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# Risk Management of Low Air Void Asphalt Concrete Mixtures

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**JOINT TRANSPORTATION RESEARCH PROGRAM**
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

# Risk Management of Low Air Void Asphalt Concrete Mixtures

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**16. Abstract**


Various forms of asphalt pavement distress, such as rutting, shoving and bleeding, can be attributed, in many cases, to low air voids in the mixtures during production and placement. The occurrence of low air void contents during plant production may originate as a result of an accidental increase in binder content or mix fines (or both). When low air voids are encountered during production, the specifying agency must decide whether to require the material that has already been placed to be removed and replaced or whether it can be left in place with a reduction in pay. Consequently, the Indiana Department of Transportation (INDOT) initiated this research project to develop a decision-support tool for dealing with such events that is based on projected rutting performance of the pavement system. The study was conducted along three paths. In the first, INDOT sponsored two pavement test sections at the National Center for Asphalt Technology (NCAT) Test Track. The second path involved testing mixes in the INDOT Accelerated Pavement Testing (APT) Facility. In both cases, mixtures were produced in local hot mix plants by either increasing the fines content or the binder content. The NCAT test sections included low void mixes in the surface course only and performance was measured by the progression of rutting. Significant rutting developed in the low void mixes. The results suggested that removal be considered for mixtures with air voids below 2.75% but that no pay adjustment was necessary for air voids above this level. However, the NCAT results were limited to one pavement structure, one set of materials, one climate and low voids in the surface mix only. In the APT, low air void mixtures were placed in either the surface or the intermediate course and different materials were used. The pavement response (permanent deformation of the top pavement layers) resulting from repetitive APT wheel passes was measured using a laser based system. Lastly, a simplified mechanistic analysis, using a software program called QRSS (Quality Related Specification Software) was used in an attempt to simulate the effects of low void mixtures on pavement performance and service life with different materials in different pavement layers and under different traffic loads. The results of these efforts were used along with engineering judgment to formulate the desired decision-support tool.


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EXECUTIVE SUMMARY

# RISK MANAGEMENT OF LOW AIR VOID ASPHALT CONCRETE MIXTURES

## Introduction

Various forms of asphalt pavement distress, such as rutting, shoving, and bleeding, can be attributed, in many cases, to low air voids in the mixtures during production and placement. The occurrence of low air void contents during plant production may originate as a result of an accidental increase in binder content or mix fines (or both). When low air voids are encountered during production, the specifying agency must decide whether to require the material that has already been placed to be removed and replaced or whether it can be left in place with a reduction in pay. This decision involves a performance risk to the department of accepting a mix that may perform poorly and a monetary risk to the contractor who may be required to remove and replace a mix that could perform satisfactorily. Consequently, the Indiana Department of Transportation (INDOT) initiated this research project to develop an objective decision-support tool for dealing with such events that is based on projected rutting performance of the pavement system.

## Findings

The study was conducted along three paths. In the first, INDOT sponsored two pavement test sections at the National Center for Asphalt Technology (NCAT) Test Track. The second path involved testing mixes in the INDOT Accelerated Pavement Testing (APT) Facility. Lastly, a simplified mechanistic analysis, using a software program called QRSS (Quality Related Specification Software) was used in an attempt to simulate the effects of low void mixtures on pavement performance and service life.

- The two sections INDOT sponsored at the NCAT Test Track were subdivided in two and a third section served as the control. The four test sections incorporated low void surface mixes produced by either increasing the fines content or the binder content. Performance was measured by the progression of rutting.
- Significant rutting developed in all of the low void mixes. Mixes with excessive binder contents tended to rut faster than mixes with a change in gradation, but the rutting was unacceptable in all cases.
- The results suggested that removal be considered for mixtures with air voids below 2.75% but that no pay adjustment was necessary for air voids above this level. However, the NCAT results were limited to one pavement structure, one set of materials, one climate, and low voids in the surface mix only.
- In the APT, low air void mixtures were placed in either the surface or the intermediate course and different materials were used. The pavement response (permanent deformation of the top pavement layers) resulting from 13,000 APT wheel passes was measured using a laser based system.
- Similar rutting developed in each lane, regardless of whether the low void mixture was in the surface or the intermediate layer and regardless whether the low voids were caused by excess binder or a change in the gradation.
- A mechanistic model was developed to extend the APT study and examine the rutting behavior when the low void mix was placed lower in the pavement. The model was able to accurately reproduce the rutting observed in the APT, indicating the model worked reasonably well. Modeling suggested that rutting would still occur even if the low void mix were deeper in the pavement structure but that the rut would be wider than if the surface mix rutted.
- The Quality Related Specification Software (QRSS) was used in an attempt to expand the dataset to include different mixes, binders, traffic levels, air void contents, and locations in the pavement. QRSS uses the same models as the Mechanistic Empirical Pavement Design Guide (MEPDG, now called Pavement ME) to predict and compare the performance of as-designed and as-built mixtures. The comparison is based on predicted pavement stiffness (dynamic modulus), distress (permanent deformation, in this case), and change in service life. The concept was that the change in service life could be used objectively to determine when to remove and replace a mix as well as what monetary penalty to assess in cases where a substandard mix could be left in place at reduced pay.
- Attempts to predict the behavior of the mixes at NCAT using QRSS were unsuccessful as rutting was underpredicted in all cases. The predictions of the performance in the APT were more successful, suggesting that perhaps QRSS could be used as intended.
- Additional predictions of performance were mixed in terms of producing reasonable, expected results. Rutting was sometimes less than would be expected. Excessive changes in mixtures were required to yield a change in service life of greater than two years. In some cases, substantial changes in mix properties produced no appreciable change in the service life, contrary to experience. This mixed performance may be due, in part, to the fact that this study examined very low void contents and accelerated loading conditions that far exceeded typical construction variations, which is what QRSS was developed to do. QRSS is limited in the range of variables and the number of MEPDG runs used to develop the predictions; the cases explored in this study may have been outside the range of conditions QRSS was made to assess.
- The results of these efforts were used along with engineering judgment to formulate a draft decision-support tool that considers the traffic level and air void content.

## Implementation

The results of this study should be used as shadow specifications on several projects to assess the effects of testing variability and the monetary impacts on contractors if low void mixtures are produced. The shadowing can be used to refine the levels and consider penalties. This could also be accomplished by examining air void data from acceptance testing on past construction projects to assess the impacts of the proposed limits.

In addition, the Office of Research and Development could test mixtures for the shadowed projects (or others) and perform additional runs of the MEPDG to expand the dataset and verify the accuracy of the QRSS predictions.

Lastly, INDOT and the researchers should stay abreast of any further refinements of the QRSS software that could allow for direct input of test results, rather than relying on prediction models based on limited mix parameters. If these refinements are made, the predictions used in this study to assess the performance of low void mixtures could be revisited and the decision-support tool further refined.

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## 1. INTRODUCTION

The objective of asphalt concrete (AC) mixture design is to determine the combination of asphalt binder and aggregate that will provide desired behavior as part of the pavement structure. The design involves laboratory procedures for: evaluating and selecting aggregate sources and gradation; selecting a design compactive effort; and selecting the grade and amount of binder for the specific aggregate blend. The selection of a final mix design is based on optimizing the mixture volumetrics. Mixture volumetrics are used again during production to assess the quality of the produced mixture.

The Indiana Department of Transportation (INDOT) uses the Superpave system for designing all asphalt mixtures and selects the design binder content as that which provides 4.0% air voids at the design number of gyrations ($N_{design}$), which is based on the design traffic level. INDOT accepts hot mix asphalt based on the produced volumetric properties, specifically the binder content, air void content at $N_{design}$ and voids in the mineral aggregate (VMA) at $N_{design}$. In addition, in-place density and smoothness are also pay factors. During production, plate samples are removed from the mat behind the paver screed. Portions of these plate samples are compacted in the gyratory compactor to the design gyrations, and, after cooling, the bulk specific gravity and VMA of the specimens are determined. Mixture sublots placed with air void contents below 1.0% risk removal and replacement at the contractors' expense. Mixtures with air void contents between 1.0% and 3.0% are accepted at a lower rate of payment (*1,2*). The Failed Materials Committee adjudicates non-complying material on a case-by-case basis; using engineering judgment, they try to consider in their decision such factors as how low the air void content is, the traffic level, the depth of the failed material within the pavement structure, and other mitigating circumstances.

INDOT's specifications are based on the percent of test results within the acceptance limits, so-called Percent Within Limits (PWL) specifications (*2,3*). Upper and Lower Quality Indices are determined based on the averages and standard deviations of the mixture properties for individual lots and the upper and lower specification limits defined in the Standard Specifications (*2*). Then the percentage of the produced material that falls within the specification limits is determined, taking the number of samples into consideration. Under this scheme, a single low test value or a low sublot value will not trigger the failed materials policy; these test results are averaged. Since this statistical method of quality management was implemented, the number of lots exhibiting low air voids has reportedly decreased and uniformity has increased, but low voids may still occur.

Based exclusively on experience, without a rational decision-making process, the Department carries a higher risk level of accepting an inferior product that may not perform as intended. At the same time, contractors face the increased risk of reduced pay or the cost of removal and replacement when there is a possibility the material will perform acceptably. Consequently, INDOT initiated this research project to evaluate the impact of low air voids on rutting performance in order to develop a decision-support tool for determining whether to accept or reject a mixture with inadequate air voids and for assessing a monetary penalty if the material is allowed to remain in place.

### 1.1 Literature Review

The two most common AC mixture design methods, namely Marshall (*4*) and Superpave (*5,6*), use air void content (AVC) as the main controlling element that determines binder content. The design AVC represents the ultimate level desired in situ as a result of compaction efforts. It is commonly considered by the pavement engineering community to be the single most important factor that affects mixture behavior and pavement performance. In the typical Marshall methodology, the design AVC ranges between 3 and 5%. In the Superpave methodology, the design AVC is fixed at 4%. A study by Christensen and Bonaquist (*7*) re-evaluated this target value for the Superpave system. The study concluded that a design AVC in the range of 3 to 5% is adequate for all Superpave mixture types (i.e., surface, intermediate and base), for all aggregate gradations (i.e., dense, coarse and fine), and for all binder grades.

The focus of this research is on low air void AC mixtures. Low in-place air voids have been historically associated with distress types such as flushing/bleeding and rutting/shoving. During the development of the Marshall design methodology (*8*), it was found that surface AC mixtures constructed to an in situ AVC of 2.5% or less shoved under traffic loads during hot weather conditions. These mixtures were predominantly dense graded, having a maximum aggregate size of 19.0 mm (0.75 in.). The Marshall study also evaluated dense graded sand-asphalt mixes having maximum aggregate size of 4.75 mm (0.19 in.). These mixes exhibited instability at in-place AVCs higher than 3%. This resulted in a 2% translation of the AVC requirement range, for these mixes only, to 5 to 7% (instead of 3 to 5%).

In a study of in-place rutting, Brown and Cross (*9*) 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 of the ruts. The researchers concluded that a low AVC in situ or in recompacted specimens was a good indicator for rutting and pointed to a previous study with similar results (*10*). Another study set out specifically to identify mix design parameters that may affect rutting (*11*). In this research 42 pavements were sampled from 14 different states. Again, based on coring, trenching and laboratory tests, the following conclusions were obtained: (i) pavements that rutted had in-place AVCs below 3%; and (ii) most of the observed rutting was confined to the top 3 to 4 inches of the pavement.

Somewhat in contradiction to the above studies, reported field experience can also be found in which mixes designed and constructed with low AVCs behaved adequately. The following lists several examples. Davis (*12*) reported that dense graded large-stone mixes, with maximum aggregate sizes of 50.0 mm or larger, behaved extremely well with no rutting or cracking at in-place AVCs of 3% or less; these mixes also had very soft "lively" binders. During the WesTrack experiment (*13*), the AC mixture in test section 43 was designed to a target AVC of 1.7% (Nevada DOT mix). After paving, the average in-place AVC of the corresponding test section was also very low: 1.6%. Despite this fact, this mix experienced minimal rutting/shoving compared to all other sections in the experiment. In addition, low void AC mixtures had been suggested in the context of perpetual pavements to provide increased fatigue resistance at the bottom of the asphalt course (*14*). Following this concept results in a so-called rich-bottom pavement. For example, researchers in California (*15*) proposed a pavement reconstruction strategy which included a bottom AC layer, 50 to 75 mm (2 to 3 inches) thick, designed to an AVC of 2%. Detailed reports on such mixture designs and "rich-bottom" construction can be found in Monismith, et al. (*16*), Scullion (*17*), and Willis and Timm (*18*) among others. It is important to keep in mind, however, that most of these cases refer to mixes that were intentionally designed at low void contents and usually refer to base mixtures.

Based on this literature review it may be concluded that low AVC, either in the design phase or in the field immediately after construction, may serve as an indicator for problematic rutting behavior. The actual behavior within the pavement structure, however, may or may not be satisfactory depending on other factors, such as: (i) other mix attributes; (ii) location of the mix within the pavement structure; (iii) traffic intensity; and (iv) environmental conditions.

The occurrence of low AVCs may originate during plant production as a result of accidental increase in binder content or mix fines (or both). Low voids can also originate during the construction phase as a result of over-compacting an adequately designed mix. It should be realized however, that these events are not encountered often in construction projects, especially over-compaction. Probably for this reason very limited effort has been expended by the engineering and research community to study the resulting mixtures (e.g., the low voids region was avoided in SHRP (*19*)). Consequently, if such situations do occur in the field, there are currently no rational mechanisms for quantifying the impact on pavement rutting performance.

## 2. PROBLEM STATEMENT

The problem addressed by this proposal is: what action INDOT should take when a low void AC mixture has been placed? When low voids are encountered, the current practice is, in general terms, to accept the product with monetary adjustments. Mixtures that are accidently produced with AVCs of less than 2% may be removed and replaced at the expense of the contractor. For a more detailed adjudication refer to the INDOT's failed materials policy and asphalt pavement specifications (*1,2*). It is important to note that these rules apply equally to all road types, all mix types, all aggregate gradations, and all binder grades. To this end, INDOT is concerned with the behavior of the low AVC mixes left in-place while the contractors are concerned with the monetary implications. Therefore, there is a need to evaluate the performance risk to INDOT versus the monetary risk to the contractors.

## 3. OBJECTIVES

The main objective of this research is to provide INDOT with a decision strategy based on managing the risk when accepting or rejecting AC layers with low voids. The final outcome was expected to be similar to the current approach, i.e., either acceptance with monetary adjustments or replacement. However, the objective here is to develop a decision strategy based on rational (mechanistic) arguments and projected pavement performance.

## 4. FINDINGS AND DELIVERABLES

This section of the report describes the approach to address the objectives and the findings.

### 4.1 Research Approach

Addressing the objectives of this project eventually required a three-pronged approach. First, INDOT-sponsored test sections at the National Center for Asphalt Technology (NCAT) Track were used to evaluate the performance of one surface mixture produced with low voids caused by excess binder or excess fines. Second, asphalt mixtures were produced using a different set of materials and were placed in the INDOT/Purdue Accelerated Pavement Testing (APT) Facility; in this case, the low void materials were placed in either the surface or the intermediate course to evaluate the effect of depth in pavement on performance. Lastly, the Quality Related Specification Software (QRSS) was used in an attempt to expand the dataset to different materials, traffic levels and depths in the pavement. QRSS uses the same performance prediction models that are used in the Mechanistic Empirical Pavement Design Guide (MEPDG) scheme to evaluate the differences in the performance of as-designed versus as-built mixtures. This change in service life can then be used to objectively determine monetary penalties and the need to remove and replace material that fails to meet the specifications.

### 4.2 Results from NCAT Phase III Experiment with Low Void Surface Mixtures

In the NCAT Phase III experiment, INDOT sponsored two 61 m (200 ft) long test cells, referred to as S7 and S8. Each cell was further split into two, providing INDOT with four 31.5 m (100 ft) long experimental sections, denoted S7A, S7B, S8A and S8B. The pavement structure in these sections may be considered perpetual. It originated from the first experimental phase at the track (year 2000). Looking from bottom to top, the layers consisted of 300 mm (12 in.) of improved roadbed, 150 mm (6 in.) of crushed granite base, 125 mm (5 in.) of asphalt treated permeable base, 380 mm (15 in.) of AC base and 100 mm (4 in.) of AC surface.

For the purpose of this study, the surface AC layer in these four sections was milled to a depth of 50 mm (2 in.) and repaved. The mixture design for the new surface was done according to the Superpave methodology with an unmodified PG 64-22 binder (designated a PG67-22 in Alabama) and a compactive effort of 60 gyrations. (The 60 gyration level is the standard for all ESAL levels in Alabama and well-designed mixes, such as the N6 control section, have performed well for over 10 million ESALs.) A dense aggregate gradation was used with a nominal maximum aggregate size of 12.5 mm (0.5 in.). The design binder content, corresponding to a target AVC of 4%, was 5.8%. Another section on the track (N6) using the same binder, aggregate, gyration level, etc., but designed at 4% air voids, served as the control section for this study.

The plant-produced mix for the four test sections differed (deliberately) from the design mixture in order to produce low voids. For section S7A, the binder content was 0.7% higher, i.e., 6.5% instead of 5.8%, and the gradation was slightly finer. For section S7B, the binder content was only 0.3% higher, i.e., 6.1% instead of 5.8% and the gradation was (also) slightly finer. For sections S8A and S8B, the aggregate gradations were similar to the design gradation, but the binder contents were increased by 0.4% and 0.3% (respectively). These changes to the original design reduced the AVCs of the resulting mixes (determined using laboratory recompaction) to 1.4, 2.1, 2.0 and 1.0% for sections S7A, S7B, S8A and S8B respectively. Details on the mixtures are provided in Appendix A.

Construction of the Phase III experiment at NCAT was completed in October 2006. The average as-built AVCs immediately after compaction of sections S7A, S7B, S8A and S8B were 2.2, 3.9, 3.9 and 2.3% respectively. Loading began during November 2006 with the overall goal of applying 10 million equivalent single axle loads (ESALs) during a two-year period. About 2.4 million ESALs were applied at NCAT in the course of the first few winter months. During this period none of the sections experienced measurable rutting. However, as temperatures began to increase in the spring, the sections started to rut and rutting progressed rapidly. Figure 4.1 shows the progression of rutting in Section 8B versus time and traffic. The ultimate rutting level was reached near the end of August 2007 (after about 3.8 million ESALs) and remained relatively constant through the fall. Loading of these sections was terminated due to safety reasons after the total application of 5.6 million ESALs, and the sections were reconstructed.

Average maximum rutting levels were as follows: 35, 20, 22 and 30 mm for sections S7A, S7B, S8A and S8B respectively. Figure 4.2 shows the condition of Section 7A before it was milled and reconstructed. Assuming that this rutting comes from the low void mixes and not from the underlying structure, these values are very high as they constitute between 43 to 67% of the original lift thickness.

In February 2008, the sections were reconstructed with similar mixtures (see Appendix A). Rutting developed quickly again beginning in May 2008 when the temperatures increased. The total rutting in the four sections was between 12 and 35 mm (0.5 and 1.4 in.) at the conclusion of the study in December 2008. The N6 control section did not exhibit this type of rutting and performed acceptably for the duration of the study.

In both construction stages, the test sections that rutted the most and at the highest rate had very high binder contents. A high fines content (passing the 0.075 mm sieve) alone did not result in the most significant rutting.

Based on the results of the test sections at the test track, NCAT (*20*) suggested that acceptable rutting performance could be expected if the AVC is greater than 2.75% and that no penalties should be assessed above this level. At AVCs below this level, the rutting rate increased dramatically and removal could be

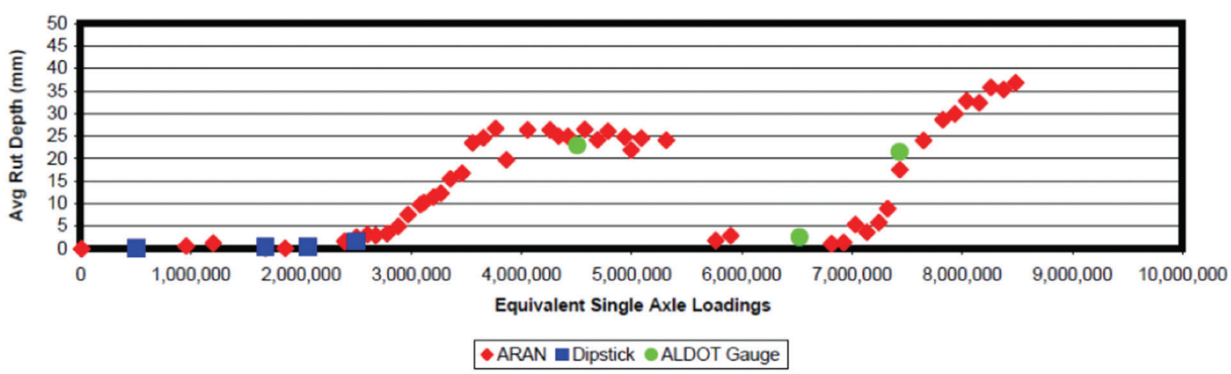


**Figure 4.1** Progression of rutting in NCAT Test Track Section 8B.

**Figure 4.2** Severe rutting before reconstruction.

considered. A graph summarizing the test track results is provided in Figure 4.3 (*20*).

## 4.3 Results from the Indiana Accelerated Pavement Testing Facility

The second approach executed for this study made use of the INDOT/Purdue APT Facility which is an enclosed, climatically controlled facility where pavement sections can be constructed in a 6 m by 6 m (20 ft by 20 ft) pit using full-scale construction equipment. The pit is 1.8 m (6 ft) deep to allow a subgrade to be constructed below the pavement. A carriage spans the pit and the loading mechanism is moved across using an elevator motor. A downward force of up to 89 kN (20,000 lbs) can be applied to the pavement through half of a single axle, equipped with either dual tires or a super single tire. The load can be applied in one direction (i.e., unidirectional mode) or two directions; lateral wheel wander can also be simulated in the test. Rutting distress is accelerated in effect because of the relatively slow speed of travel of 5 mph (8 km/h). The temperature in the APT facility can be increased up to 140°F (60°C) by heating the ambient air with suspended heaters. Surface rutting profiles are measured transversely across each lane using a laser based system.

Details on the operation of the APT for this experiment and the modeling of the results are provided in Appendix B. Brief summaries and highlights are provided here. For this experiment, uniaxial loading with the super single tire and wander was used.

### *4.3.1 Testing Layout and Materials*

At the beginning of this study, two perpetual pavement design sections remained in place in the APT from a previous study. The total AC thickness in Lanes 1 and 2, shown in Figure 4.4, was 432 mm (17 in.), and the AC thickness in Lanes 3 and 4 was 356 mm (14 in.). Both were supported by a two-layered subgrade composed of 406 mm (16 in.) of cement stabilized soil overlying untreated soil. The top 100 mm (4 in.) of the pavement was milled and removed in 2009 so that the low void mixture experiment could proceed. Embedded gauges targeting mechanical responses remained in the pavement structure from the previous experiment. However, after construction it was found that most of the instrumentation was out of scale and could not be used reliably any further.

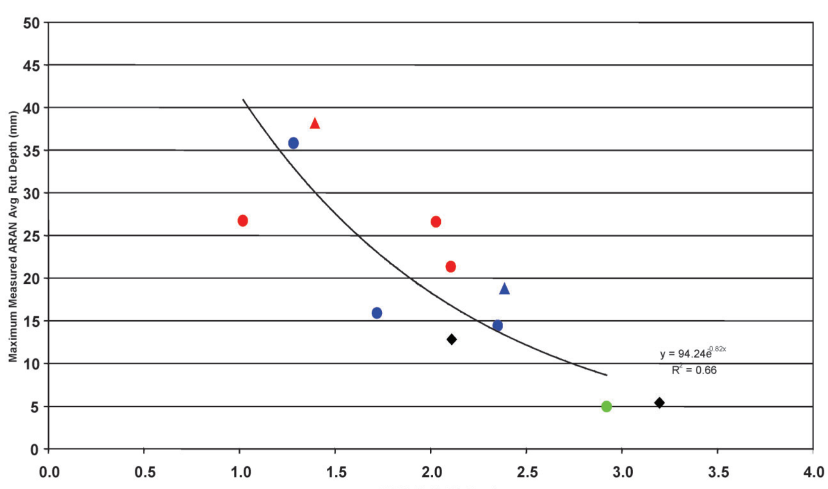


**Figure 4.3** Relationship between rutting and QC air voids based on NCAT Test Track performance (*20*).

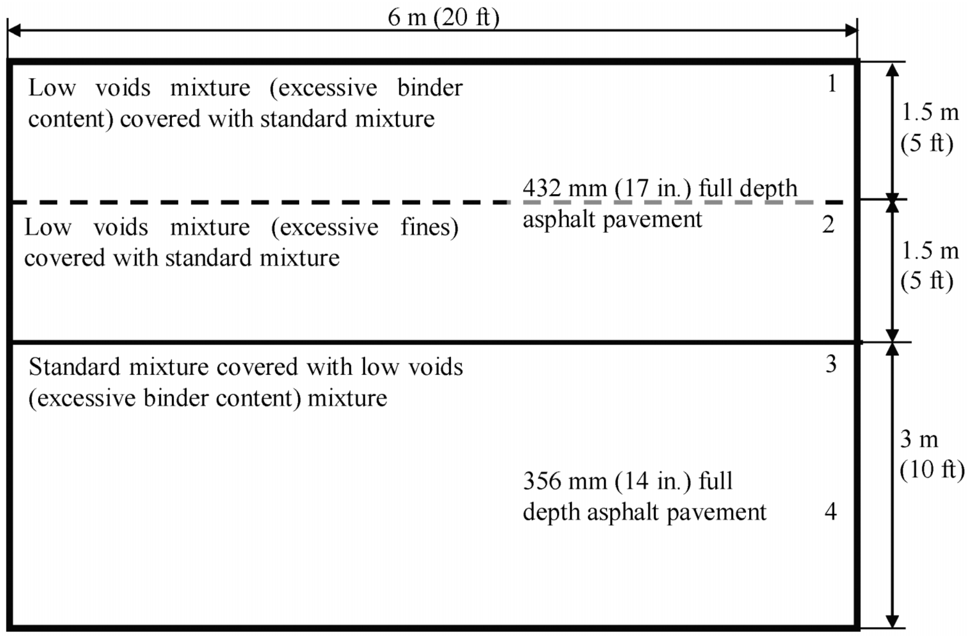


**Figure 4.4** Layout of test sections in the accelerated pavement testing facility.

After milling, new mixtures were placed in two 50 mm (2 in.) lifts over the existing perpetual structure. In Lanes 1 and 2, the lower 50 mm (2 in.) lift consisted of a low air void content mixture while the top 50 mm (2 in.) complied with standard design specifications. Excessive binder content was the cause for the low voids in Lane 1, while in Lane 2 the low voids were due to excessive fines content. The top 100 mm (4 in.) in Lanes 3 and 4 were composed of a standard mixture 50 mm (2 in.) thick overlaid by a low voids mixture due to excessive binder content. The above described configuration can be seen in Figure 4.4.

The three mix types placed in the APT were based on an existing mix design used by a local producer to pave several roads in the area. The mix was a 9.5 mm surface mix with a PG 64-22 binder designed with an $N_{design}$ of 75 gyrations (for a traffic volume of 300,000 to 3,000,000 Equivalent Single Axle Loads). The mixes were composed of dolomite coarse aggregate, dolomite manufactured sand, reclaimed asphalt pavement (RAP) and natural sand. The proportions of the various components of the mixtures are shown in Table 4.1.

TABLE 4.1
**Proportions of Mix Components by Mass of Mix**

| | | Low Voids Mix | |
|---|---|---|---|
| | Standard Mix | Excess Binder | Excess Fines |
| Coarse aggregate | 46.0% | 45.2% | 40.0% |
| Natural sand | 10.0% | 10.0% | 11.0% |
| Manufactured sand | 24.0% | 24.0% | 29.0% |
| RAP | 15.0% | 15.0% | 15.0% |
| Virgin PG 64-22 | 5.0% | 5.8% | 5.0% |
| Total binder | 5.7% | 6.5% | 5.7% |

In terms of climate, the goal was to impose a constant temperature level of 30°C (86°F) in the pavement throughout the experiment. An embedded "temperature tree" was used to monitor the prevailing temperature at various depths. In actuality, the temperatures varied within the range of 24.4 to 31.7°C (76 to 89°F).

Surface profile measurements were collected repeatedly during testing using a laser beam assembly along seven cross sections, spaced 0.3 m (1 ft) apart, located before and after the middle of the tested lane (lengthwise). To better understand the evolution and source of any surface rutting, changes in layer thicknesses were monitored as well. To accomplish this, at least partially, holes were drilled in the pavement so that their bases/bottoms served as targets for the laser beam. These holes were relatively narrow, protected by nylon sleeves 25 mm (1 in.) in inner diameter; the sleeves were glued to the drill-hole sides along the circumference to prevent closure under loading. Each sleeve was installed flush with the surface and extended to one-third to one-half of the drilled depth, enabling the layer thickness to change at the measurement point.

Figure 4.5 shows a "drill" plan, not drawn to scale, presenting a close-up view of the central area of a 6 m (20 ft) long test section. (Figure 4.6 shows a photograph of the installed drill holes.) Five drill-hole lines are shown, spaced 0.30 m (1 ft) apart before and after the middle of the test section. Five holes were drilled in each line, symmetrically spread around the centerline of the test lane at 125 mm (5 in.) intervals. The drill depths along the LH, LH-2 and LH+1 lines were 50 mm (2 in.); the holes in lines LH-1 and LH+2 extended to a depth of 100 mm (4 in.) below the pavement surface. Once the array of holes was installed and before any loading was applied to the pavement, ten replicate surface profiles

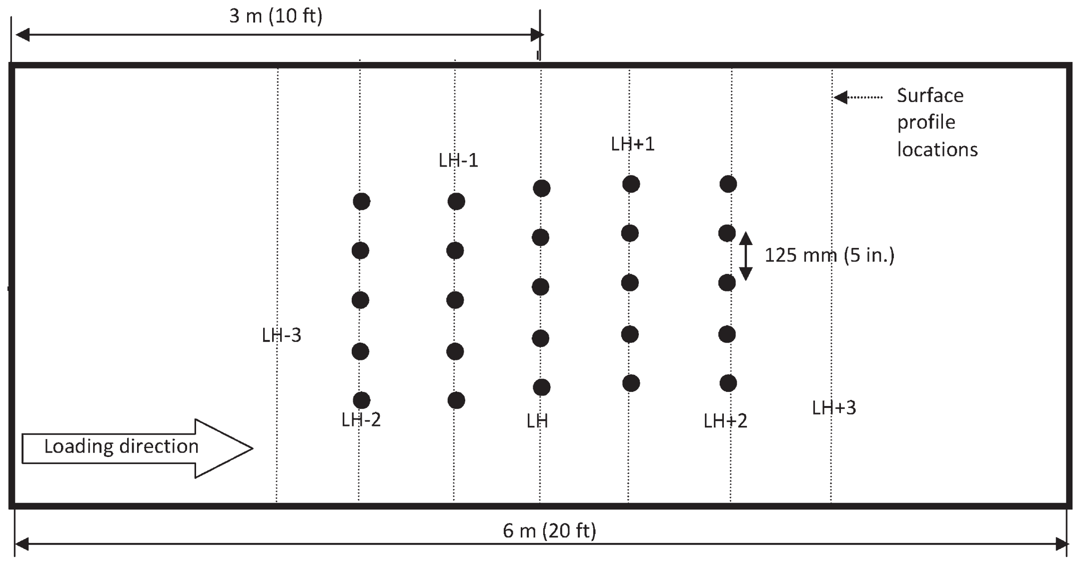


**Figure 4.5** Layout of drill holes and surface profile measurements in test lanes.

were measured along the five lines, capturing the drill points. Ten replicate profiles were also measured along two additional lines that did not contain any holes (LH-3 and LH+3 in the figure). The resulting dataset served as the benchmark for all subsequent load induced deformations.

*4.3.2 Measurements and Analysis*

The laser profile measurements collected during the 13,000 passes applied (Appendix B, Table B.1) are analyzed hereafter. The surface profile evolution along the LH-3 line from Land 3, where the low voids mixture was placed on top of a standard mix, (see Figures 4.4 and 4.5) is shown in Figure 4.7. If a virtual straightedge were placed on the surface, resting on the heaving noticed on both sides of the chart, the maximum rutting level is seen to have been about 6 mm (0.25 in.). The tire treads can also be seen in the central part of the figure between transverse locations 400 and 700 mm. Figure 4.8 shows the rutting along the LH line with the 50 mm (2 in.) holes. In this figure, the vertical deformation of the bottom of the holes after 13,000 passes relative to their initial elevations is also shown. It may be seen that, similar to Figure 4.7, the overall rutting level is about 6 mm (0.25 in.). Additionally, this figure reveals that the top low voids lift is roughly "responsible" for 50% of the observed/overall surface rutting.

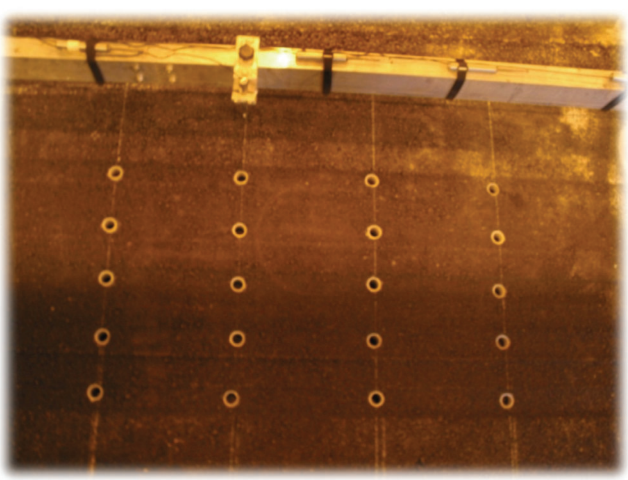

**Figure 4.6** Photograph of installed drill holes with sleeves, laser bar assembly visible at top.

An attempt to analyze the profile lines that included 100 mm (4 in.) holes, namely LH-1 and LH+2, was unsuccessful. After viewing the available measurements, it was realized that the laser was failing to hit the bottom of the holes. The reason for this is the inability of the automatic positioning system to repeatedly return to exactly the same location (lengthwise). (This experimental aspect could be improved upon in future studies.) The results from Lanes 1 and 2 are similar to the findings from Lane 3; i.e., the maximum rutting level is about 6 mm (0.25 in.) and the top lift is not the only contributor to the observed surface rutting. This is, perhaps, not surprising since the low void mixes are all within the top 100 mm (4 in.) of the surface. Conventional wisdom would suggest that poor quality mixes this close to the surface could have a significant impact on rutting, but that the effect might be diminished if the substandard mix were located deeper in the pavement structure. (To illustrate the importance of the top 100 mm, consider that LTPPBind (*21*), the binder grade selection software, typically calls for high binder grades in the top 100 mm of the pavement.)

A mechanistic model was used to extend the APT study and examine the rutting behavior when a low void layer is located deeper in the pavement system. Details on the model and assumptions are provided in

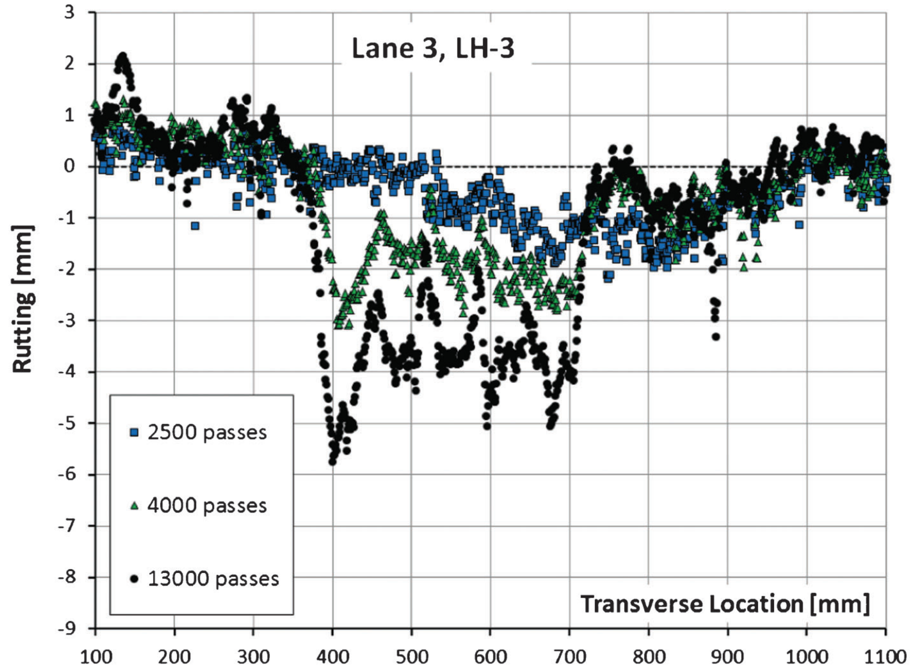


**Figure 4.7** Selected laser profiles for APT Lane 3–Line LH-3 (refer to Figure 4.5).

Appendix B. The model was used to compute the stress history in a cross-section (from the layered model) due to 13000 passes of the APT carriage (considering wander and different loading levels). That stress history was in turn used as input for a viscoplastic model (see Appendix B). Initially, only the top two lifts, having a combined thickness of 100 mm (4 in.), were assumed to contribute to the observed rutting as the remainder of the structure had already endured loading from a previous study. The necessary viscosities were subsequently obtained from inverse analysis by matching the measured rutting in the experiment. The match obtained for Lane 3 is shown in Figure 4.9. One indication for the reasonableness of the modeling effort was that the resulting shear viscosity ($\eta_G$) of the standard mix was much higher than the shear viscosity

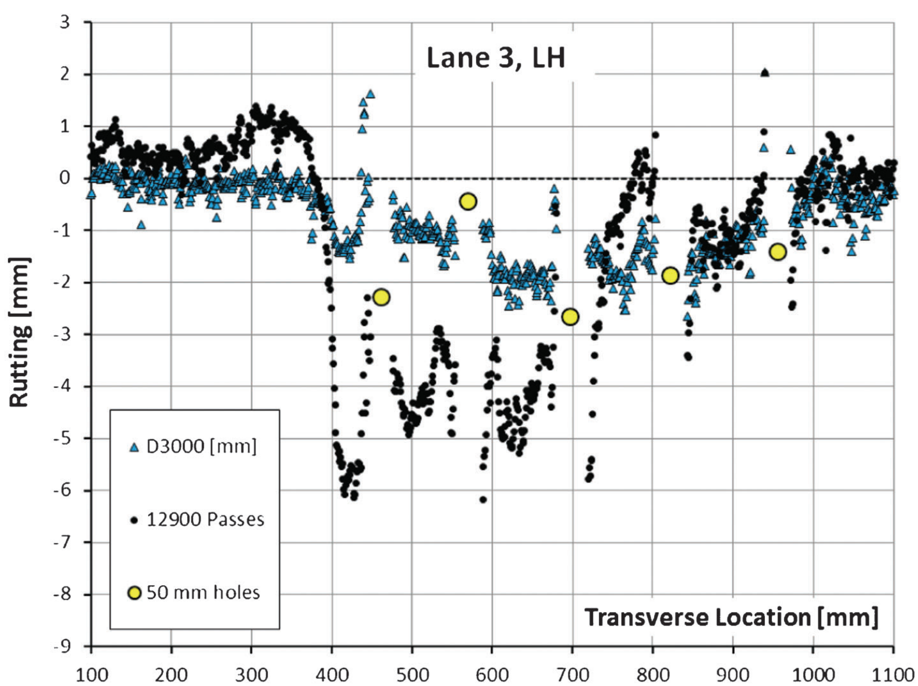


**Figure 4.8** Selected laser profiles for APT Lane 3—Line LH (refer to Figure 4.5).

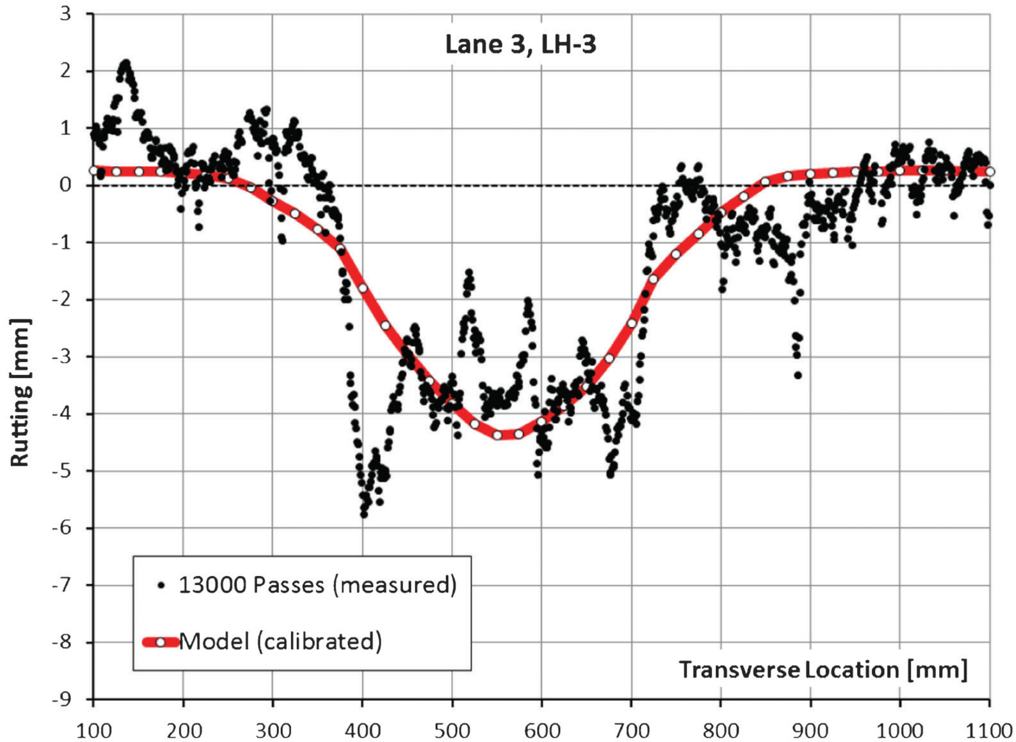


**Figure 4.9** Surface rutting data and calibrated model.

of the low voids mix. Also, as expected, the bulk viscosity ($\eta_K$) of the low voids mix was much higher than the bulk viscosity of the standard mix.

Using the calibrated viscosity values for the low voids mix, such an asphalt lift having a thickness of 50 mm (2 in.) was virtually inserted into the APT pavement at different depths from the top. When placed (in the model) under a surface lift made of standard mix, the results from Lanes 1 and 2 were adequately reproduced. This provided further confidence that the model is functioning suitably. When the low voids mixture was placed further down from the pavement surface, below additional 50 mm (2 in.) lifts made of standard mix, the overall rutting level at the surface did not improve, only the width of the rut slightly increased.

While it is generally acknowledged that a substandard mix deeper in the pavement structure will produce a wider rut, the finding that the overall surface rutting was not reduced is somewhat counter-intuitive.

### 4.4 Results of Analysis Using Quality Related Specification Software (QRSS)

The NCAT low voids experiment evaluated the performance of one set of mixtures in the surface course only. The APT experiment mainly evaluated the performance of another set of mixtures placed in the surface and intermediate courses; in addition, a modeling effort was used to place the low void mix deeper in the pavement. In order to further expand the dataset to different materials and traffic levels, and to estimate the effects of changes in the air void content on the service life of the pavement, the Quality Related Specification Software (QRSS) was used.

QRSS was developed under NCHRP Project 9-22, *A Performance-Related Specification for Hot Mixed Asphalt* (*22*). The software can be used to calculate the expected pavement performance, in terms of rutting, fatigue and thermal cracking, and smoothness based on mix design parameters (mixture volumetrics and material properties). The Witczak model is used to predict the expected performance. This prediction can then be compared to a similar prediction based on the as-produced mixture properties. Comparison of the as-designed to the as-produced properties can be used to estimate the impacts of changes in the mix properties from design to construction on the pavement service life. A plot showing the comparison of the service lives of a mix design and a lot of that mixture produced with a low air void content is shown in Figure 4.10.

The Witczak equation predicts the dynamic modulus of a mixture based on the binder viscosity (estimated based on PG grade); air voids; effective binder content; the cumulative percent aggregate retained on the 19 mm (3/4 in.), 9.5 mm (3/8 in.) and the 4.75 mm (No. 4) sieves; and the percent passing the 0.075 mm (No. 200) sieve.

QRSS uses pre-solved performance predictions using the Mechanistic-Empirical Pavement Design Guide (MEPDG) to estimate levels of distress. Because running the MEPDG, now designated Pavement ME, can be time-consuming, it was not thought to be feasible to use the MEPDG directly as a quality

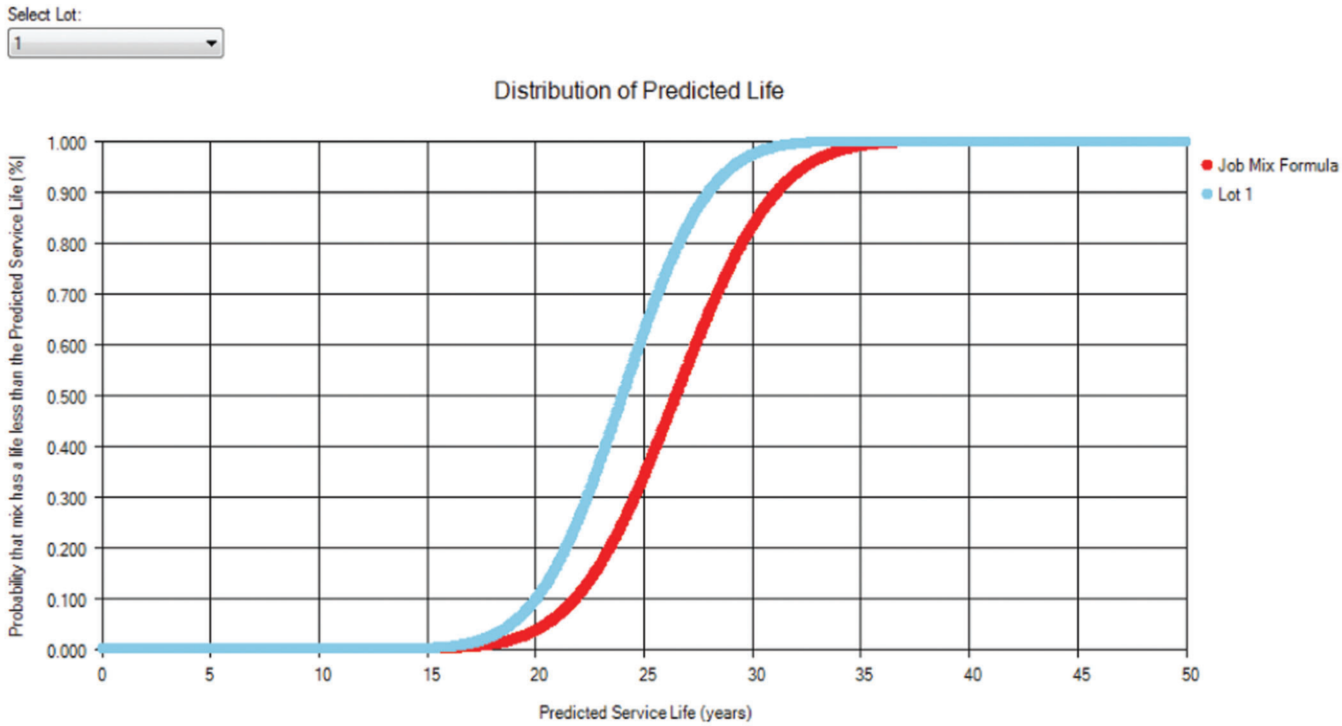


**Figure 4.10** Comparison of predicted life of mix design versus lot with low air voids.

assessment tool. Therefore, the NCHRP 9-22 researchers performed over 800 MEPDG runs to "pre-solve" predictions of pavement performance in terms of rutting. (Fatigue cracking, thermal cracking and roughness can also be estimated but these distresses are typically not related to low air voids.)

For this project, QRSS was used to analyze a number of existing mix designs for different traffic levels from this and other research projects. Then the mixture volumetrics and material properties were varied to assess the rutting performance of the mix compared to the initial design. Several assumptions were required to use the software for this project.

- First, on the material side, it was assumed that RAP contents of up to 25% would have no effect on binder grade. INDOT specifications currently allow up to 25% binder replacement with no change of binder grade for most mixes. For higher RAP contents, the binder grade was estimated to be one grade higher.
- A location in southern Indiana (Bloomington) was selected to use for the climatic inputs; the climate is more severe for rutting in the southern part of the state.
- Mixes were assumed to be adequately compacted (7%) in the field since the focus of this study is on mixes with low air voids at $N_{design}$ and not with excessive field compaction, which is extremely rare.
- The QRSS report indicated that the base and subgrade below the asphalt layers have little effect on rutting behavior, so constant resilient modulus values were used for the base, subbase and subgrade (50000, 20000 and 3480 psi, respectively).
- A change in binder content of 0.4% would be expected to produce a change of about 1% in the air void content at $N_{design}$. This is the estimate used in the Superpave mix design procedure and is based on many decades of experience. The binder content was used to vary the air void content in most of the simulations since it was easier to change than gradation and results of the NCAT Test Track experiment showed that the sections with the highest amount of rutting had very high binder contents.
- A design life of 20 years is used for asphalt pavements, except for special trial cases, such as when analyzing the short-duration NCAT Test Track results.
- INDOT would be willing to accept a risk level of 10%. Since QRSS reports the effects of changes in mixtures in terms of a change in service life, a 10% risk was assumed to equal a change of service life of 2 years.

Details on the most telling QRSS predictions are provided in Appendix C; many more predictions were performed that did not yield reasonable or meaningful results, as will be discussed later. The overall findings are summarized and discussed here.

Attempts to predict the excessively high rutting observed at the NCAT Test Track using QRSS were unsuccessful. The rutting was under-predicted in all cases. This is, perhaps, not unreasonable since the traffic loading is compressed into a short time frame and mixture parameters were, deliberately, far outside typical norms. Since QRSS uses a large, but still limited, number of pre-solved MEPDG runs, situations that are very unusual are outside the solution space used for the QRSS.

Attempts to model the performance in the APT were more successful. In this case, the amount of rutting predicted was quite close, if the upward heaving outside the wheel path is ignored and only the downward consolidation is considered. The rutting predicted by

TABLE 4.2
**Example of Changes in E*, Rut Depth and Service Life with Changes in Air Voids**

| Mix Designation | Binder Content, % | Air Voids, % | Predicted | | |
|---|---|---|---|---|---|
| | | | E* (ksi) | Rut Depth (in.) | Service Life (yrs) |
| Design | 5.6 | 4.0 | 392.8 | 0.200 | 20.533 |
| Lower voids | 6.0 | 3.0 | 395.0 | 0.203 | 20.168 |
| Lowest Voids | 6.4 | 2.0 | 392.0 | 0.204 | 19.973 |

QRSS was about 4 mm and the observed rutting in the APT, neglecting the heaving, was 4-5 mm. This finding was encouraging.

In terms of predicted difference in the service life, however, the difference was not as great as anticipated. For example, Table 4.2 shows the effects of changing the air voids from 4% at design to 3% and 2% at production for the mix placed in the APT. (The gradation is held constant.) The changes in the dynamic modulus (E*) are quite small and, in fact, the mix at 3% air voids is slightly stiffer than the mix design at 4%. The rutting is virtually unchanged and the effects on the service life, while moving in the assumed correct direction (i.e., decreasing), are small. While there are reports of low void mixes performing well, as shown by the literature review, these are typically for low voids in base mixes where the low voids presumably improve fatigue performance. Experience generally shows that low voids in surface mixes are problematic. Increased rutting and a change in service life of more than 6-7 months would typically be expected for a mix with only 2% air voids.

Adding fines to the mix stiffened the mix, even when done in conjunction with a high binder content. This may be a limitation of the predictive equation, which considers only four sieve sizes (19, 9.5, 4.75 and 0.075 mm) and does not consider the amount of material finer than the 0.075 mm sieve nor the quality of that material (such as plasticity index).

Excessive changes were required to yield a change in predicted service life greater than two years. In some cases, it appeared that substantial changes in the mixture volumetrics produced essentially no change in the rutting performance. This may be a result of the limited number of MEPDG solutions performed in the development of QRSS. The changes explored in this study may have been outside the range of properties used to develop the software.

The results of the QRSS runs supported the contention from the APT that the total rutting does not improve when the low void mix is deeper in the pavement as the amount of rutting predicted was essentially the same. Similarly, the predicted service life did not change much when the location of the low void mix changed from the surface to the intermediate course.

QRSS results did suggest that rutting would decrease as the traffic level decreases for a given mix and when a higher grade of binder was used. The binder grade had a significant impact on the stiffness of the mixture and therefore on the predicted rutting.

In order to explore the impacts of changes in mix and other properties, especially binder content and air voids (but also traffic level, gradation, binder grade, etc.), variability of the test results was not fully explored. High variability could mask the impacts of changes in the air voids, for example.

In summary, the QRSS results for this study were mixed in terms of passing a test of reasonableness. While the basic premise of comparing as-designed to as-produced mix performance is sound, the predictive abilities of the software may be limited to more "typical" construction variation. Changes in air voids that experience suggests would be expected to yield significant changes in mix stiffness, rutting performance and service life, often produced only small changes or none at all. This reduces the perceived reliability of the predictions. In defense of QRSS, however, this study, looking at excessively low air void contents and accelerated loading conditions, explored conditions that far exceed typical construction variation.

## 5. CONCLUSIONS

The measurements and modeling in this study indicate that similar rutting performance should be expected if a low void mix is placed as a surface layer or placed 50 mm (2 in.) below the surface underlying a standard mix. The source of the low voids, whether it originates from excessive binder content or excessive fines (with a corresponding small increase in binder content) did not seem to impact the ultimate behavior. Mixes with very high binder contents, with or without increased fines, did tend to rut at a faster rate, but unacceptable rutting still occurred at NCAT and in the APT. Using mechanistic considerations, deeper positions for the low voids mix were explored, and it was found that surface rutting is negatively affected even if such a layer is placed deeper in the pavement, up to a depth of 300 mm (12 in.). Hence, combining the APT and NCAT study findings, the following is recommended for higher traffic intensities (see Table 5.1). The extension for lower traffic level is based on engineering judgment and the performance of the NCAT control section. The QRSS results are not considered reliable enough to significantly affect this tool, but the apparently reasonable simulation outputs were considered to some extent.

The proposed decision support tool in Table 5.1 is provisional, based on limited data from the APT and NCAT studies, supplemented with QRSS analysis of

TABLE 5.1
**Proposed Decision Support Tool for Dealing with Low Void Mixes**

| AVC [%] | Traffic Intensity (20 year) Lower (ESALs <3,000,000) | Higher (ESALs >3,000,000) |
|---|---|---|
| 3.0 | 1 | 1 |
| 2.9 | 1 | 2 |
| 2.8 | 2 | 2 |
| 2.7 | 2 | 2 |
| 2.6 | 2 | 3 |
| 2.5 | 3 | 3 |

Where 1 = accept without monetary reduction, 2 = consider leaving in place with monetary reduction, 3 = consider removing and replacing.

additional mixtures. The table is formulated as a rough guide, not taking explicitly into account the specifics of the low void mix (e.g., maximum aggregate size or other factors), details about the pavement system, in situ climatic conditions, and as-built layer properties and volumetrics. This is done intentionally so that it could gain practical acceptance by allowing room for engineering judgment on part of the decision makers.

The proposed decision support tool does require removal and replacement at a higher air void content than the current INDOT specifications; i.e., Table 5.1 calls for removal at air void contents of 2.5 or 2.6% compared to potential removal at more than 2.0% difference from the design (or less than 2.0% air) according to section 401.19. While this may be worrisome to the contracting industry, the number of instances of low void mixtures had decreased substantially since the implementation of PWL specifications. Raising the bar decreases the risk to INDOT of poor performance. The lower limit for full payment is the same (3.0% air) for higher traffic and somewhat more forgiving at 2.9% for lower traffic. This study is not intended to change the bonus schedule for high quality and low variability in production.

The monetary penalty for low voids should be commensurate with the loss of service life. It was anticipated that QRSS would help to quantify that loss. While QRSS can provide some numbers, INDOT and the industry's comfort level with the service life predictions needs to be assessed; this could be accomplished through the implementation efforts described below. In the meantime, the pay factors in 401.19 between the 100% pay level and the lower limit for Category 2 could be used as is. The pay factors could also be considered for air voids falling in Category 3 if there are perceived extenuating factors that suggest it is reasonable to leave the material in place. Category 3 recommends considering removal and replacement, but does not mandate it.

Open-graded mixes, which are currently addressed in Section 401.19 of the INDOT Standard Specifications (*2*), were not studied in this project and no changes in the management of these mixes are recommended at this time.

## 6. RECOMMENDATIONS FOR IMPLEMENTATION

The proposed decision support tool should be used as a shadow specification on a number of trial projects to assess the impacts on contractors' pay. Based on a comparison of pay factors under the current specifications and the proposed decision support tool, the criteria can be refined as necessary. Analysis of results from actual field projects will also allow assessment of the impacts of test and production variability, which may mask the effects of changing mix parameters but which does relate to PWL specifications. Compared to the current procedures, the proposed tool is not radically different but is based on mechanistic analysis of real and simulated mixtures. The proposed tool does give some additional allowance when low void mixes are encountered on low volume roads where experience and the mechanistic analysis suggest the risk of rutting is lower.

Alternatively, and perhaps more easily or as a first step, past air void data from acceptance testing could be used to evaluate the effects of the proposed changes.

The QRSS version 1.0 is limited in terms of the number of MEPDG runs (pre-solutions) available and also in options to input mixture properties. For example, the option of inputting measured dynamic modulus values is not yet available. Using measured dynamic moduli would allow for more accurate predictions for specific local materials. The Witczak predictive equation, which has been shown to be a reasonably accurate global prediction model in most cases, is based on a limited number of input values. Regardless of the type or size of the mixture, for example, only four gradation parameters are considered. The binder grade is currently used to estimate the binder viscosity; an option to input actual binder properties is not yet available. Should a new, refined version of QRSS be developed, it may be worthwhile to revisit this experiment and test whether the refined software yields more reasonable and reliable service life predictions.

Lastly, if this approach appears feasible and there are enough cases of low void materials to justify a significant amount of additional effort, it would be possible to perform actual Pavement ME runs on the mixtures from the trial projects suggested above. Performing new analyses rather than depending on the pre-solved solutions could expand the solution space to more extreme variations in properties. The Office of Research and Development has access to Pavement ME and could assist in this effort.

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## APPENDIX A. NCAT TEST TRACK MIXES

TABLE A.1
**Original Phase III Sections—QC Data (2007)**

| Property | S7A | S7B | S8A | S8B | Design |
|---|---|---|---|---|---|
| 25 mm (1 in.) | 100 | 100 | 100 | 100 | 100 |
| 19 mm (3/4 in.) | 100 | 100 | 100 | 100 | 100 |
| 12.5 mm (1/2 in.) | 98 | 100 | 97 | 98 | 97 |
| 9.5 mm (3/8 in.) | 90 | 91 | 88 | 88 | 86 |
| 4.75 mm (No. 4) | 71 | 76 | 66 | 63 | 64 |
| 2.36 mm (No. 8) | 58 | 53 | 53 | 49 | 51 |
| 1.18 mm (No. 16) | 45 | 42 | 41 | 38 | 40 |
| 0.600 mm (No. 30) | 32 | 30 | 30 | 28 | 29 |
| 0.300 mm (No. 50) | 18 | 17 | 18 | 18 | 17 |
| 0.150 mm (No. 100) | 12 | 11 | 11 | 12 | 11 |
| 0.075 mm (No. 200) | 8.0 | 7.4 | 7.5 | 7.8 | 7.4 |
| Binder content, % | 6.5 | 6.1 | 6.2 | 6.1 | 5.8 |
| Air voids, % | 1.4 | 2.1 | 2.0 | 1.0 | 4.0 |
| VMA, % | 16.0 | 15.2 | 16.0 | 14.7 | 16.6 |
| Average maximum rut depth*, mm | 35 | 20 | 22 | 30 | — |

*After 4 million to 5.6 million ESALs.

TABLE A.2
**Phase III Reconstructed Sections—QC Data (2008)**

| Property | S7A | S7B | S8A | S8B |
|---|---|---|---|---|
| 25 mm (1 in.) | 100 | 100 | 100 | 100 |
| 19 mm (3/4 in.) | 100 | 100 | 100 | 100 |
| 12.5 mm (1/2 in.) | 98 | 98 | 97 | 97 |
| 9.5 mm (3/8 in.) | 91 | 88 | 85 | 88 |
| 4.75 mm (No. 4) | 80 | 74 | 69 | 72 |
| 2.36 mm (No. 8) | 55 | 52 | 47 | 50 |
| 1.18 mm (No. 16) | 42 | 40 | 37 | 38 |
| 0.600 mm (No. 30) | 32 | 29 | 28 | 28 |
| 0.300 mm (No. 50) | 21 | 18 | 17 | 17 |
| 0.150 mm (No. 100) | 13 | 12 | 11 | 11 |
| 0.075 mm (No. 200) | 8.4 | 7.6 | 7.3 | 7.1 |
| Binder content, % | 5.8 | 5.9 | 5.5 | 6.1 |
| Air voids, % | 2.4 | 1.7 | 2.4 | 1.3 |
| VMA, % | 14.3 | 14.3 | 14.3 | 14.3 |
| Average maximum rut depth*, mm | 18 | 17 | 12 | 35 |

*After approximately 3.5 million ESALs.

# APPENDIX B. LOADING CONDITIONS AND MODELING OF APT RESULTS

By Eyal Levenberg

## LOADING CONDITIONS AND RUTTING MEASUREMENTS

Loading in the INDOT/Purdue Accelerated Loading Test (APT) Facility was executed using a super single tire inflated to 0.7 MPa (100 psi), making a circular contact area with the pavement with a 165 mm (6.5 in.) radius. Thirteen (13) load "packages" were executed, each containing 1000 wheel passes, applied in unidirectional mode without wander. Every single "package" was composed of ten "sets" of 100 wheel passes having different loading intensities increasing from 8.9 kN to 89 kN (2000 to 20000 lbs.). In addition, each loading package was assigned an individual lateral carriage position, i.e., different wander position relative to the center of the tested lane (refer to Table B.1).

Knowing the lateral location of the wheel was important for the modeling efforts so these fixed offsets were used.

## MODELING APT PAVEMENT RESPONSE

A mechanistic model was used to extend the APT study and examine the rutting behavior when a low void layer is located deeper in the pavement system. A relatively simple model was selected, in which the pavement is idealized as a four layered system, consisting of 356 mm (14 in.) of asphalt, 406 mm (16 in.) of cement treated soil, 1066 mm (42 in.) of untreated soil, and the concrete floor of the test pit (semi-infinite). The constitutive response of all four layers was assumed to be linear (isotropic) elastic, obeying the constitutive relation (summation convention applies):

$$\varepsilon_{ij}^{e} = \frac{s_{ij}}{2G} + \frac{\sigma_{kk}}{9K}\delta_{ij} \tag{1}$$

In which $\varepsilon_{ij}^{e}$ is the elastic strain tensor, $s_{ij}$ is the deviatoric component of the stress tensor$\sigma_{ij}$, $G$ is the shear modulus, and $K$ is the bulk modulus.

After assuming the Poisson's ratios for each layer, moduli values were obtained from FWD testing carried out at a temperature level of 32°C (90°F). This temperature level is slightly higher than the prevailing temperature during the APT study, but the resulting backcalculated moduli are considered more representative given that the loading speed of the APT carriage was slow (*1*). By simulating the super single wheel movement, the layered model was utilized to compute the history of stresses in the asphalt lifts along a cross-section. Computations were performed every 25 mm (1 in.), both in the vertical direction (i.e., downward in the pavement) to a depth of 325 mm (13 in.) and also in the transverse direction to an offset distance of 1000 mm (3.3 ft) from the line of travel (i.e., a grid of $41 \times 7$ points). The wheel movement was simulated quasi-statically, by applying the load at different distances (lengthwise) from the cross section; 28 distances were used for this purpose, spaced unevenly between 2000 mm (6.5 ft) and zero (0). Because of the linear nature of the model, superposition and symmetry considerations could be used to generate the full stress history in the asphalt lifts during the entire 13000 passes of the APT carriage from the above calculations.

In order to simulate rutting originating from the asphalt layer, a viscoplastic (VP) constitutive model was assumed for each of the asphalt lifts. In analogy with the linear elastic constitutive model, Equation 1, the VP equation takes the form:

$$\dot{\varepsilon}_{ij}^{vp} = \frac{s_{ij}}{\eta_G} + \frac{\sigma_{kk}}{\eta_K}\delta_{ij} \tag{2}$$

In which $\dot{\varepsilon}_{ij}^{vp}$ is the VP strain-rate tensor, $\eta_G$ represents viscosity resisting shear deformation, and $\eta_K$ represents a viscosity resisting bulk deformation. As can be seen, when $\eta_K$ increases towards infinity no isotropic VP strains can develop in the material, only VP shear deformations; this condition has the potential to represent a low voids mix for which VP deformations will be predominantly shear related. For standard mixtures, VP strains will develop under load in both shear and volumetric modes. Also, $\eta_G$ in standard mixes is expected to be higher compared to $\eta_G$ in a low void mix, representing the greater resistance to shear deformation of the former. The choice for Equation 2 was inspired by studies dealing with the permanent deformation (compaction) of ice and snow (*2*).

It should be noted that in order to generate realistic results using this simple VP model, neither $\eta_G$ nor $\eta_K$ can be considered constant; they should depend on temperature, age/time and possibly on VP strain history. None of these dependencies is explored herein. Temperature is assumed constant; time/age effects are ignored due to the short duration of the APT experiment; and VP strain history is not included because it introduces nonlinear behavior that precludes the use of superposition and therefore dramatically increases the computational cost.

At this point, the computed stress history in a cross-section (from the layered model) due to 13000 passes of the APT carriage (considering wander and different loading levels) is used as input for the VP model. Initially, only the top two lifts, having a combined thickness of 100 mm (4 in.), were assumed to contribute to the observed rutting as the remainder of the structure had already endured loading from a previous study. The necessary viscosities were subsequently obtained from inverse analysis by matching the measured rutting in the experiment. The match obtained for Lane 3 is shown in Figure B.1. One indication for the reasonableness of the modeling effort was that the resulting shear viscosity ($\eta_G$) of the standard mix was much higher than the shear viscosity of the low voids mix. Also, as expected, the bulk viscosity ($\eta_K$) of the low voids mix was much higher than the bulk viscosity of the standard mix.

Using the calibrated viscosity values for the low voids mix, such an asphalt lift having a thickness of 50 mm (2 in.) was virtually inserted into the APT pavement at different depths from the top. When placed (in the model) under a surface lift made of standard mix, the results from Lanes 1 and 2 were adequately reproduced. This provided further confidence that the model is functioning suitably. When the low voids mixture was placed further down from the pavement surface, below additional 50 mm (2 in.) lifts made of standard mix, the overall rutting level at the

TABLE B.1
**Application Order of Loading Packages in Lane 3**

| Loading Package # | Cumulative Number of Passes | Lateral Offset, mm (in.) |
|---|---|---|
| 1 | 1000 | 0 (0) |
| 2 | 2000 | 0 (0) |
| 3 | 3000 | -125 (-5) |
| 4 | 4000 | -75 (-3) |
| 5 | 5000 | 0 (0) |
| 6 | 6000 | +50 (+2) |
| 7 | 7000 | -75 (-3) |
| 8 | 8000 | 0 (0) |
| 9 | 9000 | +125 (+5) |
| 10 | 10000 | -125 (-5) |
| 11 | 11000 | +100 (+4) |
| 12 | 12000 | -25 (-1) |
| 13 | 13000 | 0 (0) |

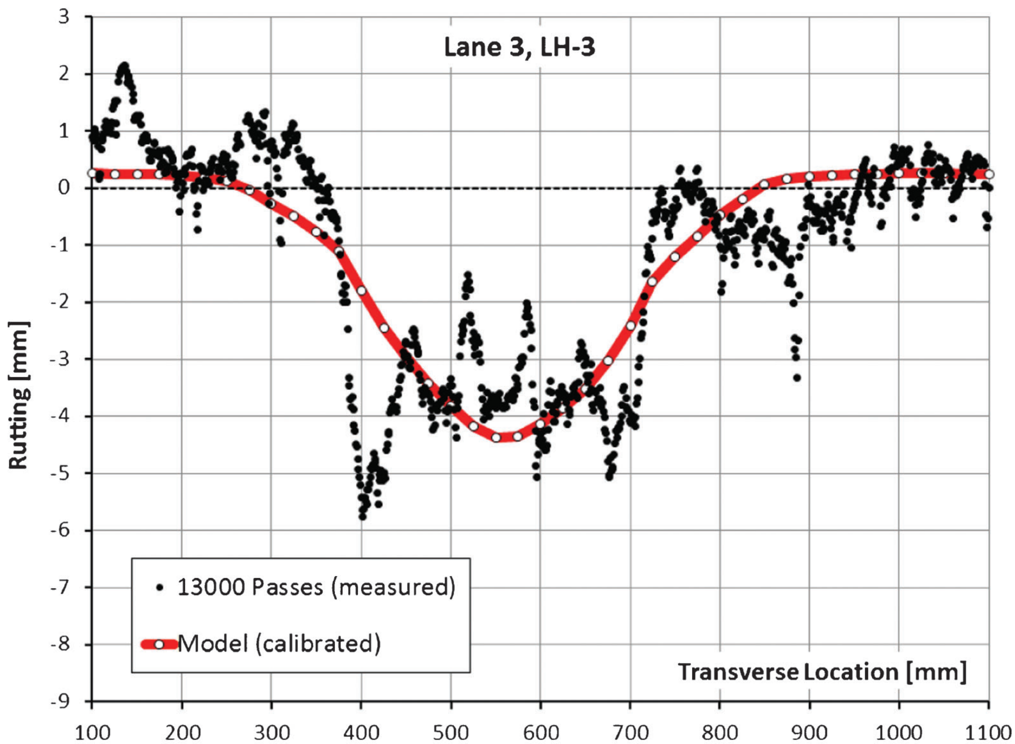


**Figure B.1** Surface rutting data and calibrated model.

surface did not improve, only the width of the rut slightly increased.

## APPEDNDIX B. REFERENCES


1. Levenberg, E., R. S. McDaniel, and J. Olek. *Validation of NCAT Structural Test Track Experiment Using INDOT APT Facility*. Publication FHWA/IN/JTRP-2008/26. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2009. doi: 10.5703/1288284314311.
2. Ambach, W., and H. Eisner. Effective Shear Viscosity and Effective Bulk Viscosity of Firn of a Temperate Glacier. *Proceedings of the Second Symposium on Applied Glaciology, Colbeck, SC, Ed., Annals of Glaciology*, vol. 4, 1983, pp. 10–12.

## APPENDIX C. EXAMPLE QRSS SIMULATION

This appendix presents some examples of the QRSS simulations to show comparisons of various materials, air void contents, location in the pavement, etc. This is not an exhaustive list of all of the simulations run as a part of this project, and it highlights only some of the data input. QRSS-generated summary reports of the data inputs and simulation results run 20 to 100 pages and more, depending on the level of detail, which would be much too voluminous to include in this report.

TABLE C.1
**Example QRSS Simulation Results**

| | | Gradation, mm | | | | | | | Predicted | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mix Description** | **Low Void Location** | **19** | **9.5** | **4.75** | **0.075** | **Binder, %** | **Air Voids, %** | **ESALs, $\times 10^6$** | **Rut, in.** | **E*, ksi** | **Life, yrs** | **Δ Life, yr** |
| NCAT Design | — | 100 | 86 | 64 | 7.4 | 5.8 | 5.8 | 10 | 0.82 | 308.5 | 2.1 | — |
| NCAT 7A | Surface | 100 | 90 | 71 | 8.0 | 6.5 | 6.5 | 10 | 0.76 | 394.0 | 2.57 | 0.48 |
| NCAT 8B | Surface | 100 | 88 | 63 | 7.8 | 6.1 | 6.1 | 10 | 0.771 | 374.4 | 2.72 | 0.63 |
| APT Design Surf | — | 100 | 96 | 69 | 5.0 | 5.7 | 5.7 | 0.81 | 0.035 | 399.4 | 19.69 | — |
| APT Design Int | — | 100 | 96 | 69 | 5.0 | 5.7 | 5.7 | 0.81 | 0.121 | 525.1 | 22.95 | — |
| APT 3% Surf[1] | Surf | 100 | 96 | 69 | 5.0 | 6.1 | 6.1 | 0.81 | 0.036 | 393.7 | 19.75 | 0.061 |
| APT 2% Surf[1] | Surf | 100 | 96 | 69 | 5.0 | 6.5 | 6.5 | 0.81 | 0.036 | 388.9 | 19.82 | 0.128 |
| APT 2% Int[2] | Int | 100 | 96 | 69 | 5.0 | 6.5 | 6.5 | 0.81 | 0.122 | 511.2 | 22.45 | -0.51 |
| APT 2% Surf Higher Fines | Surf | 100 | 96 | 75 | 8.0 | 6.5 | 6.5 | 0.81 | 0.032 | 431.5 | 19.26 | -0.42 |
| APT 2% Surf High Fines | Surf | 100 | 96 | 72 | 6.0 | 6.5 | 6.5 | 0.81 | 0.033 | 416.4 | 19.45 | -0.24 |
| N100 Cat 4 9.5mm Design | — | 100 | 96.1 | 69.8 | 5.6 | 5.7 | 5.7 | 20.2 | 0.15 | 420.6 | 19.6 | — |
| N100 Cat 4 19 mm Design | — | 97.3 | 76.1 | 46.7 | 5.7 | 4.2 | 4.2 | 20.2 | 0.59 | 503.5 | 26.3 | — |
| N100 Cat 4 9.5 mm 2% Air | Surf | 100 | 96.1 | 69.8 | 5.6 | 6.5 | 6.5 | 20.2 | 0.17 | 366.4 | 20.4 | 0.76 |
| N100 Cat 4 19 mm 1% High binder | Int | 97.3 | 76.1 | 46.7 | 5.7 | 5.2 | 5.2 | 20.2 | 0.61 | 471.8 | 25.0 | -1.28 |
| N100 Cat 4 9.5 mm PG76-22 | — | 100 | 96.1 | 69.8 | 5.6 | 5.7 | 5.7 | 20.2 | 0.09 | 603.9 | 19.8 | 0.2 |
| N100 9.5 PG76-22 2% Air | Surf | 100 | 96.1 | 69.8 | 5.6 | 6.5 | 6.5 | 20.2 | 0.11 | 526.1 | 20.5 | 0.73 |
| N100 Cat 4 9.5 9% In Situ | Surf | 100 | 96.1 | 69.8 | 5.6 | 6.5 | 6.5 | 20.2 | 0.18 | 353.3 | 20.6 | 0.97 |

[1]When placed over intermediate course matching design, intermediate course rutted the same as design.

[2]When placed under surface as designed (i.e., not low in air voids), surface course rutted the same as design.