Materials Characterization of Cold Asphalt Recycling of Rural and Urban Low-Volume Roads

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Pavement cores were taken from different county roads and city streets throughout the State of Indiana with the specific purpose of obtaining materials for laboratory testing and evaluation. Detailed information was gained from these analyses on the asphalt content, asphalt penetration and viscosity, aggregate gradation, pavement layer thickness, and other parameters of the existing asphalt pavements. The state was divided into three geographic and climatic regions, and into rural and urban traffic types. Within these categories, samples were taken from various road sections for varying numbers of layers. The data obtained from these experiments were statistically analyzed and the results were examined and discussed in an attempt to characterize these pavements. This procedure was adopted mainly because of the lack of information available on the existing pavement materials, which is a situation that is typically faced by most low-volume road agencies. It was found, among other things, that (a) the variability of asphalt content in rural or urban low-volume roads could be considered small enough that no detrimental effects would be experienced by the final recycled mix; (b) the average variability within a road section is similar for urban and rural asphalt pavements; and (c) the geographical location of the pavement has no significant influence on the oxidation of the various asphalt layers that form those pavements. The significance of these and other factors believed to influence the performance of cold, recycled asphalt pavements was determined from these analyses.

Existing asphalt pavements from low-volume roads are likely to consist of layers of asphalt concrete of different composition and characteristics. It is also likely that a section of pavement selected for recycling can vary in materials composition from one end to the other or one layer to another. These variations could have been the result of normal construction practices, normal maintenance practices, or weather and pavement age variations.

Existing stockpiles of salvaged material could similarly have been obtained from pavements that also have different characteristics. Test data from samples obtained in highly cracked areas can display properties different from test samples taken from uncracked areas of the same asphalt pavement. The variability introduced by these characteristics can be high in many cases. However, some pavements can be relatively uniform throughout the test section being analyzed.

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Pavement cores were taken from different low-volume roads throughout the State of Indiana with the specific purpose of obtaining materials for laboratory testing and evaluation. It was expected that information would be obtained from these analyses that would aid in the creation of a practical and realistic set of guidelines for the recycling of asphalt pavements in Indiana counties and cities. The entire network of county roads and city streets of the state was the inference population of this evaluation.

PAVEMENT SAMPLING AND TESTING PROCEDURES

Pavement Sampling Procedures

A portable drill with a 4-in diameter bit was used to obtain the pavement cores. The locations of the low-volume road pavements sampled were selected on the basis of the following:

- Their geographical distribution in the state (northern, central, or southern);
- Their potential for recycling, such as pavements with extensive deterioration that are in need of immediate repair;
- Their volume and type of traffic, such as farm to market and suburban pavements; and
- Their typical characteristics.

The selected road was considered a representative pavement section of a particular county or city through an initial discussion with the local highway engineer and a visual on-site inspection.

The number of samples collected and the locations and parameters measured were believed to provide a statistically sound representation of these asphalt pavements and the materials of which they were composed. The data obtained from the pavement cores were used in the statistical analysis of variance (ANOVA) method to determine the extent of the existing variability among and within pavements throughout the state, and to identify the main factors responsible for this variability (*1*).

Pavement Testing Procedures

The pavement cores obtained from the locations shown in Figure 1 were subjected to a series of laboratory tests to obtain data for the response variables used in the statistical analyses.

The cores that represented various pavement layers were weighed in air, and the height of each layer was measured and recorded. The cores were sliced along their diameter into

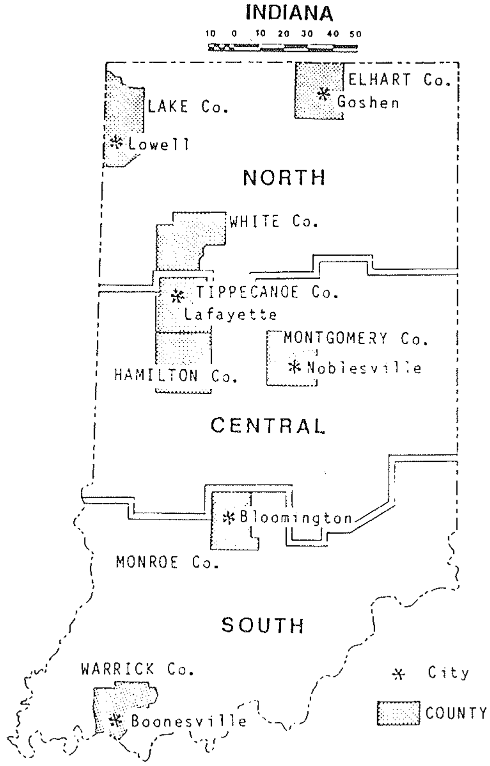

FIGURE 1 Location of low-volume roads.

smaller samples that represented the individual layers that formed each particular pavement core. There were between one and four layers in each core.

The following information was obtained from each sliced layer using standard ASTM test procedures (*2*).

- Specific gravity (density) of the layer was obtained by means of ASTM D 2726.
- Marshall test parameters were obtained following the procedures delineated in ASTM test D 1559. The Marshall stability (lb) and the Marshall flow (0.01 in) were obtained for each layer at room temperature (±72° F) instead of the 140° F that the standard test calls for.
- The asphalt content and the gradation of the recovered aggregate were obtained after the core layer was subjected to extraction procedures given in test ASTM D 2172.
- The sieve analysis of the extracted aggregate was performed using ASTM C 136.
- The recovery of the extracted asphalt was obtained using the test procedures specified in ASTM D 1856.
- The penetration and viscosities of the weathered binders from each layer were determined following standard procedures ASTM D 5 and ASTM D 2170, respectively.

ANALYSIS OF TEST DATA

Statistical Analysis Variables

Six response variables were selected from all the parameters measured for each core layer. These variables were believed to best characterize the weathered and in-place material that formed the low-volume roads analyzed. The response variables were as follows:

- Asphalt content,
- Asphalt penetration (0.1 mm),
- Kinematic viscosity (cSt),
- Aggregate gradation modulus,
- Marshall stiffness, and
- Pavement thickness.

A total of 159 values for the parameters of the recovered original binders was recorded. The asphalt content (percent by total weight of mix) was determined for each separate core layer of the pavement of a county road or city street. A total of 227 asphalt contents were determined.

The aggregate gradation modulus, a measure of the surface area of the extracted aggregate, was used to analyze the existing variability in the original aggregate gradation. A review of the literature revealed that the coarseness of an aggregate gradation can be expressed by a single number that reflects the amount of material passing the 10 standard sieves from 1 1/2 in to No. 200 (*3, 4*). This number can be obtained by adding all the percentages of material passing these sieves for a sample and dividing the sum by 100. This parameter is sufficiently sensitive to reflect changing requirements for mix proportions or asphalt content requirements as the aggregate grading varies (*4*). Because 227 sieve analyses were performed on the extracted aggregate, the same number of observations were made for the aggregate gradation modulus.

The Marshall stiffness of the existing asphalt pavement mixture was obtained by dividing the Marshall stability (lb) by the Marshall flow (0.01 in) of each core layer. The Marshall stiffness (lb/in) has been used in previous studies to evaluate asphalt pavement mixtures properties (*3, 5*). This parameter was believed to better characterize the stability and flow properties of the existing pavement layers than if stability and flow were considered as two, separate test response variables. A total number of 178 Marshall stiffness values were obtained in this part of the study.

The last dependent variable, the thickness of each pavement layer, was measured and recorded. This variable was considered to be of some significance in this study because it is an approximation of the quantity of asphaltic concrete material that can be milled off the existing pavement. A total of 228 layer thicknesses (in inches) were recorded.

Six independent variables or factors were used in this study, as shown in Table 1 and the following list:

- Geographic or climatic region,
- Traffic type (rural and urban),
- Political zone (county and city),
- Roads sampled,
- Pavement core samples, and
- Pavement layer.

The geographic or climatic regions in which the low-volume road asphalt pavements were located were incorporated in the statistical analysis of the data. This was done to determine if there were significant climatic effects on the weathering of the original asphalt binder of pavements located in the northern, central, and southern parts of the state (see Figure 1). The penetration data of the recovered asphalt were used to analyze the effects of somewhat mild weather in southern Indiana against the effects of the most severe winter weather in northern Indiana.

TABLE 1 MAIN FACTORS CONSIDERED

Independent Variables	Sample Size	Description
Climatological regions	3	Northern Indiana Central Indiana Southern Indiana
Traffic type	2	Rural Urban
Zones surveyed	14	8 counties 6 cities
Roads sampled	58	34 county roads 24 city streets
Pavement cores	117	74 from county roads 43 from city streets
Pavement layers	227	114 from county roads 113 from city streets

The political zones (county and city) in which these asphalt pavements were located are also shown in Figure 1. A total of eight different counties and six cities were surveyed in this study, and pavement cores were taken from representative locations.

A total of 34 county roads and 24 city streets were sampled. This factor allowed the existing variation between and within county and city asphalt pavements to be determined by comparing the data obtained for the response variables that were described earlier.

A total of 74 pavement core samples from county roads and 43 samples from city streets were taken. This factor allowed a comparison to be made of the response variables within a given county or city low-volume road. The extent of the variability along the length of a given section of the same asphalt pavement could then be determined.

A total of 144 pavement layers from county roads and 83 layers from city streets were sampled. This factor enabled a determination to be made of the variability between layers from the same asphalt pavement core.

Results of the Statistical Analyses

The analysis of variance (ANOVA) method was used to determine the extent of the materials variability in low-volume road asphalt pavements (*1*). The ANOVA method consisted of mathematical models that incorporated the main factors or independent variables, the use of statistical packaged programs that manipulated the data or response variables, and the careful analysis and interpretation of the output obtained from analyses of these data (*6*). The mathematical and statistical definitions, general models, data layout, and other assumptions used in this experimental design can be found elsewhere (*7*). The ANOVA test results are summarized in Table 2.

Asphalt Content of the Reclaimed Pavement Material

It was found that the average asphalt contents of low-volume county road and city street pavements did not vary significantly. The statistical analysis of the data on this parameter also showed that no significant differences existed between all the roads within a particular county or city. No differences also existed in the asphalt content of all the road sections when they were all considered as a single factor in the analysis. No significant differences existed within a particular road section. It was found that on average, a county road or city street asphalt pavement could be considered to have an asphalt content equal to the average result of a minimum of four asphalt extraction results.

This means that low-volume road asphalt pavements in counties and cities throughout Indiana could be considered to have similar variations in average asphalt content. The same considerations can then be applied to this parameter in the mix design of either rural or urban cold recycling asphalt mixtures throughout the state.

The main differences in asphalt contents existed between the various layers that constituted the pavements. The asphalt content of the upper layer (surface course) was generally found

TABLE 2 SUMMARY OF ANOVA TESTS RESULTS

	Variables					
Source	Asphalt Content	Pene-tration	Viscosity	Gradation Modulus	Marshall Stiffness	Thickness
Traffic Type (TR)						
Zones Z (TR)		*			*	*
Roads R (TR Z)		*	*			*
Samples S (TR Z R)						
Layers (L)	*				*	*
L*TR						
L*Z (TR)	+				*	
L*R (TR Z)	*	*	*	*		*
L*S (TR Z R)						

Notes:
* Statistically significant at $\alpha = 0.05$;
+ Statistically significant at $\alpha = 0.10$

to be ±1.0 percent (by total weight of mix) higher than that of the lower layers. The asphalt contents of the lower layers varied within ±0.8 percent (Table 3).

The other main conclusion that can be drawn from the statistical analysis of the data is that the asphalt content within a road section varies significantly from layer to layer vertically and not necessarily within the section and horizontally across the pavement. Each layer of pavement should be milled off separately, and the salvaged material of each layer should be stored or used individually if the variation in asphalt content among layers is found to be larger than ±1.0 percent. The depth of cutting, planing, or milling is an important factor in obtaining a reclaimed material with small variations in asphalt content. Determinations of the pavement layers' thickness should be made as accurately as possible.

Penetration and Viscosity of the Original Binder

The parameters of penetration and viscosity measure the extent to which oxidation and other chemical and weather-related factors have altered the ductility and flexibility of the original asphalt binder. These changes usually result in high viscosity values and low penetrations of the recovered asphalt. The outcome is an asphalt pavement with various degrees and types of distress. Penetration and viscosity values were found to be significantly different from one road pavement to another, and within a particular road or street section, from layer to layer. From the observations of the ANOVA results it was concluded that there were no practical differences of these two parameters among the pavements of the eight counties and six cities analyzed.

It was also found that although these two parameters are weather related, the effects of the various climatic regions found in the State of Indiana (see Figure 1) were minimal or nonexistent. Asphalt binders from the pavements of low-volume county roads or city streets can be considered to age in a similar manner. Finally, the variations in the hardness of the original asphalt within the road section to be rehabilitated seem to be minimal and of small practical importance. However, the variations between layers from pavement to pavement were found to be significant. This means that the various layers of a particular asphalt pavement can be scarified, ripped, or cut and mixed together, and can be considered as having an average asphalt penetration value throughout the entire recycled section for mix design purposes.

These findings are important to the proper design of the recycled mix. Rejuvenating, softening, modifying, or recycling agents are generally used to restore the ductility and the original properties of the asphalt. The optimum quantities and type of recycling agent depend to a large extent on the hardness of this asphalt residue. It can therefore be stated that the same mix design can be used in a recycling project if the salvaged material within a particular pavement section comes from layers with a similar asphalt penetration and viscosity. These two parameters should be carefully determined, and the same type and proportions of recycling agent should be used only for the particular road section for which they were determined.

Gradation of the Extracted Aggregate

Aggregates recovered from existing pavements were not found to differ significantly in gradation. Aggregate gradations from

TABLE 3 DEPENDENT VARIABLE MEAN VALUES FOR ALL PAVEMENT LAYERS

DEPENDENT VARIABLES		PAVEMENT LAYER 1	2	3	4
Asphalt Content	mean:	5.98	4.90	5.05	4.87
	s:	1.42	2.85	3.75	1.03
(%)	n:	117	84	23	3
Penetration of Recov.	mean:	42	40	48	29
	s:	8	10	9.6	22.6
Asphalt (0.1 mm)	n:	78	59	20	2
Kinematic Viscosity	mean:	679.4	750.6	677.0	1137.5
	s:	90.0	616.5	346.4	1055.0
of Recov. Asph. (cSt)	n:	78	59	20	2
Gradation Modulus of	mean:	6.36	6.10	6.29	6.37
	s:	0.03	0.43	1.14	0.86
Extracted Aggregate	n:	117	84	23	3
Marshall Stiffness	mean:	445.51	329.08	352.75	366.05
	s:	52.25	190.97	234.50	249.30
(lb/in. x 10^3)	n:	93	65	18	2
Pavement Layer	mean:	1.33	1.87	1.68	2.08
	s:	0.44	1.41	0.89	0.63
Thickness (in.)	n:	106	79	20	3

Note: n = Number of observations per pavement layer.

s = Standard deviation.

the pavements of low-volume county roads and city streets were found to be similar, as can be seen by the narrow gradation band of the graph shown in Figure 2. The gradation range of a standard, virgin aggregate for base course asphalt mixtures is plotted in this graph for the sake of comparison.

The aggregate gradations were found to differ only between layers of the various road sections considered in this study. A close analysis of the aggregate gradation moduli of these aggregates (see Tables 2 and 3) shows that the differences obtained between average values are not great enough to be of any practical significance. This means that an average value of the gradation (percentage of material passing) of the various layers that are being considered for recycling in a particular project can be used for mix design purposes. These average gradation values would inform the design engineer of the required sizes and proportions of virgin aggregate that the reclaimed pavement material needs to meet a particular standard gradation for base, subbase, or surface course mix.

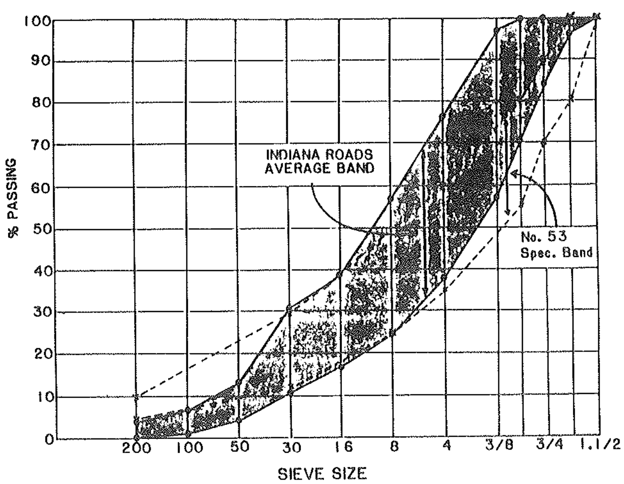

FIGURE 2 Aggregate and standard gradation of average roads.

The aggregate gradation modulus measures to some extent the necessary amounts of binder that a particular aggregate may require to perform well as a paving mix under varying traffic loads and weather conditions (*4, 7*). The statistical analysis of these data showed that the differences in aggregate gradation among pavements of low-volume roads from counties and cities were insignificant. The differences in the gradation moduli between pavement layers showed a statistical significance (Table 3); however, a closer inspection of the mean values of these data indicated that there were no practical differences. The top layers showed a slightly larger gradation modulus (more fines) than the lower layers (see Table 2), but these differences were not great enough to be considered of practical significance.

Marshall Stiffness of the Asphalt Pavement Layers

This parameter measures the relative stability and strength of an asphalt pavement mixture, which in turn relate to the properties of the materials that form a particular mix. The soundness, strength, and size distribution of the aggregate, or interlocking characteristics, influence the stability and stiffness of the mix. The properties of the binder are also reflected in this parameter. Hard, stripped asphalt with no binding properties, and soft, oily asphalt create weak and unstable mixes.

The statistical analysis of the Marshall stiffness data obtained from the core layers of rural and urban road pavement in Indiana led to the following conclusions.

The stability of the mixes that formed the various pavement layers were statistically different from each other, and the top layers were the stiffest of them all in most cases (see Tables 2 and 3). This is because newer, less deteriorated and therefore stronger mixes form the wearing surface of most pavements in service.

The differences in average Marshall stiffness between the county and city pavements of the study were also found to be statistically significant. However, a close analysis of the ANOVA test results indicated that the mean squares of the data for the layers factor was by far the largest of the mean square values. It was therefore concluded that the only practical differences among pavement stiffness occurred among the layers that formed the pavement.

The practical significance of these findings is that if a recycling project is undertaken with the sole objective of restoring the surface or top few inches of a deteriorated asphalt pavement (i.e., surface recycling), the strength and stability of the underlying materials must be carefully determined. If a new, recycled asphalt mix is placed on top of weak and unstable pavement layers, the structural support will be such that the old distresses and faults that made the pavement a candidate for rehabilitation in the first place are likely to be evident again in a short time. More detailed information on cold recycling methods that improve the structural capacity and increase the service life of asphalt pavements can be found elsewhere (*3, 7-9*).

Pavement Layer Thickness

This parameter was analyzed to help characterize the variability that exists in the asphalt pavements of Indiana's secondary roads system. It is a parameter of limited significance for the design of recycled mixtures; however, it helps to measure the relative quantities of existing materials that are available for recycling, and determines the depth of cutting during the reclaiming operation.

The statistical analysis of these data indicated that pavement layer thicknesses were significantly different between the layers of a particular low-volume road pavement, and between the layers of pavements from the various counties and cities investigated in this study. The lower layers of the pavement are thicker, on average, than the upper layers. This is because the lower layers are usually formed of a thick base course and the upper layers are formed of relatively thin surface treatments or asphalt overlays.

It was found that most common routine maintenance practices adopted by county and local highway agencies were temporary measures that consisted of patching, chip seals, and surface treatments with a limited service life and that offered almost no structural support. Heavily traveled roads generally received a hot-mix asphalt overlay when necessary. A breakdown of the type of low-volume road pavements found throughout Indiana was not possible in this study because of a lack of recorded information on the types of materials and construction techniques used to build and maintain most of these roads. Therefore, no attempt was made to determine the significance of the variability that existed between the various types of pavements.

However, it was found from available historical data and from observations of the core samples in the lab that almost all surface layers of city streets were hot-mix asphalt overlays. Most of these layers were built on top of an existing overlay or on top of some kind of cold-mix asphalt material. Lower layers, if any, were generally composed of granular base material or weathered asphalt concrete. However, about half of county roads sampled were found to have a surface layer of hot-mix asphalt concrete in regions in which traffic was heavy. Remote and lightly traveled county roads were found to have a cold-mix (plant-mix or surface treatment) pavement type. The surface layer, which in some cases was as thin as half an inch, was found to be built on top of a granular base course or a weathered cold- or hot-mix asphalt concrete. Sand mixes generally were not found among the pavements analyzed. The subgrade of the pavement was usually composed of existing clayey and sandy soils.

CONCLUSIONS AND RECOMMENDATIONS

An extensive study was conducted to determine the variability of the characteristics and materials that form the low-volume roads of Indiana's counties and cities. The analysis of variance of the data obtained from the properties of the evaluated pavement cores led to the following conclusions.

The pavement samples obtained before milling, ripping, breaking, or other processing occurred were likely to exhibit variable results from the penetration and viscosity of the original asphalt binder to the stiffness of the existing asphalt mix.

The average asphalt content found in county roads and city streets did not vary significantly. This means that the same considerations can be applied to this parameter in the design of either rural or urban cold recycling mixtures. It was also found that the asphalt content was approximately the same for all pavements within a particular county or city, and within a section of road from one end to the other.

The main differences were found among the various layers that constituted the pavements under study. Each layer of pavement should be milled off separately, and the salvaged material of each layer should be stored or used individually if the variation in asphalt content between layers is found to be greater than ± 1.0 percent by weight of total mix. The depth of cutting, planing, or milling is an important factor in obtaining a reclaimed material with small variations in asphalt content. Determinations of the pavement layer's thickness should be made as accurately as possible when large variations exist.

The analysis of the penetration and viscosity data of the recovered original asphalt binders showed similar results. The geographic location or climatic factor of low-volume road pavements does not significantly affect the penetration or viscosity of the existing binders. No practical differences existed between the county or city pavements analyzed. The penetration and viscosity values were found to be significantly different only from one road pavement to another, and within a particular road section, from layer to layer. This appeared to result mainly from local effects that are probably associated with the type and amount of distress of that particular road section. Although it was reported in some references that there is a relationship between asphalt hardening and cracking, no attempt was made to document such an observation on this project (*8, 9*).

Inspection of the data indicated that variations in penetration and viscosity test results on recovered asphalts were randomly located throughout the asphalt pavements studied. These observations and a consideration of the great standard deviations associated with these test data indicate that a great number of test locations would be required to discover the extent of pavements that have different test properties. In most cases, the amount of testing required would be more extensive than most agencies would consider feasible and would be of practical use only if the testing resulted in different mix designs for each section of the project that had different test properties. However, traffic loads and other factors associated with low-volume roads do not justify an extensive testing program or the breakdown of the project into separate subunits of different mix design. For practical purposes, the various layers of a particular low-volume road pavement can be scarified, ripped, or cut and mixed together, and can be considered to have an average asphalt penetration or viscosity value throughout the entire recycled section for mix design determinations.

Aggregates that were recovered from existing low-volume road pavements were found to have a similar gradation. Aggregate gradations from county roads and city streets fall within a relatively narrow gradation band (Figure 2). The statistical analyses showed some significant differences between the aggregates of the various layers that form the asphalt pavements, but a close evaluation of the results indicated that these differences were of no practical significance.

These findings mean that an average gradation (percentage of material passing the various sieves) of the layers being considered for recycling in a particular project can be used for mix design purposes. This average gradation value would serve to inform the design engineer of the required sizes and proportions of virgin aggregate that the reclaimed asphalt pavement material needs to meet a particular standard gradation for a base, subbase, or surface course mix.

The statistical analyses of the Marshall stiffness data obtained from core layers of low-volume road pavements showed that in most cases the top layer was the stiffest of the asphalt courses that formed the pavement under study. This indicated that the wearing surface was formed of stronger mixes than the lower layers, for most pavements in service.

No practical differences were found between the Marshall stiffness of county road and city street pavements, and within a particular section of road. These findings indicate that the strength and stability of the underlying layers of a candidate pavement must be carefully evaluated. If a new, recycled asphalt mix is placed on top of weak and unstable pavement layers, the structural support will be such that the distresses and faults that made the pavement a candidate for rehabilitation in the first place are likely to be evident again in a short time.

It can generally be concluded that the material characteristics of low-volume road pavements in Indiana that are candidates for recycling can be expected to have a relatively high level of variability. Some improvement can be obtained during the processing from pavement to reclaimed material through a controlled milling or reclaiming operation. For example, when recycled pavement of a better quality is needed, the project could be separated into subunits that might have different mix designs.

Finally, it is recommended that the following procedures be followed to sample asphalt concrete pavements from low-volume roads before the reclaiming process begins:

- Obtain samples and perform laboratory tests as outlined in the testing procedures section of this paper.
- Establish construction units only on the basis of aggregate gradation and percentage of asphalt, unless it can clearly be demonstrated that penetration or viscosity test properties are significantly different.
- Perform a detailed mix design study for each individual recycling project being undertaken. Final mix designs should be based on reclaimed and processed asphalt pavement material whenever possible.

REFERENCES

1. V. L. Anderson and R. A. McLean. *Design of Experiments: A Realistic Approach*, Marcel Dekker, Inc., New York, NY, 1974, 418 pp.
2. *1984 Annual Book of Standards*, Vol. 04.03, Sec. 4: Construction—Road and Paving Materials, Traveled Surface Characteristics, American Society for Testing and Materials, Philadelphia, Pa., 1984, 861 pp.
3. M. Tia, L. H. Castedo-Franco, and L. E. Wood. *An Investigation of Recycling Bituminous Pavements*. Final Report JHRP-83-4. Purdue University, West Lafayette, Ind., March 1983.
4. S. B. Hudson and H. F. Waller. *NCHRP Report 69: Evaluation of Construction Control Procedures—Aggregate Gradation Variations and Effects*. HRB, National Research Council, Washington, D.C., 1969, 58 pp.
5. A. A. Gadallah. *A Study of the Design Parameters for Asphalt Emulsion Treated Mixtures*. Final Report JHRP-76-30. Purdue University, West Lafayette, Ind., 1976.
6. *SAS User's Guide: Statistics*. SAS Institute, Cary, N.C., 1982, 800 pp.
7. L. H. Castedo-Franco. *Materials Characterization and Economic Considerations of Cold-Mix Recycled Asphalt Pavements*. Ph.D. thesis. Purdue University, School of Civil Engineering, West Lafayette, Ind., 1985.
8. J. A. Epps. State-of-the-Art Cold Recycling. In *Transportation Research Record 780*, National Research Council, Washington, D.C., 1980, pp. 68-100.
9. J. A. Epps, D. N. Little, and R. J. Holmgreen. *NCHRP Report 224: Guidelines for Recycling Pavement Materials*. TRB, National Research Council, Washington, D.C., Sept. 1980.
