Construction variables. Table 16 shows the results of the correlation analysis performed on nine construction variables. Again the correlation coefficients are low with the best correlation being with the material passing the #8 sieve followed by the VTM with R values of -0.53 and -0.32, respectively for the wearing course. The percent passing the #8 sieve showed up as significant in other models and will be discussed in detail later.

Since it is difficult to quantify the construction dates and construction traffic control, only qualitative evaluations can be made. The construction seasons given in Table 76 were related to the rate of rutting (rut depth divided by the square root of traffic in million ESAL's). The results are shown in Figure 95 which indicates that pavements placed during the spring had slightly higher rates of rutting than pavements placed later in the year. The reason for this increased rate of rutting for pavements placed during the spring could be more hot weather traffic being placed on the new pavement without sufficient time for the asphalt cement to oxidize and harden where pavements placed later in the year would go through a winter before being trafficked during hot weather.

Figure 96 shows that channelized construction traffic (1-way or 2-way) just after paving increases the rut depth. Such traffic is more critical for mixes which are marginally resistant to rutting.

Post construction longitudinal variables. The results of the correlation analysis for the sixteen post construction longitudinal variables are shown in Table 17. Significant correlations were found between the percent passing the #8 sieve and rutting (R = -0.60) for the wearing mixes and between asphalt content and rutting (R= 0.62) for the binder mixes. Figure 97 shows the relationship between the percent passing the #8 sieve and rutting for wearing mixes. The plot shows an increase in rutting with a decrease in the amount of material passing the #8 sieve for the wearing mixes with an R-square of 0.22. This trend was not repeated for the binder mixes. For the binder mixes an increase in asphalt content leads to an increase in rutting with an R-square of 0.35 as shown in Figure 98. The percent voids in the fine aggregate also showed a somewhat significant trend (R= -0.45) for the binder mixes. In other words, more angular and rough textured fine aggregate tended to reduce rutting. VTM (particularly the lower 20th percentile) also showed a trend in both layers. High VTM values are associated with low rut depths. Surprisingly better correlations are indicated between VTMS and average surface rut depth (excluding the traffic) for both layers.

Post construction transverse variables. Table 18 shows the results of the correlation analysis performed on the post construction transverse variables. Significant correlations with rutting were found between GTM flow (R= 0.51), static base Marshall stability (R= -0.53), static base stability/flow ratio (R= -0.52), rotating base stability/flow ratio (R= 0.50), static base bearing capacity (R= -0.51) and rotating base Marshall stability (R= -0.51) for the wearing mixes. Other less significant correlations (R |0.5|) between rutting and the wearing mix properties of GSI (R = 0.48), stability/flow ratio for the GTM (R = 0.49), bearing capacity (R = -0.49) for the GTM, and bearing capacity (R = -0.49) for rotating base compaction were found. The GSI of the binder mix had an R value of 0.47.

Figures 99 and 100 show the relationship between GSI and rutting (at the worst site) for the wearing and binder mixes respectively. The plots show an increase in rutting with an increase in GSI with R-square values of 0.21 for the wearing mixes and 0.22 for the binder mixes.

Figures 101 and 102 show the relationship between recompacted stability and flow using static base compaction for the wearing mixes. Similar trends were seen with the other two compaction methods and will not be mentioned in detail. Figure 101 shows a decrease in rutting with an increase in stability, with an R-square of 0.28 for the wearing mix. Figure 102 shows the relationship between rutting and flow, with an R-square of 0.15. As the flow increases the rutting also increases. The GTM flow had the best R-square (0.26) of the three compactive efforts. Figures 103 and 104 show the relationship between static base stability/flow ratio and bearing capacity respectively with rutting for the wearing mixes. Both parameters show a decrease in rutting with an increase in the parameter. The relationships have an R-square of 0.27 for stability/flow ratio and 0.26 for bearing capacity.

Again, better correlations are indicated between in-place VTMS and absolute surface rut depths (excluding the traffic) for both layers.

Threshold Analysis

Threshold values were identified for mix design variables and post construction variables. The various threshold values were determined for the above parameters by examining plots of the percent of fair to poor pavements occurring at greater than or less than a given value of that parameter. A change in slope of the line indicates an increase or decrease in the occurrence of fair to poor pavements giving a threshold value. If a change in slope was not very apparent, then the values corresponding to about 10 percent fair/poor sites were considered.

Mix design variables. Threshold values for the mix design variables of VTM, VMA, flow and number of blows per side (obtained from the approved job-mix formula) were not readily apparent from plots of the data. Threshold values for mix design stability, stability/flow ratio and bearing capacity were determined for both the wearing and binder mixes. Figures 105 and 106 show the relationship between mix design stability and rutting for the wearing and binder mixes, respectively. The relationships show a decrease in rutting with an increase in mix design stability with an R-square of 0.10 for the surface and 0.04 for the binder. Figure 107 shows the percent of fair to poor pavements with a mix design Marshall stability greater than the given value for both the wearing and binder mixes. The slope of the curves change at 2800 pounds for both mixes indicating a threshold value of 2800 pounds below which the incidence of fair to poor pavements increases.

Figures 108 and 109 show the relationship between the mix design stability/flow ratio and rutting for wearing and binder mixes, respectively. The relationship shows a slight decrease in rutting with an increase in the ratio. The relationships have very low R-square values (0.04 and 0.00) respectively. Figure 110 shows the relationship between the mix design stability/flow ratio and the occurrence of fair to poor pavements for both the wearing and binder mixes. The slopes of the lines show threshold values of 250 for the wearing and 275 for the binder mix. Mixes with design stability/flow ratios below these threshold values would show an increased likelihood of rutting. Some highway agencies have minimum specification requirements for mix design stability/flow ratio.

Figures 111 and 112 show the relationship between the mix design bearing capacity and rutting for the wearing and binder mixes respectively. The relationship shows a slight decrease in rutting with an increase in the mix design bearing capacity. The relationships have very low R-square values (0.04 and 0.00) respectively. Figure 113 shows the relationship between the bearing capacity and the occurrence of fair to poor pavements for both the wearing and binder mixes. The slopes of the lines show threshold values of 275 for both wearing and binder mixes. Mixes with bearing capacities below this threshold value would show an increased likelihood of rutting.

It appears that mix design stability/flow ratios are slightly better than the bearing capacity to indicate potential rutting based on the data evaluated in this study. However, due to the poor correlations and the difference between the “as designed” and “as built” mix properties, threshold values from mix design variables could be misleading.

Construction variables. All of the threshold values identified for the construction variables were also identified for the post construction variables. Selecting threshold values based on parameters not subjected to traffic loadings could lead to misleading conclusions and, therefore, are not reported.

Post construction longitudinal variables. Threshold values were identified for in-place VTM, percent natural sand in the fine aggregate and the percent passing the #8 and #200 sieves for the post construction longitudinal variables. Figures 114 and 115 show the relationship between the average in-place VTM and rutting for the wearing and binder mix, respectively. The R-square for this relationship is 0.04 for the wearing mix and 0.10 for the binder, which is too low to be useful. However, a trend of an increase in rutting with a decrease in VTM is evident. Figure 116 shows the percent of pavements rated fair to poor at greater than a given air void content versus rutting for the wearing and binder mixes. The plot shows a change in the slope of the line at 3.0% VTM for the wearing mixes and 2.0% VTM for the binder mixes. Below these threshold values the occurrence of fair to poor pavements increased.

Figures 97 and 117 show the relationship between the percent passing the #8 sieve and rutting for the wearing and binder mixes respectively. The R-square for this relationship is 0.22 for the wearing and 0.01 for the binder. Figure 118 and 119 show the relationship between the percent passing the #8 sieve and the percent of fair to poor pavements for the wearing and binder mixes. From a review of these plots in conjunction with Figures 97 and 117 (particularly the rate of rutting of 0.2 inches per square root of million ESAL's) it appears that mixes with between 45-50 percent passing the #8 sieve for wearing mixes and 25-30 percent passing for binder mixes generally performed the best. However, it must be realized that the gradation obtained from extracting pavement cores is generally finer than the mix produced at the plant because of degradation resulting from compaction during construction, coring and sawing operations.

Figures 120 and 121 show the relationship between the percent passing the #200 sieve and rutting for the wearing and binder mixes respectively. The R-square values are 0.02 and 0.01 respectively which are much too low to be useful. Figure 122 shows the relationship between the percent passing the #200 sieve and the percent of fair to poor pavements. The plot shows that the slope of the line changes at 5% for the wearing mixes and 4°A for the binder mixes with an increase in the occurrence of fair to poor pavements occurring above these limits. However, the spread of data is too small and insufficient to recommend these values as threshold values.

Figure 123 shows the relationship between the percent natural sand in the fine aggregate and the percent fair to poor pavements. It appears that mixes with less than 20% natural sand in the fine aggregate contained fewer fair to poor pavements than mixes with over 20% natural sand in the fine aggregate. Ten pavements (Nos. 1, 14, 15, 18, 19, 20, 26, 32, 33 and 34) had no natural sand in both wearing and binder course mixes. Of these ten pavements, eight were good to excellent and two were fair in performance.

Post construction transverse variables. Threshold values were found for GSI, lower 20th percentile VTM, and the recompacted properties of VMA, VTM, stability, stability/flow ratio and bearing capacity for both the wearing and binder mixes. Similar results were found for the different recompactive efforts utilized so only the static base samples will be discussed because static base compaction was used by PennDOT for mix design and production control.

Figures 99 and 100 show the relationship between GSI and rutting for the wearing and binder mixes respectively. The relationship has an R-square value of 0.21 for the wearing mix and 0.22 for the binder mixes. The graphs show a definite trend of increased rutting with an increase in GSL Figure 124 shows the relationship between GSI and the percent of fair to poor pavements. The plot shows a significant increase in the percentage of fair to poor pavements when the GSI is above 1.2 for both wearing mixes and binder mixes. This trend agrees with previous work at NCAT (10) which shows that mixes with a GSI of 1.0 will be stable, mixes with a GSI of 1.1 to 1.3 will rut moderately and mixes with a GSI of over 1.3 will rut severely. Average GSI values of 1.35 and 1.26 for wearing and binder courses, respectively, obtained in this study are on the high side and indicate potential for rutting.

Figures 125 and 126 show the percent of fair to poor pavements with VMA'S greater than the given value for the wearing and binder mixes respectively. The data shows that the percentage of fair to poor pavements increases when the recompacted VMA falls below 15% for the wearing mixes and below 12 to 13% for the binder mixes.

Figures 101 and 127 show the relationship between recompacted stability and rutting for the wearing and binder mixes. The relationship has an R-square value of 0.28 for the wearing mixes and 0.12 for the binder mixes. Figure 128 shows the relationship between stability and the percent of fair to poor pavements. The results show an increase in the percent of poor to fair pavements when the recompacted stability drops below 3400 lbs. for wearing mixes and 3600 lbs. for binder mixes.

Figures 102 and 129 show the relationship between recompacted flow and rutting for wearing and binder mixes, respectively. The relationships have an R-square value of 0.15 for the wearing mixes and 0.05 for the binder mixes. A threshold value for flow could not be determined.

Figures 103 and 130 show the relationship between recompacted stability/flow ratio and rutting for the wearing and binder mixes, respectively. The relationship has an R-square value of 0.27 for the wearing mixes and 0.01 for the binder mixes. Figure 131 shows the relationship between stability/flow ratio and the percent of fair to poor pavements. The results show an increase in the percent of poor to fair pavements when the recompacted stability/flow ratio drops below 280 for wearing mixes and 260 for binder mixes.

Figures 104 and 132 show the relationship between recompacted bearing capacity and rutting. The relationships have an R-square value of 0.26 for the wearing mixes and 0.01 for the binder mixes. Figure 133 shows the relationship between bearing capacity and the percentage of fair to poor pavements. The results show that the percentage of fair to poor pavements increases when the recompacted bearing capacity drops below 300 for the wearing and below 280 for binder mixes.

Stepwise Regression Analysis

Rutting appears to be a complex phenomenon in which no one parameter is able to predict rut depth with an acceptable level of significance as evidenced by the low correlation coefficients reported. The stepwise procedure for selection of single regressor variables, which when retained stepwise in a multiple linear regression equation, are most correlated to the dependent variable. Two stepwise procedures were utilized to analyze the groups of independent variables. The dependent variable utilized is the average surface rut depth divided by the square root of traffic.

The two stepwise procedures utilized were the forward and backward methods. In the forward selection procedure, the single variable which is most correlated to the dependent variable in a step is added to the multiple regression equation until no variables remain that, when added to the model, reduce the deviations sum of squares at a 0.5 significance level. In the backward procedure, the single variable which is least correlated to the dependent variable in a step is deleted from the multiple regression equation. The procedure stops when all variables remaining in the model are significant at the 0.1 level. It should be noted that the R-square values for individual independent variables reported in the stepwise regression analysis may be different than those reported earlier. The stepwise regression procedure requires balanced data (no missing values) for every level of each factor in the model. Therefore, only sites with complete data for the variables selected for the model were analyzed.

Design variables. The stepwise procedure for the mix design variables is summarized in Table 21. All 10 mix design variables predicted rutting with an R-square of 0.33 for the wearing mixes and 0.43 for the binder mixes. For the wearing mixes, the percent passing the #8 sieve, number of blows per side, stability and flow made a significant contribution to the model (R-square = 0.30) with the percent passing the #8 sieve making the largest single contribution (R-square = 0.24).

For the binder mixes, the forward stepwise procedure identified VMA, flow, %AC, and the percent passing the #8 and #200 sieves, as making significant contributions to the model with an R-square of 0.40. The backward procedure selected the %AC and percent passing the #8 sieve as significant with an R-square of 0.22. From this information it is evident that the mix design parameters do not do a good job of predicting rutting especially when the "as placed" mix is significantly different from the 'as designed" mix as discussed earlier.

Construction variables. The stepwise analysis of the construction variables was limited to the four independent variables VTM, AC and the percent passing the #8 and #200 sieves. The conformal indexes were left out of this portion of the analysis due to the difficulty in determining the usefulness of results from conformal indexes. The results of the stepwise analysis are summarized in Table 22. The remaining construction variables predicted rutting with an R-square of 0.34 for the wearing and 0.47 for the binder mixes. The R-square values are still low, however they are higher than the mix design variables. For the wearing mixes the stepwise procedures identified the variables percent passing the #8 and #200 sieve and the VTM as having a significant effect on rutting with an R-square value of 0.34. The percent passing the #8 sieve was identified as having the most significant contribution to rutting with an R-square of 0.28. For the binder mixes all four variables made significant contributions to the model with an R-square of 0.47. The variable AC was identified as making the least contribution to the model.

Post construction longitudinal variables. The results of the stepwise analysis for the post construction longitudinal variables are shown in Table 23. Again, the conformal indexes were removed from the model prior to analysis. The analysis shows that the eight post construction longitudinal variables of AC, passing the #8 and #200 sieves, penetration, viscosity, percent crushed particles in the coarse aggregate, percent natural sand in the fine aggregate and average VTM predict rutting with an R-square value of 0.55 for the wearing mixes and 0.64 for the binder mixes.

For the wearing mixes the stepwise procedure identified all of the variables except the penetration and viscosity of the recovered asphalt as contributing significantly to the model with a combined R-square of 0.54. The percent passing the #8 sieve made the largest single contribution to the model with an R-square of 0.44. For the binder mixes the AC, percent passing the #8 sieve, percent crushed particles, average VTM, viscosity, and percent passing the #200 sieve contributed significantly to the model with an R-square of 0.64. The variables AC, percent passing the #8 sieve, average VTM and viscosity contributed to the model with an R-square of 0.54 based on backward selection procedure. It is interesting to note that AC contributed significantly to rutting in binder mixes and not in wearing mixes. This indicates that the binder mixes in Pennsylvania need to be made relatively leaner and, therefore, stiffer to resist rutting.

Post construction transverse variables. With the exception of GSI and creep the post construction transverse variables have been included in other models. Rather than repeating the analysis, the transverse variables were included with the longitudinal variables to create a new data set. The new data set included the variables that could be performed during mix production quality control to determine if a quality control test program utilizing recompacted samples of the produced mix could predict rutting. The variables were divided into three groups for analysis based on the recompactive method utilized. These three groups included GTM recompaction, static base recompaction and rotating base recompaction. The variables selected were AC, average in-place VTM, percent passing the #8 and #200 sieves, recovered asphalt penetration and viscosity, percent crushed particles, percent natural sand in the fine aggregate, creep, and the recompacted properties of stability, flow, stability/flow ratio, bearing capacity, VTM and VMA. GSI was included in the GTM recompacted model. The results are shown in Tables 24 through 26 for GTM, static base and rotating base recompaction variables, respectively.

GTM variables. The model for predicting rutting based on the sixteen GTM variables has an R-square of 0.68 for the wearing mixes and 0.95 for the binder mixes. The results of the stepwise procedure is shown in Table 24. For the wearing mixes the forward procedure selected the percent passing the #8 sieve, GSI, average VTM, creep, VMA, and the percent passing the #200 sieve as all contributing significantly to the model with an R-square of 0.64. The backward procedure selected the variables of the percent passing the #8 sieve and the stability/flow ratio as the only significant variables with an R-square of 0.51.

The forward procedure for the binder mixes selected all of the variables as significant with the exception of penetration and flow with an R-square of 0.97. The backward procedure selected the variables of percent passing the #200 sieve, viscosity, percent crushed particles, average in-place VTM, GTM VTM, GTM VMA, creep, stability, and stability/flow ratio. The backward model has an R-square of 0.93.

Static base variables. The model for predicting rutting based on the fifteen static base variables has an R-square of 0.72 for the wearing mixes and 0.97 for the binder mixes. The results of the stepwise procedure for the static base variables are shown in Table 25. For the wearing mixes the forward procedure selected the percent passing the #8 sieve, the percent natural sand in the fine aggregate, average in-place VTM, VMA, and stability as all contributing significantly to the model with an R-square of 0.70. The backward procedure selected the variables of the percent passing the #8 sieve, VMA, average in-place VTM, and the stability/flow ratio as the significant variables with an R-square of 0.66.

The forward procedure for the binder mixes selected all of the variables as significant with the exception of AC, stability and stability/flow ratio with an R-square of 0.92. The backward procedure selected all of the variables as significant with the exception of the percent passing the #8 sieve, AC, penetration, and the percent natural sand in the fine aggregate. The backward model has an R-square of 0.95.

Rotating base variables. The model for predicting rutting based on the fifteen rotating base variables has an R-square of 0.73 for the surface mixes and 0.93 for the binder mixes. The results of the stepwise procedure for the rotating base variables are shown in Table 26. For the wearing mixes the forward procedure selected the percent passing the #8 sieve, the percent natural sand in the fine aggregate, recompacted VTM, the average in-place VTM, VMA, and stability as all contributing significantly to the model with an R-square of 0.71. The backward procedure selected the variables of the percent passing the #8 sieve, average in-place VTM, VMA and the stability/flow ratio as the significant variables with an R-square of 0.67.

The forward procedure for the binder mixes selected all of the variables as significant with the exception of AC, percent passing the #200 sieve, and bearing capacity with an R-square of 0.93. The backward procedure selected all of the variables as significant with the exception of penetration, flow, percent natural sand, percent passing the #8 and #200 sieve, and percent AC. The backward model has an R-square of 0.87.

The above analysis shows that many variables contribute to rutting and that no one variable adequately predicts rut depths. Many of the variables utilized above, such as recovered penetration and viscosity, contribute to rutting. However, they can not be controlled or predicted during design and construction. A meaningful model to predict rutting would contain variables that both significantly contribute to the model and can be controlled during design and/or construction. Eight variables were selected to represent mix properties that are controllable during design and construction. The mix design variables were not utilized because they were not representative of the mix ‘as placed”. These eight variables are the 20th percentile VTM from cores C7-C11 to represent the mix design VTM; the VMA calculated from recompacted samples to represent mix design VMA; the percent passing the 1/2, #8 and #200 sieves and the percent crushed faces from the in-place cores (Cl -C5); the recompacted flow to represent the mix design flow; and the mix design stability. For the GTM samples, the GSI was included.

Two models for each mix type, wearing and binder, were developed for each of the three compaction methods. The first model utilized all eight (9 for the GTM) variables. The second model only utilized those variables that contributed significantly to the model.

GTM model. The model for predicting rutting based on all of the GTM variables has an R-square of 0.56 for the wearing mixes and 0.62 for the binder mixes. For the wearing mixes, the stepwise procedure identified the percent passing the #8 sieve, the recompacted flow and the GSI as contributing significantly with an R-square of 0.42 as shown in Figure 134. For the binder mix all variables except recompacted flow were significant with an R-square of 0.62 as shown in Figure 135.

Rotating base model. The eight selected variables for predicting rutting has an R-square of 0.38 for the wearing mix and 0.49 for the binder mix. The stepwise procedure selected all variables as significant except recompacted flow for the wearing mix with an R-square of 0.37. The model is shown in Figure 136. For the binder mix the 20th percentile VTM, the percent crushed faces and the percent passing the 1/2 inch and the #8 sieves contributed significantly with an R-square of 0.48 as shown in Figure 137.

Static base model. The model for predicting rutting using the static base variables had an R-square of 0.37 for the wearing mix and 0.63 for the binder mix. The stepwise procedure identified the recompacted flow, percent crushed faces, and the percent passing the #8 sieve and #200 sieves as significant. The model using these four variables has an R-square of 0.34 and is shown in Figure 138. The model for the binder mix (Figure 139) has an R-square of 0.52 and contains the 20th percentile VTM, VMA, and percent passing the 1/2 inch and the #8 sieves.

Only onevariable appeared ineachmodel forthe wearing mixes. This variable wasthe percent passing the #8 sieve. Forthebinder mixes, the WMandthe percent passing the l/2 inch and the #8 sieves appeared in each model. This would seem to indicate that the gradation is one of the most important parameters to control in preventing rutting. However, the gradations for the mixes were very similar, especially for the #8 sieve and therefore, the effect of this variable could be overstated in the model. The models are applicable over the ranges of the test data for the indicated variables and should not be extrapolated to other mixes or levels of traffic.

Summary. Obviously, rutting is a complex phenomenon as evidenced by the many independent variables selected by the stepwise procedure as significantly contributing to rutting. Each selected variable contributes significantly to rutting and, therefore, must be considered while designing the HMA mix and controlling HMA construction quality. Ideally, a simple, end-result test method capable of determining rutting potential is needed which can be used to design the HMA mix in the laboratory and control its quality on a daily basis in the field. Until such a test method is available it is prudent to use specifications for mix composition, mix design, and construction quality control, which are based on significant independent variables and their respective threshold values, to minimize the rutting problem.

Heavy Duty Specifications

Seven of the 34 projects evaluated were constructed using the heavy duty specifications implemented by PennDOT in 1987. These seven projects (Sites 5,7,24, 26,32, 33 and 35) have been in service for only 2 to 3 years. The subjective rating and the average rate of rut development occurring in these heavy duty pavements are as follows:

Site #	Rating	Avg Rut Depth/SQRT TESALS
5	F	N/A*
7	P	0.211
24	E	0.078
26	E	0.000
32	G	0.132
33	F	0.197
35	E	0.000
	Average	0.103

*Overlaid prior to profilometer testing

Four of the seven heavy duty pavements were rated good to excellent. Sites 5 and 33 received fair ratings and site 7 a poor rating. The low ratings of Sites 5 and 7 could be attributed to low mix design air void contents (3.0 and 3.2 percent for Site 5 and 3.6 and 3.5 percent for Site 7 in the wearing and binder mixes, respectively). It should be noted that the heavy duty mix specifications were subsequently revised to require mix design air voids of not less than 4.0 and 4.5 percent for wearing and binder mixes, respectively. Site 32, which received a ‘good” rating contained 1.8 percent more minus 200 as placed than designed in the wearing mix. Site 33, which received a “fair” rating, had excessive minus 200 in both the wearing and binder mix (2.5 and 1.6 percent more than the JMF, respectively). The remaining three sites are rated as excellent.

The average rate of rutting of the heavy duty pavements is 0.103 inches per square root million ESALS for all 7 sites, and 0.053 when Sites 5, 7 and 33 are excluded due to their low mix design VTMs. Both of these values are well below the threshold value of 0.20 determined earlier. It should be noted that the rate of rutting is also less than the average rate of rutting of 0.167 which includes poor to excellent sites.

The preceding data and discussion indicate that the current PennDOT heavy duty specifications have minimized the rutting problem. Further changes in the specifications, especially the HMA mix production quality control, based on the results of this study are expected to improve the resistance of PennDOT HMA mixes to rutting induced by high pressure truck tires and high traffic volumes.

SUMMARY AND CONCLUSIONS

This research project was undertaken to evaluate 34 in-service heavy duty pavements across Pennsylvania to identify the material properties, mix design parameters, pavement construction properties, and pavement in-service properties which are responsible for the premature rutting (permanent deformation) of some HMA pavements. Of the 34 projects, 10 were excellent, 9 were good, 12 were fair, and 3 were poor based on a subjective rating system which was validated in this study.

Traffic, mix design, and construction data was collected for all projects. The total estimated traffic carried by the pavements (ranging in age from 2 to 19 years) ranged from less than 1 million ESALS to over 30 million ESALS.

Eleven six-inch diameter cores were taken from each project to determine the VTM (voids in total mix), creep (permanent deformation), mix composition (asphalt content and gradation), fractured face count of coarse aggregate, particle shape and texture of fine aggregate, and recovered asphalt penetration and viscosity. The cores were also reheated and compacted using three compaction methods: gyratory testing machine (GTM), rotating base-slanted foot mechanical Marshall compactor, and static base mechanical Marshall compactor. Recompacted specimens were tested for VTM, Marshall stability and flow.

Transverse surface profiles of the pavement were obtained at two locations: worst site and a representative site within 500 ft of the worst site. Maximum surface rut depth and the rut depth in individual layers were determined from the surface profile and the thickness of the layers measured from transverse sets of cores. The maximum surface rut depth at the worst location on all projects ranged from 0.04 inch to 1.66 inch. In a majority of cases the underlying layers in conjunction with the wearing course contributed to the surface rut depth.

Mix Design. The number of blows/face used was 50 for 24 projects, 65 for 3 projects (Turnpike), and 75 for 7 projects in designing the wearing mixes. Only 7 projects of 34 projects had wearing mix design VTM equal to or greater than 4.0 percent. Of 26 binder mixes, 12 mixes had VTM equal to or greater than 4.0 percent. This indicates that both the wearing and binder mixes were designed closer to the minimum VTM value of the 3-5 percent range used by PennDOT.

Construction. Construction data indicates that the percentage of minus 200 material was generally higher in the "produced mix" compared to the "designed mix" for both wearing and binder mixes. In the case of the binder mixes, the percentage of material passing 1/2" and No. 8 sieve was also generally higher in the "produced mix" compared to the "designed mix" indicating that the "produced mix' was finer.

In-service Properties. Excessive minus 200 in both wearing and binder mixes, and excessive material passing 1/2" and No. 8 sieves in binder mixes as reported during construction (testing of loose mixtures) was confirmed by the core test data. Average in-place VTMs in the wearing and binder courses were determined to be 3.2 and 3.0 percent which are significantly lower than lower than the mix design VTMs. This indicates that the laboratory compactive effort was inadequate and/or excessive fines created during construction filled the voids. Obviously, there are many projects which have VTMS lower than 3 percent. According to past experience HMA pavements approach the potential for rutting when the VTM is 3 percent or less.

Of the three compactors used to recompact the mix from the pavements, Marshall compactor with rotating base and slanted foot gave the highest density (least VTM) for both wearing and binder mixes. This compactor is recommended for use by PennDOT to obtain the near maximum potential compaction of mixes which is likely to be achieved in heavy duty pavements subjected to high pressure truck tires.

Average GSI (gyratory shear index) values of 1.35 and 1.26 for wearing and binder courses, respectively, are on the high side and indicate potential for rutting. Whereas a value of 1.00 is considered ideal to prevent rutting, values up to 1.20 may be acceptable.

Statistical Analysis

Some 60 independent variables covering the general design, construction and post construction data for each pavement were selected to determine their effect on rutting. The dependent variable selected for analysis was rut depth in inches divided by square root of total traffic in million ESALS. A threshold value of 0.2 for this dependent variable was determined in this study. Pavements are expected to develop undesirable amounts of rutting if this value is exceeded.

All data pertaining to the 60 independent variables and the dependent variable was analyzed using correlation analysis, linear regression analysis, and stepwise multiple variable analysis methods.

Since rutting is a complex phenomenon, no one independent variable alone could predict rutting with any degree of confidence. However, the following significant trends were observed and threshold values identified.

Mix Composition and Design. Rutting potential increased as (a) minus 200 content increased, (b) fractured face count of coarse aggregate decreased, (c) percentage of natural sand in the fine aggregate increased, (d) percentage of asphalt content increased, (e) Marshall mix design stability decreased, (f) mix design stability/flow ratio decreased, and (g) mix design bearing capacity of mix decreased. Threshold values to control the rutting are as follows:

	Wearing Mix	Binder Mix
Percent natural sand in the fine aggregate	Less than 20%	Less than 20%
Marshall mix design stability, lbs.	Above 2800	Above 2800
Design stability/flow ratio	Above 250	Above 275
Design bearing capacity	Above 275	Above 275

Threshold values of Marshall mix design stability, design stability/flow ratio, and design bearing capacity are considered high. These values (obtained from the job-mix formula) cannot be used because the "as placed" mixes were generally significantly different from the 'as designed" mixes. Optimum pavement performance was generally observed when the percentage of material passing No. 8 sieve was 45-50 for wearing mixes, and 25-30 for binder mixes. The indicated maximum percentage of natural sand in the fine aggregate is 20. It is reasonably close to the present specification requirement of 25 percent which is considered adequate.

In-Service Properties. Rutting potential increased as(a) in-place VTM decreased, (b) gyratory shear index (GSI) increased, (c) recompacted VMA decreased, (d) recompacted VTM decreased, (e) recompacted stability decreased, (f) recompacted stability/flow ratio decreased, and (g) recompacted bearing capacity decreased. Threshold values to control the rutting are as follows:

	Wearing Mix	Binder Mix
Average in-place VTM	Above 3.0%	Above 2.0%
GSI	Below 1.2	Below 1.2
Recompacted VMA	Above 15%	Above 12%
Static base recompacted stability, lbs.	Above 3400	Above 3600
Static base recompacted stability/flow	Above 280	Above 260
Static base recompacted bearing capacity	Above 300	Above 280

Again, the threshold values of stability, stability/flow and bearing capacity cannot be used because these were obtained on aged, recompacted mixtures.

RECOMMENDATIONS

Data from this research project indicates that the current PennDOT heavy duty specifications have minimized the rutting potential of HMA pavements in Pennsylvania. However, the following recommendations are made to improve and optimize the resistance of PennDOT HMA mixes to rutting induced by high pressure truck tires and increasing traffic volumes.

Materials

1. Coarse aggregate retained on No. 4 sieve. Continue to use at least 85 percent of particles with two or more fractured faces for wearing and binder courses.

2. Fine aggregate. Continue to use at least 75 percent manufactured sand in the fine aggregate for both wearing and binder courses. Encourage use of 100 percent manufactured sand if possible.

3. Size. Although limited data is available from this project to justify increasing the maximum size of aggregate for wearing and binder courses, it is prudent to do so based on nationwide experience. Use 1 1/2" maximum aggregate size (at least 5 percent retained on 1") for binder courses. Encourage increased use of ID-3 wearing course (3/4" maximum aggregate size).

Mix Design

1. Mechanical Marshall compactor with rotating base and slanted foot (75 blows/face) gave the highest density (least air void content), for both wearing and binder courses, compared to the gyratory testing machine (GTM) and conventional static base marshall compactor (75 blows/face). Rotating base/slanted foot Marshall compactor should be used, at least in the central laboratory, to obtain near maximum potential compaction of mixes which will likely to be achieved after 2-3 years' traffic. This will minimize the potential over-asphalting of mixes designed for heavy duty pavements and high pressure truck tires.

2. Design mixes with at least 4.0 percent air voids when using rotating base/slanted foot Marshall compactor.

3. Current specifications for VMA, stability and flow appear adequate.

Mix Production Quality Control

1. Binder course mixes "as placed" were generally finer than mixes "as designed". On

average, the percentages passing 1/2", No. 8 and No. 200 exceeded the job-mix formula values by 4.3, 2.5 and 1.0 percent, respectively. Wearing course mixes "as placed" have 1.1 percent (average) higher minus 200 than the job-mix formula. Better mix gradation control is necessary. If the quality control charts or historical RPS data indicate that the values are consistently on the high or low side of the JMF, the mix design should be revised to incorporate production gradation. If all RPS lots on a project get 100 percent payment, it does not mean necessarily that the mix is satisfactory from a rutting standpoint because the mix could consistently be finer than designed and still meet the specification requirements.

2, Air void content in laboratory compacted samples of "produced mix" is more important than that of the "designed mix". If the produced mix contains excessive minus 200 material, its air void content will be lower than the designed mix and, therefore, potential for rutting will increase. It appears from the preliminary review of the test data that the percentage of air void content obtained from the daily compacted Marshall specimens should be made a pay item in the RPS specifications in lieu of minus 200 material. A control of air void content will indirectly control the amount of minus 200 material in the mix. Some states use this approach because air void content of the daily compacted Marshall specimens is the most important parameter affecting rutting. Air void content should not be allowed to fall below 3.0 percent.

3. There is some indication of increased rutting potential if the freshly laid wearing course is subjected to high temperatures and channelized traffic for extended periods of time. Project construction traffic control should be planned in advance to minimize this effect. Whenever possible, the wearing course should not be placed until all binder courses have been completed.

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