Performance of Recycled Hot-Mix Asphalt Mixtures in Georgia

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The Georgia Department of Transportation (GDOT) has been constructing recycled asphalt pavements routinely for about 4 years. This research project was undertaken to evaluate the performance of recycled pavements compared to virgin (control) asphalt pavements. Five projects, each consisting of a recycled section and a control section, were subjected to detailed evaluation. In situ mix properties (such as percent air voids, resilient modulus, and indirect tensile strength), recovered asphalt binder properties (such as penetration, viscosity, $G^*/\sin\delta$, and $G^*\sin\delta$), and laboratory recompacted mix properties (such as gyratory stability index and confined, dynamic creep modulus) were measured. A paired *t*-test statistical analysis indicated no significant differences between these properties of virgin and recycled mix pavements that have been in service from 1½ to 2¼ years. Ten additional virgin mix pavements and 13 additional recycled pavements were also evaluated as two independent groups. No statistically significant differences were found between the recovered asphalt properties (penetration and viscosity) of these virgin and recycled pavements in service. The current GDOT recycling specifications and mix design procedures appear to be satisfactory based on the results of this study.

Hot-mix recycling of asphalt pavements is increasingly being used as one of the major rehabilitation methods by highway agencies throughout the United States. Besides saving in costs and energy, it also conserves natural resources. The Georgia Department of Transportation (GDOT) has been constructing recycled hot-mix asphalt (HMA) pavements routinely for about 4 years. Most of the recycled pavements in Georgia have been constructed using AC-20 asphalt cement, whereas virgin HMA pavements are generally constructed using AC-30 asphalt cement. The performance of these recycled pavements was evaluated in comparison to virgin HMA pavements constructed during the same period to determine similarities. This would also provide information for adjusting the specification and mix design method for recycled mixtures, if needed.

PRIMARY OBJECTIVES

The primary objectives of this project are as follows:

1. Evaluate the performance of the in-place recycled and virgin (control) HMA pavements from the same project both visually as well as in the laboratory;
2. Compare the performance of recycled HMA projects with that of virgin (control) HMA projects; and
3. Review GDOT's present recycling specifications and recommend changes where necessary.

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This study was divided into two tasks. Task 1 involved identifying existing field projects that have used both recycled and virgin (control) mixes on the same project and conducting a detailed comparative evaluation. Task 2 consisted of evaluating at least 10 recycled HMA pavements and at least 10 virgin mix pavements constructed independently throughout the state during the past 2 to 3 years. The properties of the binders recovered from the mixtures of these projects formed a data base for comparative purposes.

Each task involved collecting construction data of all the projects, visual evaluation of the in-place pavements, sampling, and extensive laboratory testing of the field cores taken from each project.

REVIEW OF LITERATURE

Research by Little and Epps (*1*), Little et al. (*2*), Brown (*3*), Meyers et al. (*4*), and Kandhal et al. (*5*) has indicated that the structural performance of recycled mixes is equal to and, in some instances, better than that of the conventional mixes.

The properties of the recycled mixture are believed to be mainly influenced by the aged reclaimed asphalt pavement (RAP) binder properties and the amount of RAP in the mixture. Kiggundu et al. (*6*) showed that mixtures prepared from the recycled binder blends generally age slower than virgin mixtures. This may be because the RAP binder has already undergone oxidation, which tends to retard the rate of hardening (*4,6*). Kiggundu and Newman (*7*) have indicated that the recycled mixtures withstood the action of water better than the virgin mixtures. Dunning and Mendenhall (*8*) have also shown that the durability of recycled asphalt concrete mixtures is greater than that of the conventional mixtures.

The amount of the RAP used in a recycled mixture depends on the type of hot-mix plant used for preparing the mix and also on environmental considerations. The specified maximum permissible amounts of RAP vary from state to state. GDOT limits the amount of RAP to 40 percent of the total recycled mixture for continuous type plants and to 25 percent for batch type plants (*9*). According to the specification, when blended with virgin asphalt cement, the RAP binder should give a viscosity between 6,000 and 16,000 poises after the thin film oven test.

SAMPLING AND TESTING PLAN (TASK 1)

Only five existing field projects could be identified for this task, which had both recycled and virgin HMA mixtures on the same project in the wearing course. The selection of these projects ensured that the recycled and the virgin sections (*a*) used the same virgin aggregates in the mixtures, (*b*) were produced by the same HMA plant, (*c*) were placed and compacted by the same equipment and crew, and (*d*) were subjected to the same traffic and environment during service.

The project details of both the recycled and the control (virgin) wearing course mixtures for the five projects are given in Table 1. As shown in the table, GDOT also uses AC-20 Special (designated as AC-20S), which is required to have a penetration range of 60 to 80.

The recycled and the control sections for all five projects were visited. A representative 150 m (500 ft) long test area was selected in each section for detailed evaluation. The pavement was visually evaluated for surface distress such as rutting; ravelling and weathering; alligator (fatigue) cracking; and transverse cracking.

A total of eight 101 mm (4 in.) diameter cores and four 152 mm (6 in.) diameter cores were obtained from each 150-m (500-ft) representative section from the outside wheel track. Cores were obtained at an interval of 30 m (100 ft).

Laboratory tests were conducted on the field cores according to the flow chart shown in Figure 1. All the field cores were sawed to recover only the recycled or the control (virgin) wearing course portion of the pavement.

The mix from the 152 mm (6 in.) diameter cores was reheated to 133°C (300°F) and recompacted in the laboratory using the U.S. Corps of Engineers Gyratory Test Machine (GTM). This was done to evaluate the rutting potential and shear properties of the recycled and the control mixes. Properties such as gyratory stability index (GSI), gyratory elasto-plastic index (GEPI), and roller pressure, which are discussed later, were determined as the mix was compacted. Air void contents of the compacted specimens were also obtained. Confined, dynamic creep tests were performed on the recompacted specimens at 60°C (140°F), 138 kPa (20 psi) confining pressure, and 828 kPa (120 psi) vertical pressure. Dynamic loading was applied for 1 hr and then the specimen was allowed to recover for 30 min.

The extraction of the aged asphalt cement from the HMA mixtures was accomplished by the ASTM D2172 (Method A) procedure using trichloroethylene. The asphalt cement from the solution was recovered using the Rotovapor apparatus as recommended by the Strategic Highway Research Program (SHRP). The recovered asphalt cement was tested for viscosity at 60°C (140°F) and penetration at 25°C (77°F). Also, the complex shear modulus (G*) and the phase angle (δ) of the recovered asphalt binder were determined using a dynamic shear rheometer (DSR) according to the AASHTO Performance Graded Binder Specification (MP1) for the state of Georgia. Test temperatures of 64°C (148°F) and 22°C (72°F) were used to determine the potential for rutting and fatigue cracking, respectively, as contributed by the binder.

TABLE 1 Project Construction Details (Task 1)

					Virgin Asphalt CementProperties			Mix Properties	
Site No.	County	Section	Age yrs	RAP %	Grade	Viscosity (60C) Pa·s	Pen. 25C	Asphalt Content (%)	% Air Voids (mat)
18C	Coffee	Virgin	1.50	0	AC-30	299	***	6.0	9.0
18R	Coffee	Recycled	1.50	15	AC-30	299	***	5.7	9.3
22C	Ware	Virgin	1.75	0	AC-30	270	***	6.0	6.6
22R	Ware	Recycled	1.75	10	AC-20S	191	***	5.7	6.9
23C	Chatham	Virgin	1.50	0	AC-30	281	***	***	***
23R	Chatham	Recycled	1.50	25	AC-20	199	***	5.4	6.5
25C	Emanuel	Virgin	2.25	0	AC-30	297	***	5.8	7.9
25R	Emanuel	Recycled	2.25	20	AC-20	206	***	5.7	7.4
28C	Columbia/ Richmond	Virgin	1.50	0	AC-30	305	***	6.0	8.3
28R	Columbia/ Richmond	Recycled	1.50	20	AC-30	305	***	5.8	7.8

*** Data not available

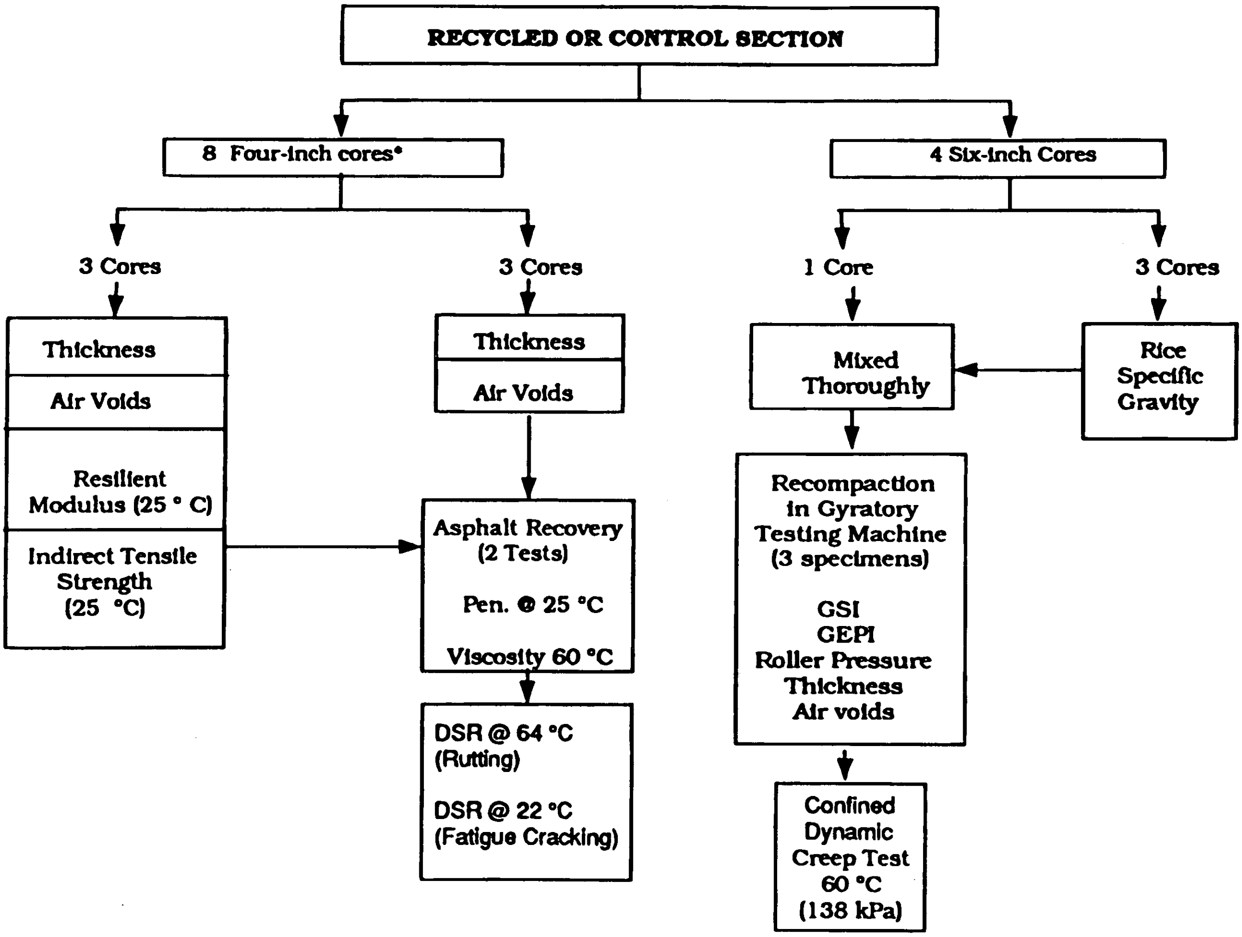

FIGURE 1 Core testing plan (Task 1).

The tests conducted on the 101 mm (4 in.) diameter field cores were (*a*) air void content, (*b*) resilient modulus at 25°C (77°F), and (*c*) indirect tensile test at 25°C (77°F).

TEST DATA (TASK 1)

As mentioned earlier, visual evaluation of the recycled and the control sections was carried out. A summary of the observations made during the pavement evaluation is presented in Table 2. These results were analyzed and quantified to compare the relative performance of recycled and control sections. Laboratory tests were conducted on the cores obtained from the project sites according to the testing plan shown in Figure 1.

In Situ Mix Properties

Figure 2 shows the test data obtained on the field cores from the five projects (both recycled and control sections). The test data include air void content, resilient modulus at 25°C (77°F), and indirect tensile strength at 25°C (77°F).

Recompacted Mix Properties

The mix obtained from the field cores was heated and recompacted in the GTM as mentioned earlier. Based on the experience of the National Center for Asphalt Technology, a vertical pressure of 828 kPa (120 psi) and a 1-degree initial gyration angle was used. The common gyratory indices and shear properties such as GSI, GEPI, and roller pressure were obtained (*10*).

Figure 3 gives the average recompacted mix properties such as air void content, GEPI, GSI, and roller pressure. Figure 4 shows the average test data obtained from the confined, dynamic creep tests.

Recovered Asphalt Binder Properties

The recovered asphalt cement was tested for penetration at 25°C (77°F) and absolute viscosity at 60°C (140°F). The results from these tests are shown in Figure 5. Two samples were tested from each section and, therefore, the test data reported are the average of two tests.

Because the main concern of this project is performance, it was necessary to determine the rheological properties of the recovered

TABLE 2 Pavement Surface Evaluation (Task 1)

Site No.	County	Mix Type	Average Rut Depth (Inch)	Ravelling & Weathering	Alligator Cracking	Transverse Cracking	Longitudinal Cracking	Other Surface Distress
18C	Coffee	Virgin	0.069	None	None	Low	None	WBL has more transverse cracks
18R	Coffee	Recycled	0.069	None	None	None	None	None
22C	Ware	Virgin	0.069	None	None	None	None	None
22R	Ware	Recycled	0.063	None	None	None	None	None
23C	Chatham	Virgin	0.044	None	None	None	None	None
23R	Chatham	Recycled	0.066	None	None	None	None	None
25C	Emanuel	Virgin	0.009	None	None	Low	Low (continuous)	Map Cracking
25R	Emanuel	Recycled	0.063	None	None	Low	Low (continuous)	Long. refl. crack
28C	Columbia/ Richmond	Virgin	0.013	None	None	None	None	None
28R	Columbia/ Richmond	Recycled	0.078	None	None	None	None	Open Surface Texture

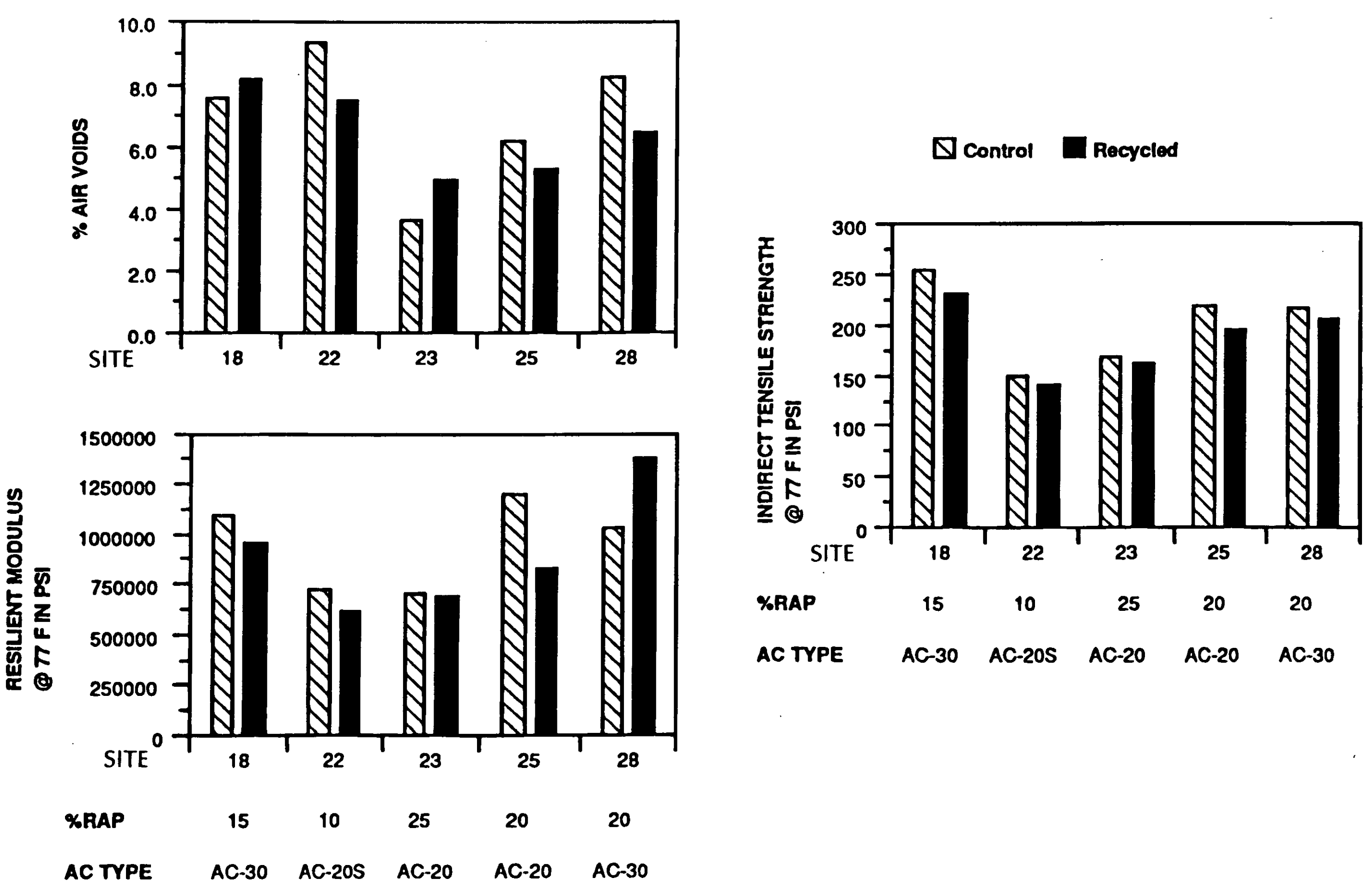

FIGURE 2 In situ mix properties (Task 1).

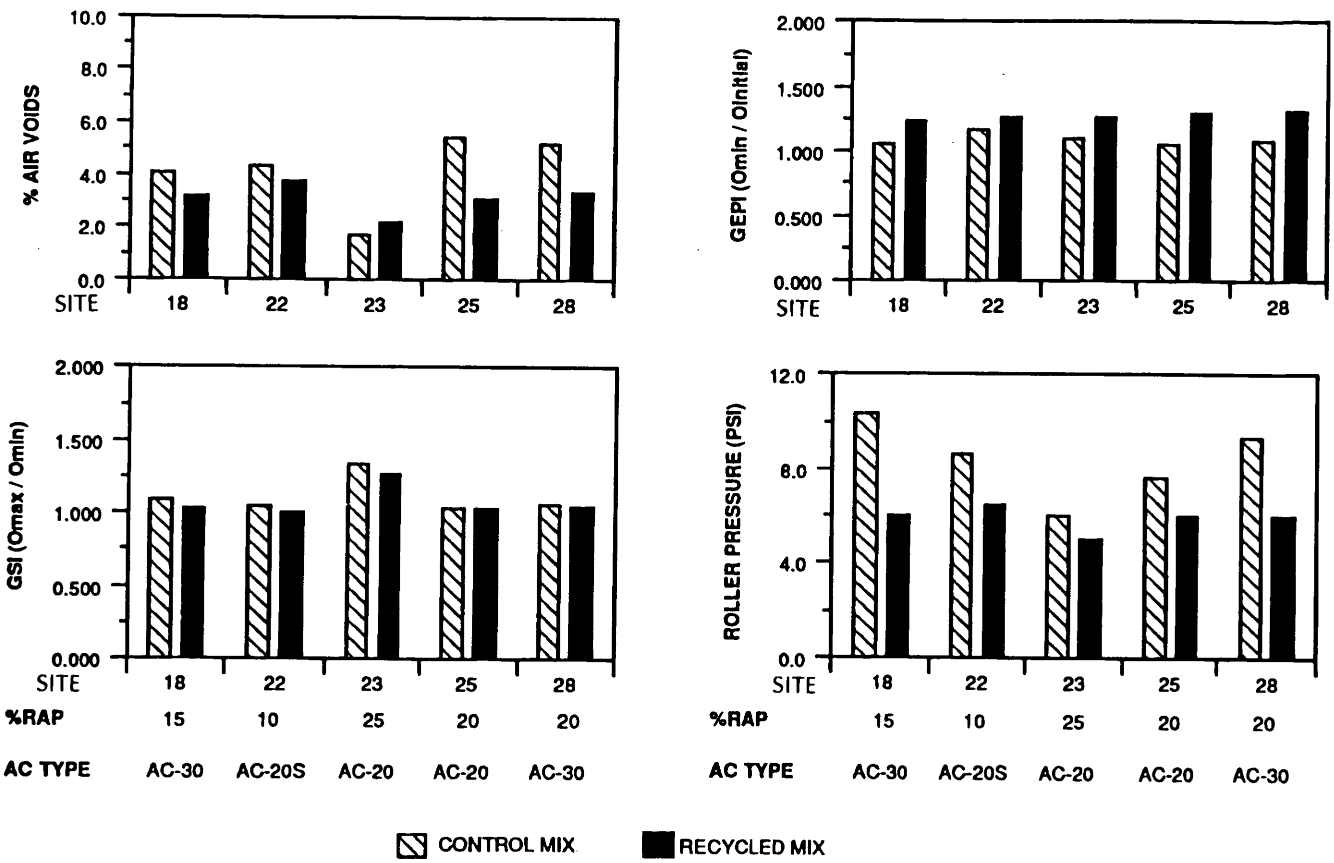

FIGURE 3 Recompacted mix properties (Task 1).

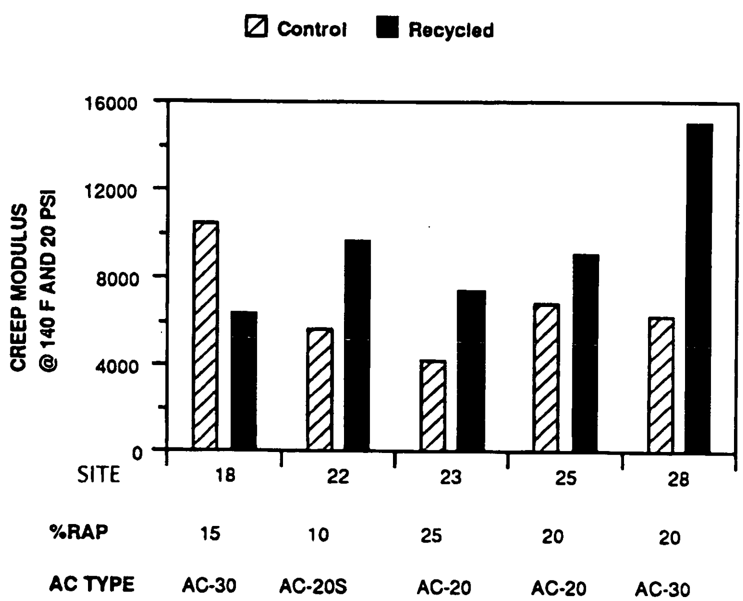

FIGURE 4 Creep modulus values (Task 1).

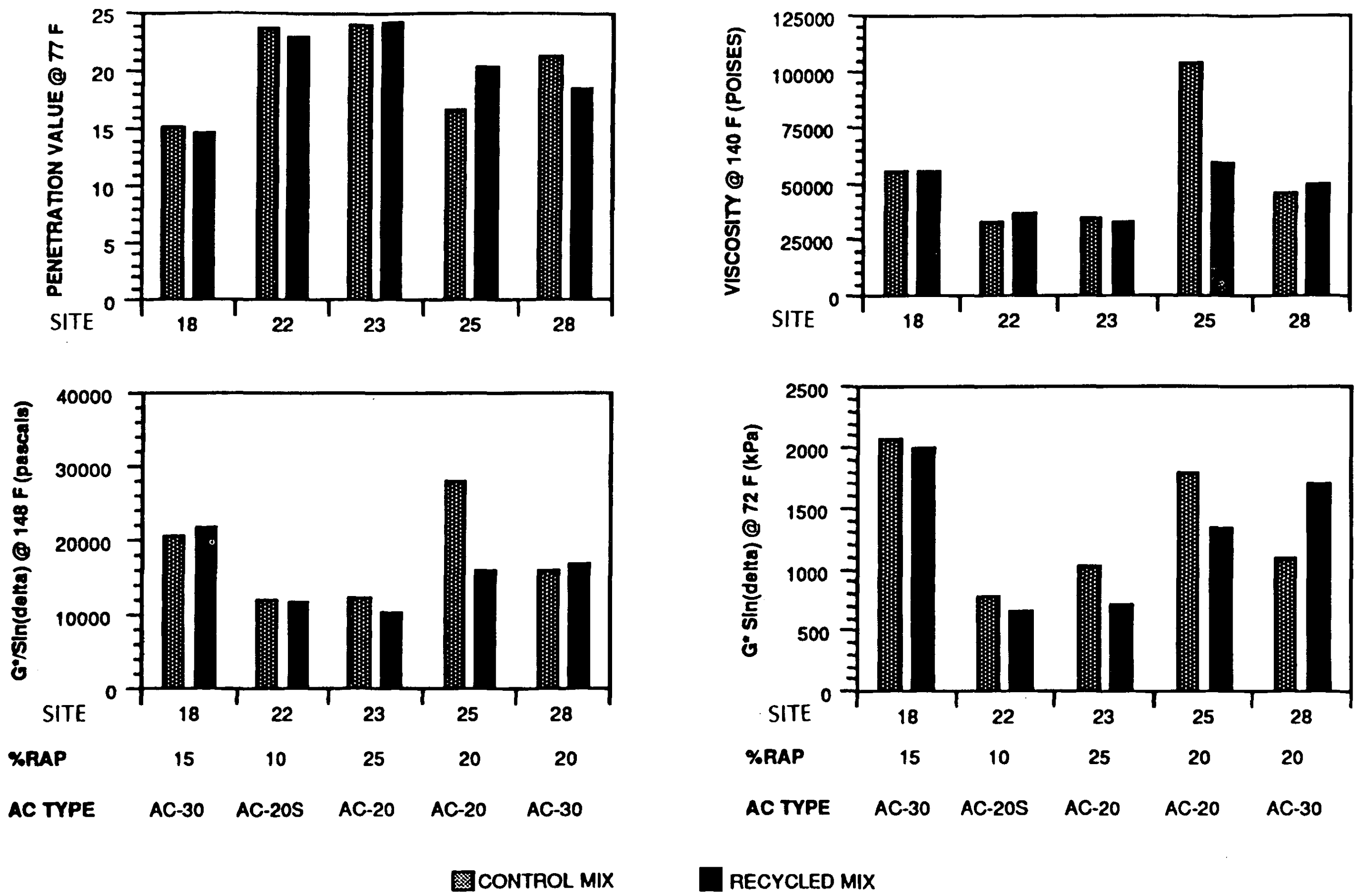

FIGURE 5 Recovered asphalt binder properties (Task 1).

binder using performance-based SHRP binder tests such as the dynamic shear rheometer (DSR). This testing was done using the SHRP asphalt binder specification proposed for the state of Georgia. The viscoelastic behavior of the recovered asphalt cement was characterized by measuring the complex shear modulus (G*) and the phase angle (δ) of the asphalt cement. G* is the ratio of the maximum shear stiffness (τ_{max}) to maximum shear strain (γ_{max}). The time lag between the applied stress and the resulting strain is the phase angle δ.

According to SHRP specifications, rutting potential or the permanent deformation of the mix is controlled by limiting the rutting factor G*/sinδ at high test temperatures to values greater than 2.2 kPa after rolling thin film oven test (RTFOT) aging. For this study, the specification test temperature for the state of Georgia for rutting was assumed to be 64°C (148°F) since the recommended SHRP paving grade that satisfies requirements for most of the geographical area of Georgia is PG 64-22. Higher rutting factors at 64°C (148°F) indicate better rutting resistance.

Fatigue cracking normally occurs at low to moderate temperatures. According to the SHRP specifications, it is controlled by limiting the fatigue cracking factor G*sinδ of the recovered asphalt binder to values less than 5,000 kPa at the test temperature. The test temperature for fatigue cracking in Georgia was assumed to be 22°C (72°F). The five pavement sections in Task 1 have been in service from 1½ to 3½ years, averaging about 2 years. The recovered asphalt binder is therefore expected to be softer than the corresponding pressure aging vessel (PAV) residue, which simulates 5 to 10 years in service. However, the fatigue factor can be used in this study to compare the potential fatigue behavior of the control and recycled sections. Lower fatigue cracking factors indicate better ability for the asphalt binder to dissipate stress without cracking.

Figure 5 shows the values of G*/sinδ and G*sinδ obtained for these five projects.

ANALYSIS OF TEST DATA (TASK 1)

A paired *t*-test is appropriate for analyzing the test data in Task 1 to determine if there is a significant difference between the test values obtained in recycled and control section. Task 1 consists of five pairs (projects), each pair consisting of one recycled and one control section. Average test values were used in the analysis. Table 3 gives the paired *t*-test results.

Visual Evaluation

The extent of distress was quantified and is reported elsewhere (*10*). No significant rutting, ravelling, or alligator cracking has occurred in any of the sites (Table 2). Rutting occurs when the HMA mix is too soft. Alligator (fatigue) cracking can occur if the HMA mix is too stiff or brittle. The overall pavement surface evaluation and rating indicates that both recycled and control sections are performing equally well after the average service life of about 2 years. It would

TABLE 3 Paired *t*-Test Results (Task 1)

	Property	Average of 5 Projects			Are Differences Significant at 5% Level?
		Control	Recycled	t calc[a]	
A.In-Situ Mix					
	Air Voids (%)	7.0	6.5	0.818	No
	Resilient Modulus @ 25C (MPa)	6,530	6,150	0.469	No
	Indirect Tensile Strength @ 25C (kPa)	1,393	1,289	3.994	Yes
B.Recompacted Mix					
	Air Voids (%)	4.1	3.1	2.022	No
	GSI	1.1	1.1	2.181	No
	GEPI	1.1	1.3	7.467	Yes
	Roller Pressure (kPa)	57.9	40.7	4.192	Yes
	Creep Modulus (MPa)	46.3	65.8	1.378	No
C.Recovered Asphalt					
	Penetration @ 25C (0.1 mm)	20	20	0.047	No
	Viscosity @ 60C (Pa·s)	5,466	4,688	0.850	No
	G*/Sin(delta) (kPa) @ 64C	17.9	15.4	1.012	No
	G* Sin(delta) (kPa) @ 22C	1,356	1,288	0.371	No

[a] t critical = 2.776 for 5 number of observations (sample size) at 5% level of significance

be interesting to revisit these test sections in the future to ascertain their relative performance.

In Situ Air Voids

The paired *t*-test analysis as reported in Table 3 indicates no significant difference between the air voids in recycled and control sections. Average air voids in the five projects are 7.0 and 6.5 percent, respectively, in control and recycled sections. Air voids significantly affect the rate of aging of asphalt binders in HMA pavements. High air voids accelerate the aging process. It is encouraging to know that the recycled sections do not have air voids higher than those in the control sections.

Recovered Asphalt Binder Properties

The paired *t*-test (Table 3) indicates no significant difference between the penetration of control and recycled sections. Among the five recycled sections, AC-20 or AC-20S asphalt cements have generally resulted in relatively higher penetration values compared with AC-30 asphalt cements (Figure 5). Sites 25 and 28 used the same amount of RAP (20 percent) but different grades of asphalt cements. Site 28 with AC-30 gave a lower penetration value than Site 25 with AC-20 asphalt cement. Site 18 has the lowest penetration of all the sites because this pavement had relatively higher air void content at the time of construction compared with the remaining pavements (Table 1).

The viscosity histogram shown in Figure 5 indicates comparable viscosity values for control and recycled sections in all sites except Site 25. Generally, the viscosity values are consistent with the penetration values. Except for Site 25, the use of AC-30 asphalt cement generally resulted in relatively higher viscosity values compared with AC-20 or AC-20S asphalt cements. The paired *t*-test (Table 3) indicates no significant difference between the viscosity of the control and the recycled sections.

The G*/sinδ (rutting factor) histogram shown in Figure 5 shows comparable values for control and recycled sections in all sites except Site 25. The paired *t*-test (Table 3) indicates no significant difference between the G*/sinδ values of the control and the recycled sections. This means the binders are equally resistant to rutting. It is interesting to note that the G*/sinδ histogram and the viscosity histogram have similar trends. Both tests were conducted at high temperatures: DSR at 64°C (148°F) and viscosity at 60°C (140°F). The viscous component of the complex shear modulus G*, therefore, appears to be dominant in the recovered asphalt cements.

The G* sinδ (fatigue cracking factor) histogram shown in Figure 5 indicates that all values are well below 5000 kPa as expected. The paired *t*-test (Table 3) indicates no significant difference between the G* sinδ values of control and recycled sections. This means they are equally resistant to fatigue cracking. The G* sinδ histogram is consistent with the penetration histogram (Figure 5) because both tests are conducted at very close temperatures. Again, the use of AC-30 asphalt cement (Sites 18 and 28) generally gave high G* sinδ values (more prone to fatigue cracking) compared with AC-20 or AC-20S asphalt cements. Site 18 has the highest G* sinδ value because this pavement had relatively high air void content at the time of construction, as mentioned previously.

In Situ Mix Properties

The resilient modulus histogram shown in Figure 2 indicates comparable values for control and recycled sections in all sites except 25 and 28. However, the paired *t*-test indicates no significant difference between the control and recycled sections when all five projects are considered in statistical analysis (Table 3). Since the resilient modulus is an indicator of the mix strength under dynamic loading, both control and recycled sections appear to have comparable structural strengths.

The indirect tensile strength histogram (Figure 2) shows that the tensile strength values of the control mixes are slightly higher than those of the recycled mixes in all the five sites. The paired *t*-test (Table 3) indicates a significant difference between the indirect tensile strength values of the control and the recycled sections. Because these projects are only 1½ to 2¼ years old, the implications of this test, if any, are not evident visually in the form of some distress.

Recompacted Mix Properties

The air voids histogram shown in Figure 3 indicates lower air voids in recycled sections (except Site 23) compared to corresponding control sections. However, if all five projects are considered, the paired *t*-test (Table 3) indicates no statistically significant difference between the control and recycled sections. Both control and recycled mixes in Site 23 were recompacted in the laboratory to very low air voids contents of 1.7 and 2.2 percent, respectively. This indicates a potential for rutting in the future if the site is subjected to heavy traffic loads. Site 23 has the lowest in situ air voids (Figure 2), but it has not rutted (Table 2) because the in situ air voids are currently more than 3.5 percent.

The GSI is a measure of the stability of the mix. GSI in excess of 1.00 indicates an increase in plasticity. The GSI histogram shown in Figure 3 indicates that the GSI values of the control and recycled mixes are comparable. It also indicates that Site 23 may be subject to rutting or plastic deformation. The paired *t*-test (Table 3) also indicates no statistically significant difference between the control and recycled mixes.

The GEPI is a measure of internal friction present in the mix. GEPI values near 1 are found in fresh stable HMA mix with low shear strain. The GEPI histogram shown in Figure 3 indicates consistently higher values for recycled mixes compared to control mixes. This means the recycled mixes have less internal friction compared to control mixes. This could be because 100 percent virgin aggregate particles have more interlocking effect than the recycled mix, which contains a mixture of virgin aggregate particles and RAP particles. The RAP particles are usually not as angular as virgin aggregate particles because of the milling operation. Also, the RAP particles are already coated with asphalt binder and therefore may not have a rough surface texture. The paired *t*-test (Table 3) indicates that the GEPI values of control and recycled mixes are statistically significantly different.

The roller pressure values measured during the GTM compaction procedure are shown in the histogram in Figure 3. It is evident from the histogram that the recycled mixes have lower roller pressure compared to control mixes in all cases. The paired *t*-test also indicates that the difference is statistically significant. The roller pressure is a measure of resistance to deformation of the mix. A higher roller pressure indicates greater resistance of the mix against deformation.

The creep histogram shown in Figure 4 indicates higher creep modulus (higher resistance to permanent deformation) for recycled mixes compared to control mixes in all sites except Site 18. However, the paired *t*-test (Table 3) shows that the differences are not statistically significant. The creep modulus data are unlike GEPI and GSI data, which showed that the recycled mixes have lower resistance to permanent deformation compared to control mixes. No significant rutting has been observed in the field in recycled and control sections as yet (Table 2).

SAMPLING AND TESTING PLAN (TASK 2)

This task consisted of evaluating 13 projects involving only the recycled wearing courses and 10 projects involving only virgin mix wearing courses constructed generally during the same period throughout the state of Georgia. The results obtained from these projects (combined with those from Task 1) formed a data base for determining general trends in the characteristics and performance of recycled mixes compared with virgin mixes used in the wearing courses.

Visual evaluation of all projects in Task 2 was performed as in Task 1. Surface distresses such as rutting and cracking were measured and quantified. Four 152 mm (6 in.) diameter cores were obtained at an interval of about 30 m (100 ft) from the representative test area for further laboratory testing. The cores were obtained from the outside wheel track area.

The field cores were sawed to separate the top recycled or the virgin mix layer for the testing. After determining the density (and therefore air void content) of the cores, asphalt cement was extracted and recovered from the cores after the procedures mentioned in Task 1. Penetration at 25°C (77°F) and viscosity at 60°C (140°F) of the recovered asphalt cements was then determined.

TEST DATA (TASK 2)

The projects selected in Task 2 consisted of pavements throughout Georgia that were constructed using either the recycled mix or the virgin mix. Specific recycled project details are given in Table 4. Visual pavement surface evaluation of these pavements was conducted at the beginning of the project. The observations are given

TABLE 4 Specific Recycled Projects Details (Task 2)

Virgin Asphalt Grade	No. of Projects	Specified Penetration	Supplied Penetration	% RAP Used	Age of pavement (years)
AC-10	2	80+	98-123	40	3.50
AC-20	10	60+	82-93	10 - 30	1.5 - 3.0
AC-20S	4	60 - 80	67-84	10 - 25	1.25 - 5.0
AC-30	2	60+	—	15 - 20	2.0 - 3.5

elsewhere (*10*). Most of the virgin and recycled pavements did not exhibit any distress at this time and performed comparably.

Bulk-specific gravity of the cores was determined to calculate the air void content. As in Task 1, asphalt cement was recovered from the field cores. Penetration and viscosity of the recovered asphalt binder were determined.

Figure 6 shows the range and average of the test data on in situ air void content, penetration, and viscosity for virgin and recycled pavements.

ANALYSIS OF DATA (TASK 2)

The Task 2 part of the study involved the evaluation of 15 independent virgin mix pavements and 18 independent recycled mix pavements to obtain a test data base for comparison. These projects are located throughout the state of Georgia. It should be noted that many variables (such as the percentage and properties of RAP used, grade of the virgin asphalt cement, and age of the pavement) are involved in the 18 recycled mix projects shown in Table 4.

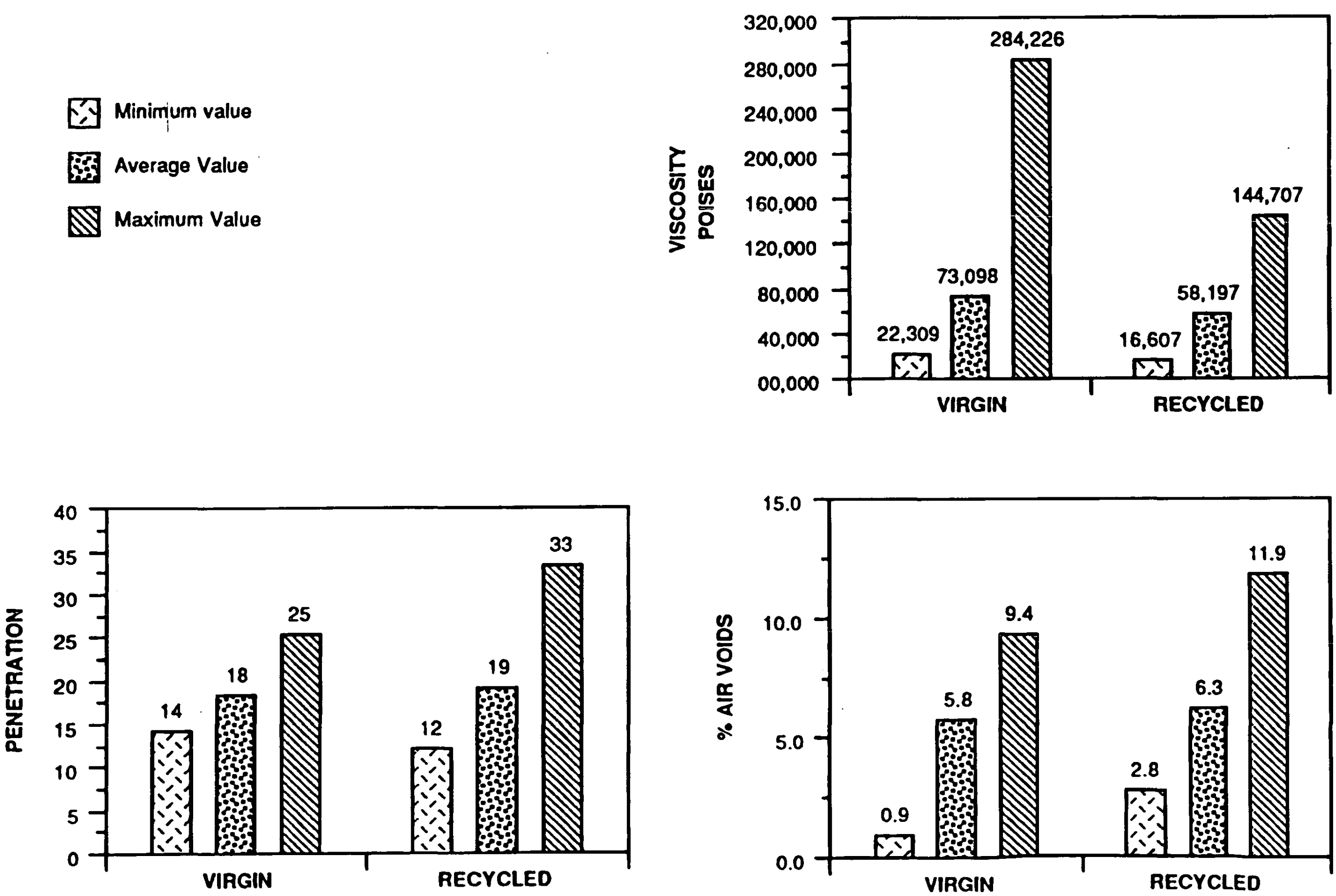

FIGURE 6 Histograms of percent air voids, penetration, and viscosity (Task 2).

Because of these variables, the recovered asphalt cement properties are expected to vary significantly. Pavement surface evaluation ratings of virgin mix pavements and recycled mix pavements are given elsewhere (*10*). There was no significant overall difference in the performance of virgin and recycled pavements at the time of inspection (Jan.–Feb. 1993).

The test data (air voids, penetration, or viscosity) obtained in Task 2 can be treated as two independent groups (virgin mixes and recycled mixes) of unequal sizes (15 virgin and 18 recycled mixes). One of the objectives of this study is to determine whether the characteristics of the recycled mixes are significantly different from those of the virgin mixes. This can be accomplished by performing statistical analysis using the independent samples *t*-test for testing the equality of means of percent air voids, penetration, and viscosity data at 5-percent level of significance. It is assumed that the sample means are reasonable estimates of their respective population means. Table 5 gives the results of the statistical analysis.

In Situ Mix Properties

The air voids histogram given in Figure 6 shows the minimum, average, and maximum values of air voids in virgin and recycled pavements. The average in situ air voids in virgin and recycled pavements are 5.8 and 6.3 percent, respectively. The *t*-test analysis (Table 5) indicates no statistically significant difference between the air voids of virgin and recycled pavements at the time of core sampling.

Recovered Asphalt Binder Properties

The penetration histogram showing the minimum, average, and maximum values of penetration in virgin and recycled pavements is also given in Figure 6. The average penetration values of virgin and recycled pavements are 18 and 19, respectively. The *t*-test analysis (Table 5) indicates no statistically significant difference between the penetration value of the two pavement types.

The average viscosity values of virgin and recycled pavements are 73,098 and 58,196 poises, respectively, as shown in the viscosity histogram (Figure 6). The *t*-test analysis indicates no significant difference between the viscosity values of the two pavement types.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from this study.

1. Both virgin and recycled sections of the five projects in Task 1 are performing satisfactorily after 1½ to 2¼ years in service with no significant rutting, ravelling and weathering, and fatigue cracking.
2. The differences between the following properties of virgin and recycled sections of Task 1 projects were found to be not statistically significant at a 5-percent level of significance based on paired *t*-tests.
   –In situ mix properties such as percent air voids and resilient modulus at 25°C (77°F).
   –Aged asphalt binder properties such as penetration at 25°C (77°F), viscosity at 60°C (140°F), SHRP rutting factor $G^*/\sin\delta$ at 64°C (148°F), and SHRP fatigue cracking factor $G^* \sin\delta$ at 22°C (72°F).
   –Recompacted mix properties such as percent air voids, GSI, and confined dynamic creep modulus at 60°C (140°F).
3. The differences between the indirect tensile strength at 25°C (77°F), the GEPI, and the roller pressure values of virgin and recycled sections of Task 1 projects were found to be statistically significant at a 5-percent level of significance.
4. Task 2 pavements were treated as two independent groups (virgin mixes and recycled mixes) of unequal sizes (15 virgin and 18 recycled mixes) for statistical analysis. Independent samples *t*-test was used for testing the equality of means of percent air voids, penetration, and viscosity of the two groups. No statistically significant difference was found in these three properties of virgin and recycled pavements at a 5-percent level of significance.
5. There was no significant overall difference in the performance of virgin and recycled pavements based on visual inspection.
6. Based on the evaluation of Task 1 and Task 2 pavements, it can be concluded that the recycled pavements are generally performing as well as the virgin pavements. Therefore, it can be implied that the existing GDOT recycling specifications, recycled mix design procedures, and quality control are satisfactory. The specification to achieve a viscosity of 6,000 to 16,000 poises for the blend (RAP binder + virgin binder) appears reasonable based on the present data.
7. Some selected virgin and recycled pavements (especially those included in Task 1) should be reevaluated after another 2 to 3

TABLE 5 Testing Equality of Means by *t*-Test (Task 2)

Property	Sample Size		Average		Standard Deviation		t calc	t critical	Are Differences Significant at 5% Level?
	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled			
In-Situ Air Voids (%)	14	18	5.8	6.3	2.27	2.34	0.62	2.040	No
Penetration at 25C (0.1 mm)	15	18	18.3	19.1	3.7	5.0	0.51	2.037	No
Viscosity at 60C (Pa·s)	15	18	7,310	5,820	7,150	3,330	0.79	2.037	No

years of service. This should include pavement surface evaluation and determination of aged asphalt properties of the same representative section used in this study.

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