A Comparison of Flow Number for Plant-Produced Mix to Field Rut Depths under Full-Scale Loading

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ABSTRACT: Researchers are attempting to develop performance tests that can be conducted during the mix design process to identify distress susceptible mixes. One performance test which has shown potential for evaluating the rutting resistance of Hot-Mix Asphalt (HMA) mixtures is the repeated load permanent deformation test. In this test, the flow number is determined as the load repetition value at which the tertiary flow or rapid shear deformation starts in the specimen. Limited studies have shown reasonable correlations between the flow number and field performance. Further investigation of this correlation is needed for future implementation of the flow number in asphalt mix design. In 2006, the National Center for Asphalt Technology (NCAT) Pavement Test Track began testing 16 new surface mixes under full-scale accelerated loading. During the construction of these mixes, plant produced laboratory compacted specimens were made for flow number testing. The laboratory test results were compared with field rut depths of the mixture loaded over 10 million Equivalent Single Axle Loads (ESALs) at the Test Track. The results of this analysis showed that the flow numbers of surface mixtures had average correlations with their associated rut depths at 5 and 10 million ESALs. In addition, another average correlation was found between the rate of rutting (mm/million ESALs) and flow number. This correlation could be used to determine the flow number criteria at different design traffic levels, which may be implemented in the mix design process.

KEY WORDS: Flow number, performance testing, rutting.

1 INTRODUCTION

Rutting in asphalt concrete layers typically occurs in one of the following two mechanisms:

- Rutting can occur from a volumetric reduction in the mixture. As an HMA layer densifies, the aggregate particles in the asphalt mixture develop better stone-on-stone contact to a point. However, when the pore pressure in the binder prevents aggregate contact, the mix loses strength, and rutting occurs (Brown et al. 2002).
- Rutting can also be the result of shear strain development (typically in the top 100 mm of the HMA layer). When the HMA mixture experiences high magnitudes of shear strain, dilation occurs, and the mix deforms (Brown et al. 2002, Christensen 1998).

Mixture rutting is a gradual process stemming from accumulated unrecoverable (plastic) strain in the HMA layers. As rutting progresses and the HMA layer thickness consolidates, lateral movement (shoving) of the HMA occurs under trafficking. This represents a change caused by deformation flow, not volume change (Brown et al. 2002).

Pavement rutting typically occurs in three distinct phases: primary, secondary, and tertiary. Primary rutting happens during the early phases of trafficking. Permanent strain accumulates gradually in the structure; however, the magnitude of permanent strain accumulated per cycle is minimal. Secondary consolidation occurs when the rate of permanent strain per cycle is consistent (i.e. the slop of the curve is relatively linear). The final phase of permanent deformation, tertiary flow, begins when the rate of permanent strain accumulation per cycle increases dramatically, which results in an unstable structure where rutting and shoving occur (Huang et al. 2008, Zhou et al. 2004).

1.1 Flow Number

Simple Performance Tests (SPTs) have been proposed to quickly quantify the resistance of an HMA mixture to common pavement distresses. The repeated load permanent deformation test (also known as the flow number test) has been proposed as one such test for permanent deformation (Witczak et al 2002). This test is conducted by applying several load repetitions on a test cylinder of HMA to characterize the mixture's creep characteristics in relationship to permanent deformation (Bonaquist et al. 2003, Mohammad et al. 2006).

The flow number (F_n) is defined as "the number of load pulses when the minimum rate of change in permanent strain occurs during the repeated load test" (Bonaquist et al, 2003). In other words, the F_n is the number of load cycles at which tertiary flow begins. This value can characterize how well a mixture will resist rutting. The higher the F_n is, the more stable the mix is expected to be in the field (Clyne et al. 2003).

Past research at WesTrack has shown that Fn can rank mixes well in comparison to field measurements (Bonaquist et al. 2003). When comparisons are made between the F_n test and other permanent deformation tests, correlations with the Asphalt Pavement Analyzer (APA) and Hamburg Wheel-Tracking Device are stronger than with the dynamic modulus (Bhasin et al. 2004).

The Federal Highway Administration (FHWA) conducted a study at its Accelerated Loading Facility (ALF) which compared the field rut depths from six test sections with different binders to laboratory testing F_n results. This study concluded that a strong correlation between F_n and field rutting was initially developed, but as trafficking continued on test sections, the correlation between the lab and field began to dissolve (Azari et al. 2008).

Based on past research, pavement engineers have begun to feel more comfortable using this test as an SPT for evaluating the permanent deformation resistance of a mixture; however, more research needs to be conducted to develop stronger correlations between flow number test results and field rutting (Archilla et al. 2007; Kaloush and Witczak, 2002).

1.2 Objective and Scope

In order for flow number testing to be used as an SPT, correlations between laboratory flow number test results and field rut depths are required to establish a minimum criterion. Thus, the objective of this study was to develop preliminary correlations between Fn test results of HMA mixes and their field performance. These correlations can be refined with more data in the future for incorporation into the Superpave mix design methodology to identify rut resistant mixtures.

The objective of this research was accomplished by comparing Fn test results from plant produced laboratory compacted specimens to field-measured rut depths in newly constructed surface mixtures at the 2006 NCAT Test Track. Rut depths were measured weekly for all the test sections at the track using an inertial profiler.

2 TEST PLAN

In 2006, NCAT rebuilt its 2.74 km (1.7 mile) pavement test track in Opelika, Alabama. The test track is an ALF where pavement structures are subjected to approximately 10 million ESALs of trafficking in two years.

A fleet of five vehicles traveling at 72 kph (45 mph) loaded the asphalt pavement structures 16 hours a day, five days a week. These vehicles were tractors pulling three flat-bed or box trailers. This "triple trailer" configuration consisted of a 5,443 kg (12 kip) steer axle, 18,144 kg (40 kip) tandem axle, and five trailing single axles weighing approximately 9,072 kg (20 kip).

Sixteen surface mixtures (Table 1) were placed on the track between 2006 and 2008 as part of a surface mixture performance study. These mixtures underwent a series of laboratory and field tests to fully quantify their permanent deformation characteristics. These surface mixtures were placed on the standard test track perpetual buildup consisting of the track subgrade (A-4), 152.4 mm (6 in) granular base, 101.6 mm (4 in) of permeable asphalt treated base, and 381 mm (15 in) of HMA.

Table 1: HMA quality control (QC) mixture properties

Section	Year	Binder	NMAS, mm	%P_4	%P_{200}	%QC Air	%AC	%RAP	Field Density, %
W3	2006	PG 76-22	12.5	65	7.5	1.9	5.7	20	92
W4	2006	PG 67-22	12.5	66	7.6	2.1	5.8	20	93.9
W5	2006	PG 67-22	12.5	58	8.3	1.7	5.0	45	95.3
S2	2006	PG 76-22	9.5	59	6	2.4	7.4	15	94.6
S6	2006	PG 76-22	12.5	69	7.3	2.9	7.3	15	94.4
S7A	2006	PG 64-22	12.5	71	8.0	2.2	6.5	0	97.8
S7A	2008	PG 64-22	12.5	80	8.4	2.4	5.8	0	NA
S7B	2006	PG 64-22	12.5	76	7.4	1.4	6.1	0	96.1
S7B	2008	PG 64-22	12.5	74	7.6	1.7	5.9	0	NA
S8A	2006	PG 64-22	12.5	66	7.5	2.1	6.2	0	96.1
S8A	2008	PG 64-22	12.5	69	7.3	2.4	5.5	0	NA
S8B	2006	PG 64-22	12.5	63	7.8	2.0	6.1	0	97.8
S8B	2008	PG 64-22	12.5	72	7.1	1.3	6.1	0	NA
E5	2006	PG 67-22	12.5	53	6.2	3.2	4.4	45	94.2
E6	2006	PG 76-22	12.5	59	7.3	3.5	4.6	45	95.5
E7	2006	PG 76-22	12.5	59	7.2	3.6	5.2	45	96.2

*NA: Not applicable

2.1 Field Performance Measurements

Every Monday, weather permitting, trucking operations were suspended at the track to conduct surface condition surveys. These surveys documented the performance of the experimental sections. Field performance evaluations focused on the middle 45.7 m (150 ft) of each 61 m (200 ft) test section to eliminate the effects of transition at section ends. Rutting was measured using a high speed Automated Road Analyzer (ARAN) van and calibrated using dipstick measurements.

2.2 Laboratory Flow Number Testing

Test specimens were cut and cored from 150 by 170 mm Superpave gyratory compacted specimens. The final samples were 100 mm in diameter and 150 mm tall with air voids between 6.5 and 7.5 percent as this target range was closer to the field densities of the mixes. The samples used in this study were also previously tested for dynamic modulus (E*). Both E* and F_n testing were completed in an Asphalt Mixture Performance Tester (AMPT).

LTPPBind version 3.1 estimates the 50% reliability Performance Grade (PG) for the Opelika, Alabama area is a PG 64-22 binder; therefore, F_n testing was originally conducted at 64°C. Using this temperature would have allowed direction comparisons between Fn and APA results that had been previously tested for these mixtures. However, when testing commenced at this temperature, many of the specimens reached the F_n very quickly (under 30 cycles). To alleviate this problem, the testing temperature was reduced to 58°C (one binder grade), and the test results reached a reasonable Fn.

The specimens were run without the use of a confining pressure at a deviator stress of 486 kPa. While unconfined, the HMA sample was subjected to a 0.1 second axial compressive load followed by a 0.9 second rest period (Zhou et al. 2004). During this process, permanent strain was measured versus the number of load cycles. The permanent axial strains are then differentiated to calculate F_n after testing was completed.

Two models, classic power and Francken, are commonly used to determine the F_n of an HMA specimen. Comparing the results of the power model to those of the Francken model, the Fn results determined using the Francken model were more repeatable and provided a good representation of all three stages of deformation including the tertiary or permanent deformation stage (Biligri et al. 2007). Thus, the Francken model was used to determine the onset of tertiary flow for the following analyses (Francken 1977):

$$\varepsilon_p(N) = aN^b + c(e^{dN} - 1) \quad (1)$$

Where: $\varepsilon_p(N)$ = permanent strain at 'N' cycles
N = Number of cycles
a, b, c, d = regression coefficients.

3 TEST RESULTS

The F_n results and field-measured rut depths at two trafficking levels are provided for the 156 surface mixes in Table 2. The F_n and microstrain values are the average of three replicates conducted on a single mixture. This table also provides the total amount of ESALs trafficked on each test section before it was replaced.

Eight of the sixteen mixes did not undergo 10 million ESALs of trafficking. At approximately 5.7 million ESALs of traffic, sections S7A, S7B, S8A, and S8B exhibited excessive rutting; therefore, on February 1, 2008, these four sections were milled and inlaid with similar mixes. These new mixes (noted by construction year 2008) underwent an abbreviated trafficking pattern as well.

Table 2: Test results and field measurements

Section	Year	Flow Number		Strain at Tertiary Flow	Rutting, mm		Total Traffic, ESALs $*10^6$
		F_n, cycles	COV, %		At ≈ $5*10^6$ ESALS	At $10*10^6$ ESALS	
W3	2006	416	36	25,565	2	2.6	10.02
W4	2006	287	29	24,300	3.4	5.3	10.02
W5	2006	473	24	19,239	1.9	1.9	10.02
S2	2006	1110	3	20,424	0.7	0.7	10.02
S6	2006	1177	58	21,543	1.3	2.3	10.02
S7A	2006	348	26	28,245	33.4	NA	5.70
S7A	2008	127	26	28,986	20.5	NA	4.32
S7B	2006	407	23	20,792	21.3	NA	5.70
S7B	2008	271	26	26,620	16.5	NA	4.32
S8A	2006	301	62	17,606	23.0	NA	5.70
S8A	2008	118	43	23,894	11.2	NA	4.32
S8B	2006	280	36	22,106	24.6	NA	5.70
S8B	2008	126	18	28,842	28.9	NA	4.32
E5	2006	1185	69	20,816	1.2	1.2	10.02
E6	2006	1603	64	23,027	0.6	0.6	10.02
E7	2006	1777	52	18,984	0.6	0.7	10.02

4 CORRELATIONS BETWEEN LABORATORY AND FIELD PERFORMANCE

Three analyses were conducted as part of this investigation. The first analysis compared the field rut depth to the strain magnitude at the onset of tertiary flow. The second analysis attempted to link the F_n of a mix to the field rut depths at both 5 and 10 million ESALs. The third analysis normalized the rut depth by traffic level and compared it to the F_n of each mixture.

4.1 Strain at the Onset of Tertiary Flow versus Field Rut Depth

During F_n testing, strain magnitude at the start of tertiary flow was determined using the Francken model. It was hypothesized that mixtures failing at lower strain magnitudes would perform better in the field compared to mixtures exhibiting higher strains at the start of tertiary flow since the mixture would be stiffer and, therefore, more rut resistant. A plot was then generated to compare the strain at the start of tertiary flow to rut depths at 5 and 10 million ESALs (Figure 1).

As can be seen from the data, neither comparison developed much of a trend between rut depths and strain at tertiary flow. Three data points in the 5 million ESAL analysis seem to dissolve the correlation between the strains at tertiary flow and rut depth. These three data points were all a part of the low air void surface experiment (S8A 2008, S7B 2006, S8B 2006) where mixes were over-asphalted to reduce the mixture QC air voids and induce severe rutting.

These test sections were part of an experiment that exhibited much higher rut depths (see Table 2) than conventional rutting failure thresholds. The mixtures that were a part of this study were removed and replaced after 5.7 million ESALs; therefore, data were not available for a 10 million ESAL comparison.

The 10 million ESAL correlation is based on minimal data, and it only has one test section that exhibited rutting greater than 5 mm. To strengthen and validate this correlation, more test sections which exhibit more significant rutting are needed. Based on data gathered for this analysis, strain at the start of tertiary flow is not an adequate design qualification for predicting the resistance to permanent deformation for an HMA mixture.

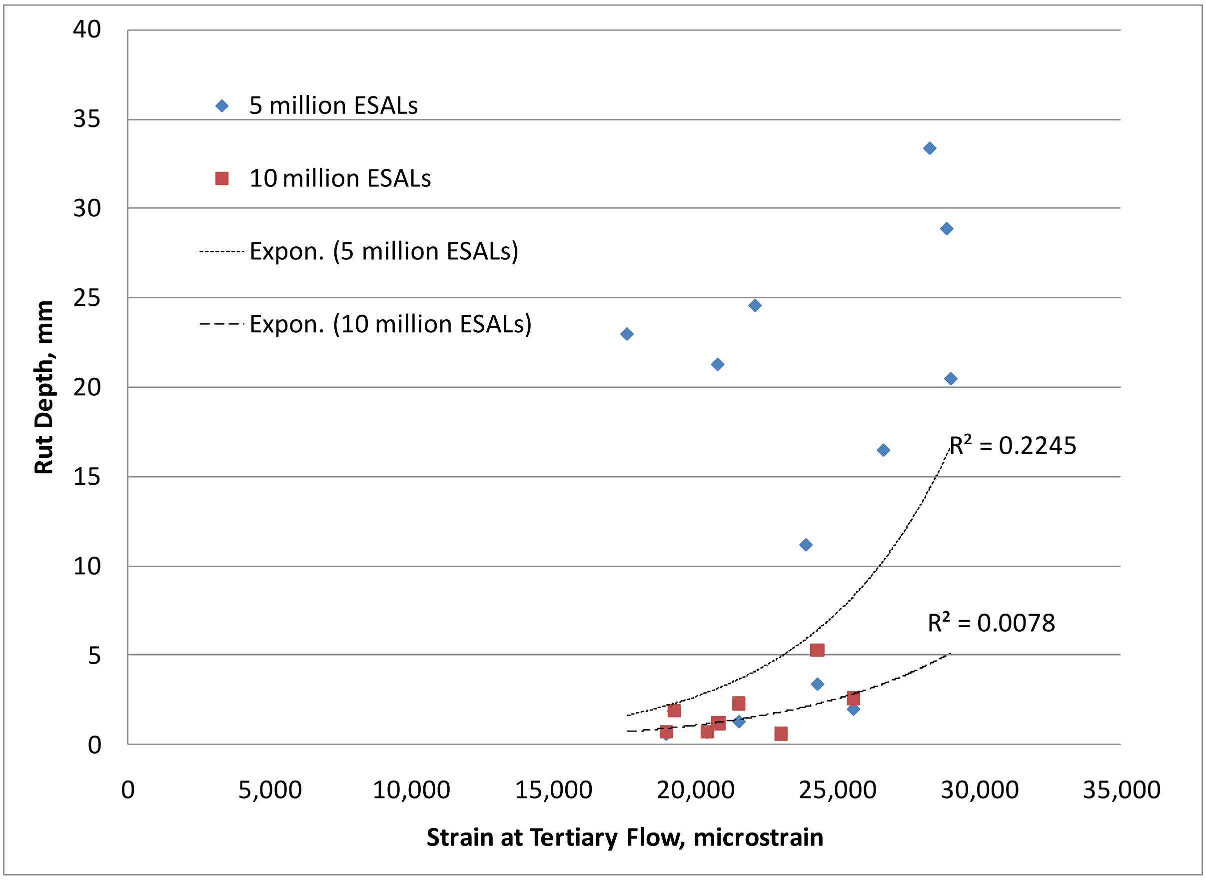

Figure 1: Strain at onset of tertiary flow versus rut depth.

4.2 Flow Number versus Rut Depth

If a single F_n could be prescribed as a criterion for rut-resistant mixtures, then the Fn test could easily be implemented as a performance tool in mixture design. To validate this concept, the Fn values determined using the Francken model were plotted against field measured rut depths at 5 and 10 million ESALs.

While the two relationships graphically look different, statistically speaking, the models for both 5 and 10 million ESALs have the same R^2 (0.71). The 10 million ESAL data were once again skewed by the lack of substantial rutting at this traffic volume. The dataset was once again reduced by the exclusion of the low air voids experiment. More data are needed to model the relationship at 10 million ESALs.

Both the 5 and 10 million ESAL rut depths are more comparable to flow number than strain at the onset of tertiary flow; therefore, it would be more appropriate to use flow number as a permanent deformation criterion than strain at the onset of tertiary flow.

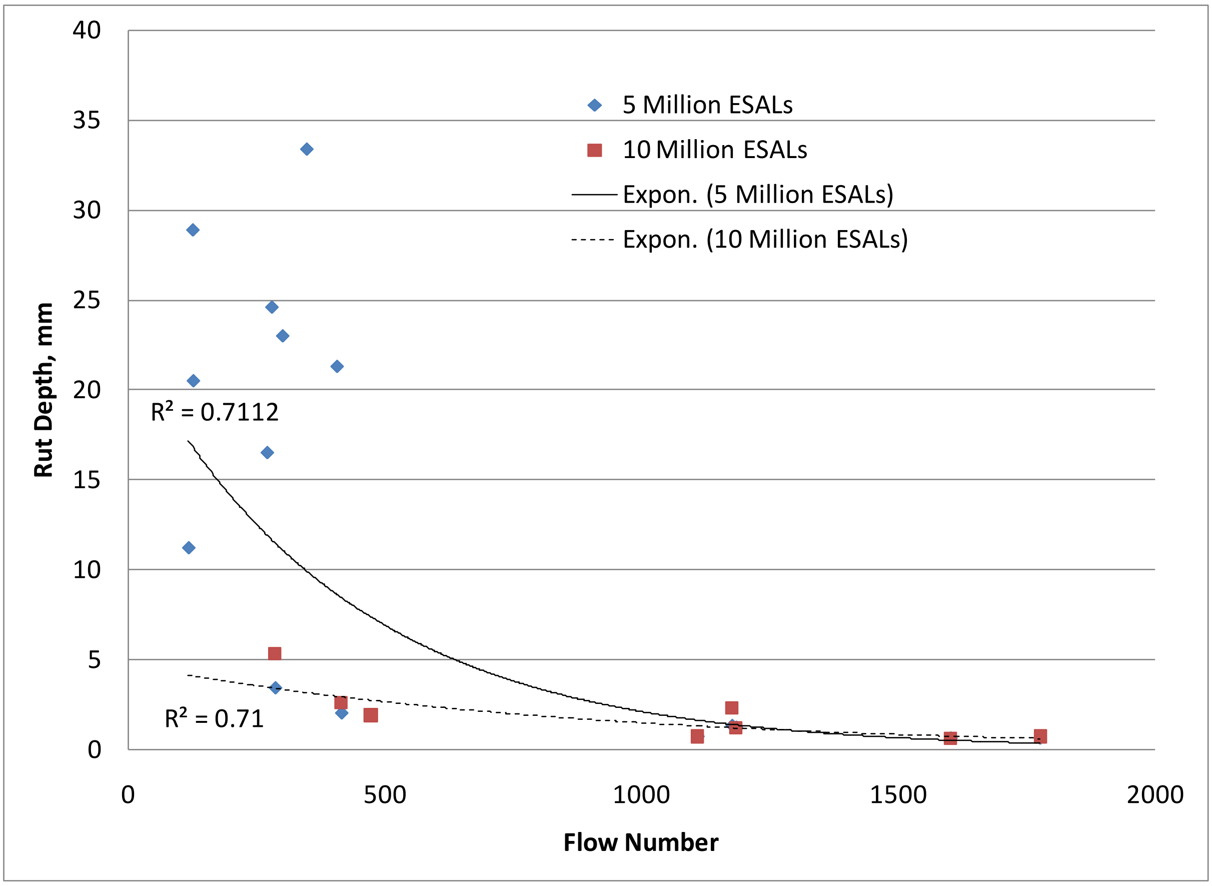

Figure 2: Flow number versus rut depth.

4.3 Flow Number versus Rate of Rutting

In order for F_n to be practical in the design process, a set of criteria need to be developed for multiple trafficking volumes. A practitioner should be able to look at a design table and determine a required F_n for the expected traffic on a pavement structure.

For this analysis, the rut depths were normalized by traffic to determine the rate of rutting (mm/million ESALs). Field rutting measurements became erratic above 12.5 mm; therefore, the rate of rutting was calculated by dividing the last measurement less than or equal to 12.5 mm by traffic volume to the date the measurement was taken. If a test section never accumulated 12.5 mm of rutting, then the entire trafficking cycle was used to calculate the rate of rutting. Table 3 shows how the field rate of rutting for each mix analyzed was calculated. Figure 3 shows the correlation between the laboratory Fn and the field rate of rutting determined in Table 3.

This correlation allows the determination of design F_n values for different traffic levels. The general trend was that mixes with lower F_n values had higher rates of rutting. One should notice that the model slightly under predicts the rate of rutting in many of the test sections. This is due to three test sections that seem to skew the model to the left in Figure 3. These three test sections had F_n values slightly less than 130. While all three test sections exhibited excessive rutting, their rates of rutting were very different. This leads one to believe that there might be a critical F_n value below which a mix will fail in the field no matter the rate.

Table 3: Determining rate of rutting.

Section	Year	F_n	Rut Depth, mm	Traffic until Critical Rut Depth, *10^6 ESALs	Rate of Rutting, mm/10^6 ESALs
W3	2006	416	2.6	10.02	0.26
W4	2006	287	5.3	10.02	0.53
W5	2006	473	1.9	10.02	0.19
S2	2006	1110	0.7	10.02	0.07
S6	2006	1177	2.3	10.02	0.23
S7A	2006	348	11.7	2.88	4.06
S7A	2008	127	11.6	2.33	4.98
S7B	2006	407	12	3.46	3.47
S7B	2008	271	12.5	2.43	5.14
S8A	2006	301	12.3	3.27	3.76
S8A	2008	118	11.5	2.76	4.17
S8B	2006	280	11.5	3.35	3.43
S8B	2008	126	8.9	1.83	4.86
E5	2006	1185	1.2	10.02	0.12
E6	2006	1603	0.6	10.02	0.06
E7	2006	1777	0.7	10.02	0.07

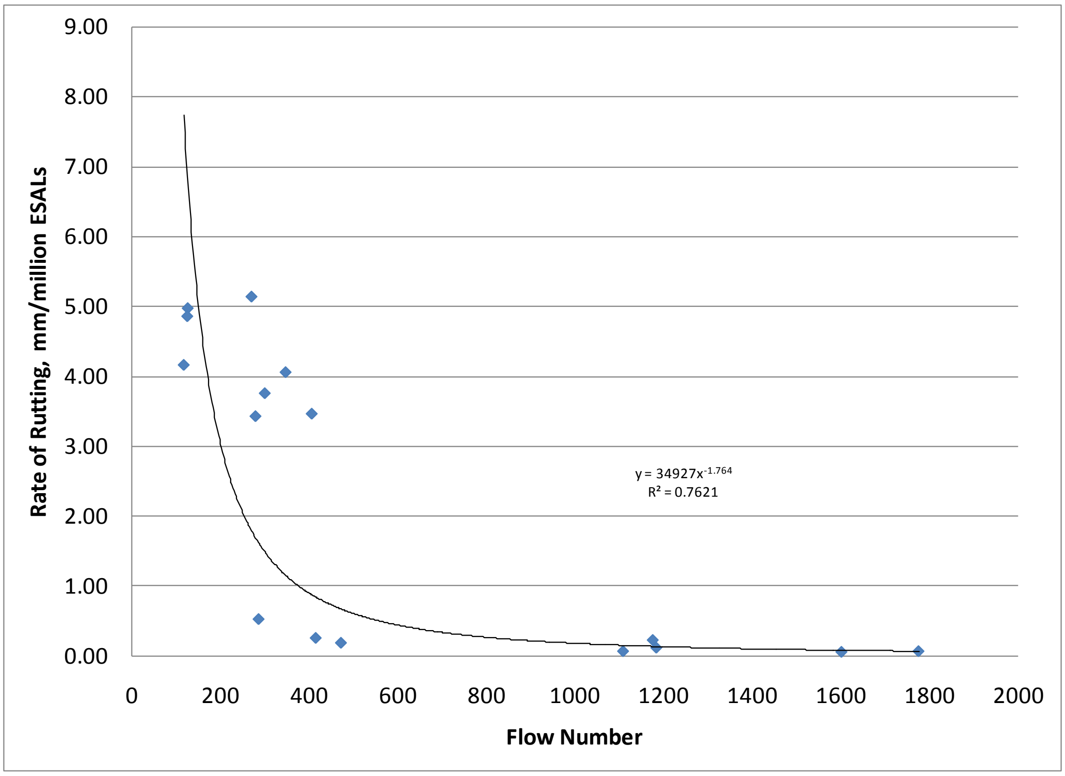

Figure 3: Rate of rutting versus flow number.

5 FLOW NUMBER CRITERIA

When trying to determine which correlation should be used to develop F_n criteria, two considerations must be addressed. First, the correlation should be relatively strong. Second, in order for state agencies to use this correlation, the relationship must provide criteria for a range of field rutting thresholds and design traffic levels.

When considering the correlations that were developed, the relationship which showed the most promise in developing flow number criteria was the relationship between flow number and the rate of rutting. More data are needed with greater rut depths to strengthen the 5 and 10 million ESAL versus flow number relationships.

6 CONCLUSIONS AND RECOMMENDATIONS

Based on the correlations drawn between the F_n test results and the field rut depths from the 2006 NCAT Pavement Test Track study, the following conclusions can be drawn:

- No correlations between rut depths and the strain at the onset of tertiary flow were discovered at the test track.
- Better correlations were found between the laboratory-tested F_n and the field measured rut depths at 5 and 10 million ESALs. However, more data were available for the 5 million ESAL analysis than the 10 million ESAL analysis.
- The rates of rutting in the field provided the strongest correlations to F_n values. This analysis technique can provide Fn criteria for multiple traffic levels and rut depth criterion; however, the relationship needs to be strengthened before it can be implemented.

Since F_n is emerging as a performance test which can be incorporated into the design process, the following recommendations are made:

- Continue to conduct research to develop a more robust correlation between the laboratory F_n and the rate of rutting in the field. This is a practical approach for using F_n in HMA mixture design. This could include testing mixtures at multiple stresses and temperatures to fully characterize the mixtures.
- Develop a methodology for using F_n in a multi-layer analysis. Binder layers also rut and influence the stability of surface mixtures. Using both Fn values will allow the rut-susceptibility of the entire pavement structure to be considered; this dataset could be bolstered with the inclusion of other test sections at the track if this analysis had been developed.
- This research was conducted on plant-produced mix. More research should be conducted on relating plant-produced mixes to laboratory prepared mixes.

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