to those containing synthetic rubber, but digestion conditions (time and temperature) are less critical for synthetic rubber.

3. The elastic recovery of strain of the digestions is linearly related to the rubber concentration.

4. For car-tire retreader's buffings, the elastic recovery of the digestions tends to increase as the size of the rubber particles used decreases.

5. Little or no change in the elastic recovery of certain specimens was observed when they were stored at 55°C (which imitated curing over an extended period in road service).

ACKNOWLEDGMENT

This paper is presented with the permission of the executive director of the Australian Road Research Board. Views expressed in the paper are solely my own.

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Effect of Aggregate Top Size on Asphalt Emulsion Mixture Properties

MICHAEL S. MAMLOUK AND LEONARD E. WOOD

Since base-course aggregate gradations have top sizes larger than 25.4 mm (1 in) in most cases, the adequacy of using the standard Marshall procedure in evaluating asphalt-stabilized base courses has been questioned. The findings of a comprehensive laboratory investigation that focused on the evaluation of the effect of aggregate top size on the Marshall test results of cold-mixed asphalt emulsion mixtures are reported. Marshall specimens were prepared by using a high-float asphalt emulsion, HFMS-2s, and aggregate top sizes of 19 and 38 mm (0.75 and 1.5 in). Other factors included in the study were asphalt emulsion content, aggregate type, and aggregate gradation. Marshall tests were performed at 22°C (72°F) to evaluate the mixture properties. Test results for such factors as stability, flow, stiffness, and index were obtained. Other mixture properties, such as specific gravity, air voids, retained moisture, and total liquid, were also evaluated. According to the test results, increasing the aggregate top size in the asphalt emulsion mixture from 19 to 38 mm increased the bulk specific gravity and decreased the air voids. The retained moisture and total liquid in the mixture after curing were not largely affected by the aggregate top size. The modified Marshall test results were altered to some extent by the change in aggregate top size. It is recommended that the effect of aggregate top size be taken into consideration when the standard Marshall procedure is used in designing asphalt emulsion mixtures with large aggregate top sizes.

In recent years, a great deal of interest has been shown in, and much effort has been devoted to, the development of various types of stabilized materials for use in pavement construction. The use of asphalt emulsions as stabilizing agents has increased tremendously in the past two decades, precipitated by apparent economic and environmental benefits (1). Asphalt emulsions can be mixed at ambient temperatures, which saves both the cost and amount of fuel needed for hot mixes. Asphalt emulsion mixtures also eliminate the dust and combustion pollutants that result from the drying and mixing of the aggregate. In spite of their widespread use, the behavior of these mixtures has not been sufficiently well understood to enable the development and acceptance of a rational design procedure and set of criteria (2).

According to the standard preparation procedure of Marshall specimens [102 mm (4 in) in diameter by 64 mm (25 in) high], the aggregate top size should not exceed 25.4 mm (1 in). Since base-course aggregate gradations frequently have top sizes greater than 25.4 mm, the adequacy of the standard Marshall procedure in the design of asphalt-stabilized base courses has been questioned. This study reports the findings of a comprehensive laboratory investigation that focused on the evaluation of the effect of aggregate top size on the Marshall test results of cold-mixed asphalt emulsion mixtures. Two aggregate top sizes were used: 19 and 38 mm (0.75 and 1.5 in). One asphalt emulsion type, three asphalt emulsion contents, two aggregate types, and two aggregate gradations were included in the study. A modified Marshall test was used in the evaluation process. Marshall test results such as stability, flow, stiffness, and index were obtained at a test temperature of 22°C (72°F). Other mixture properties, such as specific gravity, air voids, and retained moisture, were also evaluated.

Figure 1. Aggregate gradations.

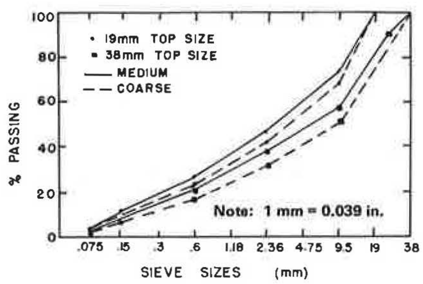
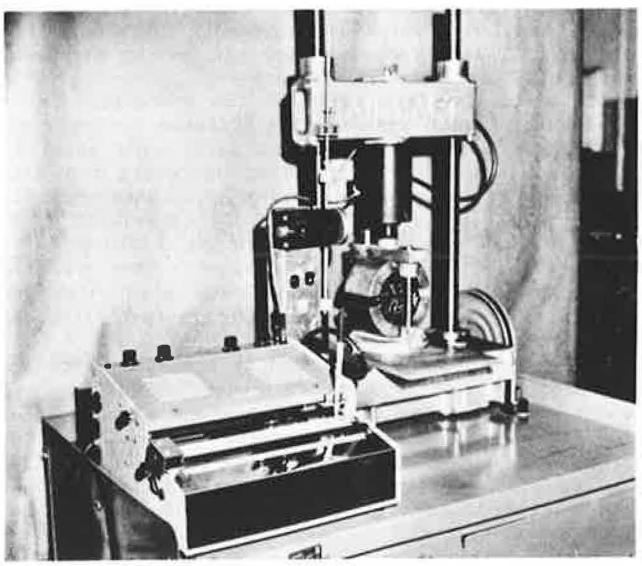


Table 1. Experimental design.

		19-mm Top Size		38-mm Top Size	
Gradation	Asphalt Residue (%)	Sand and Gravel	Limestone	Sand and Gravel	Limestone
Medium	2.5	O	O	O	O
	3.25	X	X	X	X
	4.0	O	O	O	O
Coarse	2.5	O	O	O	O
	3.25	X	X	X	X
	4.0	O	O	O	O

Note: O = two replicates and X = three replicates.

Figure 2. Autographic Marshall equipment.

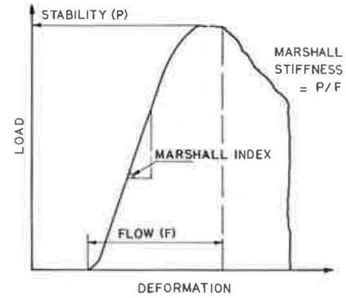


MATERIALS

Aggregate Types, Gradations, and Top Sizes

Two aggregate types were used in the study. The first type was totally a mixture of sand and gravel that consisted approximately of 50 percent calcareous and 50 percent siliceous pieces. About 60 percent of gravel particles retained on the 4.75-mm (no. 4) sieve had crushed faces. The second type was totally crushed limestone. Two aggregate gradations were used--a medium and a coarse gradation with a maximum size of 38 mm. The medium gradation followed the midspecification of the Indiana State Highway Commission (ISHC) no. 53-B gradation band. The coarse gradation was selected at the "quarter point", midway between the midpoint and the lower

Figure 3. Marshall stability, flow, stiffness, and index.



limit of the specification band. The two gradations were also scalped at the 19-mm sieve to provide similar aggregate gradations with a 19-mm top size. The scalped percentage was balanced over the remaining sizes, which changed the gradation curves as shown in Figure 1. Other properties of the aggregates are given below:

Property	Sand and Gravel	Limestone
Apparent specific gravity	2.710	2.741
Bulk specific gravity	2.644	2.696
Absorption (%)	1.560	1.280

Asphalt Emulsion

A high-float asphalt emulsion of one type and grade was used: HFMS-2s (ASTM D977). The physical properties of the emulsion were as follows (25°C = 45°F):

Property	Value
Saybolt Furol viscosity (s)	50+
Residue by distillation (%)	70.0
Penetration of residue after distillation (25°C, 5 s, 100 g)	200+
Specific gravity of residue after distillation (25°C)	0.999

SPECIMEN PREPARATION

Specimens 102 mm (4 in) in diameter and 64 mm (2.5 in) high were prepared according to the mix procedure suggested in previous studies (3,4). One initial added moisture content of 3 percent of the aggregate dry weight was used. Three asphalt emulsion contents were evaluated to provide residue contents of 2.5, 3.25, and 4 percent of the aggregate dry weight. Specimens were compacted at a room temperature of 22°C by using 50 blows of a standard Marshall hammer on each side of the specimens. Either two or three replicate specimens were prepared for each factor combination (see Table 1). All specimens were cured for three days at room temperature.

Testing Procedure

After specimens were cured, the bulk specific gravity was determined according to ASTM D2726. Specimens were tested at a room temperature of 22°C by using the Marshall equipment shown in Figure 2. The machine was connected to a chart recorder to provide a continuous recording of load versus deformation throughout the test (see Figure 3). The modified Marshall stability and Marshall flow were determined according to standard American Society for Testing and Materials (ASTM) procedure except for test temperature. Two other parameters were also obtained--Marshall stiffness and Marshall index (3,4). Marshall stiffness is defined as the ratio between Marshall stability and flow, and Marshall index is the slope of the linear portion of the load versus deformation trace. Other properties of the mixture, such as density, voids content, and moisture content at time of testing, were evaluated. After the test was completed, specimens were broken apart and dried and the oven-dry bulk specific gravities were obtained.

Statistical analysis was performed on the data to determine the effect of aggregate top size on the asphalt emulsion mixture properties as well as Marshall test results. Other factors, such as aggregate type, aggregate gradation, and asphalt emulsion content, were also evaluated. A level of significance of 5 percent was used throughout the analysis.

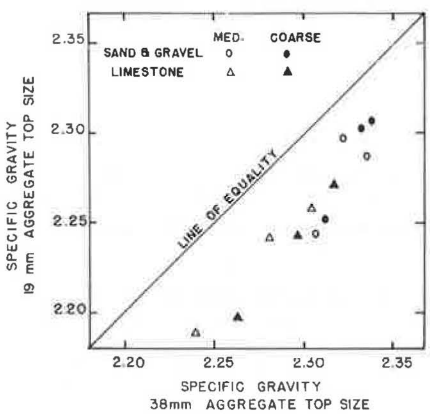
ANALYSIS OF STUDY RESULTS

Specific Gravity and Air Voids

The specific gravity of the asphalt emulsion mixture is a useful parameter for the mixture evaluation. In this study, specific gravity was used to measure the effect of changes in the mixture ingredients. High specific gravities of the mixture are recommended in order to reduce further compaction by traffic, which results in rutting of the pavement. High specific gravities also reduce moisture absorption, which affects the potential of stripping. On the other hand, a certain amount of air voids in the mixture is needed to enhance the rate of curing of the mixture and to improve drainage.

Two types of specific gravities were evaluated: the air-cured bulk specific gravity at time of testing and the oven-dry bulk specific gravity. According to the test results, the aggregate top size had a marked effect on the air-cured bulk specific gravity of the specimens. Large top-size aggregates provided higher values of air-cured specific gravity than small top-size aggregates, as Figure 4 shows. The average air-cured specific gravities of all specimens in the study were 2.258 for the 19-mm top-size aggregates and 2.304 for the 38-mm top-size aggregates. This effect was more apparent for the limestone mixtures than for the sand and gravel mixtures. In addition, the air-cured specific gravities of mixtures with 19- and 38-mm top sizes were highly correlated. The correlation coefficient between the two variables was 0.953 for all mixtures included in the study.

Figure 4. Air-cured bulk specific gravity of mixtures with 19- and 38-mm aggregate top sizes.



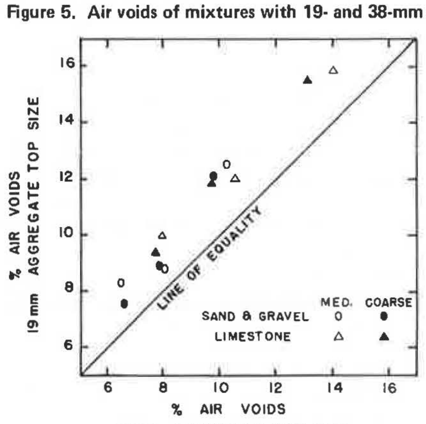
On the other hand, asphalt emulsion content showed a significant effect on the air-cured bulk specific gravity of the specimens. Increasing the asphalt emulsion content in the mixture fills the voids among aggregate particles and also allows for more compaction to occur due to lubrication. Therefore, higher percentages of asphalt emulsion content increase the bulk specific gravity of the mixture. At 2.5, 3.25, and 4 percent asphalt residue contents, average values of 2.251, 2.290, and 2.302 of air-cured specific gravities were obtained, respectively. In addition, the sand and gravel mixtures provided a larger average specific gravity than the limestone mixtures.

The oven-dry bulk specific gravity of specimens followed the same general pattern as the air-cured specific gravity. Mixtures with large aggregate top sizes had high values of oven-dry bulk specific gravity. This effect was apparent in all mixtures, especially the limestone mixtures.

The amount of air voids in the compacted specimens after curing was markedly affected by aggregate top size. Small percentages of air voids were obtained for mixtures with 38-mm aggregate top size compared with mixtures with 19-mm aggregate top size (see Figure 5). A correlation coefficient of 0.987 was obtained between air voids for mixtures with small and large aggregate top sizes. Moreover, the air voids showed trends highly correlated with, and almost the reverse of, those for the air-cured specific gravity.

The air voids were affected by aggregate type and asphalt emulsion content. Larger values of air voids were obtained for the limestone mixtures than for the sand and gravel mixtures. In addition, increasing the asphalt emulsion residue content from 2.5 to 3.25 and 4 percent decreased the average air voids from 12.887 to 9.730 and 8.001 percent, respectively.

Figure 5. Air voids of mixtures with 19- and 38-mm aggregate top sizes.



Retained Moisture and Total Liquid

The moisture included in the asphalt emulsion mixture comes from the water added during the initial mixture preparation as well as the moisture included in the asphalt emulsion itself. The moisture portion is very important in the preparation of the cold-mixed asphalt emulsion mixture because it increases the workability of the mix and provides a uniform coating of asphalt residue on the aggregates. However, a large amount of moisture has an adverse effect on the mixture and reduces the strength. During the curing process the water evaporates, leaving the asphalt residue adhering to the aggregate. The rate of strength development of the asphalt emulsion mixture is directly related to the rate at which the mixture loses moisture.

The effect of aggregate top size did not show a significant influence on the amount of moisture retained in the compacted specimens after curing.

Both mixtures with small and large aggregate top sizes gave approximately the same moisture content values for the corresponding cases, as shown in Figure 6. The average retained moisture was 1.109 percent of the aggregate dry weight for mixtures with 19-mm aggregate top size, whereas the corresponding value for mixtures with 38-mm aggregate top size was 1.032 percent.

Aggregate type and gradation did not change the amount of retained moisture in the mixture to a large extent. On the other hand, mixtures with high asphalt emulsion contents had low air-void contents, which resulted in the reduction of moisture loss from the specimens during curing. In addition, increasing the asphalt emulsion content increased the initial water content in the mixture because of the water included in the asphalt emulsion itself. Average values of retained moisture were 0.70, 1.16, and 1.35 percent for mixtures with 2.5, 3.25, and 4 percent asphalt residue contents, respectively.

The total liquid in the compacted specimens after curing is one of the characteristics used frequently in the evaluation of asphalt emulsion mixes. The liquid content in the mixture is the sum of the asphalt emulsion residue content and the amount of retained moisture. In this study, the total liquid content was not largely affected by the changes in the aggregate top size. The average total liquid content was 4.36 percent of the aggregate dry weight for all mixtures with the small-sized aggregate and 4.28 percent for mixtures with the large-sized aggregate. The influence of change of aggregate top size is illustrated in the following table:

Aggregate	Total Liquid (%)	
Top Size (mm)	Sand and Gravel	Limestone
19	4.318	4.399
38	4.217	4.347

The total liquid content, like the retained moisture content, was also affected by other factors.

Marshall Stability and Flow

The Marshall test is commonly used to characterize hot-mixed asphalt mixtures (the test has not been standardized for cold-mixed asphalt emulsion mixtures). In this investigation, Marshall stability and flow values of the mixture were obtained at room temperature. The effect of aggregate top size on the modified Marshall test results was evaluated.

In most cases (see Figure 7), mixtures with a 19-mm top-size aggregate resulted in higher modified Marshall stability values than mixtures with 38-mm top-size aggregate. However, the difference between these values for the two mixtures was not large. An average stability value of 6.09 kN (1370 lbf) was obtained for specimens with small top-size aggregate, whereas the average value for specimens with large top-size aggregate was 5.76 kN (1296 lbf).

Other factors in the study showed some effects on the modified Marshall stability. The crushed limestone mixes achieved a significantly higher stability than the sand and gravel mixes in spite of their lower specific gravities. Both aggregate types, however, showed the same trends in stability values for the different asphalt emulsion contents. The interaction effect of the different factors is shown in Figure 8. A peak stability was obtained at the middle asphalt emulsion content level. As the figure shows, the asphalt emulsion content variable is influential for all mixes except those with 38-mm limestone aggregate.

The modified Marshall flow did not show a consistent trend for the two aggregate top sizes (see Figure 9). Although mixes with the large top-size aggregate had slightly higher flow values than those with the small top-size aggregate, the difference was not great. Due to the variability of the data, aggregate type, aggregate gradation, and asphalt emulsion content did not show a marked effect on the flow values. The largest flow values were obtained for mixes with 38-mm aggregate top size, coarse gradation, and 2.5 percent asphalt emulsion residue.

Figure 6. Retained moisture of mixtures with 19- and 38-mm aggregate top sizes.

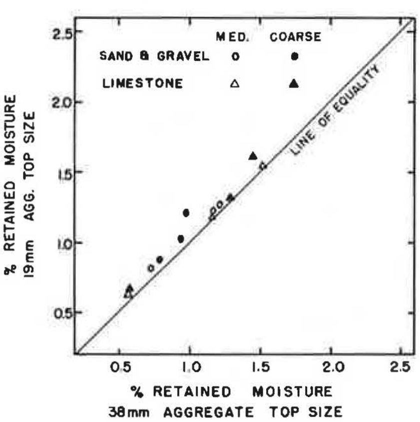


Figure 7. Modified Marshall stability of mixtures with 19- and 38-mm aggregate top sizes.

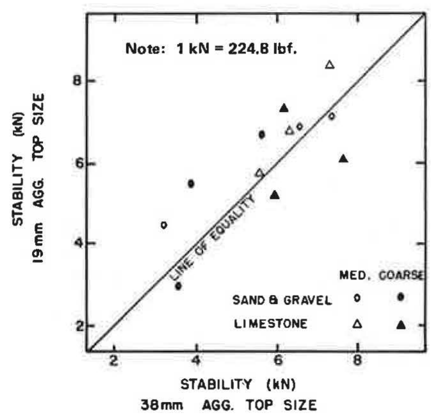


Figure 8. Effect of aggregate top size, type, and gradation and asphalt emulsion content on Marshall stability.

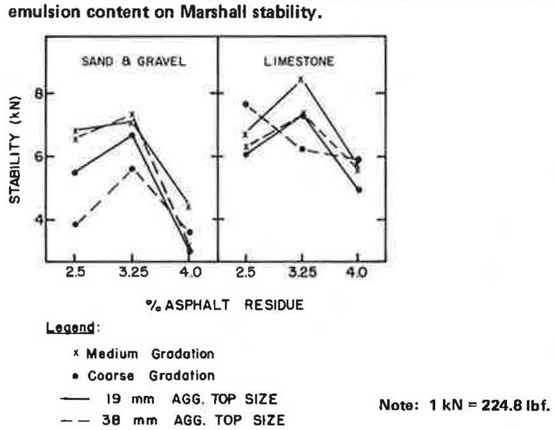


Figure 9. Modified Marshall flow of mixtures with 19- and 38-mm aggregate top sizes.

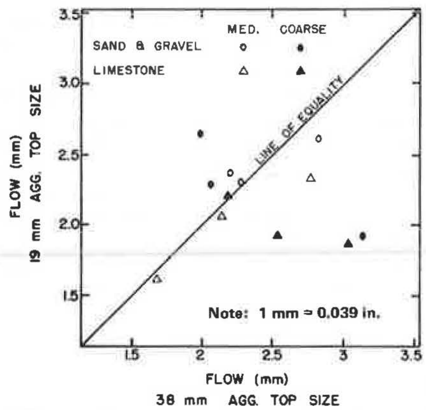
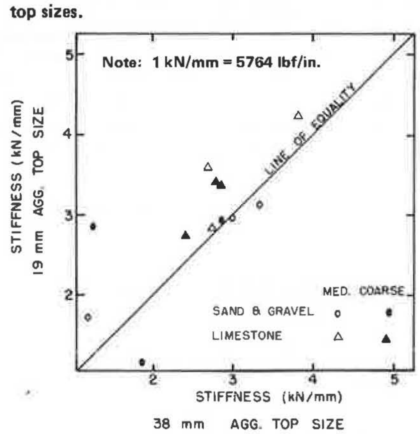


Figure 10. Marshall stiffness of mixtures with 19- and 38-mm aggregate top sizes.



Marshall Stiffness and Index

Mixtures with the small top-size aggregate resulted in larger Marshall stiffness values than mixtures with large top-size aggregate in most cases, as shown in Figure 10. Average Marshall stiffness values of 2.98 and 2.63 kN/mm (17 000 and 15 000 lbf/in) were obtained for mixtures with small and large top-size aggregates, respectively. In addition to aggregate top size, larger Marshall stiffness values were obtained for limestone mixes than for sand and gravel mixes. In addition, asphalt emulsion content showed some effect on the Marshall stiffness. Large values of stiffness were obtained for 2.5 and 3.25 percent asphalt emulsion residues in comparison with 4 percent residues. Moreover, medium-graded mixtures resulted in larger stiffness values than coarse-graded mixtures in almost all cases.

The Marshall index showed the same trend as the stiffness values, although the pattern was slightly different. There was no consistent trend in aggregate top size for the different factor combinations. However, large index values were obtained for limestone mixtures compared with the corresponding values for sand and gravel mixtures. In addition, increasing the asphalt emulsion residue content from 2.5 to 3.25 and 4 percent resulted in a decrease in the index values in most cases. The average Marshall index values of specimens with 19- and 38-mm aggregate top sizes for the two types of aggregates are given below:

Aggregate Top Size (mm)	Marshall Index: Sand and Gravel	Marshall Index: Limestone
19	4.530	7.121
38	4.349	9.048

SUMMARY AND CONCLUSIONS

A comprehensive laboratory investigation was performed to evaluate the performance of cold-mixed asphalt emulsion mixtures used in black bases. The study concentrated on the influence of aggregate top size on the mixture characteristics. The effect of aggregate type, aggregate gradation, and asphalt emulsion content was also investigated. A modification of the Marshall test was used in the study. Marshall stability, flow, stiffness, and index were obtained at room temperature (approximately 22°C). Other mixture parameters were also evaluated, such as specific gravity, air voids, retained moisture, and total liquid after curing.

Based on the results of the study, some conclusions were derived. Increasing the aggregate top size in the asphalt emulsion mixture from 19 to 38 mm increased both the air-cured and oven-dried bulk specific gravities and decreased the amount of air voids. The retained moisture and total liquid in the mixture after curing were not largely affected by the aggregate top size. At the same time, modified Marshall stability, flow, stiffness, and index were altered to some extent by the change in aggregate top size. Therefore, the effect of aggregate top size should be taken into consideration when the standard Marshall procedure is used in designing asphalt emulsion mixtures with large aggregate top sizes.

The results of this study serve several purposes. They provide highway engineers with a better understanding of the influence of different factors on the design parameters and properties of asphalt-emulsion-treated mixtures by use of Marshall equipment. Furthermore, the results provide additional design parameters that could be used in conjunction with the conventional parameters for the Marshall method of mix design to better control the mixture properties.

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Overview of Pay-Adjustment Factors for Asphalt Concrete Mixtures

RICHARD M. MOORE, JOE P. MAHONEY, R.G. HICKS, AND JAMES E. WILSON

In the fall of 1979, the Oregon State Highway Division and Oregon State University, with participation from the University of Washington, initiated a research project to study the impact of variations in material properties on asphalt pavement life. The study is aimed at developing a rational approach to assessing the effects of variations from specification limits so that a firm basis can be established for the development of pay factors. To collect information on the status of quality-control procedures and the use of pay-adjustment factors, a questionnaire was distributed to all state agencies, the District of Columbia, and the Federal Highway Administration. Each agency was asked to respond to questions on their current method for acceptance or rejection of asphalt concrete paving materials and related pay-adjustment factors. The results of the questionnaire are summarized. Analysis of the results indicates the following: (a) Most state agencies will accept one or more property characteristics of asphalt concrete that are outside specification tolerances, (b) most state agencies apply a pay-adjustment factor to accepted materials that are outside specification tolerances, (c) only 26 percent of the state agencies consider their pay factors to be proportional to reduced pavement serviceability, (d) approximately half of the agencies consider pay-factor plans to be effective in encouraging compliance with specifications, and (e) there is a wide disparity in the pay-adjustment factors used by the different agencies.

In the fall of 1979, the Oregon State Highway Division and Oregon State University initiated a research project to study the impact of variations in material properties on asphalt pavement life. The University of Washington is cooperating in the study with Oregon State University. The questionnaire was prompted by an increase in the occurrence of pavement problems during recent years and in the proportion of pavements constructed with a significant amount of material outside of specification limits (1). The effect of construction noncompliance on pavement serviceability has been questioned by highway agencies and has resulted in frequent controversy with contractors on the assessment of pay adjustments. The general result is reduced pay to the contractor for material that is determined to be outside the specification tolerances. The current study is aimed at developing a rational approach to assessing the effects of variations from specification limits so that a firm basis can be established for the development of pay factors.

The American Association of State Highway Officials (AASHO) Road Test (1958-1960) emphasized to the highway industry the significance of the relation of the variability of material test properties to highway specifications (2). As a result, many agencies have been developing and experimenting with various combinations of statistically based specifications to provide a more accurate evaluation of the end products and to allow acceptance of noncompliance work in conjunction with a reduced payment for that work. In 1976, 33 states were using or had tried some form of statistically oriented end-result specification (3).

In an effort to collect current information on the status of quality-control procedures and the use of pay-adjustment factors, a questionnaire was developed and distributed to all state agencies, the District of Columbia, and the Federal Highway Administration (FHWA) in November 1979. Questionnaires were returned by all except four states (a 92 percent response rate). Each agency was asked to respond to seven questions concerning their current method for acceptance or rejection of asphalt concrete paving materials. The items of emphasis on the questionnaire included

1. Acceptance of noncompliance construction and materials with or without pay adjustments,
2. Identification of properties tested for acceptance and the method of test used,
3. Pay-adjustment factors used in relation to each tested property,
4. Rationale used in establishing pay-adjustment factors,
5. Relation of pay-adjustment factors to pavement serviceability or other criteria,
6. Effectiveness of pay-adjustment factors in encouraging compliance with specifications, and
7. Summary opinions regarding the use of pay adjustments.

Although the required information could be placed on the questionnaire, the states were encouraged to include copies of supplemental information that would assist in the overall evaluation. Most states did provide supplemental materials.

Although emphasis in this paper is placed on the results of current state practice, a rational approach is presented and discussed that shows significant promise in developing pay factors. The rational development of pay factors is based on selected material properties that can be developed in the laboratory. Preliminary test results and corresponding pay factors are shown for one recent paving project constructed in the state of Oregon.

QUESTIONNAIRE RESULTS

Seven primary questions were contained in the questionnaire. The responses received for each of these questions are discussed below.

Acceptance of Below-Specification Work and Materials

Question 1 was, Do you accept asphalt concrete pavement construction and materials that do not satisfy specification requirements? The responses to this question are summarized below: