Use of Ground Tire Rubber in Asphalt Concrete Pavements— A Design and Performance Evaluation

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North Carolina State University, with support from the North Carolina Department of Transportation, has explored the design and performance of two types of rubberized pavements: ground rubber mixed with an asphalt binder at elevated temperatures (wet process) and rubber mixed with a gap-graded aggregate before the addition of asphalt cement (dry process). The wet process mixtures contained 11 percent ground tire rubber by weight of the binder. The dry process mixtures incorporated 2 percent ground tire rubber by weight of the aggregate. The Marshall and the Corps of Engineers gyratory testing machine (GTM) procedures were used to design conventional dry process and wet process surface course mixtures. These mixtures were tested with respect to resilient modulus, creep, and fatigue to obtain input parameters for a computerized performance prediction model. The addition of rubber was found to increase asphalt demand by 0.5 percent for the dry process and 1.5 percent for the wet process. The performance model estimated that the new rubberized pavement systems would have shorter service lives compared to a new conventional pavement system. When the wet process mixture was used to overlay a distressed conventional system, it performed as well as an equal thickness of a conventional overlay.

Federal mandates on the use of ground tire rubber in asphalt pavements have forced many state highway agencies to explore the feasibility of several types of asphalt-rubber combinations. North Carolina State University, with funding from the North Carolina Department of Transportation (NCDOT), has explored the design and performance of two types of asphalt rubber combinations: ground rubber introduced in the binder at elevated temperatures (wet process), and rubber granules mixed with a gap-graded aggregate before the addition of the binder (dry process). The optimum asphalt contents for the rubberized mixtures were determined using a modified Marshall procedure as well as the Corps of Engineers gyratory testing machine. After the optimum asphalt contents were determined, the rubberized mixtures were characterized in terms of resilient modulus, diametral fatigue, and incremental static (creep) testing. Owing to cost and time constraints, a computer performance prediction model was used instead of a full-scale field test to compare performance of the conventional and rubberized pavements. Performance of six different conventional and rubberized pavement systems was investigated, including new and rehabilitated pavements.

The use of ground tire rubber in asphalt pavements has shown promise in previous studies (*1–5*). The addition of rubber has been found to reduce temperature susceptibility and increase the ductility, resiliency, flexibility, and fatigue life of paving mixtures. The introduction of rubber to conventional mixtures has also been shown to increase asphalt demand in most cases. Field tests have shown that rubberized mixtures can exhibit less fatigue cracking and rutting than equal thicknesses of conventional pavements.

The specific objectives of this research were

1. To design the rubberized mixtures using the Marshall and GTM design procedures.
2. To characterize the rubberized mixtures in terms of resilient modulus, creep, and fatigue.
3. To compare the performance of the rubberized and conventional mixtures using a computerized performance prediction model.

MATERIALS

The aggregate used for this study was a 100 percent manufactured granite supplied by the Martin Marietta Company. Before the aggregate was used in the fabrication of test samples, it was dried overnight at 148.9°C, sieved into size fractions, and recombined using a standard or modified North Carolina surface course gradation. The gradation used for the wet process surface mixtures was a standard heavy duty surface (HDS) gradation, shown in Figure 1. The dry process gradation was gapped in the No. 8 to No. 50 sieve size range. Gapping the aggregate for the dry process mixtures was considered necessary in order to maintain sufficient air voids.

The rubber was supplied by BAS Engineering of Irvine, California. The rubber appeared to be angular with a smooth texture and was free from steel belts, cords, or other contaminants. It was easily sieved into size fractions using the same procedure as for the aggregate, and recombined using the gradations shown in Table 1. The rubber gradations in the wet and dry processes were suggested by TAK Engineering, a consulting firm with experience in asphalt-rubber applications. The amount of rubber used in the dry process mixture was 2 percent by weight of the aggregate.

The asphalt cement was graded as AC-20, and verified using the absolute and kinematic viscosity tests (ASTM 2170, 2171). The wet process binder was produced in the laboratory in 1-gal batches and contained 11 percent rubber by the total weight of the binder. The gradation of the rubber used in this process is shown in Table 1. An extender oil and reaction catalyst was also added at 7 percent and at 2 percent by total weight of the total binder, respectively. The procedure used for combining the ingredients of the wet process binder is as follows:

1. The base asphalt was heated to 176.7°C.
2. The extender oil was added to the asphalt and mixed for 2 min at medium shear (800 rpm).

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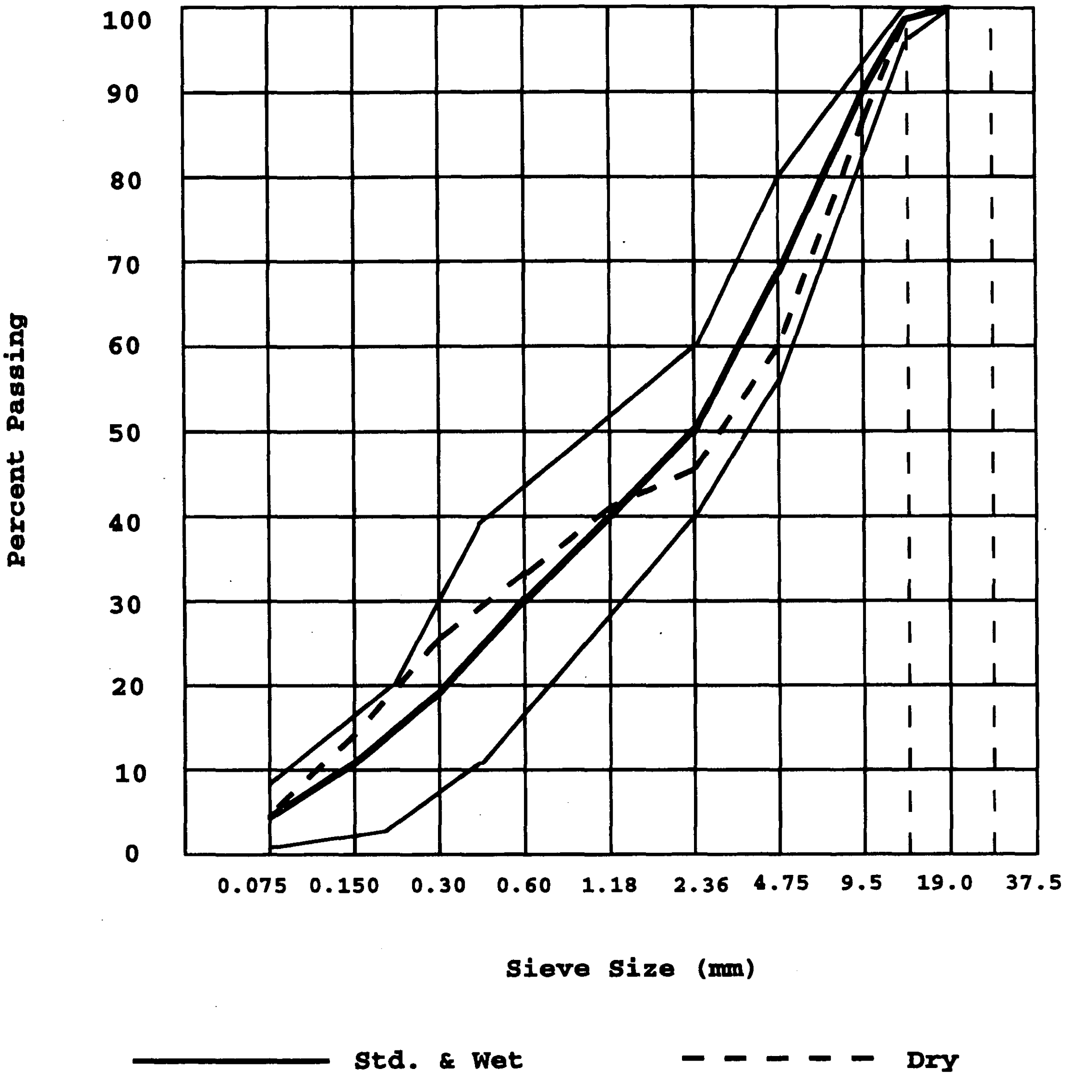

FIGURE 1 HDS specifications and gradations used.

3. The catalyst was added to the asphalt and mixed at medium shear for 10 min.
4. The rubber was added to the asphalt and mixed for 90 min at medium shear.

The wet process mixture had a texture that made it easily distinguishable from the conventional binder. The viscosity of the wet process binder seemed to be higher than the AC-20, but no formal viscosity test data are available. The coarse texture of the wet process binder made the validity of a conventional viscosity test doubtful. The rubber particles did not dissolve completely in the asphalt cement, causing blockages in the viscosity tubes and making the test results highly variable.

TABLE 1 Rubber Gradations

Sieve Size	Wet Process % Passing	Dry Process % Passing
#4	100	100
#8	100	90
#16	100	50
#30	75	40
#50	50	20
#80	10	-

SPECIMEN FABRICATION

Owing to the nature of the rubber materials, several modifications in the standard specimen fabrication procedures were made. The conventional samples were mixed at 148.9°C and compacted at a minimum of 140.5°C. The binder in the wet process samples was found to coat the aggregate better if mixed at 176.7°C. The densities of the wet process samples were also found to be adequate if compacted at 140.5°C. Mixing of the dry process specimens consisted of several steps to avoid excessive smoking and burning of the rubber particles. The rubber, which was at room temperature, was dry mixed with aggregate at 176.7°C for 30 sec. The aggregate and rubber were then placed in a 176.7°C oven for 5 min. The binder, which was heated to 148.9°C, was then added to the aggregate and rubber and mixed for 150 sec. After being cured for 1 hr at 148.9°C, the mixture was compacted at a minimum temperature of 140.5°C. The samples were either compacted with the Marshall hammer (75 blows) or gyratory testing machine (826.8 kPa, 1° angle, 60 revolutions), depending on the design method. Marshall size (6.35 cm × 10.16 cm) cylindrical samples were used for both design methods.

MIXTURE DESIGN

Marshall Method

The Marshall samples were tested for Marshall stability and flow following ASTM D1559, and the air voids were determined using ASTM D2726 and D2041. The procedure for the selection of the optimum asphalt content using the Marshall method was modified from that most widely used (*6*). If the requirements for stability, flow, and voids in mineral aggregate (VMA) were met, the asphalt content that yielded 5 percent air voids was selected as the optimum. This method for selecting the optimum asphalt content, currently used by NCDOT, produces samples with void contents similar to those in new pavements. The selection of a high initial air void content is thought to reduce wheel track bleeding due to traffic. The optimum asphalt contents, determined using this modified Marshall procedure, are shown in Table 2. The properties measured at the optimum asphalt content for the Marshall mixtures are shown in Table 3.

Gyratory Testing Machine (GTM)

The determination of the optimum asphalt content using the gyratory testing machine (GTM) was performed in accordance with ASTM D3387. The optimum was generally selected by averaging the asphalt contents that yielded the maximum unit weight, gyratory shear (Sg) or gyratory shear factor (GSF), and gyratory compactibility index (GCI). The optimum asphalt content was limited by the gyratory stability index (GSI), which must be less than or equal to 1.00. Mixtures with a GSI larger than 1.00 are considered unstable due to the binder overfilling the voids, resulting in loss of aggregate interlock and strength. The optimum asphalt contents for all mixtures, as determined by the GTM, are shown in Table 2. The properties at optimum asphalt content are shown in Table 4.

From Table 2 it can be seen that the asphalt demand for the dry process mixtures increased 0.5 to 0.8 percent over that required by the conventional mixture. The increase in asphalt content was larger for the wet process mixture. In this case the asphalt demand increased 1.5 percent. This large increase in binder demand for the wet process may be due to the fact that the wet process binder contains only 80 percent asphalt cement by weight. The actual amount of asphalt cement in the wet process mixtures is 5.25 percent, which is similar to the asphalt content of the conventional mixtures. The recommended optimum asphalt contents were based on the GTM design because the GTM's ability to measure the compaction stability of a mixture was considered important in the design of rubberized mixtures. The GTM was also used to fabricate the specimens for the mixture characterizations because this method of compaction was also thought to better represent field compaction than the Marshall method.

TABLE 2 Optimum Asphalt Contents

	% Asphalt Total Weight		
Design Method	**Standard**	**Dry Process**	**Wet Process**
GTM	5.0	5.5	6.5
Marshall	5.1	5.8	6.6
Recommended	**5.0**	**5.5**	**6.5**

TABLE 3 Marshall Mixture Design Properties at Optimum Asphalt Content

Property	Standard	Dry Process	Wet Process
Unit Weight (kg/m^3)	2298.6	2250.6	2221.8
Stability (kN)	15.5	13.7	12.3
Flow (0.25 mm)	10.8	12.5	11.2
Air (%)	5.0	5.0	5.0
Tensile Strength (MPa)	1.54	1.27	1.12

From Table 3, it may be noted that the rubberized mixtures generally had lower Marshall stability, tensile strength, and unit weight values than the conventional mixtures while the VMA and flow increased. The rather large decrease in unit weight values for the rubberized mixtures, compared to the conventional mixture, is most probably caused by the increases in asphalt content of the rubberized mixtures. In the dry process, the unit weight decrease could be due to the specific gravity of the rubber being lower than the aggregate it displaces. The increase in asphalt demand, and subsequent reduction in aggregate interlock, may explain the reductions in Marshall stability, tensile strength, and resilient modulus values found in the rubberized samples. The presence of rubber in the aggregate matrix may produce "weak links," which could also reduce the strength of the rubber mixtures. From Table 4, it may be noted that the dry process mixtures had larger Sg and GSF values compared to the conventional and wet process mixtures. In the GTM design, the unit weights of the rubber mixtures were also lower than those of the conventional mixture. The unit weights here could be thought

TABLE 4 Gyratory Mixture Design Properties at Optimum Asphalt Content

Property	Standard	Dry Process	Wet Process
Unit Weight (kg/m^3)	2378.7	2337.1	2338.7
GCI	0.981	0.983	0.987
Shear (kPa)	414.8	822.7	312.1
GSF	1.6	2.82	1.18
GSI	1.02	1.00	1.00
Tensile Strength (MPa)	1.70	1.55	1.10

of as representing those found at the end of a pavement's service, explaining the increase in unit weights here compared to those in the Marshall design.

Mixture Characterization

The mixture characterization was performed to obtain input for the VESYS—3AM performance prediction model and all tests were performed in accordance with the VESYS manual (*7*). The resilient modulus tests were performed in the indirect tensile mode on all mixtures at 4.4°, 21.1° and 37.8°C using a Retsina Mark IV pneumatic resilient modulus device. The deformations were measured using linear variable displacement transducers (LVDTs) and a strip chart recorder. The procedure for the test was similar to ASTM D4123 with a loading time of 0.1 sec and rest period of 2.9 sec. The sample sizes used for the tests were 10.16 cm in diameter and 6.35 cm in height. The resilient modulus was calculated using the following equation:

$$M_r = \frac{P(0.2734 + \mu)}{td}$$

where

M_r = resilient modulus (MPa),
P = applied load (N),
μ = Poisson's ratio (assumed here as 0.35),
t = sample thickness (mm), and
d = recoverable deformation (mm).

The results of the resilient modulus testing are shown in Figure 2. It can be seen from this figure that the conventional mixture had the highest resilient modulus of all the mixtures at all test temperatures. The difference between the resilient modulus for the conventional and rubberized mixtures decreases with increasing temperature. This may mean that the addition of rubber affects the temperature susceptibility of the mixtures.

The fatigue tests were performed at 21.1°C on the surface mixtures. These tests were performed even though the VESYS prediction model only requires the fatigue parameters for the lowest asphalt layer in a pavement system. The sample size used for the fatigue tests was the same as used in the resilient modulus tests. The fatigue tests were performed on an MTS model 810 in the indirect tensile mode and with computerized data acquisition. The total strain at the 200th cycle, called the initial total strain, and the cycles to failure were measured for all samples. Different stress levels were used to produce failures of the samples ranging from 1,000 to 100 000 loading cycles. Failure of the samples was defined as a total deformation exceeding 3.81 mm. The initial strain and cycles to failure were plotted for the mixtures, as shown in Figure 3. The following fatigue model was then developed for all the mixtures:

$$N_f = K1\left(\frac{1}{\varepsilon}\right)^{K2}$$

where

N_f = cycles to failure,
ε = initial total strain,
$K2$ = inverse of the absolute value of the slope of the regression line,
$K1$ = $100\,(I)^{K2}$, and
I = initial total strain causing failure at 100 cycles.

The parameters $K1$ and $K2$, shown in Table 5, were used only for fatigue model comparison because the VESYS model does not require the fatigue parameters of the surface course. From Figure 3 it can be seen that rubberized mixtures performed better than the conventional HDS mixture. The models for the rubber samples are similar, with the dry process performing slightly better than the wet process.

The incremental static loading (creep) tests were also performed at 4.4°, 21.1° and 37.8°C in accordance with the VESYS manual (*7*). The test consisted of axially loading a cylindrical sample for 0.1, 1.0, 10, 100, and 1,000 sec. The permanent deformation after each incremental loading interval was summed and denoted as the accumulated permanent strain for a given loading time. The accumulated permanent strains and loading time were plotted as shown in Figures 4, 5, and 6. A cyclic load of 0.1 sec duration and 2.9 sec

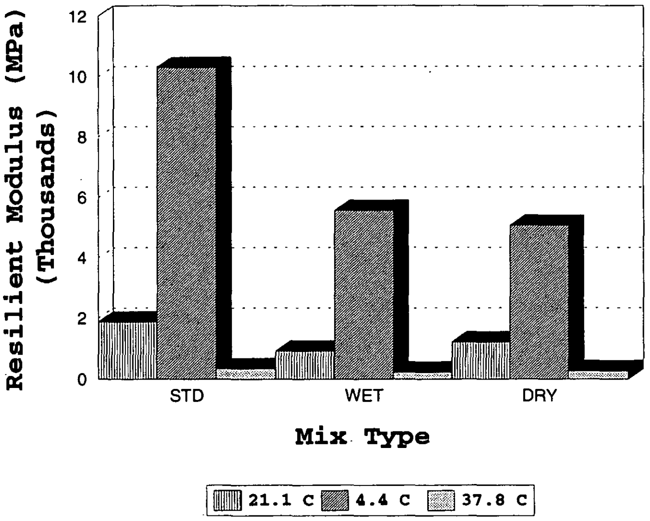

FIGURE 2 Resilient modulus test results.

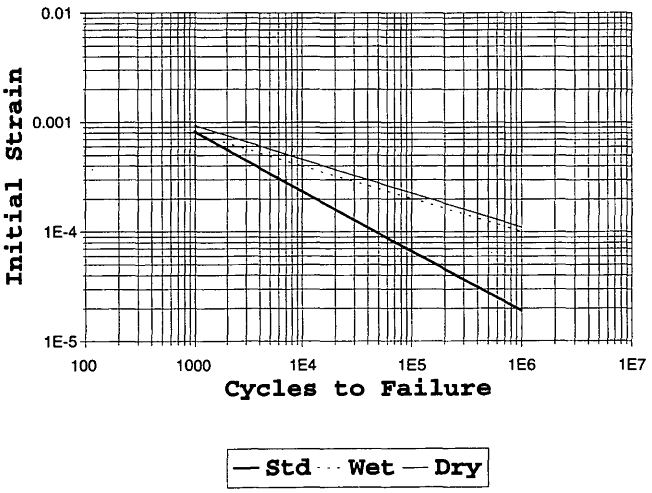

FIGURE 3 Fatigue test results.

TABLE 5 Fatigue Parameters for Surface Course Mixtures

Parameter	Standard	Dry Process	Wet Process
K1	2.15×10^{-3}	1.44×10^{-7}	3.63×10^{-8}
K2	1.84	3.25	3.36

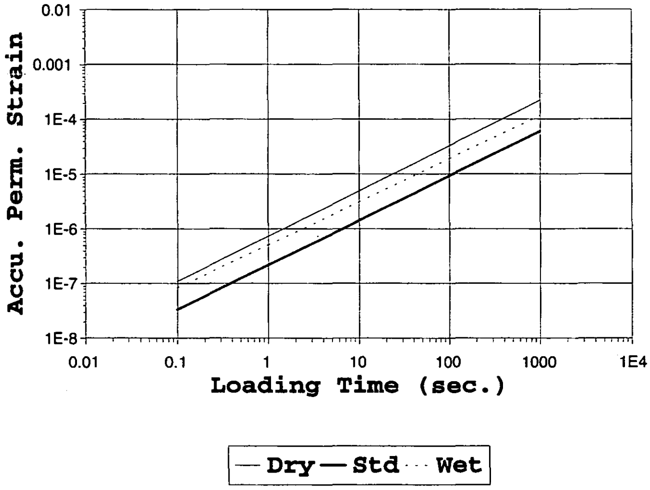

FIGURE 4 Creep test results—4.4°C

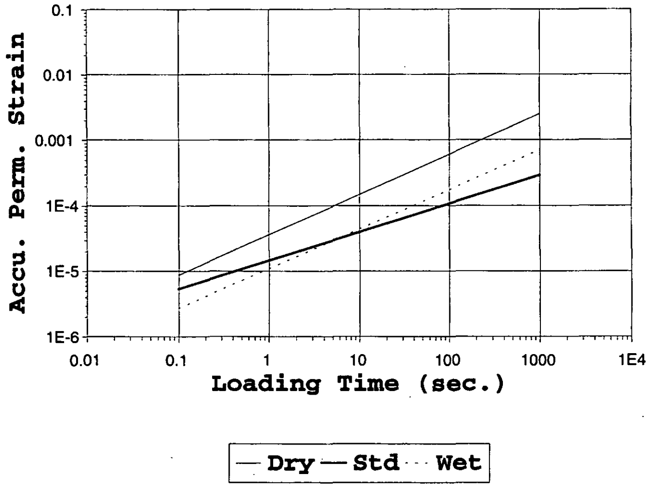

FIGURE 5 Creep test results—21.1°C.

rest was also applied after the last incremental loading of 1,000 sec to obtain the recoverable strain. From these plots the creep parameters Alpha and GNU were calculated as follows:

$$\text{Alpha} = 1 - S$$

$$\text{GNU} = \frac{IS}{\varepsilon_r}$$

where

I = permanent strain corresponding to a creep load of 0.1 seconds,
S = slope of the regression line, and
ε_r = recoverable strain due to a cyclic load.

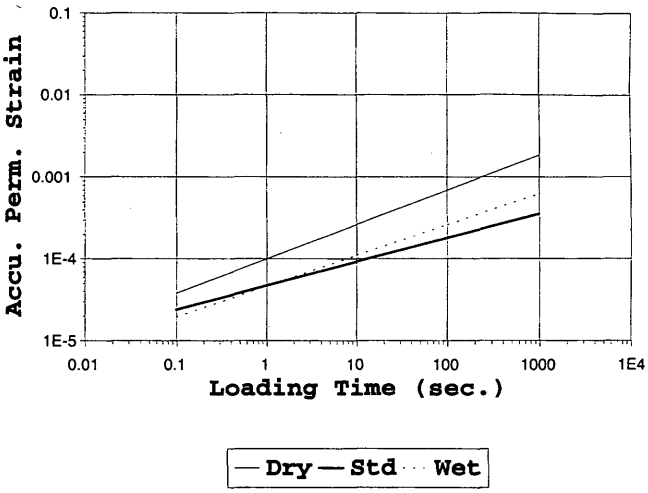

FIGURE 6 Creep test results—37.8°C.

A list of the Alpha and GNU parameters is shown in Table 6. From Figures 4 through 6, it can be seen that the dry process surface mixture had the highest permanent strain at all loading times and at all test temperatures. The conventional and wet process mixtures had similar creep lines. However, crossing of the creep lines suggests that the permanent strain for a given mixture depends on the temperature and the loading time.

Performance Predictions

The six pavement systems analyzed are shown in Figures 7 and 8. The new construction systems 1 through 3 contain an aggregate base course (ABC), a conventional binder layer, and a conventional wet process or dry process surface mixture. The mechanistic parameters for the conventional binder, aggregate base course, and clay subgrade were determined in a previous study (*8*) and are given in Table 7. The traffic was set at 300 ESALs per day with a 15.24 cm tire contact radius and 826.8 kPa tire pressure for all systems. The average seasonal pavement temperature was 4.4°C for winter, 37.8°C for summer and 21.1°C for spring and fall. The initial present serviceability index (PSI) was set at 4.6 and the terminal PSI at 2.5. As shown in Figure 8, the equivalent effective thicknesses of the distressed layers, used for the rehabilitated systems, were estimated to be ½ and ⅔ of the original thicknesses of the surface and binder course layers, respectively. An overlay thickness of 5.1 cm was used for the rehabilitated systems. The predicted service lives for all the new construction and rehabilitation systems are shown in Figure 9. The new conventional system had the longest service at 11.4 years. The new wet process system had a service life of

TABLE 6 Creep Parameters for Surface Course Mixtures

Parameter	Standard	Dry Process	Wet Process
Alpha(4.4°C)	0.0071	0.0031	0.0045
Alpha(21.1°C)	0.0358	0.0237	0.0193
Alpha(37.8°C)	0.0335	0.0282	0.0197
GNU(4.4°C)	0.1830	0.1730	0.2140
GNU(21.1°C)	0.5650	0.3960	0.3860
GNU(37.8°C)	0.6230	0.7050	0.5780

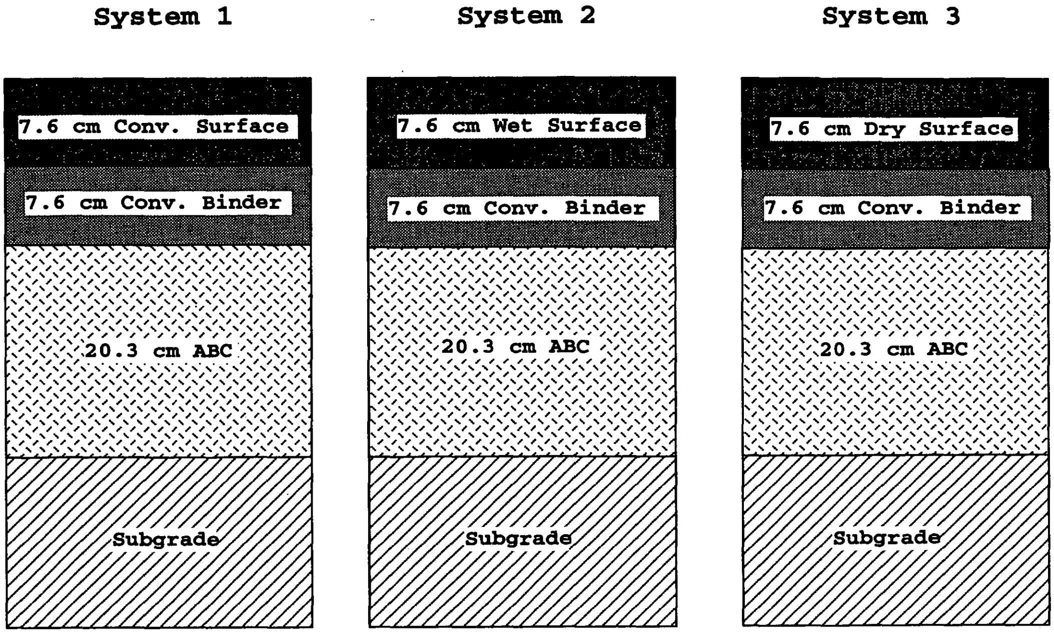

FIGURE 7 New construction systems 1, 2, and 3.

7.8 years, while the new dry process system had a service life of 5.0 years. The conventional and wet process overlays of conventional pavements had similar service lives at 8.2 and 8.0 years, respectively, while the dry process overlay had a service life of 6.2 years.

CONCLUSIONS

From the results of this investigation the following specific conclusions can be drawn:

- The addition of rubber to these asphalt concrete mixtures increased the asphalt demand. The gyratory testing machine predicted asphalt contents for the dry and wet process that were 0.5 and 1.5 percent higher, respectively, than those for the conventional mix. Since the GTM is able to predict the compaction stability of the mixtures, it was judged to be better suited for the design of rubber mixtures than the modified Marshall procedure.
- The fatigue models developed for the mixtures suggest that the rubber mixtures may be more resistant to fatigue cracking. However, the VESYS model predicted that the pavement systems containing rubberized asphalt surface layers failed in fatigue earlier than the conventional systems. Since a conventional binder course was used as the lowest asphalt layer for all of the systems in the VESYS analysis, these results indicate that the rubberized surface mixtures are less able to resist fatigue crack initiation and propagation than the conventional HDS mixture.
- The creep models developed for the mixtures suggest that the rutting performance of the wet and conventional mixtures is simi-

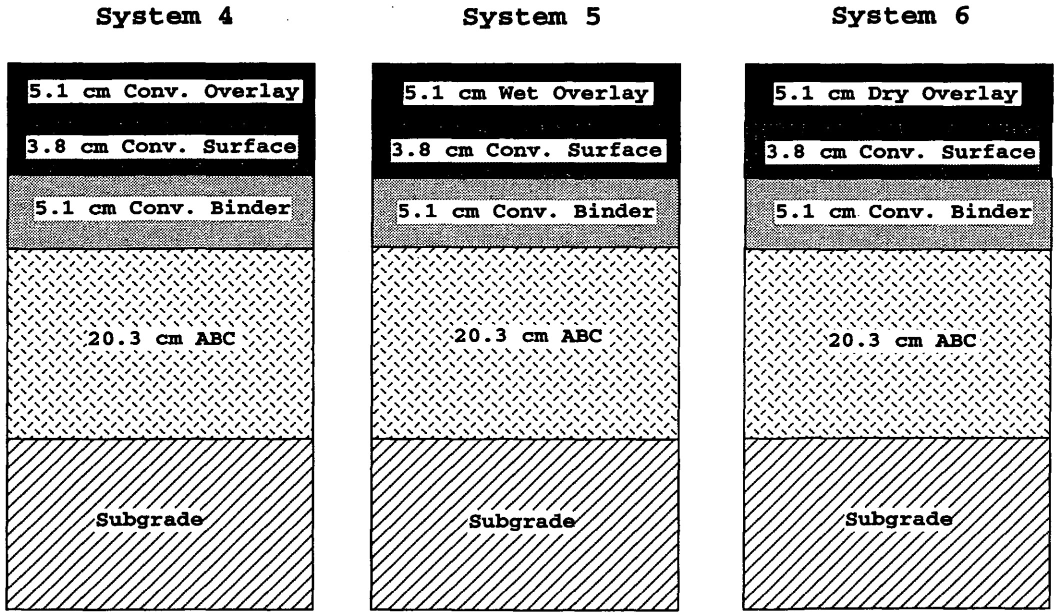

FIGURE 8 Rehabilitation systems 4, 5, and 6.

TABLE 7 Mechanistic Parameters for the Binder and Non-Asphaltic Layers

Parameter	Binder	Aggregate Base	Subgrade
Mr (MPa)			
4.4°C	12,953	186	27.6
21.1°C	2,225	179	20.7
37.8°C	407	200	62.0
Alpha			
4.4°C	0.410	0.810	0.850
21.1°C	0.620	0.840	0.850
37.8°C	0.690	0.870	0.720
GNU			
4.4°C	0.009	0.010	0.160
21.1°C	0.050	0.010	0.160
37.8°C	0.038	0.005	0.040
K1	1.95×10^{-7}		
K2	3.75		

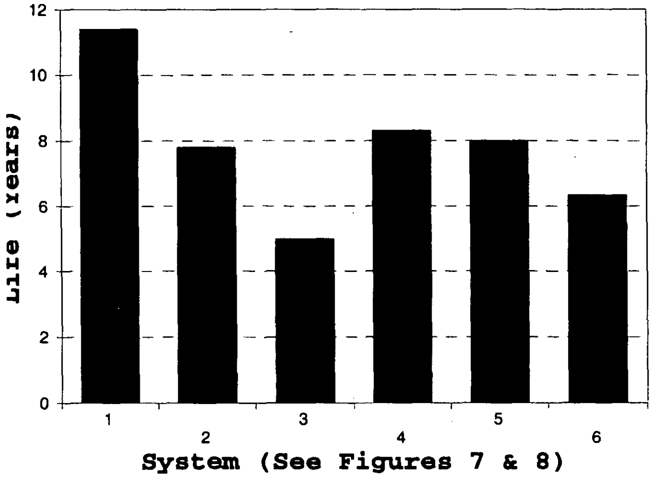

FIGURE 9 Predicted pavement lives.

lar. When the wet process is used as an overlay on a system containing an aggregate base, the performance is similar to a pavement system with an equal thickness of conventional overlay.

- The creep models also suggest that the wet process and conventional mixtures perform better in terms of creep than the dry process. The high gyratory shear strength that was obtained during the design of the dry process samples would appear to indicate these mixtures would be able to resist the shear deformation in late-stage rutting. However, these measurements were recorded with the vertical compaction pressure still acting on the specimen according to the ASTM procedure. After this vertical pressure is removed, all the dry process samples rebounded enough to exhibit cracking on the sides. For this reason, the GTM may not accurately predict the shear performance of dry process samples. It would appear that the amount of rebound after compaction, or the overall effect of the resiliency of the rubber, plays a major role in the parameters obtained in the GTM design of dry process mixtures. Because of the volume changes observed, it is believed that the samples tested to obtain the performance prediction parameters are at variance with those tested during their fabrication in the GTM.

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