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Importance and Cost-Effectiveness of Testing Procedures Related to Flexible Highway Pavement Construction in Florida

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ABSTRACT

The cost-effectiveness of in-place density testing procedures for flexible highway pavement construction in Florida was determined using statistical analyses of test results from typical construction projects. The analyses were performed to establish the probability of density test failure, and corresponding margin of failure, for different levels of testing and lengths of projects. Materials analyzed included embankment, stabilized subgrade, limerock base, and asphalt concrete pavement. A reduction in apparent structural strength due to density test failure was computed on the basis of relationships established between elastic moduli and density. This structural deficiency was corrected by an additional thickness of material sufficient to reduce the pavement surface deflection to the same level as that encountered in a properly constructed pavement. An elastic layer computer program was used to determine these additional thicknesses. The cost-effectiveness of any particular testing frequency was based on the cost of testing plus the cost of the additional material to correct for deficient density. Results indicated that current density testing frequencies are generally cost-effective for projects 3 or more miles in length, with the exception of the limerock base, for projects barely 3 mi long, where increased testing was indicated, and for projects 10 or more miles in length, where reduced testing frequencies could be considered. For projects 1 mi long and shorter, for embankment, stabilized subgrade, and limerock base, results indicated that testing frequencies needed to be increased to attain cost-effectiveness.

Test methods for the control and acceptance of flexible pavement construction have evolved over the years. The Florida Department of Transportation (FDOT) "Sampling and Testing Guide" and current specifications are periodically revised to incorporate improvements derived from research and changes in technology. Statistically based quality assurance specifications are currently in use for asphalt concrete pavement construction.

Although the testing requirements and specifications are considered reliable, the FDOT was concerned about the cost-effectiveness of the testing program and wanted to ascertain if testing frequency could be altered to provide cost savings without a reduction in quality. This question was addressed in a research program that encompassed a review of current testing procedures for highway pavements, the determination of the costs of testing, the collection of test results from several highway projects, and a statistical analysis to determine how altering the frequency of testing would affect cost.

OVERVIEW

Although a number of material tests were included in the FDOT study, the major emphasis was on density tests for asphalt and underlying foundation materials because these represented a major portion of the testing budget and because the relationship between material density and strength and stiffness constituted the major control for the structural integrity of the pavement. The overall scheme for the study of density testing is shown in Figure 1. Referring to the figure, assume that the frequency of density testing for any of the materials in the pavement is reduced. There will be other ramifications besides a reduction in testing costs. Because fewer locations in the road are being sampled, there will be more scatter in the results, and the average measured density will have to be viewed as a less precise indicator of the in-place density of the material. There will be a greater probability that test results will indicate a density lower than the overall condition of the roadway. In conducting the tests, there is no way of knowing when such a misleading sample has been taken; hence, the misleadingly low density is used as the material property. If the actual or "true" density of the material is somehow known, statistical theory may be used to estimate how low this misleadingly low density reading is likely to be for a particular frequency of testing. This calculation is performed in the FDOT study, after determining the "true" density values as the average of the results of a large number of tests performed on several roadway projects in Florida. Furthermore, when a reduced density is obtained for a material, a reduced elastic modulus and a reduced strength will be calculated. This will cause increased material thickness requirements to be calculated, resulting in increased material costs. These increased material costs will tend to offset the reduced testing costs realized by reducing testing frequency. The major goal of the study was to determine at what level of testing these two effects would balance and minimize the total cost.

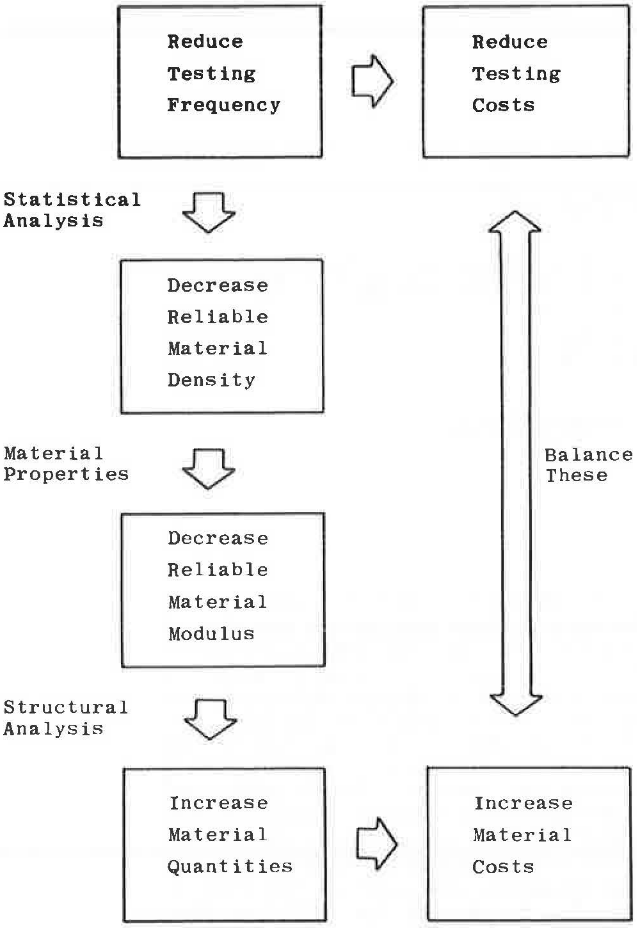

FIGURE 1 Overall scheme of study.

It should be emphasized that the actual material density in the roadway is determined by the basic nature of the material and by various construction procedures, and is obviously not affected by how often or how seldom a person measures the density of that material. Testing frequency alters only the perception of the density. This perceived density, however, is all that the engineer has for guidance, and if it is likely to be reduced, increased material quantities must be used. It is as if the decreased reliability of density measurements that occurs with reduced testing necessitates a higher factor of safety in the structural design of the roadway.

At present, density testing frequencies for FDOT are expressed in terms of tests per lift per mile of roadway. To unify the testing frequency into tests per mile, and to provide a common basis for calculations of pavement structural response and material quantities, a particular pavement section was defined for analysis in this study. Its geometry, shown in Figure 2, is typical of primary highways in Florida.

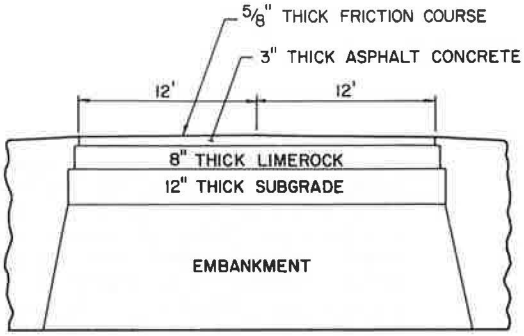

FIGURE 2 Typical roadway section.

DENSITY TESTING

Test Methods

For soils, the FDOT performed either the standard or modified Proctor laboratory test (T99 or T180) on samples of material from the field to establish a minimum specified density henceforth referred to simply as specified density. The nuclear field test (T-238) was performed on the in-place compacted material in the field and had to yield a result equal to or greater than the specified density from the Proctor test if the material was to be considered acceptable. The specified density for embankment material was 100 percent of the T99 Proctor density, and for subgrade material and limerock base it was 98 percent of the T180 Proctor density.

For asphalt, control strips were used. The material of the strips was required to have a density, measured in the laboratory, of at least 95 percent of the maximum possible density. The specified density to be attained by nuclear field tests of the in-place material was 98 percent of the density obtained from nuclear field tests on the control strip.

The frequency of Proctor tests, for embankment, subgrade, and limerock base materials, was one per soil type plus one per roadway mile. Nuclear density tests were performed at rates of one per alternate lift per 500 ft on embankment material, one per lift per 500 ft on subgrade and limerock base, and one per lift per lane per 1,000 ft, plus one per lift per lane per 5,000 ft on asphalt. This translates into 43, 21, 21, and 12 tests per mile for the typical section of Figure 2, for embankment, subgrade, limerock, and asphalt, respectively. In addition, retests of material that had previously failed the nuclear density measurements were permitted for embankment, subgrade, and limerock.

For the analysis in this paper, the result of each nuclear density test was expressed as a variable (Δ_d) given by

$$\Delta_d = \rho_n - \rho_s \tag{1}$$

where ρ_n was the density measured by the nuclear field test of in-place material and ρ_s was the specified density as determined from the appropriate Proctor test result. Hence, Δ_d represented the margin by which the material passed or failed the density test (a negative result implies failure) and is subsequently referred to as density margin.

Project Data

As mentioned previously, the statistical analysis was based on densities measured on several primary (Interstate-level) highway construction projects in Florida. The mean and standard deviation of the density margins (Δ_d) measured on each of these projects, along with the number of measurements taken, are presented in Table 1 in which each line represents either a separate project or a distinct portion of a project.

TABLE 1 Statistics for Density Measurements on Individual Projects

Material	No. of Projects (m)	Project Index (j)	No. of Density Tests (n_j)	Mean Density Margin, $\bar{x}_j$ (pcf)	Standard Deviation of Density Margins, s_j (pcf)
Embankment	6	1	124	4.73	2.80
		2	316	1.77	1.61
		3	79	3.27	2.52
		4	51	3.48	2.67
		5	54	3.67	2.19
		6	62	2.50	2.08
Subgrade	3	1	117	7.70	2.68
		2	159	2.80	3.28
		3	69	3.67	2.81
Limerock	3	1	72	2.33	2.70
		2	282	1.51	3.62
		3	121	3.80	2.54
Asphalt	2	1	64	2.03	1.22
		2	51	2.45	1.33

STATISTICAL ANALYSIS

Population Characteristics

Before the effect of altered testing frequency on perceived material density could be analyzed, the "true" density had to be determined. Strictly, this would be accomplished by testing at all locations in the material and obtaining a population of results. It was assumed that the properties of this population could be approximated by pooling the test results from all projects listed in Table 1. For embankment, subgrade, limerock, and asphalt, the population average ($\bar{\mu}$) and standard deviation (σ) were computed from

$$\bar{\mu} = (1/N)(\sum_{j=1}^{m} n_j \bar{x}_j) \tag{2}$$

$$\sigma^2 = (1/N)\,[\sum_{j=1}^{m} (n_j - 1)s_j^2 + \sum_{j=1}^{m} n_j \bar{x}_j^2] - \bar{\mu}^2 \tag{3}$$

$$N = \sum_{j=1}^{m} n_j \tag{4}$$

where n_j, $\bar{x}_j$, s_j, j, and m are as defined in Table 1.

On the basis of the calculated mean and standard deviation for the population of density tests for each material, and considering the measured density margins (Δ_d) for each population to be normally distributed, the probability of a test failing to indicate at least the specified density (the probability of test failure) was given by the shaded area of Figure 3(a), and denoted p. Values for p were obtained using the tables for normal distributions given by Spiegel (1).

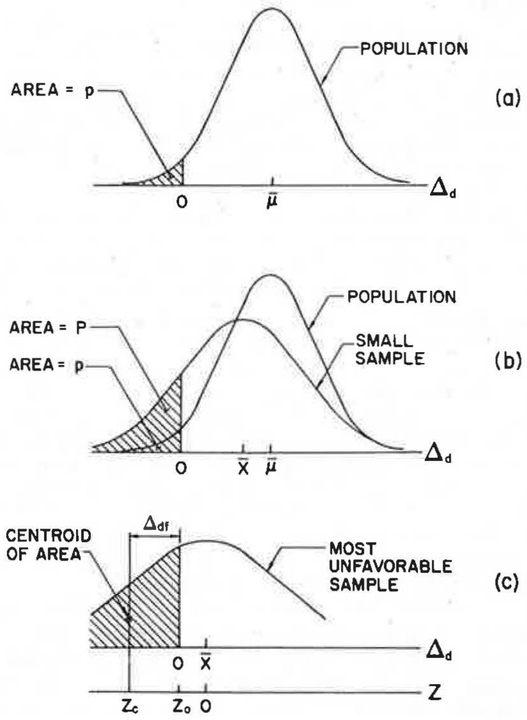

FIGURE 3 Statistical parameters and definitions.

The population parameters are given for each material in Table 2.

Sample Sizes

Current testing frequencies for embankment, subgrade, limerock base, and asphalt materials were given earlier. It was mentioned that retesting was permitted when test results failed to attain the specified density and that both the failing test and the retest were included in computing the material properties. Over an extended period of time, the fraction of failing density tests should equal the probability of test failure for the population, indicated in Table 2, and this proportion was added to the testing frequencies presented previously. The resulting frequencies are given in Table 2.

All testing frequencies for this study were finally expressed as percentages of the current frequencies of Table 2. Statistical calculations were performed for frequencies of 25, 33, 50, 100, and 200 percent of current frequency.

TABLE 2 Pooled Statistics for Each Population

Material	No. of Tests in Population N	Mean Density Margin, $\bar{\mu}$ (pcf)	Standard Deviation of Density Margins, σ (pcf)	Probability of Test Failure, p (%)	Current Testing Frequency (tests/mi)
Embankment	686	2.82	2.43	12.3	48
Subgrade	345	4.64	3.71	10.6	23
Limerock	475	2.22	3.38	25.6	26
Asphalt	115	2.22	1.28	4.1	12

Projection of Sample Properties

On any given job, the number of nuclear density tests performed (the sample size) will represent only a small portion of the population. The mean ($\bar{x}$) and the standard deviation (s) for density margins obtained from any given sample of size n will depend on the random locations at which nuclear density tests are performed and cannot be expected to equal the average and standard deviation for the population, as shown in Figure 3(b). Similarly, two samples of the same size taken from the same material would not produce the same mean and standard deviation. Also, because the mean and standard deviation vary from sample to sample, so must the probability of test failure (P). For any particular sample size n, the distributions of $\bar{x}$, s, and P for all possible random samples forms a sampling distribution, which for the mean and failure probability is the normal distribution and for the standard deviation is the chi-square distribution. This theory is described in texts on engineering statistics, an example of which is Miller and Freund (2). The mean for each of the sampling distributions equals the corresponding parameter for the population, and the standard deviation for each sampling distribution increases as the sample size decreases, reflecting the lower reliability of the smaller sample.

For a particular sample size n, 95 percent of all randomly chosen samples will indicate a mean ($\bar{x}$), a standard deviation (s), and a failure probability (P) within certain intervals known as the 95 percent confidence intervals. These intervals, as given by Miller and Freund (2), are

$$\bar{\mu} - 1.96\,(\sigma/n^{1/2}) \leq \bar{x} \leq \bar{\mu} + 1.96\,(\sigma/n^{1/2}) \tag{5}$$

$$\chi_1^2 \leq [(n-1)s^2/\sigma^2] \leq \chi_2^2 \tag{6}$$

$$p - 1.96\,[p(1-p)/n]^{1/2} \leq P \leq p + 1.96\,[p\,(1-p)/n]^{1/2} \tag{7}$$

where χ_1^2 and χ_2^2 are positions along the chi-square distribution, such that the areas under the distribution from zero to χ_1^2 and from zero to χ_2^2 are 0.025 and 0.975, respectively. Other variables are as previously defined.

The minimum value of the mean, and the maximum values of the standard deviation and failure probability, obtained from the limits in Equations 5, 6, and 7, will characterize the most unfavorable sample for the particular sample size n for the 95 percent confidence limits. Only 2.5 percent of samples of this size, taken at random, can be expected to indicate poorer material. This most unfavorable sample will subsequently be used as an indicator of the effect of altering the sample size n. Note that as n decreases, this most unfavorable sample becomes more severe, indicating a lower mean and a higher standard deviation and failure probability. Note also that it is reasonable to consider the minimum mean density margin and the maximum standard deviation of the density margin to occur simultaneously, because poor material can be expected to exhibit both low density and high variability.

The calculated effect of testing frequency on the most unfavorable sample, considering its mean density margin, its standard deviation, and its probability of test failure, is shown in Figures 4-6. Separate results are shown for a 1-mi-long project and a 10-mi-long project because testing frequencies were expressed as tests per mile, and hence, for a particular percentage of current testing frequency, project length affected the sample size. Although not shown in the figures, calculations were also performed for a 3-mi project length.

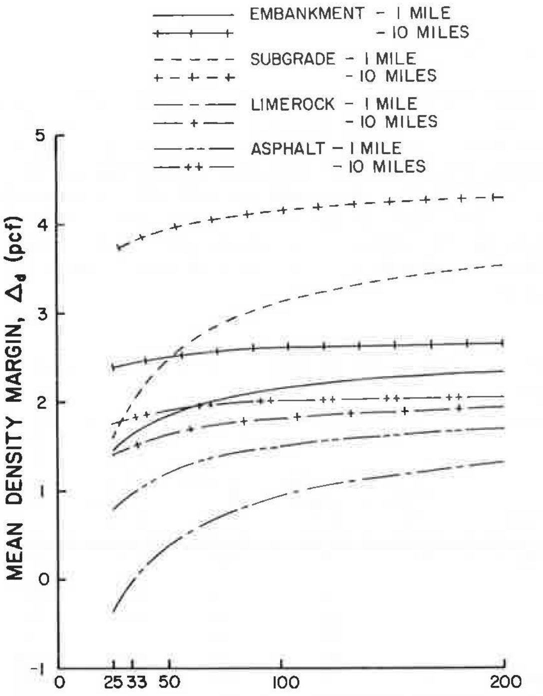

FIGURE 4 Effect of testing frequency on mean density margin for most unfavorable sample at 95 percent confidence.

Mean Failure Margin

In computing the structural response of the pavement, which would be consistent with the density of the most unfavorable sample, it was necessary to establish a magnitude of margin by which these density levels failed to attain the specified density.

A typical distribution of measured density margins, as obtained from nuclear density tests, is shown in Figure 3(c) for the most unfavorable sample of size n. The lower horizontal axis in the figure is in terms of the standard variable (Z) commonly used in statistics for normal distributions. With $\bar{x}$ and P known for the most unfavorable sample, the value of

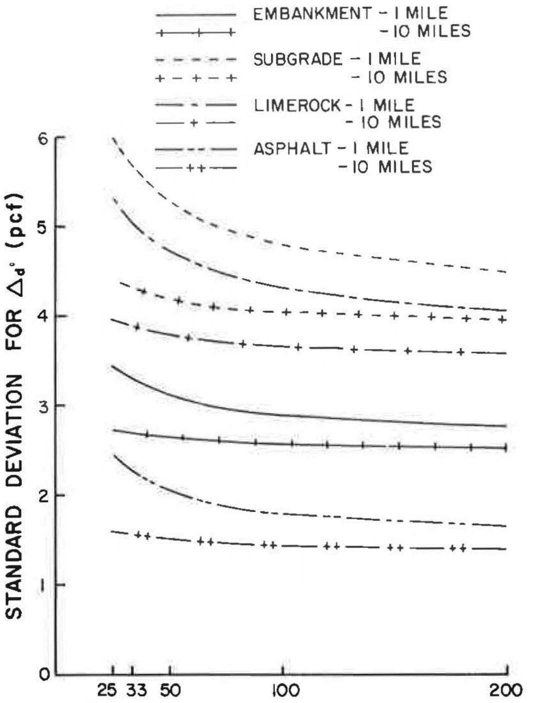

FIGURE 5 Effect of testing frequency on standard deviation of density margin for most unfavorable sample at 95 percent confidence.

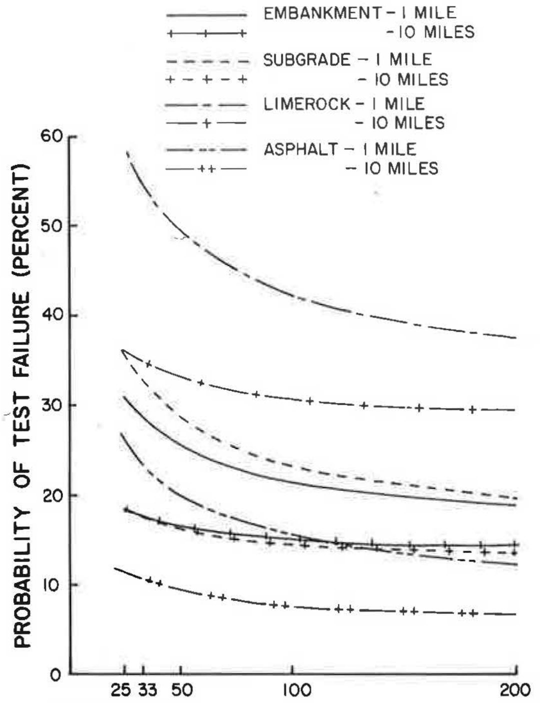

FIGURE 6 Effect of testing frequency on density test failure probability for most unfavorable sample at 95 percent confidence.

Z_o, corresponding to a test that barely meets the specified density, was calculated from tables for normal distribution listed by Spiegel (1). The crosshatched area in Figure 3(c) represented those test locations failing to meet the specified density. The centroid of this area represented the density level indicated by a typical failing test. The standard distance (Z_c) to the centroid, as shown in Figure 3(c), was calculated from the function for the normal distribution and from tables of the ordinates of the normal distribution in Spiegel (1). The density margin (Δ_{df}) corresponding to the centroid was termed the mean failure margin and was given by

$$\Delta_{df} = s(Z_o - Z_c) \qquad (8)$$

where s, Z_o, and Z_c referred to the most unfavorable sample.

The effect of testing frequency on the mean failure margin is shown in Figure 7. According to Figure 3(c) and Equation 8, the mean failure margin must increase as either the failure probability or the standard deviation increases. Hence, the limerock exhibited the highest mean failure margin because of its high failure probability and standard deviation (Figure 5 and 6), whereas the asphalt exhibited the lowest mean failure margin. The subgrade exhibited a mean failure margin much higher than that of the embankment because of its higher standard deviation, even though their failure probabilities were similar (Figures 5 and 6).

MATERIAL PROPERTIES

For a number of combinations of testing frequency and project length, the statistical analysis, described in the preceding section, calculated mean failure margins (Δ_{df}) that were representative

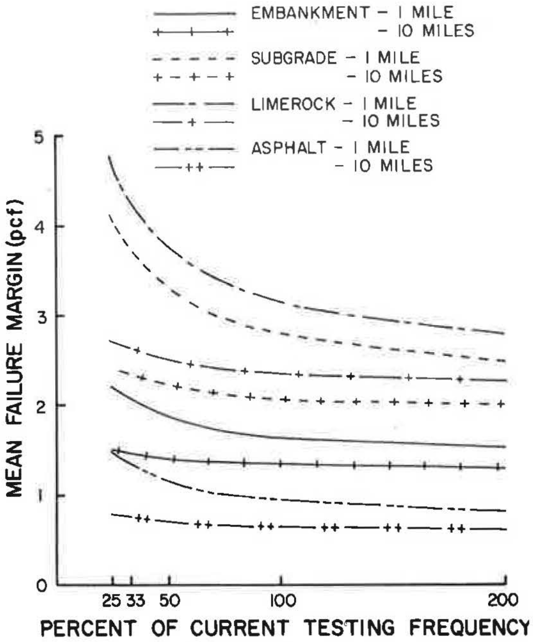

FIGURE 7 Effect of testing frequency on mean density failure margin for most unfavorable sample at 95 percent confidence.

of the most unfavorable sample for each sample size. These failure margins were next translated into elastic moduli. The results were referred to as attained moduli and were expressed as fractions of the modulus corresponding to the specified density, which was referred to as the specified modulus. To accomplish these calculations the mechanical properties of each material had to be defined.

Because subgrade and embankment soils were basically identical, even if not treated and compacted in the same manner, the same strength-density relationship could be used for both. Laboratory tests were performed on samples of the material and the following relation was fitted to the test results:

$$\log \beta = -0.0027 - 0.0352\,\Delta_{df} \qquad (9)$$

where β was the ratio of the attained compressive strength to the specified compressive strength. Note that Δ_{df} was taken as positive. Finally, the ratio of the attained to the specified elastic modulus was taken as equal to the ratio (β) of the compressive strengths.

The limerock was known to conform well to standard relations between density and California bearing ratio (CBR) and between CBR and liquid foundation stiffness (k), as published in handbooks (3,4). These relations were combined to obtain a relation between liquid foundation stiffness (k) in pci and density (ρ) in pcf:

$$\log k = 0.7625 + 0.01695\,\rho \qquad (10)$$

The specified density for this material was 117 pcf, for which Equation 10 computed a liquid stiffness of 556.7 pci. Density (ρ) was computed as

$$\rho = 117\ \text{pcf} - \Delta_{df} \qquad (11)$$

where Δ_{df} was taken as positive. Using ρ from Equation 11, Equation 10 was used to compute the attained liquid stiffness (k_a). The ratio (β) of the attained elastic modulus to the specified elastic modulus was taken as equal to the ratio of the liquid foundation stiffnesses. Hence, for limerock,

$$\beta = k_a/556.7\ \text{pci} \qquad (12)$$

For asphalt, the ratio of attained elastic modulus to specified elastic modulus was given by

$$\beta = 1 - (\Delta_{df}/1.43)(0.115) \qquad (13)$$

that was based on a maximum asphalt unit weight of 143 pcf and a modulus air void relationship, presented by Ruth and Maxfield (5), similar to that presented by Southgate (6).

For the most unfavorable samples at 95 percent confidence, the attained elastic moduli, expressed as percentages of specified moduli, are shown in Figure 8. The results in Figure 8 are equal to 100 β and were computed directly from the mean failure margins of Figure 7. Note that the results for a particular material were a function of both the magnitude of the mean failure margin and the degree of sensitivity of the elastic modulus to this density loss. Hence, the moduli for the limerock were not so bad, even though this material exhibited large margins of density test failure.

STRUCTURAL ANALYSIS

Correction of Perceived Material Deficiency

Any particular layer of material will be subjected to nuclear density testing when it has been compacted in place. If the results of the test sample indicate that the specified elastic modulus has not been attained, the resulting loss in pavement strength and stiffness will be offset by adding an additional thickness of material to the original design thickness, or specified thickness, of a higher layer. Hence, the apparently deficient material must be replaced by higher cost material. When reduced testing frequencies cause perceived deficiencies in material strength and stiffness to be either more severe or more widespread, or both, the additional thicknesses of material at higher levels in the pavement system generate additional costs that offset the savings in testing costs.

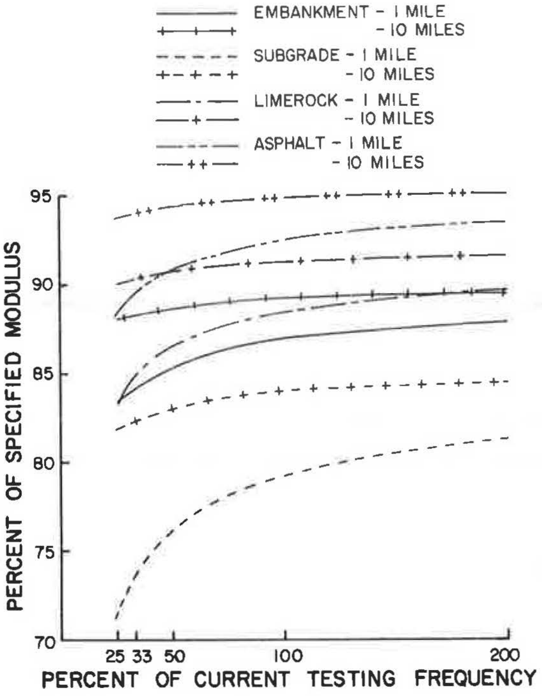

FIGURE 8 Effect of testing frequency on elastic modulus.

For this study, deficient embankment or subgrade was compensated for by additional limerock, and deficient limerock or asphalt was compensated for by additional asphalt.

Pavement Response Calculations

When compensating for deficient material by using additional material in another layer, the governing criteria was that the surface deflection of the pavement be held constant at a specified magnitude equal to that obtained when every layer had the specified thickness shown in Figure 2 and an elastic modulus equal to the specified modulus. This deflection, derived from specified thicknesses, specified densities, and specified moduli, will be referred to as the specified deflection. To provide a data base from which the compensating additional thicknesses could be calculated, pavement surface deflection was calculated for various combinations of elastic moduli and layer thicknesses. In organizing the deflection calculation cases, the elastic modulus for each of the four material layers was varied separately, keeping the moduli of the other three layers constant and calculating for several thicknesses of the layer being used to compensate for structural deficiency. For example, when the embankment modulus was varied, calculations were performed for several thicknesses of limerock base. Results are shown in Figures 9-12.

The ELSYM5 computer program, developed at the University of California, Berkeley, was used to perform the deflection calculations. This model considered the pavement to be composed of several elas-

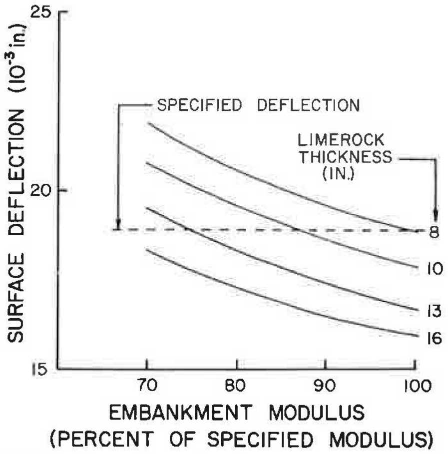

FIGURE 9 Effect of embankment modulus on pavement deflection for several thicknesses of limerock.

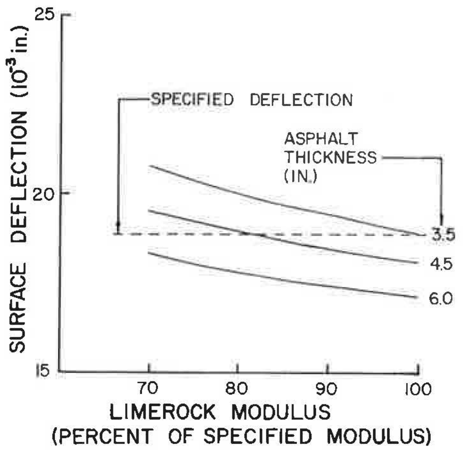

FIGURE 11 Effect of limerock modulus on pavement deflection for several thicknesses of asphalt.

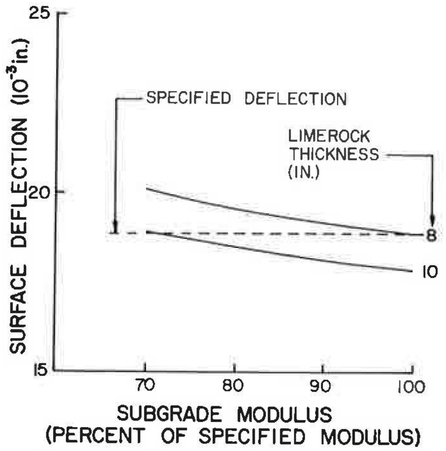

FIGURE 10 Effect of subgrade modulus on pavement deflection for several thicknesses of limerock.

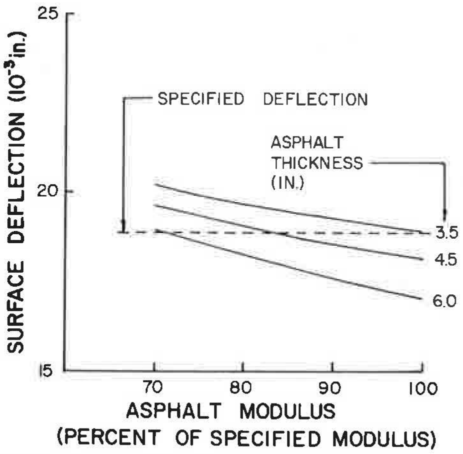

FIGURE 12 Effect of asphalt modulus on pavement deflection for several thicknesses of asphalt.

tic layers, each of uniform thickness and infinite extent in all horizontal directions, with the lowest layer (the embankment) being of infinite depth. The loading was a 20-kip single axle load.

Additional Material Thicknesses

The most unfavorable sample for a 95 percent confidence interval, as defined previously, was used as the base for determining additional material quantities. The deficiency in elastic modulus for this sample, at various testing frequencies, was shown in Figure 8. For each testing frequency, for each material, the elastic modulus deficiency was found from Figure 8. This result was then used in Figures 9, 10, 11, or 12, depending on which material was deficient, to estimate what thickness in the compensating layer would be required to maintain the specified deflection. This required interpolation between the various curves in Figures 9-12. The specified thickness for this layer was then subtracted from the resulting thickness to obtain the additional thickness requirement consistent with the occurrence of the most unfavorable sample.

COST ANALYSIS

Additional Material Costs

Additional costs, incurred for the additional material thicknesses, were computed for a mile of the typical section of Figure 2. The calculation was given by

$$C_m = t_m A P \alpha_m \qquad (14)$$

where t_m was the additional material thickness, in inches, found from Figures 9-12, A was the area of a 1-mi length of the typical roadway section of Figure 2, in square yards, P was the probability of density test failure for the material perceived to be deficient, as found from Figure 6, and α_m was the cost of the additional compensating material per inch of thickness per square yard of area (\$1.06/in./yd²) for asphalt and \$0.43/in/yd² for limerock). Note that the deficiency in density occurs only over a fraction of the pavement corresponding to the probability of test failure.

An example of these results is provided by the upper curve of Figure 13, which indicates the cost

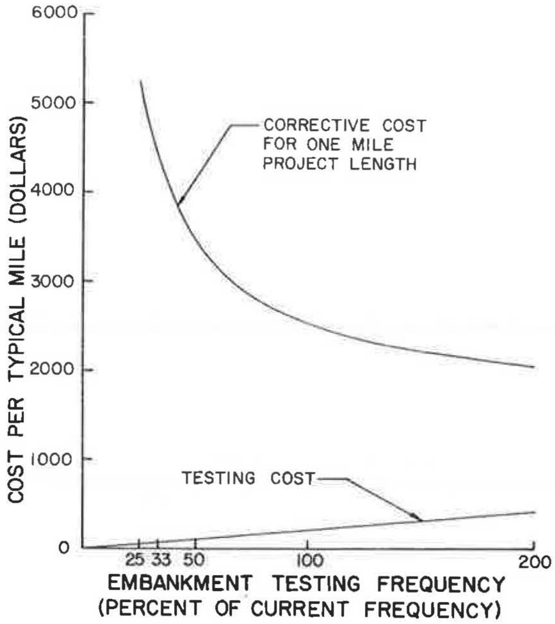

FIGURE 13 Effect of embankment testing frequency on cost of testing and cost of additional limerock.

of additional limerock to compensate for deficient embankment.

Testing Cost

The cost of testing was directly proportional to testing frequency and is shown, for the embankment, by the linear relation in Figure 13. Testing costs were obtained from FDOT accounting data and interviews with FDOT personnel and included technician salaries, cost of transporting specimens to laboratories, equipment depreciation, and interest lost because of capital devoted to equipment. Salaries of supervisors and administrators were not included because these costs were not strongly related to testing frequency and it was difficult to quantify what portion of these salaries was actually devoted to material testing. The unit testing costs finally used in the analysis were \$4.47 per test, \$14.97 per test, \$10.70 per test, and \$23.84 per test for embankment, subgrade, limerock base, and asphalt, respectively. In this context, one test constitutes one comparison of a nuclear density result with the specified density.

Total Cost

For each testing frequency, the cost of testing and the cost of additional material were added. For example, the two relations in Figure 13 were added to obtain the curve in Figure 14 for a 1-mi project length. The optimum frequency of testing occurred when this total cost, as it will be called, was a minimum. As for previous calculations, cost calculations were performed for project lengths of 1 mi, 3 mi, and 10 mi. Total costs for testing and for compensating material for deficient embankment, deficient subgrade, deficient limerock, and deficient asphalt are shown in Figures 14-17. Note that, although referred to as total costs, the results in Figures 14-17 include only density testing plus an increment of material costs and reflect only a small portion of the total cost of highway construction.

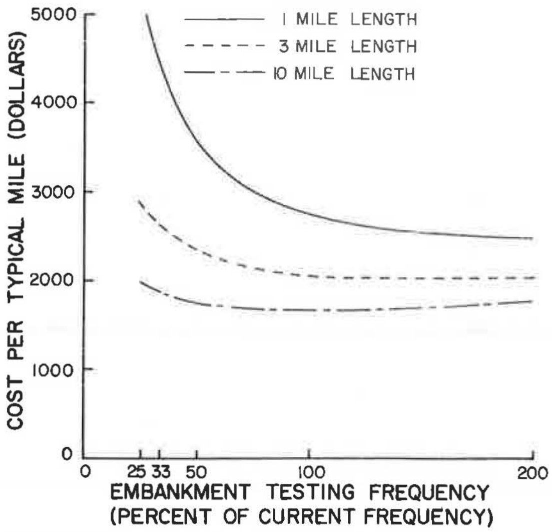

FIGURE 14 Effect of embankment testing frequency on total cost of testing and additional limerock.

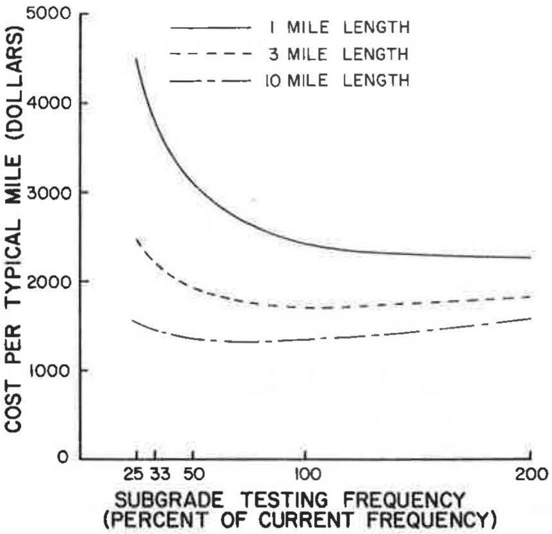

FIGURE 15 Effect of subgrade testing frequency on total cost of testing and additional limerock.

According to Figures 14 and 15, density testing of embankment and subgrade material is cost-effective at the current testing frequency, except for projects less than 3 mi in length, where additional testing could create overall cost savings.

According to Figure 16, density testing of limerock base is cost-effective only for the very longest projects. For projects 3 mi long and shorter, additional density testing could create cost savings. This result reflects the greater variability of the limerock base material relative to the subgrade and embankment material.

According to Figure 17, density testing of asphalt is cost-effective for shorter projects, those 3 mi in length and shorter. For longer projects, cost savings could apparently be realized by reducing the amount of density testing, reflecting the greater reliability and uniformity of asphalt properties relative to those of soil materials.

Finally, note that the general trend was for shorter length projects to need higher testing frequencies than longer projects, to achieve cost-ef-

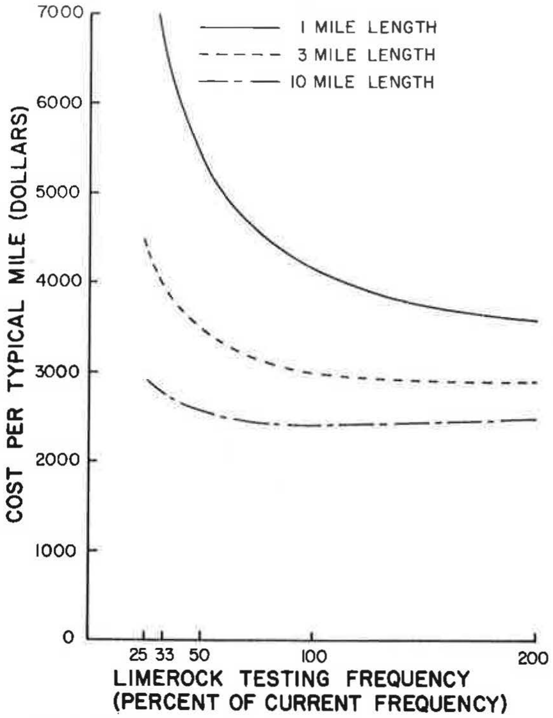

FIGURE 16 Effect of limerock testing frequency on total cost of testing and additional asphalt.

fectiveness, and for shorter projects to be characterized by higher total costs for all testing frequencies. This reflected the current practice of specifying density testing rates on a per lift per mile basis. Hence, at a given percentage of current testing frequencies, smaller sample sizes were actually being considered for the shorter projects. It may be that testing frequency needs to be related to project length in some manner to prevent the sample size from becoming too small.

CONCLUSIONS

The cost-effectiveness of current frequencies of density testing for highway pavement materials in Florida was evaluated using statistical concepts, density test results from actual highway construction projects, relationships between density and elastic modulus for the various materials, and measured costs of the material itself and the testing of the material. Several important findings resulted:

1. Limerock base material indicated the greatest variability in density and asphalt indicated the least variability, even though the mean difference between the in-place density and the specified density was similar for the two materials. This caused the two materials to respond to the statistical analysis in very different ways, with the limerock requiring much higher frequencies of density testing to achieve cost-effectiveness. Embankment and subgrade materials exhibited degrees of variability intermediate between those of asphalt and limerock.
2. Current density testing frequencies are generally cost-effective for projects from 3 to 10 mi long. The only exceptions to this conclusion were limerock base for projects 3 mi long, where cost savings were indicated for increased testing, and asphalt for projects 10 mi long, where cost savings were indicated for reduced testing. This reflects the greater and lesser variability of these materials, as described previously.

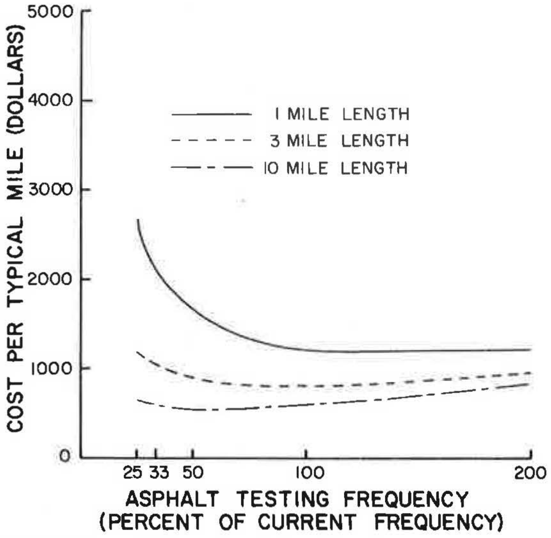

FIGURE 17 Effect of asphalt testing frequency on total cost of testing and additional asphalt.

3. Cost savings were indicated for increased testing frequencies for embankment, subgrade, and limerock base materials for very short (1-mi-long) projects. This was a direct result of testing frequencies being specified entirely as per lift per mile, resulting in unfavorably small sample sizes for short projects. It might be useful to make testing frequencies partly a function of project length.

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