Significance of Various Factors in the Recycling of Asphalt Pavements on Secondary Roads

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In this paper are presented the results of field and laboratory investigations undertaken to determine the role that material variability, mix design factors, and other parameters play in the performance of recycled asphalt pavements on secondary roads. After the pertinent literature on the economics and procedures associated with various recycling methods was reviewed, a sampling program was developed to collect cores from existing pavements. This coring program was undertaken to evaluate the variability of the materials that form the asphalt pavements of county roads and city streets in Indiana. Statistical analyses of the data obtained on these cores showed that there is practical significance in the variation of parameters, such as asphalt content, aggregate gradation, and asphalt penetration, within a section of road, between county and city asphalt pavements, and among geographic regions in the state. Characterization of these materials allowed the author to simulate in the laboratory actual conditions such as hardness of the binder, gradations of aggregates and reclaimed asphalt pavement material, asphalt contents, and other properties of the recycled mix within the range of values measured from pavement core samples. The effects of these parameters were measured by means of the Marshall and resilient modulus tests. It was found that a stable and sound pavement can generally be obtained using cold-mix recycling techniques if normal reclaiming procedures are followed and regular asphalt emulsion binders are added.

Construction, rehabilitation, and maintenance of asphalt pavements in Indiana have been done almost exclusively with virgin selected materials *(1)*. Recycling of asphalt pavements is not widely accepted as a corrective measure for structural and surface distress of asphalt pavements on primary and secondary roads.

One of the main problems faced when planning the rehabilitation of a secondary road (e.g., farm-to-market roads and residential city streets) is the lack of information on the materials that form the pavement to be recycled.

The FHWA has sponsored a number of recycling operations through Demonstration Project 39, which has the objective of advancing this technology and sharing the experience and results obtained. The economics and feasibility of this rehabilitation technique are extensively documented for demonstration projects throughout the country *(2)*. There are still, however, many questions that remain unanswered such as (a) how much variability exists in the pavement materials of secondary roads targeted for rehabilitation? and (b) what is the practical effect of this variability on the performance of a recycled pavement? These and other questions about the recycling of asphalt pavements on secondary roads in Indiana were addressed in this study.

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GENERAL CONSIDERATIONS

Recycling Process

Pavement recycling can be categorized according to the construction procedure used, the types of materials to be recycled, and the structural benefits to be gained. The main forms of asphalt pavement recycling are (a) surface recycling, (b) in-place surface and base recycling, and (c) central plant recycling. Most of the operations involved in each of these recycling techniques can be performed either cold (with materials and equipment at ambient temperatures) or hot (central plant recycling) *(3)*.

Selection of a cold- or a hot-mix recycling technique is generally based on available funds, time to completion, and other specialized efforts that are involved in either process. Hot-mix central plant recycling allows better control of materials and therefore a good-quality mix is produced. However, the costs and quality of hot-mix recycling are justified in most cases only for high-volume, first-class pavements. The normal procedure for recycling asphalt pavements on secondary roads has been the cold-mix process. The mix produced is generally used as base course material with some form of surface treatment or hot-mix asphaltic concrete overlay *(1, 4)*. For this reason, this study was concentrated on the process and materials involved in cold-mix recycling of asphalt pavements.

Factors Involved in Cold-Mix Recycling of Asphalt Pavements

There are numerous factors involved in any recycling operation. Two important economics- and materials-related factors are (a) the economics of recycling, including such items as hauling distances, energy usage, availability of virgin materials, traffic control and disruption, construction time, rural or urban environment, project size, contractor availability *(2)*, and (b) the variability in paving materials, which is related to such factors as weather effects, traffic wear, and the nature of the paving materials used (i.e., different binders and aggregate contents and compositions).

These factors, to varying degrees, influence the selection of recycling or conventional procedures for restoring a distressed pavement. The economic considerations involved in recycling secondary road asphalt pavements in Indiana are analyzed next.

ECONOMIC CONSIDERATIONS

It is widely known that one of the major criteria that determine whether or not a new process will be accepted is economics. If it can be demonstrated that recycling of asphalt pavements has economic advantages over new material construction, recycling could be accepted as a viable pavement rehabilitation alternative.

Construction costs and other economic data from asphalt pavement projects in Indiana and throughout the country were obtained for 1985 and previous construction periods in order to document the main economic differences that exist between conventional asphalt pavement rehabilitation methods and the recycling process. Current data were obtained through telephone and personal conversations with highway authorities, from the latest reports found in the literature, and by cost indexing prices before 1985. The cost index method used is the one recommended by the Engineering News Record (ENR) and described in the Texas Transportation Institute guidelines *(5)*.

Cost Components

A review of most of the reports prepared for FHWA Demonstration Project 39, as well as other information available, revealed that, on average, material cost represents 46.6 percent of the total cost of a cold in-place recycling project and that equipment and labor represent 29.7 and 23.7 percent of the project's cost, respectively *(1–4)* (Figure 1). Records from several hot-mix asphalt overlay operations in Indiana showed that materials average 90.5 percent of the total cost and that equipment accounts for 4.8 percent and labor for 4.7 percent of the cost of overlaying a pavement. Chip-and-seal or surface treatments in Indiana were found to have an average cost breakdown of 9.5 percent for labor and 90.5 percent for equipment and materials *(1)* (Figure 1).

The main economic advantage that recycling appears to have over conventional paving procedures is to be found in the raw materials required for the project because the salvaged material removed from the roadway has an intrinsic value attributable to the asphalt and aggregate components of the old pavement. However, a closer analysis of the cost data revealed that, in almost all recycling projects, the material cost was attributable to the new asphalt or recycling agent used to restore the properties of the aged binder.

Another important cost component of this type of mixture is the virgin aggregate used to upgrade the gradation of the existing aggregate to a standard particle distribution. The effects of varying amounts of virgin aggregate on the final cost per ton for asphalt mixtures, at 1985 prices in Indiana, are shown in Figure 2. As can be seen, virgin aggregate alone can, in some cases, almost triple the final cost of the mix if asphalt mixtures that contain 100 percent cold-mix recycled and 100 percent virgin materials are compared. This is because the production and hauling cost of virgin materials can be quite high in some parts of the state.

Cost Comparison and External Factors

Construction and rehabilitation of asphalt pavements in general (including cold-mix recycling) are subject to changes in price of the main material components of the asphalt mix. Studies by Schnormeier *(6)* and others *(1, 4, 5)* showed that asphalt cement price variations have the largest influence on the variation of the price of asphalt mixtures in general. Consultations with several highway agencies and local contractors throughout Indiana resulted in a list of average prices paid in 1985 (Figure 3).

From these data it can be seen that prices for new base and binder materials for Interstate projects in Indiana varied substantially more than did prices for the same materials in urban

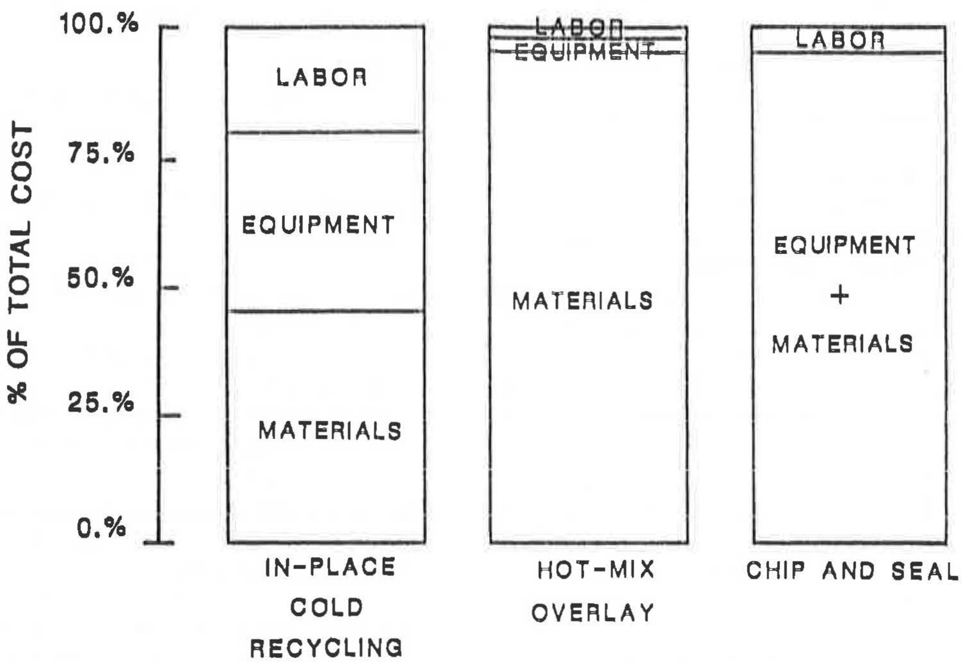

FIGURE 1 Cost breakdown for various rehabilitation alternatives.

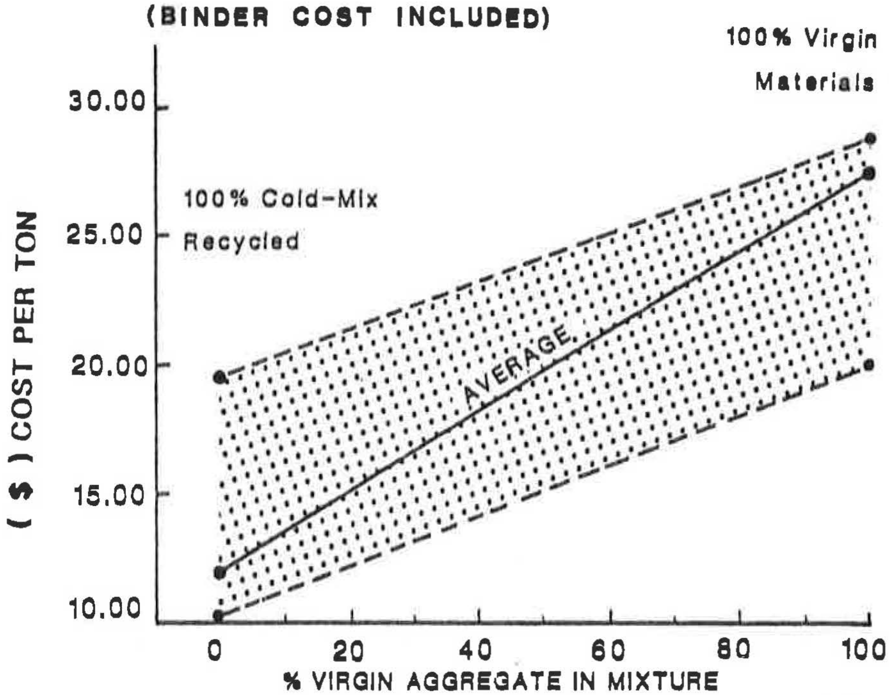

FIGURE 2 **Effect of varying amounts of virgin aggregate on the cost of asphalt mixtures.**

areas. This is because the cost per ton of these materials depends on, among other things, conditions such as location of projects and quantities of material required for particular projects.

When the prices paid in 1985 for hot-mix recycling (used only for high-volume pavements) are compared with those paid for virgin mix, it can be seen that hot-mix recycling was almost as expensive as new materials construction. This has created a situation in which hot-mix recycling procedures have been abandoned in favor of conventional, hot-mix asphaltic concrete operations that use virgin materials, and the various benefits associated with recycling (e.g., little or no use of virgin materials, retention of original grade) are negated thereby.

The remaining data shown in Figure 3 are the prices for cold-

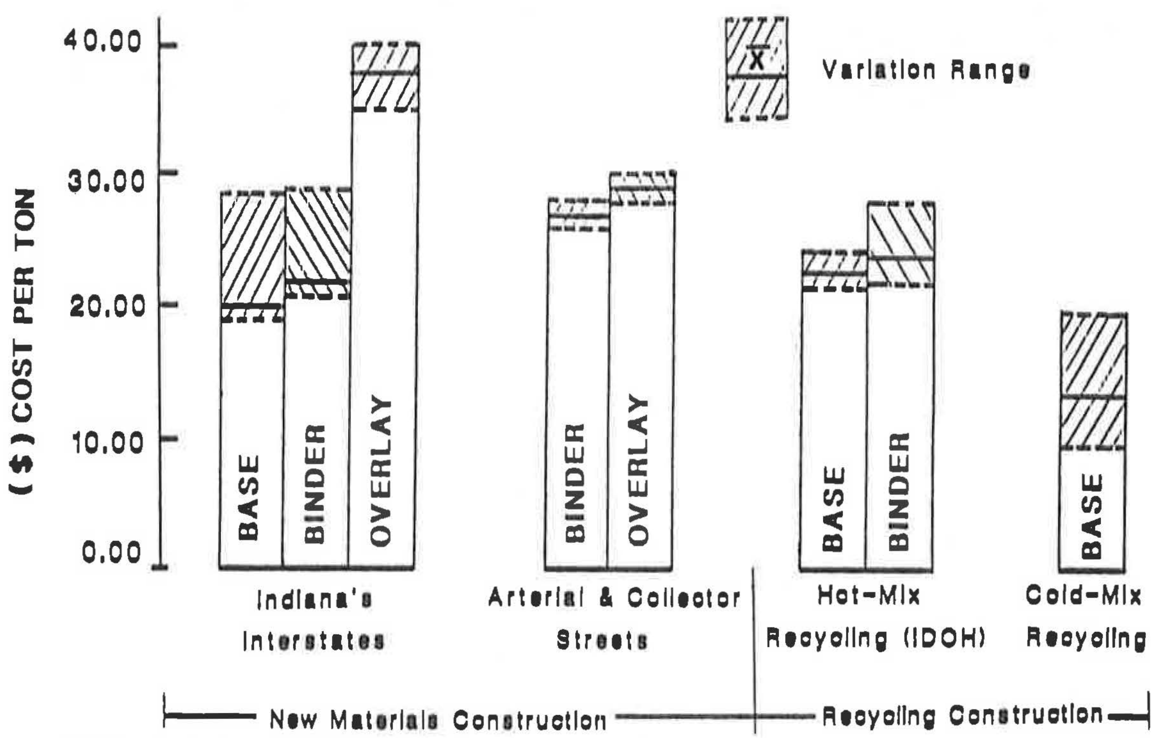

FIGURE 3 **Cost of various new and used pavement materials in Indiana.**

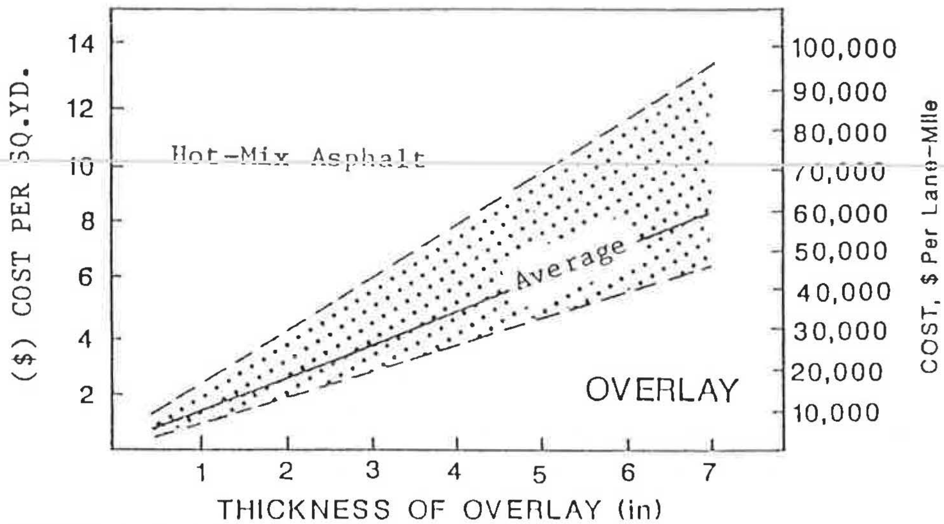

FIGURE 4 Cost of hot-mix asphalt overlay of various thicknesses *(5)*.

mix recycling materials as reported by some Indiana contractors and highway agencies that have used this process for rehabilitating county roads and residential urban streets.

Because the most common rehabilitation alternative for repairing a distressed asphalt pavement in need of structural improvement in Indiana is the placement of an asphalt overlay, cost figures were sought for this procedure in order to compare these figures with the cost of alternative cold-mix recycling.

It was found that, in general, the savings and differences in cost for these two alternatives were significant. An approximate range of prices was obtained for hot-mix overlays (Figure 4) and in-place cold-mix recycling (Figure 5). The data shown in Figure 4 were updated from figures given by the Texas Transportation Institute *(5)*, and Figure 5 was developed from data reported in the literature *(1, 2, 4)* and consultations with local contractors, highway agency personnel, and personnel from the Bureau of Local Roads and Streets of the Illinois DOT. The data presented in these figures indicate that significant savings may be realized when recycling is chosen instead of an asphalt overlay for rehabilitating an asphalt pavement on a secondary road.

There is at least one other item that has a direct bearing on the reduction or minimization of highway construction cost in general, and that is the energy used in the transportation of the materials, in the operation of equipment for processing those materials, and in manufacturing the finished product. The literature (in particular, the reports prepared for Demonstration Project 39) gives notice of the various relationships that exist between costs of a conventional asphalt paving process and recycling procedures in terms of hauling distances of virgin and reclaimed materials (aggregates as well as binder). It is reported that as the distance that new materials must be hauled increases, the advantage of recycling increases significantly *(7)*. Energy saved also increases as the proportion of reclaimed material in the final mix increases (Figure 2).

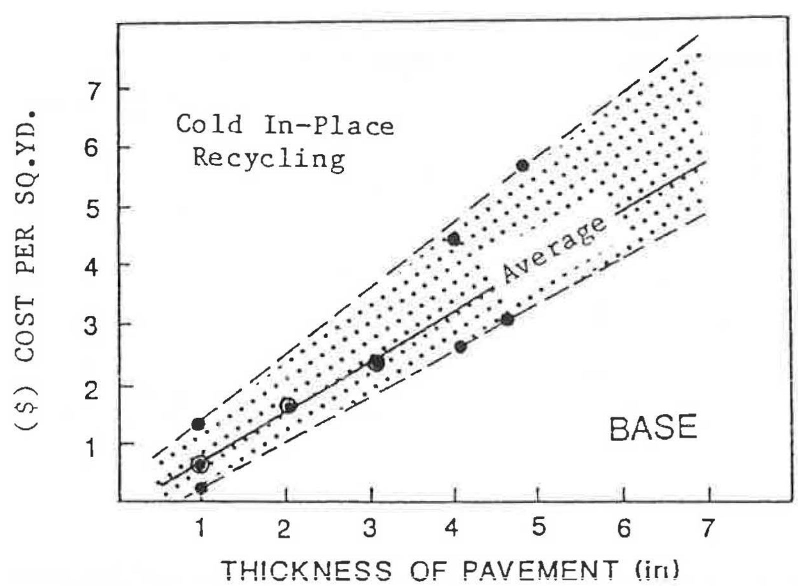

FIGURE 5 Cost of cold in-place recycled material.

Summary of Findings

The preliminary conclusions that can be developed from this information follow.

1. The cost of the new binder or recycling agent used to restore the properties of the reclaimed asphalt pavement (RAP) material accounted for more than half the total cost of cold-mix recycling projects.
2. The final cost of a recycling project is increased as more virgin materials are added to the recycled mix.
3. Significant savings in energy are possible if in-place cold-mix recycling techniques are used instead of central plant hot- or cold-mix recycling. The cost of transporting materials to and from the plant accounts for most of these savings. Savings are even more substantial when recycled mixtures are compared with conventional hot-mix asphaltic overlays.
4. The overall costs for cold-mix recycling operations are dependent on the assumptions and particular techniques adopted for each individual recycling project, as well as other factors such as traffic, weather, materials, location, and equipment.
5. The cost or energy effectiveness of cold-mix recycling cannot be determined from the information found in most of the available literature or reported here. The level and length of service to be obtained from recycled pavements have not yet been established *(1, 4)*.

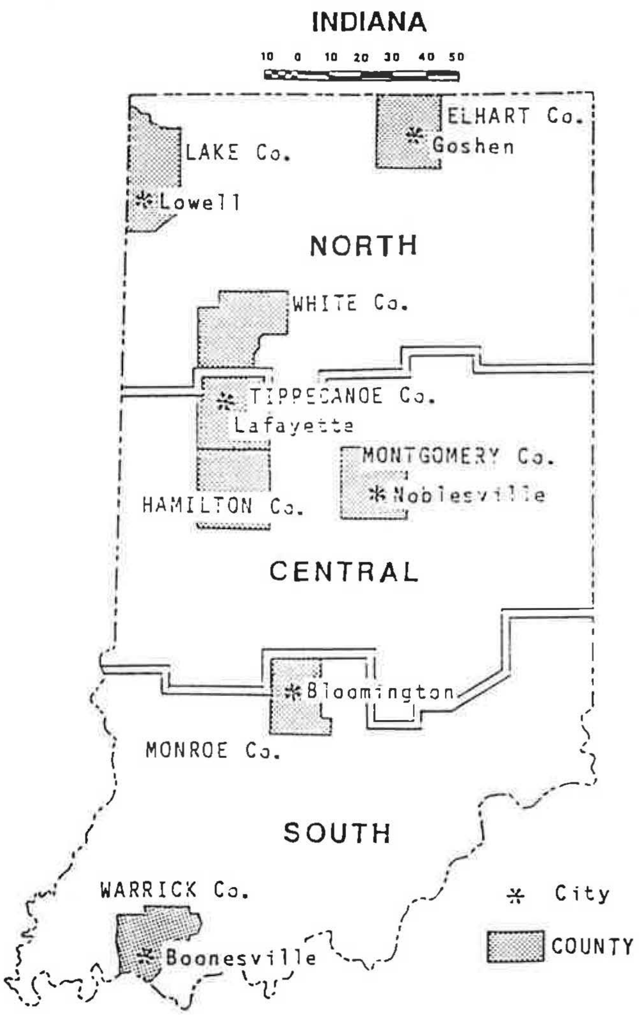

FIGURE 6 Location of pavements sampled.

TABLE 1 DEPENDENT VARIABLES

Name	Unit	Total No. of Observations
Asphalt content	%	227
Penetration	0.1 mm	159
Kinematic viscosity	cSt	159
Aggregate gradation modulus	–	227
Marshall stiffness	lb/in.	178
Layer thickness	in.	208

EVALUATION OF EXISTING PAVEMENT MATERIALS

Representative asphalt pavements from secondary roads (counties and cities) throughout Indiana were sampled at the locations shown in Figure 6. The properties of the materials that form those roads were determined in the laboratory by means of standard ASTM test procedures *(8)*. The objective of this field and laboratory work was to collect data on parameters such as asphalt content, aggregate gradation, penetration and viscosity of the recovered binder, and other important characteristics of the existing asphalt pavements given in Table 1.

These data were then evaluated using statistical analysis methods such as the analysis of variance (ANOVA) procedure *(9)* for the main factors given in Table 2. The results of these statistical analyses (Table 3) helped determine the significance of the variability found in the parameters measured. These determinations, in turn, allowed conclusions to be drawn regarding the feasibility of using the cold-mix recycling technique for rehabilitating or maintaining asphalt pavements on secondary roads in Indiana.

The information obtained from these analyses can be summarized as follows:

1. There was no significant effect that could be attributed to the geographic location of the existing asphalt pavement in terms of viscosity or penetration, or both, of the asphalt binder recovered from pavement cores. The weather in northern, central, and southern Indiana (refer to Figure 6) has, for practical

TABLE 2 MAIN FACTORS CONSIDERED

Independent Variable	Sample Size	Description
Climatological regions (refer to Figure 6)	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

TABLE 3 SUMMARY OF ANOVA TESTS RESULTS

Source	Asphalt Content	Penetration	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)						

NOTE: * = statistically significant at $\alpha = 0.05$ and + = statistically significant at $\alpha = 0.10$.

purposes (according to the statistical analyses of the data), similar effects on the aging of the binders from all of the pavement cores analyzed in this study.

By simply plotting the average viscosity and penetration values obtained for as many as 227 samples of existing asphalt pavements, it can be shown that the results lie within a close range: approximately 600 to 900 cSt for viscosity and 30 to 55 dmm (0.1 mm) for penetration (Figure 7).

A statistical analysis of the penetration and viscosity data showed that the only significant differences for these two parameters were found among the layers (up to four) that form a particular road or street section. However, a closer analysis of the mean values of the viscosity and penetration of the aged binders from each layer revealed that these variations in hardness from one layer to the other appear to be minimal and of small practical importance *(1)*.

The results of the statistical analysis could then have a twofold interpretation: (a) either each pavement layer must be removed (reclaimed) separately and treated individually for mix design purposes (ideal but not always practical) or (b) the various constituent layers must be scarified, ripped or cut, and mixed together. The resulting reclaimed material would then be considered to have an average asphalt penetration and viscosity value (the average of various samples depending on the size of the project) that can be used for mix design purposes.

The results of this statistical analysis also indicated that (a) the hardness (penetration and viscosity) of extracted binders from county roads does not vary significantly from that of asphalt pavements on city streets, (b) there were no significant differences in these parameters within county or city street pavements, and (c) there were no significant differences within a particular road segment along the horizontal plane of the pavement.

2. It was found that, in general, the asphalt content of the top layer of pavement was higher than the asphalt content of the lower layers. Figure 8 shows mean asphalt content values for the top two layers of each pavement sampled in various counties and cities in Indiana. The lines connecting the data points in this graph are used only for clarity and to show the overall trend found for the asphalt content of the pavements evaluated. Even though this can be considered typical of wearing surface layers compared with binder and base course layers, it should be pointed out that almost all secondary road pavements are made of a series of asphaltic concrete layers

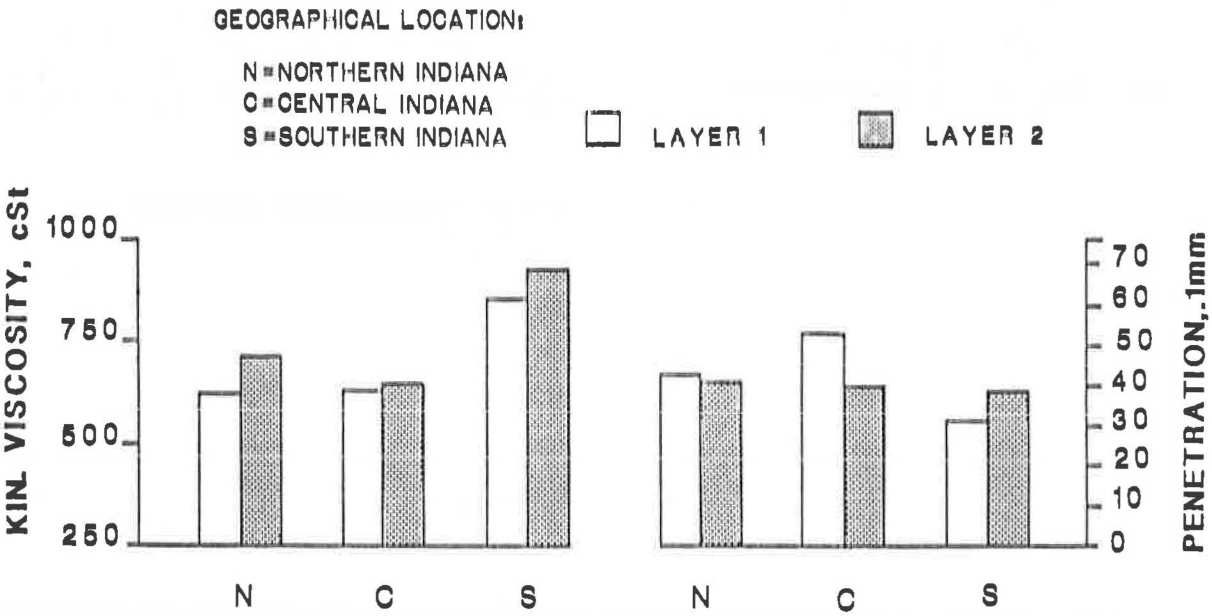

FIGURE 7 Viscosity and penetration of aged binders from various locations.

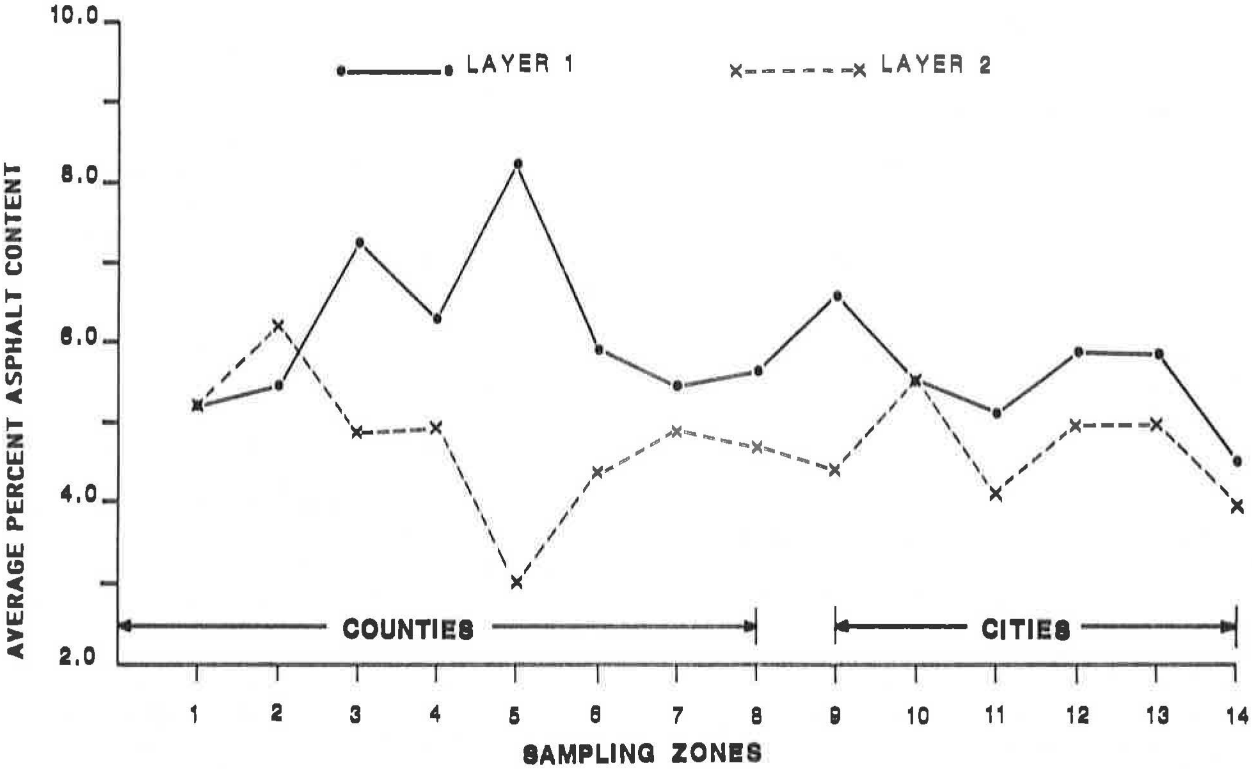

FIGURE 8 Average values of asphalt content of secondary road pavements in counties and cities.

placed, throughout the years, on top of each other (stage construction) and that the old wearing surface course layers become the base and subbase of the upper pavement layer.

The results of statistical analysis showed significant differences only among pavement layers (Table 3). In general, asphalt contents were within ±1.0 percent (by weight of total mix) of each other (except for County Zone 5 in Figure 8). These results lead to conclusions similar to those for viscosity and penetration of the asphalt pavement layers: (a) each layer can be milled off separately and the salvaged materials can be stored or used individually if the variations in asphalt content are greater than 1.0 percent and (b) for variations less than 1.0 percent, the layers can be reclaimed simultaneously and an average asphalt content value can be assumed for all of the salvaged material.

3. Asphalt pavements on county roads were found to have average aggregate gradations similar to those of city streets. Similar results were observed from samples within counties and within cities, within a section of the same road, and even among the various layers that form the pavement (Table 3). All of the gradation analysis results (227 samples) fall within the range of values shown in Figure 9.

4. Other findings were that, in general, top layers were thicker and more stable [as measured by the Marshall stability test *(8)*] than were lower layers. The variability in this parameter and in the thickness of the layer was found not to be statistically significant.

No significant differences were found between pavements of county roads and city streets nor within a particular road section for these two parameters. That top layer mixtures were found to be more stable than bottom layers was attributed to upper layers being relatively newer material and therefore less deteriorated than the lower layers they covered.

For a sound recycling design, the engineer will have to take these findings into consideration in order to account for a recycled pavement that may require a more stable subgrade than those found in this evaluation.

LABORATORY BEHAVIOR OF COLD RECYCLED ASPHALT MIXTURES

The final task of this study was an evaluation of cold-mix recycled asphalt pavement samples in the laboratory. The information gained from the results discussed in the previous section was used in the laboratory for the preparation of recycled mixtures that closely resembled an in situ cold-mix recycled asphalt pavement material.

Reclaimed asphalt pavement (RAP) material from actual city streets was used to prepare most of the laboratory specimens tested following ASTM standard test procedures *(8)*. These RAP materials were prepared with gradations, asphalt content, penetration, and other parameters within the range of in situ values.

This laboratory study covered four different RAP materials, six different recycling agents (three common asphalt emulsions and three commercial recycling agents), various RAP gradations, two artificially aged binder contents, curing time, and other mix design parameters.

The major findings obtained from the laboratory evaluation can be summarized as follows:

1. Initial mixing water contents less than 3.0 percent (by dry weight of the RAP) produced the best performing cold recycled mixes.

2. The amount of recycling agent has a significant effect on the behavior of the recycled mix. Recycled mixes with agent contents lower than 1.0 percent (by dry weight of the RAP) showed inconsistent trends of initial strength or stability properties. This apparently indicates that low agent contents are difficult to distribute uniformly throughout the mix, which yields a nonuniform paving material with unpredictable performance in the field.

On the other hand, excessive agent contents (more than 3.0 percent by dry weight of RAP) produced unstable mixes that would be expected to undergo excessive deformations and pavement bleeding in the field. The ideal range of recycling agent (liquid asphalts or modifying oils, or both, or chemicals) for the reclaimed asphalt pavement materials appears to be somewhere between 2.0 and 3.0 percent by weight of the dry RAP.

3. An aeration period before compaction and after moisture is mixed in and the recycling agent is added appears to be necessary to lower the total fluid content of the recycled mix. It was found that this initial period produced compacted recycled mixtures with high early strength and stability that allowed better handling of the test specimen in the laboratory.

4. The choice of recycling agent, modifying oil, or rejuvenating or softening agent should be based on economic considerations and the availability of these materials. All six agents considered in this laboratory study performed well in altering the hardness of the aged asphalt cement and produced recycled mixtures with characteristics similar to those of cold-mix asphalt made with virgin materials.

5. The effect of curing time following compaction was found to be significant. In the first 7 days of curing at ambient conditions (approximately 72°F), the increase in strength and stability of the mix was found to be related principally to the characteristics and amounts of agent added. Softer residue agents produced early cured recycled mixtures of low or even decreasing stabilities until evaporation of the water and other fluids began. Harder residue recycling agents yielded higher stability and strength values initially. In general, all test parameters measured for the recycled mix at various curing times increased to a maximum value and leveled off thereafter.

6. The effect of the RAP gradation (the gradation of the reclaimed material obtained after planing, crushing, ripping, or scarifying the aged asphalt pavement layers) was found to be significant at the levels used in this laboratory analysis. In most cases, however, it was found that cold recycled mixtures prepared with RAP gradations within the gradation range corresponding to those commonly produced by normal reclaiming procedures yielded mixtures with characteristics similar to those of mixtures the RAP material of which was processed to include more fines (i.e., additional processing of the RAP). The effects of RAP gradation were found to depend on the type of agent used as well as the amount present in the recycled mix.

7. Finally, recycled mixtures prepared with aged RAP mate-

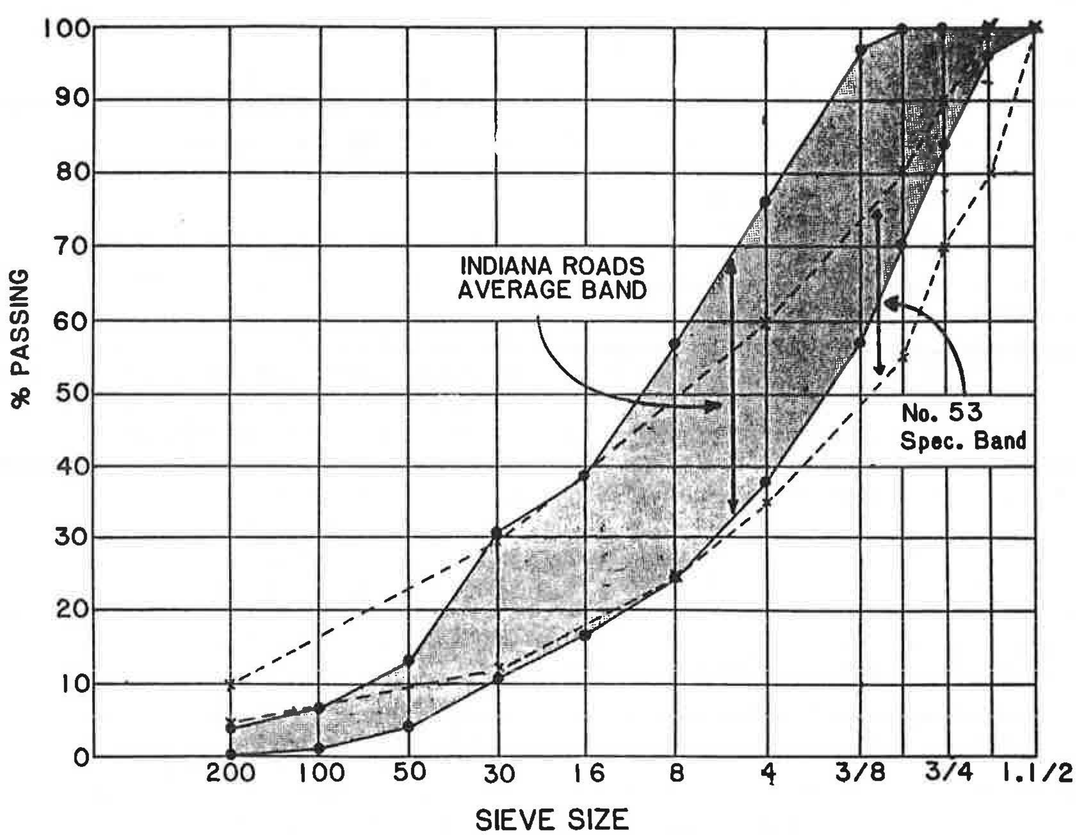

FIGURE 9 Average gradation of aggregate extracted from asphalt pavements on secondary roads.

rials of varying original asphalt contents were found to yield paving mixtures with different stabilities as measured by the Marshall test *(8)*. A combined stability-flow parameter (i.e., Marshall stability measured at room temperature divided by final flow) was found to be the most sensitive laboratory test parameter for detecting the behavior of these mixes. In most cases, a higher original binder content in the RAP yielded a lower combined stability-flow parameter for the final recycled mix.

OVERALL CONCLUSIONS

It is recommended that cold-mix recycling techniques be included in county and city highway maintenance programs in Indiana as an alternative for rehabilitating or maintaining asphalt pavements on secondary roads. Cost, energy, and mix design analyses should be used to establish whether other rehabilitation or maintenance techniques are more viable or practical than recycling.

It is believed that asphalt pavements on secondary county roads or city streets in Indiana can be rehabilitated with cold-mix recycled materials. This technique could be the least expensive alternative for restoring the original serviceability of the pavement.

Approximate costs associated with various materials and procedures (e.g., asphalt overlay, in-place recycled mix) can be used by the design engineer to estimate the approximate construction costs of the various alternatives available for a particular project. These preliminary economic evaluations can then be used as one of the factors to be considered in the selection of the most appropriate procedure for the project.

Standard construction units based on aggregate gradation and asphalt content of the material to be recycled can be established. Individualized construction units could be developed if it were demonstrated that penetration or viscosity test properties, or both, were quite different.

Whenever possible the degree of oxidation or brittleness of the original asphalt to be recycled should be known. This information can be obtained by extracting and then recovering the aged asphalt from the RAP. The harder the recovered asphalt, the softer the residue of the recycling agent must be. Common liquid asphalt emulsions were found to behave just as well as commercially available chemicals and modifying oils. The choice between these commercial products should be made initially on an economic basis. After narrowing the alternatives to two or three particular products, laboratory analysis of recycled mixes prepared with available RAP and the selected recycling agents should be performed to choose the agent that produces acceptable recycled mixtures.

The strength and stability properties of the recycled mix should be evaluated after a sufficient curing period has elapsed in order to obtain representative strength and stability values for a particular mix. Oven curing at 140°F for 3 days can be used to accelerate the curing process. A curing time of 7 days out of the mold may also be used for this purpose.

Optimum mixing moisture and recycling agent contents should be determined using trial mixtures and laboratory test procedures. Excessive (i.e., more than 3.0 percent) or deficient (i.e., less than 1.0 percent by weight of dry RAP) amounts of these two fluids should be avoided because unstable and weak mixtures, which exhibit unpredictable behavior, are produced.

The findings of the study of the effects of RAP gradations indicated that an existing asphalt pavement reclaimed or salvaged by conventional methods and equipment generally does not need extra processing.

It is also recommended that final mix designs be based on reclaimed and processed asphalt pavement material. Every recycling job should be approached with as much planning, design, and expertise as practically feasible.

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