

Application of VESYS3AM in Characterization of Permanent Deformation

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The mechanistic system rutting model VESYS3AM was used to predict the rutting performance of three full-scale accelerated pavement test pads. Since the VESYS3AM system rutting model is not formulated to calculate layer rutting, a method was devised to extract the information by manipulating the layer input rutting parameters. Two MDDs were installed into each MLS test pad to determine layer deformation under a uniformly applied set of loads. For simplicity, all comparisons were made for a two-layer system; that is, an AC layer and a sub-system. The layer deformations from the MDDs were used to calibrate the VESYS3AM model parameters α and μ .

The study represents a laboratory and field determination of material properties, which could be used to model rutting if they were reproduced in other pavements. The predictions from the VESYS3AM system model matched field rutting performance data. Also, the layer rutting contributions were computed, and these compared favorably to MDD measurements.

Keywords: VESYS, Permanent Deformation, Rutting, Performance Prediction, Mobile Load Simulator

INTRODUCTION

Present Serviceability Index (PSI) is the key indicator of the need for repairing, rehabilitating or reconstructing a pavement and rut depth is an important variable in the computation of the PSI. The accumulated rutting also causes a public hazard through the occurrence of aquaplaning due to water ponding in the ruts. Field observations indicate that longitudinal cracking occurs at the interface between the wheel

and non-wheel path areas, as a result of consolidation and or deformation in the wheel path. The cracking and hydro-pounding in the rutted area accelerates pavement deterioration. Clearly, rutting of any degree or form is unacceptable to pavement engineers. However, almost all flexible pavements are susceptible to rutting. Thus, one of the most important aspects in pavement research is to establish a reliable performance prediction equation for pavement design and pavement management purposes.

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In this study, attempts were made to characterize rutting performance through the VESYS3AM program using laboratory and field data. Elastic parameters used in VESYS3AM were derived from repetitive triaxial tests and the FWD backcalculation process. The rutting performance data from the Texas Mobile Load Simulator (MLS) was used. Since the MLS applies controlled traffic to the pavement with one type of truck axle and suspension, the problem of finding an appropriate load equivalency factor to convert mixed traffic to an equivalent axle load was eliminated. All 48 tires in the MLS were inflated to approximately 690 kPa (100 psi). Although overload tests have been conducted by the MLS, only the results from legal load of 150kN (34 kips) per tandem axle have been presented here. The axle repetitions mentioned in this paper represent half of a tandem axle, or a 75kN single axle. Three test pads discussed here have been subjected to two different types of loading; that is, channelized and wandering traffic. The wander pattern applied by the MLS is slightly more concentrated than that of normal traffic. Appropriate factors were applied to account for this, as well as to convert channelized MLS traffic into normally wandering traffic.

One of the challenges in rutting performance prediction is to not only assess overall surface rutting, but also rutting in individual layers. MDDs were installed into every MLS test pad to measure layer rutting. Surface rutting, layer rutting, and other associated information at different axle repetitions were measured at every MLS test site. Asphalt cores were tested under repetitive triaxial conditions to evaluate the rutting potential of the individual layers. Comparisons of layer rutting with field MLS data were made via the VESYS3AM program for three test sites.

OBJECTIVES

The purpose of this study is to use field and laboratory data to calibrate the VESYS3AM system model so that it can approximate the MLS-measured rutting throughout the life of the pavement. Efforts were made to ensure that the predictions were close to the

field rutting performance data in each individual layer. Only after this is accomplished can a performance model be used to predict surface behavior with confidence. It would be inadequate to adjust a rutting model so that it only matched the field-measured surface rutting but failed to explain the proportion of rutting contributed by each pavement layer.

This study represents a laboratory and field determination of material properties which could be used to model rutting if they were reproduced in other pavements. Also, the outcomes of the study could be used to support development of an appropriate laboratory test procedure to model field behavior.

SITE DESCRIPTION

The data from three test sites was used in the investigation. These are pad F5 on US59 in Victoria, and pads 281S1 and 281N1 on US281 in Jacksboro, Texas. The averaged rut depths for pads F5, 281S1, 281N1 are approximately 10.3 mm, 4.31 mm, and 10.11 mm, respectively. These rut depths are from the locations on top of the MDD instrumentation, averaging the left and right wheel paths. The average rut depths between 3 m and 9 m for pads F5, 281S1, and 281N1 are approximately 11 mm, 3.3 mm, and 8.05 mm, respectively (Chen and Lin, 1999). Figures 1 and 2 show the profile of these three test sites. The transverse profiles at the center (6 m line) of the test pads are presented in Figure 3. Tests were terminated at 640 000, 1600 000 and 750 000 axle repetitions for pads F5, 281S1 and 281N1, respectively. Since there were changes in testing parameters (load level, rest period) for pads 281S1 and 281N1 after 1500 000 and 600 000 (respectively) axle repetitions, only the test results prior to the changes are presented here. Some areas of pad F5 were as much as 90% cracked, as measured using a grid system developed by Chen (1998). According to the Yoakum District Pavement Engineer, the condition of F5 at 640 000 axle repetitions warranted rehabilitation, and so the test was terminated. Detailed information on F5 is documented by Chen (1998). Although there was only minor distress on 281S1 after 1 600 000 axle

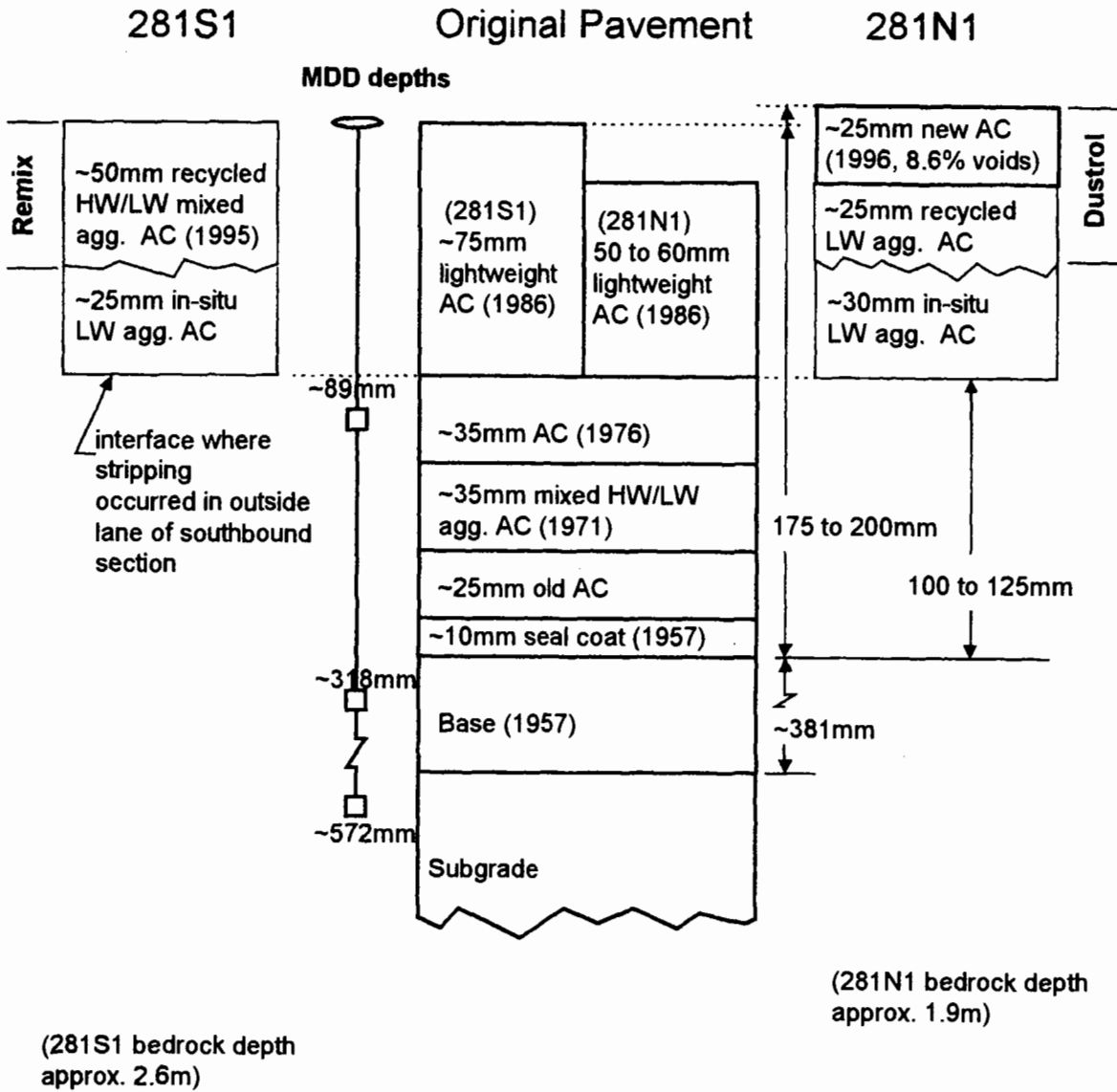


FIGURE 1 Pavement Sections for Pads 281S1 and 281N1

repetitions, the objective to determine the effectiveness of the rehabilitation strategy was achieved, and the test was terminated. No load-associated cracks were observed on pads 281S1 or 281N1. The test on 281N1 was terminated at 750 000 axle repetitions because a conclusion on the comparative study of 281S1 and 281N1 had been reached.

F5, Victoria, Texas

The pavement section is located on a frontage road of US59 near Victoria of the Yoakum District. The pavement consists of 75 mm of type D ACP, 300 mm of lime-treated gravel base (LTB) and 150 mm of lime-stabilized subgrade (LTS). The LTB layer is uncrushed river gravel mixed with 1.5% lime. The

in-situ clay subgrade was stabilized with 5% lime to a depth of 150 mm. Comprehensive test results for this test pad are presented in Chen and Hugo (1998) and Hugo *et al.* (1997).

Channelized traffic was applied to this test pad. Thus, the F5 test pad received more damage than would be caused by normal, wandering traffic. The channelized rutting caused by channelized traffic is evident in Figure 3. For a Structural Number (SN) of approximately 3.4 and a design terminal serviceability index of 2.0, AASHTO recommends a factor of 1.08 to convert 150kN (34 kips) tandem axles to ESALs on the F5 test pad (AASHTO, 1993). Since the MLS axle repetitions used in this paper represent half of a tandem axle, a factor of 0.54 (half of 1.08) was applied before considering any changes in wander pattern. Considering the width of the wheel path under channelized trafficking, a factor of 2 was used to compensate for the load concentration of channelized trafficking. To convert channelized MLS axle repetitions to ESALs under normal traffic, a factor of ($2 * 0.54 = 1.08$) was used for pad F5. For pad 281S1, the MLS was set to apply a wander pattern, which is discussed later.

No validated relationship has been established to link the pavement performance under MLS testing to performance under normal traffic with environmental impacts. However, factors were selected to assess the ability of the VESYS3AM program to model performance.

281S1, Jacksboro, Texas

The test section is in an in-service pavement located on US281 near Jacksboro of the Fort Worth District. The first asphalt layer of the test section was constructed in 1957. There were four major overlays/rehabilitations that were completed in 1971, 1976, 1986, and 1995. Figure 1 shows the complete pavement history. The last major rehabilitation was done in 1995, with 50 mm of recycled ACP. Prior to that, in 1986, there was a major rehabilitation using 76 mm of lightweight aggregate ACP. The pavement structure consists of a total ACP thickness of approximately 180 mm, and a crushed aggregate base of 380 mm.

Laterally distributed loads were applied to the Jacksboro test section within a width of approximately 880 mm, which is the maximum-width wander pattern available from the MLS. Chen *et al.* (1999) reported that the “naturally” occurring wheel paths were about 1.1 m wide for this part of the highway. Due to the more concentrated load applied by the MLS, a conversion factor of 1.2 was used in the analysis. The SN for pad 281S1 is approximately 5.5. For a 150kN (34 kip) tandem axle, SN of 5.5, and design terminal serviceability index of 2.0, AASHTO recommends a factor of 1.08. As discussed earlier, this factor was halved (since the factor is for tandem axles) before considering changes in the applied wander pattern. To convert MLS axle repetitions to ESALs under normal traffic, a factor of $0.54 * 1.2 = 0.648$ was used for pad 281S1.

Chen (1999) reported that bedrock was encountered at a depth of 2.62 m. This bedrock information was incorporated in the VESYS3AM analyses. The bedrock was considered to have an infinite depth and a modulus of 13.78 GPa.

281N1, Jacksboro, Texas

The pavement structure of 281N1 is very similar to 281S1. The major difference is the rehabilitation strategy done in 1996. The southbound lanes of US281 were treated in 1995 with a 50 mm nominal recycling (*Remixer*) operation. The northbound lanes were given a *Dustrol* overlay in 1996, consisting of 25 mm of conventional (no lightweight aggregate) ACP. Below the 25 mm conventional ACP is a nominal 25 mm of recycled ACP. The difference in rehab methods has resulted in a slightly thinner ACP on the southbound lanes than on the northbound lanes. A drilling rig was used to prepare the MDD holes. During the drilling, the bedrock was encountered at 1.93 m from the surface. The bedrock depth was considered in the VESYS3AM analyses, as discussed above.

To convert MLS axle repetitions to ESALs under normal traffic, a factor of ($0.54 * 1.2 = 0.648$) was used for pad 281N1. 600 000 axle repetitions have been applied by the MLS, with an average rutting of 10.11 mm.

VESYS3AM

The VESYS3AM program developed by Kenis et al. (1977) using multi-layer visco-elastic theory was applied in this study. The basic assumption of VESYS3AM rutting models is that the permanent strain is proportional to the resilient strain as follows:

$$\epsilon_p(N) = \epsilon_r \mu N^{-\alpha} \tag{1}$$

where,

- $\epsilon_p(N)$ = vertical permanent strain at load repetition N
- ϵ_r = elastic or resilient strain at the 200th load repetition
- α, μ = material properties that are function of stress state, temperature

From the observations of laboratory-repeated load tests, the logarithmic relationship between the number of repeated loads and permanent strain is approximately linear over a range of load applications. The linear relationship can be described as:

$$\text{Log} (\epsilon_p(N)) = I + S \text{Log} N \tag{2}$$

Where,

- $\epsilon_p(N)$ = the accumulated vertical permanent strain at load repetition N
- N = the number of load applications
- I = the intercept with the permanent strain axis (arithmetic strain value, not log value)
- S = the slope of the linear portion of the logarithmic relationship

By Equation 2, the material parameters, α and μ , are defined as:

$$\alpha = I - S \tag{3}$$

$$\mu = IS/\epsilon_r \tag{4}$$

α and μ are the two parameters that control the permanent deformation behavior of the model. In particular, α is the rate of decrease or increase in permanent deformation as the number of load applications increases, and μ represents the constant of proportionality between permanent and elastic strains (ϵ_r).

TABLE I Suggested Ranges for Rutting Parameters, α and μ , by Kenis (1997)

Layer	Rutting Parameter	Suggested Range
1 (AC)	μ	0.60 to 1.00
	α	0.50 to 0.75
2 (Granular Base)	μ	0.30 to 0.50
	α	0.64 to 0.75
3 (Subgrade)	μ	0.01 to 0.04
	α	0.75

Laboratory repetitive triaxial tests were conducted to determine α and μ values of AC materials. The calculated α and μ values from the repetitive triaxial tests together with material (e.g., thickness and stiffness), weather and traffic parameters were used in VESYS3AM to predict the rutting. Modifications of α and μ values were needed in order to meet the field measurements. Note that no repetitive triaxial test was conducted for the base and subgrade materials to determine α and μ values. The α and μ values used in the study for base and subgrade were obtained from Kenis' recommendation (in Table I) and several trial runs. The values of α and μ depend strongly on the testing methods and the procedures used for fabricating and testing the specimens. Therefore, adjusting α and μ in VESYS3AM to match the field-measured performance is a justifiable maneuver, as long as those parameters are obtained from the cores sampled from the test sites (Kenis et al., 1997).

Characterizing the rutting contributed by a specific pavement layer is an important issue when a performance model such as VESYS3AM is used. Only with such characteristics can the real cause of the rutting be modeled by the performance model chosen. VESYS3AM does not have the capability to directly compute the rutting from each individual layer, but in current form will only yield the total surface rutting. Adjustments to the VESYS3AM analysis procedure were made to estimate the rutting from each individual layer. For instance, the μ value of the AC layer was set to zero in order to compute the rutting contributed by base and subgrade layers. Similarly, μ values for base and subgrade were set to zero to compute the contribution of the AC layer. When μ is zero, the rutting will be zero, because $\epsilon_p(N) = \epsilon_r \mu N^{-\alpha}$.

TABLE II AC α and μ Obtained by Repetitive Triaxial Tests at 40°C (104°F)

Test Sites AC Layer	281N1		281S1	
	Upper	Lower	Upper	Lower
μ	0.12	0.14	0.09	0.15
α	0.53	0.57	0.53	0.64

Although the VESYS5 version now incorporates both system and layer rutting models, it was not available to the authors at the time of writing the paper.

There is a disadvantage to using a more comprehensive model to characterize the base and subgrade materials; that is, more material parameters need to be acquired through field or laboratory tests, and this encumbers the application into routine analysis. The fundamental parameters α and μ are the two which describe the permanent deformation with respect to axle repetitions. In the VESYS program, different α and μ values can be assigned to AC, base and subgrade layers. Representative AC cores and shelby-tube samples can be obtained to run repetitive triaxial tests to yield α and μ values for VESYS analyses. However, in the lab it is difficult to reconstruct the granular base sample to represent the field condition. Additional efforts may be required to accurately calibrate the α and μ values for granular base layers.

Parameters α , μ , and E

Kenis *et al.* (1997) suggested that the α and μ values obtained by laboratory tests are subject to adjustment before they can be used to predict field rutting. Furthermore, they showed that adjusting the field-calibrated α and μ values at one site could result in good predictions of rutting at another site. The α and μ values obtained from the repetitive triaxial tests at 40°C for 281S1 and 281N1 are given in Table II. Repetitive triaxial tests were conducted at two different temperatures; that are, 20°C and 40°C. Interpolation and extrapolation was required to find α and μ at other temperatures. From the thermocouples installed in both test sites of US281, the pavement temperatures during the test periods range from 15.6 to 35°C. A

decision was made to use 15.6, 25.6, 35, and 30 °C to represent the mean four-season temperatures for both US281 test sites. Table III shows the calibrated and adjusted α and μ values for 281S1 and 281N1. Table IV presents the calibrated α and μ values used for F5. Note that the values of α in Table III (p. 26) are similar for the test sites 281N1 and 281S1. However, the μ values of 281N1 are about double those of 281S1. This was not unexpected due to the difference in the nature of the rehab processes. It also ties in with the quantitative analysis done by Hugo *et al.* (1999) in their comparison of the rutting performance of 281 N1 and 281S1. In contrast, the α and μ values for F5 in Table IV are drastically different from those in Table III, since F5 is in a different location and the material properties and mix characteristics are totally different (Hugo *et al.* 1997).

TABLE III The Rutting Parameters α and μ for 281N1 and 281S1

		281N1			
Layer	Rutting Parameter	MID-DEPTH AC Temperature			
		15.6°C	25.6°C	35°C	30°C
1	μ	0.45	0.46	0.52	0.48
(AC)	α	0.75	0.73	0.71	0.72
2	μ	0.21	0.21	0.21	0.21
(Base)	α	0.75	0.75	0.75	0.75
3	μ	0.02	0.02	0.02	0.02
(Subgrade)	α	0.75	0.75	0.75	0.75
4	μ	0.04	0.04	0.04	0.04
(Bedrock)	α	0.75	0.75	0.75	0.75
		281S1			
Layer	Rutting Parameter	MID-DEPTH AC Temperature			
		15.6°C	25.6°C	35°C	30°C
1	μ	0.20	0.21	0.23	0.22
(AC)	α	0.75	0.74	0.72	0.73
2	μ	0.07	0.07	0.07	0.07
(Base)	α	0.73	0.73	0.73	0.73
3	μ	0.02	0.02	0.02	0.02
(Subgrade)	α	0.75	0.75	0.75	0.75
4	μ	0.04	0.04	0.04	0.04
(Bedrock)	α	0.75	0.75	0.75	0.75

TABLE IV The Rutting Parameters α and μ for F5

Layer	Rutting Parameter	MID-DEPTH AC Temperature (°C)			
		15.6°C	25.6°C	35.0°C	30.0°C
1 (AC)	μ	0.30	0.31	0.34	0.32
	α	0.75	0.74	0.72	0.73
2 (Base)	μ	0.28	0.28	0.28	0.28
	α	0.75	0.75	0.75	0.75
3 (Subgrade)	μ	0.02	0.02	0.02	0.02
	α	0.75	0.75	0.75	0.75
4 (Bedrock)	μ	0.04	0.04	0.04	0.04
	α	0.75	0.75	0.75	0.75

Table I shows the ranges for α and μ in different layers suggested by Kenis et al. (1997). The suggested values were based on the calculations for the accelerated pavement facility used by FHWA. Note that not all α and μ values used in this study are in the range suggested by Kenis et al. (1997). When α and μ values that were in the suggested range were used, the predictions would not match the field performance data.

Table V illustrates the modulus values of pads 281N1, 281S1 and F5 at different temperatures. The moduli in Table V were derived from FWD backcalculation, elastic MDD data, and laboratory triaxial test results. Additional information regarding the effects of temperature on the FWD results can be found in Chen et al. (2000). The temperature and modulus relationship used in this study is given as:

$$E_{T_w} = E_{T_c} / [(1.8T_w + 32)^{2.4462} * (1.8T_c + 32)^{-2.4462}] \tag{5}$$

Where,

E_{T_w} : the adjusted modulus of elasticity at T_w , MPa

E_{T_c} : the measured modulus of elasticity at T_c , MPa

T_w : the temperature to which the modulus of elasticity is adjusted, °C

T_c : the mid-depth temperature at the time of FWD data collection, °C

Equation 5 was derived from in-situ FWD tests. An FWD was applied to test the 281S1 and 281N1 pave-

ments just outside the test pad areas. For these tests, an FWD was kept stationary, running periodically as the pavement temperature changed. During this test, the mid-depth (89 mm deep) pavement temperature ranged from 10 to 43.3°C. The program MODULUS 5.1 was then used to backcalculate the moduli at different temperatures.

The seasonal temperatures for 281N1 and 281S1 were accounted for using different temperatures and related moduli. For pad F5, it was assumed that seasonal variation in temperature had little or no effect on the modulus of the asphalt layer. The basis for this was the fact that the FWD deflections remained fairly constant at various pavement temperatures due to the thin AC pavement structure (Chen and Hugo, 1998). Furthermore, the asphalt had substantially cracked very early during trafficking. Thereafter the composite modulus varied very little due to temperature.

TABLE V AC Moduli at Four Seasons for 281N1, S1, and F5

Temperature		Modulus of AC
°F	°C	GPa
<i>281N1</i>		
77 ^a	25.0	2.07
60	15.6	3.81
78	25.6	2.00
95	35.0	1.24
86	30.0	1.58
<i>281S1</i>		
77 ^b	25.0	4.14
60	15.6	7.62
78	25.6	4.01
95	35.0	2.47
86	30.0	3.16
<i>F5</i>		
60	15.6	2.35
78	25.6	2.35
95	35.0	2.35
86	30.0	2.35

a. temperature at which the modulus (2.07 GPa) was measured in 281N1

b. temperature at which the modulus (4.14 GPa) was measured in 281S1

FIELD RUTTING MEASUREMENTS AND COMPARISONS WITH VESYS ANALYSES

Field Rutting Measurements

One of the most important aspects in monitoring rutting performance is to quantify each layer's contribution to rut depth. In this regard, two MDDs were installed for every MLS test pad. Each MDD hole contains three LVDTs to measure deflections at three different depths, as shown in Figure 4. The surface rutting was collected using a transverse profiler. A detailed description of the transverse profiler and data collection can be found in Chen and Hugo (1998). The surface rutting and layer rutting values presented in this study are the averaged values from both wheel paths.

Ideally, the LVDT should be placed at each layer interface, so that the deflection contribution by each layer could be directly measured. Mechanical limitations made this impossible, so the MDD sensors were installed as close as possible to the ideal depths. MDDt, MDDm, and MDDb are used to refer to the LVDTs at the depths of 89 mm, 318 mm and 572 mm, respectively. All three LVDTs are anchored at a depth of approximately 2.2 m. During the installation process, bedrock was encountered at a depth of 1.93 m for test pad 281N1. Figure 4 shows the MDD depths and their relation to the pavement layers for Pads 281S1, 281N1, and F5.

The permanent deformation recorded by the bottom LVDT (MDDb) is the subgrade contribution to rutting. The difference between MDDm and MDDb displacement is the rutting contributed by the bottom 250 mm of base material (see Figure 4 of 281S1). Also, the difference between MDDt and MDDm displacement is the contribution of the bottom 95 mm of AC and top 130 mm of base. The rutting contributed by the top 89 mm of AC was the difference between surface rutting and permanent displacement recorded by the MDDt. Since no LVDTs were installed at the pavement surface, assumption(s) had to be made in order to compute the rutting for each pavement layer. There are many assumptions that can be used to assist

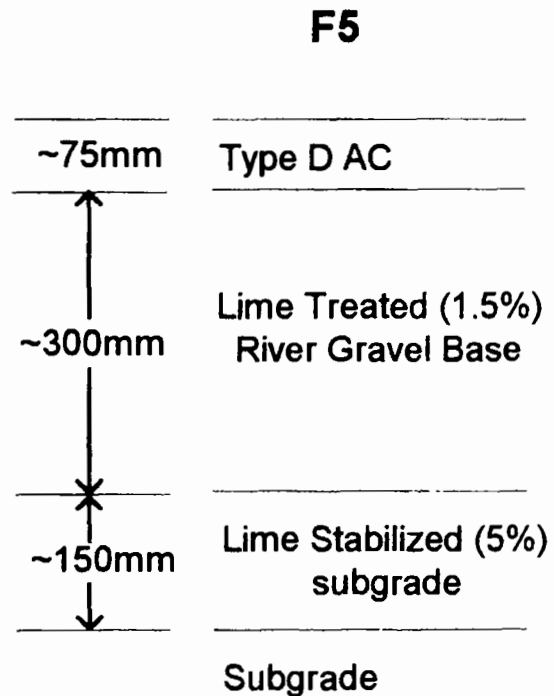


FIGURE 2 Pavement Section for Pad F5

computation of layer rutting. Two assumptions were explored:

Assumption 1

The rutting from the bottom 250 mm of base is proportional to the top 130 mm of base. Thus, the rutting from the 380 mm of base material was calculated by multiplying the 250 mm base rutting by 1.5 (or $1.5 \cdot (\text{MDDm} - \text{MDDb})$) since it is the ratio of the 380 mm base over the 250 mm thick base.

$$\text{Rutting}_{380 \text{ mm base}} = 1.5(\text{MDDm} - \text{MDDb}) \quad (6)$$

Lower AC rutting was then computed by prorating the measured base deformation, as in Equation 7. The factor of 0.5 in Equation 7 is the ratio of the top 130 mm over the measured bottom 250 mm of base.

$$\text{Rutting}_{\text{lower } 95 \text{ mm AC}} = (\text{MDDt} - \text{MDDm}) - 0.5(\text{MDDm} - \text{MDDb}) \quad (7)$$

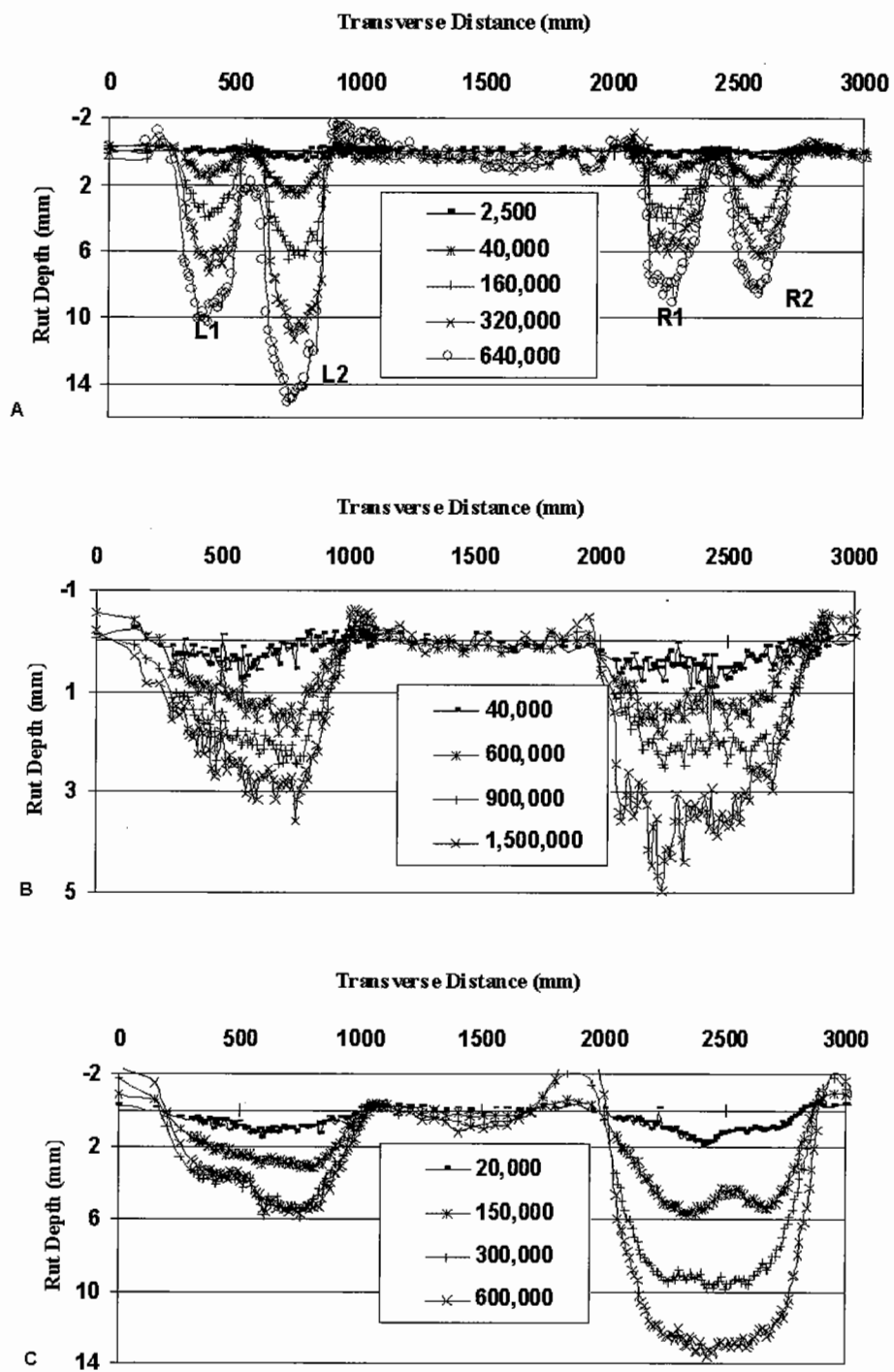


FIGURE 3 Transverse Profiles at Center (6m Line) of Test Pads (A) F5 (Channelized Traffic); (B) 281S1 (Wandering Traffic) (C) 281N1 (Wandering Traffic)

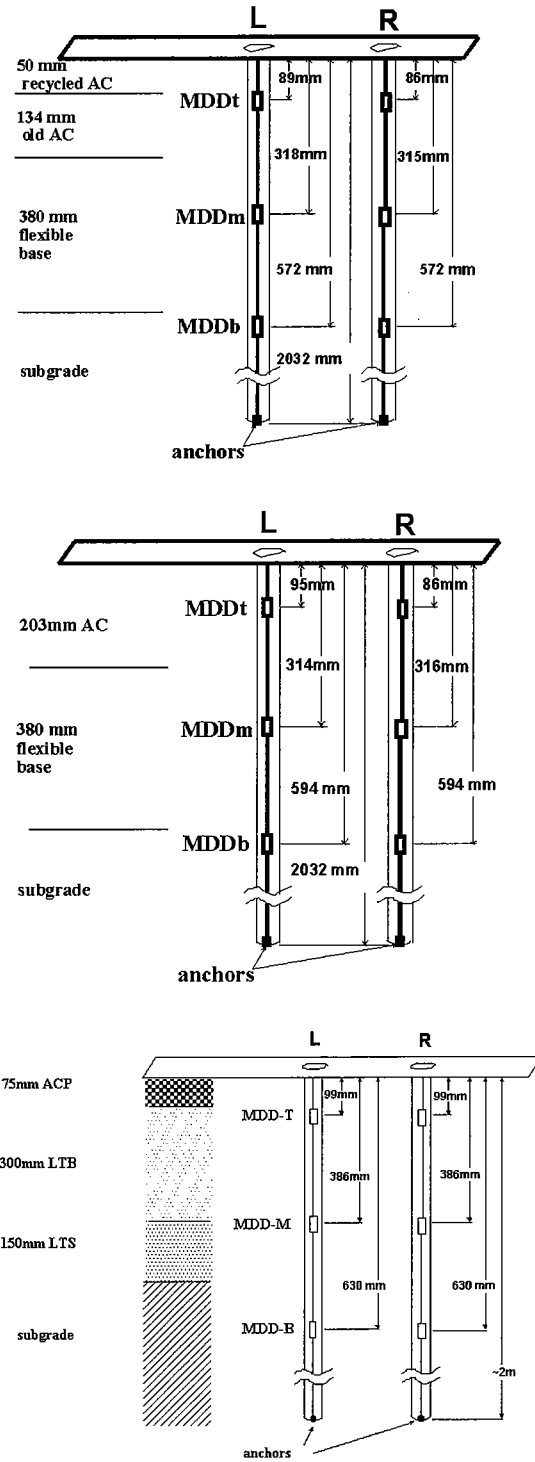


FIGURE 4 MDD and Pavement Layer Depths (Top 281S1, Middle 281N1, Bottom F5)

TABLE VI Rutting and Percent Rutting Contributed by Surface and Base and Subgrade layers in 281N1 (MLS-Measured vs. VESYS3AM-Predicted)

<i>MLS-Measured</i>						
<i>MLS Axles</i>	<i>ESALs</i>	<i>MLS Measured Average Overall Rutting mm</i>	<i>Rutting Contributed by AC mm</i>	<i>% Rutting Contributed by AC %</i>	<i>Rutting Contributed by Base & Subgrade mm</i>	<i>% Rutting Contributed by Base & Subgrade %</i>
0	0	0	0	0	0	0
20,000	12,960	2.28	1.92	84	0.36	16
40,000	25,920	2.55	2.01	79	0.54	21
80,000	51,840	2.82	2.12	75	0.69	25
150,000	97,200	4.51	2.90	64	1.61	36
300,000	194,400	7.37	5.95	81	1.42	19
450,000	291,600	8.74	6.89	79	1.85	21
600,000	388,800	10.11	7.83	77	2.28	23
<i>VESYS3AM-Predicted</i>						
<i>MLS Axles</i>	<i>ESALs</i>	<i>VESYS3 AM Predicted Average Overall Rutting mm</i>	<i>Rutting Contributed by AC mm</i>	<i>% Rutting Contributed by AC %</i>	<i>Rutting Contributed by Base & Subgrade mm</i>	<i>% Rutting Contributed by Base & Subgrade %</i>
0	0	0	0	0	0	0
50,000	32,400	2.97	2.15	73	0.84	28
100,000	64,800	3.51	2.53	72	0.99	28
150,000	97,200	3.88	2.78	72	1.10	28
200,000	129,600	4.93	3.56	72	1.36	28
250,000	162,000	5.57	4.02	72	1.52	27
300,000	194,400	6.05	4.37	72	1.64	27
350,000	226,800	7.63	5.77	76	1.85	24
400,000	259,200	8.64	6.61	76	2.01	23
450,000	291,600	9.41	7.23	77	2.13	23
500,000	324,000	9.67	7.41	77	2.20	23
550,000	356,400	9.92	7.58	76	2.27	23
600,000	388,800	10.14	7.74	76	2.33	23

For 281N1, the factors of 1.5 in Equation 6 and 0.5 in Equation 7 need to be adjusted according to the pavement thickness.

Assumption 2

The rutting on the top of the base should in fact occur at a higher rate than that at the bottom of the base because the stress on the top of the base is higher. Thus, to compute the non-proportional base rutting, ELSYM5 was used with the assumption that the permanent deformation was proportional to the elastic deformation. Although the elastic response may not be proportional to the permanent deformation, this

assumption has been used for years. For example, the Asphalt Institute's rutting criteria is used to limit the subgrade compressive strain. The elastic deformations for the top 130 mm and bottom 250 mm of base were computed at various pavement temperatures. The temperature and moduli relationships are shown in Table V. A trend was found that as pavement temperature increases, the rutting rate for the top 130 mm increases as well. It is important to know that although temperature has no effect on base moduli, higher temperature does weaken AC layers and allows more stress to penetrate into base layers and causes higher rutting from those base layers.

TABLE VII Rutting and Percent Rutting Contributed by Surface and Base and Subgrade layers in 281S1 (MLS-Measured vs. VESYS3AM-Predicted)

<i>MLS-Measured</i>						
<i>MLS Axles</i>	<i>ESALs</i>	<i>MLS Measured Average Overall Rutting mm</i>	<i>Rutting Contributed by AC mm</i>	<i>% Rutting Contributed by AC %</i>	<i>Rutting Contributed by Base & Subgrade mm %</i>	<i>% Rutting Contributed by Base & Subgrade %</i>
0	0	0	0	0	0	0
20,000	12,960	0.35	0.16	47	0.18	53
40,000	25,920	1.24	1.00	81	0.24	19
80,000	51,840	0.70	0.44	63	0.26	37
300,000	194,400	1.13	0.74	65	0.40	35
450,000	291,600	1.95	1.38	71	0.57	29
600,000	388,800	2.33	1.73	74	0.60	26
750,000	486,000	2.53	1.82	72	0.71	28
900,000	583,200	3.39	2.47	73	0.92	27
1,050,000	680,400	3.80	2.57	68	1.23	32
1,200,000	777,600	4.12	2.91	71	1.20	29
1,350,000	874,800	4.12	2.92	71	1.20	29
1,500,000	972,000	4.31	3.10	72	1.21	28
<i>VESYS3AM-Predicted</i>						
<i>MLS Axles</i>	<i>ESALs</i>	<i>VESYS3 AM Predicted Average Overall Rutting mm</i>	<i>Rutting Contributed by AC mm</i>	<i>% Rutting Contributed by AC %</i>	<i>Rutting Contributed by Base & Subgrade mm</i>	<i>% Rutting Contributed by Base & Subgrade %</i>
0	0	0	0	0	0	0
125,000	81,000	1.43	1.00	70	0.42	30
250,000	162,000	1.70	1.19	70	0.50	30
375,000	243,000	1.88	1.31	70	0.56	30
500,000	324,000	2.28	1.59	69	0.69	30
625,000	405,000	2.55	1.76	69	0.77	30
750,000	486,000	2.75	1.90	69	0.84	30
875,000	567,000	3.31	2.36	71	0.95	29
1,000,000	648,000	3.70	2.65	72	1.03	28
1,125,000	729,000	4.00	2.88	72	1.10	28
1,250,000	810,000	4.12	2.96	72	1.14	28
1,375,000	891,000	4.24	3.04	72	1.17	28
1,500,000	972,000	4.35	3.11	72	1.21	28

Stress dependency of the flexible base was ignored for the analysis. The rate of the rutting was computed to be a factor of 1.8; that is, the rutting for 380 mm base is equal to 1.8 of MDDm-MDDb (rutting from the bottom 250 mm of base) for 281N1. It was because the stress is higher and thus the elastic deformation is higher for the top 130 mm than the bottom

250 mm of base. For 281S1, the factor was found to be 1.72. The factors of 1.8 and 1.72 were higher than the 1.5 in Equation 6, as expected. Thus, the lower AC of 281N1 can be computed as in Equation 8.

$$\text{Rutting}_{\text{lower 95 mm AC}} = (\text{MDDt}-\text{MDDm})-0.8(\text{MDDm}-\text{MDDb}) \quad (8)$$

TABLE VIII Layer Rutting for Pads 281N1 and 281S1 at the End of 600,000 Axle Repetitions

	281N1 (mm)	281S1 (mm)
Top (AC)	6.00	1.62
Bottom (AC)	1.83	0.10
Base & Subgrade	2.28	0.60

For the lower AC of 281S1, the factor of 0.8 in Equation 8 needs to be replaced with 0.72.

The results for surface and layer rutting were computed using assumption 2 and are presented in Tables VI, VII, and IX for 281N1, 281S1, and F5, respectively. In the same tables, the measured rutting and percent rutting contributed by surface and base and subgrade layers are also presented. Since the majority of the rutting for pads 281S1 and 281N1 were from the AC layer, the influences of using either assumption 1 or 2 was less than 10% for both cases.

VESYS3AM Predictions

By using the parameters presented above and the scheme devised to extract layer rutting from the VESYS3AM program, the rutting and percent rutting contributed by each layer of test pad 281N1 was calculated. These values are shown in Table VI. More than 70% of rutting was from the AC layer throughout MLS loading, as measured by MDDs. The base and subgrade layers contributed less than 30%. In the preparation of analysis inputs, VESYS3AM required the amount of seasonal traffic for rutting computation. For instance, the 20 000 MLS axles were first converted to ESALs (with a factor of 0.648), then that value was divided by four to obtain the number of axles per season.

Calculation of Layer Rutting

281N1

To obtain AC layer rutting from the VESYS3AM analyses, μ values for base and subgrade were set to zero. Thus, only the AC layer contributed to the overall surface rutting. One way to check if the procedure is correct is to examine the summation of the percent

rutting in the AC, base and subgrade, which of course should equal to 100%. As in Table VI, the percent rutting in the AC plus base and subgrade is close to 100%, with errors of less than 1%. This means that the analysis procedure and the α and μ values chosen in Table III are suitable for modeling the rutting contributed by each individual layer. It is very important that the set of α and μ values not only meet the total surface rutting, but also match individual layer rutting. Furthermore, the same set of parameters was used to predict the permanent deformations at different stages of trafficking. The predictions match well with the field measurements at various test stages, as evident in Table VI. Figures 5, 6 and 7 show the graphical comparisons between field measurements and predictions for site 281N1. The VESYS3AM predictions were done by calculating total damage accumulated over entire loading applications. The entire loading applications were divided into 12 stages, which result in the 12 rutting predictions shown in Table VI. Not all VESYS3AM predictions were fallen at the same times when the permanent deformation data was collected. Another way to perform VESYS3AM analysis is to compute the rutting at the same axle repetitions as those under the MLS. However, the analysis in VESYS3AM uses four seasonal inputs to compute rutting. Although inputs that reflect the actual temperature at each set of axle repetitions can be used, this was abandoned to maintain consistent inputs throughout the analyses. It was found that the analyses using VESYS3AM to compute the rutting at every discrete repetition was not as accurate as if done over entire loading sets. One of the reasons is that in field testing, the early stages of the test were completed in days or weeks, with a temperature range no greater than 6°C. For instance, the first 20,000 axle repetitions for 281N1 were completed in one day, while the mid-depth (AC) temperatures remained about 31.5°C. However, in the VESYS3AM analyses, the same 20 000 axle repetitions were divided into four seasons with temperatures of 15.6, 25.6, 30, and 35°C.

In view of Figures 5, 6 and 7, the VESYS3AM predictions match well with the field measurements for both surface total and layer rutting over the entire test period.

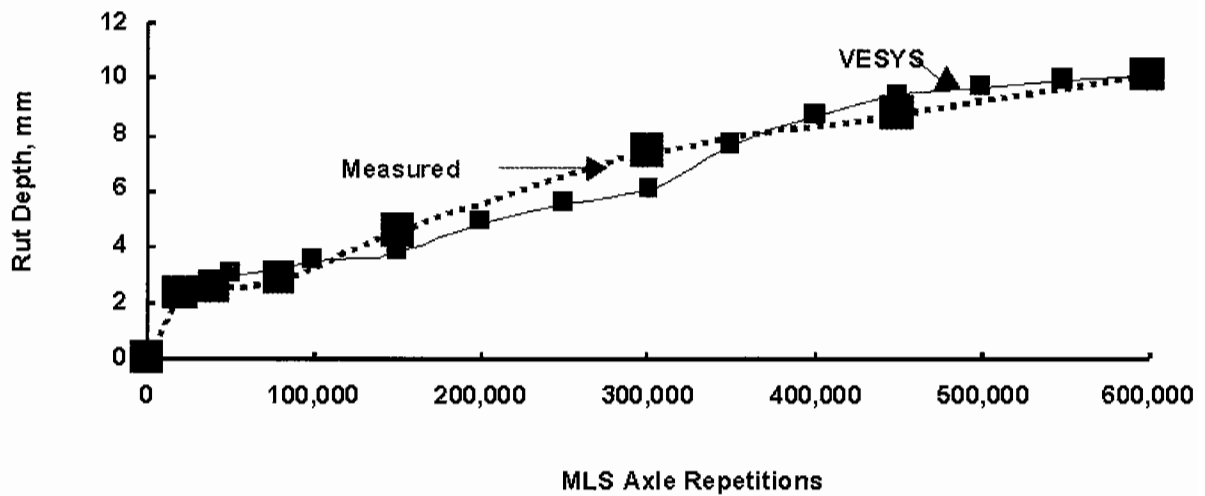


FIGURE 5 Comparison of MLS-Measured and VESYS3AM-Predicted Overall Surface Rutting in 281N1

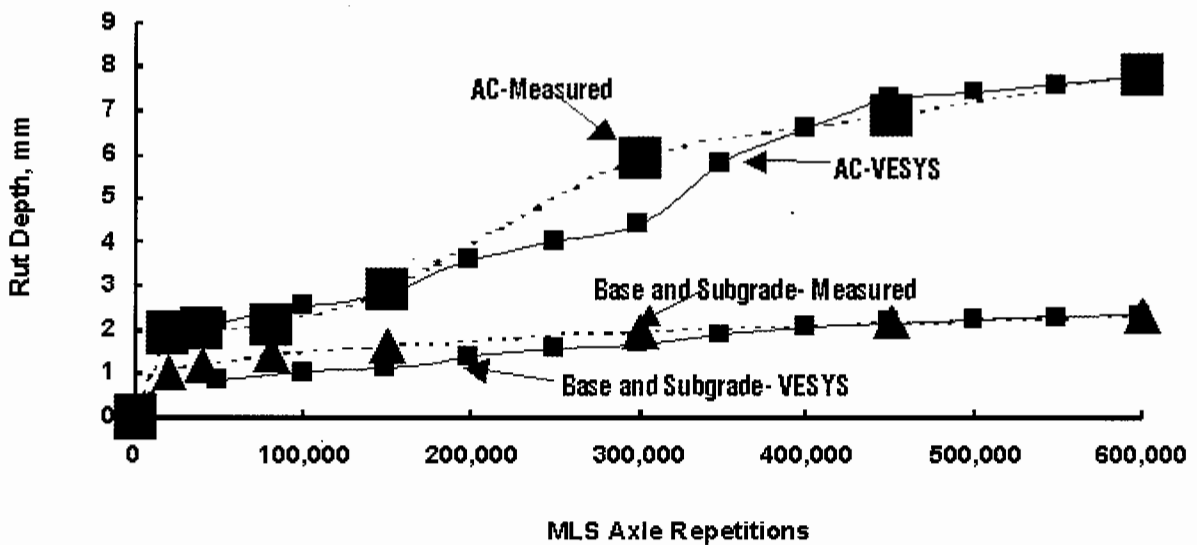


FIGURE 6 Comparison of the MLS-Measured and VESYS3AM-Predicted Rutting in AC and Base and Subgrade in 281N1

281S1

Figures 8, 9, and 10 depict the comparison of the rutting and the percent rutting contributed by AC, base and subgrade layers for both the field measurements (281S1) and VESYS3AM predictions. It was observed that the AC layer is the primary contributor

to the total surface rutting at all repetitions. VESYS3AM predictions overestimate the rutting at the early stages of the test, then “catch up” to meet the field measurements at later stages. Table VII presents the measured rutting and percent rutting contributed by the AC, base and subgrade layers for 281S1.

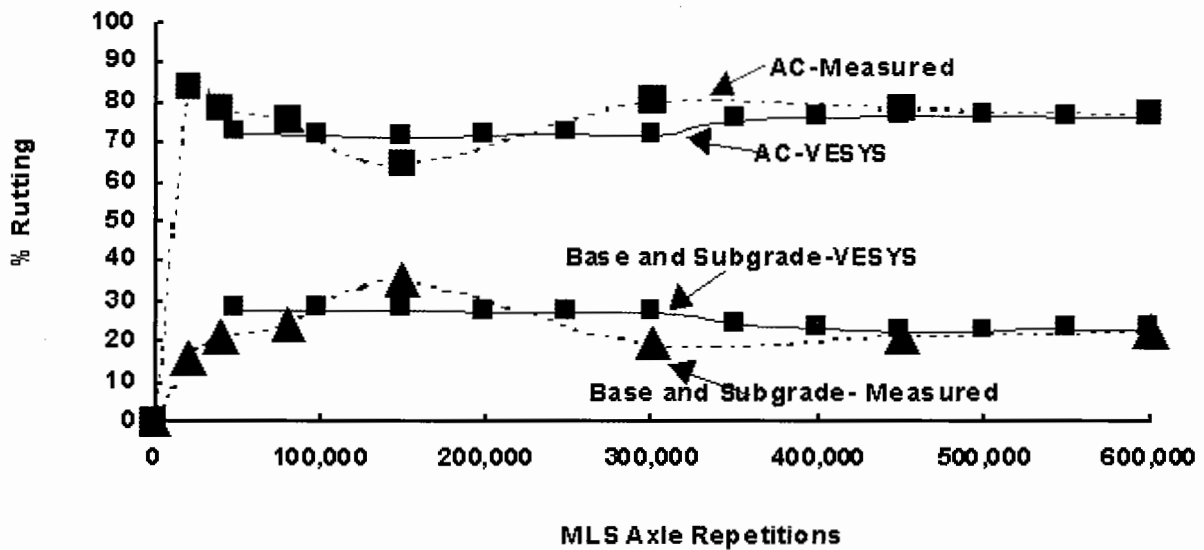


FIGURE 7 Comparison of MLS-Measured and VESYS3AM-Predicted Percent Rutting Contributed by AC and Base and Subgrade in 281N1

Table VII also shows the VESYS3AM-predicted rutting and percent rutting contributed by each layer.

From 20 000 to 1500 000 axles, the AC of 281S1 contributes approximately 70% of overall surface rutting, while the AC in 281N1 contributes approximately 75%, as measured by MDDs. It can be concluded that the AC is the primary cause of the rutting of US281 for both north and southbound lanes. Efforts were made to examine the source of rutting in the AC layer using the MDD data. It was found that approximately 9.8% of the total rutting in 281S1 was from the lower AC, but for the same layer 18% was found in 281N1, as shown in Table VIII. Nazarian et al (1999) reported that the stiffness of upper and lower AC of the northbound pads was 30% and 40% lower than those of the southbound pads. Thus, both upper and lower AC layers in the northbound pads should have (and did have) higher rutting than the southbound pads. After 600 000 axle repetitions, average surface rutting of 2.32 and 10.11 mm were recorded for 281S1 and 281N1, respectively. The top 89 mm layer of pads 281S1 and 281N1 yielded 1.62 mm and 6 mm of rutting, respectively.

F5

The pavement system, in terms of layer thickness and materials, of pad F5 is quite different from those of 281N1 and 281S1. Also, channelized traffic was applied to pad F5, as opposed to wandering traffic applied to pads 281N1 and 281S1. Although no test was conducted to determine α and μ , it is beneficial to see if the VESYS3AM can match the field performance data using selected inputs. These values were derived using the ranges suggested by Kenis (1997) in Table I, with adjustments made through several trial runs. Not all selected inputs were within those suggested by Kenis. Figures 11 through 13 are graphs of the data in Table IX. The comparison of the field-measured and VESYS3AM-predicted overall surface rutting is presented in Figure 11.

As evident in Table IX and Figure 13, the majority of the rutting came from the granular base layer (Chen and Hugo, 1998). The contribution from the AC layer only accounted for approximately 30%. Although 1.5% of lime was added to improve the local river gravel material, the constructed base strength still did not meet the design requirements.

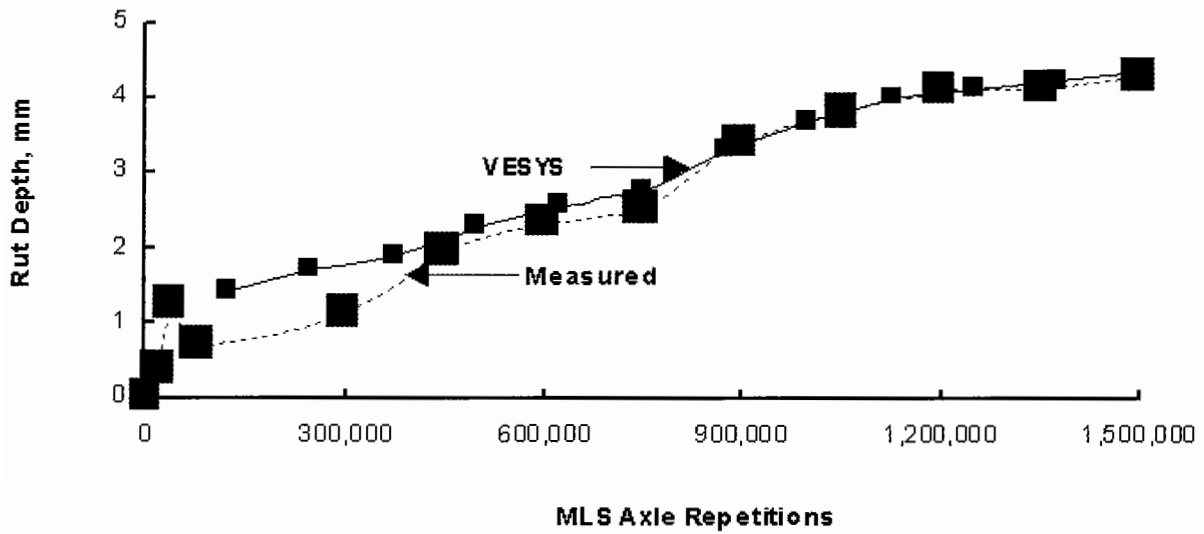


FIGURE 8 Comparison of MLS-Measured and VESYS3AM-Predicted Overall Surface Rutting in 281S1

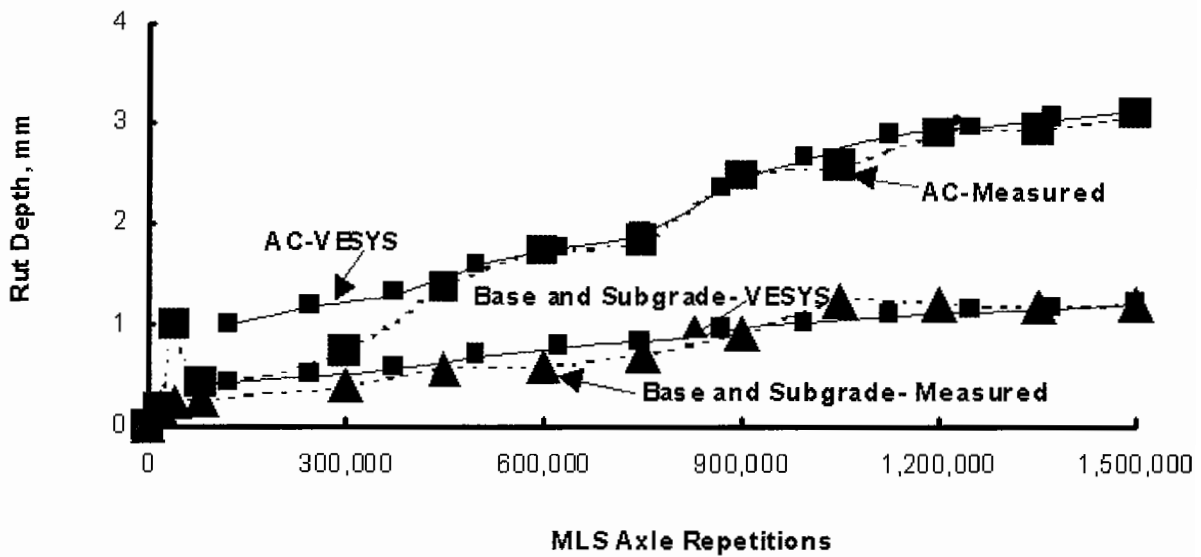


FIGURE 9 Comparison of the MLS-Measured and VESYS3AM-Predicted Rutting in AC and Base and Subgrade in 281S1

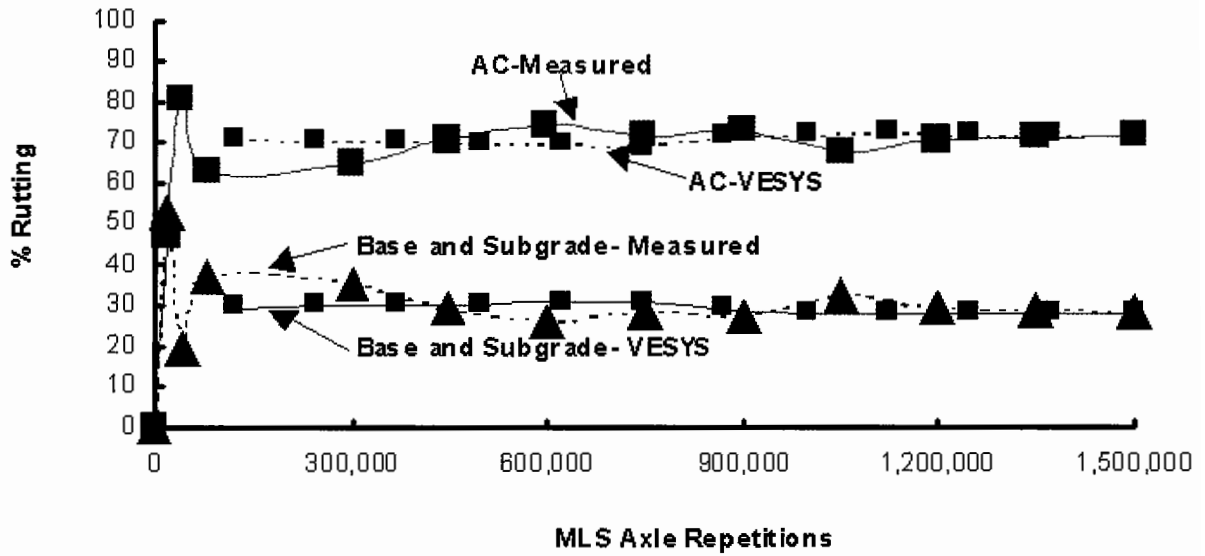


FIGURE 10 Comparison of MLS-Measured and VESYS3AM-Predicted Percent Rutting in AC and Base and Subgrade in 281S1

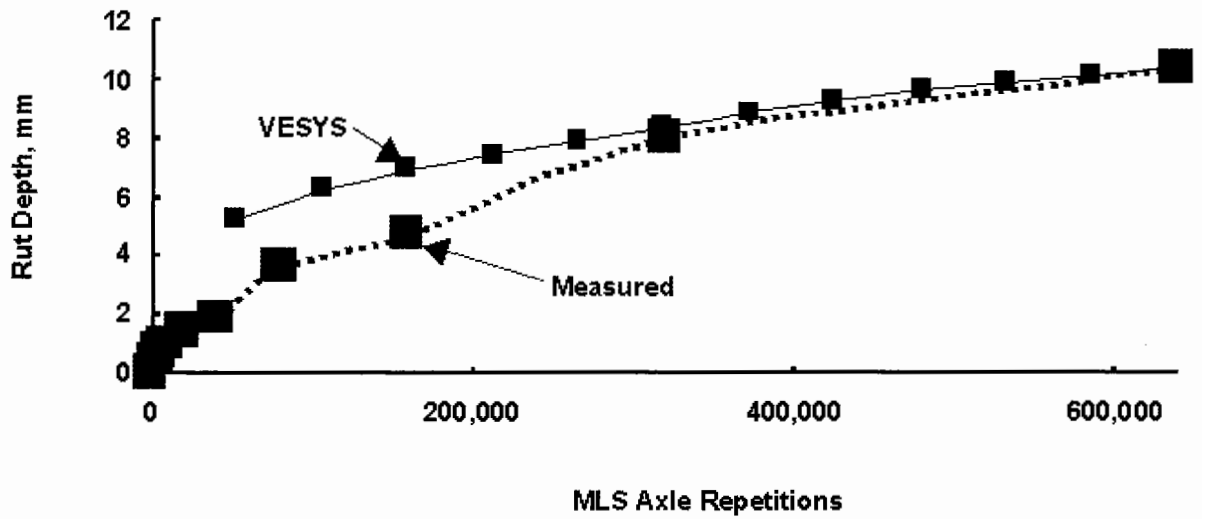


FIGURE 11 Comparison of MLS-Measured and VESYS3AM-Predicted Overall Surface Rutting in F5

TABLE IX Rutting and Percent Rutting Contributed by Surface and Base and Subgrade layers in F5 (MLS-Measured vs. VESYS3AM-Predicted)

<i>MLS-Measured</i>						
<i>MLS Axles</i>	<i>ESALs</i>	<i>MLS Measure d Average Overall Rutting mm</i>	<i>Rutting Contributed by AC mm</i>	<i>% Rutting Contributed by AC %</i>	<i>Rutting Contributed by Base & Subgrade mm</i>	<i>% Rutting Contributed by Base & Subgrade %</i>
0	0	0	0	0	0	0
2,500	2,700	0.44	0.04	8.0	0.41	92.0
5,000	5,400	0.78	0.07	9.0	0.71	91.0
10,000	10,800	1.05	0.11	10.2	0.94	89.8
20,000	21,600	1.46	0.16	11.0	1.30	89.0
40,000	43,200	1.88	0.20	10.4	1.69	89.6
80,000	86,400	3.62	1.50	41.4	2.12	58.6
160,000	172,800	4.73	1.78	37.6	2.95	62.4
320,000	345,600	7.94	2.98	37.5	4.96	62.5
640,000	691,200	10.30	3.56	34.5	6.75	65.5
<i>VESYS3AM-Predicted</i>						
<i>MLS Axles</i>	<i>ESALs</i>	<i>VESYS3 AM Predicted Average Overall Rutting mm</i>	<i>Rutting Contributed by AC mm</i>	<i>% Rutting Contributed by AC %</i>	<i>Rutting Contributed by Base & Subgrade mm</i>	<i>% Rutting Contributed by Base & Subgrade %</i>
0	0	0	0	0	0	0
53,333	57,600	5.21	1.47	28	3.75	72
106,667	115,200	6.19	1.73	28	4.44	72
160,000	172,800	6.84	1.90	28	4.90	72
213,333	230,400	7.42	2.11	28	5.26	71
266,667	288,000	7.88	2.27	29	5.55	70
320,000	345,600	8.28	2.40	29	5.81	70
373,333	403,200	8.77	2.69	31	6.03	69
426,667	460,800	9.20	2.91	32	6.23	68
480,000	518,400	9.57	3.10	32	6.41	67
533,333	576,000	9.84	3.19	32	6.58	67
586,667	633,600	10.10	3.27	32	6.73	67
640,000	691,200	10.33	3.34	32	6.88	67

DISCUSSION

In the VESYS3AM program, α and μ values are the two derived parameters in the rutting model. Although the VESYS3AM program does not compute the layer rutting directly, an adjustment to the analysis procedure does allow the user to obtain the layer rutting. For example, to obtain the AC layer rutting, μ values of base and subgrade were set to zero.

One of the ways to check if the proposed method is correct is to examine the summation of the layer rutting from AC, base and subgrade. If the sum is nearly 100%, that means the procedure is correct. The summations of layer rutting were verified in this study, and they were within 1% of 100%. The calibrated VESYS3AM results match well with the field measurements for both surface and layer rutting.

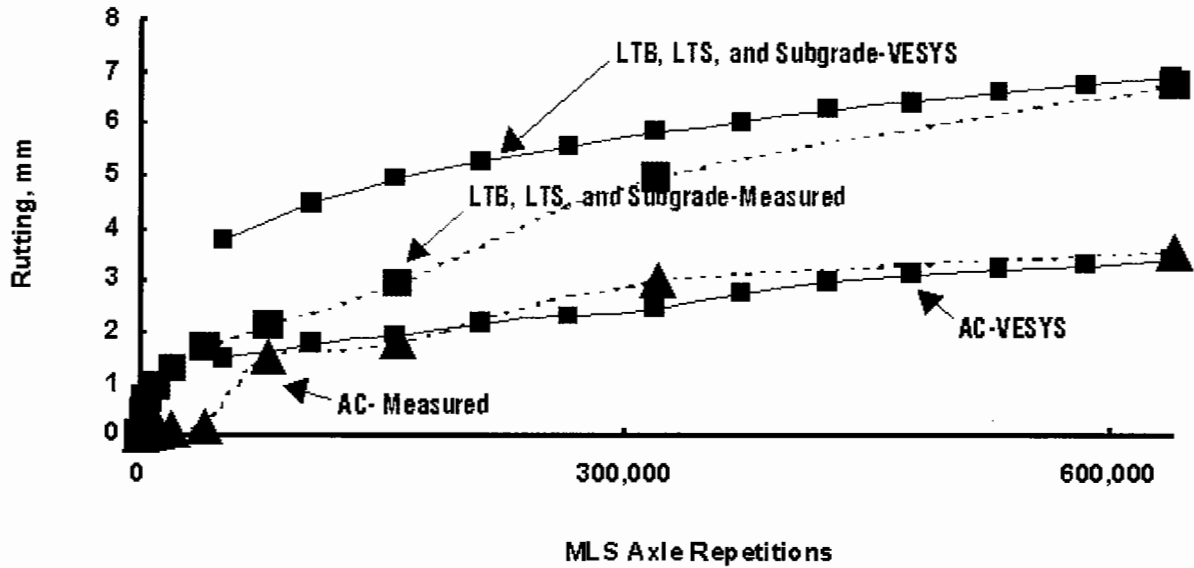


FIGURE 12 Comparison of MLS-Measured and VESYS3AM-Predicted Rutting in AC and Base and Subgrade in F5

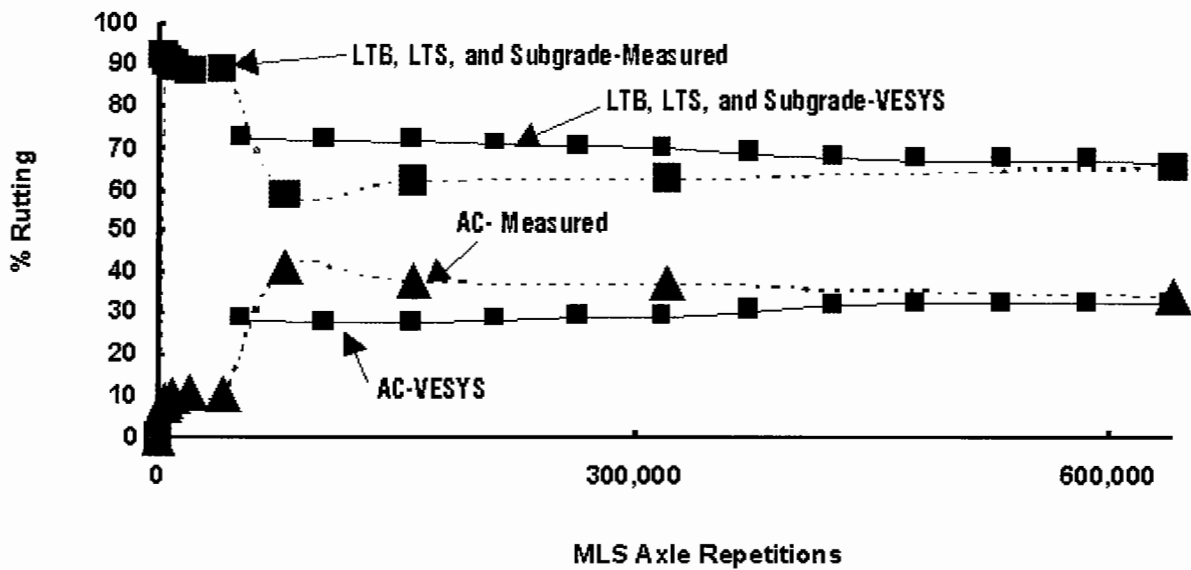


FIGURE 13 Comparison of MLS-Measured and VESYS3AM-Predicted Percent Rutting in AC and Base and Base and Subgrade in F5

As pointed out earlier, the pavement materials used for 281S1 and 281N1 had many characteristics in common and the α values used in the analysis of these two pads were similar. However, the μ values that

were used for 281N1 were approximately double those of 281S1 because of the difference in the nature of the two rehab processes. Not surprisingly, these α and μ values failed to predict the rutting for pad F5,

so a different set of values was used. In general, predictions from VESYS3AM match well with the field measurements, except during the early stages of trafficking.

Although the average rutting of 281S1 was only 4.31 mm after 1.5 million axle repetitions, the test was terminated. The number of axle repetitions was equivalent to 8 years of traffic for the region, and the total rut was much less than the specified design limit. Furthermore, the rate of deformation had become very small. In terms of the FHWA requirement, the design life of eight years of traffic had been met. Of course, the pavement had been somewhat shielded by the MLS, protecting it from the full environmental impact. Nevertheless, the District Pavement engineer felt satisfied with the performance of the Remixer rehabilitation process that had been used on 281S1.

Prediction of Remaining Life

The successful calibration of the VESYS3AM rutting performance model with the field measurements provided an opportunity to attempt performance prediction by extrapolating the rutting results to different axle repetitions. As shown in Figure 14, the field

observed results for pad 281N1 provided an opportunity to calibrate the VESYS3AM model. Since there is a close agreement between the predictions and measurements up to 600 000 axle repetitions (10.11 mm of rutting), the prediction of remaining life can be done with a high level of confidence. The extrapolation was taken to a limiting value of 25 mm. The same set of input data was used throughout the prediction, the only change being the amount of traffic. The result of the extrapolation of all three test sites using the parameters presented above are shown in Figure 15 . The remaining life for a specified criterion (either 12.7 mm or 19.1 mm) can be obtained from this figure for these three pavements. It is apparent that test pad 281S1 was the section with the least rutting potential. It is interesting to see that pad F5 yielded the most rutting before 600,000 axle repetitions but 281N1 caught up at the later stages.

In view of these findings, the authors are confident that the VESYS3AM model has the potential to do prediction of remaining life once it has been calibrated. Additional MLS test results should provide data that can be used to obtain further support for this hypothesis.

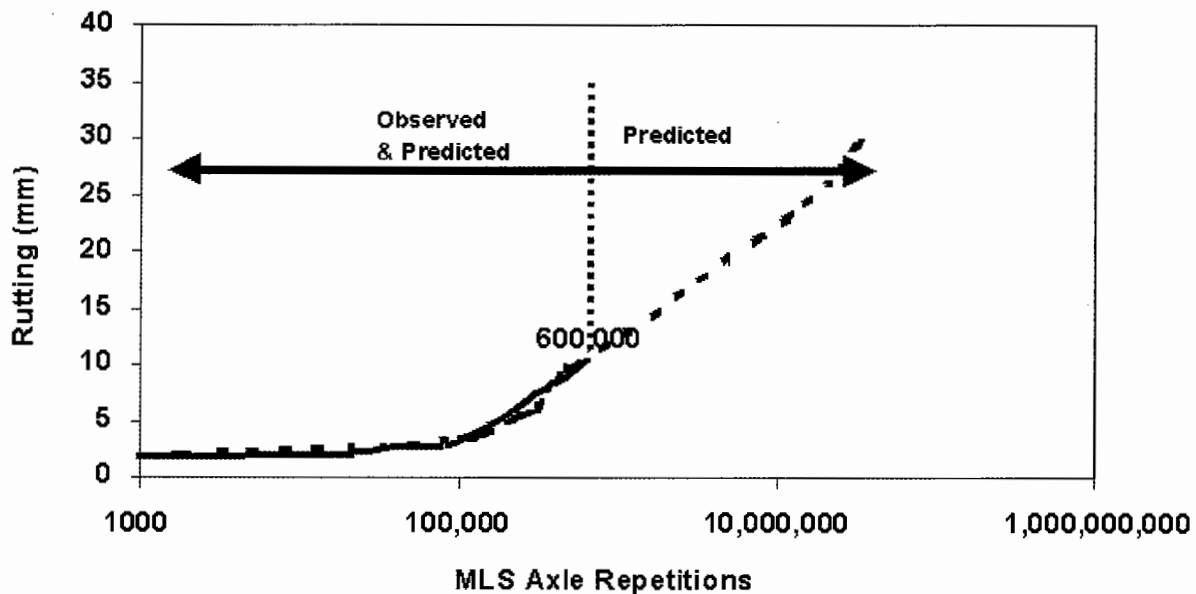


FIGURE 14 Concept of Remaining Life Prediction (281N1)

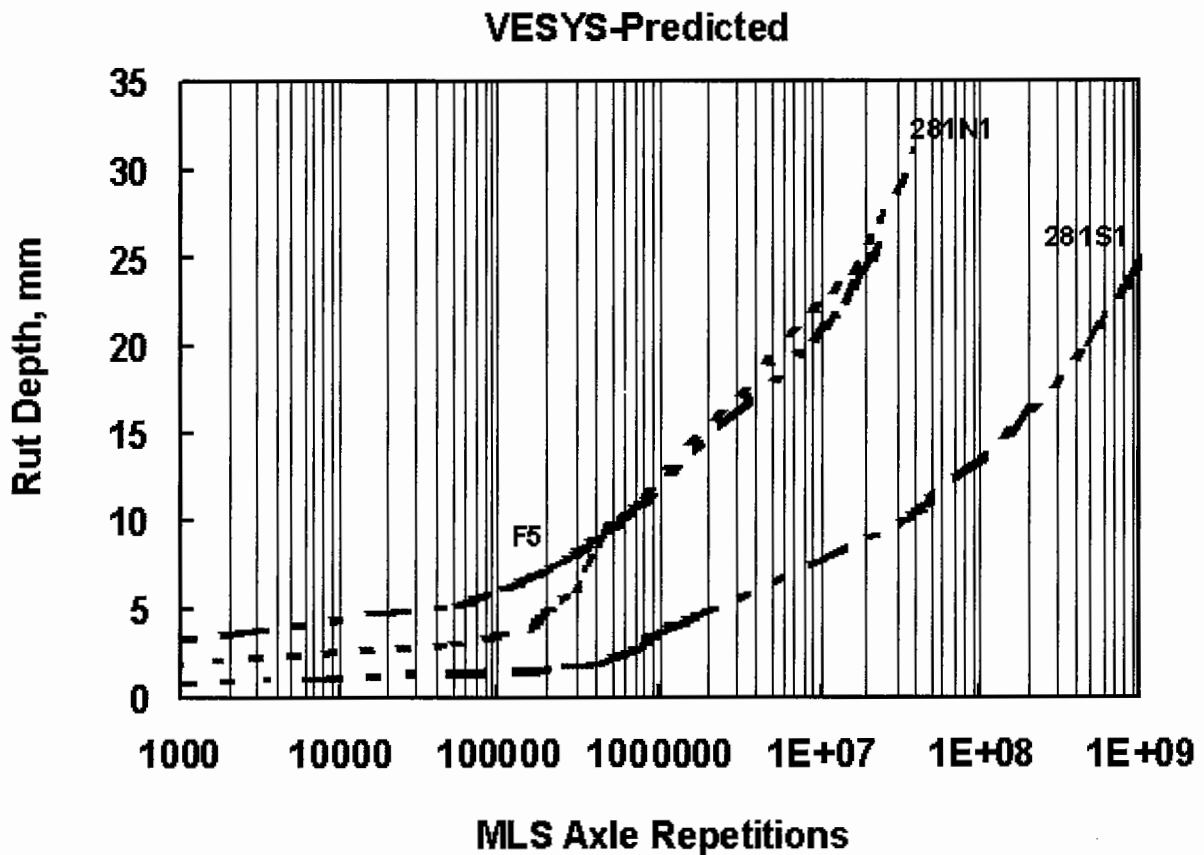


FIGURE 15 Remaining Life Predictions

Although VESYS was applied to predict the pavement performance under short-term or accelerated loading conditions, the authors feel that the VESYS program can also be used to predict long-term performance. Ongoing research has been planned which will apply the VESYS program to estimate pavement performance using LTPP data.

CONCLUSIONS

The field performance data from three MLS test sites was used to calibrate the VESYS3AM program. They are pad F5 in Victoria, TX and pads 281S1 and 281N1 in Jacksboro, TX. Pad F5 was a thin (75 mm) newly

constructed pavement, and 281S1 281N1 are the thick (> 180 mm) aged (>40 years) in-service pavements. VESYS3AM was used to predict surface and layer rutting. Selection of input parameters for VESYS3AM was presented. For simplicity, all comparisons were made for two layer systems; that is, the AC layer and the subsystem (e.g., base and subgrade or, or base, subbase and subgrade).

The laboratory test results were used as a starting point, then a set of field calibrated values were selected. Laboratory testing was done only for the asphalt layers, because the majority (70%) of rutting was from the asphalt layer of two test pads. It was found that the selected α and μ , and other material inputs could be used to adequately describe the rut-

ting behavior. The predictions from VESYS3AM match well with field rutting performance data nicely for various axle repetitions. MDD data indicated that the majority of the rutting for pads 281S1 and 281N1 was from the AC layer, which contributed more than 70%. However, for pad F5 the AC layer contribution was less than 40%. VESYS3AM predictions were able to match those MDD measurements.

The study represents a field determination of these properties that could be used to model rutting if they were reproduced in other pavements. These field values could be also be used for comparisons with laboratory-determined values to support development of an appropriate laboratory test procedure to model field behavior. The authors believe that the remaining life of pavement sections can be predicted with confidence using calibrated VESYS3AM analyses.

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