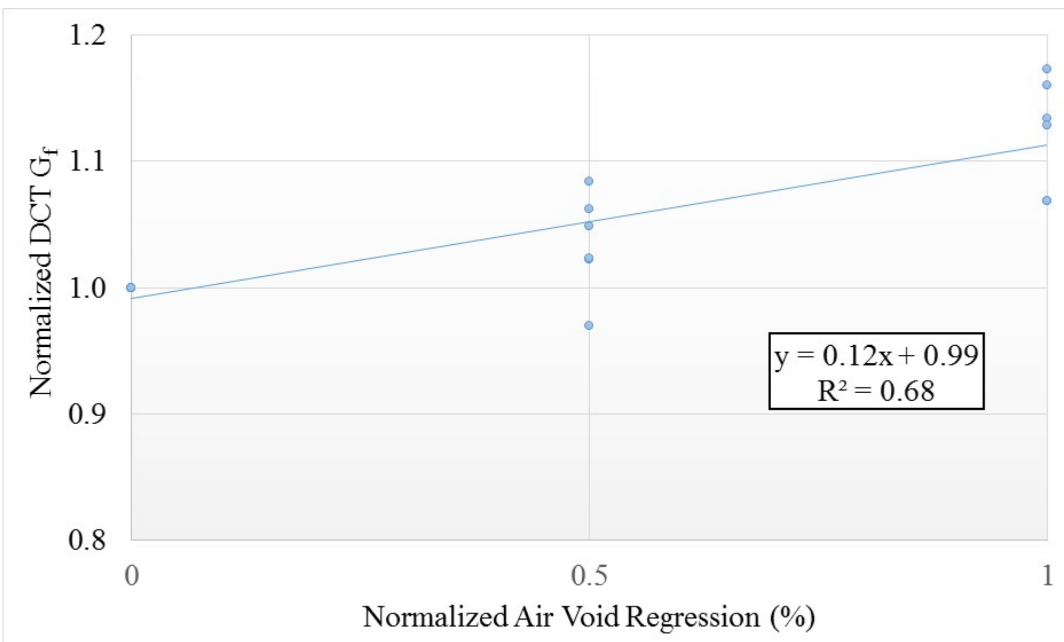


Figure 18 Normalized DCT Fracture Energy versus Air Void Regression

4.3 HWTT Results and Analysis

As mentioned previously, the Hamburg data was analyzed by two methods: the AASHTO method and the method proposed by Yin et al. (2014). Table 21 summarizes the rutting results from the Hamburg tests for each of the eighteen unique sets tested (six mix designs each at three design air void contents). This summary shows the average rut depth at 10,000 and 20,000 passes, the number of passes to a 12.5 mm rut depth threshold, and Creep Slope as calculated by the spreadsheet developed by the Iowa DOT (2018). For most of the six mixtures, rut depths at 10,000 passes and Creep Slopes increased slightly with lower design air void targets. However, the increases in rut depths very minor and none of the mixtures exceeded the common definition of failure (greater than 12.5 mm of rutting in the first 10,000 passes of the test) for mixtures with unmodified binders. The mixtures with the greatest amount of rutting were Mix 2 (Medium Traffic, PG 58-28, 20% RAP, 0% RAS) and Mix 3 (High Traffic, PG 58-28, 15% RAP, 0% RAS). These were the only two mixtures that had evidence of stripping in the HWTT. Table 22 summarizes the results from the Stripping Inflection Point (SIP) calculation using the Iowa DOT spreadsheet for these two mixtures. The only mix that had an SIP less than the common 10,000 pass threshold was Mix 3 at 3.0 percent design air voids. It should be noted that the predominant aggregate in Mix 2 and Mix 3 was from the same source (King's Bluff). The other four mixes that had no signs of stripping completed the full 20,000 passes with rut depths well below the 12.5 mm criterion. These results suggest the mixtures using aggregate from the King's Bluff source may benefit from the addition of an anti-stripping agent. However, additional testing would be needed to verify this assumption.

Table 23 shows the analysis of HWTT results using the method proposed by Yin et al. There are two key differences between the analysis presented in Table 21 and Table 23. First, the analysis in Table 23 evaluates only corrected rut depths, which excludes rutting caused by mixture stripping. Secondly, the Stripping Number (SN) in this table is calculated using a different methodology than the SIP and will be considerably lower than SIP for the same mixture. A benefit of this method of analysis of HWTT results is that it more clearly separates damage attributed to rutting and stripping. This is important because the fix for these two distress mechanisms is very different. Thus, from the results in Table 23, it can be seen that rutting results were satisfactory for all of the mixtures, and, as noted above, Mix 2 and Mix 3 were susceptible to moisture damage. A summary of all specimens that were tested along with the Hamburg data plots for each set is provided in Appendix C.

Table 21 Summary of Hamburg Rut Depths: AASHTO Method, 46°C, No Stripping Correction

Mix ID	Design Air Voids (%)	Average Rut Depth at 10,000 passes (mm)	Average Rut Depth at 20,000 passes (mm)	Passes to 12.5 mm Rut Depth	Creep Slope (Iowa Method) (mm/1000 passes)
Mix 1	4.0	3.3	5.2	>20,000	0.12
	3.5	3.7	6.7	>20,000	0.15
	3.0	3.9	6.8	>20,000	0.14
Mix 2	4.0	4.4	>12.5	17,800	0.21
	3.5	6.1	>12.5	14,600	0.26
	3.0	7.2	>12.5	13,100	0.37
Mix 3	4.0	2.4	10.5	>20,000	0.08
	3.5	3.1	>10.2	>19,500	0.09
	3.0	6.8	>12.5	13,700	0.17
Mix 4	4.0	2.1	3.3	>20,000	0.05
	3.5	2.8	3.9	>20,000	0.07
	3.0	2.4	3.6	>20,000	0.04
Mix 5	4.0	1.3	1.5	>20,000	0.02
	3.5	1.4	1.6	>20,000	0.02
	3.0	1.6	1.9	>20,000	0.03
Mix 6	4.0	2.3	2.7	>20,000	0.02
	3.5	2.0	2.6	>20,000	0.03
	3.0	1.9	2.6	>20,000	0.02

Table 22 Stripping Inflection Points Calculated using Iowa DOT Spreadsheet Method – Mixes 2 and 3

Hamburg Parameters	Mix 2			Mix 3		
	4.0% V_a	3.5% V_a	3.0% V_a	4.0% V_a	3.5% V_a	3.0% V_a
Stripping Slope (SS) (mm/1,000 passes)	1.63	1.81	2.46	1.43	1.18	1.74
SS/CS	7.9	7.0	6.7	18.7	12.8	10.5
SIP (passes)	12,877	10,578	10,208	13,879	13,254	8,027

Table 23 Summary of Hamburg Rut Depths: 46°C, Corrected Rut Depths Only (No Stripping Effects)

Mix ID	Design Air Voids (%)	Average Rut Depth at 10,000 passes (mm)	Average Rut Depth at 20,000 passes (mm)	Passes to 12.5 mm Rut Depth	Stripping Number (Yin et al.)
Mix 1	4.0	3.3	5.2	>20,000	>20,000
	3.5	3.7	6.7	>20,000	>20,000
	3.0	3.9	6.8	>20,000	>20,000
Mix 2	4.0	3.4	4.3	>20,000	3,227
	3.5	3.8	4.8	>20,000	2,637
	3.0	4.4	5.6	>20,000	2,572
Mix 3	4.0	2.3	2.8	>20,000	3,359
	3.5	2.3	2.8	>20,000	3,396
	3.0	2.8	3.4	>20,000	2,255
Mix 4	4.0	2.1	3.3	>20,000	>20,000
	3.5	2.8	3.9	>20,000	>20,000
	3.0	2.4	3.6	>20,000	>20,000
Mix 5	4.0	1.3	1.5	>20,000	>20,000
	3.5	1.4	1.6	>20,000	>20,000
	3.0	1.6	1.9	>20,000	>20,000
Mix 6	4.0	2.3	2.7	>20,000	>20,000
	3.5	2.0	2.6	>20,000	>20,000
	3.0	1.9	2.6	>20,000	>20,000

Figure 19, Figure 20, and Figure 21 show the corrected Hamburg rut depths (at 20,000 passes) at 4.0, 3.5, and 3.0 percent design air voids for the low, medium, and high traffic mixes, respectively. These corrected rut depths exclude damage attributed to stripping. It can be seen from Table 22 and from Figure 19 through Figure 21 that all of the corrected rut depths were significantly lower than the common failure threshold of 12.5 mm (6.8 mm was the maximum corrected rut depth observed for these mixtures).

Overall, regressing the design air voids from 4.0 percent to 3.0 percent for these six mixtures resulted in a 0.3 to 0.4% increase in asphalt content, but it did not cause a significant increase in the rutting susceptibility of these mixtures.

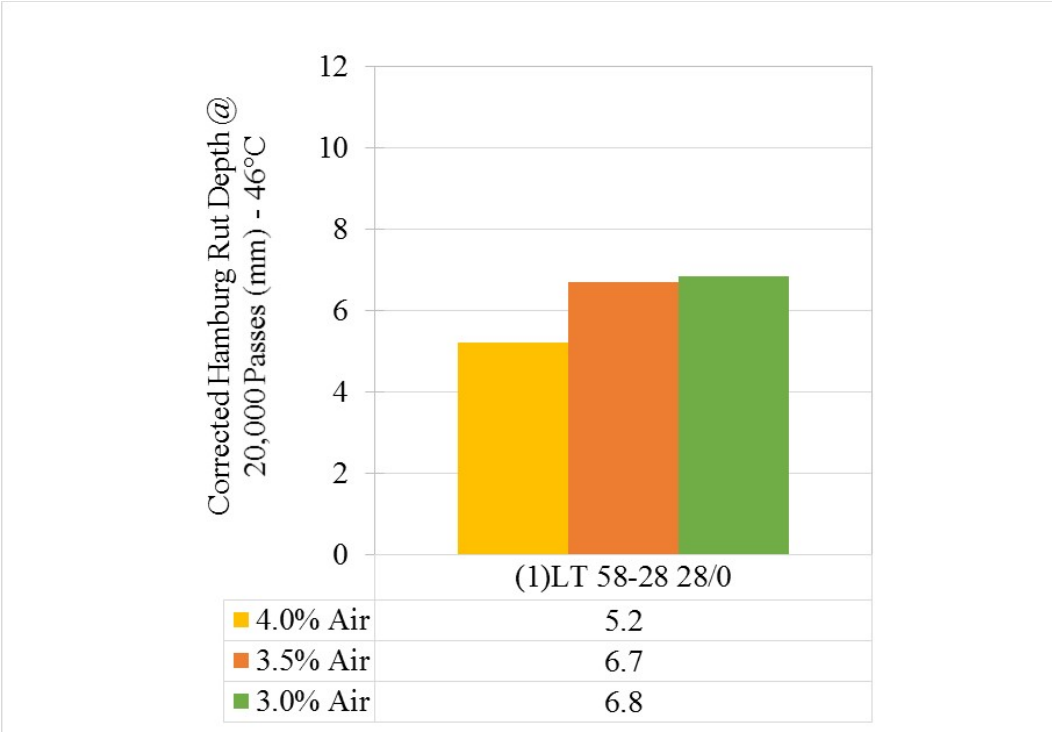


Figure 19 Corrected Hamburg Rut Depths (Excluding Stripping Effects) for Low Traffic Mixes at 46°C

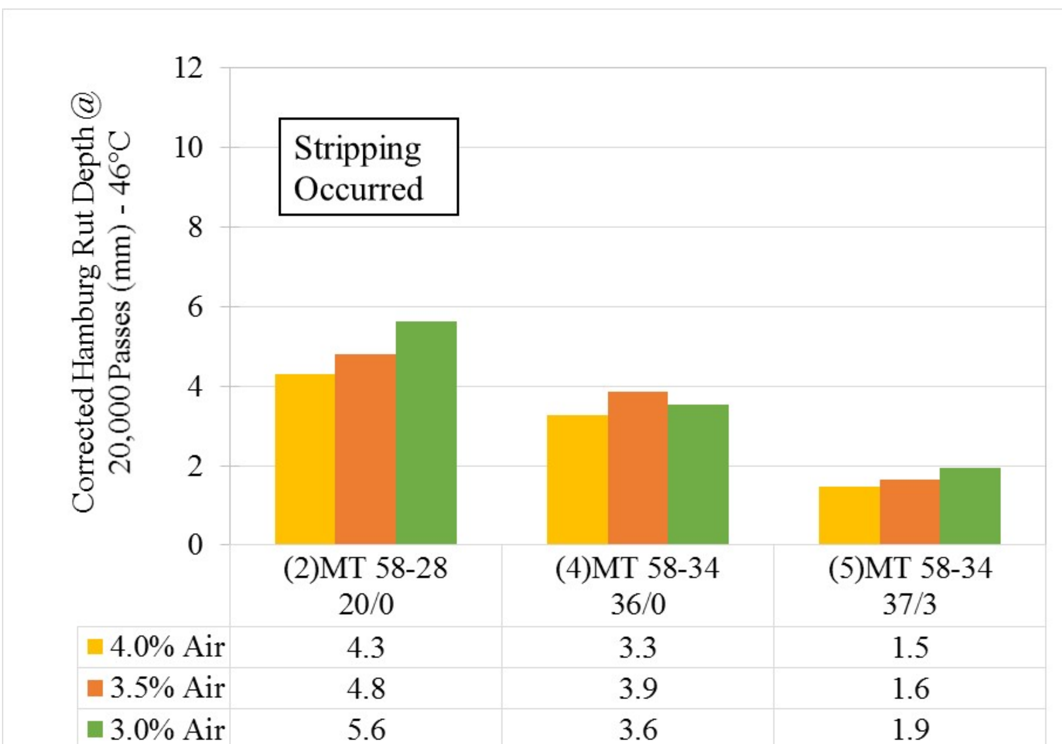


Figure 20 Corrected Hamburg Rut Depths (Excluding Stripping Effects) for Medium Traffic Mixes at 46°C

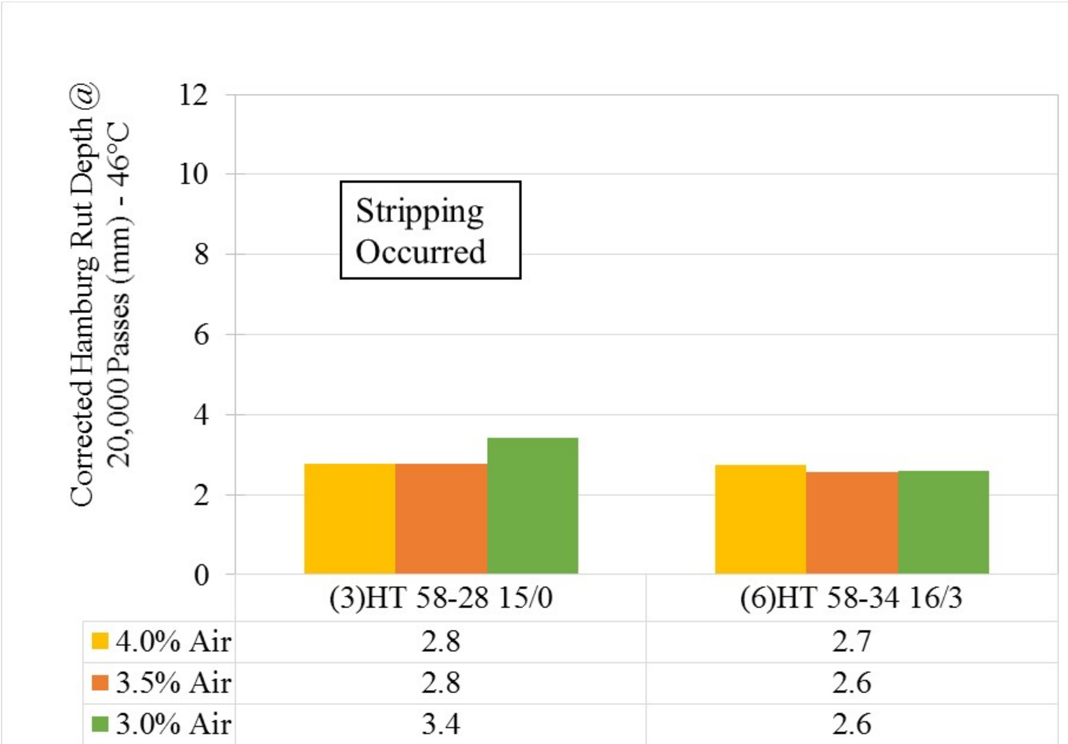


Figure 21 Corrected Hamburg Rut Depths (Excluding Stripping Effects) for High Traffic Mixes at 46°C

4.4 Performance Diagrams for Balance Mix Design

In a balanced mix design framework, a performance diagram can be a useful tool to examine the balance between the rutting and cracking susceptibility of an asphalt mixture. Using such a diagram, a cracking parameter is plotted against a rutting parameter to assess the interaction between the two as the asphalt content of the mix (or other mix variable) is changed. In this case, the I-FIT FI (an intermediate temperature cracking parameter) was plotted against the corrected rut depths from the Hamburg data analysis. Figure 22 through Figure 24 show these performance diagrams for the low, medium, and high traffic mixes, respectively. For the majority of the mixtures, the vertical change (increase in flexibility) on the diagrams is more than the horizontal change (increase in rut depths) as the asphalt content of the mixture is increased due to air void regression. One thing to note is that the data series appear to shift to the left (lower permanent deformation) as the traffic level of the mixtures is increased. Additionally, for the high traffic mixes (Figure 24), minimal additional rutting was observed for mixtures regressed to lower air void targets. This is likely because these mixes were designed to 100 gyrations and have very strong aggregate structures.

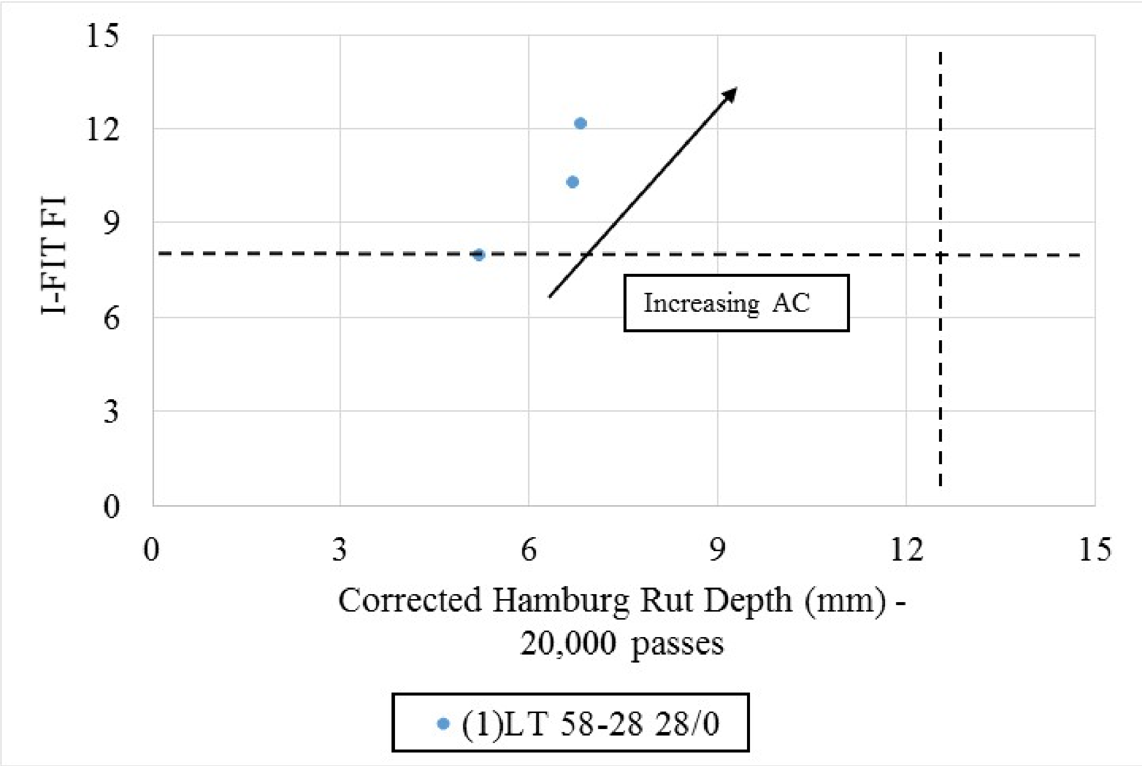


Figure 22 Performance Diagram of I-FIT FI versus Corrected Hamburg Rut Depth for Low Traffic Mixes

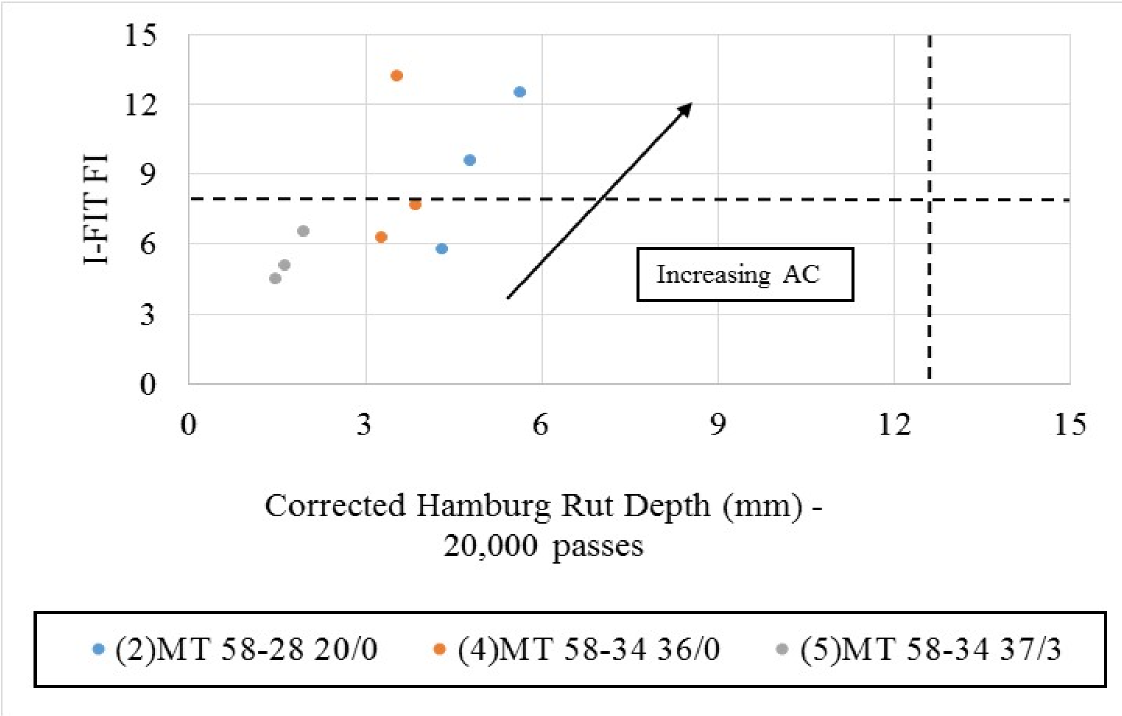


Figure 23 Performance Diagram of I-FIT FI versus Corrected Hamburg Rut Depth for Medium Traffic Mixes

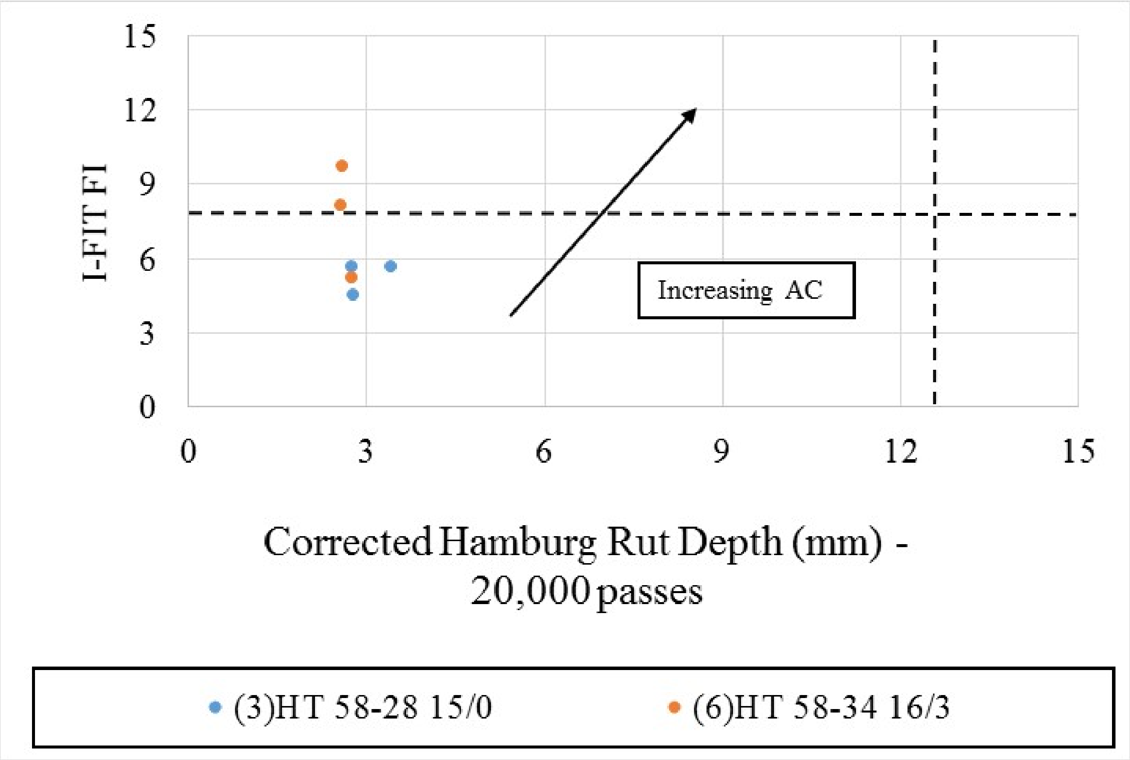


Figure 24 Performance Diagram of I-FIT FI versus Corrected Hamburg Rut Depth for High Traffic Mixes

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Project WHRP 0092-16-06 evaluated the impacts of the air void regression approach has on cracking, rutting, and moisture damage resistance of asphalt mixtures. A total of six mixtures were designed for different traffic levels (low, medium, and high) with various contents of RAP and RAS. Mixture performance tests included the Illinois Flexibility Index (I-FIT) per AASHTO TP 124 to evaluate intermediate temperature cracking resistance, the Disc-Shaped Compacted Tension (DCT) test per ASTM D 7313 for low-temperature cracking resistance, and the Hamburg Wheel Tracking Test (HWTT) per AASHTO T 324 for rutting and moisture damage resistance.

The results of this study are summarized as follows:

Asphalt Content

- Regressing the air voids of mixtures from 4.0 to 3.0 percent resulted in 0.3 to 0.4 percent higher design asphalt contents.

I-FIT Results

- Regressed air voids resulted in a clear improvement in the average I-FIT Flexibility Index values of all the mixes except Mix 3 (High Traffic, PG 58-28, 15% RAP, 0% RAS) at the 3.0% design air void content. Statistical analysis indicated that four of the six mixes regressed to 3.0 percent air voids had significantly higher FI results. Therefore, based on the I-FIT FI results, the regressed air voids approach to mix design will have a significant, positive impact on the cracking resistance of the mixtures.

- The average coefficient of variation of the 18 I-FIT sets tested in this study was 21.1%, which is consistent with values reported in the literature.

DCT Results

- Average DCT Fracture Energy results increased as design air void contents were regressed from 4.0 to 3.0 percent. However, the increases were much less than for the I-FIT results. A statistical analysis indicated that regressing the air voids from 4.0 to 3.0 percent did not statistically improve the DCT Fracture Energy results. Other studies have also shown that the DCT test is relatively insensitive to asphalt content.

- The average coefficient of variation for DCT Fracture Energy results was 12.3%.

HWTT Results

- HWTT tests were conducted at 46°C at the request of the POC. This was slightly different than the HWTT test temperature of 45°C recommended by Bahia et al (2016) for Wisconsin.

- For this study, HWTT results were analyzed using the AASHTO standard approach and a modified procedure suggested by Yin et al. The AASHTO approach defines the Stripping

Inflection Point as the intersection of the creep phase and the stripping phase. The Yin method uses a mathematical algorithm that separates rutting due to permanent deformation from damage caused by the stripping.

- Results analyzed using the current AASHTO approach indicated that Mix 2 (Medium Traffic, PG 58-28, 20% RAP, 0% RAS) and Mix 3 (High Traffic, PG 58-28, 15% RAP, 0% RAS) were susceptible to moisture damage. The other four mixes had no signs of stripping in the Hamburg test and completed the full 20,000 passes without exceeding the 12.5 mm criterion.
- All of the corrected rut depths results using the Yin procedure were well below the common Hamburg rutting threshold of 12.5 mm. Based on the results of this study, designing Wisconsin asphalt mixtures with the air voids regressed to 3.0 percent is not likely to cause any problems with increased rutting susceptibility.

5.2 Recommendations

Results from this project indicate that the regressed air voids approach can improve cracking resistance without compromising the deformation resistance of asphalt mixes. Therefore, a three stage implementation strategy is recommended as follows:

Stage 1. Full implementation of the regressed air voids approach to 3.0% air voids without performance tests. The following activities should also occur as part of this stage:

a. Notify contractors of future plans to implement the Hamburg, IFIT, and possibly the DCT test.

b. Conduct training on these performance tests.

c. Determine an appropriate aging protocol for the cracking tests for Wisconsin.

d. Gather additional laboratory performance data on WI mixtures.

e. Identify field performance issues.

f. Keep informed of other ongoing research studies that provide further guidance on other test methods, conditioning procedures, and criteria for possible use in specifications.

Stage 2. Add Hamburg rutting and stripping criteria based on three traffic levels. This could be accomplished by adding a new row in Table 460-2 Mixture Requirements to include the Hamburg test (AASHTO T 324) and criteria. During the implementation of Stage 2, the following activities should be considered:

a. Establish criteria for cracking tests based on based on information collected in Stage 1 and other research.

b. Set a strategy on how to implement performance tests as part of Quality Assurance.

Stage 3. Implement mixture performance tests for Balanced Mix Design and Quality Assurance and rescind the regressed air void design requirement.

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Appendix A. I-FIT Test Results

Table A1 Individual Specimen I-FIT Results

Mix ID	Specimen ID	Design Air Voids (%)	Specimen Air Voids (%)	Strength (kPa)	Slope	FE (J/m^2)	FI	ASTM E178 Outlier
Mix 1	128A	4.0	7.5	453.5	-2.40	2,011	8.38	
	128C	4.0	7.2	436.4	-2.98	1,949	6.55	
	130C	4.0	7.3	418.0	-2.08	2,086	10.03	
	130D	4.0	7.2	439.5	-2.32	2,133	9.19	
	140B	4.0	6.8	461.9	-2.59	1,891	7.29	
	140D	4.0	7.5	462.8	-3.43	2,163	6.31	
	132D	3.5	6.8	412.7	-2.25	2,109	9.38	
	133C	3.5	7.4	384.1	-2.40	1,821	7.58	
	133D	3.5	7.3	384.6	-1.68	2,117	12.59	
	134A	3.5	7.1	443.3	-2.45	2,290	9.36	
	134C	3.5	7.1	381.7	-1.66	2,171	13.06	
	134D	3.5	7.1	372.6	-1.94	1,884	9.69	
	135B	3.0	7.3	386.5	-1.89	2,204	11.69	
	135C	3.0	7.5	354.5	-1.51	2,029	13.44	
	136D	3.0	7.4	378.1	-2.00	1,968	9.82	
	137C	3.0	7.3	362.6	-1.00	2,531	25.19	X
	137D	3.0	7.3	351.7	-1.55	2,061	13.33	
	138B	3.0	6.9	422.2	-1.74	2,189	12.55	
Mix 2	227C	4.0	6.7	363.5	-1.90	1,534	8.06	
	230A	4.0	7.3	380.6	-3.07	1,482	4.82	
	232C	4.0	6.9	391.1	-3.22	1,436	4.47	
	232D	4.0	7.3	365.6	-2.32	1,447	6.24	
	227A	4.0	7.2	369.7	-2.08	1,622	7.81	
	227B	4.0	6.8	424.4	-3.20	1,465	4.58	
	228A	3.5	7.3	356.7	-2.47	1,573	6.36	
	228A	3.5	7.0	371.7	-2.07	1,775	8.57	
	233C	3.5	7.2	281.5	-1.21	1,539	12.70	
	233D	3.5	7.0	311.8	-1.38	1,623	11.73	
	234B	3.5	6.6	302.3	-1.32	1,564	11.84	
	234C	3.5	6.7	335.2	-1.77	1,771	10.01	
	235B	3.5	6.5	354.8	-2.30	1,592	6.92	
	235D	3.5	6.9	333.4	-2.00	1,680	8.41	
	229A	3.0	7.2	345.0	-1.91	1,845	9.65	
	236A	3.0	6.5	290.0	-1.51	1,553	10.25	
	236B	3.0	6.7	296.8	-1.27	1,751	13.83	
	236C	3.0	7.0	302.0	-1.24	1,686	13.55	
	236D	3.0	7.2	266.3	-1.02	1,628	15.90	

Mix ID	Specimen ID	Design Air Voids (%)	Specimen Air Voids (%)	Strength (kPa)	Slope	FE (J/m^2)	FI	ASTM E178 Outlier
	238C	3.0	7.4	255.1	-0.98	1,556	15.82	
	238D	3.0	7.4	260.1	-1.22	1,454	11.92	
Mix 3	336A	4.0	7.2	410.8	-3.75	1,153	3.08	
	336C	4.0	6.8	424.2	-3.51	1,252	3.56	
	337A	4.0	6.7	417.0	-3.83	1,200	3.14	
	337B	4.0	7.3	372.9	-2.90	1,364	4.70	
	337D	4.0	6.8	392.3	-3.04	1,354	4.46	
	338A	4.0	6.9	354.2	-2.69	1,292	4.81	
	338C	4.0	6.6	345.3	-2.21	1,388	6.28	
	338D	4.0	7.1	335.0	-1.95	1,216	6.23	
	351A	3.5	7.4	358.3	-2.42	1,341	5.55	
	351B	3.5	7.2	359.7	-2.17	1,355	6.25	
	351C	3.5	6.6	389.5	-2.42	1,383	5.70	
	352A	3.5	6.9	367.7	-2.29	1,395	6.10	
	352C	3.5	6.6	383.0	-2.80	1,391	4.97	
	352D	3.5	7.1	345.3	-1.79	1,492	8.34	X
	353A	3.5	7.4	320.3	-2.15	1,315	6.11	
	353D	3.5	6.5	333.5	-2.40	1,162	4.85	
	354A	3.0	7.1	332.2	-2.07	1,427	6.88	
	354C	3.0	7.0	327.7	-1.68	1,473	8.78	X
	355B	3.0	6.8	358.2	-2.33	1,510	6.48	
	355C	3.0	6.7	350.4	-3.09	1,248	4.04	
	355D	3.0	6.6	340.9	-2.33	1,237	5.32	
	356A	3.0	7.0	383.2	-2.72	1,527	5.60	
	356B	3.0	6.7	358.8	-2.39	1,291	5.41	
	356C	3.0	7.1	343.1	-2.39	1,419	5.94	
Mix 4	427A	4.0	7.5	453.9	-2.81	2,027	7.21	
	428A	4.0	7.5	449.1	-3.75	1,685	4.49	
	428B	4.0	7.5	441.4	-3.09	1,710	5.54	
	428C	4.0	7.5	370.3	-1.47	2,014	13.73	X
	428D	4.0	6.9	414.5	-2.60	1,842	7.09	
	430B	3.5	7.5	473.5	-2.54	2,167	8.53	
	430D	3.5	6.8	437.6	-4.34	1,752	4.04	
	431A	3.5	7.5	433.4	-2.97	1,892	6.36	
	431B	3.5	7.4	420.7	-2.17	2,086	9.59	
	432A	3.5	7.4	432.0	-2.14	2,083	9.73	
	432D	3.5	6.9	375.0	-1.94	1,660	8.54	
	433A	3.0	7.4	367.3	-1.33	2,189	16.50	
	433C	3.0	7.5	351.1	-1.49	2,015	13.56	
	434A	3.0	7.5	324.1	-1.41	1,931	13.68	

Mix ID	Specimen ID	Design Air Voids (%)	Specimen Air Voids (%)	Strength (kPa)	Slope	FE (J/m^2)	FI	ASTM E178 Outlier
	434C	3.0	6.7	354.0	-1.96	1,696	8.66	
	434D	3.0	7.3	352.9	-1.33	1,991	14.93	
	435A	3.0	7.0	386.7	-1.87	1,962	10.47	
Mix 5	527B	4.0	7.3	392.0	-2.29	1,312	5.73	
	527C	4.0	7.0	461.0	-3.52	1,580	4.48	
	528A	4.0	7.2	413.6	-2.84	1,396	4.91	
	528B	4.0	7.0	403.4	-2.33	1,653	7.08	
	529C	4.0	6.9	447.4	-3.85	1,488	3.86	
	529D	4.0	6.7	441.4	-3.88	1,420	3.66	
	530A	4.0	6.9	404.7	-3.72	1,483	3.99	
	530D	4.0	6.7	417.0	-5.55	1,326	2.39	
	531C	3.5	7.1	417.6	-2.73	1,567	5.74	
	531D	3.5	7.2	431.0	-2.43	1,760	7.23	
	532C	3.5	7.0	409.8	-2.79	1,687	6.05	
	532D	3.5	7.5	426.8	-2.84	1,737	6.11	
	533A	3.5	7.2	448.1	-4.44	1,388	3.13	
	533B	3.5	7.2	478.6	-6.20	1,555	2.51	
	534A	3.5	6.8	397.5	-2.87	1,366	4.75	
	534B	3.5	6.7	396.4	-2.80	1,403	5.02	
	535A	3.0	6.7	433.8	-2.62	1,666	6.36	
	535C	3.0	6.8	424.8	-3.34	1,643	4.92	
	536A	3.0	7.3	411.3	-2.43	1,707	7.02	
	536C	3.0	7.4	359.4	-1.77	1,609	9.10	
	536D	3.0	6.5	381.5	-3.52	1,540	4.38	
	537B	3.0	6.8	368.3	-1.93	1,677	8.67	
	538B	3.0	6.7	405.7	-2.93	1,457	4.97	
	538D	3.0	7.1	380.4	-2.39	1,579	6.61	
Mix 6	627A	4.0	6.7	410.7	-3.12	1,556	4.99	
	627C	4.0	6.7	448.3	-2.66	1,649	6.21	
	627D	4.0	6.9	443.9	-3.26	1,724	5.29	
	628A	4.0	6.8	444.8	-3.47	1,575	4.54	
	628B	4.0	6.9	450.1	-3.40	1,842	5.41	
	629C	4.0	7.0	448.4	-3.52	1,852	5.26	
	630B	4.0	6.8	426.1	-3.24	1,598	4.93	
	630C	4.0	7.1	418.0	-2.40	1,810	7.54	X
	631D	3.5	6.9	383.8	-2.38	1,774	7.44	
	632A	3.5	7.0	381.7	-2.15	1,868	8.69	
	632C	3.5	7.0	389.0	-1.63	1,885	11.56	
	633C	3.5	7.5	331.8	-1.70	1,495	8.78	
	634A	3.0	6.7	382.0	-2.20	1,772	8.05	

Mix ID	Specimen ID	Design Air Voids (%)	Specimen Air Voids (%)	Strength (kPa)	Slope	FE (J/m^2)	FI	ASTM E178 Outlier
	635A	3.0	6.6	375.9	-2.12	1,909	9.00	
	635D	3.0	7.1	323.6	-1.63	1,742	10.66	
	636A	3.0	7.0	337.2	-1.75	1,823	10.40	
	636B	3.0	6.6	378.4	-1.86	2,035	10.96	

Table A2 Summary of Statistical Analysis – I-FIT FI – from Minitab

One-way ANOVA: Mix 1

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	Mix 1 -3 Va, Mix 1 -3.5 Va, Mix 1 -4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	48.91	24.455	8.09	0.005
Error	14	42.34	3.024		
Total	16	91.25			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.73895	53.60%	46.98%	32.00%

Means

Mix ID	N	Mean	StDev	95% CI
Mix 1 -3 Va	5	12.166	1.488	(10.498, 13.834)
Mix 1 -3.5 Va	6	10.277	2.113	(8.754, 11.800)
Mix 1 -4Va	6	7.959	1.493	(6.436, 9.482)

Pooled StDev = 1.73895

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping	
Mix 1 -3 Va	5	12.166	A	
Mix 1 -3.5 Va	6	10.277	A	B

Mix 1 -4Va	6	7.959	B

Means that do not share a letter are significantly different.

One-way ANOVA: FI versus Mix 2 Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	Mix 2-3.5Va, Mix 2-3Va, Mix 2-4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	158.06	79.032	15.79	0.000
Error	18	90.07	5.004		
Total	20	248.13			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.23694	63.70%	59.67%	51.04%

Means

Mix ID	N	Mean	StDev	95% CI
Mix 2-3.5Va	8	9.569	2.374	(7.907, 11.230)
Mix 2-3Va	7	12.987	2.493	(11.211, 14.763)
Mix 2-4Va	6	5.997	1.633	(4.078, 7.915)

Pooled StDev = 2.23694

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping		
Mix 2-3Va	7	12.987	A		
Mix 2-3.5Va	8	9.569		B	
Mix 2-4Va	6	5.997			C

Means that do not share a letter are significantly different.

One-way ANOVA: FI versus Mix 3

Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	Mix 3-3.5Va, Mix 3-3Va, Mix 3-4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	6.442	3.2212	3.41	0.054
Error	19	17.966	0.9456		
Total	21	24.409			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.972414	26.39%	18.65%	2.31%

Means

Mix ID	N	Mean	StDev	95% CI
Mix 3-3.5Va	7	5.647	0.560	(4.878, 6.417)
Mix 3-3Va	7	5.667	0.915	(4.898, 6.436)
Mix 3-4Va	8	4.532	1.257	(3.813, 5.252)

Pooled StDev = 0.972414

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping
Mix 3-3Va	7	5.667	A
Mix 3-3.5Va	7	5.647	A
Mix 3-4Va	8	4.532	A

Means that do not share a letter are significantly different.

One-way ANOVA: FI versus Mix 4

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	Mix 4 -3.5Va, Mix 4 -3Va, Mix 4 -4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	135.60	67.801	12.35	0.001
Error	13	71.37	5.490		
Total	15	206.97			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.34300	65.52%	60.21%	49.51%

Means

Mix ID	N	Mean	StDev	95% CI
Mix 4 -3.5Va	6	7.798	2.202	(5.732, 9.865)
Mix 4 -3Va	6	12.97	2.90	(10.90, 15.03)
Mix 4 -4Va	4	6.082	1.306	(3.552, 8.613)

Pooled StDev = 2.34300

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping	
Mix 4 -3Va	6	12.97	A	
Mix 4 -3.5Va	6	7.798		B
Mix 4 -4Va	4	6.082		B

Means that do not share a letter are significantly different.

One-way ANOVA: FI versus Mix 5

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	Mix 5-3.5Va, Mix 5-3Va, Mix 5-4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value

Mix ID	2	16.94	8.470	3.36	0.054
Error	21	52.86	2.517		
Total	23	69.80			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.58661	24.27%	17.06%	1.09%

Means

Mix ID	N	Mean	StDev	95% CI
Mix 5-3.5Va	8	5.067	1.585	(3.900, 6.233)
Mix 5-3Va	8	6.506	1.736	(5.339, 7.672)
Mix 5-4Va	8	4.512	1.423	(3.346, 5.679)

Pooled StDev = 1.58661

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping
Mix 5-3Va	8	6.506	A
Mix 5-3.5Va	8	5.067	A
Mix 5-4Va	8	4.512	A

Means that do not share a letter are significantly different.

One-way ANOVA: FI versus Mix 6

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	$\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	Mix 6 -3.5Va, Mix 6 -3Va, Mix 6 -4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	72.94	36.469	28.12	0.000
Error	13	16.86	1.297		
Total	15	89.80			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)

1.13877	81.23%	78.34%	68.85%

Means

Mix ID	N	Mean	StDev	95% CI
Mix 6 -3.5Va	4	9.117	1.739	(7.887, 10.348)
Mix 6 -3Va	5	9.815	1.241	(8.715, 10.916)
Mix 6 -4Va	7	5.233	0.520	(4.303, 6.163)

Pooled StDev = 1.13877

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping	
Mix 6 -3Va	5	9.815	A	
Mix 6 -3.5Va	4	9.117	A	
Mix 6 -4Va	7	5.233		B

Means that do not share a letter are significantly different.

Appendix B. DCT Test Results

Table B1 Individual Results DCT Tests

Mix ID	Design Air Voids (%)	Sample ID	Air Voids (%)	Peak Load (kN)	Fracture Energy (G_f) (J/m^2)	ASTM E178 Outlier?
Mix 1	4.0	141B	7.4	2.85	344.7	
	4.0	142A	7.4	2.79	351.9	
	4.0	142B	7.1	3.09	351.3	
	4.0	143A	7.4	2.90	378.3	
	4.0	144A	7.2	2.85	299.6	X
	4.0	144B	7.5	3.17	357.8	
	3.5	160A	6.6	3.32	406.1	
	3.5	161A	6.6	3.07	337.6	
	3.5	162A	7.2	2.74	365.0	
	3.5	162B	6.9	2.79	444.0	
	3.5	163A	6.7	2.78	343.2	
	3.0	164A	6.9	2.81	342.1	
	3.0	164B	7.1	2.91	395.6	
	3.0	165A	7.0	2.96	487.0	
	3.0	166A	6.9	2.82	350.1	
	3.0	166B	7.3	2.56	349.5	
	3.0	167A	6.7	2.97	503.2	
Mix 2	4.0	239A	7.5	2.44	307.2	
	4.0	239B	7.6	2.61	397.8	
	4.0	240B	7.8	2.85	417.8	
	4.0	241A	7.4	2.71	354.7	
	4.0	242A	7.3	2.51	299.5	
	4.0	242B	7.6	2.73	421.0	
	3.5	243A	7.0	3.05	400.8	
	3.5	244B	7.4	2.76	349.3	
	3.5	245A	7.0	2.57	402.2	
	3.5	246A	7.3	2.82	511.8	X
	3.5	246B	7.2	2.67	384.4	
	3.0	248B	7.1	2.66	331.5	
	3.0	249A	6.9	2.44	560.8	
	3.0	249B	7.1	2.71	387.6	
	3.0	250A	7.1	2.68	420.6	
Mix 3	4.0	339A	7.2	3.38	424.3	
	4.0	339B	7.2	3.41	387.2	
	4.0	340A	6.9	3.24	321.4	
	4.0	341B	7.3	2.96	412.3	
	4.0	342A	7.0	3.30	424.3	

Mix ID	Design Air Voids (%)	Sample ID	Air Voids (%)	Peak Load (kN)	Fracture Energy (G_f) (J/m^2)	ASTM E178 Outlier?
	4.0	342B	7.1	3.41	352.6	
	3.5	343A	7.1	3.13	448.9	
	3.5	343B	7.2	2.91	332.0	
	3.5	344A	6.8	3.13	406.6	
	3.5	344B	7.3	3.35	422.9	
	3.5	345B	7.2	3.19	367.2	
	3.0	347B	7.0	2.94	425.0	
	3.0	348B	7.1	3.18	341.5	
	3.0	349A	6.8	3.52	551.1	
	3.0	349B	7.1	3.00	459.6	
	3.0	350A	6.9	2.91	406.2	
Mix 4	4.0	441A	6.9	3.28	337.2	
	4.0	442A	7.0	3.15	340.4	
	4.0	443A	7.5	3.27	406.7	
	4.0	443B	7.1	3.21	399.6	
	4.0	444A	7.2	3.46	425.2	
	4.0	444B	7.0	3.07	299.1	
	3.5	445B	6.7	3.20	412.0	
	3.5	446B	6.9	3.52	444.6	
	3.5	447A	7.0	3.47	409.7	
	3.5	447B	7.4	3.13	384.7	
	3.5	448A	6.9	3.07	376.1	
	3.5	448B	7.2	3.26	367.5	
	3.0	449A	7.3	3.31	432.8	
	3.0	449B	7.4	3.29	332.3	
	3.0	450A	7.3	3.36	566.6	
	3.0	450B	6.9	3.34	363.6	
	3.0	451A	7.1	2.96	460.1	
	3.0	451B	7.5	3.24	435.8	
Mix 5	4.0	539A	6.7	3.67	562.8	
	4.0	539B	7.4	3.67	597.5	
	4.0	540B	7.3	3.24	463.5	X
	4.0	542A	7.1	3.69	565.4	
	4.0	542B	7.1	3.39	537.9	
	3.5	543A	6.9	3.41	652.8	
	3.5	543B	7.3	3.28	424.6	
	3.5	544A	7.0	3.47	588.7	
	3.5	544B	7.3	3.45	606.4	
	3.5	545B	7.1	3.58	593.7	
	3.5	546A	7.0	3.05	426.5	

Mix ID	Design Air Voids (%)	Sample ID	Air Voids (%)	Peak Load (kN)	Fracture Energy (G_f) (J/m^2)	ASTM E178 Outlier?
	3.0	547A	7.1	3.60	628.6	
	3.0	547B	7.4	3.42	595.3	
	3.0	548A	6.7	3.26	522.1	X
	3.0	548B	7.4	3.42	613.9	
	3.0	549A	6.8	3.09	589.0	
	3.0	550A	7.0	3.62	597.0	
Mix 6	4.0	653A	6.5	3.75	552.4	
	4.0	654A	7.4	3.14	537.0	
	4.0	654B	7.2	3.57	419.0	
	4.0	655A	7.3	3.30	363.9	
	4.0	656A	7.4	3.39	474.7	
	4.0	656B	7.5	3.48	654.3	
	3.5	657A	7.6	3.05	473.8	
	3.5	658B	7.6	3.21	477.6	
	3.5	659A	7.3	3.55	568.7	
	3.5	660B	7.6	3.25	526.4	
	3.0	661A	7.0	3.45	561.6	
	3.0	661B	7.1	3.38	483.2	
	3.0	662A	7.0	3.41	487.9	
	3.0	662B	7.7	3.37	590.9	
	3.0	664B	7.7	3.34	548.6	

Table B2 Summary of ANOVA Results – DCT Fracture Energy (-18°C)

One-way ANOVA: Gf (J/m2) versus Mix 1

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	$\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	M1-3.5Va, M1-3Va, M1-4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	6268	3134	1.15	0.346
Error	13	35326	2717		
Total	15	41593			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
52.1282	15.07%	2.00%	0.00%

Means

Mix ID	N	Mean	StDev	95% CI
M1-3.5Va	5	379.2	45.1	(328.8, 429.5)
M1-3Va	6	404.6	72.8	(358.6, 450.5)
M1-4Va	5	356.81	12.89	(306.44, 407.17)

Pooled StDev = 52.1282

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping
M1-3Va	6	404.6	A
M1-3.5Va	5	379.2	A
M1-4Va	5	356.81	A

Means that do not share a letter are significantly different.

One-way ANOVA: Gf (J/m2) versus Mix 2

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	M2_3.5Va, M2_3Va, M2_4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	8386	4193	1.02	0.392
Error	11	45147	4104		
Total	13	53533			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
64.0645	15.67%	0.33%	0.00%

Means

Mix ID	N	Mean	StDev	95% CI
M2_3.5Va	4	384.2	24.6	(313.7, 454.7)
M2_3Va	4	425.1	97.7	(354.6, 495.6)

M2_4Va	6	366.3	54.3	(308.8, 423.9)

Pooled StDev = 64.0645

Tukey Pairwise Comparisons
Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping
M2_3Va	4	425.1	A
M2_3.5Va	4	384.2	A
M2_4Va	6	366.3	A

Means that do not share a letter are significantly different.

One-way ANOVA: Gf (J/m2) versus Mix 3

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	$\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	M3_3.5Va, M3_3Va, M3_4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	7410	3705	1.17	0.341
Error	13	41194	3169		
Total	15	48604			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
56.2917	15.25%	2.21%	0.00%

Means

Mix ID	N	Mean	StDev	95% CI
M3_3.5Va	5	395.5	46.3	(341.2, 449.9)
M3_3Va	5	436.7	77.0	(382.3, 491.1)
M3_4Va	6	387.0	42.2	(337.3, 436.6)

Pooled StDev = 56.2917

Tukey Pairwise Comparisons
Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping
M3_3Va	5	436.7	A
M3_3.5Va	5	395.5	A

M3_4Va	6	387.0	A

Means that do not share a letter are significantly different.

One-way ANOVA: Gf (J/m2) versus Mix 4

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	M4_3.5Va, M4_3Va, M4_4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	12218	6109	1.84	0.193
Error	15	49842	3323		
Total	17	62060			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
57.6438	19.69%	8.98%	0.00%

Means

Mix ID	N	Mean	StDev	95% CI
M4_3.5Va	6	399.1	28.6	(348.9, 449.3)
M4_3Va	6	431.8	81.9	(381.7, 482.0)
M4_4Va	6	368.0	49.4	(317.9, 418.2)

Pooled StDev = 57.6438

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping
M4_3Va	6	431.8	A
M4_3.5Va	6	399.1	A
M4_4Va	6	368.0	A

Means that do not share a letter are significantly different.

One-way ANOVA: Gf (J/m2) versus Mix 5

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	M5_3.5Va, M5_3Va, M5_4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	8750	4375	1.03	0.386
Error	12	50959	4247		
Total	14	59709			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
65.1656	14.66%	0.43%	0.00%

Means

Mix ID	N	Mean	StDev	95% CI
M5_3.5Va	6	548.8	98.1	(490.8, 606.8)
M5_3Va	5	604.79	16.17	(541.29, 668.28)
M5_4Va	4	565.9	24.4	(494.9, 636.9)

Pooled StDev = 65.1656

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping
M5_3Va	5	604.79	A
M5_4Va	4	565.9	A
M5_3.5Va	6	548.8	A

Means that do not share a letter are significantly different.

One-way ANOVA: Gf (J/m2) versus Mix 6

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	$\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Mix ID	3	M6_3.5Va, M6_3Va, M6_4Va

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mix ID	2	3245	1623	0.28	0.758
Error	12	68628	5719		

Total	14	71874

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
75.6243	4.52%	0.00%	0.00%

Means

Mix ID	N	Mean	StDev	95% CI
M6_3.5Va	4	511.6	45.0	(429.2, 594.0)
M6_3Va	5	534.4	47.2	(460.7, 608.1)
M6_4Va	6	500.2	103.6	(432.9, 567.5)

Pooled StDev = 75.6243

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Mix ID	N	Mean	Grouping
M6_3Va	5	534.4	A
M6_3.5Va	4	511.6	A
M6_4Va	6	500.2	A

Means that do not share a letter are significantly different.

Appendix C. HWTT Results

Table C1 Specimen Air Voids (%) – Hamburg Specimens

Mix ID	Design Air Voids (%)	Specimen ID	Replicate ID	Specimen Air Voids (%)
Mix 1	4.0	107	1	7.1
	4.0	108	1	6.7
	4.0	109	2	7.4
	4.0	110	2	7.1
	3.5	111	1	7.1
	3.5	112	1	6.8
	3.5	113	2	7.1
	3.5	114	2	6.8
	3.0	115	1	7.1
	3.0	116	1	7.0
	3.0	117	2	7.0
	3.0	118	2	7.3
Mix 2	4.0	219	1	7.0
	4.0	252	1	7.5
	4.0	253	2	7.4
	4.0	254	2	7.5
	3.5	220	1	7.0
	3.5	255	1	7.2
	3.5	257	2	7.1
	3.5	258	2	7.1
	3.0	259	1	6.9
	3.0	260	1	6.8
	3.0	261	2	7.1
	3.0	262	2	7.1
Mix 3	4.0	309	1	7.1
	4.0	310	1	6.9
	4.0	311	2	6.9
	4.0	312	2	6.7
	3.5	363	1	6.8
	3.5	364	1	6.9
	3.5	365	2	6.7
	3.5	366	2	6.8
	3.0	370	1	6.8
	3.0	371	1	6.7
	3.0	372	2	7.0
	3.0	373	2	7.0
Mix 4	4.0	407	1	7.2
	4.0	408	1	7.3
	4.0	409	2	7.2

Mix ID	Design Air Voids (%)	Specimen ID	Replicate ID	Specimen Air Voids (%)
	4.0	410	2	7.4
	3.5	411	1	7.0
	3.5	412	1	7.2
	3.5	413	2	7.2
	3.5	414	2	7.1
	3.0	415	1	7.0
	3.0	416	1	7.1
	3.0	417	2	7.0
	3.0	418	2	7.0
Mix 5	4.0	509	1	6.8
	4.0	510	1	6.9
	4.0	511	2	7.1
	4.0	512	2	7.4
	3.5	513	1	7.1
	3.5	514	1	7.0
	3.5	515	2	7.1
	3.5	516	2	6.6
	3.0	559	1	6.6
	3.0	560	1	6.6
	3.0	561	2	6.6
	3.0	562	2	6.9
Mix 6	4.0	607	1	6.7
	4.0	608	1	6.9
	4.0	609	2	6.8
	4.0	610	2	6.9
	3.5	611	1	7.1
	3.5	612	1	7.4
	3.5	613	2	7.4
	3.5	614	2	7.4
	3.0	615	1	7.1
	3.0	616	1	7.2
	3.0	617	2	7.2
	3.0	618	2	7.0

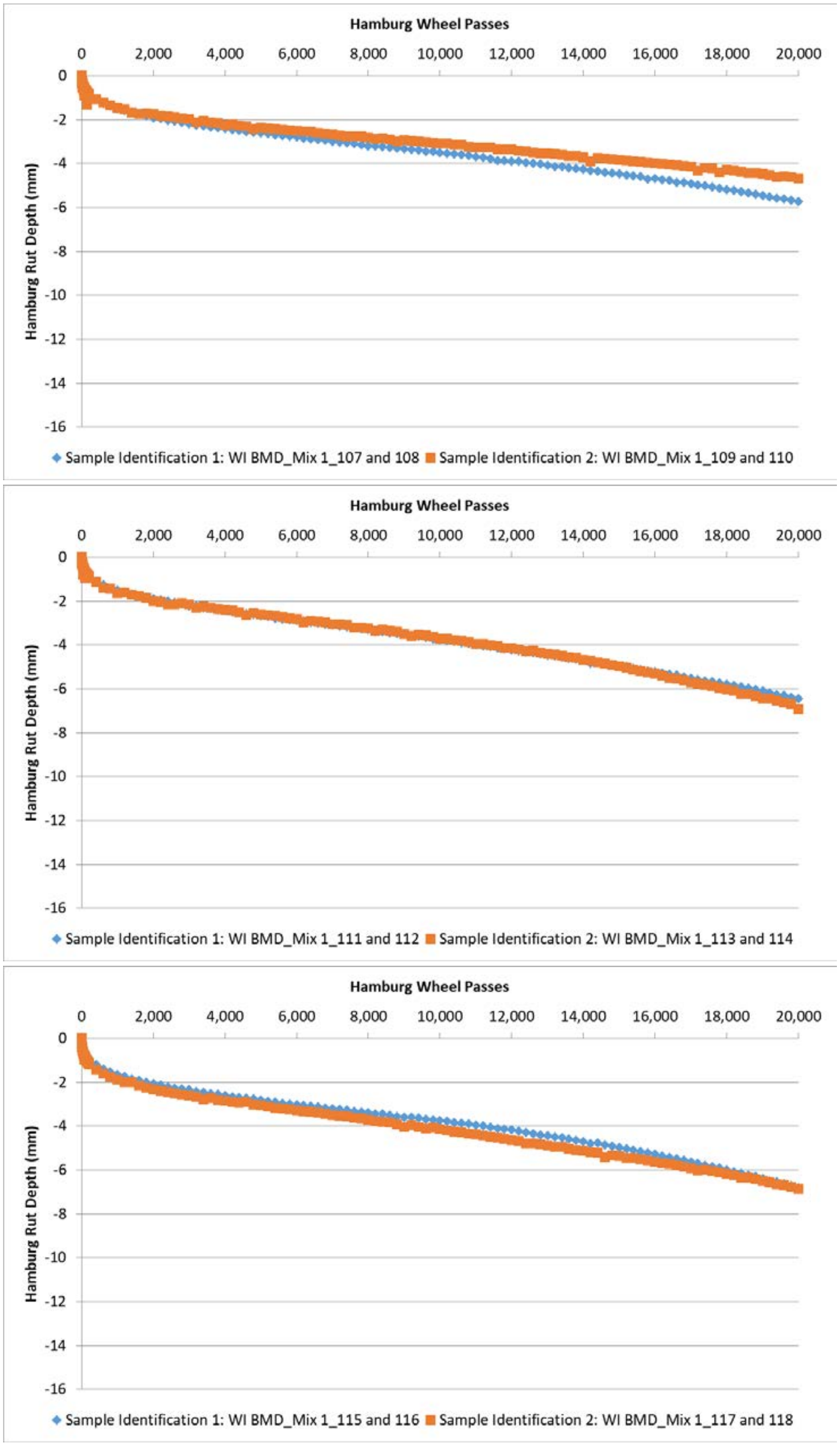

Figure C1 Hamburg Rut Depth versus Number of Cycles – Mix 1
(4.0% Design Air, Top – 3.5% Design Air, Middle – 3.0% Design Air, Bottom)

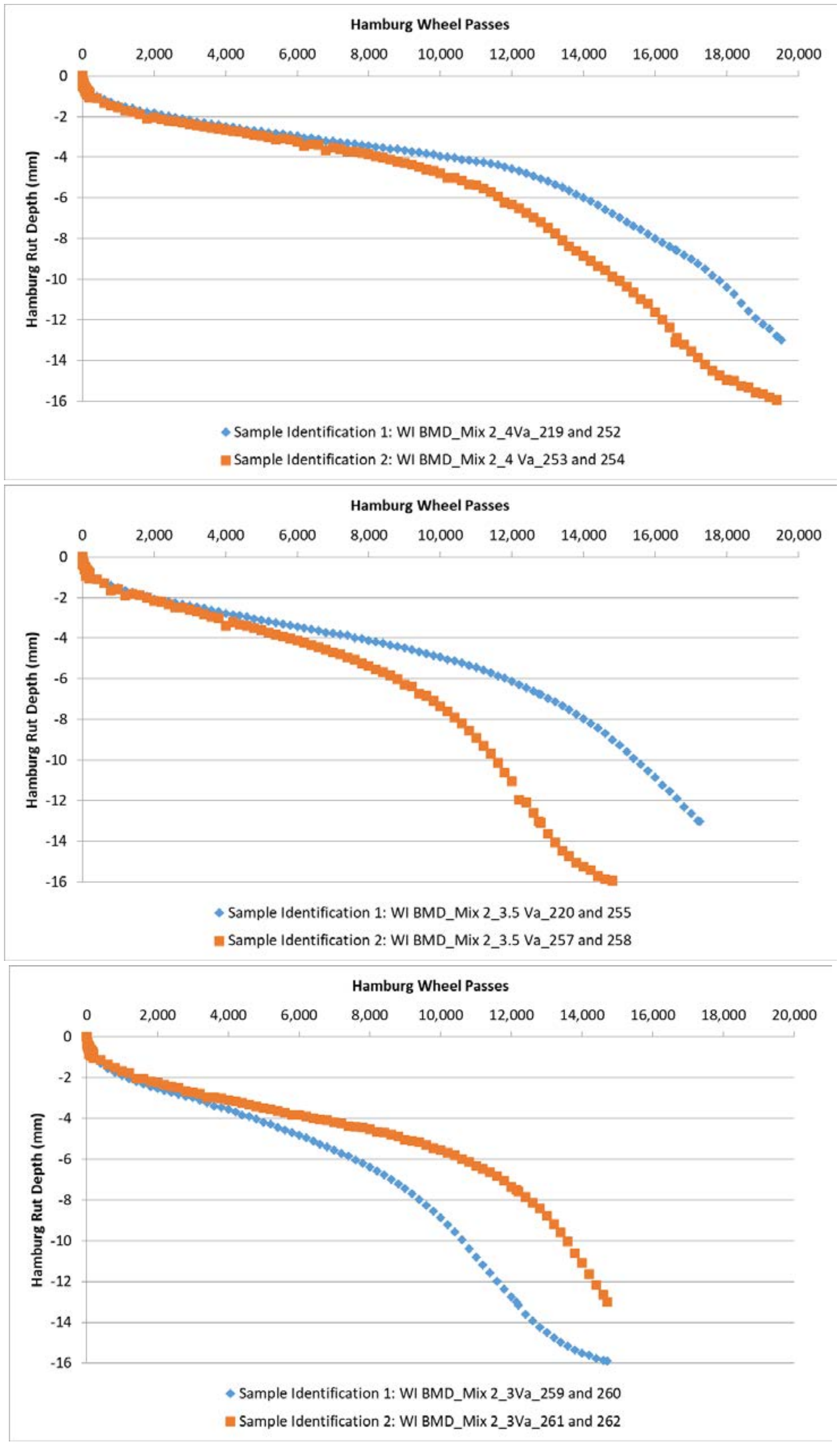

Figure C2 Hamburg Rut Depth versus Number of Cycles – Mix 2
(4.0% Design Air, Top – 3.5% Design Air, Middle – 3.0% Design Air, Bottom)

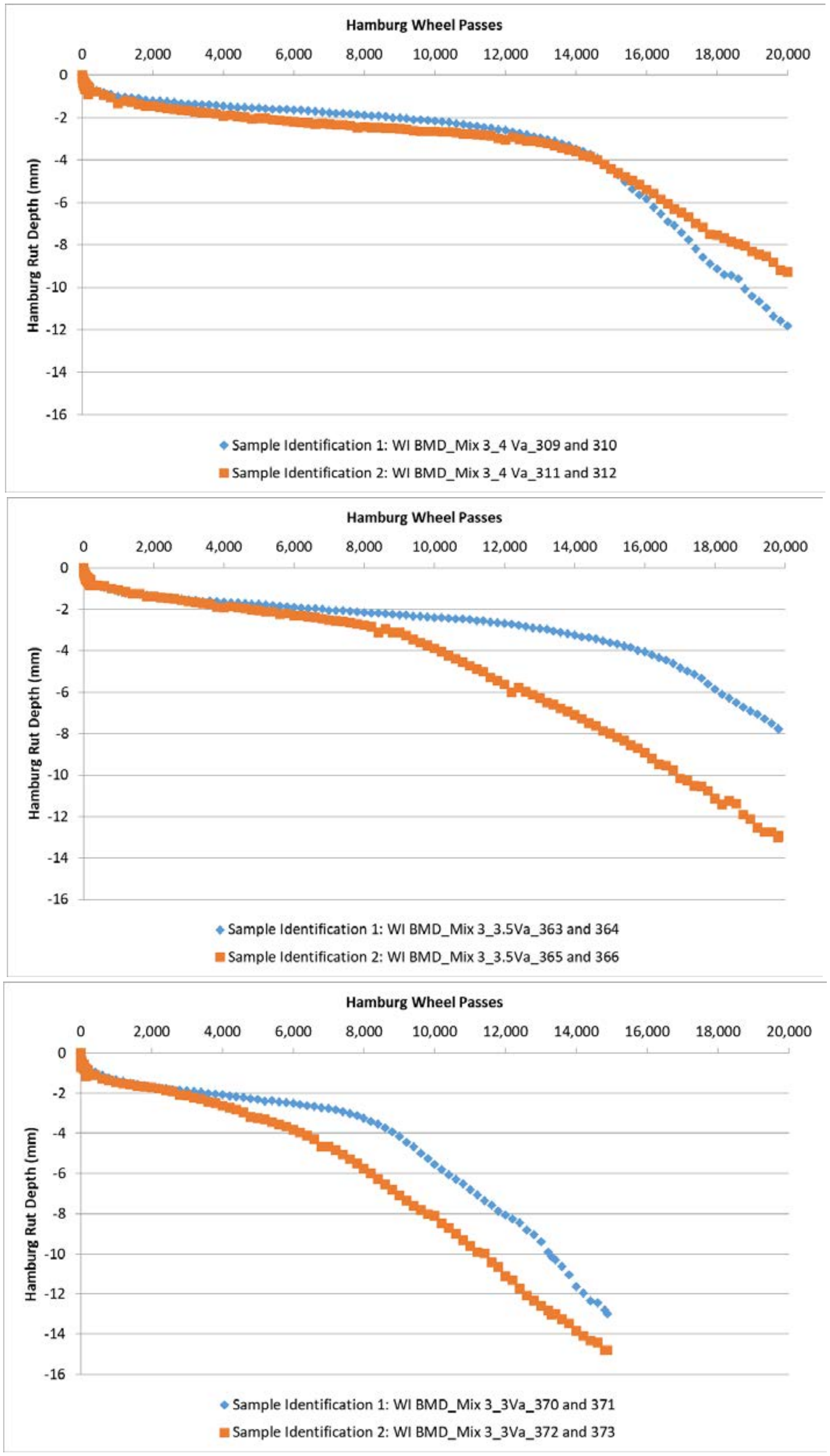

Figure C3 Hamburg Rut Depth versus Number of Cycles – Mix 3 (4.0% Design Air, Top – 3.5% Design Air, Middle – 3.0% Design Air, Bottom)

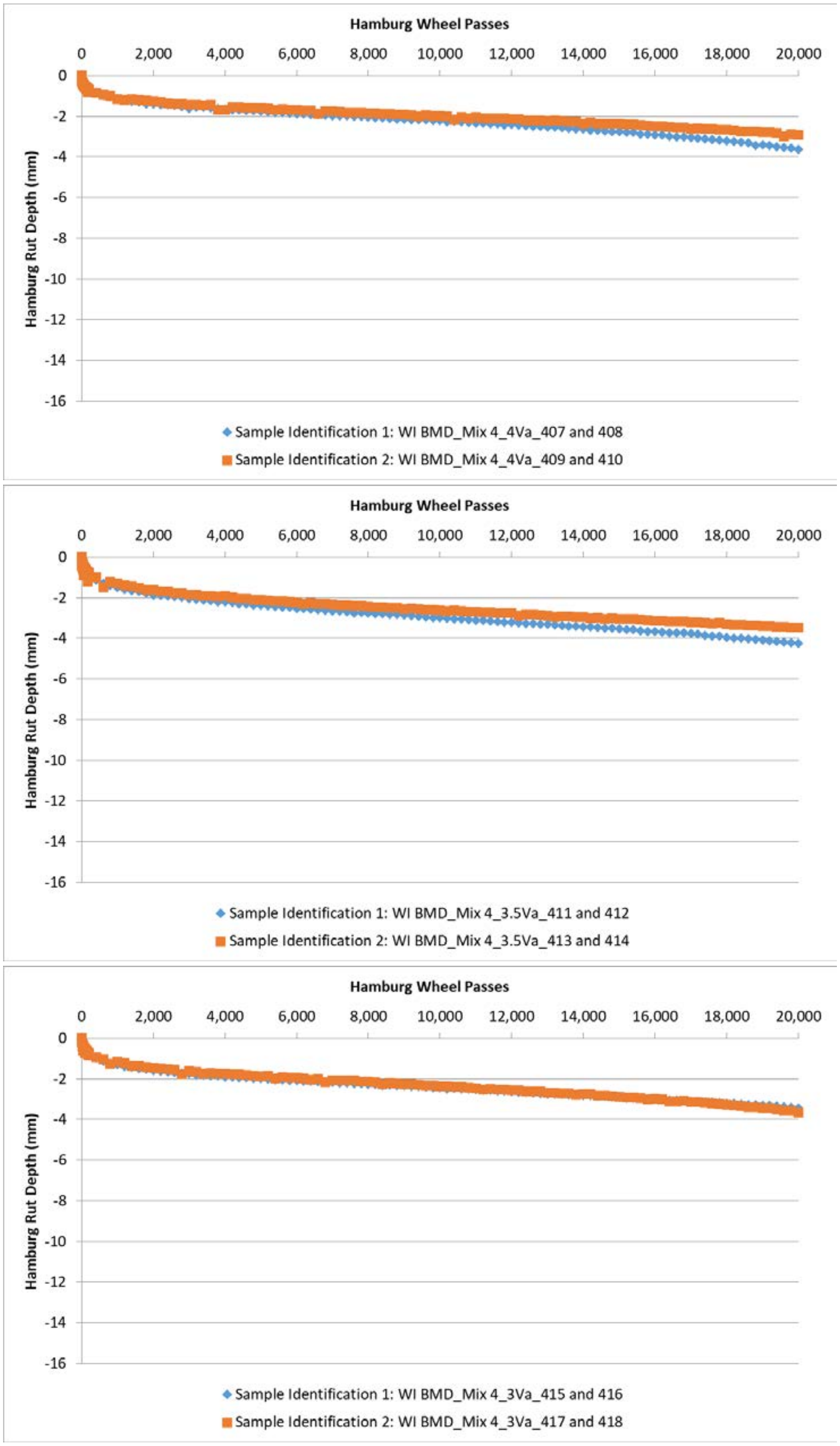

Figure C4 Hamburg Rut Depth versus Number of Cycles – Mix 4
(4.0% Design Air, Top – 3.5% Design Air, Middle – 3.0% Design Air, Bottom)

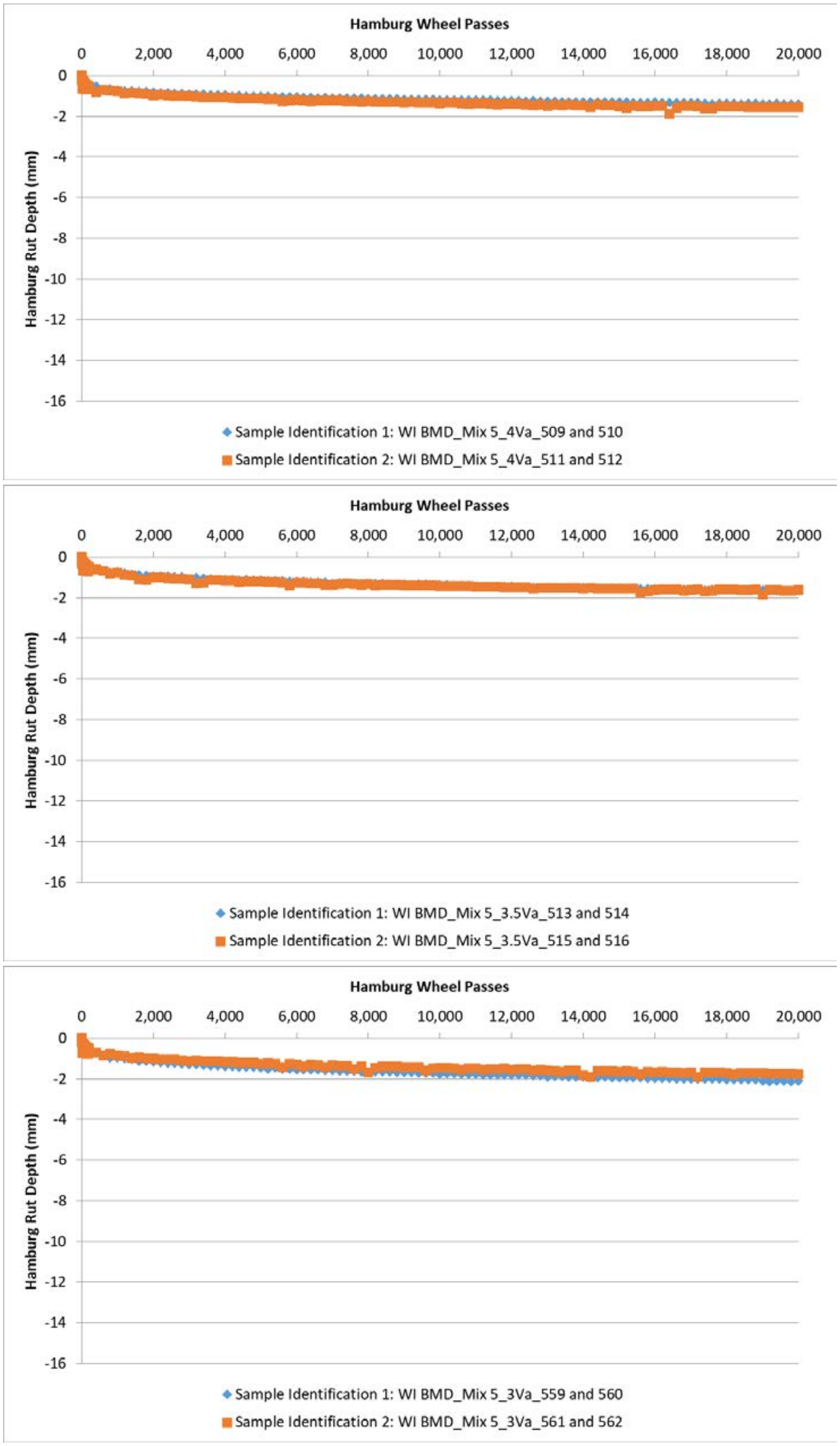

Figure C5 Hamburg Rut Depth versus Number of Cycles – Mix 5
(4.0% Design Air, Top – 3.5% Design Air, Middle – 3.0% Design Air, Bottom)

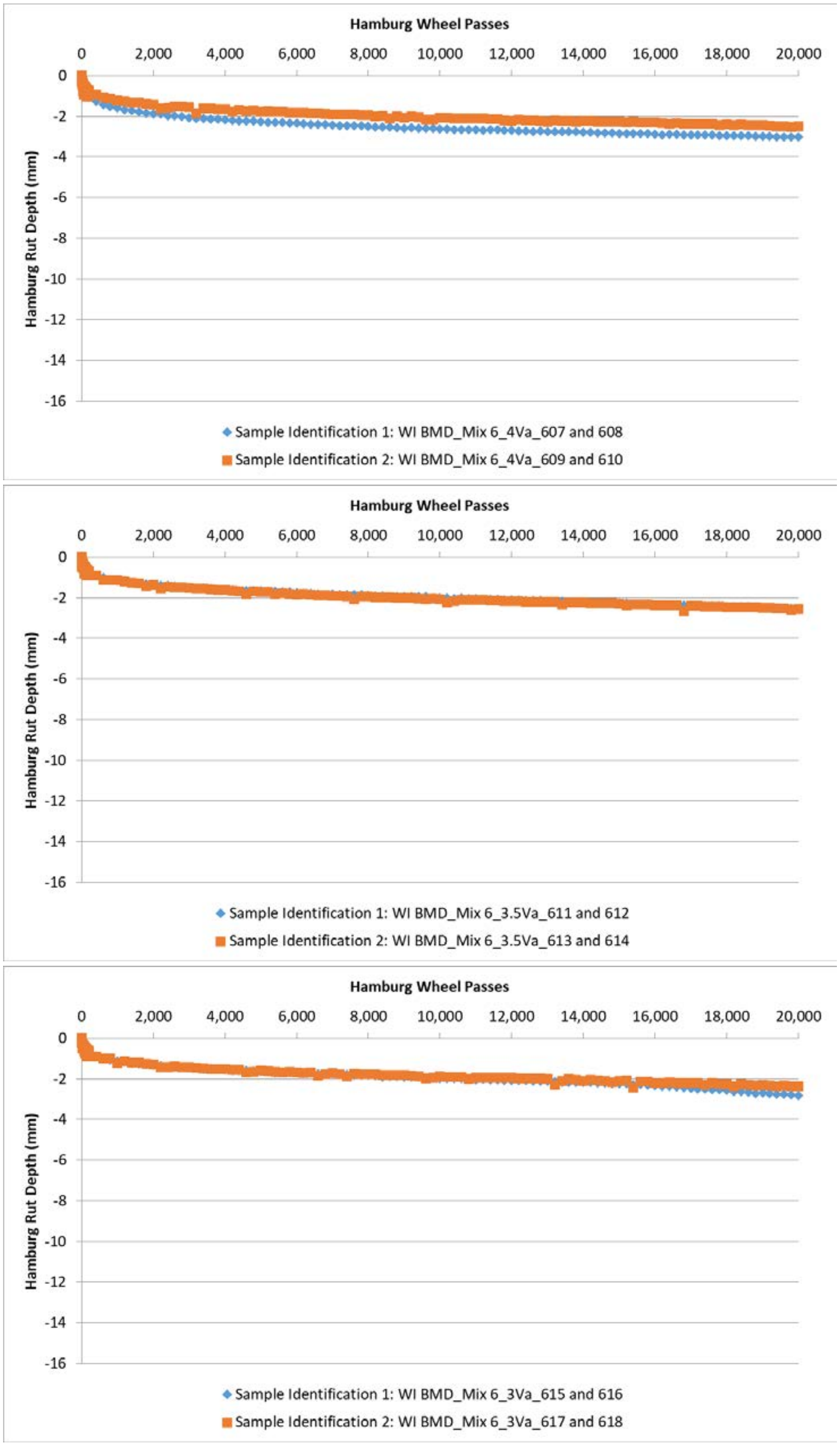

Figure C6 Hamburg Rut Depth versus Number of Cycles – Mix 6
(4.0% Design Air, Top – 3.5% Design Air, Middle – 3.0% Design Air, Bottom)