ANALYSIS OF VARIABILITY AND NORMALITY ASSUMPTION OF THE VDOT VOLUMETRIC CONTRACTOR DATA

Samer W. Katicha, Ph.D. [1]
Senior Research Associate, Center for Sustainable Transportation Infrastructure, VTTI
3500 Transportation Research Plaza
Virginia Tech, Blacksburg, VA 24061-0105
Phone: (540) 231-1586, fax: (540) 231-1555, email: skaticha@vt.edu

Gerardo W. Flintsch, Ph.D., P.E.
Director, Center for Sustainable Transportation Infrastructure, VTTI
Associate Professor, The Charles E. Via, Jr. Department of Civil and Environmental Engineering
3500 Transportation Research Plaza
Virginia Tech, Blacksburg, VA 24061-0105
Phone: (540) 231-9748, fax: (540) 231-1555, email: flintsch@vt.edu

Kevin McGhee, P.E.
Associate Principal Research Scientist
Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903
Phone: (434) 293-1956, fax (434) 293-1990, email: Kevin.McGhee@VDOT.Virginia.gov

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[1] Corresponding author

ABSTRACT

The paper investigates the statistical measures of process mean, standard deviation, correlation, and normality assumptions for the Virginia Department of Transportation (VDOT) volumetric properties of voids in total mix (VTM), asphalt content (AC), and voids in mineral aggregates (VMA) based on three years of contractors' testing data. The VTM had an overall pooled standard deviation of 0.86 percent and showed evidence of a binormal distribution 96 percent of which resulted from a single normal distribution. No difference based on mix type (Base Mix [BM], Intermediate Mix [IM], Surface Mix [SM], or Stone Matrix Asphalt [SMA]) was observed, therefore suggesting this binormal distribution is due to other factors. The average AC, on the other hand, was found to depend on mix type with three distinct groups: BM and IM (around 4.35 percent), SM (around 5.30 percent), and SMA (around 6.40 percent). The standard deviation for the combined BM and IM and that of the SM were found to be similar (around 0.30 percent) and different from the standard deviation of the SMA (around 0.42 percent). The average of the VMA was found to depend on mix type and specifically on the maximum nominal aggregate size ranging from 13.84 percent for the BM to 18.18 percent for the SMA. The standard deviation was found to be independent of mix type (around 1.00 percent). For normality assumptions, only the AC passed one of the three tests of normality. Taking the effect of AC a high correlation of 0.85 between VTM and VMA was observed.

INTRODUCTION

The Virginia Department of Transportation (VDOT) has worked toward end-result specifications (ERSs) in hot-mix asphalt (HMA) since the mid-1960s. The latest efforts towards this purpose (*1*) suggested expanding the VDOT quality measures for asphalt concrete acceptance to include the asphalt concrete volumetric properties of voids in total mix (VTM) and voids in mineral aggregates (VMA) along with the already used asphalt content (AC) and gradation. For asphalt concrete pavement acceptance, the authors suggested the use of field density and ride quality (smoothness) with permeability as a secondary quality check. The statistical quality measure suggested for use is the percent within limits (PWL) procedure stipulated by the American Association of State Highway and Transportation Officials (AASHTO) in R-009-05, Standard Recommended Practice for Acceptance Sampling Plans for Highway Construction, and R042-06, Recommended Practice to Develop a Quality Assurance Plan for Hot-Mix Asphalt. This method differs from the current VDOT provisions by combining the average and standard deviations into a single measure, which is the PWL.

PERCENT WITHIN LIMITS (PWL)

The PWL has become the preferred quality measure for highway construction materials (*2*). The method is based on the work of Liberman and Resnikoff (*3*) and is documented in a number of Federal Highway Administration (FHWA) reports (*4–6*). The procedure is based on the assumption that the measurements are independent, identically distributed normal random variables (*3*). Deviations from these assumptions can be a result of a skewed distribution or bimodal distribution of the data (*2*).

In addition to data normality assumptions, the effective application of the PWL requires that “appropriate” process limits be used. What is meant by “appropriate” is that these limits should be reasonable for both the contractor and the specifying agency; therefore, these limits should be realistically achievable by the contractor given the currently used technologies. Perhaps the best source of information that can guide the development of process limits is the one obtained from historical information about process accuracy and variability (i.e., what have we been achieving?). The VDOT has a wealth of data about the production of asphalt concrete mixtures. The data are stored in a database that contains aggregate gradations, AC and volumetrics (the VTM and VMA) for designed and produced material. While available, this data had not been analyzed statistically to evaluate variability during production. Hughes et al. (*1*) suggested that some previously proposed limits were not appropriate; the analysis of the VDOT’s database can help redefine these limits.

PURPOSE AND SCOPE

The purpose of this paper is to analyze historical data from asphalt concrete production to help develop realistic specification limits. For example, from the historical standard deviation of a given process, an agency can choose to set the process acceptance limits as the limits of the 95% confidence interval; different confidence intervals can be chosen depending on the agency’s overall strategy to improve material production. The investigated parameters were VTM, AC, and VMA. This is in support of the current efforts by the VDOT to move towards ERSs for asphalt concrete materials and construction.

The VDOT's central database was queried for contractor test results of the AC, VTM, and VMA. Average, variance, correlation, and normality assumptions were evaluated for 2006 through 2008. Process variation is relevant to setting specification limits of an acceptance plan while data normality is an important characteristic as it is an assumption made in most acceptance plans.

RESULTS AND DISCUSSION

Analysis of historical volumetric properties can provide valuable information to help develop specification limits for a quality assurance (QA) acceptance plan. The analysis performed evaluated normality assumptions and identified the current process variation and the correlation between the different variables. Process variation is essential in determining realistic specification limits, while correlation between the different variables will affect the choice of an analysis method. The volumetric properties used are the VTM, AC, and VMA. The statistical parameters investigated are process mean, variance (or standard deviation), normality assumptions, and correlation between the variables (VTM, AC, and VMA).

Voids in Total Mix (VTM)

The VTM is defined as the percentage by volume of air voids in the mix. The VTM is the primary design parameter in the Superpave™ mix design procedure where a target VTM (generally 4 percent) is set at a certain number of design gyrations (using the Superpave^{TM} gyratory compactor). This target VTM is achieved by adjusting the AC. The VTM affects the mix performance and, ultimately, the pavement performance in terms of distress development.

VTM Process Mean and Variance

Figure 1 shows the laboratory-measured VTM for all mixes used during the 2006, 2007, and 2008 paving seasons versus the target VTM as reported in the job-mix formula (JMF) sheet. Mixes were combined after a preliminary analysis of the VTM revealed statistical measures (the mean and standard deviation) did not depend on the mix type (i.e., Base Mix [BM], Intermediate Mix [IM], Surface Mix [SM], and Stone Matrix Asphalt [SMA]). Figure 1 is based on more than 10,000 observations included in the VDOT's central database. No data subdivision into project, district, or asphalt plant was undertaken. The VDOT requires mixes to be designed for a VTM of 4 percent according to Superpave^{TM}. However, the approved JMF VTM is not always 4 percent. After inquiring with the VDOT's Districts Materials Divisions it was found that deviations from the 4 percent target VTM can be due to two reasons: 1) when trial batches achieve a VTM close to 4 percent (e.g., 3.8 to 4.2 percent), this percentage will be approved by the district as it is deemed "close enough" to 4 percent for all practical reasons; and 2) sometimes, based on experience, districts will approve a VTM different than 4 percent (e.g., 3 percent) knowing this is the required laboratory-measured VTM the contractor has to use to achieve appropriate field compaction or other characteristics. For a target VTM greater than 3 percent, the average laboratory-measured VTM was lower than the target VTM (i.e, the calculated average falls under the line of equality). The difference increased with an increasing target VTM. Not enough test data are available to make a definitive conclusion for values below a 3 percent design VTM, although it seems the measured VTM is greater than the target VTM.

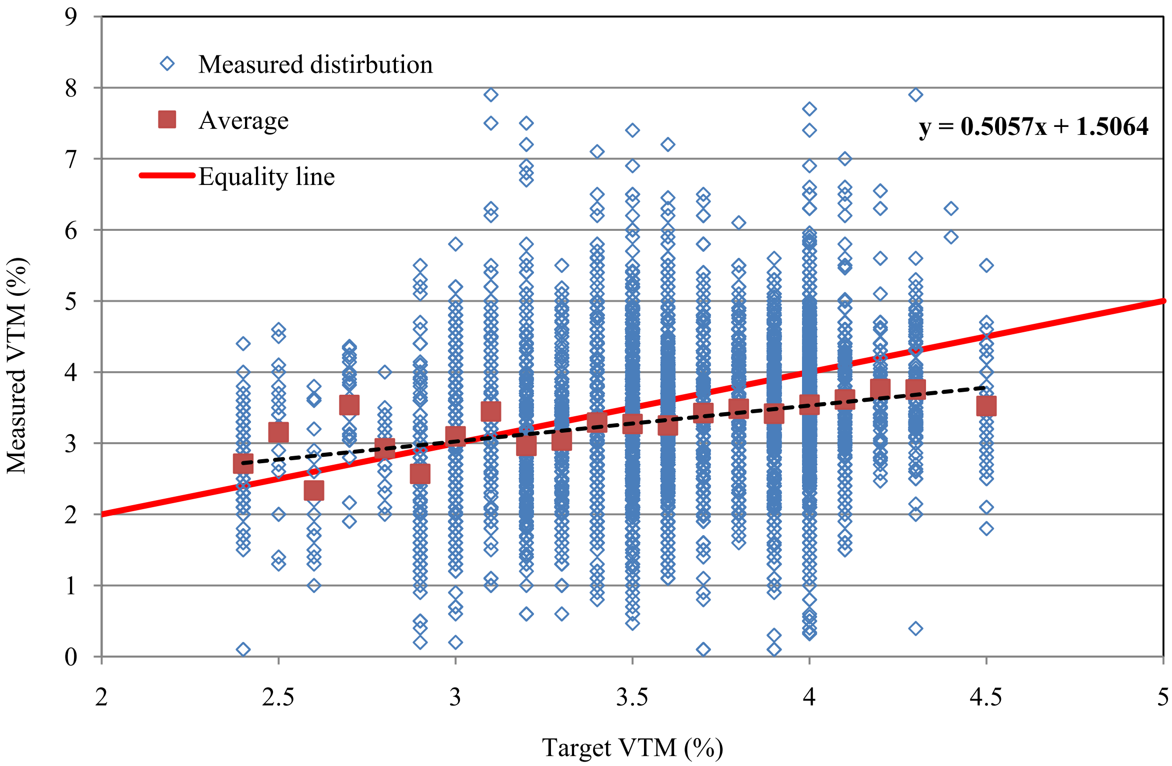

FIGURE 1 Measured VTM vs. target VTM.

The standard deviations at each target VTM are presented in Figure 2. The standard deviations varied between 0.49 and 1.11 percent. These two extreme values are for a target VTM of 2.8 and 2.9 percent and are based on 21 and 126 measurements, respectively, and therefore cannot be considered representative of the actual population standard deviation. Most VTM measurements were taken for a target VTM between 3.5 and 4 percent for which the standard deviation varied between 0.78 and 0.89 percent. Bartlett's test for equal VTM variance (i.e., the square of the standard deviation) was performed on measurements taken for a target VTM between 3.5 and 4 percent. The test result rejected the hypothesis that the variances at different target VTMs are equal. Although statistical analysis rejected the assumption of equal variances, the difference between 0.78 and 0.89 percent is relatively small from a practical engineering perspective so that a pooled standard deviation would be appropriate to characterize the process variation. The pooled standard deviation was calculated as 0.86 percent using Equation 1.

$$S_p = \sqrt{\frac{\sum_{i=1}^{k}\left((n_i-1)s_i^2\right)}{\sum_{i=1}^{k}(n_i-1)}} \qquad (1)$$

Where,

S_p = pooled standard deviation

S_i = standard deviation at a specific VTM

n_i = number of samples at a specific VTM

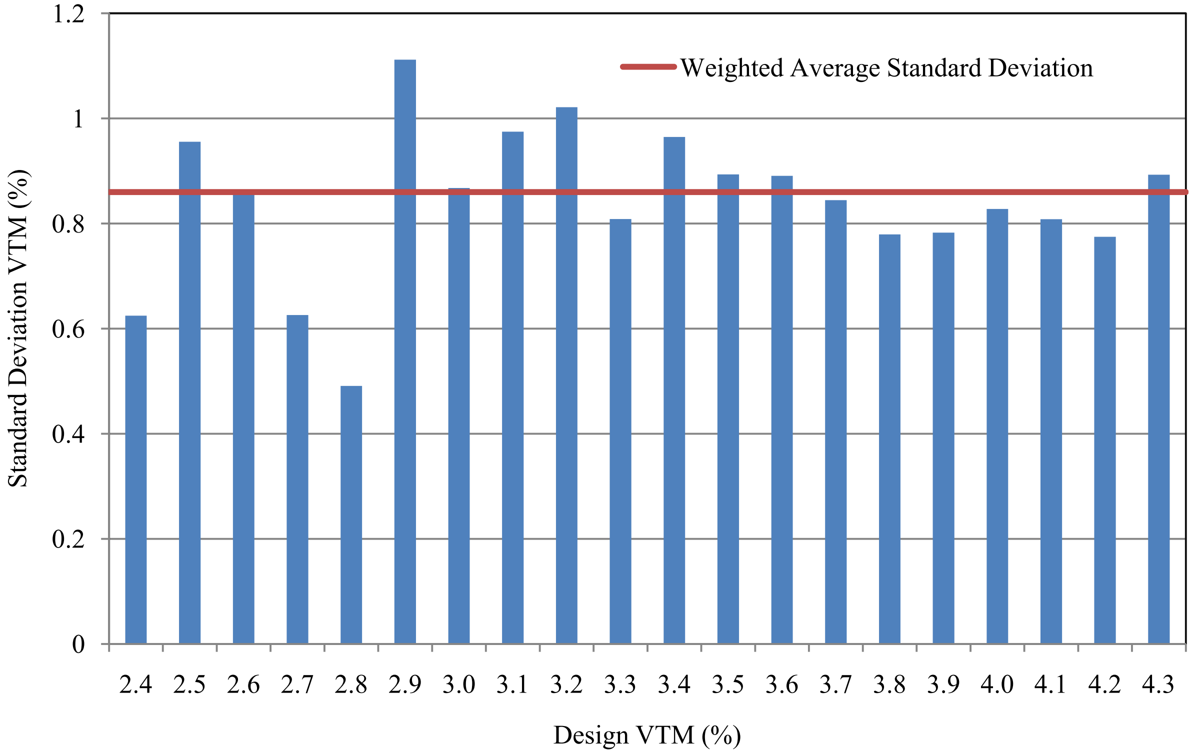

FIGURE 2 VTM standard deviation.

Normality Test

Normality of the process is important due to the fact that most statistical data analysis methods such as the PWL were developed under the assumptions of normality. Deviations from normality can cause statistical measures to be incorrectly calculated. For example, Burati and Weed (*2*) investigated the effect of deviation from normality on the calculation of the PWL by simulating distributions with different skewness levels. Figure 3 shows the VTM cumulative distribution for a target VTM of 4 percent for all mixes (BM, IM, SM, and SMA). Graphically, the figure suggests that the measured VTM follows more or less a normal distribution with an average of 3.5 percent, which is less than the target 4 percent. However, the distribution failed Pearson's Chi-square test, D'Agostino's K-squared test, and the Anderson-Darling test for normality. Deviations from normality are more easily observed when the VTM histogram shown in Figure 4 is compared to the normal distribution with average and standard deviations calculated from the experimental data. Figure 4 suggests there are two peaks in the distribution at approximately 3.5 and 4.6 percent. Further analysis showed that these two peaks are also observed when the data are analyzed according to the mix type (BM, IM, SM, and SMA) and therefore cannot be attributed to different mixes having a different average VTM. To illustrate the two peaks, a binormal distribution (i.e, the (sum of two normal distributions) was fitted to the data as shown in Figure 4. The binormal distribution is defined according to Equation 2.

$$B_{\alpha,\mu_1,\mu_2,\sigma_1,\sigma_2}(x) = \alpha N_{\mu_1,\sigma_1}(x) + (1-\alpha)N_{\mu_2,\sigma_2}(x) \qquad (2)$$

Where,

$B_{\alpha,\mu_1,\mu_2,\sigma_1,\sigma_2}$ = binormal distribution
N_{μ_1,σ_1} and N_{μ_2,σ_2}= normal distribution with different parameters
μ = mean of the normal distribution
σ = standard deviation of the normal distribution
α = parameter between 0.5 and 1

The parameters α, μ_1, μ_2, σ_1, and σ_2 are determined to provide the best fit to the experimental data. For the case of a 4 percent target VTM, α was calculated as 0.96, and μ_1, μ_2, σ_1, and σ_2 were calculated as 3.50 percent, 4.73 percent, 0.78 percent and 0.15 percent, respectively. This suggests most of the data (96 percent) come from a single normal distribution while deviations from normality are due to 4 percent of the experimental data. Causes for the deviations from normality are not easily determined; however, possible causes can be attributed to a specific production plant or a specific production period where, for some reason, the process had noticeably different characteristics.

The skewness calculated for the data consisting of a 4 percent target VTM was 0.1 (note that skewness is a shape measure and is independent of the numerical values of the test data). Based on the results presented by Burati and Weed (*2*), this number is likely too low to appreciably affect the calculations of the PWL compared to the case where the data are normally distributed.

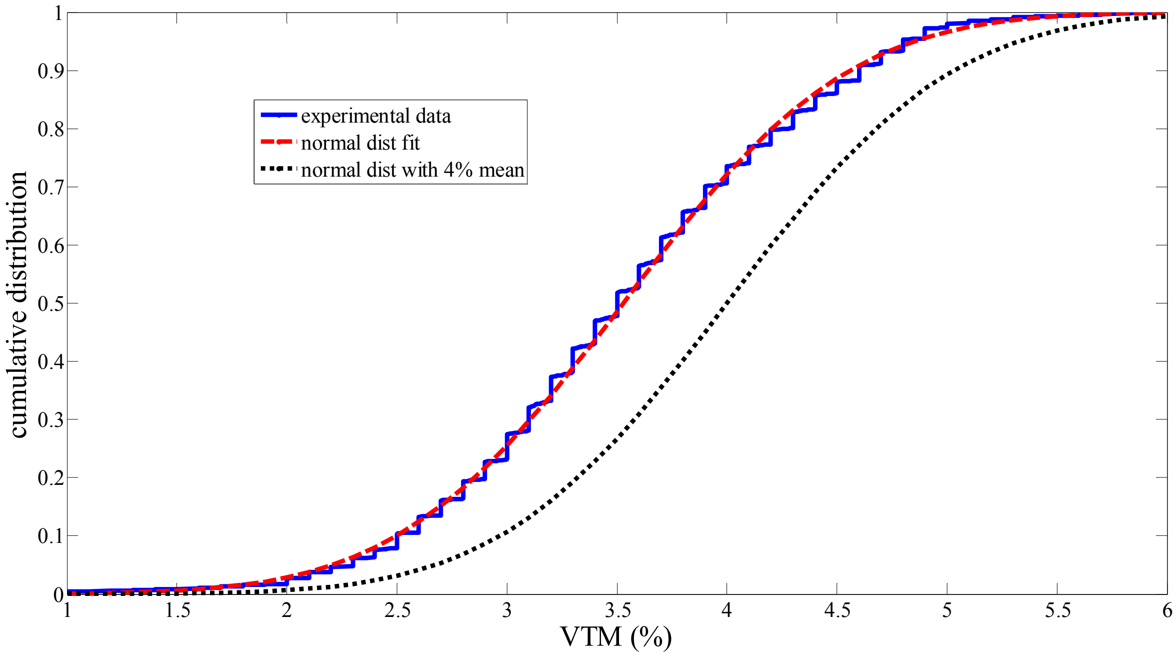

FIGURE 3 Cumulative VTM distribution for a design VTM of 4 percent.

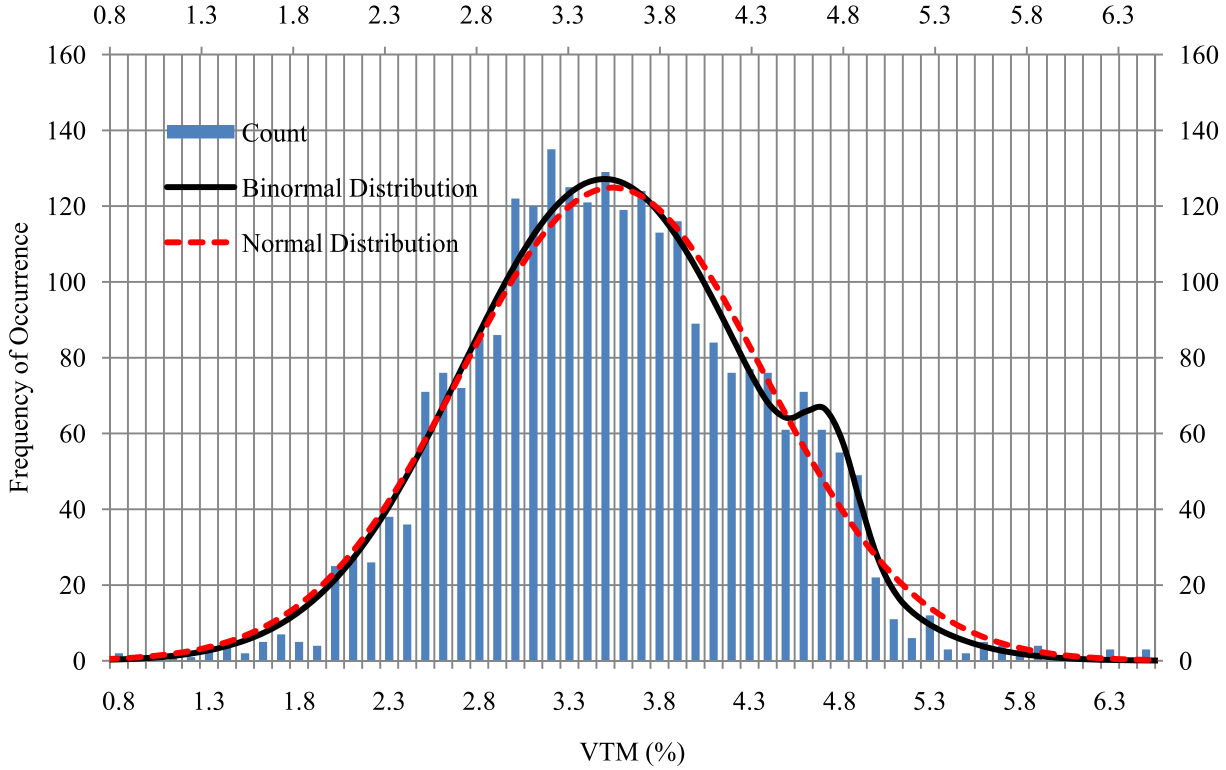

FIGURE 4 VTM histogram for 4 percent target VTM.

Confidence Intervals for the Mean and Standard Deviation

Confidence intervals for the process mean and standard deviation for different sample sizes were determined assuming the VTM standard deviation is equal to 0.86 percent (pooled standard deviation). This was chosen as it represents a realistic process variation as evidenced from the analysis of the VTM data. From the central limit theorem, averages calculated from data sampled from any well-behaved statistical distribution tend to be normally distributed with the standard deviation calculated according to Equation 3.

$$\sigma_\mu = \frac{\sigma}{\sqrt{n}} \tag{3}$$

Where,
σ = population standard deviation (0.86 percent)
σ_μ = standard deviation of mean response of n samples
n = number of samples

From the standard deviation, confidence intervals for the mean response can be obtained for different sample sizes and confidence levels as presented in Table 1. These intervals can be interpreted as follows for the case of three samples: 99 percent of the time, the calculated mean will fall within a 1.29 ($0.86 \times 2.59/\sqrt{3}$) percent distance from the actual mean response (assuming the process standard deviation is equal to 0.86 percent). Therefore, calculated mean values that are more than 1.29 percent from the design process mean (for example, 4 percent) are very unlikely (occurs 1 percent of the time) so that it can be assumed that the actual achieved mean is different from 4 percent.

TABLE 1 Confidence Interval of Mean Response for Different Sample Sizes

Property	Sample Size	Confidence Interval for Different Percentages											
		99	95	90	80	70	60	50	40	30	20	10	5
VTM	3	1.29	0.98	0.82	0.64	0.52	0.42	0.34	0.26	0.19	0.13	0.06	0.03
	5	0.98	0.74	0.63	0.49	0.39	0.32	0.26	0.20	0.15	0.10	0.05	0.02
	10	0.70	0.53	0.44	0.35	0.28	0.23	0.18	0.14	0.10	0.07	0.03	0.02
	30	0.41	0.31	0.26	0.21	0.17	0.13	0.11	0.08	0.06	0.04	0.02	0.01
AC	3	0.45	0.34	0.29	0.22	0.18	0.15	0.12	0.09	0.07	0.04	0.02	0.01
	5	0.34	0.26	0.22	0.17	0.14	0.11	0.09	0.07	0.05	0.03	0.02	0.01
	10	0.24	0.18	0.15	0.12	0.10	0.08	0.06	0.05	0.04	0.02	0.01	0.01
	30	0.14	0.11	0.09	0.07	0.06	0.05	0.04	0.03	0.02	0.01	0.01	0.00
VMA	3	1.50	1.14	0.96	0.75	0.60	0.49	0.39	0.30	0.22	0.15	0.07	0.04
	5	1.14	0.87	0.73	0.57	0.46	0.37	0.30	0.23	0.17	0.11	0.06	0.03
	10	0.81	0.62	0.52	0.40	0.33	0.26	0.21	0.16	0.12	0.08	0.04	0.02
	30	0.48	0.36	0.31	0.24	0.19	0.16	0.13	0.10	0.07	0.05	0.02	0.01

TABLE 2 Confidence Interval for the Standard Deviation for Different Sample Sizes

Property	Sample Size	Confidence Interval for Different Percentages											
		99	95	90	80	70	60	50	40	30	20	10	5
VTM	3	1.85	1.49	1.30	1.09	0.94	0.82	0.72	0.61	0.51	0.41	0.28	0.19
	5	1.57	1.32	1.20	1.05	0.95	0.86	0.79	0.71	0.64	0.55	0.44	0.36
	10	1.33	1.18	1.10	1.00	0.94	0.88	0.83	0.78	0.72	0.66	0.59	0.52
	30	1.12	1.04	1.00	0.95	0.91	0.88	0.85	0.82	0.79	0.76	0.71	0.67
AC	3	0.64	0.52	0.46	0.38	0.33	0.29	0.25	0.21	0.18	0.14	0.10	0.07
	5	0.55	0.46	0.42	0.37	0.33	0.30	0.27	0.25	0.22	0.19	0.15	0.13
	10	0.47	0.41	0.38	0.35	0.33	0.31	0.29	0.27	0.25	0.23	0.20	0.18
	30	0.39	0.36	0.35	0.33	0.32	0.31	0.30	0.29	0.28	0.26	0.25	0.23
VMA	3	2.15	1.73	1.52	1.27	1.10	0.96	0.83	0.71	0.60	0.47	0.32	0.23
	5	1.82	1.54	1.39	1.22	1.10	1.01	0.92	0.83	0.74	0.64	0.52	0.42
	10	1.55	1.37	1.28	1.17	1.09	1.02	0.96	0.90	0.84	0.77	0.68	0.61
	30	1.31	1.21	1.16	1.10	1.06	1.02	0.99	0.96	0.92	0.88	0.83	0.78

Unlike the confidence intervals for the mean response, confidence intervals on the standard deviation are based on the assumption that the data are normally distributed. In this case, the sample variance follows a chi-square distribution (Equation 4).

$$(n-1)\frac{s^2}{\sigma^2} \sim \chi^2_{n-1} \tag{4}$$

The confidence intervals for the process standard deviation for different sample sizes are presented in Table 2. These intervals extend from zero to the value reported in the table. These can be interpreted as follows for the case of three samples: 99 percent of the time, the calculated standard deviation will be less than 1.85 percent (assuming the process standard deviation is equal to 0.86 percent).

Asphalt Content (AC)

The AC is defined as the percentage by weight of asphalt binder in the mix. In the Superpave™ mix design procedure, the AC is adjusted to achieve the target VTM. To determine process variability, the AC content was analyzed for all mixes (SM, BM/IM, and SMA). The AC distribution (histogram) for 2008 is presented in Figure 5. Initial analysis of the data showed it was not normally distributed; rather it revealed two prominent peaks at approximately 4.4 and 5.4 percent and a less prominent peak at 6.4 percent. Further analysis of the data showed these peaks corresponded to the average AC for the BM and IM, SM, and SMA, respectively. Further analysis of each mix type showed that the data were normally distributed (Figure 5) according to D'Agostino's K-squared test for normality; however, it fails Pearson's Chi-square test and the Anderson-Darling test. The mean and standard deviation for each mix type (BM/IM, SM, and SMA) are presented in Table 3. As expected, coarser mixes required less AC while the SMA required the most AC.

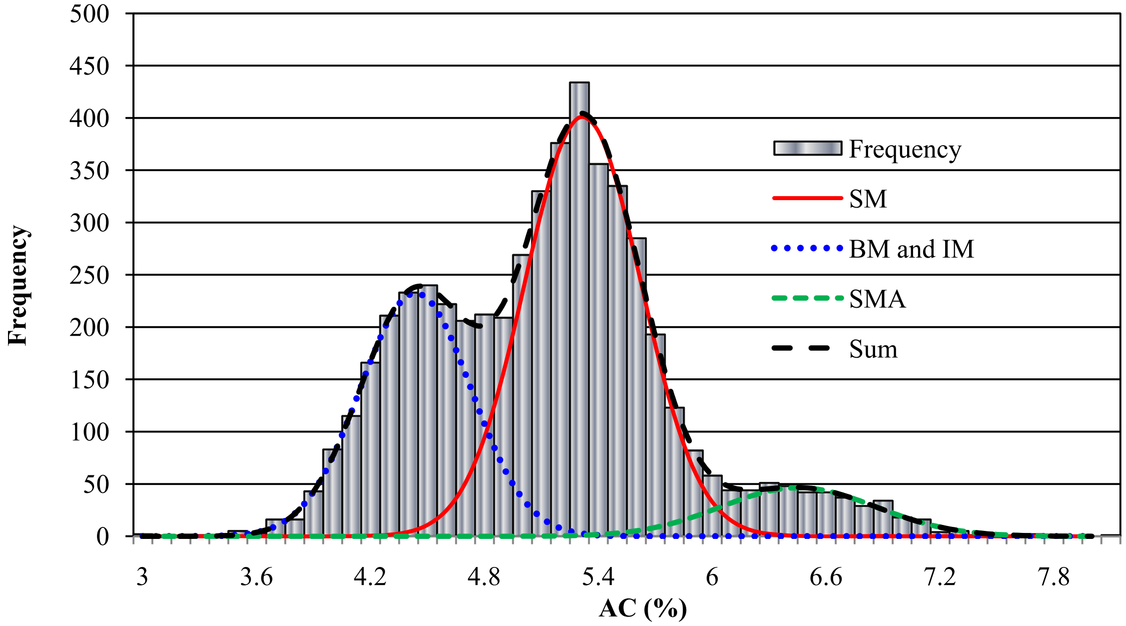

FIGURE 5 AC distribution (2008).

TABLE 3 Mean and Standard Deviation Measures of AC for All Mixes

Year	BM/IM		SM		SMA	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
2008	4.44	0.29	5.32	0.30	6.45	0.41
2007	4.33	0.25	5.24	0.32	6.39	0.45
2006	4.34	0.28	5.28	0.32	6.22	0.45

Confidence Intervals of the Mean and Standard Deviation

Confidence intervals for the AC process mean and standard deviation for different sample sizes were determined assuming the AC standard deviation, which is equal to 0.3 percent. The 0.3 percent was chosen as a compromise reflecting the standard deviation of the SM and BM/IM mixes. The SMA was not considered because of the relatively small percentage of SMA used in paving projects (less than 10 percent). The results for the mean and standard deviation are presented in Table 1 and Table 2, respectively.

Correlation between the VTM and AC

The correlation among acceptance measures determines what acceptance sampling plan to use. High correlation among acceptance measures requires acceptance plans that take the correlation into account, while low correlation can be ignored as it does not sensibly affect the results. How to handle multivariate acceptance using the PWL for the correlated and uncorrelated cases is discussed in (*7*, *8*).

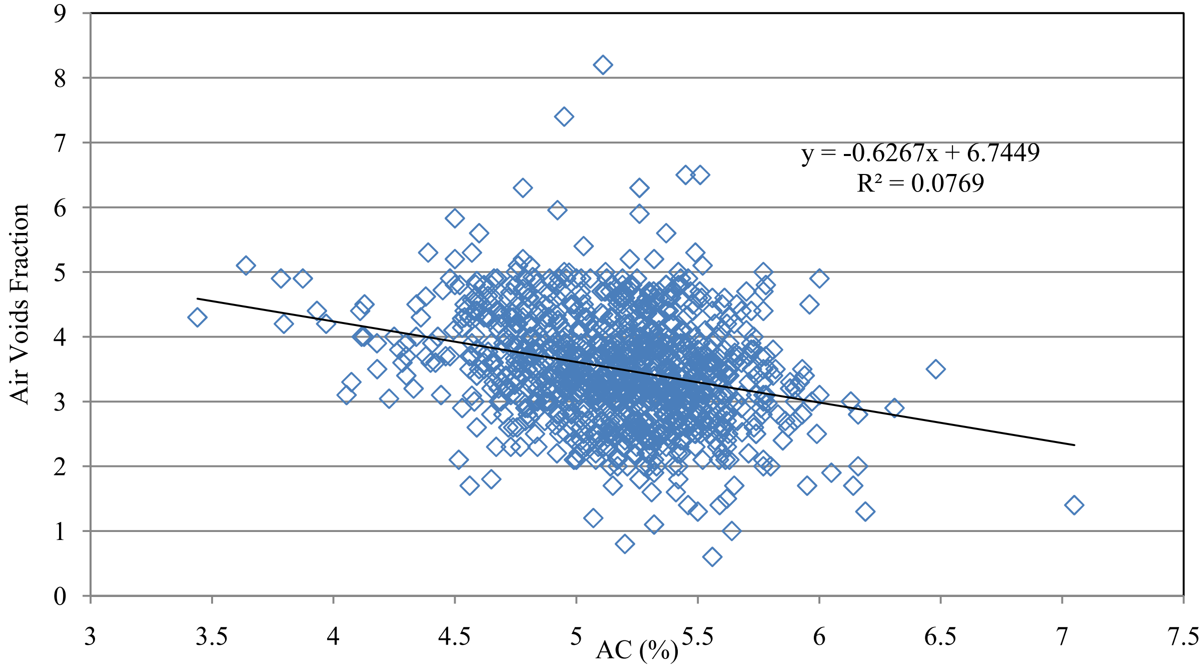

FIGURE 6 VTM-AC plot for SM mixes and 4 percent target air voids.

A plot of the VTM versus the AC is presented in Figure 6. The general trend shows a decrease in the VTM with an increase in the AC. This is expected as an excess binder added to the mix fills the available air voids. Although there is a general trend relating the VTM to the AC, the calculated correlation of -0.28 (the negative sign is because an increase in one variable results in a decrease in the other) between the two variables is not very high, and much of the variation in one of the two variables is independent of the other.

Voids in Mineral Aggregates

The VMA was suggested to be included in the VDOT quality acceptance plan (*1*) as it is already being measured. The average VMA for all mixes from 2006 to 2008 is presented in Table 4. These fall within the VDOT's specifications (*9*). The differences between the means are all statistically significant. The BM had the lowest average VMA values while the SMA had the highest average VMA values. The VMA distribution for SM9.5 mixes is presented in Figure 7. This distribution failed all three tests of normality. Two theoretical distributions are plotted to illustrate the deviations from normality. The first distribution is the normal distribution with the average and standard deviation taken from Table 4 (16.15 and 0.92 percent). The second distribution is the skew normal distribution, which provides a better representation of the experimental data. The standard skew normal distribution is defined as:

$$f(x) = 2\phi(x)\Phi(\alpha x) \qquad (5)$$

where,

$f(x)$ = standard skew normal distribution
$2\phi(x)$ = standard normal distribution
$\Phi(x)$ = standard cumulative normal distribution
α = shape parameter related to skewness (for α = 0, the standard normal distribution is recovered)

The skew normal distribution is provided to illustrate the experimental data's deviation from normality. Note that, although the skew normal distribution provides a better representation of the experimental data, it still fails Pearson's goodness of fit test (though not as "badly" as the normal distribution).

TABLE 4 Mean, Standard Deviation, and Skewness Measures for the VMA

Mix	Average (%)	Standard Deviation (%)	Skew
SM9.5	16.15	0.92	0.479
SM12.5	15.61	0.88	0.613
BM	13.84	1.00	-0.005
SMA	18.18	1.09	0.615

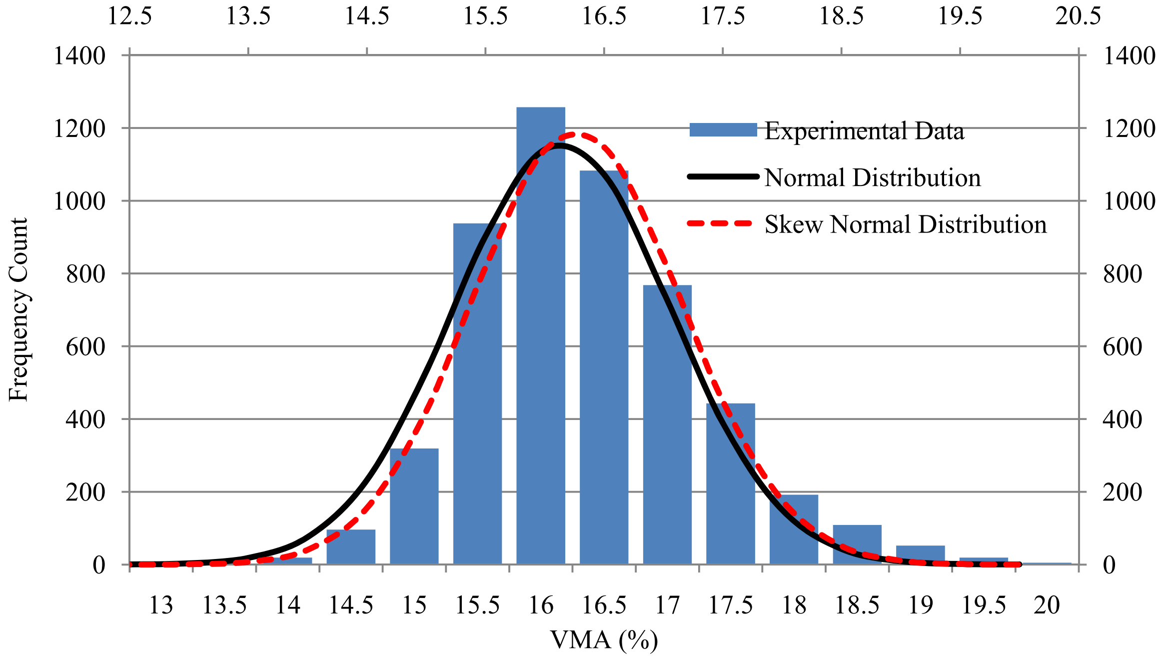

FIGURE 7 Measured VMA for SM9.5.

Confidence Intervals of the Mean and Standard Deviation

Similar to the case for the VTM and AC, confidence intervals of the process mean and standard deviation for the VMA for different sample numbers were determined assuming the VMA standard deviation equals 1.0 percent (based on results from Table 4). The 1.0 percent was chosen as a single value compromise for all mix types. The results for the mean and standard deviation are presented in Table 1 and Table 2, respectively.

Correlation between the VMA, VTM, and AC

Correlation between the different performance measures should be considered for proper statistical evaluation. Failure to recognize this may lead to erroneous results, especially when the correlation is high. The correlations between the VTM, VMA, and AC are presented in Table 5. Table 5 shows that, to some degree, all three measures are correlated. The largest correlation is between the VTM and VMA (around 0.65) followed by the VMA and AC (around 0.4) and the VTM and AC (around -0.25). Since all three measures are correlated, the partial correlation between the VTM and VMA with the effect of the AC removed (Equation 6) was calculated with results ranging between 0.81 and 0.85. This strong correlation is expected since the VMA is a measure of total volume that does not consist of the aggregate skeleton and comprises the effective binder volume and the VTM. To visualize the correlation between the VMA as the dependent variable and the VTM and AC as the independent variables, a multiple linear regression was performed. The results are presented in Figure 8 where the VMA calculated from the regression model (regressed VMA) is plotted against the measured VMA. This shows that the VMA can be fairly well estimated from the VTM and AC.

$$\rho_{VTM.VMA/AC} = \frac{\rho_{VTM.VMA} - \rho_{VTM.AC}\rho_{VMA.AC}}{\sqrt{1-\rho_{VTM.AC}^2}\sqrt{1-\rho_{VMA.AC}^2}} \quad (6)$$

Where,

$\rho_{VTM.VMA/AC}$ = partial correlation between the VTM and VMA with the effect of the AC removed

$\rho_{VTM.VMA}$ = correlation between the VTM and VMA

$\rho_{VTM.AC}$ = correlation between the VTM and AC

$\rho_{VMA.AC}$ = correlation between the VMA and AC

TABLE 5 Correlations between the VTM, AC, and VMA

Mix	Correlation			
	VTM/VMA	VTM/AC	VMA/AC	VTM/VMA.AC
SM9.5	0.66	-0.23	0.38	0.83
SM12.5	0.58	-0.33	0.43	0.85
BM	0.63	-0.22	0.45	0.84
SMA	0.68	-0.25	0.27	0.81

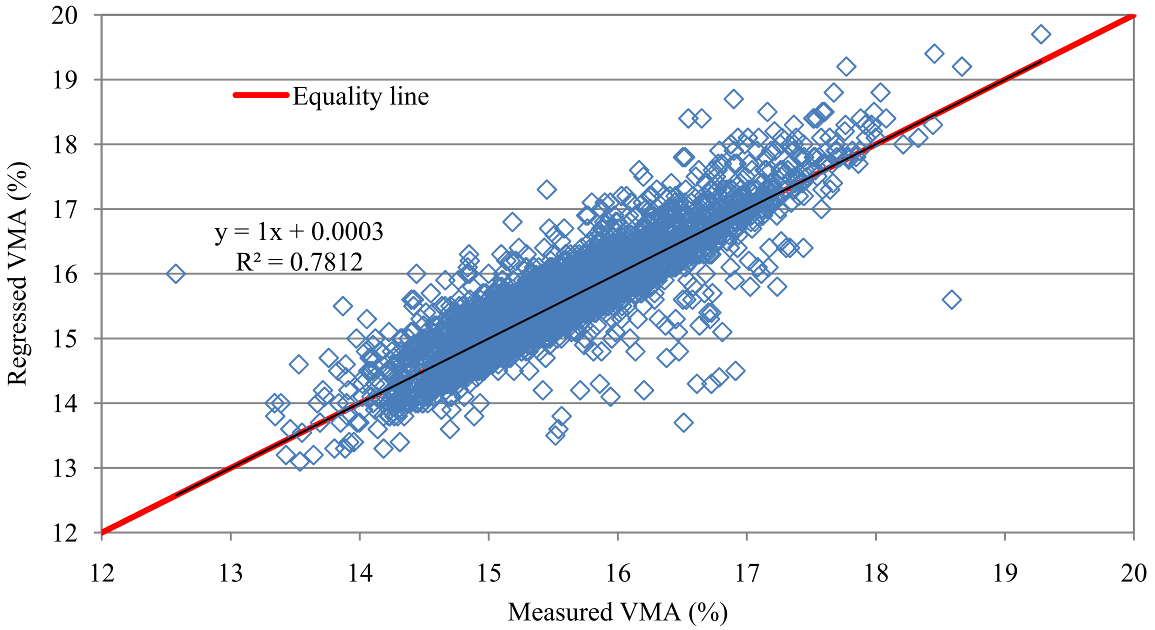

FIGURE 8 Comparison between predicted VMA and measured VMA.

SUMMARY AND CONCLUSIONS

To support the VDOT's current efforts for the move towards ERSs, statistical measures of process mean, standard deviation, correlation, and normality assumptions for the VDOT's volumetric properties of VTM, AC, and VMA based on three years of contractor testing data were evaluated. The following conclusions can be made:

- For all practical purposes, the VTM, VMA, and AC can be considered normally distributed. Although only the AC data distribution passed one of the three normality tests, deviations from normality for all three properties seem to be relatively small to considerably affect calculation results. The developed confidence intervals for each property can be used to set specification realizable limits in a quality acceptance plan.

- The VMA does not add significant new information to that provided by the VTM and AC regarding mix characteristics. A statistical analysis of the VDOT production data demonstrated the VMA to be highly correlated with the VTM and AC. Including the VMA in an acceptance plan should be based on engineering considerations that clearly show its benefits relative to the introduced complexity in the analysis of the data.

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