Relationship Between Permanent Deformation of Asphalt Concrete and Moisture Sensitivity

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In recent years, the Nevada Department of Transportation has observed cases of severe rutting during the first warm weather following a chip seal application. Cores from these pavements have shown evidence of severe stripping. Sealing the surface appears to accelerate moisture damage by trapping moisture that would otherwise escape in the pavement layers. This observation led to the hypothesis that rutting was occurring in the asphalt concrete layer owing to a loss of cohesion and shear strength as a result of moisture damage. To test this hypothesis, a preliminary study was undertaken to determine if moisture susceptibility was related to permanent deformation. Samples from behind the paver were collected from 20 Nevada construction projects during 1985 and 1986. These materials were compacted, and a preliminary creep test described by ASTM was performed to determine the permanent strain. Samples from each of these projects were moisture conditioned, and a strain ratio (i.e., conditioned percent strain divided by unconditioned percent strain) was developed to relate unconditioned to conditioned results. Conclusions from this research were that moisture conditioning appears to play a significant role in permanent deformation. A preliminary multiple regression equation was developed by using strain ratio and daily 18,000-lb equivalent single-axle loads (ESALs) to predict average project rut depth. This equation yielded a correlation coefficient of 0.70.

Several years ago, isolated cases of severe rutting during the first warm weather following a chip seal application were noted in Nevada. Cores from these pavements showed evidence of moderate to severe stripping in one or more of the asphalt concrete layers.

Sealing the surface appears to accelerate moisture damage by trapping moisture that would otherwise escape in the pavement layers. This observation led to the hypothesis that rutting was developing in the asphalt concrete layer owing to a loss of cohesion and shear strength as a result of moisture damage.

To evaluate this hypothesis, a four-phase research program was designed to investigate the impact of moisture sensitivity on the permanent deformation behavior of asphalt concrete.

RESEARCH PROGRAM

The research program was designed in four phases. The objectives of these phases are as follows:

Phase 1. Determine if the moisture sensitivity for asphalt concrete paving mixtures can be related to permanent deformation.

Phase 2. Evaluate various testing procedures for creep testing.

Phase 3. Develop a relationship between the most promising test procedures and pavement performance.

Phase 4. Verify any performance models developed in Phase 3.

This paper will present the results of Phase 1 of this research program.

Samples for this phase were collected from behind the paver for 20 Nevada construction projects placed during 1985 and 1986. These materials were compacted, and a preliminary creep test described by the proposed ASTM test method (*1*) was used to determine the permanent strain of these samples.

Information on rutting and traffic for the corresponding in-place pavements was obtained from the Nevada Department of Transportation (NDOT) Pavement Management System (PMS) (*2*).

DESCRIPTION OF CONSTRUCTION PROJECTS

Variables in the construction projects included different sources of aggregate, asphalt cement grades and sources, and the presence of an antistrip agent. Sources of aggregate varied greatly from project to project. Generally, two grades of asphalt were used in construction: an AR-4000 and an AR-8000. There were, however, several projects where AC-20R and AC-10 were used. Sources of asphalt cement varied between projects.

In summary, the data base included the following points:

1. Thirteen projects with AR-4000,
2. Three projects with AR-8000,
3. Three projects with AC-20R, and
4. One project with AC-10.

Those construction projects were located throughout the state (Figure 1). Environmental information available in existing NDOT-University of Nevada, Reno (UNR) data bases (*3*) for these projects included elevation, air freeze-thaw cycles,

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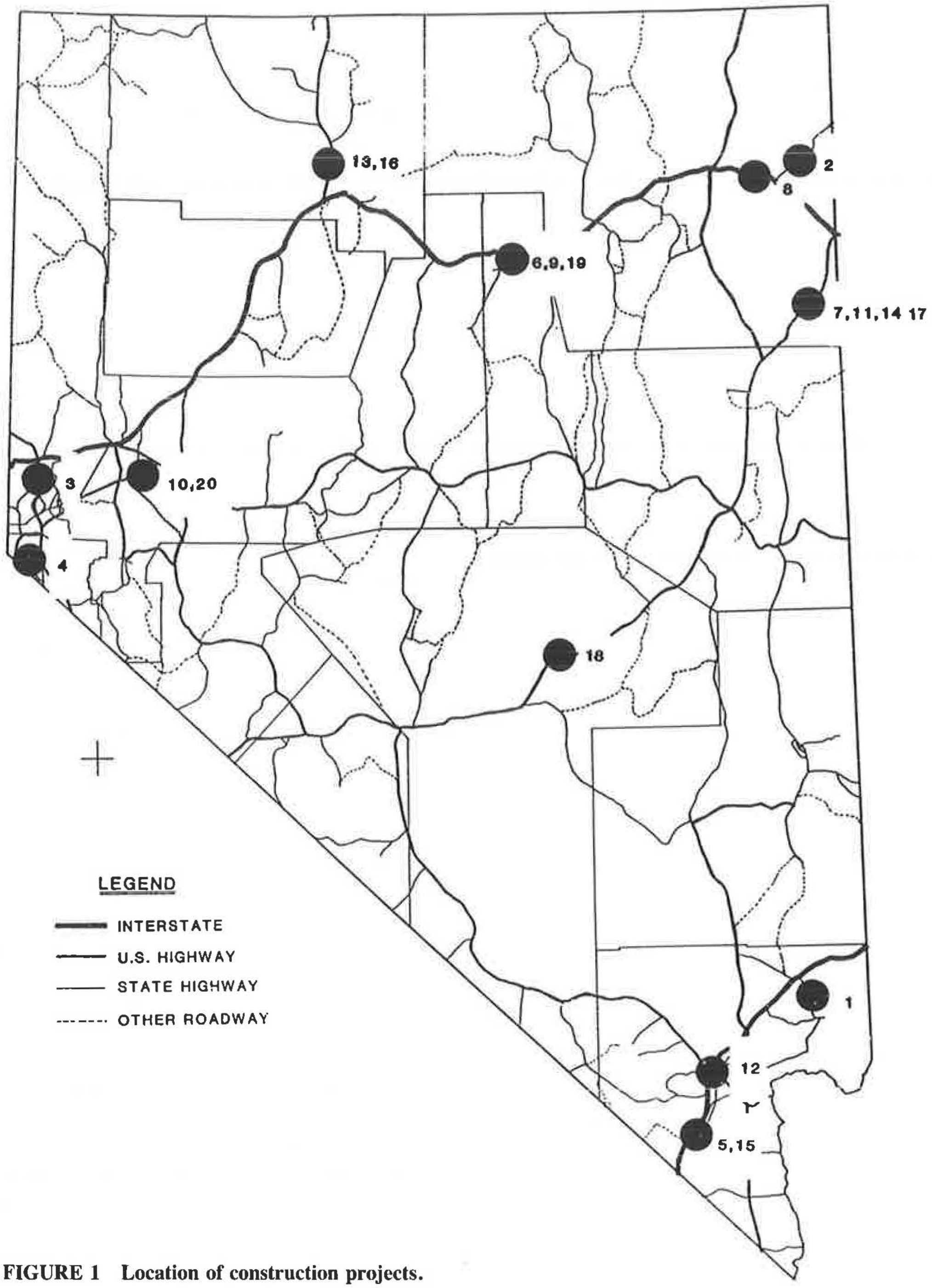

FIGURE 1 Location of construction projects.

number of wet days, annual precipitation, and yearly temperature mean highs and lows (Table 1).

Elevations ranged from 1,500 to 6,500 ft. The air freeze-thaw cycles ranged from 43 to 216 cycles per year. The number of wet days varied from 18 to 67, with an annual precipitation of 5.17 up to 14.05 in. Mean yearly high temperatures ranged from 84°F to 108°F, whereas mean yearly low temperatures ranged from 8°F to 32°F. Before 1985, portland cement was used extensively as an antistrip additive and mineral filler. Since 1986, the addition of hydrated lime, usually 1.5 percent, to prewet aggregate has become increasingly popular in the northern half of the state. The date of construction of each of these projects is also shown in Table 1.

Information from the PMS (*2*) records for traffic is shown in Table 2. The ADT ranges from 180 to 16,600. The percentage of trucks fluctuated between 2.3 percent and 24.0 percent. Daily 18,000-lb equivalent single-axle loads (ESALs) ranged from 3 to 861.

NDOT's PMS (*2*) was used to estimate the average rut depth over the entire project length. (Many sections were over 5 mi long, and, as a result, the rut depths for the entire project were averaged for use.) Table 3 shows the average

TABLE 1 ENVIRONMENTAL INFORMATION FOR CONSTRUCTION PRODUCTS

Type of Information	Low	High
Elevation	1,500 - 6,000	2,500 - 6,500
Air Freeze/Thaw Cycles	43	216
Number of Wet Days	18	67
Annual Precipitation	5.17	14.05
Mean Annual Temperature	8 - 32	84 - 108

TABLE 2 TRAFFIC VARIABLES FOR INDIVIDUAL PROJECTS

Project Site	Average Daily Traffic	Percent Trucks (%T)	Number of Trucks	Daily 18K ESAL
1	820	2.2	18	3
2	180	10.0	18	4
3	10,990	7.0	769	798
4	5,500	2.0	111	16
5	9,400	6.0	564	75
6	2,167	31.4	681	861
7	187	38.0	71	136
8	1,832	41.0	751	748
9	2,167	31.0	672	749
10	610	8.0	49	48
11	187	38.0	71	69
12	16,600	2.4	400	110
13	895	29.1	260	150
14	187	38.0	71	69
15	9,400	6.0	564	75
16	895	29.1	260	75
17	187	38.0	71	69
18	110	33.6	37	16
19	2,167	31.0	672	749
20	2,342	15.0	351	48

TABLE 3 AVERAGE RUT DEPTHS FROM PROJECT SITES

Project Site	Year Constructed	Average Rut Depth (inches) 1988	1987
1	1985	0.00	0.00
2	1986	0.00	0.00
3	1985	0.16	0.28
4	1985	0.13	0.22
5	1986	0.00	0.06
6	1986	0.20	0.06
7	1986	0.00	0.00
8	1985	0.14	0.00
9	1986	0.20	0.23
10	1986	0.16	0.00
11	1986	0.17	0.00
12	1986	0.08	0.13
13	1985	0.00	0.00
14	1986	0.00	0.00
15	1986	0.00	0.00
16	1986	0.00	0.00
17	1986	0.17	0.00
18	1986	0.03	0.00
19	1986	0.20	0.23
20	1986	0.16	0.00

rut depth for each project for each year for which data were available. In many of the sites chosen note that there is a fluctuation in rut depths from year to year. This is most likely because the rut depths were measured in different areas of the same project from year to year.

SAMPLE PREPARATION AND TEST METHOD

Sample Preparation

Loose-mix material was sampled by NDOT during construction and delivered to UNR in sealed canisters. This material was then reheated and split into three to five individual 1,100-g samples. Each sample was then reheated to 230°F for 2 hr before compaction. A Hveem kneading compactor was used with a compactive effort to produce samples with air voids between 6 and 8 percent (30 blows at 250 psi). Samples were then placed in a 140°F oven for 1.5 hr before the application of an 11,600-lb leveling load.

Samples were extruded, cooled to 77°F, and the heights and bulk specific gravities were determined according to the appropriate ASTM standards (ASTM D3549 and D2726, respectively).

The permanent strains for both unconditioned and moisture conditioned samples were determined as described next.

Creep Testing

The creep test selected was a uniaxial, static, unconfined version of the proposed ASTM standard (*1*). Conventional-sized samples (4 in. in diameter by 2.5 in. high) were used for testing. Sample ends were well greased with a graphite-based lubricant before the seating of the loading platens. The testing setup is shown in Figure 2.

The test consisted of a static preconditioning followed by a static load. Preconditioning consisted of the application of a 182.2-lb step load for 2 min followed by a 5-min rest period. Testing started immediately at the end of this rest period and consisted of another 182.2-lb static step load applied for 1 hr. This was followed by a 15-min rest period. Vertical deformations were continuously measured over the entire height of the sample by linear variable differential transducers (LVDTs) with a full range of 0.2000 in. Deformations were measured on both sides of the sample, 180 degrees apart (Figure 2). These deformations were electronically averaged and recorded every 60 sec throughout the test. All samples were tested at 77°F. The data were then used to calculate compressive strains:

$$\varepsilon = (d_{75}/H_1)$$

where

ε = permanent strain (%),
H_1 = original height of the sample (in.), and
d_{75} = deformation of the sample after the final rest period of the creep test (i.e., 75 min) (in.).

This same calculation was used for both conditioned and unconditioned samples.

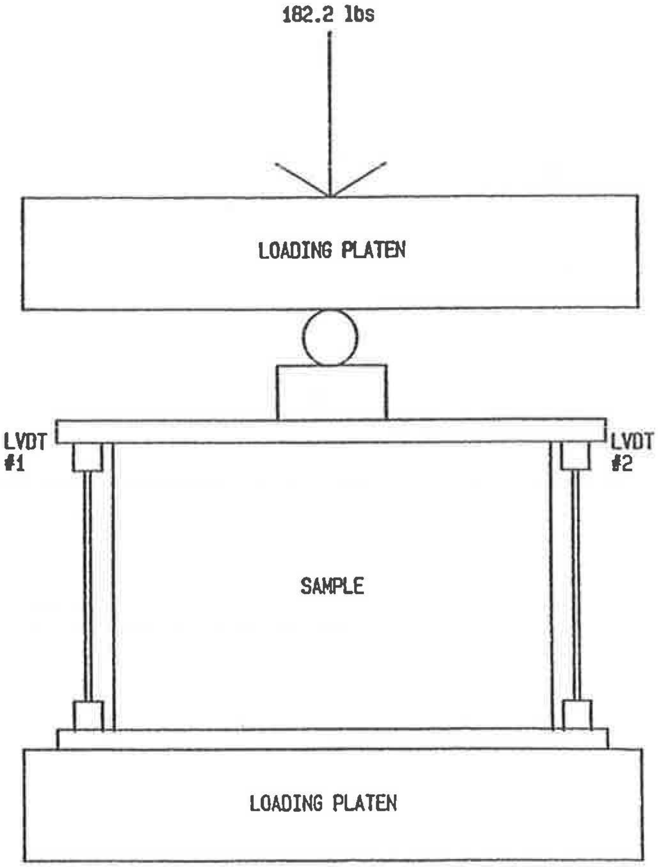

FIGURE 2 Creep test setup.

Moisture Conditioning

This procedure was consistent with Lottman's procedure for accelerated conditioning, which is used to determine the retained strengths of asphalt concrete materials (*4*). The moisture-conditioning procedure consisted of immersing the samples in water and applying a vacuum of 24 in. Hg for 10 min to achieve a minimum of 90 percent saturation. The samples were then wrapped in plastic and placed in a 0°F freezer for a minimum of 15 hr. Samples were then unwrapped and transferred to a 140°F water bath for 24 ± 0.5 hr. Samples were then immediately placed in a 77°F water bath for 2 hr to cool to test temperature.

ANALYSIS OF TEST RESULTS

Estimate of Test Method Precision

Three samples from each of 10 construction projects were prepared, tested, and used to estimate the within-sample set variation of the creep test procedure. An additional set of two samples was prepared for all 20 projects and was used to estimate the impact of moisture conditioning on permanent deformation. The flowchart for the testing sequences is shown in Figure 3.

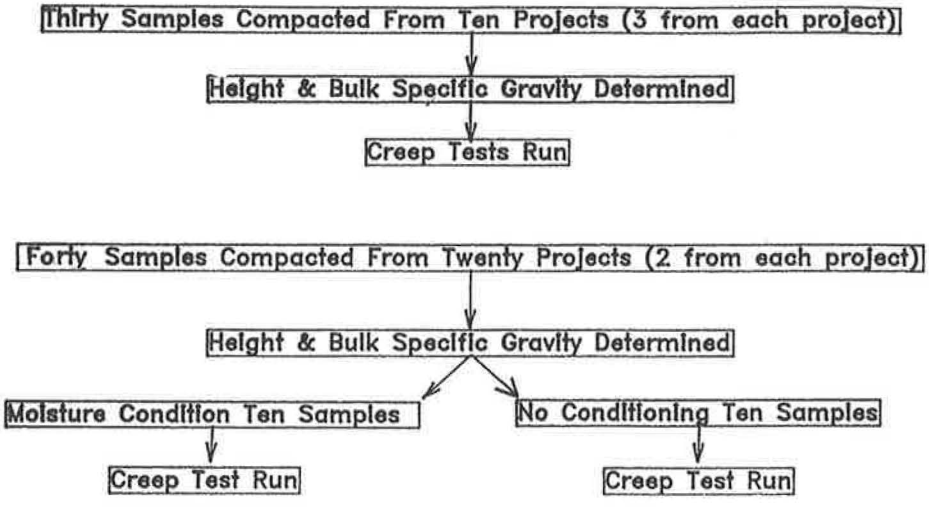

FIGURE 3 Flow chart of testing sequence.

Within-Sample Set Variation

An estimate of within-sample set test precision (unconditioned samples only) was developed. Both the procedure and the requisite degrees of freedom conformed to ASTM C670 and C802 standards for the calculation of within-laboratory statistics.

Unconditioned creep tests were completed for three replicates prepared from 10 different construction projects (Table 4). The within-sample set variance was calculated, and an average variance was determined. The resulting within-sample set standard deviation (i.e., square root of variance) was 0.089 percent strain. Therefore, two test results would not be expected to vary by more than 0.252 percent strain (i.e., $2\sqrt{2}$ times the standard deviation).

Figures 4 and 5 show typical ranges of test results for sets of three samples. Figure 4 indicates the widest range of test results observed. Figure 5 shows the best correlation for a set of three tests. Although data scatter such as that shown in Figure 4 occurred occasionally, the close correlations shown in Figure 5 were more typical.

Variation in Percent Permanent Strains Between Projects for Unconditioned Samples

The average percent of permanent strains for the unconditioned sets of three samples ranged from 0.194 to 0.470 (Table 4). The single lowest and highest percents permanent strain for individual samples that was observed in any sample set were 0.106 and 0.497, respectively.

A Student's *t*-test was used to compare the means from each of the sets of three samples to determine if the means were statistically different. The equation used was

$$t_{\mathrm{calc}} = (X - x)/(s/\sqrt{n})$$

where

t_{calc} = calculated t-value,
X = sample mean,
x = sample mean to be compared with X,
s = standard deviation, and
n = number of samples.

TABLE 4 ANALYSIS OF WITHIN-SAMPLE TEST VARIATION FOR UNCONDITIONED SAMPLES

	UNCONDITIONED STRAIN (%)				
SAMPLE SET	1	2	3	MEAN	VARIANCE
A	0.106	0.183	0.293	0.0963	0.0088
B	0.354	0.295	0.261	0.2163	0.0022
C	0.463	0.250	0.367	0.2377	0.0114
D	0.485	0.461	0.465	0.3153	0.0002
E	0.259	0.127	0.497	0.1287	0.0352
F	0.218	0.301	0.368	0.1730	0.0056
G	0.299	0.372	0.332	0.2237	0.0013
H	0.361	0.360	0.339	0.2403	0.0002
I	0.454	0.247	0.357	0.2337	0.0107
J	0.421	0.294	0.368	0.2383	0.0041
		Avg Strain	=	0.2103	Avg Variance = 0.0080
					Avg Std Dev = 0.089

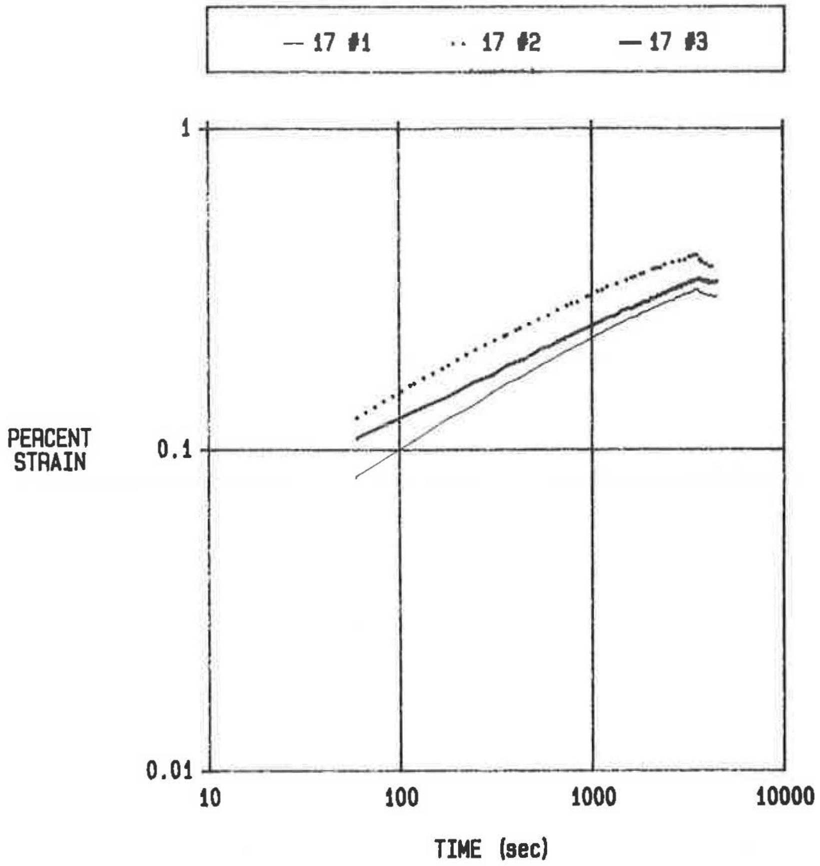

FIGURE 4 Percent strain versus time for sample set 17.

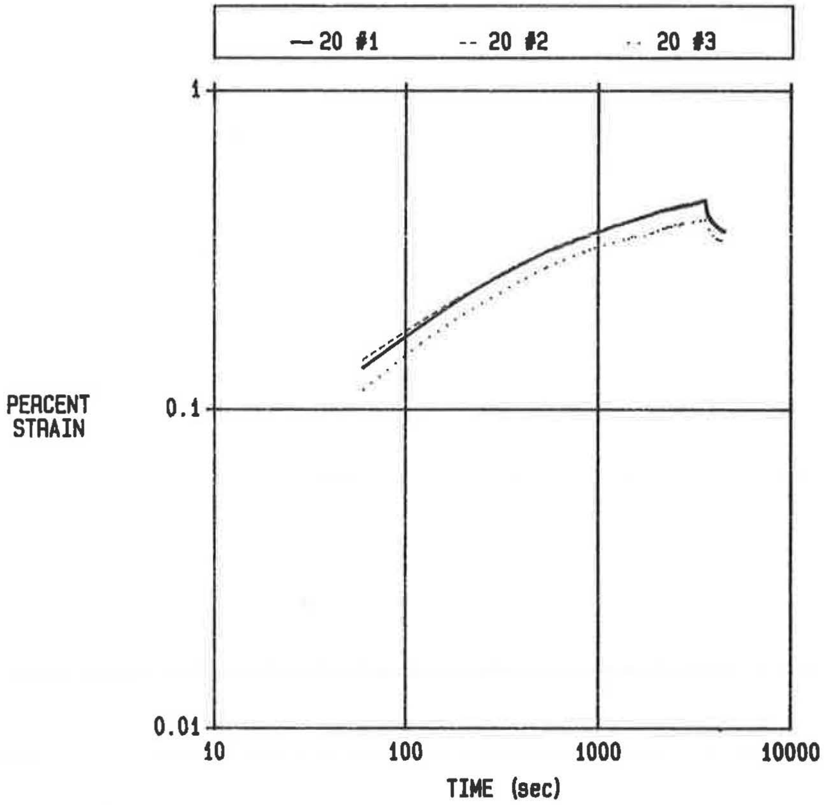

FIGURE 5 Percent strain versus time for sample set 20.

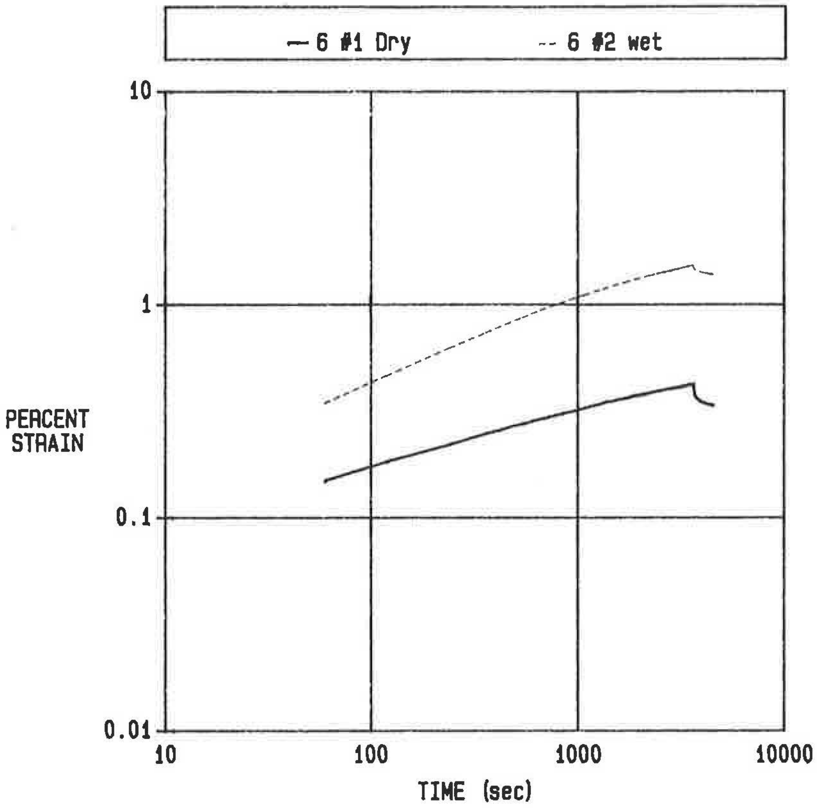

FIGURE 6 Percent strain versus time for sample set 6.

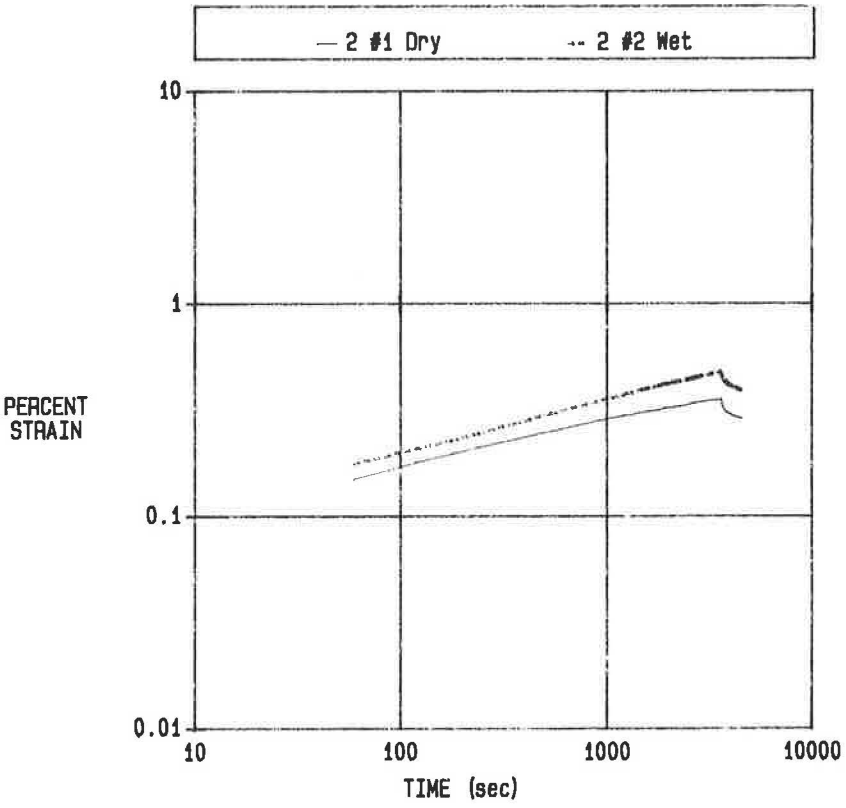

FIGURE 7 Percent strain versus time for sample set 2.

Conclusions are drawn by comparing t_{calc} to t_{table} available from most statistical textbooks. The conclusions are

Means are statistically different:

$$t_{calc} > t_{table}$$

No reason to believe that means are statistically different:

$$t_{calc} < t_{table}$$

The largest mean (0.470) was arbitrarily selected as X. The smallest mean (0.194) was selected as x. The standard deviation s was 0.089 for a set of three (i.e., n) samples. The t_{calc} for these values is 5.37. At a 95 percent confidence interval (t_{table} = 4.303), these two means (0.470 and 0.194) are statistically different. However, at a 99 percent confidence level (t_{table} = 9.925), there is no statistical difference.

The remaining means were also compared with the 0.470 mean. None of these means proved to be significantly different at a confidence level of 95 percent. These results indicate that there is no statistical difference between the materials used for any of the construction projects investigated.

This conclusion may mean several things. First, the test method as performed is not sensitive to mixture properties. Second, the precision of the test is too large to allow a distribution among distinctions between different types of mixtures. Third, the mixtures selected for evaluation do not differ in material properties. Another parameter, such as sample size, sample conditioning, test temperature, or load, needs to be used to accentuate differences between the mixtures (5).

Moisture conditioning was selected as a new parameter for this preliminary study. The sample size and test temperature were held constant because of the conventional size and available room temperature, respectively. The load used was suggested by the test method. Moisture conditioning was used to make the test more severe and to provide data that might be related to the rutting of asphalt concrete pavements.

Influence of Moisture Conditioning on Percent Permanent Strain

As was previously indicated, the authors felt that moisture sensitivity, a typical problem for Nevada mixtures, might contribute to increased permanent strain. Therefore, one sample from each of the 20 construction projects was subjected to moisture conditioning before testing. For comparison purposes, a corresponding sample from each project was also tested without conditioning.

The resulting data are presented in Table 5. A paired t-test was performed to see if these two data bases were statistically different. This type of t-test is somewhat more involved, and the statistical equation will not be presented here. However, although the calculation of a paired t-value is complicated, conclusions are drawn in the same manner as for the Student's t-test (described in the previous section).

The t_{calc} from the paired t-test was 6.82, and the t_{table} was 2.086 for a 95 confidence level. The conclusion is that the percents of permanent strain after moisture conditioning are statistically significantly different from the corresponding unconditioned values.

ESTIMATING FIELD PERFORMANCE WITH LABORATORY TESTING

A mathematical relationship describing the changes between the unconditioned and conditioned percent strains was developed with the following equation:

$$SR = (\varepsilon_U/\varepsilon_C)$$

TABLE 5 PERMANENT STRAIN DATA FOR USE IN COMPARISON OF UNCONDITIONED TO CONDITIONED SAMPLES

SAMPLE SITE	UNCONDITIONED PERMANENT STRAIN(%)	CONDITIONED PERMANENT STRAIN(%)	PERMANENT STRAIN RATIO (%)
1	0.268	0.415	154.9
2	0.289	0.390	134.9
3	0.376	0.802	213.3
4	0.410	1.791	436.8
5	0.293	0.786	268.3
6	0.333	1.386	416.2
7	0.270	0.440	162.9
8	0.311	1.098	353.1
9	0.261	0.928	355.6
10	0.339	1.269	374.3
11	0.489	0.631	129.1
12	0.292	0.697	238.7
13	0.250	0.773	309.2
14	0.410	0.413	100.7
15	0.294	1.082	368.0
16	0.287	1.000	348.4
17	0.41	0.474	115.6
18	0.474	1.401	295.5
19	0.354	0.940	265.5
20	0.339	1.363	402.1

where

SR = strain ratio,
ε_U = unconditioned percent permanent strain, and
ε_C = conditioned percent permanent strain.

The strain ratio, along with other parameters obtained from the 1988 NDOT PMS, were used to develop various prediction equations. The daily 18,000-lb ESALs were used because the data were readily available from the PMS. There were no data available for cumulative 18,000-lb ESALs.

First, a relationship between just the traffic (daily 18,000-lb ESALs) and the rut depth was developed:

$$RD = 0.026 + 0.000191(ESAL)$$

where

RD = rut depth (in.), and
ESAL = daily 18,000-lb ESALs.

The correlation coefficient (r^2) for this equation is 0.53, indicating that there is a reasonable correlation between traffic and rut depth. This is as expected.

Second, a relationship between just the strain ratio and the average 1988 rut depth was developed. The resulting equation was

$$RD = -0.0489 + 0.0448(SR)$$

where

RD = rut depth (in.), and
SR = strain ratio (%).

This equation has an r^2 of 0.34, which indicates that there is some correlation between this parameter and rut depth.

Next, both the daily 18,000-lb ESALs (1988 data) and the strain ratio were used to develop the multiple regression equation:

$$RD = -0.0574 + 0.0332(SR) + 0.000163(ESAL)$$

The combination of both parameters increased the r^2 to 0.70.

Other independent variables for pavement age, presence of antistripping additive, and the grade of asphalt were added to the regression model, and multiple stepwise regressions were developed. The multiple stepwise regression indicated that of all of these parameters only the strain ratio and daily 18,000-lb ESALs were significant. Pavement age is suspected not to be significant because of the young age of the pavements analyzed. The presence of an antistripping additive is most likely responsible for large changes in the strain ratio. Therefore, including it in any regression would be redundant.

Although these variables do not show up as significant at this time, it is likely that as the projects age and the database is expanded, pavement age and grade of asphalt will begin to be significant. It may also be that as these sites age the air void content and cumulative 18,000-lb ESALs, in place of the daily 18,000-lb ESALs, will play an increasingly important role in any prediction model.

From analysis of tnis work the authors feel that some refinement in data input is necessary for the remaining phases of this research program. For example, it is suggested that rut depth measurements be made in the same places for each site every year. These measurements should also be made as close as possible to the location where the material was sampled. The authors also believe that possibly the 80th percentile rut depth should be used. This would serve to cut down on the variability noticed in the PMS data.

CONCLUSIONS

The following conclusions can be drawn from the work completed in Phase 1 of this research program:

1. Moisture susceptibility of mixtures appears to play a significant role in permanent deformation. Therefore, moisture-conditioned samples will be included in the remaining phases of this research program.
2. None of the means of sets of three samples prepared from materials from 10 different construction projects was statistically different at a 99 percent confidence level. This would indicate that a change in test parameters (i.e., sample size, load, or test temperature) or sample conditioning is needed to create a more severe test that can distinguish between different mixtures.
3. Use of the strain ratio (i.e., moisture-conditioned percent strain/unconditioned percent strain) and the daily 18,000-lb ESALs in a multiple regression yielded the following equation: RD (inches) = $-0.0574 + 0.0332(SR) + 0.000163(ESALs)$. This equation has an r^2 of 0.70. The development of this equation was based on pavements that are 3 years old or less and daily ESALs ranging from 3 to 860. The reader should note that this equation was developed for a preliminary study to determine if moisture susceptibility were related to permanent deformation.
4. Future research is needed to look at test method variations in sample size, load, and test temperature.
5. Future pavement performance data should include rut depth measurement in the same place on each site every year and the 80th percentile rut depth. This would cut down on the variability noticed in the PMS data.

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