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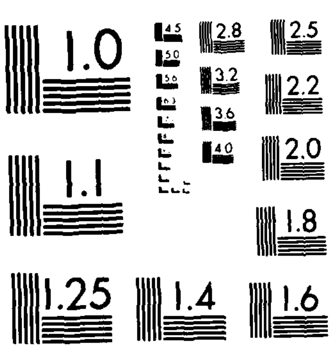

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Field Validation of Statistically Based Acceptance Plan for Bituminous Airport Pavements

Volume 5—Summary of Validation Studies

James L. Burati, Jr.
Herbert W. Busching
Soronadi Nnaji

Department of Civil Engineering
Clemson University
Clemson, South Carolina 29631

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16. Abstract

This report summarizes a research project that was conducted to investigate the use of Marshall properties for acceptance purposes. Since the Marshall properties are physically related, they can be expected to be statistically correlated. It is therefore necessary to determine whether correlations exist among the properties, and how such correlations should be considered when developing acceptance plans.

The research consisted of 3 major phases; a laboratory analysis, field data collection and computer simulation analyses. A laboratory analysis was conducted to establish whether correlations are present among asphalt content, gradation, and the Marshall values for stability, flow and air voids. Another aspect of the laboratory analysis investigated 3 methods for determining maximum specific gravity (MSG) for air voids determination. Field data were also collected from 5 paving projects. Finally, computer simulation was used to evaluate the performance of 7 methods for determining the payment factor for the Marshall properties.

It is recommended that ASTM D-2041 be used to establish MSG values for both the job mix formula and for field quality control testing. It is also recommended that the quality index approach be used to estimate individual PWL values for each of the Marshall properties. These PWL values can then be used with a payment schedule to determine individual payment factors for the 3 properties. The overall Marshall payment factor is then the average of the 3 individual factors.

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PREFACE

This report presents the findings of a research project entitled "Field Validation of Statistically-Based Acceptance Plan for Bituminous Airport Pavements", Report No. DOT/FAA/PM-84/12, that was conducted to investigate the use of Marshall properties for acceptance purposes. The results of the research effort are presented in the series of reports listed below:

Burati, J.L., Brantley, G.D. and Morgan, F.W., "Correlation Analysis of Marshall Properties of Laboratory-Compacted Specimens," Final Report, Volume 1, Federal Aviation Administration, May, 1984.

Burati, J.L., Seward, J.D. and Busching, H.W., "Statistical Analysis of Marshall Properties of Plant-Produced Bituminous Materials," Final Report, Volume 2, Federal Aviation Administration, May, 1984.

Burati, J.L. and Seward, J.D., "Statistical Analysis of Three Methods for Determining Maximum Specific Gravity of Bituminous Concrete Mixtures," Final Report, Volume 3, Federal Aviation Administration, May, 1984.

Nnaji, S., Burati, J.L. and Tarakji, M.G., "Computer Simulation of Multiple Acceptance Criteria," Final Report, Volume 4, Federal Aviation Administration, August, 1984.

Burati, J.L., Busching, H.W. and Nnaji, S., "Field Validation of Statistically-Based Acceptance Plan for Bituminous Airport Pavements -- Summary of Validation Studies," Final Report, Volume 5, Federal Aviation Administration, September, 1984.

The application of multiple price adjustments is significantly more involved than the case when only one property, e.g., density, is considered. Since the Marshall properties (i.e., stability, flow and air voids) are physically related, they can be expected to be statistically correlated. If this is truly the case, then it may not be sufficient to treat each of the three properties individually. It is necessary to determine whether correlations exist among these properties, and whether such correlations should be considered when developing acceptance plans.

The objectives of the research described in the reports listed above include:

1. Review current methods for determining maximum specific gravity for use in air voids calculations for possible incorporation into the FAA Eastern Region P-401 specification,

2. Investigate the use of price adjustments when more than one characteristic is being used for acceptance purposes and recommend to the FAA potential procedures for dealing with multiple price adjustments,

3. Develop the procedures necessary to evaluate the performance of multiple properties acceptance plans,

4. Implement proposed Marshall properties acceptance plans on demonstration projects under field conditions, and

5. Attempt to correlate values of asphalt content and aggregate gradation with those from Marshall tests to determine whether or not correlations exist among these properties.

This report, Volume 5, presents a summary of the total research effort. Volume 4 presents the results of computer simulation analyses used in the development and evaluation of multiple-property price adjustment systems. The results of laboratory analyses and an analysis of field data for the correlation among the Marshall properties are presented in Volumes 1-3.

CHAPTER I

INTRODUCTION

During the 1978 construction season, the Federal Aviation Administration (FAA) Eastern Region incorporated statistically-based aspects into its bituminous surface course specification (P-401) for the first time. This specification included price adjustment factors for mat density. In conjunction with the implementation of the specification, the FAA sponsored a research project to 1) evaluate the performance of the original specification, 2) make recommendations for improving existing specifications and, if possible, 3) expand the scope of the statistical specification to include additional acceptance characteristics and price adjustment factors.

During the initial research effort, goals 1) and 2) were accomplished and preliminary comments concerning goal 3) were made. Findings and recommendations of the research were presented in (1). The report presented some preliminary acceptance plans for the Marshall parameters and recommended additional study before the parameters were actually considered for acceptance purposes. The current report presents the findings and results of a research effort to continue the initial research and expand upon it significantly by considering an acceptance program for multiple characteristics, i.e., the Marshall properties of stability, flow and air voids.

The application of multiple price adjustments is significantly more involved than the case when only one characteristic, density, is considered. Since the Marshall properties to be considered, stability, flow, and air voids, are determined from a single test (i.e., physically related), they can be expected to be statistically correlated. If this is truly the case, then it may not be sufficient to treat each of the 3 properties individually. It was necessary, therefore, to determine whether correlations exist among the properties, and to consider these correlations when developing the acceptance plan.

Research Plan

The research consisted of 3 major areas of investigation that were conducted concurrently. The first major area was a laboratory analysis consisting of a designed experiment under controlled conditions to establish whether correlations exist among the values of asphalt content, aggregate gradation, and the Marshall test values of stability, flow and air voids. Another aspect of the laboratory phase was a comparison of maximum specific gravities (MSG) for use in air voids determination. For laboratory-mixed asphaltic concrete samples, MSG was determined by the pycnometer (ASTM D-2041, Type D) and solvent immersion (2) methods. These values were then compared with those from the individual constituents method used by FAA (2). The second major area was the collection and analysis of field data from 5 construction projects. The final area of investigation was a computer simulation analysis to investigate the performance of acceptance plans with multiple acceptance characteristics. Simulation was used to evaluate the performance of 7 methods for determining payment factors for the Marshall properties.

CHAPTER II

LABORATORY ANALYSIS

The laboratory analysis consisted of 2 designed experiments. The first experiment was designed to identify whether or not pairwise correlations exist among any of the following characteristics: asphalt content, aggregate gradation, Marshall stability, Marshall flow, and air voids. The second experiment was designed to compare the results of maximum specific gravity determinations using each of 3 techniques: individual constituents, solvent immersion, and plastic pycnometer (ASTM D-2041, Type D). Each of these is described in the following sections.

Marshall Correlation Experiment

The purpose of this experiment was to collect data necessary for understanding the random nature of the Marshall properties of stability, flow, and air voids. It was assumed that these variables have a trivariate normal distribution, i.e., each is normally distributed but with some correlation present among the values of the 3 variables. The main emphasis of this investigation, therefore, concerned the 3 correlations -- stability with flow, stability with air voids, and flow with air voids. The experimentation was conducted in a controlled environment so that the only factors affecting the sample correlations should be asphalt content and aggregate gradation. The Marshall correlation experiment is summarized in the following sections. Full details of the experiment, along with the complete results and conclusions, are available in (3).

Experimental Design

The experiment consisted of using 6 different asphalt contents (5.0, 5.5, 6.0, 6.5, 7.0, and 7.5 percent) that were evenly distributed over the P-401 specification limits, and 4 different aggregate gradations that covered the range of the P-401 gradation limits. This resulted in a total of 24 combinations of asphalt content and aggregate gradation.

The 4 gradations selected are shown graphically in Figure 1 and listed in Table 1. The gradations correspond to:

1) the upper limit of the allowable FAA grading band (designated FAA Upper or FAAU),

2) the lower limit of the allowable FAA grading band (FAA Lower or FAAL),

3) the midpoint of the allowable FAA grading band (FAA Midpoint or FAAM), and

CHAPTER III

FIELD DATA COLLECTION

In addition to the laboratory investigatioin, field data were collected for analysis from a number of bituminous runway paving projects. The field data collection and analysis phase of the research effort is summarized in the following sections. Full details of the field data collection, along with the complete results and conclusions, are available in (5).

Projects Studied

It was originally intended to gather data from 5 paving projects. Due to the funding difficulties resulting from the lack of an ADAP program at the time, it was difficult to find 5 suitable projects. Data were collected on the only 5 paving projects to be constructed in the Eastern Region during the 1981 construction season. However, 2 of the projects had such small total tonnages of P-401 material that there were not sufficient data to provide meaningful information. The 5 projects on which data were collected include:

1) the FAA NAFEC facility near Atlantic City (designated Atlantic City),

2) Baltimore-Washington International Airport (BWI),

3) Rochester-Monroe County Airport, Rochester, NY, runway paving project (Rochester),

4) Rochester-Monroe County Airport taxiway project (Rochester 2), and

5) Manassas Municipal Airport, Manassas, VA (Manassas).

The tonnages on Rochester 2 and Manassas were so small that only a few paving days were required on each project. As a result, data and discussion are presented for only the Atlantic City, Rochester, and BWI projects.

Research Procedure

The specifications on the projects studied included a price adjustment provision for mat density based upon the percentage of the material within specification limits (PWL). The Atlantic City project also included price adjustment features for joint density as well. While none of the projects included a price adjustment for any of the Marshall properties, all of the specifications based substantial compliance for stability, flow, and air voids on at least 90 percent of the material being within specification limits (90+ PWL). It was

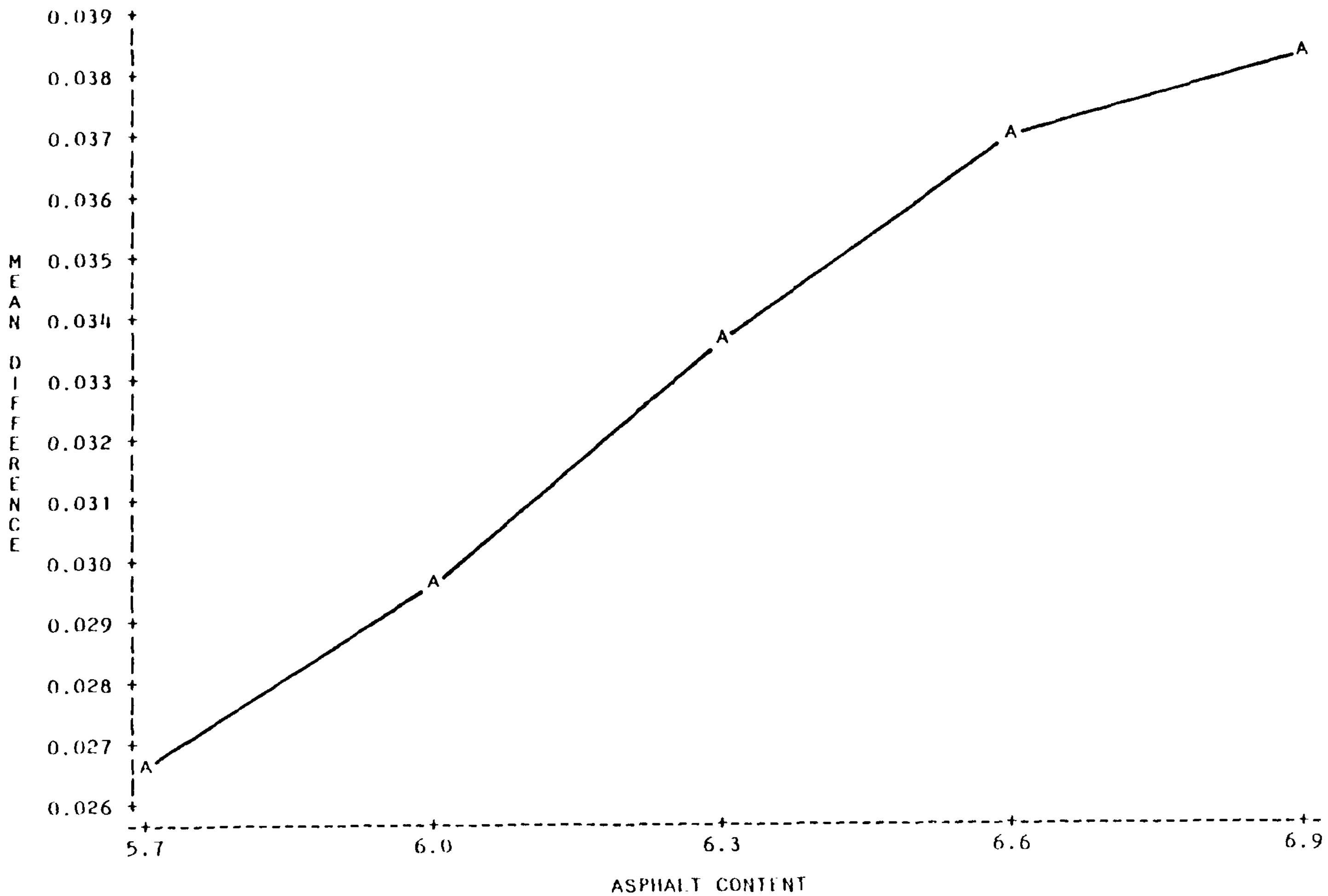

FIGURE 7. PLOT OF MEAN DIFFERENCE BETWEEN ASTM D-2041 AND INDIVIDUAL CONSTITUENTS RESULTS VERSUS ASPHALT CONTENT

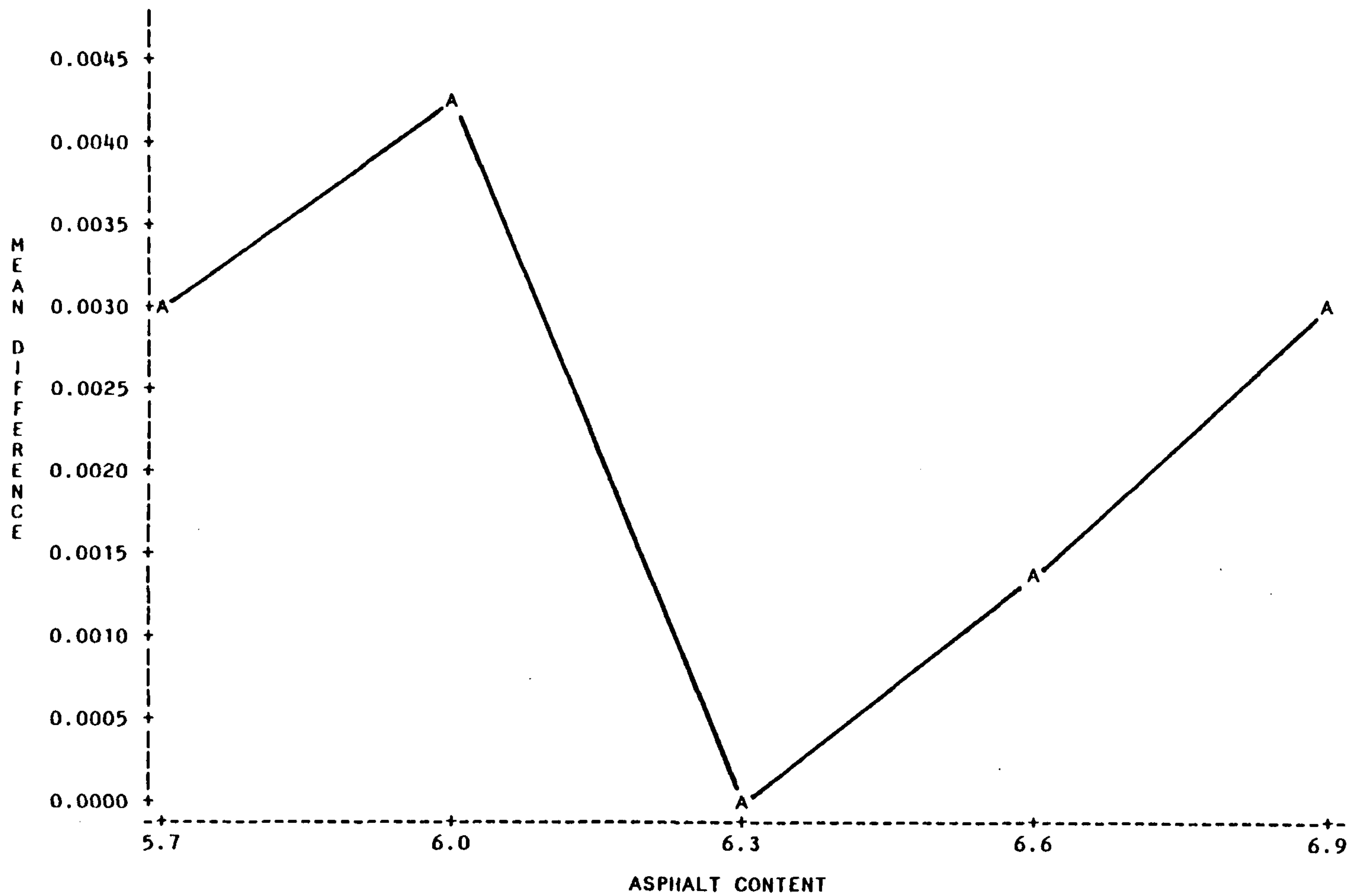

FIGURE 6. PLOT OF MEAN DIFFERENCE BETWEEN SOLVENT IMMERSION AND INDIVIDUAL CONSTITUENTS RESULTS VERSUS ASPHALT CONTENT

For the SI to IC comparison, there was no statistically significant difference between the 2 methods at the 0.05 level for any of the 5 asphalt contents tested. However, the 5.7, 6.0, and 6.9 percent asphalt contents were significantly different at the 0.10 significance level. For the PYC to IC comparison, there was a statisiically significant difference between the 2 methods at the 0.05 level for all 5 of the asphalt contents tested.

The final analysis conducted was a one-way analysis of variance (ANOVA) to test whether the differences between each of the 2 experimental methods and the IC method varied with asphalt content. Figures 6 and 7 present the mean differences between the methods plotted against asphalt content for the SI to IC and PYC to IC comparisons, respectively. The analysis procedure generated F-statistics for testing the null hypothesis that the slope of the line in each of Figures 6 and 7 is zero. This is analogous to saying that asphalt content does not affect the differences between the methods. The results of the F-tests indicate that there is no significant asphalt content effect at the 0.05 level for the SI to IC comparison, but that there is a statistically significant asphalt content effect at the 0.05 level for the PYC to IC comparison. These results should be obvious by an examination of Figures 6 and 7.

Conclusions from MSG Experiment

The solvent immersion method for determining MSG provides results that generally are equivalent to the individual constituents method. The plastic pycnometer method (ASTM D-2041, Type D) provides MSG values that are, on the average, smaller than those obtained by the individual constituents method. This is due to the fact that in the solvent immersion procedure the asphalt cement is dissolved by the solvent. This allows the solvent to be absorbed into the aggregate surface pores in the same manner the water is absorbed when apparent specific gravities of the aggregates are determined.

The procedure of developing a correction factor between the individual constituents and the pycnometer MSG values at the optimum asphalt content is not recommended. This is because the laboratory results indicate that the difference between the individual constituents and plastic pycnometer results varies with the asphalt content of the mixture. In light of this, the correction factor must also vary with asphalt content.

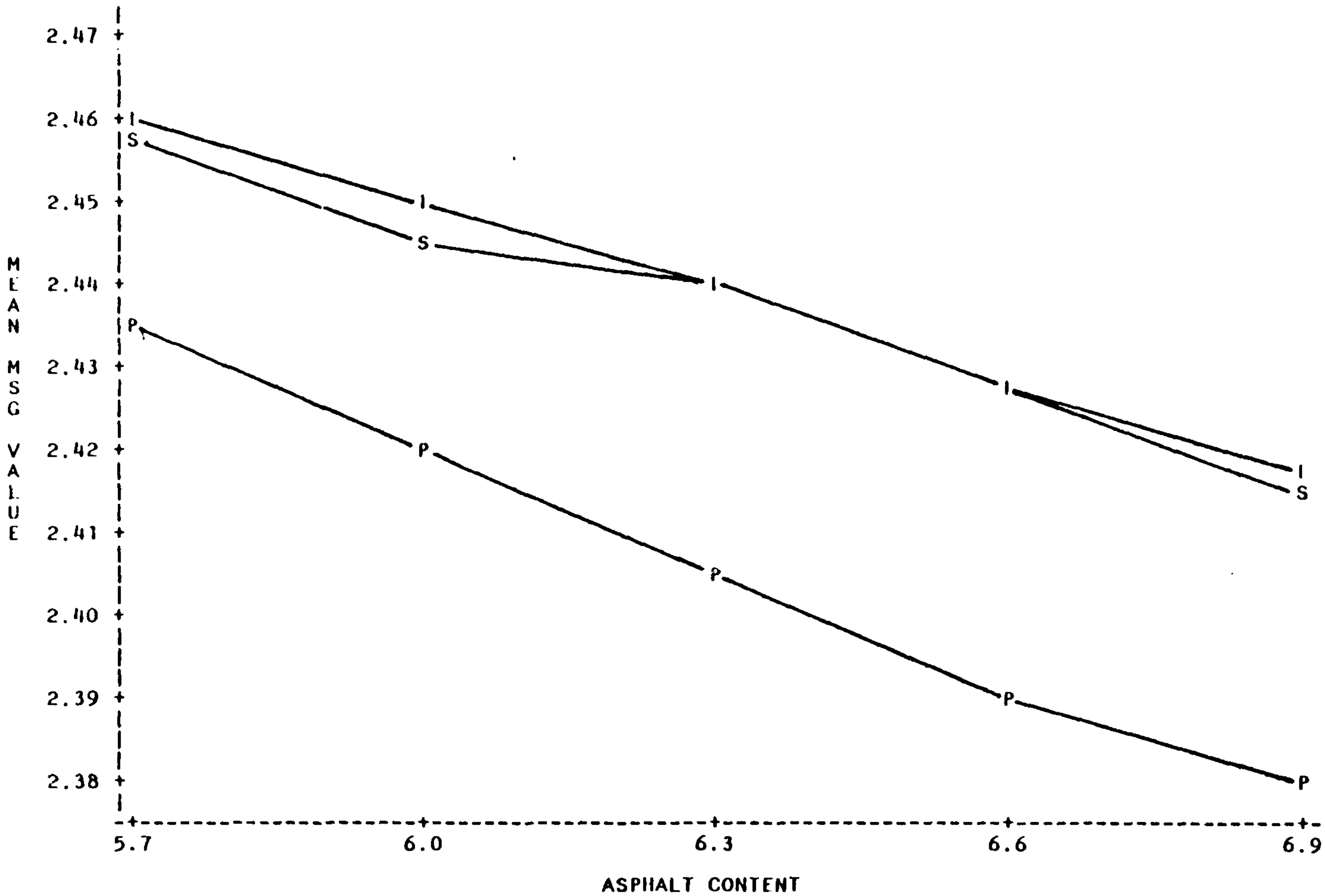

FIGURE 5. PLOT OF MEAN MAXIMUM SPECIFIC GRAVITY VALUES VERSUS ASPHALT CONTENT FOR THE FIVE REPLICATES TESTED

TABLE 2. MAXIMUM SPECIFIC GRAVITY RESULTS

Replicate	Asphalt Content (%)	Method: Individual Constituents (IC)	Method: Solvent Immersion (SI)	Method: ASTM D-2041 (PYC)
1	5.7	2.461	2.460	2.437
	6.0	2.450	2.443	2.421
	6.3	2.439	2.440	2.406
	6.6	2.428	2.425	2.389
	6.9	2.418	2.414	2.381
2	5.7	2.461	2.454	2.430
	6.0	2.450	2.444	2.422
	6.3	2.439	2.443	2.405
	6.6	2.428	2.428	2.388
	6.9	2.418	2.414	2.384
3	5.7	2.461	2.461	2.431
	6.0	2.450	2.444	2.424
	6.3	2.439	2.437	2.401
	6.6	2.428	2.430	2.394
	6.9	2.418	2.412	2.376
4	5.7	2.461	2.459	2.435
	6.0	2.450	2.446	2.419
	6.3	2.439	2.436	2.404
	6.6	2.428	2.427	2.393
	6.9	2.418	2.419	2.380
5	5.7	2.461	2.456	2.438
	6.0	2.450	2.452	2.416
	6.3	2.439	2.439	2.409
	6.6	2.428	2.423	2.391
	6.9	2.418	2.416	2.377
Average of All 5	5.7	2.461	2.458(.00292)[a]	2.434(.00356)[a]
	6.0	2.450	2.446(.00363)[a]	2.420(.00305)[a]
	6.3	2.439	2.439(.00274)[a]	2.405(.00303)[a]
	6.6	2.428	2.427(.00270)[a]	2.391(.00255)[a]
	6.9	2.418	2.415(.00265)[a]	2.380(.00351)[a]

[a]Number in parentheses is the standard deviation for the 5 replicates

the 4 gradations used in the Marshall correlation analysis was selected for the MSG experiment. The optimum asphalt content for this mix was determined, in accordance with the ERLPM, to be 6.3%. Five asphalt contents were selected for the experiment. These were: 5.7, 6.0, 6.3 (optimum), 6.6, and 6.9 percent. A total of 5 replicate tests were conducted for each asphalt content for a total of 25 samples that were mixed.

The general procedure was as follows. The specific gravities of the limestone, natural sand, and asphalt cement were used to determine the maximum theoretical specific gravity for each mixture by the IC method. A 7920 gram sample was mixed, and a portion of the sample, 1250 grams, was used for a SI MSG determination. Then, 6000 grams were used for the PYC MSG determination procedure. This procedure was followed for each of the 5 asphalt contents in random order, and was repeated for each of the 5 replications.

Analysis of Results

The results of the MSG values determined theoretically using the IC approach for each of the 5 asphalt contents are presented in Table 2. Also in Table 2 are the results of the MSG values obtained experimentally from each of the 5 replicates for each of the 5 asphalt contents. Figure 5 presents a plot of the average MSG values from the 5 replicates versus asphalt content.

Three statistical analyses were conducted on the data generated from the laboratory test results. The Statistical Analysis System (SAS) was used for the analyses. First, the MSG values obtained using SI and PYC were compared using a sample t-test procedure (PROC TTEST) in SAS. The procedure computes a t-test statistic to test the null hypothesis that the means of the 2 groups of data, in this case, SI and PYC, are equal. Also included in the procedure is a F-statistic to test the equality of the variances of the 2 groups. The tests were conducted individually on the data for each asphalt content. The results of this t-test process were that the null hypothesis of equal means for SI and PYC could be rejected at the 0.05 level of significance for each of the 5 asphalt contents, and that the null hypothesis of equal variances could not be rejected at the 0.05 level for any of the 5 asphalt contents. In other words, the results indicated that there was a statistically significant difference between the mean results obtained with SI and those obtained with PYC, but that neither method contained more variability than the other.

The second analysis compared the SI and PYC results directly with the IC MSG values. To test each procedure, the experimentally obtained MSG values were subtracted from the constant theoretical MSG values from the IC method. A t-test was then conducted at each asphalt content (using SAS procedure UNIVARIATE) to test the hypothesis that the mean of the differences was zero. A zero mean difference implies that the 2 methods provide the same results.

Since very few sample values fall outside the 95% confidence limits, it can not be concluded that the true value for correlation is statistically significantly different from zero at the 0.05 level of significance. However, the generally consistent trends towards either positive or negative correlation argue in favor of mild corelations being present. A moderately low positive correlation appears to exist between stability and flow from below to approximately 0.5% above the optimum asphalt content (Figure 2). A moderately low negative correlation exists between stability and air voids at approximately the optimum asphalt content and below for each gradation tested (Figure 3). And, a mild negative correlation exists between flow and air voids at optimum asphalt content and above (Figure 4).

The correlations for stability and air voids, and stability and flow appear to be dependent upon the aggregate gradation from approximately 0.5% to 1.5% above optimum asphalt contents. Such large deviations from the optimum asphalt content should, however, rarely be encountered in a properly controlled asphaltic concrete mixing operation.

Conclusions from Marshall Correlation Analysis

The results of the correlation analysis of the laboratory-compacted Marshall specimens indicate that relatively mild, but generally consistent, correlations exist among the Marshall properties. A positive correlation exists between stability and flow, while negative correlation is present between stability and air voids, and between flow and air voids. These correlations are not significant enough to justify eliminating one or more of the Marshall properties from use in a multiple price adjustment system, but they appear to be significant enough to violate an assumption of statistical independence among the properties.

Maximum Specific Gravity Analysis

This phase of the laboratory analysis was designed to investigate the laboratory determination of maximum specific gravity (MSG) for use in determining air voids content of a compacted asphaltic concrete paving mixture. The FAA ERLPM provided a procedure for developing a factor for adjusting MSG values obtained from either ASTM D-2041, Type D (PYC) or solvent immersion (SI) methods to an equivalent MSG by the theoretical individual constituents (IC) method. The laboratory analysis investigated the different results obtained by these 3 methods and whether these differences vary with asphalt content. A summary of the MSG analysis is presented below. Full details of the experiment, along with the complete results and conclusions, are available in (4).

Experimental Design

The experiment was designed to investigate any differencses that may exist in the determination of MSG by IC, SI, and PYC. These differences were determined at the optimum asphalt content for the material and at asphalt contents both above and below optimum. One of

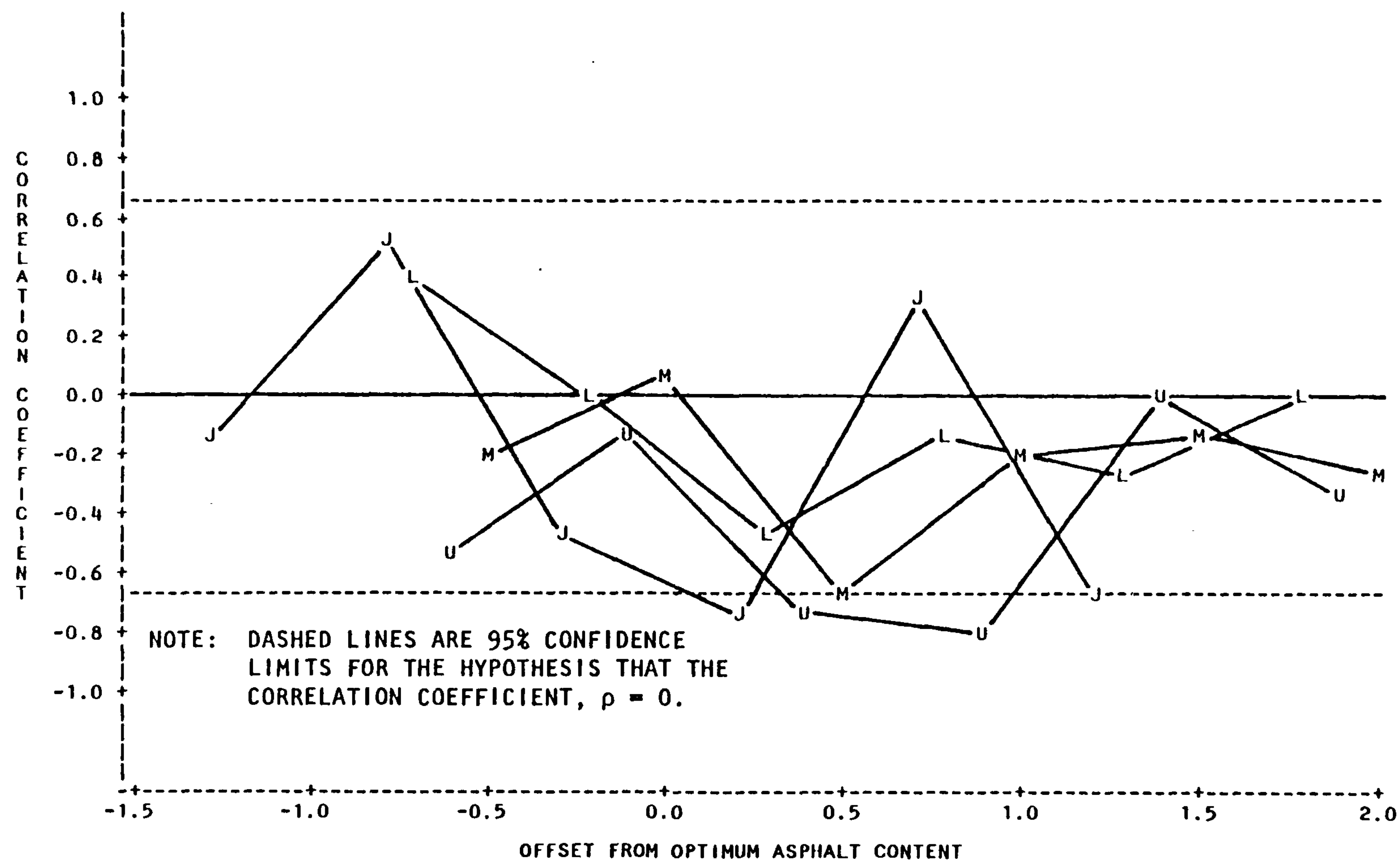

FIGURE 4. PLOTS OF FLOW VS AIR VOIDS CORRELATION COEFFICIENTS BY GRADATION

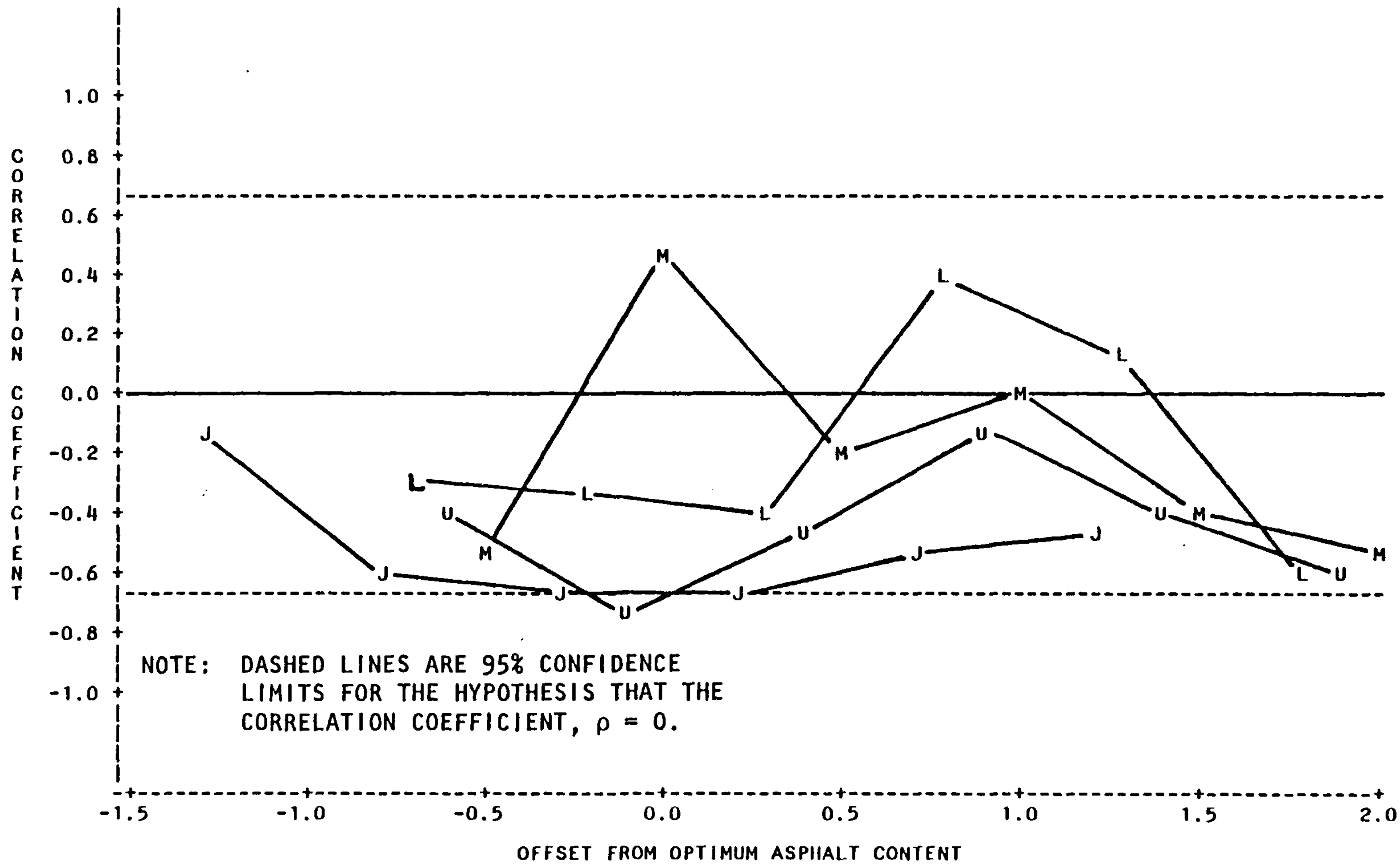

FIGURE 3. PLOTS OF STABILITY VS AIR VOIDS CORRELATION COEFFICIENTS BY GRADATION

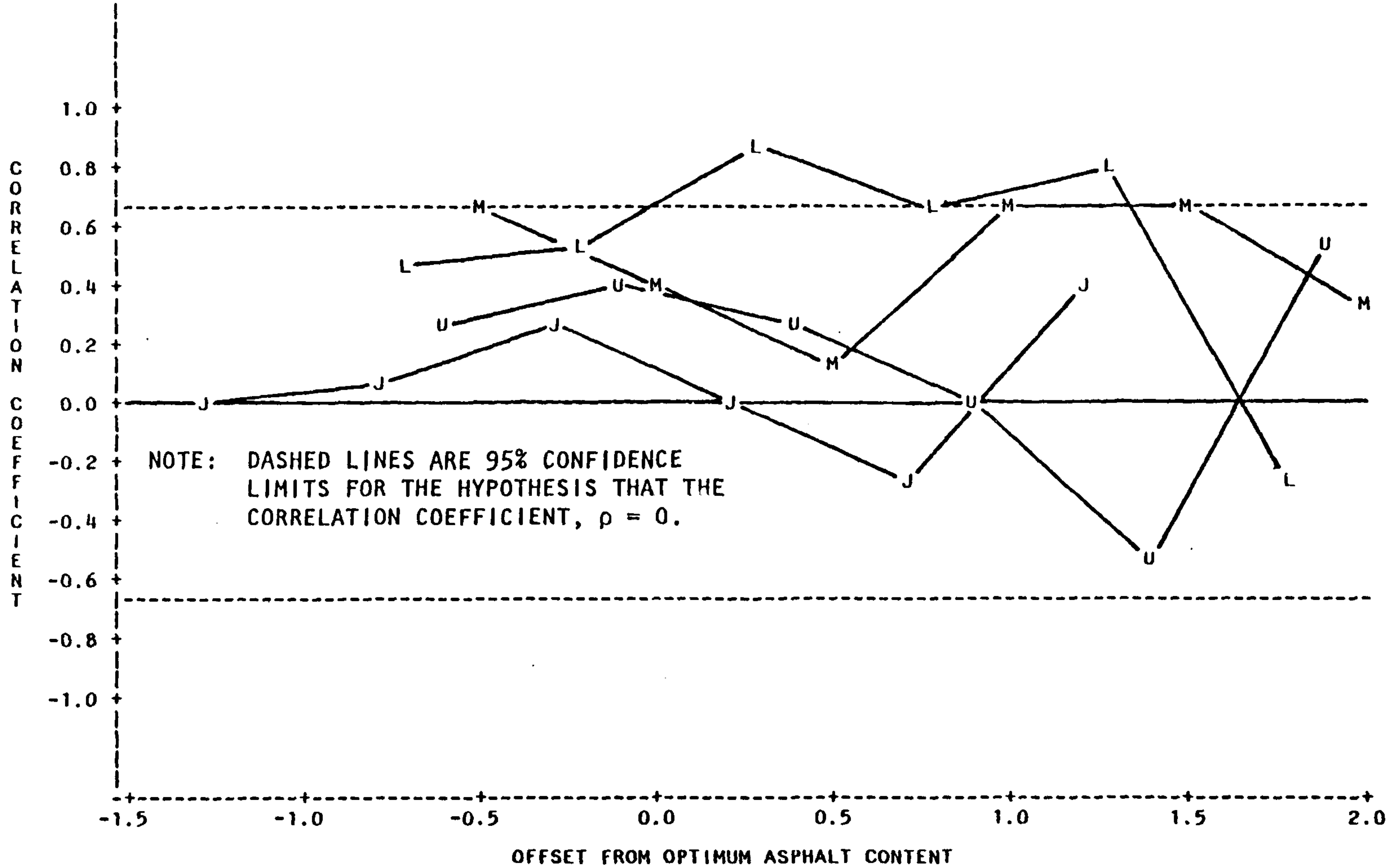

FIGURE 2. PLOTS OF STABILITY VS FLOW CORRELATION COEFFICIENTS BY GRADATION

4) the job mix formula gradation from one of the field projects studied (Rochester or JMF).

Preliminary calculations indicated that at least 9 specimens for each of the 24 asphalt content/aggregate gradation combinations were needed to detect a correlation of 0.5 with a probability of 0.6. Since it was not possible to prepare and test all 216 specimens (9 x 24) in a short period of time, the specimens were divided into groups of 24 where each group contained each asphalt content/aggregate gradation combination. Within each group the order in which the specimens were prepared and tested was random.

Three sets of specimens (a total of 72) were prepared and tested to familiarize the laboratory technicians with the FAA Eastern Region Laboratory Procedures Manual (ERLPM) (2) and to 'break-in' the equipment, that was purchased new for the project, before actual experimentation began. In addition, a statistical analysis, consisting of analysis of variance (ANOVA) and Duncan's multiple range test, was conducted to determine whether time, i.e., the order in which the groups were tested, had an effect on the measurements. It was determined that there was no time effect for the 9 replications of Marshall test specimens.

Analysis of Correlation Results

As noted above, the objective of the experiment was to determine whether or not corelations exist among the Marshall properties. To be more specific, the experiment was intended to determine how well Marshall stability correlated with Marshall flow, Marshall stability correlated with air voids, and Marshall flow correlated with air voids for each of the 24 asphalt content/aggregate gradation combinations tested (4 gradations x 6 asphalt contents). Since each property appeared to be related to the optimum asphalt content, the correlation coefficients were plotted with each gradation adjusted for its respective optimum asphalt content.

The results of the correlation analysis are plotted in Figures 2 - 4. The figures represent plots of the correlation coefficients versus offset from optimum asphalt content for each of the 4 gradations for the 3 possible correlations, i.e., stability with flow, stability with air voids, and flow with air voids, respectively.

The correlation coefficients can vary from -1.0, perfect negative correlation, to +1.0, perfect positive correlation. A correlation coefficient of zero indicates no correlation between the variables being considered. The horizontal reference lines at +0.67 and -0.67 for each correlation plot correspond to the 95% confidence limits for the null hypothesis that the true correlation is zero.

TABLE 1. AGGREGATE GRADATIONS USED FOR MARSHALL LABORATORY TESTING PHASE

	PERCENT PASSING				
SIEVE	ALLOWABLE SPEC LIMITS	FAAU	FAAM	FAAL	JMF
3/4 in.	100	100	100	100	100
1/2 in.	82-96	96	89	82	98.6
3/8 in.	75-89	89	82	75	84.6
No. 4	59-73	73	66	59	66.5
No. 8	46-60	60	53	46	55
No. 16	34-48	48	41	34	42
No. 30	24-28	38	31	24	31
No. 50	15-27	27	21	15	20
No. 100	8-18	18	13	8	8.5
No. 200	3-6	6	4.5	3	3.8

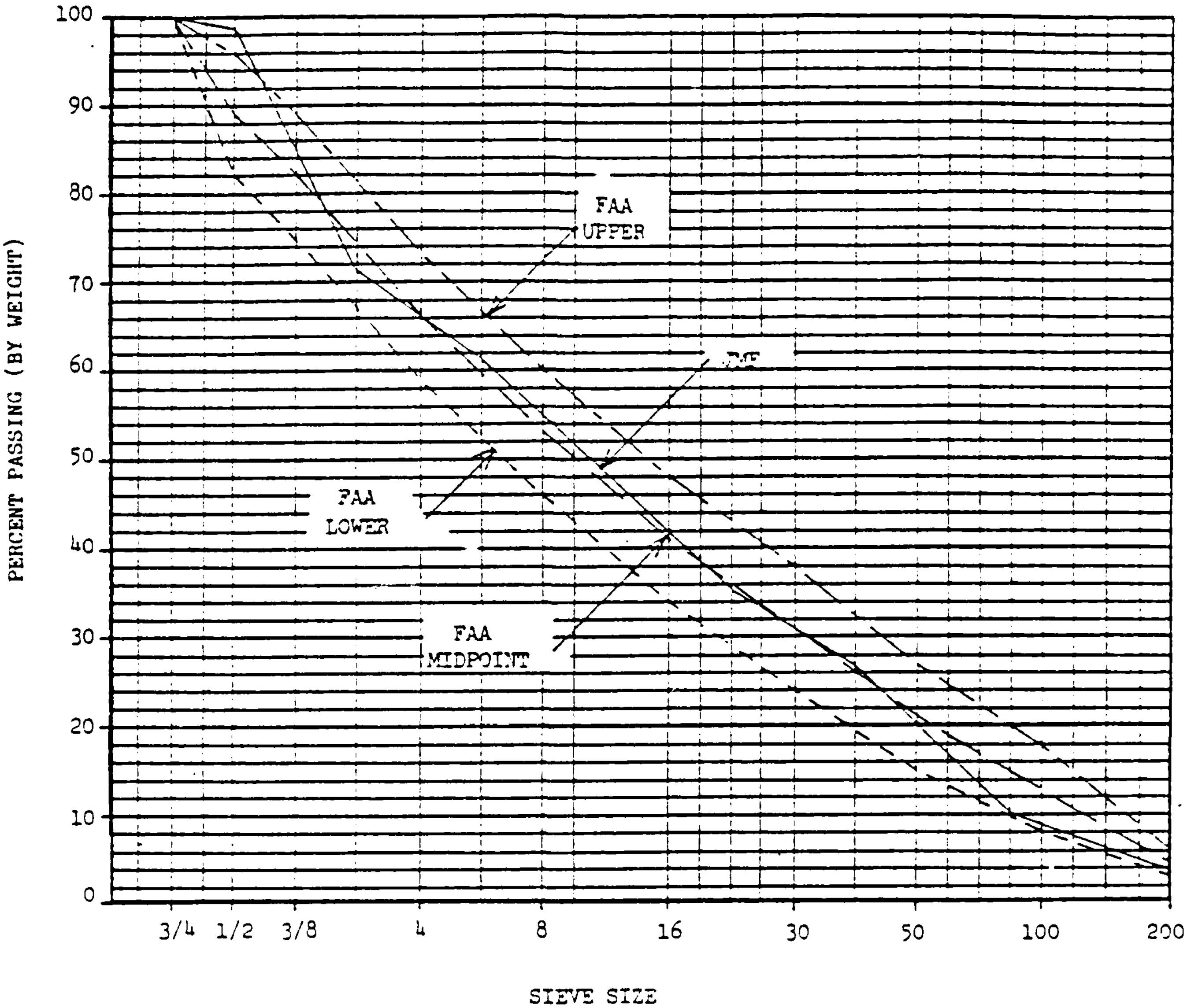

FIGURE 1. AGGREGATE GRADATIONS USED FOR THE MARSHALL LABORATORY TESTING PHASE

necessary, therefore, on each of these projects to estimate PWL for stability, flow, and air voids for each lot of material. In this way, the contractor received daily feedback on his performance with respect to the Marshall properties.

Each of the projects was visited by the researchers before paving began for a pre-paving conference in which the goals and objectives of the research effort were discussed with all parties involved. Additionally, each project was visited by the researchers at least once during paving operations to observe and verify that all sampling and testing procedures were in accordance with the ERLPM.

Analysis of Results

Summaries of the Marshall test results from the 3 field projects are presented in Tables 3 through 5.

Correlation Analysis

One of the major areas of interest in evaluating the field data was to determine whether correlations exist among the 3 Marshall properties for material placed under field conditions. The results of such an analysis could then be compared with the correlation levels obtained in the laboratory phase of the project. The correlations considered are: Marshall stability with Marshall flow, Marshall stability with air voids, and Marshall flow with air voids.

The correlation coefficients for each of the 3 projects studied are presented in Table 6. Generally similar patterns can be seen in the table for the Atlantic City and Rochester projects, while the BWI project exhibits markedly different results for the correlations in which flow is considered. The discrepency may be due to the fact that nearly every flow value on this project was recorded as either 10 or 11. Of 67 test specimens, 27 were recorded as 10.0 and 32 were recorded as 11.0. This type of 'consistency' was not recorded on the other 2 projects, and may have had a considerable effect in the different correlation values obtained on the BWI project. A comparison with Figures 2 through 4 indicates the correlation results on the Atlantic City and Rochester projects agree with the general trends exhibited in the laboratory data.

Regression Analysis

To compare the field results with those from the laboratory analysis, a multiple regression analysis was conducted in an effort to develop a predictive equation for estimating Marshall stability, flow, and air voids from the extracted asphalt content and aggregate gradation. When each truck sample was taken for the purpose of Marshall testing, a portion of the sample was used for the contractor's extraction quality control test. In this way, asphalt content and extracted gradation were determined for each sample used for the Marshall tests.

TABLE 3. SUMMARY OF FIELD MARSHALL TEST RESULTS FROM THE ATLANTIC CITY PROJECT

DAY	NO. OF TESTS	STAB MEAN	STAB ST DEV	FLOW MEAN	FLOW ST DEV	VOIDS MEAN	VOIDS ST DEV
1	4	2420	119.3	9.0	1.22	2.7	0.62
2	2	2585	338.9	9.0	0.28	3.5	0.28
3	3	2719	244.6	8.0	1.17	3.7	0.26
4	4	2553	271.3	9.1	0.36	3.4	0.96
5	4	2438	304.3	9.8	0.89	3.7	0.61
6	4	2370	190.1	9.2	0.66	3.9	0.28
7	4	2055	65.2	9.0	0.34	4.0	0.19
8	4	2242	220.7	10.3	1.27	3.2	0.72
9	6	2609	337.7	11.5	0.87	2.3	0.65
10	4	2412	234.4	10.6	1.08	3.9	0.31
11	4	2881	248.5	10.0	0.76	3.8	0.80
12	4	2739	212.8	9.3	0.47	4.2	0.61
13	2	2338	262.3	11.2	0.71	2.2	0.57
14	4	2682	335.8	10.0	0.47	3.6	1.10
15	4	2672	546.1	9.3	0.39	4.3	1.08
16	1	2449	--	9.8	--	3.7	--
17	4	2252	250.9	9.8	0.80	4.1	0.67
18	4	2524	115.8	9.7	0.34	3.9	0.37
19	3	2629	116.3	9.9	0.43	3.1	0.17
20	3	2741	180.0	9.6	0.29	3.5	0.55
21	4	2774	270.2	10.1	0.70	3.0	0.67
22	3	2909	191.7	9.9	0.12	3.0	0.30
23	3	2661	142.0	10.2	1.17	2.4	0.23
24	4	2711	162.1	10.3	0.75	2.7	0.39
25	4	2641	429.9	9.9	0.22	4.3	0.79
26	4	2972	332.6	10.5	0.52	2.1	0.15
27	5	2225	93.9	9.7	0.59	3.4	0.21
28	3	2372	72.2	9.3	0.53	3.6	0.95
29	4	2535	640.9	10.1	0.54	3.2	0.36
30	4	2411	139.4	10.1	0.45	3.4	0.30
31	4	2336	53.9	10.3	0.57	2.6	0.17

TABLE 3. (Continued)

DAY	NO. OF TESTS	STAB MEAN	STAB ST DEV	FLOW MEAN	FLOW ST DEV	VOIDS MEAN	VOIDS ST DEV
32	4	2392	45.9	10.1	0.52	2.6	0.51
33	4	2426	80.7	9.9	0.27	3.5	0.90
34	4	2454	124.9	10.5	0.52	3.9	0.37
35	4	2477	229.9	10.4	0.40	3.9	0.66
36	4	2413	200.3	10.3	0.54	4.0	0.83
37	5	2456	223.7	10.1	0.41	3.5	0.20
38	4	2520	334.3	9.7	0.39	4.0	0.88
39	4	2513	232.0	10.5	0.50	3.7	0.69
40	5	2435	263.3	10.5	0.98	2.9	0.45
41	5	2171	88.2	10.0	0.69	3.1	0.60
42	5	2297	206.8	10.4	0.63	3.5	0.37
43	3	2385	146.2	10.5	0.62	3.1	0.40
44	4	2224	75.9	9.9	0.35	3.5	0.39
45	6	2495	139.1	10.3	0.79	3.7	0.49
46	5	2423	210.1	10.1	0.54	3.5	0.63
47	5	2484	210.1	10.6	0.67	3.2	0.83
48	2	2295	153.4	10.3	0.00	3.6	0.07
49	5	2414	274.7	10.1	0.49	3.8	0.55
50	4	2444	169.5	10.1	0.54	4.1	0.40
51	3	2512	64.0	10.2	0.42	3.5	0.32
Pooled		2493	241	10.0	0.65	3.43	0.59

TABLE 4. SUMMARY OF FIELD MARSHALL TEST RESULTS FOR THE BWI PROJECT

DAY	NO. OF TESTS	STAB MEAN	STAB ST DEV	FLOW MEAN	FLOW ST DEV	VOIDS MEAN	VOIDS ST DEV
1	4	2846	47.5	10.6	0.56	3.0	0.08
2	4	2896	34.5	10.4	0.34	3.1	0.10
3	4	2794	75.4	10.5	0.58	3.4	0.22
4	4	2706	55.4	11.3	0.50	3.4	0.17
5	4	2808	58.0	10.3	0.50	3.6	0.15
6	4	2761	62.6	10.8	0.50	3.4	0.13
7	4	2733	17.7	10.3	0.50	3.5	0.13
8	2	2796	5.7	10.5	0.71	3.6	0.07
9	4	2825	78.0	10.5	0.58	3.3	0.08
10	4	2750	55.8	10.5	0.58	3.3	0.15
11	4	2821	83.1	10.5	0.58	3.5	0.12
12	3	2772	61.6	10.7	0.58	3.5	0.10
13	1	2333	--	11.0	--	3.8	--
14	3	2789	47.6	11.3	0.58	3.6	0.15
15	4	2800	90.1	10.8	0.50	3.6	0.17
16	4	2779	79.6	10.8	0.50	3.4	0.13
17	4	2810	55.6	10.3	0.50	3.4	0.15
18	4	2783	67.3	10.8	0.50	3.5	0.08
19	2	2821	53.0	10.0	0.00	3.6	0.21
Pooled		2796	63	10.6	0.52	3.45	0.14

[illegible] 5. SUMMARY OF FIELD MARSHALL TEST RESULTS FOR THE ROCHESTER PROJECT

NO OF TESTS	STAB MEAN	STAB ST DEV	FLOW MEAN	FLOW ST DEV	VOIDS MEAN	VOIDS ST DEV
1	2952	--	11.6	--	4.4	--
1	3089	--	11.5	--	4.1	--
3	2948	136.3	11.[illegible]	0.93	4.0	0.26
3	3387	165.0	12.[illegible]	0.60	3.1	0.10
3	3091	198.1	13.4	1.74	3.8	0.35
3	3036	257.5	12.8	1.01	3.2	0.70
4	3407	192.5	11.5	1.34	4.2	0.42
4	3329	139.2	12.4	1.67	3.4	0.33
4	3364	195.7	12.9	1.17	3.6	0.10
4	3218	270.6	12.6	0.89	3.6	0.05
4	3081	101.4	13.3	0.71	3.9	0.19
4	3115	163.5	11.6	0.96	4.0	0.24
4	3414	303.0	11.9	0.95	3.2	0.34
4	3051	92.0	13.1	1.62	3.7	0.17
4	3219	183.4	12.1	1.34	3.6	0.26
3	3258	179.5	14.1	0.72	4.2	0.58
[illegible]	3253	194	12.4	1.19	3.75	0.32

TABLE 6. CORRELATION COEFFICIENTS FOR MARSHALL PROPERTIES ON THE THREE PROJECTS STUDIED

Correlation	Project		
	Atlantic City	Rochester	BWI
Stability vs. Flow	+0.069	+0.086	-0.597
Stability vs. Voids	-0.334	-0.235	-0.294
Flow vs. Voids	-0.301	-0.116	+0.075

TABLE 7. SUMMARY OF R^2 VALUES FROM MARSHALL PROPERTIES REGRESSION ANALYSES

Data Source	Property		
	Stability	Flow	Air Voids
Laboratory	0.844	0.950	0.974
Atlantic City	0.139	0.039	0.311
BWI	0.192	0.170	0.243
Rochester	0.318	0.291	0.219

A comparison of the regression analysis on the laboratory test data with the regression on the field test data provides markedly different results. The R-square values obtained in each regression analysis, i.e., laboratory data and 3 field projects, are presented in Table 7. A forward stepwise regression was conducted on the Marshall results from each of the field projects to yield the models shown in Table 8. As can be seen in Table 8, there is no consistency among projects with respect to those variables that entered the model during the stepwise procedure. Potential problems with multicollinearity make the regression coefficients highly suspect with respect to providing 'cause and effect' relationships for the parameters in the models.

The difference in the R-square values between the laboratory and the field probably lies in the vastly different environments under which the test results were obtained. The relatively high R-square values from the laboratory tests indicate that a predictive relationship does exist, at least under controlled laboratory conditions where the asphalt content and aggregate gradations can be precisely controlled. The low R-square values form the field projects tend to indicate that the high sampling and testing variability in the field, combined with the relatively high variability of the asphalt extraction test, tend to mask any predictive effect that might be present. With this in mind, it seems possible that any correlation among the Marshall properties may also be masked in the field for similar reasons.

Conclusions

The field data collection and analysis phase of the research supports the conclusions from the laboratory analysis phase with respect to the correlation among the Marshall properties. That is, there is a mild positive correlation between stability and flow, and there are mild negative correlations between stability and air voids and between flow and air voids. The results also indicate that it is not possible to establish predictive relationships between the results of asphalt extraction tests and the Marshall properties because of the production, sampling, and testing variablities present in the field.

TABLE 8. REGRESSION MODELS FOR THE FIELD MARSHALL DATA

Stability	
Atlantic City:	3289.6 - 25.2(No.4) + 136.4(No.200)
BWI:	3168.9 + 21.4(No.8) - 8.16(AC)(No.100) + 1.59(AC)(No.30) - 4.08(AC)(No.16) - 0.83(AC)(No.4)
Rochester:	142974.2 - 28924.8(AC) - 1203.0(1/2-inch) + 381.5(No.40) + 811.1$(AC)^2$ - 5.80(AC)(No.200) - 57.08(AC)(No.40) - 2.30(AC)(1/4-inch) + 208.46(AC)(1/2-inch)
Flow	
Atlantic City:	-12.11 + 4.21(AC) + 0.40(No.4) + 0.18$(AC)^2$ -0.08(AC)(No.4) - 0.01(AC)(3/8-inch)
BWI:	4.75 - 0.18(No.8) + 0.28(No.200) - 0.01(AC)(No.50) + 0.03(AC)(No.16) + 0.01(AC)(1/2-inch)
Rochester:	- 17.95 + 0.26(1/2-inch) + 0.07(1/4-inch) - 0.28(No.80) - 0.34(No.200) + 18.01(AC)
Air Voids	
Atlantic City:	45.56 - 15.41(AC) - 0.39(1/2-inch) + 0.12(No.4) + 1.01(No.50) + 0.40(No.200) + 1.04$(AC)^2$ - 0.12(AC)(No.200) - 0.20(AC)(No.50) + 0.01(AC)(No.8) + 0.09(AC)(1/2-inch)
BWI:	2.84 - 0.02(3/8-inch) - 0.02(No.4) + 0.04(No.8) + 0.11(No.50) - 0.003(AC)
Rochester:	11.77 - 0.11(1/2-inch) + 0.02(1/4-inch) - 0.02(1/8-inch) + 0.09(No.200) - 0.11(No.80) + 0.03(AC)(No.200)

NOTE: (AC) = asphalt content, %
(1/2-inch), etc. = % passing the 1/2-inch sieve
(No.4), etc. = % passing the No. 4 sieve

CHAPTER IV

COMPUTER SIMULATION ANALYSIS

The final area of the research effort was a computer simulation analysis to investigate the potential performance of a number of methods for determining the payment factor for a lot of materials when multiple acceptance characteristics, i.e., the Marshall properties, are used. Due to the complexity of the problem presented by the case of 3 acceptance criteria, it is necessary to use computer simulation to evaluate the proposed acceptance plans. A brief summary of the computer simulation analysis is presented in the following sections. Full details of the simulation and analysis procedures, along with the complete results and conclusions, are available in (6).

Experimental Design

As previously presented, the Marshall properties, stability, flow and air voids, were shown to be statistically correlated in the laboratory and field data analyses phases of the research effort. It is generally assumed that individually these properties have normal distributions. Since, however, variations in the properties occur simultaneously, they have a multivariate distribution that, in view of the above observation, may be assumed to be normally distributed. The simulation effort, therefore, consisted of sampling from a trivariate normal distribution for a given set of sample statistics. The sample statistics used in the simulation analysis were based on field data collected on 15 asphaltic concrete paving projects.

Acceptance and Payment Procedures

A number of different approaches were considered for determining the acceptable payment for a lot of material based upon the 3 Marshall properties. These approaches can be divided into 2 major categories. The first category relates to approaches which consider the multivariate nature of the problem. The second category relates to methods which consider the 3 properties individually, and then incorporate the 3 values into a single (composite) payment factor.

Trivariate Approach

The most theoretically acceptable approach to use as a means of evaluating Marshall results for acceptance is based on synthesizing the 3 values, stability, flow, and air voids, into a single number for acceptance purposes. This number is the percentage of the total volume of the trivariate normal distribution that falls within the acceptance limits for the 3 properties (trivariate PWL). This is a logical extension of the single variable acceptance approach based on PWL currently employed for density by the FAA Eastern Region.

This approach uses 9 statistics calculated from the sample results for the lot to estimate the PWL value for the lot. The statistics include the sample means and variances for stability, flow, and air voids, and the 3 correlation coefficients calculated from the sample results. To estimate PWL from the sample statistics it is necessary to perform a triple integration on a trivariate normal distribution. To accomplish this integration, a computer algorithm was developed to numerically integrate the volume under the trivariate normal distribution.

This method has the disadvantage of being dependent upon a computer to conduct the numerical integration. Alternately, a book of trivariate normal tables could be developed to estimate PWL. However, the book would require millions of tables to cover the range of possible correlation combinations. This reliance on the computer can be solved, however, if there is a dial-up computer terminal at the construction site, or if the algorithm can be adapted to run on a microcomputer that can be located at the project office. Realistically, however, this approach does not seem reasonable for immediate implementation.

Bivariate Approach

The first step considered in an effort to simplify the procedures of the trivariate approach takes advantage of the fact that, for nearly all data collected on all projects, Marshall stability met the acceptance requirements. Taking this into consideration, the problem can be reduced to a bivariate normal distribution by considering stability on an accept-or-reject basis, and using only flow and air voids for payment determination. This reduces to 19 the number of tables necessary to reasonably estimate PWL, and makes manual computations feasible.

A set of 19 bivariate normal tables was developed and appears in (6). Calculation sheets can be developed to allow a technician to determine estimated PWL, with the aid of the 19 tables, without requiring an understanding of correlation on his or her part. While the calculations are considerably more involved than those currently required for density, they are not unreasonable, and, with adequate accompanying instructions, should be feasible for field implementation.

Individual Properties Approaches

The bivariate approach still presents implementation problems at the present time. It is so different from current methods that resistance from field personnel is inevitable. In light of this, a number of approaches were also considered that are based on the same PWL estimation procedures currently employed by the FAA Eastern Region. These procedures consist of determining either a PWL or payment factor (PAY) for each of the properties individually, and then combining these in some fashion to arrive at a total PWL or PAY value for the lot. The approaches considered include:

1) multiplying the individual PWL or PAY values,

2) averaging the individual PWL or PAY values, and

3) using the smallest individual PWL or PAY value.

These approaches are similar to those currently employed by some state highway agencies that apply price adjustments for more than one characteristic (7).

Simulation Procedures

Computer simulation was used to develop Marshall test results for 100 paving lots using the results from each of the 15 paving projects for which data were available. The means, standard deviations, and correlation coefficients from each of the 15 projects were used as the 'population' statistics in the various simulation analyses.

The results of 4 Marshall tests were generated for each paving lot in the simulation analysis. The test values for the 3 correlated Marshall properties, i.e., stability, flow, and air voids, were generated simultaneously by an algorithm based on Cholesky's Sequential Matrix Decomposition (6). The simulated Marshall results were then used to determine the payment factor for the lot using each of 7 methods. The simulation procedure is presented in the flow diagram of Figure 8.

Simulation Results

Two important factors to be considered when evaluating an estimator are the bias and variability of the estimator. The variability of the estimator is represented by the variance. By way of definition, an estimator is unbiased if its expected value is the same as the parameter (in this case, payment factor) it is being used to estimate. In the simulation analyses, the mean square error (MSE) of a payment determination method is used as the norm and the minimum MSE as the criterion for choice between the methods (6). The MSE norm is chosen because it incorporates the 2 important measures of bias and variance into a single value.

A total of 7 payment determination methods were evaluated with the MSE criterion in the simulation analyses. The 7 methods include:

1) triple numerical integration using the daily sample means, standard deviations, and correlation coefficients,

2) multiplying the individual PWL values to obtain a composite PWL value,

3) averaging the individual PWL values to obtain a composite PWL value,

4) using the smallest individual PWL value as the composite PWL value,

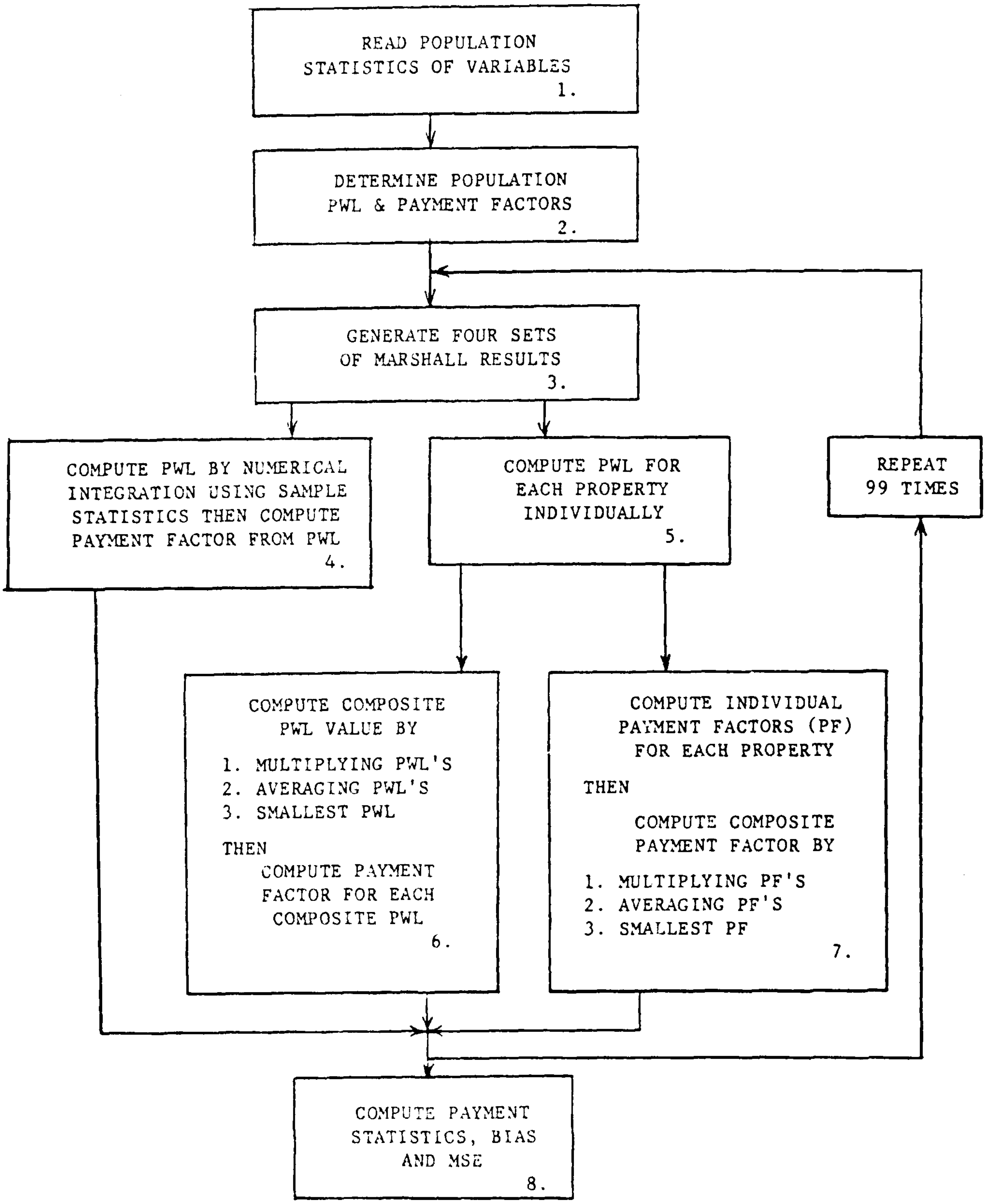

FIGURE 8. FLOW DIAGRAM FOR SIMULATION PROCEDURE

5) multiplying the individual payment factors to obtain a composite payment factor,

6) averaging the individual payment factors to obtain a composite payment factor, and

7) using the smallest individual payment factor as the composite payment factor.

The results for the simulation exercise are given in Tables 9 and 10. Table 9 presents the results of 12 simulated projects for which the data were collected during the initial research study in 1978. Table 10 presents the results for the 1981 projects along with the results using the pooled means and standard deviations from the 3 projects and the pooled correlation coefficients from all the field data. For each project in the tables, the mean and variance of the 100 payment factors are shown along with the bias and MSE values for each of the payment determination methods.

Conclusions

In the simulation analyses, the numerical integration method provided very large MSE values as compared with the individual properties methods. This is because the small sample size, i.e., 4, does not provide a good estimate of the population correlation coefficients that must be used in the numerical integration algorithm. The averaging method provides the smallest MSE values for populations with high PWL values. The majority of the projects for which data were available had high PWL values (i.e., above 90 PWL).

Therefore, the payment determination procedure that is recommended for the trivariate case of the Marshall properties is the individual property payment factor averaging method. It is difficult to select between the 2 averaging methods since neither is consistently superior for the entire range of population payment factors found on the projects studied. The individual payment factor averaging method is closer to the method currently being used for calculating mat density payments. As a result, it may be more readily implemented and accepted by the parties involved in the field. For this reason, it is recommended as the payment determination method for the Marshall properties.

Table 9. RESULTS OF COMPUTER SIMULATION ANALYSES

Project	Method*	E[PHAT]#	Var[PHAT]@	Bias	MSE
Adirondack-A	1	57.5	253.9	7.5	310.2
	2	85.9	381.5	35.9	1670.7
(50.0)$	3	98.9	10.3	48.9	2403.8
	4	91.2	176.7	41.2	1875.9
	5	90.5	216.2	40.5	1854.8
	6	96.7	28.2	46.7	2208.8
	7	91.2	176.7	41.2	1875.9
Adirondack-B	1	66.5	423.6	-29.1	1268.1
	2	93.6	154.3	- 1.9	157.8
(95.5)	3	99.8	0.9	4.3	19.0
	4	95.4	104.9	- 0.1	104.9
	5	95.2	114.1	- 0.4	114.2
	6	98.4	13.3	2.8	21.4
	7	95.4	104.9	- 0.1	104.9
Charlottesville-ANJ	1	51.5	51.2	1.5	53.5
	2	54.7	157.8	4.7	179.6
(50.0)	3	87.5	193.7	37.5	1599.6
	4	56.3	205.3	6.3	245.4
	5	51.1	323.7	1.1	324.9
	6	82.0	64.6	32.0	1089.7
	7	56.3	205.3	6.3	245.4
Charlottesville-CLW	1	52.2	57.2	2.2	62.1
	2	58.6	271.5	8.6	345.5
(50.0)	3	92.0	113.3	42.0	1876.4
	4	63.2	342.1	13.2	516.7
	5	59.4	435.2	9.4	524.1
	6	85.5	69.8	35.5	1326.7
	7	63.2	342.1	13.2	516.7

- expected payment factor @ - variance of payment factor

$ - correct payment factor for the population

* - payment determination method:

1. triple numerical integration
2. multiplying the individual PWL values
3. averaging the individual PWL values
4. using the smallest individual PWL value
5. multiplying the individual payment factors
6. averaging the individual payment factors
7. using the smallest individual payment factor

Table 9. (continued)

Project	Method*	E[PHAT]#	Var[PHAT]@	Bias	MSE
Chautauqua	1	85.3	366.0	-14.7	582.7
	2	99.0	28.5	- 1.0	29.5
(100)$	3	100.0	0.0	0.0	0.0
	4	99.0	28.5	- 1.0	29.5
	5	99.0	28.5	- 1.0	29.5
	6	99.7	3.2	- 0.3	3.3
	7	99.0	28.5	- 1.0	29.5
Chemung-Chem	1	79.9	428.3	-20.1	833.0
	2	98.9	30.1	- 1.1	31.3
(100)	3	100.0	0.0	0.0	0.0
	4	98.9	30.1	- 1.1	31.3
	5	98.9	30.1	- 1.1	31.3
	6	99.6	3.4	- 0.4	3.5
	7	98.9	30.1	- 1.1	31.3
Chemung-Fish	1	69.9	437.0	-27.4	1189.4
	2	91.3	207.4	- 6.0	243.8
(97.3)	3	99.8	0.5	2.5	6.7
	4	91.7	203.4	- 5.7	235.4
	5	91.6	204.1	- 5.7	236.3
	6	97.2	22.8	- 0.1	22.8
	7	91.7	203.4	- 5.7	235.4
Dubois	1	60.2	311.1	-25.6	966.7
	2	91.1	241.8	5.3	270.4
(85.8)	3	99.4	4.7	13.7	191.4
	4	95.2	107.0	9.4	195.3
	5	94.7	128.3	9.0	208.5
	6	98.2	16.0	12.4	169.8
	7	95.2	107.0	9.4	195.3

- expected payment factor   @ - variance of payment factor

$ - correct payment factor for the population

* - payment determination method:

1. triple numerical integration
2. multiplying the individual PWL values
3. averaging the individual PWL values
4. using the smallest individual PWL value
5. multiplying the individual payment factors
6. averaging the individual payment factors
7. using the smallest individual payment factor

Table 9. (continued)

Project	Method*	E[PHAT]#	Var[PHAT]@	Bias	MSE
Dutchess	1	75.6	387.3	-23.8	953.1
	2	95.8	87.9	- 3.5	100.2
(99.3)$	3	99.9	0.3	0.6	0.6
	4	96.9	39.5	- 2.5	45.6
	5	96.7	46.6	- 2.6	53.5
	6	98.9	5.6	- 0.5	5.8
	7	96.9	39.5	- 2.5	45.6
Linden	1	77.8	411.0	-22.2	903.5
	2	98.1	44.3	- 1.9	48.1
(100)	3	100.0	0.1	0.0	0.1
	4	98.3	27.7	- 1.7	30.5
	5	98.3	28.8	- 1.7	31.7
	6	99.4	3.3	- 0.6	3.6
	7	98.3	27.7	- 1.7	30.5
Westchester-Colp	1	75.1	428.7	-24.9	1046.5
	2	97.6	70.0	- 2.4	75.6
(100)	3	100.0	0.1	0.0	0.1
	4	97.9	62.6	- 2.1	67.1
	5	97.9	62.6	- 2.1	67.1
	6	99.3	7.0	- 0.7	7.5
	7	97.9	62.6	- 2.1	67.1
Westchester-Peck	1	54.7	158.5	4.7	180.9
	2	73.5	500.9	23.5	1054.1
(50.0)	3	95.6	77.4	45.6	2153.0
	4	79.2	398.5	29.2	1252.0
	5	75.6	590.8	25.6	1246.6
	6	90.9	95.2	40.9	1771.0
	7	79.2	398.5	29.2	1252.0

- expected payment factor   @ - variance of payment factor

$ - correct payment factor for the population

* - payment determination method:

1. triple numerical integration
2. multiplying the individual PWL values
3. averaging the individual PWL values
4. using the smallest individual PWL value
5. multiplying the individual payment factors
6. averaging the individual payment factors
7. using the smallest individual payment factor

Table 10. RESULTS OF COMPUTER SIMULATION ANALYSES - 1981 PROJECTS

Project	Method*	E[PHAT]#	Var[PHAT]@	Bias	MSE
Atlantic City	1	75.8	397.1	-24.2	981.3
	2	96.9	60.2	- 3.1	69.7
(100)$	3	99.9	0.1	- 0.1	0.1
	4	97.8	25.3	- 2.2	30.0
	5	97.8	27.1	- 2.2	32.0
	6	99.3	3.1	- 0.7	3.7
	7	97.8	25.3	- 2.2	30.0
Baltimore-Washington	1	90.2	257.9	- 9.8	354.7
	2	100.0	0.0	0.0	0.0
(100)	3	100.0	0.0	0.0	0.0
	4	100.0	0.0	0.0	0.0
	5	100.0	0.0	0.0	0.0
	6	100.0	0.0	0.0	0.0
	7	100.0	0.0	0.0	0.0
Rochester	1	87.4	330.7	-12.6	488.5
	2	100.0	0.1	0.0	0.1
(100)	3	100.0	0.0	0.0	0.0
	4	100.0	0.1	0.0	0.1
	5	100.0	0.1	0.0	0.1
	6	100.0	0.0	0.0	0.0
	7	100.0	0.1	0.0	0.1
Pooled	1	79.9	449.7	-20.1	852.8
	2	99.9	0.3	- 0.1	0.3
(100)	3	100.0	0.0	0.0	0.0
	4	99.9	0.3	- 0.1	0.3
	5	99.9	0.3	- 0.1	0.3
	6	100.0	0.0	0.0	0.0
	7	99.9	0.3	- 0.1	0.3

- expected payment factor   @ - variance of payment factor

$ - correct payment factor for the population

* - payment determination method:

1. triple numerical integration
2. multiplying the individual PWL values
3. averaging the individual PWL values
4. using the smallest individual PWL value
5. multiplying the individual payment factors
6. averaging the individual payment factors
7. using the smallest individual payment factor

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

From the research conducted and presented in this report, and in (3), (4), (5), and (6), the following major conclusions and recommendations can be stated.

Conclusions

1. Mild, but generally consistent, within-test correlations exist among the Marshall properties. A positive correlation exists between stability and flow, while negative correlations exist between stability and air voids and between flow and air voids. These correlations are significant enough to violate an assumption of statistical independence among the properties.

2. The solvent immersion method for determining MSG provides results that are generally closer to the individual constituents method than are provided by the plastic pycnometer (ASTM D-2041, Type D) method. The pycnometer results are consistently lower than the individual constituents results. Since the difference between the results is related to asphalt content, a procedure that establishes a correction factor at the optimum asphalt content is not recommended.

3. Field data confirm the laboratory results with respect to the within-test correlations present among the Marshall properties.

4. It is not possible to establish predictive relationships between the results of asphalt extraction tests and the Marshall properties due to the production, sampling, and testing variabilities present in the field.

5. Although theoretically sound, triple numerical integration to establish a trivariate Marshall PWL value for use in acceptance and payment determination is not practical for field use. This is because the sample sizes that are practical in the field, e.g., 4 or 5, do not provide a good estimate for the population correlation coefficients that must be used in the integration algorithm to determine PWL. The highly variable correlation estimates lead to high MSE values for the integration approach.

Recommendations

Maximum Specific Gravity Determination

In the conclusions stated above, it is indicated that similar results are not obtained from the 3 methods that were investigated for maximum specific gravity determination. It is recommended that the solvent immersion method be eliminated from use. While this method provided results that were closer to the individual constituents approach used by the FAA for job mix formula determination, solvent immersion is not widely used. The ASTM D-2041 procedures are much more commonly employed. Since solvent immersion and ASTM D-2041 provide statistically different results, it is not appropriate to allow the use of both methods in the same specification unless separate acceptance limits are considered.

The ASTM D-2041 approach, as originally used by the FAA Eastern Region, requires the development of a correction factor to convert the ASTM D-2041 results to equivalent individual constituents values. The current research has shown that the necessary correction factor varies with the asphalt content of the mixture. To avoid the use of a corection factor altogether, it is recommended that the maximum specific gravity for job mix formula determination be established using the ASTM D-2041 procedure. In this way, the same test procedure will be used in determining the job mix formula and for the field control tests, and no correction factor should be required.

If it is desired to maintain the use of the individual constituents approach based on apparent specific gravities of the constituents for job mix formula determination, then the solvent immersion method is preferable to the ASTM D-2041 method since it more closely approximates the individual constituents values. The solvent immersion method, however, suffers from its limited use and the required exposure of the laboratory technicians to the solvent that is used.

The use of the ASTM D-2041 method for establishing maximum specific gravity in job mix formula calculations is similar to the effective specific gravity procedures recommended by the Asphalt Institute in its publication Mix Design Methods for Asphaltic Concrete, MS-2 (8). This approach eliminates the need to use a correction factor and should lead to more consistent results between the job mix formula and the field quality control tests.

Marshall Properties Payment Factor

The payment determination procedure that is recommended for the trivariate case of the Marshall properties is the individual property payment averaging method. It is difficult to select between the 2 averaging methods investigated since neither method is consistently superior for the entire range of population payment factors found on the projects studied. The individual payment factor averaging method is closer to the method currently employed for calculating density payments. As a result, it may be more readily implemented and accepted by the parties involved on actual projects. For this reason it is recommended as the payment determination method for the Marshall properties.

The following acceptance procedure for determining the payment factor for the Marshall properties is recommended:

1. Using the random sampling procedures in the FAA Eastern Region Laboratory Procedures Manual, select 4 samples from each lot of material for Marshall properties determination.

2. For each Marshall property, i.e., stability, flow and air voids, determine the PWL value using the Quality Index approach outlined in the Eastern Region P-401 specification.

3. Using the calculated PWL values and the payment schedule in the Eastern Region P-401 specification, determine the payment factor individually for each of the 3 Marshall properties.

4. The composite payment factor associated with the Marshall properties is then calculated as the average of the 3 individual payment factors.

5. The payment factor for density is calculated using the payment schedule in the Eastern Region P-401 specification and the estimated PWL value is determined by the Quality Index approach.

6. The overall payment factor for the lot of material is calculated as the average of the Marshall properties payment factor and the density payment factor.

Implementation

The payment determination procedure recommended in the previous section was developed using data collected on 15 paving projects from the FAA Eastern Region. While the data were gathered from a specific region, the computer simulation procedures and payment determination approaches considered are general in nature, and are not limited to application in the Eastern Region. If it is desired to use these procedures in other geographic regions, it may first be desirable to verify whether the same general correlation trends are evident in the new region as were found on the projects from the Eastern Region.

To verify the Marshall correlation structure in the new region, Marshall test data can be collected on paving projects in the new region. In lieu of collecting new data, historical data on Marshall test results could be analyzed to determine the correlation structure among the 3 Marshall properties. The means and standard deviations for stability, flow and air voids would have to be determined, along with the 3 correlation coefficients, i.e., stability with flow, stability with air voids and flow with air voids. If these values for the new region were similar to those found in the Eastern Region, then the recommended payment determination procedures could be used in the new region.

If the statistics (3 means, 3 standard deviations and 3 correlation coefficients) were different for the new region than those identified in the Eastern Region, then the payment determination approach could be verified using the computer simulation procedures developed in this research. The computer simulation analysis would determine the correct PWL and payment factor for the statistics calculated for the new region. The program would also determine which of the 7 payment determination procedures were the most appropriate for the new region. The payment procedure that provided the smallest MSE values using the statistics from the new region would be the one selected. A detailed description of the computer simulation procedures and a user's guide for the simulation program are presented in (6).

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