Permanent Deformation Characteristics of Recycled Tire Rubber-Modified and Unmodified Asphalt Concrete Mixtures

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In recent years, modified asphalt mixtures have become increasingly popular in the construction of flexible pavements. These products have gained popularity because of their ability to increase resistance to rutting at warm temperatures while reducing the occurrence of thermal cracking at cold temperatures. This, coupled with the growing problem of waste rubber tires, has led to the reprocessing (grounding) of tire rubber for use in asphalt concrete mixtures. In order to investigate the warm temperature rutting hypothesis, a laboratory research program using both static and repeated load permanent deformation tests, carried out at two temperatures (77°F and 104°F), was designed to assess the potential benefits of rubberized asphalt concrete mixtures. Conclusions from this research indicated that the addition of ground tire rubber to asphalt concrete mixtures results in mixtures that exhibit less permanent deformation at high temperatures compared with unmodified mixtures. The research also indicated that permanent deformation testing should be carried out at high temperatures under repeated loading. The relative ranking of strain changes from 77°F to 104°F for both methods of testing and static testing indicates the presence of rubber; however, it does not indicate anything about the base asphalt. The repeated load testing indicates, in a reliable way, the differences that exist between binders.

In recent years, modified asphalt mixtures have become increasingly popular in the construction of flexible pavements. These products have gained popularity because of their ability to increase resistance to rutting at warm temperatures while reducing the occurrence of thermal cracking at cold temperatures. This, coupled with the growing problem of waste rubber tires, had led to the reprocessing (grounding) of tire rubber for use in asphalt concrete mixtures.

In order to investigate this hypothesis, a laboratory research program was designed to assess the potential benefits of rubberized asphalt concrete mixtures.

RESEARCH PROGRAM

The extended research program was designed to include four phases:

Phase 1: The use of conventional mix design methods for determining the optimum asphalt content for rubberized mixtures.

Phase 2: Permanent deformation characteristics of rubberized and unmodified mixtures.

Phase 3: Low-temperature cracking resistance of rubberized and unmodified mixtures.

Phase 4: Fatigue characteristics for rubberized and unmodified mixtures.

The laboratory results from Phase 2 only are discussed in this report. Phase 1 has been completed and reported in "Comparison of Mix Design Methods for Rubberized Asphalt Concrete Mixtures" (*1*). Phases 3 and 4 are currently being completed.

The scope of this research program includes one aggregate source, one gradation, and six binders. The test matrix is shown in Table 1.

MATERIALS

Aggregates

The aggregates used in this research program were obtained from Granite Rock Company, located in Watsonville, California. This material is a 100 percent crushed granite that has no history of stripping problems with in-service pavements. The physical properties are presented in Table 2.

The gradation used to prepare the mixture samples is shown in Table 3. This gradation was chosen to meet ASTM D3315 ½-in. dense mixture, Nevada Type II, and California ½-in. medium specification (Table 3). This gradation was opened up slightly on the #30 and #50 to accommodate the presence of rubber.

Binders

The three grades of neat asphalt used in this research program were obtained from a single California Valley crude source. The binders used were:

Unmodified: AC-5
AC-20
AC-40

Both the AC-5 and AC-20 were then modified with crumb rubber. The AC5 was also modified with rubber and an extender oil, yielding a very soft third modified binder. The

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TABLE 1 TEST MATRIX FOR PERMANENT DEFORMATION OF MODIFIED AND UNMODIFIED MIXTURES

	Binder	AC5 Ext. Oil		AC5		AC20		AC40	
	Modifier	Orig.	Rubber Added	Orig.	Rubber Added	Orig.	Rubber Added	Orig.	Rubber Added
Static Load	77°F		X	X	X	X	X	X	
	104°F		X	X	X	X	X	X	
Repeat. Load	77°F		X	X	X	X	X	X	
	104°F		X	X	X	X	X	X	

TOTAL OF 72 SAMPLES (each X denotes 3 samples)

source of crumb rubber was selected by the sponsor with the rubber being blended with the asphalt cement by Crafco Inc., located in Chandler, Arizona. The rubber used in this research program was ambient ground rubber having a hydrocarbon content of approximately 45 percent and a specific gravity between 1.100 and 1.200. The particle size, along with the gradation specification suggested by Crafco, are shown in Table 4. The resulting modified binders were:

Modified: AC-5 + 17% Rubber (AC5R)
AC-5 + 16% Rubber + 5% Extender Oil (AC5RE)
AC-20 + 16% Rubber (AC20R)

TABLE 2 PHYSICAL PROPERTIES OF WATSONVILLE AGGREGATE

Test	Fine Aggregate (-#4)	Coarse Aggregate (+#4)
Bulk Specific Gravity	2.589	2.682
Bulk Specific Gravity, SSD Condition	2.667	2.735
Apparent Specific Gravity	2.806	2.832
Absorption Capacity (%)	3.0	2.0

TABLE 3 COMPARISON BETWEEN LABORATORY GRADATION USED IN RESEARCH PROGRAM AND SEVERAL SPECIFICATIONS

Sieve Size	Laboratory Gradation	ASTM D3315 ½" Dense	Nevada Type II	California ½" Medium
	Cumulative Percent Passing			
3/4"	100	100	90-100	100
1/2"	98	90-100	---	89-100
3/8"	85	---	63-85	75-100
#4	58	44-74	45-63	51-74
#8	40	28-58	---	35-57
#16	28	---	---	---
#30	20	---	---	14-35
#50	14	5-21	---	---
#100	9	---	---	---
#200	5	2-10	3-9	0-11

OPTIMUM BINDER CONTENTS

In Phase 1 of this research, binder contents to be used in phases 2, 3, and 4 were selected by a committee that included the sponsor and all of the researchers involved. These selections were based on mix designs conducted at both the University of Nevada, Reno, and the U.S. Army Corps of Engineers Water Ways Experiment Station (WES). Optimum binder contents for both unmodified mixtures AC5 and AC20 were agreed upon at 5.3 and 5.7 percent by total weight of mix, respectively. However, there was disagreement about the binder content to use for each of the modified mixtures. As a result, a compromise was made that was agreeable to all parties involved in the extended program. The compromise yielded binder contents that were higher than the University of Nevada, Reno (UNR)-recommended optimums. The following table shows the binder contents used and the UNR-recommended binder content for all modified mixtures.

Type of Binder	*Binder Content Used In Preparing Samples (%, Total Weight of Mix)*	*UNR-Recommended Binder Content (%, Total Weight of Mix)*
AC5R	8.5	7.7
AC5RE	8.3	7.7
AC20R	7.9	7.4

TABLE 4 PHYSICAL PROPERTIES OF GROUND TIRE RUBBER USED IN PREPARING MODIFIED BINDERS

Sieve Size	Baker IGR-24	Manufacturer Recommendations
	Cumulative Percent Passing	
#10	100	100
#16	100	100
#30	78	70-100
#40	49	---
#50	27	---
#80	9	0-20
#100	7	---
#200	0.2	0-5

The result of this compromise is a binder-rich mixture. This should be remembered when assessing any of the permanent deformation data contained in this report.

SAMPLE PREPARATION

Samples were batched by first separating the aggregates into the 11 individual sizes (½ in., ⅜ in., ¼ in., #4, #8, #16, #30, #50, #100, #200, fines) needed to prepare samples, and then recombined to meet the desired gradation. Washed sieve analyses were performed on complete batches to ensure that the gradation had been met.

After all aggregate preparation was completed, batches were selected at random and mixed with the selected binder. Different methods of mixing and compaction were used for the rubberized and unmodified mixtures. The procedure for each method is described in the following sections.

Unmodified mixtures were blended in accordance with ASTM D 1561 (*2*). After mixing, samples were placed in a 140°F forced draft oven for 15 hr before being reheated to 230°F for compaction. Specimens 8 in. in height by 4 in. in diam were compacted in thirds using a kneading compactor. Each lift, or third, received 30 blows at 250 psi. Lifts were compacted consecutively on top of each other. After compaction of the third lift, each sample was placed in a 140°F oven for 1½ hr before the application of a 5,000-lb leveling load. Samples were allowed to cool before being extruded.

Rubberized mixtures were blended using the recommendations of Chehovits (*3*). This involves heating the aggregate to 300°F and the rubberized binder, regardless of base asphalt viscosity, to 350°F before mixing. Once again, after mixing, samples are placed in a 140°F forced draft oven for 15 hr before reheating the samples for compaction. Samples using the rubberized AC-20 were reheated to 300°F for compaction while the other two rubberized mixtures, AC5R and AC5RE, were reheated to 230°F. The same compaction procedure described previously was used with the rubberized mixtures with the exception that the 1½-hr cure time at 140°F was extended to 3 hr for the AC20R. Rubberized samples were allowed to cool before being extruded.

TESTING METHODS

After compaction, samples were allowed to cool overnight in a 77°F room before being tested for bulk specific gravity and height, ASTM D2726 and D3515, respectively (*2*). Samples were placed under a fan, again overnight, to remove any moisture that may have penetrated the sample during testing. Samples were then placed in an appropriate temperature control chamber to condition them to the testing temperature to be used, either 77°F or 104°F. After 24 to 36 hr, samples were tested for permanent deformation using one of two tests. These tests are described in detail as follows.

The first of two tests used was a modified version of the proposed ASTM creep test (*4*). This test involved a static-loading, uniaxial unconfined creep test. This test incorporated a 2-min preconditioning load, using the test load magnitude, followed by a 5-min. rest period. Immediately following the rest period, a static load was applied for a period of 60 min., followed by a 15-min. unload, or rebound, period, during which samples were allowed to rebound freely. Tests conducted at 77°F used a static stress of 50 psi, and tests conducted at 104°F used a static stress of 20 psi.

The second test used to assess permanent deformation was a triaxial, repeated-loading confined test. This test procedure followed the interim testing guidelines from the Strategic Highway Research Program (SHRP) A-003A contractor at the time this testing was started. The only change implemented by UNR was the shortening of the test time from 36,000 cycles (approximately 8 hr) to 5,200 cycles (approximately 1 hr). The test used a 1-min. preconditioning period followed immediately by a 60-min. test. The repeated loading sequence consisted of 0.1-sec duration haversine pulse followed by a 0.6-sec rest period. This sequence yields a testing frequency of 1.43 cycles/sec. All tests used a confining pressure of 15 psi. Tests conducted at 77°F used a peak deviator stress of 50 psi, whereas tests conducted at 104°F used a peak deviator stress of 20 psi.

Deformations were continuously measured for both tests using two linear variable differential transducers (LVDTs). These LVDTs were instrumented 180° apart and measured deformations over the total sample height. These deformations were electronically averaged and recorded every 60-sec throughout testing.

The data were then used to calculate compressive strains for each test over the sample height using the following equation:

$$\varepsilon(t) = [d(t)/H_o]$$

where

$\varepsilon(t)$ = strain at time t, in./in.
H_o = original height of sample, in.
$d(t)$ = deformation of sample height at time t, in.

TESTING PROGRAM

A total of 72 samples, 12 samples from each of the 6 types of binder, were prepared. This allowed for 3 replicates to be tested at each testing condition. The testing conditions used were static load at 77°F, static load at 104°F, repeated load at 77°F, and repeated load at 104°F. This testing matrix is shown in Table 1. The number of samples tested produced sufficient data to estimate the mean, standard deviation, and coefficient of variation for each type of mixture at each testing condition.

ANALYSIS OF TEST RESULTS

As stated previously, there were two different types of permanent deformation tests used in this research program. Then within each test, samples from each of the six mixtures were tested at two different temperatures. For ease of discussion, the analysis will be presented similarly; first the static test results and then the repeated load test results will be given.

Analysis of Static Permanent Deformation Testing

The average standard deviation and coefficient of variation (CV) for the strain at 60 min (i.e., strain at the end of the

TABLE 5 SIMPLE STATISTICS FOR STRAIN AT END OF LOADING FOR STATIC PERMANENT DEFORMATION TESTS COMPLETED AT 77°F

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation (%)	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	0.0079	0.0072	0.0122	0.0091	0.0027	29.8	5495
AC40	NA	NA	NA	NA	NA	NA	NA
AC5RE	0.0157	0.0165	0.0174	0.0165	0.0009	5.1	3024
AC5R	0.0132	0.0137	NA	0.0135	0.0004	2.6	3717
AC20R	0.0069	0.0090	0.0059	0.0073	0.0016	21.8	6881

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available

loading period) for all tests completed at 77°F using the static testing procedure are shown in Table 5. The AC-40 data have been removed from the data base because of sample damage before the test. It can be seen from this table that the CV is somewhat higher than desired; however, it is still in the range of acceptable test results. This table also shows an average creep modulus for each of the five remaining mixtures. A creep modulus of zero indicates that the samples failed before the 60 min of loading.

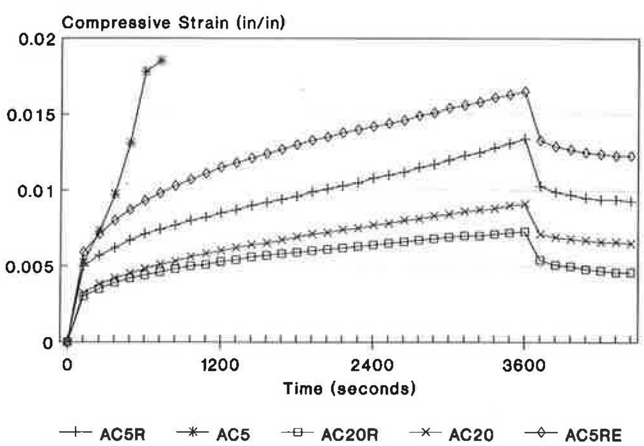


FIGURE 1 Compressive strain versus time for static loading conducted at 77°F.

The average compressive strain versus time relationship for the 77°F static test results is shown in Figure 1. Inspection of this figure shows that the mixtures behaved as expected. The unmodified mixtures show that the AC5 samples fail at about 10 min into the test and the AC20 samples yield relatively low strains. The rubberized mixtures show decreasing strain with increasing binder viscosity (i.e., AC5R strains more than AC20R, and AC5RE strains more than AC5R). It can be concluded from this figure that for this testing procedure conducted at 77°F, the addition of rubber yields mixtures that exhibit less deformation (i.e., rubberized AC5 strains less than AC5, and rubberized AC20 strains less than AC20).

The average standard deviation and CV for the strain at 60 min (i.e., strain at the end of the loading period) for all tests completed at 104°F, using the static testing procedure, are shown in Table 6. Once again, the AC40 data have been removed from the data base because of sample damage before testing. The CV is again higher than desired; however, it is still in the range of acceptable test results. The average creep modulus for each of the five remaining mixtures is also shown in this table. A creep modulus of zero indicates that the samples failed before the 60 min of loading.

The average compressive strain versus time for four of the six mixtures from the static testing at 104°F is shown in Figure 2. The AC5 samples failed drastically during the preconditioning sequence, leaving no data to present for the testing sequence. This leaves only one unmodified mixture in the figure, the AC20. All three curves for the rubberized binders

TABLE 6 SIMPLE STATISTICS FOR STRAIN AT END OF LOADING FOR STATIC PERMANENT DEFORMATION TESTS COMPLETED AT 104°F

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation (%)	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	0.0087	0.0056	NA	0.0072	0.0022	30.7	2797
AC40	NA	NA	NA	NA	NA	NA	NA
AC5RE	0.0045	0.0064	NA	0.0055	0.0013	24.7	3670
AC5R	0.0045	0.0051	0.0042	0.0046	0.0005	10.0	4348
AC20R	0.0037	0.0041	0.0059	0.0046	0.0012	25.7	4380

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available

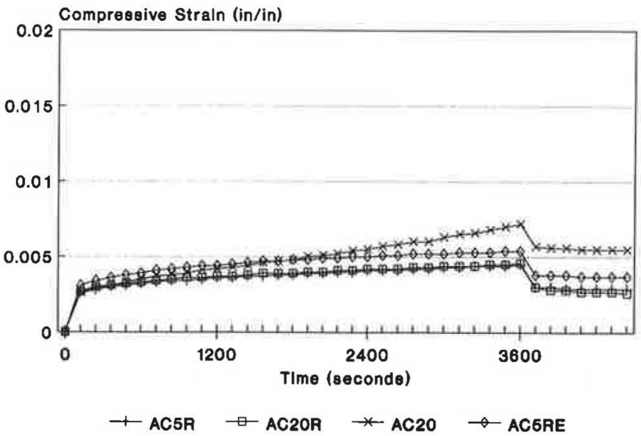


FIGURE 2 Compressive strain versus time for static loading conducted at 104°F.

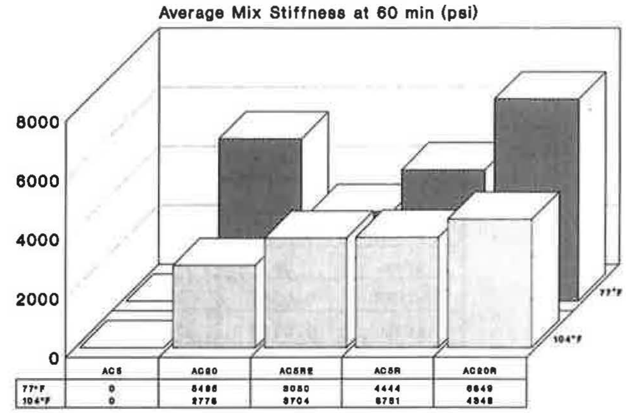


FIGURE 3 Creep modulus from static testing at 7°F and 104°F.

fell on top of each other, indicating the same response for any mixture incorporating rubber. All rubberized mixtures exhibited less strain than the AC20. It is hypothesized that in this case, the rubber is absorbing the load and the strain is therefore independent of the base asphalt cement. It should be remembered that is for a static unconfined test.

The average creep modulus calculated at 60 min of loading for the five mixtures for both temperatures of static testing is shown in Figure 3. It can be seen that the AC5 shows modulus values of zero for both temperatures. This is because of sample failure before the 60 min of loading. The AC20 shows a drop in the modulus of approximately 50 percent from 77°F to 104°F. All three of the rubberized mixtures showed a smaller drop in stiffness than the AC20. In fact, the AC5RE showed an increase in modulus from 77° to 104°. This would indicate that rubberized mixtures will suffer a smaller loss of stiffness with increasing temperature than will unmodified mixtures.

Analysis of Repeated Load Permanent Deformation Testing

The average standard deviation and CV for the strain at 60 min (i.e., strain at the end of the test) for all tests completed at 77°F using the repeated loading testing procedure are shown in Table 7. This table shows data for all six mixtures. It also shows the average creep modulus for each of the six mixtures. Like the static modulus, this modulus was calculated by dividing the strain after 60 min of testing into the peak deviator stress.

The average compressive strain versus time for the six mixtures from the repeated load testing at 77°F is shown in Figure 4. From this figure, is can be seen that both the AC5 and AC5RE failed during testing. This was because of the relatively low viscosity of the unmodified AC5 and rubberized AC5 that incorporates an extender oil, which is also of very low viscosity. The AC5R finished the testing without failure; however it exhibited large strains. The three mixtures that performed best were the AC20, AC20R, and AC40. It is interesting to note that the AC20R exhibited a higher strain than the AC20. In this case the AC20 samples exhibited strains that grouped the mixtures with the AC40, which yielded very low strain. This anomaly remains unexplained.

The average standard deviation and CV for the strain at 60 min (i.e., strain at the end of the test) for all tests completed at 104°F using the repeated loading testing procedure are shown in Table 8. This table shows data for all six mixtures. It also shows the average creep modulus for each of the six mixtures. The table indicates that the AC5 and AC20 samples

TABLE 7 SIMPLE STATISTICS FOR STRAIN AT END OF LOADING FOR REPEATED LOAD PERMANENT DEFORMATION TESTS COMPLETED AT 77°F

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation (%)	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	0.0056	0.0037	0.0037	0.0043	0.0011	25.3	11538
AC40	NA	0.0031	0.0034	0.0033	0.0002	6.5	15385
AC5RE	F	F	F	---	---	---	0
AC5R	0.0015	NA	0.0104	0.0110	0.0008	7.1	4566
AC20R	0.0088	0.0053	NA	0.0071	0.0025	35.1	7092

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available

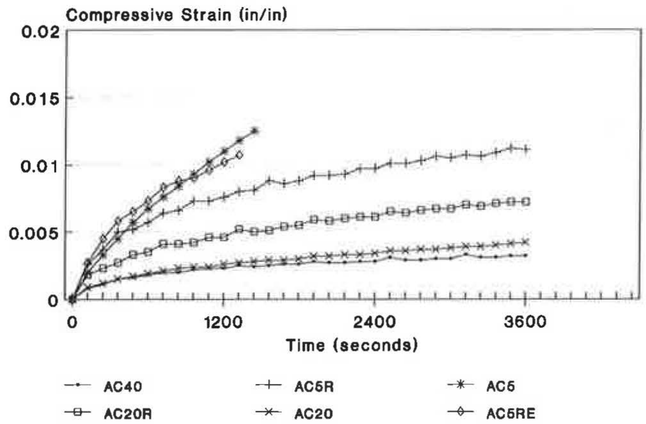


FIGURE 4 Compressive strain versus time for repeated loading conducted at 77°F.

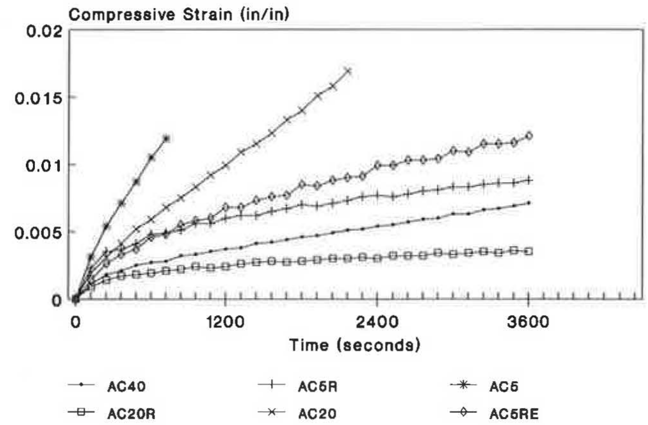


FIGURE 5 Compressive strain versus time for repeated loading conducted at 104°F.

failed before the 60 min of loading. This is shown in Figure 5. It can be seen from this figure that the AC5 failed after approximately 15 min of loading and the AC20 failed after 20 min of loading. This indicates that even though the samples failed, the AC20 mixtures were stiffer than the AC5 mixtures. The AC40 mixtures performed well, yielding relatively low strains. The modified mixtures yielded strains that also follow the idea of higher viscosity leads to lower strain. The AC5RE produced the highest strains, followed by the AC5R and the AC20R. The AC5R acted similarly to the AC40, whereas the AC20R exhibited the lowest amount of strain of any of the six types of mixtures. This indicates that for this particular aggregate source and gradation, an AC5R could be expected to behave like an AC40 in warmer temperatures. An AC20R could be expected to exceed the permanent deformation performance of an AC40. It can be concluded from this that the addition of rubber to the mixture produces a stiffer mixture at higher temperature.

The average creep modulus calculated at 60 min of loading for the six mixtures for both temperatures of repeated load testing is shown in Figure 6. It can be seen that all unmodified mixtures either exhibited very large decreases in stiffness from 77°F to 104°F or no stiffness at all. On the other hand, the rubberized mixtures exhibited either very small decreases, or as in the case of the AC5RE, showed an increase in stiffness. This again indicates that the addition of rubber to asphalt concrete mixtures reduces the magnitude of the loss of stiffness at higher temperatures.

Comparison of Static to Repeated Load Permanent Deformation Testing

The relative ranking of strain changes for both testing conditions when 77°F test results are compared with 104°F test results. The 77°F test results are useful to assess the loss in stiffness when compared with testing at 104°F; however, because of the low testing temperature, they do not appear to be appropriate for characterization of permanent deformation.

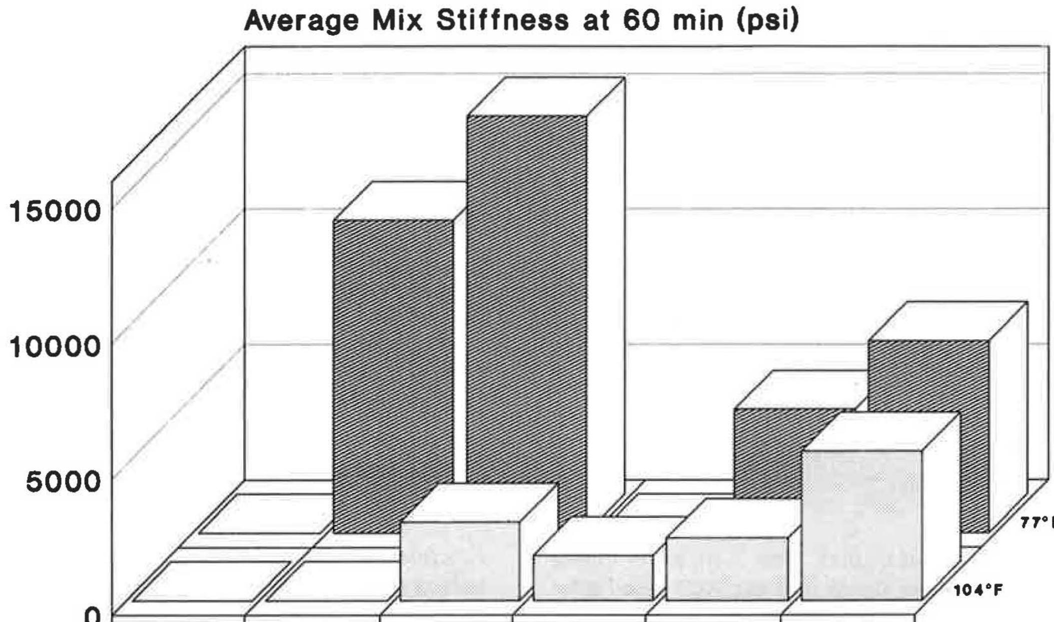
The static test results at 104°F indicate only the presence of rubber and nothing about the properties of the asphalt cement rubber blend. The repeated load testing at 104°F indicates, in a concrete manner, the differences that exist between the different binders. This is supported by comparing the static testing at 104°F (Figure 2) to the repeated load testing at 104°F (Figure 5).

On the basis of information presented in Tables 5 through 8 and Figures 1 through 6, two conclusions can be reached. First, permanent deformation testing should be carried out at elevated temperatures. Not only does rutting occur primarily at the elevated temperatures, but the modified mix-

TABLE 8 SIMPLE STATISTICS FOR STRAIN AT END OF LOADING FOR REPEATED LOAD PERMANENT DEFORMATION TESTS COMPLETED AT 104°F

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation (%)	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	F	F	F	---	---	---	0
AC40	0.0091	0.0050	0.0067	0.0069	0.0021	29.7	2885
AC5RE	0.0141	0.0108	0.0114	0.0121	0.0018	14.5	1653
AC5R	0.0076	0.0097	NA	0.0087	0.0015	17.2	2312
AC20R	0.0033	NA	0.0036	0.0035	0.0002	6.1	5797

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available



	AC5	AC20	AC40	AC5RE	AC5R	AC20R
77°F	0	11536	16385	0	4566	7092
104°F	0	0	2865	1653	2312	5497

FIGURE 6 Creep modulus from static testing at 77°F and 104°F.

tures appear to react differently at the lower temperatures. This conclusion is supported by both the static and repeated load test results. Second, permanent deformation testing should be based on repeated loading. Static testing only indicates the presence of rubber and nothing about the base asphalt.

CONCLUSIONS

The following conclusions can be drawn on the basis of the analysis presented in this paper:

1. The addition of ground tire rubber to asphalt concrete mixtures results in mixtures that exhibit less permanent deformation at high temperatures compared with unmodified mixtures, remembering that the rubberized mixtures contained higher-than-optimum asphalt contents. This proved to be true for both static and repeated load testing.
2. Permanent deformation testing should be carried out at elevated temperatures. This conclusion is supported by both the static and repeated load test results. The relative ranking of strain changes for both testing conditions when the 77°F test results are compared with the 104°F test results.
3. Permanent deformation testing should incorporate repeated loading. This is not only a better model for including the effects of moving wheel loads, but is supported by comparing the static testing at 104°F to the repeated load testing at 104°F. The static test results indicate only the presence of rubber and nothing about the properties of the base binder. The repeated load testing indicates, in a concrete manner, the differences that exist between binders.

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