Determination of Compactive Effort to Duplicate Pavement Voids for Corps of Engineers Gyratory Testing Machine

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The Corps of Engineers gyratory testing machine (GTM) has been used by various agencies to design and test asphalt mixes. Material properties such as shear strength and strain are measured during the compaction process, but a compaction process duplicating void levels in the pavement after traffic has not been clearly defined. The intent of this project was to determine the laboratory compactive effort for the GTM that duplicates the voids in pavement after it has been exposed to traffic. Samples of mix were obtained during construction of 10 field projects and tested in the laboratory with six different compactive efforts using various angles of gyration and vertical pressures. Voids were also measured in pavements immediately after construction and after several years of exposure to traffic. Regressions were then developed to allow the prediction of pavement voids from the voids obtained by the laboratory compaction procedures. A high correlation between voids obtained in the laboratory and pavement voids after several years of traffic was obtained with the GTM at two combinations of gyratory angle and vertical pressure; however, the degree of correlation was highly dependent on the inclusion of the postconstruction voids.

The gyratory testing machine (GTM) developed by the Corps of Engineers was used to design asphalt mixes for heavy-duty airfield pavements. Murfee and Manzione indicated that the GTM is still preferable to the Marshall method of mix design for pavements subjected to very heavy loads (*1*). Mississippi, Maine, and Kansas have also used the Corps GTM to analyze and design asphalt mixes.

One of the earliest models of GTM, located at Purdue University, has been used in several laboratory studies (*2,3*) from which it was concluded that bituminous mixtures can be effectively designed on the basis of their compaction and shear strain properties. The GTM can be used as a traffic simulation device to measure changes in compaction and shear strain properties of mixtures when they are placed in service, and the sensitivity of mixtures with respect to variations in gradation and asphalt content can be studied.

After considerable research using a GTM with an air roller instead of the oil-filled roller, Ruth et al. (*4*) concluded, "The gyratory compaction and densification testing procedure provides rapid assessment of a mixture's shear resistance as related to changes in asphalt content, aggregate gradation, and density." The apparatus measures the shear resistance necessary to resist rutting type deformation. Ruth et al. identified a compactive effort for the air-filled roller to simulate the density achieved by the construction process and following traffic exposure.

Although the compactive effort has been identified for the air-filled roller, it has not been clearly distinguished for the oil-filled roller. Three compaction variables—angle of gyration, vertical pressure, and number of revolutions—define the compactive effort. The vertical pressure is usually taken as the tire pressure representing the traffic that will be on the mixture, commonly 827 kPa. Although an angle of gyration of 1.745×10^{-2} rad has been used considerably, lesser angles are believed to simulate traffic better. Typical values for the number of gyrations used for evaluation have been 30 and 60 revolutions; however, the developer of the equipment has indicated a preference for evaluation at a point when the rate of compaction decreases to a minimum value of 16 kg/m^3 per 100 revolutions.

The recommended compactive effort achieved by the combination of an angle of gyration of 1.745×10^{-2}, 827-kPa vertical pressure, and evaluation when the rate of compaction reaches 16 kg/m^3 per 100 revolutions was used by the author shortly after acquisition of the GTM on various mixes manufactured in Virginia. There were indications that this compactive effort was too severe. There was a need to determine what combination of compaction variables yielded densities reached in the pavement after subjection to traffic.

PURPOSE AND SCOPE

The purpose of this study was to develop a compaction procedure for the Corps of Engineers GTM that produces approximately the same void level as that reached in the pavement after it has been exposed to traffic. The study involved the sampling of mix from 10 paving projects, construction of laboratory samples with the GTM at various compactive efforts, and sampling the paving projects after exposure to traffic to determine the void level.

RESEARCH PLAN

Samples of surface mix were obtained from 10 resurfacing projects in the state of Virginia. Each of these projects was cored after 28 to 44 months to determine void levels after traffic exposure. Although some densification may continue on some of the projects, it is believed that the void level has nearly stabilized. A follow-up coring and determination of air voids will be repeated in several years to ensure that the voids have stabilized.

The samples of mix from each project were taken to the laboratory, where gyratory shear tests were performed at various levels

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of compaction by varying the angle of gyration and vertical pressure. Six combinations of angle of gyration and vertical pressure were used. The angle of gyration was varied from 0.872 to 2.618 $\times 10^{-2}$ rad, and the vertical pressure was either 689 or 827 kPa. Voids total mix (VTM) values were determined on the compacted specimens.

An attempt was made to develop a correlation between the voids achieved at each compaction level and the voids in the pavement after it had been subjected to traffic. Other factors were considered in the correlations, such as total traffic and postconstruction pavement void level. The degree of correlation was the primary consideration in selecting the most satisfactory compaction level.

PROCEDURES

Sampling Mixes and Coring

An attempt was made to locate projects on primary and Interstate highways so that traffic would have a significant effect on the compaction of the pavement. The compaction by traffic to a critical level usually is the factor that results in instability and ultimate shear failure in permanent deformation types of distress. Since one of the projects was on a secondary route with very high traffic, a measurement of the amount of truck traffic was not readily available and will have to be obtained at a later date. For that reason this project was not included in the data analysis incorporating traffic for this paper.

Samples of plant mix were obtained from each project, and the location of the sampling was recorded so that cores could be taken at a later date. Pavement samples were also removed by dry-sawing immediately after construction to get an indication of the postconstruction void levels. If the pavement received insufficient compaction during construction, there would definitely be a major effect on the final void level after traffic exposure.

Laboratory Compaction

The plant mix obtained during construction was compacted in the GTM using each of the test combinations shown in Table 1. ASTM "Standard Test Method for Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Corps of Engineers Gyratory Testing Machine (GTM)" was used to compact the specimens, with several modifications (*5*). Instead of a constant angle of gyration at 1.745×10^{-2} rad, it was varied from 0.872 to 2.618×10^{-2} rad. Also, instead of recording the shear strength and shear strain at 30 and 60 revolutions and then concluding the test, these values were recorded at regular intervals until the rate of densification decreased to 16 kg/m^3 per 100 revolutions. At this time the compaction was stopped, wall friction was measured, and the specimen was removed from the machine. Bulk specific gravities were measured and the VTM values were calculated.

Since the Marshall test method has been used by the Virginia Department of Transportation for many years, it was also used to compact the mixes to see how well it would predict the final void level of the pavement. Because these mixes were placed under what were considered to be fairly heavy traffic conditions, a 75-blow compactive effort was used. In retrospect, the current thinking of the state paving industry and departmental engineers supports a 75-blow effort only for very heavy traffic. Some of the projects that used the 75-blow effort should probably have used the 50-blow effort instead.

RESULTS

General

Table 2 gives a summary of test results for each project. The void levels achieved during the construction process before the pavement was exposed to traffic were relatively high. The only project to achieve single-digit voids was the secondary route mentioned above, which was not included in part of the analysis because of the lack of traffic data. Certainly the void level, which ranged from 10.1 to 15.0 percent in this study, should have had an influence on the magnitude of voids reached after the pavement was exposed to traffic. The "final" voids, after exposure to several years of traffic, ranged from 4.6 to 7.7 percent. The original quantity of voids was reduced on average by approximately half.

Effects of Angle of Gyration and Vertical Pressure

By comparing the voids at the different levels of compactive effort, the effect of both the gyratory angle and vertical pressure can be seen. At the lowest angle, 0.872×10^{-2} rad, the increase in vertical pressure from 689 to 827 kPa tends to reduce the void level.

TABLE 1 Combinations of Angle of Gyration and Vertical Pressure

Compaction Level	Angle of Gyration (Radians x 10^{-2})	Vertical Pressure (kPa)
1	0.872	689
2	0.872	827
3	1.309	827
4	1.745	689
5	1.745	827
6	2.618	689

TABLE 2 Traffic and Void Data Results

						VTM at Various Compactive Efforts Angle (Radians x 10^{-2})/Vertical Pressure (kPa)					
Route	Mix	Total 18 kip Equiv X 10^3	Post Const VTM	Final VTM	75-Blow Mars. VTM	0.872/ 689	0.872/ 827	1.309/ 827	1.745/ 689	1.745/ 827	2.618/ 689
58	SM-2C	137	12.2	7.2	4.7	6.3	5.5	3.2	1.9	1.7	0.6
I-64H	S-10M	877	10.3	5.5	4.4	5.6	5.9	3.7	2.4	2.4	1.2
29	SM-2C	982	10.1	4.6	5.0	6.9	6.6	3.6	2.2	1.7	2.1
01	SM-2C	513	13.3	7.6	6.1	9.4	6.6	4.3	4.9	3.0	2.0
28	SM-2C	250	15.0	7.7	5.8	8.0	6.7	4.0	2.5	2.3	1.2
I-64											
NK	SM-2C	1066	13.2	7.2	5.1	6.6	6.2	3.6	2.5	2.4	1.2
I-66	SM-2C	1176	11.9	5.5	5.0	8.1	7.8	5.0	3.4	3.0	1.2
I-77	SM-2C	2160	11.1	5.6	3.2	6.4	6.0	4.1	3.1	2.4	---
I-81	SM-2C	2931	11.0	6.6	5.4	6.9	6.1	2.9	1.8	1.0	0.1
663	SM-3C	NA	7.3	3.1	4.2	4.3	5.4	3.1	1.2	1.4	0.2

TABLE 3 Multiple Regression Results

		Coefficients of Independent Variables and Constant Value for Regression Equations to Predict Final Pavement Voids					
				VTM at Various GTM Compactive Efforts (Radians x 10^{-2}/kPa)			
Regression (R^2)	Total ESAL x 10^7	Post Const VTM	75-Blow Marshall VTM	0.872/689	0.872/827	1.309/827	Constant
0.74	1.44	0.686		-0.128			-1.10
0.88	1.62	0.694			-0.668		2.12
0.86	0.61	0.673				-0.675	0.81
0.74	1.46	0.581	0.175				-1.62
0.86[a]		0.690		-0.0889			-1.29
[b]0.92[a]		0.730			-0.591		1.34
0.92[a]		0.726				-0.656	0.14
0.86[a]		0.617	0.118				-1.64

[a] The Route 663 project was included because unavailable traffic data was not necessary.

[b] Example of regression: Pavement VTM = 0.730 (Post const. voids) - 0.591 (GTM voids) +1.34

When a greater angle of 1.745×10^{-2} is used, the same magnitude of vertical pressure increase does not produce as much change in the void level. This smaller change is due to the fact that the void level is already low when this angle of compaction is used, and void level change becomes more difficult to distinguish. It is thought that the vertical pressure is analogous to the tire pressure of the traffic traveling on the pavement. Although vertical pressure may correlate with the degree of loading exerted by tires, the gyratory shear test is not an exact duplication of what takes place on the roadway. One should be careful in interpreting tests performed at different vertical pressures because one cannot be sure that a test performed at a certain vertical pressure will duplicate the behavior of the mix on the roadway exposed to the same tire pressure.

A similar comparison of voids obtained at different angles of gyration but the same vertical pressure can be seen for the tests using a vertical pressure of 827 kPa at angles of 0.872×10^{-2} and 1.309×10^{-2} rad. This small change in the angle of gyration had a significant effect on void levels.

Development of Regressions

Table 3 gives the coefficients for the multiple linear regressions developed to predict pavement voids after traffic by using voids from the gyratory shear tests. The first series was developed using 18-kip (80-kN) equivalent axle loads (ESALs) of total traffic, postconstruction voids, and voids obtained by the laboratory method as independent variables and pavement voids as the dependent variable. The second series was developed excluding traffic but including postconstruction voids and voids obtained by the laboratory method as the independent variables. It was observed that inclusion of the traffic variable tended to decrease rather than increase the degree of correlation.

This result tends to indicate that the effect of traffic was not represented properly by ESALs. Also, other factors that are not included, such as speed of traffic, may have had an overshadowing effect on the pavement voids. The regressions with angles of gyration of 0.872×10^{-2} or 1.309×10^{-2} rad and 827-kPa vertical pressure but containing no traffic variable both had high R^2 terms (0.92), indicating good correlations. The standard error of estimate was 0.48 percent voids, which is reasonable. A closer examination of the effects of the two independent variables on the degree of correlation was revealing. The postconstruction voids had a major effect on the degree of correlation that was achieved. An R^2 value of approximately 0.85 was achieved for the correlation using only postconstruction voids as an independent variable. Figures 1 and 2 compare the pavement voids on sampled projects and the voids predicted from the postconstructed voids and voids obtained with the GTM.

Before initiation of this project, the Virginia Department of Transportation began to use 75-blow Marshall designs and a higher design void content of 4 to 6 percent for the SM-2C mixes used in this field study. It has been observed that most of these mixes now are "dry," and even though rutting is no longer a problem, durability has suffered. The author also believes that the dry mixes tended to influence the degree of correlation in this study that was expected between the compaction method and the final pavement voids. The dry mixes are difficult to compact during construction; therefore, the void contents tend to be high. The high voids probably resulted in stiffening of the asphalt cement, which prevented the field mixes from reaching the void levels achieved in the laboratory with fresh asphalt. The postconstruction voids were extensive, and the asphalt

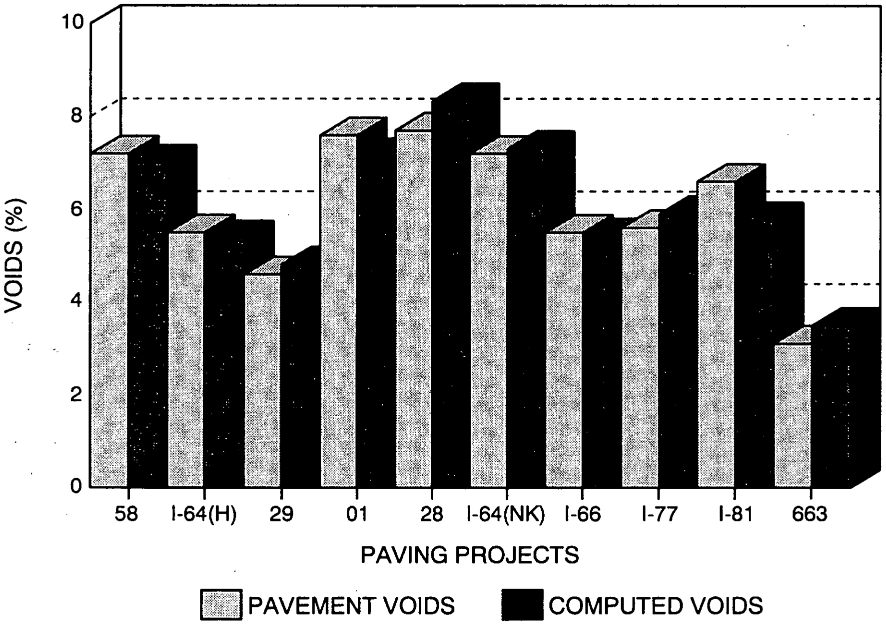

FIGURE 1 **Comparison of final pavement voids and voids estimated from regression with construction voids and GTM voids at 0.872×10^{-2} rad and 827 kPa.**

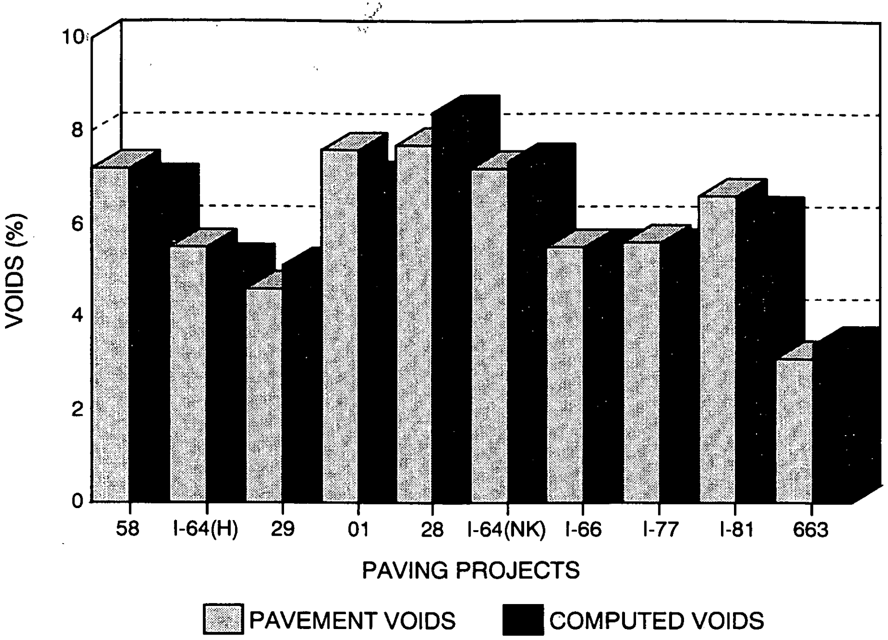

FIGURE 2 Comparison of final pavement voids and voids estimated from regression with construction voids and GTM voids at 1.309×10^{-2} rad and 827 kPa.

cement probably stiffened to the extent that traffic tended to compact all of the mixes about the same proportional amount, negating some of the compaction that would have been predicted by the laboratory tests.

From visual observations it appears that the voids of specimens using the gyratory shear test with an angle of 0.872×10^{-2} rad and 827 kPa vertical pressure most closely approximate the absolute final pavement voids. However, these results could change as additional traffic is allowed to accumulate on the sections. The correlations developed using the 75-blow Marshall voids were not quite as good as the correlations with the gyratory shear test. Figure 3 illustrates a comparison of pavement voids on

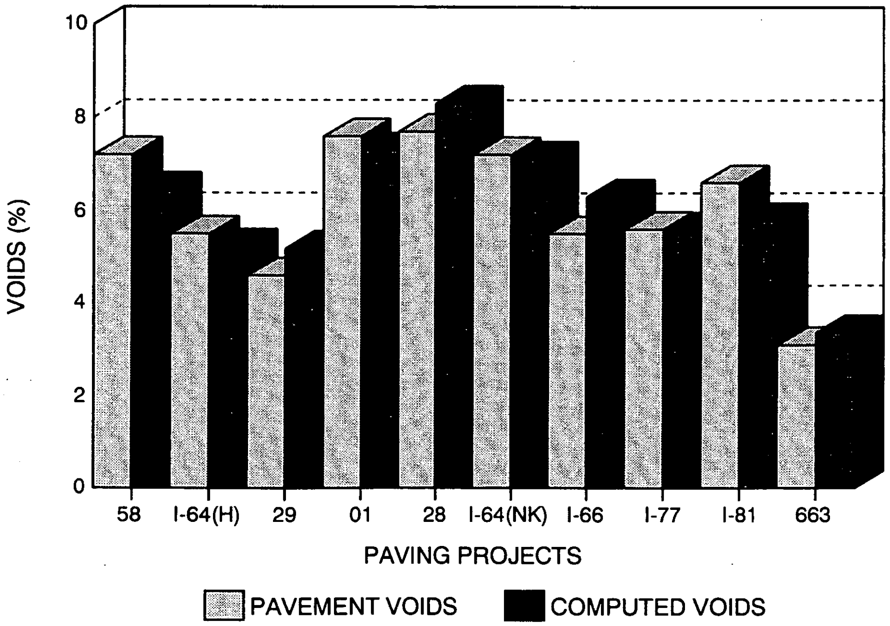

FIGURE 3 Comparison of final pavement voids and voids estimated from regression with construction voids and 75-blow Marshall voids.

the sampled projects and voids predicted by the 75-blow Marshall procedure.

CONCLUSIONS

1. A good correlation was obtained between pavement voids and voids obtained in the laboratory with the gyratory shear test; however, the degree of correlation was highly dependent on inclusion of postconstruction voids.
2. A slightly lower degree of correlation was obtained between pavement voids and voids obtained with the 75-blow Marshall compactive effort.
3. Total traffic in terms of ESALs did not aid the degree of correlation obtained, although it is known to have a significant influence on the final voids. The estimation and inclusion of traffic effects need to be refined further.

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