4-8(3)/1

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PREDICTING MOISTURE-INDUCED DAMAGE TO ASPHALTIC CONCRETE

FIELD EVALUATION PHASE

ITD-RP081-INT

INTERIM REPORT

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National Cooperative Highway Research Program
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The research reported herein is being performed under NCHRP Project 4-8(3)/1 by seven highway agencies under the general coordination of the University of Idaho.

Robert P. Lottman, Professor of Civil Engineering, University of Idaho is the principal investigator.

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Their cooperative attitude as well as their continuing diligence and interest have been extremely helpful in the conduct of the study.

ABSTRACT

This interim report presents the findings of the first 24 months of the following 60-month pavement evaluation study. A test system, developed in NCHRP 4-8(3) for the prediction of moisture damage in dense-graded asphalt concrete pavement, has been applied to laboratory specimens representing eight mixes from recently built pavements by the following participating highway agencies: Arizona, Colorado, FHWA 10, Georgia, Idaho, Montana and Virginia. The agencies are also testing cores obtained periodically from test sections of their pavements for purposes of matching the accumulated pavement moisture damage to the moisture damage predicted by the test system.

The pavement test sections represent a large range of predicted moisture damage as well as a wide range of climate and precipitation. Periodic core tests have shown an increase of retained ratios of tensile strength and resilient moduli (diametral) due to aging and moisture through the first year of pavement life. Since then, the retained ratios have decreased due to the build up of moisture and temperature effects. While it is still too early to assess the accuracy of the test system prediction, the increasing moisture damage is evident with stripping beginning in some of the moisture susceptible mixes. Final matching and evaluation will occur at the end of 60 months (July 1981).

SUMMARY OF FINDINGS

A laboratory test system was developed in NCHRP 4-8(3) whose purpose is to predict moisture damage in dense-graded asphalt concrete mixtures. Using laboratory-fabricated specimens compacted to the expected permeable voids of the intended pavement mix and made with the asphalt and aggregate materials to be used in the pavement mix, both short-term and long-term moisture damage can be predicted. Short-term moisture damage, for pavement life up to 24 months, is based on the retained mechanical properties of specimens that are vacuum saturated as compared to dry specimens. Long-term moisture damage, for pavement life up to and through 60 months, is based on the retained mechanical properties of specimens that are vacuum saturated and accelerated conditioned (freeze plus warm water soak). Mechanical properties used are tensile strength and resilient modulus (diametral loading). The retained mechanical properties are expressed quantitatively as ratios. Ratios less than 1.00 denote moisture damage; the damage increases as the ratio becomes smaller.

The above test system is now being evaluated in the current study, 4-8(3)/1, the field evaluation phase of 4-8(3). Seven highway agencies have designated eight test sections from new asphalt concrete pavements. The asphalt concrete aggregates used in most of the pavement test sections were considered to have some moisture susceptibility based on past experience. The pavement sections are in locations which have a wide range of freezing index and precipitation. Each highway agency is performing the laboratory tests and periodic sampling for

Effects of several variables are discussed in this report. Variables such as reduced permeable voids of laboratory specimens and storage time could affect moisture damage predictions. It was found that the reduction of permeable voids, about a one-third reduction, increased the predicted ratios, decreased predicted moisture damage, and may provide for better matching or since the periodic core tests show that the pavement voids are decreasing. Storage time effects, however, did not provide any significant change of predicted ratios, therefore the aging of specimens might not be necessary as a general rule.

Climate and traffic variables might influence the rate and extent of accumulated moisture damage in the pavement, but so far there is no clear effect or correlation for the pavement test sections. Also, periodic cores tested from wheel paths and from between wheel path locations show no increased moisture damage bias for the wheel path locations. About 36 months of periodic data have yet to be obtained, and it may be possible that climate and traffic effects will show up by then.

Measurement of the mechanical properties is providing test variability information for the test system. Coefficients of variation are running about 18 percent and 13 percent for pavement cores and laboratory specimens, respectively. Tensile strength measurement variability is about three percent lower than resilient modulus measurement.

In summary, not enough data have been accumulated to determine the accuracy of the moisture damage predictions. But, after 24 months it seems that the effects of environment and moisture have "settled in" the pavement and, for the pavement test sections which are predicted to have moderate to severe moisture damage, the increasing trend of moisture damage has started, with stripping beginning in some cases.

large range of prediction provides a strong basis for evaluation of the test system--a good "test of the test".

In general, the predictions (ratios) using the initial cores are about one-third greater than the laboratory specimens, implying that compaction and curing-aging conditions in the laboratory do not exactly match the pavement conditions, tending somewhat to overestimate moisture damage when using the test system. However, there did not appear to be any practical difference between core and specimen predictions for those mixes having low moisture and high damage predictions. Discussed in this report are the implications of these findings and the possibility of using three or four ranges of moisture damage prediction for specification and/or decision making purposes.

The highway agencies are obtaining sets of cores from their pavement test sections, periodically, every few months. The cores are being dried and saturated in the laboratory, and the retained mechanical property ratios are calculated. Initial pavement life, up to about 12 months, provides increased retained ratios in most cases, an interesting development. Instead of an expected gradual deterioration trend, the pavement's tensile strength and stiffness (modulus) increased more rapidly when saturated as compared to the dry state. This may be due to moisture stiffening of the asphalt mastic in the mixes. Later, the retained ratios started to decrease and the trend appears to be continuing. Most of the retained ratio decreases seemed to be confirmed after the second winter. Some of the periodic cores are now showing stripping. The pavement surface conditions (attributed to the stripping) still remain good, however.

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CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT

The phenomenon of adhesion between asphalt cement and aggregate particles in an asphaltic concrete is very complex and not clearly understood at this time. The loss of bond (stripping) due to the presence of moisture between the asphalt and the aggregate is a problem in many areas of the country and is severe from the standpoint of highway pavement performance in some instances. Although the problem is influenced by many factors, such as asphalt characteristics, aggregate properties, mix design, construction procedures, environmental conditions, and traffic, the vast amount of field experience indicates that the presence of moisture in combination with the other factors is most critical with regard to the phenomenon of adhesion between the asphalt cement and the aggregate particles.

Ultimately, identification must be made of the aggregate properties and the asphalt cement characteristics that affect adhesion. This knowledge is basic to the development of techniques that are needed for optimizing the choice of materials or for specifying appropriate corrective measures where loss of bond is likely to be a problem. However, the accomplishment of these ultimate objectives requires fundamental studies that are time consuming and necessitate the development of test systems for correlating the findings with field performance.

Research conducted under NCHRP Project 4-8(3), "Predicting Moisture-Induced Damage to Asphaltic Concrete," has provided a tentative test system for predicting the susceptibility of asphaltic concrete mixtures to moisture damage, and a general plan for a comprehensive field evaluation of the system. The essential findings are included in the final report for the project. A field study is now needed to conduct the proposed evaluation.

The objective of the field evaluation study is to provide verifications of the test system tentatively proposed in NCHRP 4-8(3) plus the addition of dynamic resilient modulus mechanical test using actual pavement test sections, and to provide additional test system modifications as necessary. The study is scheduled for 6.5 years, including 5 years of field data evaluation for each pavement test section.

Field and laboratory testing will be performed by several highway agencies using test pavements constructed in 1975 and 1976. Coordination, data analysis and correlation, and writing of reports will be accomplished by the University of Idaho.

SCOPE OF STUDY

Seven highway agencies are participating in the study. They are: Arizona, Colorado, FHWA Region 10, Georgia, Idaho, Montana and Virginia. These agencies designated a 1000 ft (305m) test section of a new asphalt pavement constructed in 1975 or 1976 for sampling and evaluation over a five-year period. (Georgia designated two such sections, one incorporating asphaltic concrete with an asphalt antistripping additive and the other without the additive.) The objective of the periodic sampling is to obtain pavement cores which are then tested to evaluate the extent of moisture damage in the pavement. The accumulated pavement moisture damage, as measured in the periodic core tests over a five-year period, is compared to the moisture damage predicted using the test system developed in NCHRP 4-8(3). Each highway agency is performing the sampling and testing for its respective pavement test section. The Final Report draft of this study, NCHRP 4-8(3)/1, is to be completed by October 1, 1981. Data cut-off for the Final Report will be during the summer of 1981.

RESEARCH APPROACH

The study is a practical field evaluation of moisture damage in asphalt concrete pavement based on a test system (method) developed in NCHRP project 4-8(3) and reported in the project's Final Report (1). The test system consists of fabricating, moisture conditioning and testing of laboratory specimens of asphalt concrete. Specimens are fabricated into three sets. One set remains dry; the second set is vacuum saturated; and the third set is vacuum saturated and then subjected to an accelerated conditioning consisting of a freeze followed by a warm water bath soak. The moisture damage prediction is based on the retained mechanical property ratios of tensile strength and resilient modulus of laboratory test specimens subjected to saturation, and to saturation plus accelerated conditioning. Test specimens have a practical size, 4 in. (10cm) diameter by 2.5 in. (6.4cm) thick. The test method details are described in ASTM format in Appendix A.

The following are the characteristics of the test system's moisture conditioning and are to be evaluated in this current study. A short-term moisture damage prediction for up to two or three years of pavement life is based on the mechanical property ratios of a set of vacuum saturated laboratory specimens and/or initial cores to a set of dry specimens and/or initial cores. A long-term prediction for up to 5 years or more is based on the mechanical property ratios of a set of saturated plus accelerated-conditioned specimens and/or initial cores to a set of dry specimens and/or initial cores.

Results from NCHRP project 4-8(3) showed that the accelerated conditioning most closely simulated the visual and mechanical properties of cores from moisture damaged pavements. The accelerated conditioning induces internal tensile stress to the asphalt concrete mixture structure through the development of internal water pressures in void fissures in the asphalt-fines matrix and at the asphalt-aggregate interfaces. The pressures are produced prior to and by the ice formation, and by the differential thermal expansion stresses between water and asphalt concrete mixture when the frozen, saturated mixture is subjected to the warm water bath. In addition, the warm water bath allows for emulsification to take place if the asphalt used in the mixture has this potential. Another result of the conditioning is that it seems to test the durability of the aggregates in the mixture, tending to break down the weaker, porous ones similar to what has been observed with weak aggregates in asphalt concrete pavement mixtures subjected to moisture.

It was desired by AASHTO that NCHRP continue with the development of the test system by applying it to new constructed asphalt pavements in the United States. NCHRP solicited agreements from seven highway agencies to participate in the study.

The University of Idaho prepared and sent to each participating agency an instructional booklet describing the test procedures and a data reporting booklet. Each participating agency was visited for purposes of aiding the start-up of the study. Each agency was requested to select an asphalt concrete pavement to be built in the agency's construction schedule for 1975-76 with an objective, if possible, of using an asphalt and aggregate combination that has potential of moisture damage. Also, each agency was requested to perform all required laboratory testing and pavement sampling.

Table 1 contains information on the eight pavement test sections constructed by the seven highway agencies. Location, pavement thickness and general materials description are listed in the table.

NCHRP project 4-8(3) showed that long range moisture damage proceeds upward from the bottom of the asphalt concrete in contact with the unbound materials or subgrade. Therefore each agency was requested to test the lowest asphalt concrete pavement core lift, cutting with masonry saw to make 2.5 in (6.4cm) high test specimen if necessary. The laboratory fabricated specimens were made with materials and permeable voids matching the lowest core lift.

A flow chart of the testing segments is shown in Figure 1. The chart shows the general complexion of the study with the central interrelationships needed for evaluation of the test system's predictability.

Beginning at the top of the chart, each agency proceeded with the obtaining of the initial pavement cores and applying the laboratory test system to predict moisture damage. Laboratory specimens were also subjected to the test system for moisture damage prediction. Laboratory specimens were made to the job mix specifications of the pavement, duplicating the asphalt content, aggregate gradation, and aggregate and asphalt type. Also, the permeable voids of the specimens were made as equal as

TABLE 1
PAVEMENT TEST SECTION LOCATIONS AND INFORMATION

STATE/ AGENCY	ROUTE	YEAR PAVED AND INITIAL CORING DATE	PAVEMENT LAYER THICKNESSES	TEST LAYER: PERIODIC CORES AND LABORATORY MIX MATCHING	TEST LAYER: MIX AGGREGATES AND ASPHALT
Arizona	Green Valley, I-19	1975 (Oct.)	7.5 in.[a] asph. conc. 10 in selected subbase	Lower 2.5 in. of asph. conc.	Santa Cruz river gravels asphalt cement (no additives)
Colorado	Arapahoe Rd., S.R. 88	1976 (Jun.)	1.5 in. asph. conc. wearing 2 in. asph. conc. leveling 7 in. asph. conc. base (3/4 in max. agg. size)	Lower 2.5 in. of asph. conc. base	Morrison cr. stone - coarse agg. Platte River (Littleton) - fine agg. asphalt cement (no additives)
FHWA Region 10	West Entrance Rd. Crater Lake N.P.	1975 (Nov.)	2 in. asph. conc. 10 in. cr. stone base	2 in. of asph. conc.	Pole Creek stockpile, Klamath County, w/14% blend sand asphalt cement (no additives)
Georgia	Walton County, US 78.	1977 (Mar.)	1.5 in. asph. conc. wearing 2 in. asph. conc. leveling 7 in. asph. conc. base (3/4 in. max agg. size)	Lower 2.5 in. of asph. conc. base	granite gneiss asphalt cement w/5% additive. all layers
Georgia	Walton County, U.S. 78	1977 (Mar)	1.5 in. asph. conc. wearing 2 in. asph. conc. leveling 7 in. asph. conc. base (3/4-in. max agg. size)	Lower 2.5 in. of asph. conc. base	granite gneiss asphalt cement w/.5% additive in wearing and leveling and top 3 in. of asph. conc. base only. Lower 4 in. of base without additive.
Idaho	Whitebird, US 95	1975 (Nov.)	3.6 in. asph. conc. 8.4 in.cr. stone base	Lower 2.5 in. of asph. conc.	Salmon River gravels asphalt cement mix additive: 1% hydrated lime

TABLE 1. (cont.)
PAVEMENT TEST SECTION LOCATIONS AND INFORMATION

STATE/ AGENCY	ROUTE	YEAR PAVED AND INITIAL CORING DATE	PAVEMENT LAYER THICKNESSES	TEST LAYER: PERIODIC CORES AND LABORATORY MIX MATCHING	TEST LAYER: MIX AGGREGATES AND ASPHALT
Montana	Deer Lodge Pass South, I-15	1976 (Jul)	4.8 in. asph. conc. 16.8 in cr. stone base	Lower 2.5 in. of asph. conc.	bench gravels asphalt cement (no additives)
Virginia	Greenwood Dr. Portsmouth I-264	1976 (May)	1.5 in. asph. conc. wearing 5.5 in. asph. conc. base (1 in max. size) 6 in. compacted agg.-sand 6 in. cement stabil. sub-grade	Lower 2.5 in. of asph. conc. base	granites - coarse agg. natural sand asphalt cement (no additives)

Note:

a. 1 in. = 2.54 cm.

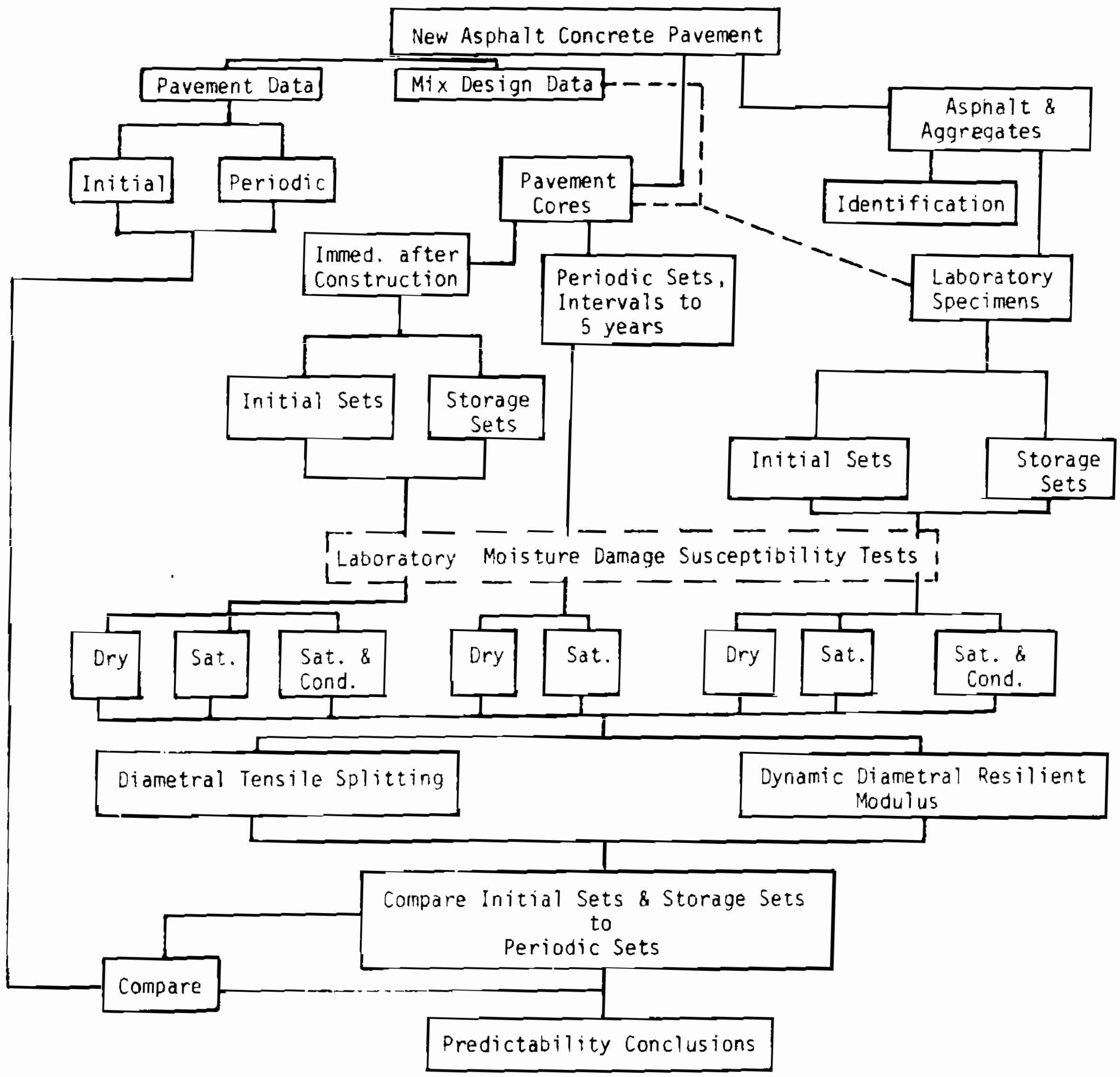

Figure 1. Flow Chart of Main Aspects of NCHRP 4-8(3)/1 Field Evaluation Phase

possible to the initial pavement cores.

The participating agencies have now completed the prediction tests and are currently into the longer phase--the periodic pavement core tests. For most of the pavement test sections, this phase has now reached two years and will continue to the end of the project. At that time there should be adequate pavement data to determine the extent of pavement moisture damage and the accuracy of the test system to predict moisture damage.

In addition to the principal objective of determining how well the NCHRP 4-8(3) test system will predict the magnitude of moisture damage, the following comparisons will also be made in the study for purposes of test system refinement and general information:

- Traffic loading. Traffic accumulation on each pavement test section will be recorded. Also, the effects of moisture damage in the wheel paths versus between wheel paths will be analyzed to determine if dynamic loading affects the moisture damage prediction based on the test system results.

- Aging of test specimens and pavement cores. The effect of several room-air storage time intervals on the prediction of moisture damage will be evaluated to determine if the test system will require laboratory aging periods for laboratory specimens and initial cores. The increase and decrease of the mechanical properties of periodic cores over the five-year sampling period will also be recorded for general information.

- Laboratory specimens and initial pavement cores. Although each agency made laboratory specimens with the same materials, blends and permeable voids as the initial pavement cores of their pavement test section, the mechanical properties may not be equal. This may be due to compaction and aging differences. Consequently the moisture damage predictions for the pavement test sections may be different depending on whether the test system was applied to laboratory specimens or initial pavement cores. An analysis will be made to determine if this difference exists and if it is significant enough to warrant a change of laboratory specimen fabrication and aging.

- Reduced permeable voids. The voids in many pavement mixtures reduce with time and traffic. The effect of reduced laboratory specimen permeable voids on moisture damage prediction will be assessed with respect to the actual long-term, pavement test section moisture damage.

- Climate. Each of the pavement test sections has different annual precipitation and temperature characteristics. Precipitation ranges from 4 to 50 in. (10 to 127cm) and freezing index ranges from 0 to 1250 degree F days (0 to 694 degree C days.) The time build-up of moisture into the bottom of the pavement may be related to precipitation. The magnitude of moisture damage may be related to freezing index. These effects will be noted as the study progresses.

- Test variability. Since each highway agency performs tensile strength and resilient modulus tests, the coefficients of variation of each four-specimen or core set of test data used for calculating the mean value-reported data will be determined for each test type, each agency, and for all the agencies combined. This test variability information is important in order to assess accuracy and levels of moisture damage prediction for future use of the test system.

- Test system improvement. Each participating highway agency is evaluating the test system for improvements in the conditioning, testing and overall efficiency of the operation. At the end of the study, agency comments will be evaluated with an objective of determining any further practical improvements in the test system.

CHAPTER 2

FINDINGS

INTRODUCTION

The findings reported herein represent approximately the first two years of pavement test section evaluation and therefore can be classified as progress information. The pavement test data are being received every few months from the highway agencies and will continue three years after the July 1978 data cut-off; accumulated data reported up to July 1978 are included in this Interim Report. However, complete data for the moisture damage predictions now exist for seven of the eight pavement test sections and are reported first in this chapter. Due to past FHWA budget restrictions, some data for the FHWA 10 Crater Lake pavement test section could not be obtained. However, their test project has now been re-budgeted and post two-year data will become available for the study.

Chapter 2 is presented in several sections. The first two sections, moisture damage predictions and pavement moisture damage trends, relate to the main objective of comparing laboratory prediction of moisture damage to pavement moisture damage build-up measured by testing the periodic cores. Sections which follow discuss data of variables that may be pertinent to moisture damage predictions, mentioned previously at the end of Chapter 1.

Central to the first two sections, and some other sections which follow, are the main graphs in Appendices B, C, and D. Mechanical property ratios for each test agency are graphed to present moisture damage predictions relative to the average pavement moisture damage trends. Plotted also are the moisture damage trends for the pavements' wheel path and between path locations in the traveled lane, being cored at periodic intervals. Short-term predictions are plotted vertically on the left of the graphs representing vacuum saturation, and long-term predictions are plotted vertically on the right of the graphs representing vacuum saturation plus accelerated conditioning.

A characteristic of this study is that each highway agency's data are being analyzed as an independent set of data, as well as being evaluated as a combined effort for measuring the effectiveness of the laboratory test system's predictability. Therefore, data presented in the tables and figures in this chapter and in the appendices may, at first, appear prolific for this kind of report, but the basic intention is to show data analysis from each of the eight pavement test sections; this does require longer tables and more figures than usual.

It should be emphasized that each highway agency is responsible for doing the moisture damage testing for its pavement test section, rather than a single research testing agency doing all the testing for all the pavement test sections. The working plan for this study specified this arrangement in order to develop more of a "real life" situation and, at the same time, provide a wide range of experience with the test system. Thus the data presented reflect individuality of testing personnel, problems, successes and hard work. Test variabilities presented later in this chapter are indicative of what could be expected nationwide when using the test system.

MOISTURE DAMAGE PREDICTIONS

Moisture damage predictions are based on the application of the test system (Appendix A) using the retained mechanical properties (ratios) of tensile strength (indirect or diametral tension) at 55 F (13C) and resilient modulus (diametral tension) at 73F (23C) and 55F (13C). Sets of laboratory fabricated specimens and initially obtained pavement cores were tested at various room and storage times including zero storage time equivalent to the standard time for performing Marshall or Hveem stability tests. The permeable voids and materials of the initial pavement cores were duplicated in the laboratory specimens. Three highway agencies were able to further compact sets of laboratory specimens to lower permeable voids, and these reduced void specimen sets were also evaluated for moisture damage. Moisture damage predictions for each of the sets are plotted on the vertical axes in the figures of Appendices B, C, and D.

Average values of moisture prediction for the initial core sets and for the laboratory specimens are listed in Table 2 for each agency. Also listed are the average predictions based on reduced void specimens. The purpose of Table 2 is to show the several levels of moisture damage prediction, short term and long term, which are expected for the pavement test sections.

The short term predictions (vacuum saturation) give higher ratios than the long term predictions (vacuum saturation plus accelerated conditioning) for the mix of a given pavement test section; this is to be expected. In some cases, the short term prediction (saturated ratios) are greater than 1.00. This means that the mechanical properties measured for saturated core and specimen sets are greater than those for dry sets. (Retained strength ratios, or percentages, greater than 1.00, or 100%, have also been recorded at times when using the immersion compression

TABLE 2
AVERAGE MOISTURE DAMAGE PREDICTIONS

Agency/Test Pavement Location	Mechanical Property Ratios[1] Tensile Strength Ratio 55 F (13C)				Resilient Modulus Ratio 73 F (23C)				Resilient Modulus Ratio 55 F (13C)			
	Initial Cores		Laboratory Specimens		Initial Cores		Laboratory Specimens		Initial Cores		Laboratory Specimens	
	Sat.[2]	Cond.[3]	Sat.	Cond.	Sat.	Cond.	Sat.	Cond.	Sat.	Cond.	Sat.	Cond.
Arizona	.66	.37	.52	.23	.93	.72	.74	.46	n.a.[4]	n.a.	n.a.	n.a.
Colorado	.90	.37	.72 (.74)[a]	.22 (.23)	1.05	.53	.79 (.89)	.25 (.28)	.86	.42	.74 (.74)	.22 (.23)
FHWA 10	.94	.61	(.81)	b.	1.02	.68	(.84)	b.	1.03	.72	(.95)	b.
Georgia (no additive)	.92	.34	.92	0	.89	.33	.80	0	.78	.39	.98	0
Georgia (no additive)	1.06	0	[a]90	0	1.09	0	1.00	0	1.17	0	.86	0
Idaho	.86	.77	.87 (.95)	.81 (.87)	.87	.80	.85 (.96)	.82 (.88)	n.a.	n.a.	n.a.	n.a.
Montana	.97	.62	.76 (.85)	.49 (.65)	.86	.75	.80 (.81)	.56 (.71)	.78	.60	.81 (.81)	.45 (.54)
Virginia	1.00	.57	1.06	.41	1.14	.54	1.11	.40	.96	.61	1.06	.47

NOTES:

1. Ratios entered are average values from different initial core and laboratory specimen room storage times.
2. Vacuum saturated.
3. Vacuum saturated plus accelerated conditioned.
4. n.a. (not available). Not programmed by agency due to early start-up of laboratory tests.

a. Numbers in parentheses represent ratios of reduced void laboratory specimens.
b. Predictions not completed at cut-off date for this report.

test method.) While the predicted saturated ratios are high for most of the mixes, they are lower for the tensile strength test on the Arizona mix (.66 for the cores, and .52 for the laboratory specimens.) Thus one would expect the tensile strength-tested periodic cores in the Arizona pavement section to show more moisture damage sooner.

Long term moisture damage predictions based on the conditioned ratios are lower than the short term. None of the conditioned ratios are above 1.00 and all are below the saturated ratios, as expected. How-ever, in contrast to the saturated ratios, the conditioned ratios reflect greater differences between the pavement section mixes. For instance, conditioned ratios for the Idaho mix are around .80 and thus the long term prediction for the Idaho pavement section is about a 20% reduction of mechanical properties due to moisture damage. In contrast, the conditioned ratio for the Georgia mix, especially with the additive, is 0, a long term prediction of 100% reduction of mechanical properties. In between these two mixes are the conditioned ratios for the mixes of the other pavement sections. Consequently a wide range of long term moisture damage prediction is established and should form a basis of test system evaluation.

Following the tensile strength tests, the interiors of cores and specimens are examined for stripping. Stripping was observed in all mixes subjected to vacuum saturation plus accelerated conditioning with the exception of the Idaho mix. Generally the severity of stripping was inversely proportional to the ratios, as expected, but the stripping appeared severe enough to obscure particular correlation to a specific ratio magnitude because of the variety of mixes tested.

The predictive ratios, averaged in Table 2, are different for different pavement test sections. Also these differences are due to type of mechanical property test performed and due to whether sets of pavement cores or sets of laboratory specimens were tested. The comparative differences between specimens and cores will be discussed later in this chapter, and a brief discussion of the ratio differences due to the type of mechanical property test will appear in Chapter 3.

PAVEMENT MOISTURE DAMAGE TRENDS

Moisture damage accumulation in each pavement test section is being measured by performing laboratory tests on sets of cores obtained at prescribed time intervals from time of paving construction. These periodic intervals are four months for the first 24 months and six months for the remaining 36 months of the five-year evaluation.

Four sets of four cores each are being obtained randomly from each pavement test section in the traveled lane at each prescribed time. Two of these periodic cores sets are obtained in the wheel paths, the other two are obtained between the wheel paths. The periodic cores are taken to the laboratory, the lower lift is removed from each core and desiccated to constant weight. (The desiccation time has averaged four to five weeks so far in the study.) Then one set of the wheel path and one set of the between wheel path cores (lower lifts) are vacuum saturated as prescribed in the test system's procedure for saturation. All the sets of cores are then brought to the test temperature and the mechanical properties are obtained.

The mean of the saturated mechanical property value of a four-core set is divided by the mean value of a matching four-core set tested dry in order to obtain a moisture damage ratio for the wheel path and for the between wheel path locations. These ratios are plotted in the figures of Appendices B, C, and D. The moisture damage trends, as measured by these ratios, can be observed relative to the short term (saturated) and the long term (conditioned) predictions for each pavement test section and for each of the three mechanical properties. A larger scale, more summarized relative pictorial of these trends is shown in Figures 2, 3, and 4.

Observed first in Figures 2, 3, and 4 are the shapes of the mechanical property ratio versus pavement age curves for each pavement section. Each pavement section has its own characteristic trend or profile and, at present, it is difficult to categorize the trends into pavement characteristic profiles. In most cases, the ratios are decreasing, proceeding in a downward trend. This is especially true for the older pavement sections, where the moisture build-up and environment effects seem to have developed a presence in the bottom of the asphalt concrete portion of the pavement sections. The exception to the downward ratio trend is the Idaho pavement which shows a developed zig-zag profile around 1.00.

For most of the pavement sections and mechanical properties, the ratios increased over 1.00 as the pavements aged up to and through 12 months. Ratios greater than 1.00 were also observed in the laboratory predictive tests (saturation), mentioned in the previous section of this chapter. The figures show that the pavement initial ratios can be lower than the ratios at 8 months; for example, see the Colorado curve in Figure 2 and the Georgia (no additive) curve in Figure 4. Exploration of these ratio increases will be discussed briefly in Chapter 3.

Presently the ratios are below 1.00 for most of the pavements as

Note: I P = Average range of long term moisture damage prediction

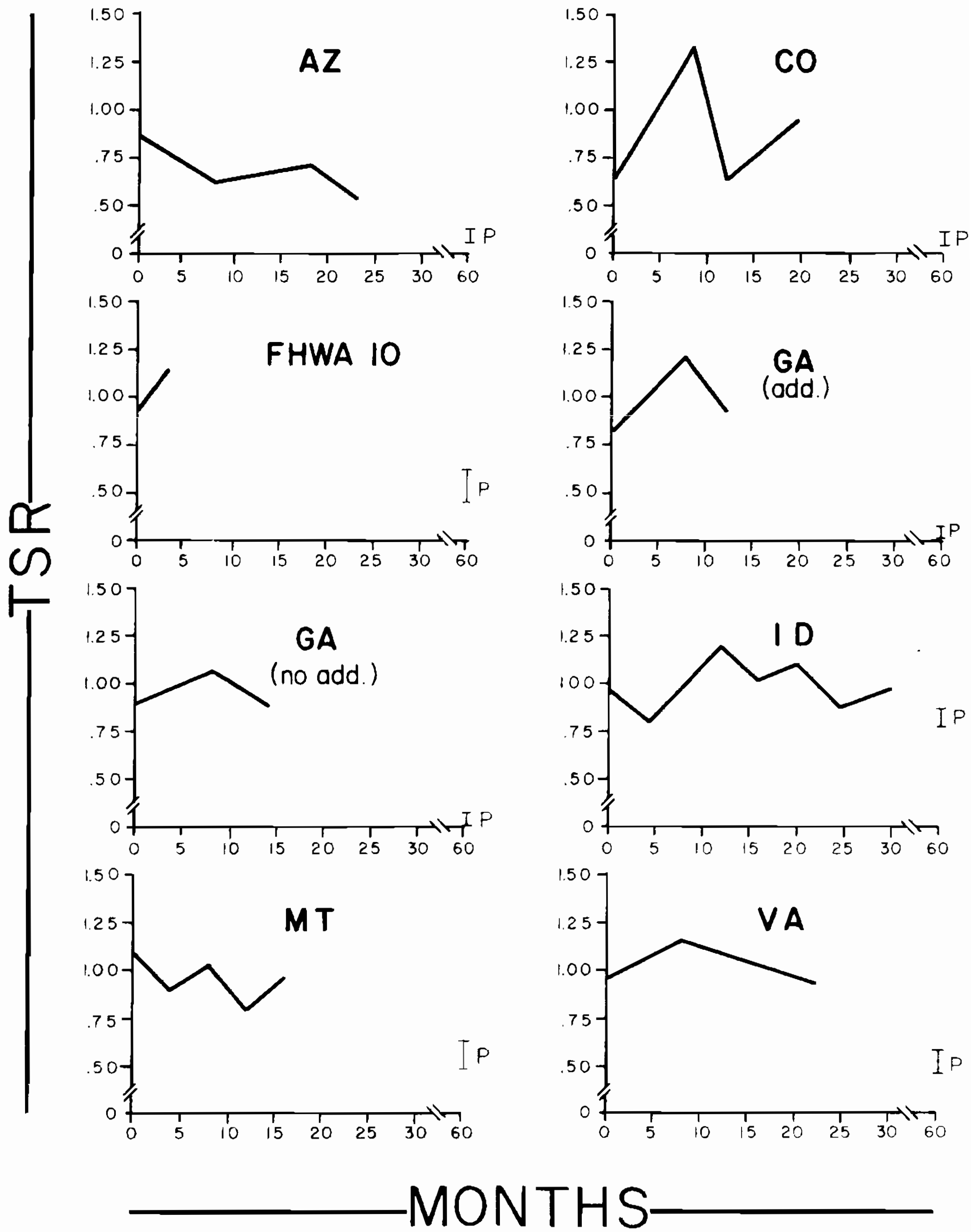

Figure 2. Tensile Strength Ratio Trends with Pavement Age, 55F (13C)

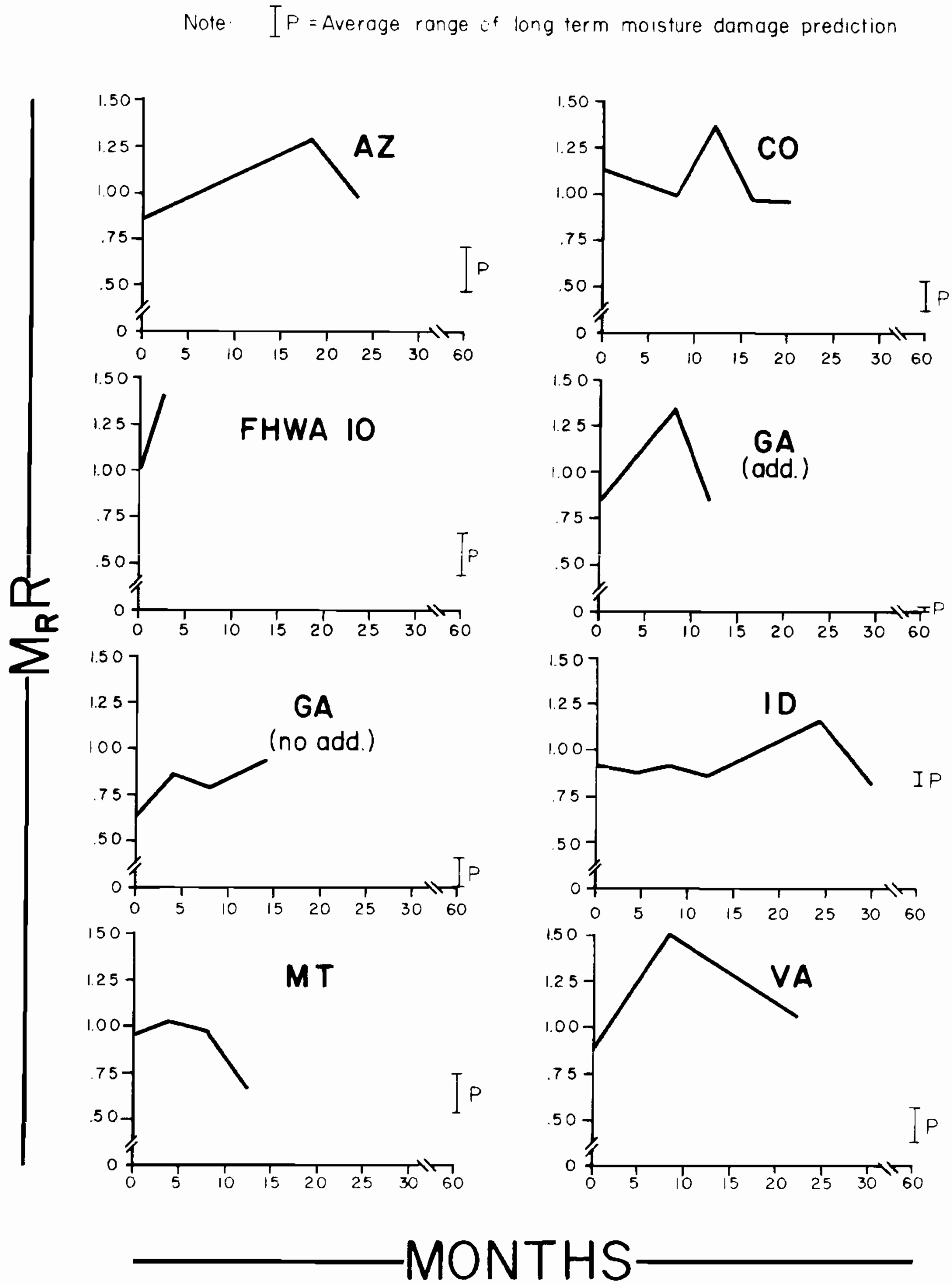

Figure 3. Resilient Modulus Ratio Trends with Pavement Age, 73F (23 C)

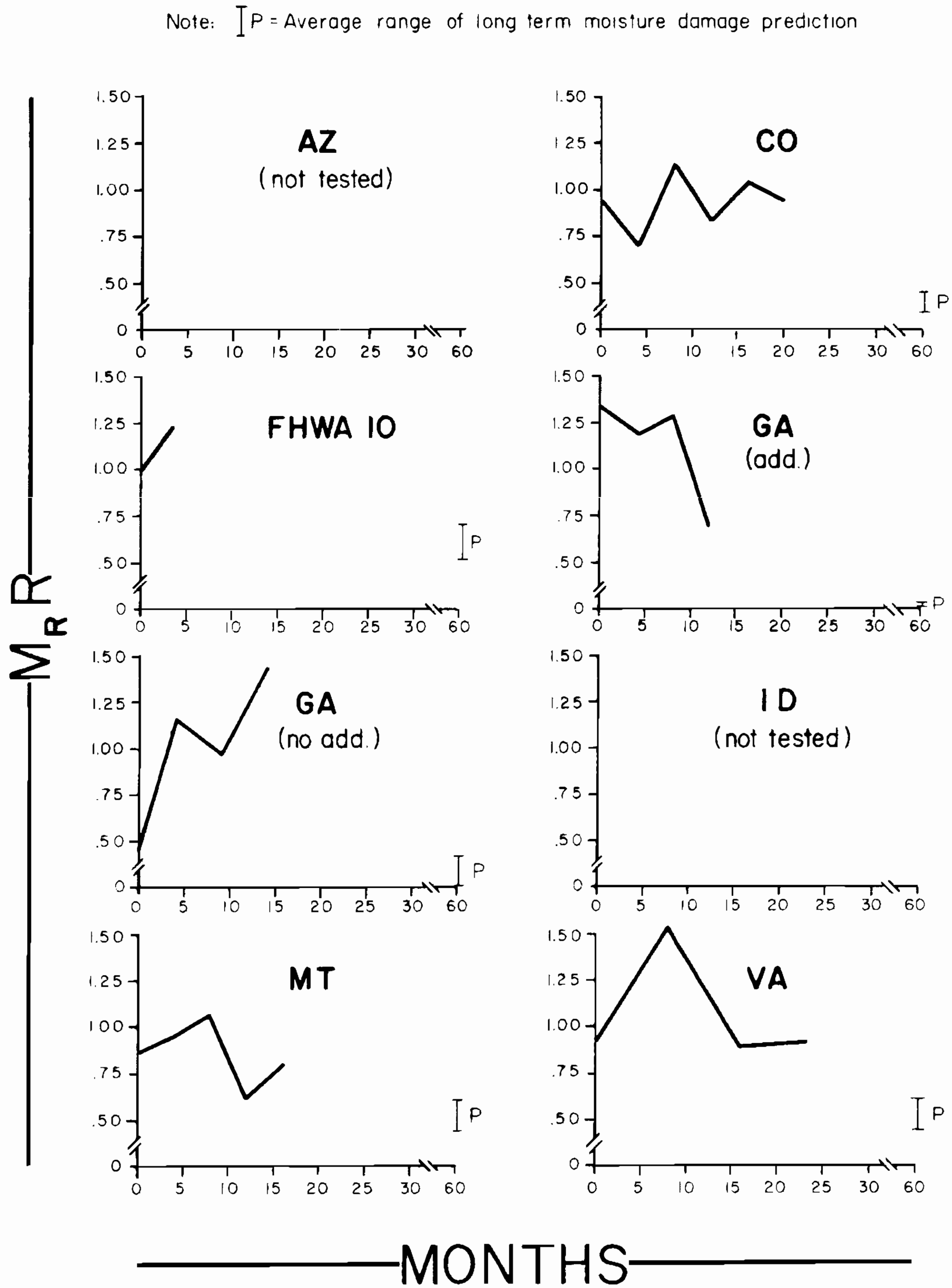

Figure 4. Resilient Modulus Ratio Trends with Pavement Age, 55F (13C)

shown in the right portions of the trend curves. Stripping is being observed in some of the periodic cores where the ratio decrease has become significant. It is apparent that the moisture damage in most of the pavements is now passing through the short term predictive time frame.

The average long term (conditioned) prediction ratio range for each pavement mix is shown in Figures 2, 3 and 4 vertically on the right side of each individual graph. These prediction ratio ranges are most important because the periodic pavement ratios must evidentially meet the prediction ratio ranges for accurate prediction using the test system. The allotted time for this study is 60 months, at which time it is hoped that the evaluation can take place; the pavements would have run through their significant course of moisture damage. While it is still too early to support an accurate prediction, the pavement trends in the figures do show that a downward ratio trend is now in progress.

While there are some differences in the pavement trends due to the type of mechanical property used to determine the ratios, a combined evaluation shows there are similar trends for a given pavement section with only a few exceptions. When all the pavements reach past 24 months, more definitive patterns will emerge. A choice of a single mechanical property test is desirable, if possible, for the test system application.

Visual pavement surface cracking and ride deterioration due to moisture damage in the bottom of the asphalt concrete are not observed at present. The surface condition of each pavement test section is being evaluated more or less on a continuous basis.

The following sections are related to the effect of several moisture damage prediction variables as well as variables which affect pavement moisture damage trends.

TRAFFIC LOADING

Some knowledge of the traffic loading effects on moisture damage in the pavement test sections is necessary in order to assess the traffic as well as the climatic influence equivalency of the accelerated conditioning portion of the test system. Traffic is being evaluated two ways.

One of the ways is to compare the periodic pavement ratios from the wheel paths to the ratios from between the wheel paths. The data from the periodic core sets are being handled independently and the ratios are plotted as separate data in the figures of Appendices B, C and D. At the present time there is no definitive trend. Moisture damage ratios of wheel path cores show lower ratios about half of the time as compared to the ratios of between wheel path cores. When the wheel path core ratios are lower, they average about .08 lower.

The second way that traffic effects are being evaluated is through the recording of the annual and accumulated 18 kip single axle load equivalents on each pavement test section. These data will then be used as the basis for evaluating the potential for rate of increase of wheel path moisture damage to the actual wheel path moisture damage.

The following is a listing of 18 kip (80 kN) equivalent SAL's per year for each agency. Arizona = 65,000; Colorado = 27,000 ; FHWA 10 = 5 ; Georgia (add. and no add.) = 130,000; Idaho = 25,000 ; Montana = 26,000 ; and Virginia = 5,037.

AGING OF SPECIMENS AND PAVEMENT CORES

Aging effects are being evaluated by comparing the moisture damage ratios to different room-air storage times in the laboratory, and to ratios and magnitudes of mechanical properties of periodic pavement cores. Pavement matching data of the test system development study, NCHRP 4-8(3), indicated that aged laboratory specimens would provide slightly greater moisture damage ratios than "unaged" laboratory specimens. It was thought the slightly greater ratios would provide more accurate matching to the acutal long-term pavement ratios.

Laboratory Storage

When all the testing was under way by the highway agencies, moisture damage ratios were determined for sets of initial pavement cores (four cores each set) and four sets of laboratory specimens (four specimens each set) at different room-air storage times. Storage times were established at 2, 5 and 10 months. Highway agencies which started early used 8, 12 and 16 months. Cores and specimens were stored uncovered on open shelves in the laboratory with dust protection.

The moisture damage ratios obtained were compared to the respective storage times. In most cases increases of storage time did not increase the ratios. An exception is the Virginia mix; increase of storage time tended to increase the ratio. When final Virginia pavement trends are determined, the significance of the ratio increase with storage time will be determined.

The figures in Appendices B, C and D show the individual storage time ratio predictions for the cores and specimens, short term (saturation) as well as long term (conditioned).

It was expected that the storage times would produce greater magnitude of mechanical properties, and they did. Testing variability effects probably caused some of the storage time mechanical properties to maximize at times less than the maximum storage times used, but nevertheless the aging effects are present.

Table 3 shows the relative increase of the mechanical properties of the initial pavement cores as compared to the laboratory specimens. A comparison to the periodic core data of the pavement test sections shows that the relative increase of mechanical properties is currently about the same as the maxima obtained from laboratory storage. However, there are indications that aging will continue in the pavement test sections, the relative increase of the pavements' mechanical properties being greater than the storage increases. The Colorado pavement is an example of this. On the other hand, as moisture damage increases, the net change of mechanical properties in the pavement sections will reduce. Perhaps, then, the laboratory storage time of 10 months or so is equivalent to 20-24 months of pavement age in terms of relative increase of mechanical properties due to aging.

Pavement Test Sections

The maxima of the relative increase of mechanical properties is shown for each pavement section under the column labeled "Periodic Pavement Cores" in Table 3. The graphs of relative trends, however, are shown in Appendices E, F and G. Some of these increases can be high, some relatively low, perhaps due to factors such as permeable voids and asphalt composition which affect aging rate. It is interesting that the relative increases for the Virginia pavement section have now ceased

TABLE 3
MAXIMUM RELATIVE INCREASE OF MECHANICAL PROPERTIES OF INITIAL PAVEMENT CORES AND LABORATORY SPECIMENS DUE TO AGING COMPARED TO ZERO MONTH ROOM STORAGE OR ZERO MONTH PAVEMENT AGE

Agency/Test Pavement Location	Tensile Strength Increase 55°F (13°C)								Ir
	Initial Cores[1]			Laboratory Specimens[1]			Periodic Pavement Cores[2]		
	Dry	Sat.[3]	Cond.[4]	Dry	Sat.	Cond.	Dry[5]	Sat.	Dry
Arizona	1.49(16)[a]	1.32(16)	1.33(16)	1.20(12) 1.41(10)	1.85(8) 1.[illegible](10)	1.47(16) 1.33(10)	1.52(23)	1.27(12)	1.42(1[illegible]
Colorado	1.39(5)	2.13(10)	1.13(10)	R1.46(10)[b]	R1.25([illegible])	R1.1[illegible](10)	1.82(12)	2.68(20)	2.5[illegible](5)
FHWA 1	1.00(0)	1.14(2)	1.00(0)	R1.00(0)	R1.00(0)	-	1.00(0)	1.00(0)	1.34(2)
Georgia (additive)	1.32(10)	1.29(5)	-	1.00(0)	1.00(0)	-	1.42(1)	1.85(4)	1.00(0)
Georgia (no additive)	1.00(0)	1.00(0)	-	1.00(0)	1.00(0)	-	1.00(0)	1.00(0)	1.08(2)
Idaho	1.79(30)	1.65(10)	1.13(10)	1.02(10) R1.17(10) 1.04(5)	1.39(10) R1.39(10) 1.42(10)	1.43(10) R1.21(10) 1.00(0)	1.85(8)	1.72(20)	1.58(1[illegible]
Montana	1.72(30)	1.42(5)	1.20(10)	R1.35(2)	R1.64(10)	R1.76(10)	1.42(12)	1.26(16)	1.99(1[illegible]
Virginia	1.38(10)	1.42(10)	1.[illegible](10)	1.36(5)	1.39(5)	1.60(10)	1.74(16)	1.95(8)	1.61(1[illegible]

NOTES.
1. Aging effects due to room storage in laboratory as compared to initial (zero storage time) laboratory specimens.
2. Aging effects due to actual pavement environmental conditions as compared to initial (zero
3. Vacuum saturated
4. Vacuum saturated plus accelerated conditioned
5. Desiccated dry in laboratory.
6. n.a. (not available). Not programmed by agency due to early start-up of laboratory tests.
a. Number in parentheses following relative increase value is room storage time or pavement service life in months at maximum increase occurrence to date.
b. Values preceded by R refer to laboratory specimens at reduced voids.

and there is now a decrease of mechanical properties. This is attributed to the drop in moisture damage ratio and the observation of stripping.

Maximum Ratio Predictions Using Storage Time

Moisture damage ratios predicted at different laboratory storage times, shown in the figures of Appendices B, C and D, reach maximum values greater than 1.00 at certain storage times. This effect is similar to the peaking effect of ratios occuring in the periodic cores of the pavement test sections mentioned previously. These maxima did not always occur as a function of storage time, but when they did there was also a maxima observed in the pavement section. For example, no tensile strength ratio maximum occurred with laboratory storage time for the Montana initial cores and laboratory specimens, and no tensile strength ratio maximum occurred in the Montana test pavement as measured by periodic core tests. Conversely, a tensile strength ratio maximum did occur with storage time for the Virginia initial cores and specimens, and a tensile strength ratio maximum also occurred in the Virginia pavement as measured by periodic core tests. The laboratory storage time maximum may occur at 5 months, for example, and the pavement section maximum may occur at 8 months of pavement age. So, the laboratory tests at different storage times can provide evidence that the moisture damage ratios will maximize and exceed 1.00 during the early life of a pavement. However, the data analysis indicates that more specific conclusions such as the time and the actual ratio predicted for the maximum in the field may not be practical yet, but only possible.

PREDICTABILITY DIFFERENCES FROM SPECIMENS AND INITIAL CORES

The test system should be applied to laboratory fabricated specimens for moisture damage prediction, not to initial pavement cores after the pavement is placed, because decisions then can be made ahead of time for selection of aggregate, asphalt and additive that will minimize moisture damage. Therefore the current state of the art of laboratory specimen fabrication involving the type of mix curing and the type of compaction which follows may produce specimens that have different mechanical properties than the actual compacted pavement mix (cores). While these differences are generally accepted as being insignificant to significant, depending on the application, what is not known is their specific influence on moisture damage ratio. Large differences will be significant.

In Table 4, a brief listing of the laboratory mix curing and laboratory compaction for specimen fabrication is shown for each highway agency.

The average mechanical property magnitudes of the initial cores and the laboratory fabricated specimens tested at zero storage time are listed in Table H-1 (Appendix H). For a given pavement section the magnitudes are not the same, sometimes a 100 percent difference is noted. On the other hand, reductions in magnitudes produced by the laboratory moisture conditioning followed similar patterns for the cores and for the specimens.

Moisture damage prediction ratios for cores and specimens are listed in Table 2 and are plotted in the figures of Appendices B, C, and D. From these data it appeared that, as a group, the initial core ratios were greater than the laboratory specimen ratios. Thus, the relative average increase of the moisture damage prediction ratios for the cores

TABLE 4
CURING AND COMPACTION OF LABORATORY MIXES

Agency	Loose Mix Curing Conditions Prior to Compaction	Type of Compaction
Arizona	Overnight @ 75 F (24 C); then heat 1 hr @ 240 F (116 C)	Combination of Marshall, Hveem and Arizona gyratory
Colorado	1 hr @ 160 F (71 C)	Hveem kneading
FHWA 10	16 hr @ 140 F (60C)	Hveem kneading
Georgia	none	Marshall
Idaho	15 hr @ 140 F (60 C)	Hveem kneading
Montana	none	Marshall
Virginia	15 hr @ 140 F (60 C)	85 blows with kneading compactor plus 10 blows with drop hammer

as compared to the specimens were calculated and listed in Table 5. The ratio averages used represent all the laboratory storage times including zero storage time, not specific storage time.

Table 5 shows that, as a group, moisture damage ratio predictions using initial pavement cores are greater than the ratios using laboratory specimens. For most pavement sections, these relative increases are about one-third greater.

An exception would be the Idaho mix where there was no relative increase, the values being close to 1. Also, relative increases appeared to be greater for ratios produced by vacuum saturation plus accelerated conditioning than by vacuum saturation only, but there are exceptions, e.g. Idaho and Georgia (add.) mixes.

The mix curing and compaction differences observed in Table 4 could not be correlated specifically to the specimen versus core ratio differences.

If the initial cores from the pavement sections are more representative of the compacted pavements than the laboratory fabricated specimens, one would place more weight on the moisture damage prediction ratios of the initial cores. The practical significance of this could be minimized, however, by considering three factors. First, if this study shows that moisture damage predictions are best applied by considering the levels or ranges of damage, then the one-third greater ratios of the cores may be minimized compared to the specimens. For example, suppose the long term moisture damage ratio predicted by using laboratory specimens is .30, then the ratio predicted by using initial cores could be .40. Both these ratios are low enough in level for one to reach a decision that there will be considerable moisture damage in the mix and

TABLE 5
RELATIVE INCREASE OF AVERAGE MOISTURE DAMAGE PREDICTION RATIOS OF INITIAL PAVEMENT CORES COMPARED TO LABORATORY SPECIMENS

Agency/Test Pavement Location	Mechanical Property Increase: Tensile Strength 55 F (13C)		Resilient Modulus 73 F (23C)		Resilient Modulus 73 F (13C)	
	Sat.[1]	Cond.[2]	Sat.	Cond.	Sat.	Cond.
Arizona	1.27	1.61	1.26	1.57	n.a.[3]	n.a.
Colorado	1.25	1.68	1.33	2.12	1.16	1.91
FHWA 10	1.16	-	1.21	-	1.08	-
Georgia (additive)	1.18	1.00	1.09	1.00	1.36	1.00
Georgia (no additive)	1.00	3+	1.11	3+	.80	3+
Idaho	.99	.95	1.02	.98	n.a.	n.a.
Montana	1.28	1.27	1.08	1.34	.96	1.33
Virginia	.94	1.39	1.03	1.35	.91	1.30

NOTES:
1. Vacuum saturated.
2. Vacuum saturated plus accelerated conditioned.
3. n.a. (not available). Not programmed by agency due to early start-up of laboratory tests.

therefore remedies will be needed. In this way the ratios predicted by laboratory specimens have served the same purpose for all practical purposes.

Second, it is always possible for a highway agency to multiply the ratios determined from the use of laboratory specimens by a factor, e.g. 1.3, to achieve ratios close to the ratios of initial cores. And, third, a highway agency could change its compaction procedure and/or its mix curing procedure to produce laboratory specimens that will give closer ratios to the initial pavement cores.

Since the above findings are based on ratio averages for all the storage times, it may be possible that laboratory specimen ratios at a specific storage time may provide predictions that are more accurate when the study is completed. However, the above group findings will still be valid.

REDUCED PERMEABLE VOIDS

In addition to the use of laboratory specimens for providing mix moisture damage predictions before the pavement is built, another advantage of using laboratory specimens is that they can be compacted at reduced voids to simulate the reduction of permeability that may occur in the pavement over the first few years. It is known that reduced voids (permeability) can reduce moisture damage by decreasing the magnitude of damage and/or by increasing the time for significant damage to occur. The ratios determined from reduced void specimens would then give a more accurate long term moisture damage prediction, providing there is evidence that the permeable void reduction will occur in the pavement.

The highway agencies participating in this study were asked to find the moisture damage ratios for reduced void laboratory specimens. Several sets of laboratory specimens had already been fabricated to match the permeable voids of the initial pavement cores. The agencies then tried to compact other sets of specimens to achieve about a one-third reduction of permeable voids. After much effort, it was concluded that most of the mixes could not be compacted further without causing aggregate fracture or without using special compaction equipment not readily available. However, three agencies were able to achieve reduced permeable voids in laboratory specimens. Their percentages of original voids are: Colorado = 69%, Idaho = 72%, and Montana = 52%.

The moisture damage prediction ratios for these mixes are listed in Table 2 and are plotted in the figure of Appendices B, C and D. The reduced permeable voids caused a reduction of moisture damage, the ratios being greater than the full-void specimens. The significant increase in the ratios (reduction of moisture damage) occurred in the Montana mix, providing up to a 50 percent increase in the ratio for the vacuum saturated plus accelerated conditioned specimens.

Magnitudes of the mechanical properties of the specimens at reduced voids can be compared to the full-void specimens at zero storage time in Table H-1 (Appendix H). For the Colorado and Idaho mix tests, the mechanical properties of the reduced void specimens increased.

The relative increases of the magnitudes of the mechanical properties of reduced-void specimens due to the aging effect of laboratory storage time are shown in Table 3. When compared to full-void specimens, reductions in the mechanical property increases occurred for the

Colorado and Idaho mixes, but did not occur for the Montana mix.

The periodic core tests for measuring the accumulated moisture damage of the pavement test sections also provide permeable void data. One half of the cores are vacuum saturated and the weights obtained are used to calculate the permeable voids. The numbers in parentheses next to the pavement (ratio) trend periodic points, plotted in the figures of Appendices B, C, and D, are the average permeable voids calculated for a periodic set of pavement cores. The voids have reduced in all the pavement sections except the Arizona and Virginia sections, and the current percentages of initial voids are: Colorado = 89%; FHWA 10 = 95%; Georgia (add.) = 69%; Georgia (no add.) = 75%; Idaho = 47%; Montana = 74%. Since there are moisture damage prediction ratios for reduced voids for the Colorado, Idaho and Montana mixes, it will be possible to compare their reduced-void predicted ratios with their periodic core ratios later in the study. Although this will be helpful, there probably will not be the exact, desired matching because the pavement reduced voids may end up to be unequal to the laboratory specimen reduced voids.

CLIMATE

Freezing index and precipitation are being recorded by each participating agency from a weather station nearest to their pavement test section locations. Table 6 shows the values for the first two years of the study.

The accelerated conditioning of the test system emphasizes freezing, temperature change and warm soaking. Climates with high freezing indices

TABLE 6
CLIMATIC FACTORS

Agency/Test Pavement Location	Freezing Index[1] (Degree F days below 32 F)[2]	Annual Precipitation[2] (inches)[3]
Arizona	0	11
Colorado	200	16
FHWA 10	610	59
Georgia	0	47
Idaho	50	15
Montana	964	16
Virginia	158	41

NOTES:
1. 1 degree F day below 32 F = 5/9 degree C day below 0 C.
2. Annual precipitation is rounded off to nearest inch.
3. 1 inch = 2.54 cm.

should produce more moisture damage because of the ice formation and the larger amount of freeze-thaw cycles (temperature change). Consequently the moisture damage rate should be higher for the FHWA 10 and Montana pavement test sections. On the other hand, warm "soaking" that causes asphalt-emulsification type of stripping could be more prevalent in the low freezing index pavement test sections, such as Arizona and Georgia, producing more moisture damage. Therefore, it is possible that the climate differences might have equivalent effects on moisture damage and their specific influence might not be discernible in this study.

High precipitation should increase the rate of moisture damage if there is entry in the pavement from surface cracks and shoulders. Therefore, the higher precipitation at the Georgia and Virginia pavement sections should increase the rate of moisture damage providing their surfaces become cracked or there is sufficient build-up of water in the shoulders. On the other hand, the sustained presence of moisture and its build-up in the bottom of the pavement from ground-water moisture appears to be the most damaging, developing in the low as well as the high precipitation locations. It is practically insured when a pavement is built; the bottom of the pavement becoming moist after a year or so of life. Therefore, similar to the climatic effect, the effect of precipitation might not be discernible in this study.

Moisture damage trends do not show any real effects from the climatic factors so far, however testing personnel of the participating agencies feel that the freezing or the freeze-thaw effects appear to have caused more moisture damage (stripping) in their pavement test sections, especially after the second winter.

TEST VARIABILITY

Standard deviation data for the tensile strength and resilient modulus testing are becoming available on a continuing basis from the participating agencies. The periodic core tests will be performed continuously to the end of the study in summer 1981. Therefore the data of Table 7 only reflect variability up to midsummer of 1978, when the data cut-off for the Interim Report occurred. However, the variability data for the laboratory specimen testing is complete.

Table 7 data entries are overall averages. For example, the Colorado testing gave an overall coefficient of variation of .115 (11.5%) for all their resilient modulus testing at 73F (23C). This includes freshly compacted and all storage time specimens at full and reduced voids. For all agencies, the coefficients include the generally higher initial values during testing start-up at the beginning of the study when most agency personnel were developing experience with resilient modulus and/or tensile strength testing. The data of Table 7 are intended to provide test variability levels; these are what one might expect when applying the moisture damage test system to cores and specimens and testing them for the mechanical properties used.

The overall coefficients of variation are above .10 and less than .20. Laboratory specimen testing variation is lower than pavement (periodic) core test variation, as expected. Average, overall specimen variation is .12 as compared to .17 for the cores. Also, tensile strength testing variation is lower than resilient modulus testing variation, .13 vs. .15. Therefore the moisture damage ratios, calculated from these tests, are affected by this variability. For example, a calculated

TABLE 7
COEFFICIENT OF VARIATION FOR TESTS OF LABORATORY SPECIMENS AND PAVEMENT CORES

Agency/Test Pavement Location	Laboratory Specimen Tests [1]			Pavement Core Tests [1]		
	Tensile Strength 55 F (13C)	Resilient Modulus 73 F (13C)	Resilient Modulus 55 F (13C)	Tensile Strength 55 F (13C)	Resilient Modulus 73 F (23C)	Resilient Modulus 55 F (13C)
Arizona	.195	.205	n.a. [2]	.196	.186	n.a.
Colorado	.089	.086	.115	.168	.211	.201
FHWA 10	.105	.143	.119	.180	.192	.165
GEORGIA (additive)	.078	.200	.140	.142	.206	.197
Georgia (no additive)	.087	.077	.068	.147	.229	.183
Idaho	.073	.086	n.a.	.127	.147	n.a.
Montana	.084	.096	.079	.151	.141	.133
Virginia	.131	.157	.196	.130	.157	.205
Overall Averages	.105	.131	.120	.155	.184	.181

NOTES:

1. Represents sets of four laboratory specimens or pavement cores;

   $\Sigma \frac{\text{std. dev.}}{\text{mean}}$ per set divided by number of sets tested.

2. n.a. (not available). Not programmed by agency due to early start-up of laboratory tests.

ratio of .40 is practically the same as a ratio of .35 or a ratio of .45.

TEST SYSTEM IMPROVEMENT

The variables and procedures used provided the test personnel of the participating highway agencies with a great deal of concentrated work at the beginning of the study. As the study progresses to routine periodic core testing, the personnel will begin to have time to reflect on the procedures of the test system. Any final decisions on its improvement for NCHRP purposes will be deferred to the end of the study. At that time the trends of pavement moisture damage will be known and matching to the predictions will then be possible.

CHAPTER 3

INTERPRETATION, APPRAISAL AND APPLICATION

Practical implications of the findings are discussed in this chapter. Most of the discussion relates to the findings of Chapter 2; other pertinent observations not directly associated with quantitative data are discussed also.

MOISTURE DAMAGE PREDICTIONS AND PAVEMENT TRENDS

All moisture damage predictions for the eight pavement test sections have been determined, however, matching the predictions to pavement section moisture damage is a continuing process. Most of the pavement moisture damage data are pavement "early life" data, reflecting about 24 months of pavement age. Long term matching of predictions and pavement moisture damage will occur at the end of an additional 36 months of pavement age when most of the pavements are 5 years old.

Moisture Damage Predictions

The test system used for moisture damage prediction (Appendix A) was developed in the NCHRP 4-8(3) study and includes the addition of resilient modulus testing as well as tensile strength testing. The measurement of moisture damage is based on retained mechanical property ratios, similar to the calculation of retained ratio of compressive strength calculated from the immersion compression test. However, the test system differs from the immersion compression test in several ways: standard Marshall or Hveem-size specimens are used; they are compacted to the permeable voids expected in the pavement mix; they are tested in three four-specimen sets at dry, vacuum saturated and vacuum saturated plus accelerated conditioned states. Diametral tensile strength and diametral resilient modulus tests are used. Two retained ratios are calculated: a saturated ratio represents the quantitative magnitude of moisture damage for pavement age up to 24 months (short term) and the conditioned ratio represents the moisture damage for greater pavement age, up to and exceeding 60 months (long-term).

Eight different mixes representing eight pavement sections were evaluated by seven highway agencies using this test system. Short term moisture damage predictions always resulted in higher retained rations than the long term predictions. Long term predictions were lower, the conditioned ratios providing a wide range (0 to .80+) depending on the pavement mix evaluated. So the predictions are now set and provide the basis for the matching comparison to actual moisture damage in the eight pavement test sections. The following is a discussion about the application of the test system and the predicted moisture damage ratios.

Applying the test system presented new kinds of tests and test equipment to most of the highway agencies, especially involving the sequence required in the test system. After personnel became familiar with the methods, the testing was found to be relatively easy. The saturation, moisture conditioning and tensile strength testing steps were picked up readily, but the resilient modulus testing took a longer time to develop expertise.

The fabrication of the laboratory specimens was initially a problem because the mix had to be compacted to the permeable voids measured in the initial pavement cores. This meant that most of the agencies had to decrease their compactive effort in the laboratory and could not use their standard number of blows and pressures. The initial compaction efforts therefore involved trial and error until a compaction effort produced specimens within $\pm$.5 of the average initial core permeable void percentage.

There were feelings that the long term, accelerated conditioning produced more moisture damage than was thought to occur eventually in the pavement mix. Most of the agency personnel had been familiar with the damage produced by saturation only, not by a "freeze-thaw" type of conditioning. Not only were low retained ratios calculated for some of the mixes but the high amount of moisture damage associated with these low ratios was observed visually when the specimens were split apart after testing. The stripping observed was sometimes extensive. Two mixes even fell apart after accelerated conditioning and their conditioned ratios were assigned a value of zero. A majority of the mixes held up better to the conditioning. The personnel testing the more resistance mixes, calculating conditioned ratios over .60, for example, were less concerned about the severity of the accelerated conditioning.

When performing the resilient modulus tests, personnel from the agencies became concerned about the spread of calculated moduli, especially for the core sets. This concern continues; coefficient of varieation remains about 18 percent--the highest variability. There is little concern with the tensile strength variability being 3 to 8 percent lower than the modulus variability percentage.

It has not been decided if the predicted ratios, which are numbers, should be applied as numbers or if they should be translated into ranges or levels of moisture damage. For instance, a badly stripped mix (visually) could have conditioned ratios of .40 or .20. But the ratio is affected also by the moisture resistance of the asphalt-mineral aggregate fines, "mastic", being the continuous phase, more or less, of the mix. Here, visual stripping is less evident to the eye and the mastic's loss of retention of cohesive strength is more subtle. Thus the numerical ratio may have importance in this context.

The recommended mechanical property test for calculation of the predicted moisture damage ratios should be decided at the end of the study. Diametral tensile strength has been shown to be easier to perform and it gives lower variabilities. On the other hand, current applications to pavement design require the use of resilient modulus values for the calculation of the stresses and strains. Tensile strength can be used in pavement design as a limiting stress for comparison only when the stress levels have already been determined. Both kinds of tests give rational units and application, and perhaps both should be recommended--a choice being made by the agency depending on the application. If moisture damage rating of a mix is necessary, then ratios are satisfactory and the use of tensile strength seems easier. But if elastic theory or its modifications will be used to determine the increase of a pavement's stresses and strains due to moisture damage, the use of resilient modulus magnitudes, as well as the retained ratios obtained from them, seems to be appropriate. The test system used in this study employs the resilient modulus test first followed by the tensile strength test on the same specimen, the resilient modulus test being considered as nondestructive. Therefore both mechanical properties can be determined without great difficulty or significantly longer test time.

Pavement Moisture Damage Trends

Moisture damage in the lower portion of the pavement test sections' asphalt concrete is being calculated quantitatively by the retained mechanical property's ratio of saturated versus dry periodic cores. Visual stripping in the cores is also being recorded as well as the general pavement surface condition. For the pavement sections which have moderate to low predictions of moisture damage, a gradual deterioration of the magnitudes of the periodic measurements will occur as the pavements age. Lower retained ratios will be expected and, at 60 months, will be compared to the predicted ratios.

At the beginning of the study it was thought that a gradual deterioration due to moisture damage would begin as soon as the high moisture susceptible pavements were built. Perhaps so, but the test measurements used in the study did not show this for a majority of these pavements. It was common to have the retained ratios of periodic cores become greater than 1.00 when pavements reached 8 to 14 months of age. This implies that the saturated mechanical properties of the compacted mix are greater than the dry properties and may be due to stiffening or embrittlement of the asphalt mastic by moisture or water molecules. As mentioned in Chapter 2, these high ratios were also calculated for storage specimens and initial cores exposed to room aging.

To test for the existence of asphalt stiffening in the presence of water, Robert L. Dunning, a petroleum science consultant in Spokane, Washington was asked to run sliding plate viscosity tests using three asphalts from this study. The asphalts were placed on porous corundum plates and viscosities were measured when the plates were dry and when they were saturated. The saturation increased the viscosity for one of the two asphalts from pavement mixes which showed the ratio increase; the other asphalt's viscosity didn't change. The viscosity of the third asphalt, from a pavement which showed a slight ratio decrease, decreased when saturated. While these tests were very limited, they do indicate that moisture stiffening of the asphalt or asphalt matrix could occur, becoming more dominant than the moisture damage during the early stages of a pavements's life.

However, as these pavements became older, usually after the second winter, the retained ratios of the periodic cores decreased, becoming less than 1.00. This downward trend is continuing and stripping is being observed in the cores of some of the pavements. It is reasonable to suggest that it takes two winters for moisture to build up and begin to penetrate into the asphalt concrete and, at the same time, provide enough environmental stresses to begin measurable moisture damage effects. Before that time, however, the pavement exposure is "unsettled" and the asphalt stiffening effects due to moisture, if existing, overpower any moisture damage effects.

During the first 24 months, periodic cores were determined and tested every four months. For the remaining 36 months, periodic cores will be obtained and tested every six months. These periodic core data should provide some evidence of seasonal trends of the retained ratios, if it exists. However, there might not be adequate testing frequency to determine this, or they might be overcome by extensive moisture damage build-up. So far there is evidence of a zig-zag pattern of retained ratio, now in a downward trend, but the correlation to the seasons of periodic pavement coring is weak at best. Perhaps further analysis will determine that pavement cores obtained after the winter have lower retained ratios than those obtained after the summer, but the data do not substantiate this. The data, however, do substantiate the downward trend development of the retained ratio after the second winter season.

It is still too early to predict a good match between predicted, long-term ratios and the retained pavement ratio for 60 months. Downward trends of retained ratio are now being measured for most of the moisture susceptible pavements. Stripping is occurring, but the general surface condition of the pavement test sections, assigned to the bottom layer moisture damage, still appears to be good. At present, around 24 months of pavement age, the retained ratios now seem to be equal or lower than the predicted, short-term saturated ratios.

EFFECTS OF VARIABLES

The effects of variables that were thought to affect the moisture damage prediction ratios were discussed in Chapter 2.

Pavement moisture damage trends are different for each of the eight test sections and it is not clear at present if these differences are due to the traffic and climate differences. As the study progresses these effects may become more pronounced. Presently these effects may be overshadowed by testing and desiccation time variability.

Most all of the pavements are showing reduced permeable voids. Reduced-void predictions were made for three of the pavement mixes, the remainder of the mixes could not be compacted further in the laboratory. Since reduced-voids usually produce lower moisture damage, the pavements' 60-month retained ratios might be higher than predicted for the specimens matching the initial core permeable voids. So the reduced-void specimens may provide ratios that are more closely matched to the 60-month pavement cores. On the other hand, there might be enough moisture damage in some of the pavements to overshadow the differences due to permeable voids.

The most significant variable affecting moisture damage prediction noticed so far is the difference of prediction ratios between initial pavement cores and laboratory specimens. Along with laboratory specimens, several sets of initial pavement cores were subjected to the test system, including accelerated conditioning, in order to determine prediction differences due to laboratory specimen fabrication methods. While it is not easy to identify a particular mix curing and/or compaction procedure that is responsible for the difference of prediction ratios, it is apparent that the cores, as a group, give long-term (conditioned) ratios about one-third greater than the laboratory specimens, as a group. How much of a concern this is, remains to be seen. The greater the moisture damage (lower the ratio), the lower the practical significance of these differences. A badly stripped mix can occur at ratios of .40 and at .30. The problem is at the higher ratios. For example, a long-term predicted ratio of .50 using laboratory specimens is contrasted to a ratio of .67 using initial pavement cores. Based on laboratory specimens, the moisture damage susceptibility of the mix could be designated as being severe, unsatisfactory. On the other hand, the moisture damage susceptibility improves, becoming more or less borderline, when initial cores are used. This behavioral difference seems to be similar for other kinds of comparisons between specimens and cores, not only for moisture damage applications. Fortunately, however, this study has produced several long term predictions based on storage or aging times. They are shown on the right, vertical scales in the figures of Appendices B, C, and D. It is possible that good matching using aged laboratory specimens will exist for the borderline mixes. Also encouraging is that high moisture resistant mixes having long term (conditioned) ratios of .80 or greater seem to give much closer ratios between specimens and cores. Thus the practical application of using laboratory specimens to predict moisture damage appears good for the high and low moisture damaged mixes. "Borderline" moisture damaged mixes may not be designated as specifically as the others, however the 60-month matching to individual storage time specimen ratios may provide a more precise application for their identification.

The practical consequences of using laboratory fabricated specimens are central to prediction. Evaluation and change decisions for pavement mixes must be made before the pavement is built. Thus the use of laboratory specimens for moisture damage prediction is necessary.

The laboratory storage time variable and the periodic core time variable influence the aging characteristics of specimens and cores.

The magnitudes of tensile strength and resilient modulus increase sometimes very significantly. The mechanical property magnitudes of the cores from the pavements, which are now showing stripping and drops in retained ratios, are now decreasing. The decrease of properties due to the magnitude of moisture damage eventually becomes larger than the increase of properties due to aging effects.

The mechanical property increases resulting from increasing laboratory storage times produced greater, sometimes lower, moisture damage ratios. These differences, perhaps helpful for the 60-month, individual boarderline mix matching, are not as significant as the ratio differences of the specimens versus cores as a group.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

Comprehensive discussions of the findings and of their extension beyond the scope of this study are limited because of the interim (progress) status of this study at present. About two-fifths of the data have been reported, and final matching of moisture damage predictions determined from application of the test system will not occur for another 36 months. However, a good possibility exists now for the occurrence of moisture damage in the moisture susceptible pavement mixes; some will have significant damage. Predictive matching to three or four "levels" of moisture damage in the pavement sections will probably be good, but not ruled out is the satisfactory matching to the numerical damage ratios.

With the above limitations in mind, the following is a brief discussion of the test system and its extension in practice.

PERFORMING THE TEST SYSTEM

The moisture damage test system, described in Appendix A and applied by the seven highway agencies in this study, requires the commitment of adequate time for preparation, testing and evaluation of results. Assuming a mix is made and cured, then four days are required for performing the steps of the test system. This is about one to one-and-a-half days more than the time required to perform the immersion compression test. The following are the main steps:

1. Compacting nine to twelve standard-type laboratory specimens

to the expected permeable voids of the pavement mix, with expected discard of additional specimens not containing the required permeable voids (calculated from step 2 below),

2. After overnight cure, vacuum saturating two-thirds of the specimens, and placing one-third of them in a freezer,

3. Placing the frozen, saturated specimens in a warm water bath, and

4. Placing all the specimens in the water bath at test temperature (protecting the unsaturated specimens from water instrusion), running the mechanical property tests (tensile strength and/or resilient modulus), calculating the short term and long term moisture damage ratios, observing the stripping, and making a decision on the moisture damage susceptibility of the mix.

These steps require the same testing personnel now employed in the materials laboratories of highway agencies. But, because of the steps involved, the "test" will be in progress at least a day longer than the immersion compression test. This requires more attention span such as keeping track of water bath times and temperatures, and the functioning of test equipment. If several mixes are being evaluated at the same time, as can be the case with evaluation of antistripping additives and/or aggregate-asphalt types and amounts, the four days of performing the test system after mixing will require concentration and preplanning so that the time allocation for the steps will fit into the laboratory working schedule.

The gradual establishing of the reliability and usefulness of the resulting data should make the effort of performing the test system worthwhile. The designing of a mix that proves out by reliable laboratory prediction to be moisture damage resistant not only provides for the conservation of road paving dollars but also develops self-satisfaction and confidence as well.

APPLYING THE TEST SYSTEM

The practical application of moisture damage ratios, perhaps allocated to moisture damage "levels", requires decision making and the placement of the most moisture resistant asphalt concrete mix. Highway agencies might base their decisions on the suitability of a mix by using acceptable or unacceptable ratio specifications. Or they might make their decision based on the probability of the severity of moisture damage by using the magnitude of the ratio or by using the three or four "levels" of moisture damage where the ratios are placed.

Proper decision making is not only based on the necessity of having accurate laboratory predictions, including what the predictions mean, but it is also based on the probability of making and placing a low, moisture damage susceptible asphalt concrete mix in the pavement that represents the laboratory results. Hopefully this study will provide some meaning for moisture damage ratios--how much stripping is associated with the ratios, how much actual pavement damage is associated with the ratios, as well as the relative change of tensile strength and modulus properties inherent in the calculating of the ratios. Very helpful information would be the knowledge of the reduction of the fatigue life of moisture damaged mixes. It would provide additional data about the relative pavement life. Although laboratory fatigue testing is out of the scope of this study, some idea of reduction of fatigue life in the pavement sections due to accumulated moisture damages could exist at the end of this study. An attempt will be made to analyze the 60-month data to do this.

Perhaps one of the difficult situations for decision-making is the construction of the moisture resistant pavement. The central materials testing laboratories of most of the highway agencies, or their designated regional laboratories, perform asphalt concrete mix design tests, including moisture damage tests. When an acceptable mix using the asphalt concrete constituents, some of which may be under ownership control of the contractor, is determined, the highway districts then become responsible for the construction. Last minute changes of materials or on-the-spot changes of asphalt content could increase the moisture damage susceptibility of the mix inadvertently. Antistrip additives, asphalt type and aggregate type could change and there may, in some cases, not be adequate laboratory time to evaluate what is now a different mix from the point of view of moisture damage susceptibility.

This problem is recognized by all senior materials engineers of highway agencies. The minimizing of moisture damaged pavements through the use of and consequential decisions from a reliable moisture damage predictive test requires also the carry-through controls at the construction level. It is advantageous for every highway agency to evaluate its operational control of materials prior to and during construction, insuring that the pavement will be built after there is sufficient time allocated for laboratory evaluation of the materials and mixes used. The time and effort to recommend a mix that is the least moisture damage susceptible is wasted when an altered mix is finally placed in the pavement and this altered mix strips or becomes otherwise moisture damaged. This not only reduces the life of the pavement but also destroys the credibility of the moisture damage predictive tests and other laboratory tests. Decision making, based in part on the degree of similarity of significant properties between laboratory-designed and as-built asphalt concrete mixes, is at least as critical for moisture damage as it is for other pavement deterioration variables, if not more so.

PAVEMENT DESIGN IMPLICATIONS

The application of reduced resilient modulus and tensile strength due to moisture damage was mentioned briefly in Chapter 3 and is a pavement design subsystem worthy of consideration. Although this won't be elaborated further for this report, some aspects of moisture damage in pavements may be worth mentioning here to conclude this report.

First, try to use an asphalt concrete mix that has no consequential susceptibility to moisture damage. If this is not possible, then reduce the moisture susceptibility. Try to achieve a large reduction of permeable voids in the laboratory designed mix and make sure these voids are not exceeded during construction. For the bottom layers of asphalt concrete, where long term moisture damage begins, keep the permeable voids as low as possible. An impermeable layer seems to be practical here if its stability is adequate and if the top layer(s) will hold its flushing tendency. The tight bottom layer should reduce the rate and amount of moisture damage and should give the further dividends of increased fatigue life.

The occurrence of traffic fatigue cracks at the bottom of asphalt concrete pavements is a problem. They provide entry of moisture, the moisture moving upward by the drawing of the colder surface of the pavement at night and in the winter. The moisture in the cracks at the bottom of the pavement cannot evaporate easily. If the mix is moisture susceptible, stripping and/or asphalt-mastic cohesion reductions will be noticed in the crack regions. No practical fix-up remedy is known, except perhaps to recycle the mix and adding more asphalt or binder to reduce permeability and future moisture damage.

Fortunately a reliable moisture damage test system should provide predictive data on the consequences of aggregate change, recycling additives, antistripping additives, aggregate pre-coating, asphalt change, etc. This information is valuable to the initial placement and future reconstruction decisions of asphalt concrete pavement. The test system employed in this study has the potential to provide evaluative data for all these variables. This is the ultimate purpose of this test system.

REFERENCES

1. Lottman, R.P., "Predicting Moisture-Induced Damage to Asphaltic Concrete", Final Report, Project 4-8(3), National Cooperative Highway Research Program, Washington, D.C., February 28, 1974.

APPENDIX A

TEST SYSTEM USED IN NCHRP 4-8(3)/1

EFFECT OF WATER-RELATED CONDITIONING ON INDIRECT TENSILE PROPERTIES OF COMPACTED BITUMINOUS MIXTURES

EFFECT OF WATER-RELATED CONDITIONING ON INDIRECT TENSILE PROPERTIES OF COMPACTED BITUMINOUS MIXTURES

1. Scope

1.1 This method covers measurement of the change of diametral tensile strength and diametral (tensile) resilient modulus resulting from the effects of saturation and accelerated water conditioning of compacted bituminous mixtures. Internal water pressures in the mixtures are produced by vacuum saturation followed by a freeze and warm water soaking cycle. Numerical indices of retained indirect tensile properties are obtained by comparing the retained indirect tensile properties of saturated and accelerated water-conditioned laboratory specimens with the similar properties of dry specimens.

2. Apparatus

2.1 Two automatically controlled water baths will be required for immersing the specimens. The baths will be of sufficient size to permit total immersion of the test specimens. They will be so designed and equipped to permit accurate and uniform control of the immersion temperature. One bath is provided for bringing the immersed specimens to the temperature of 140 ± 3.6 F (60 ± 2 C) for the warm water soak part of the specimen conditioning. The second bath is provided for bringing the immersed specimens to either the selected test temperature of 55 ± 1.8 F (12.8 ± 1 C) or of 73 ± 1.8 F (22.8 ± 1 C) for the indirect tensile testing. The baths will be constructed of or lined with stainless steel or other nonreactive material. The water in the baths will be either distilled or otherwise treated to eliminate electrolytes and the baths will be emptied, cleaned and refilled with fresh water for each series of tests.

2.2 One automatically controlled freezer will be required for freezing the specimens. The freezer will be of sufficient size to permit total containment of the test specimens. It will be so designed and equipped to permit accurate and uniform control of its air temperature. The freezer is required for bringing the specimens to the selected temperature of -0.4 ± 3.6 F (-18 ± 2 C) for the freeze portion of specimen accelerated conditioning.

2.3 One vacuum pump with capacity to pull at least 26 in (66 cm) of mercury will be required to water-saturate the test specimens. Accessory equipment will include: Pyrex or equivalent vacuum jars of at least 6 in. (15 cm) diameter and 8 in. (20 cm) high with smooth fired edges, a donut shaped gasket made of rubber-type sponge, a stiff metal round plate greater than 6 in (15 cm) diameter with suitable vacuum hose receptable and hole bored through the plate thickness, vacuum hose attached to receptable fitting and vacuum pump, and a 6 in (15 cm) diameter screen-type or highly porous specimen spacer seat approximately .25 in (1 cm) high.

2.4 A compressive testing machine as described in accordance with Method D 1074, but having the controlled deformation rate capability of .065 in per min (.165 cm per min).

2.5 Mark III or Mark IV Resilient Modulus Apparatus manufactured by Retsina Co., El Cerrito, CA 94530, or equivalent.

2.6 A balance and a room-temperature water bath with suitable accessory equipment will be required for weighing the test specimens in air and in water (saturated specimens only) in order to determine their densities, the amount of absorption, and permeable voids. This apparatus is similar to that required for Method D2726, Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens.

2.7 A supply of plastic film for wrapping and heavy-duty leak-proof plastic bags will be required to wrap and enclose the saturated specimens for preventing moisture loss during handling and freezing. Also, several metal jars of at least 4 in (10.2 cm) diameter and at least 6 in (15 cm) high will be required for bringing dry specimens to test temperature without water intrusion into the dry specimens in the water bath.

3. Test Specimens

3.1 At least nine, duplicate 4 in (102 mm) diameter by 2.5 in (63.5 mm) high cylindrical test specimens of the same mixture will be made for each test. The procedures described in either: Method D1559, Test for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus, or Method D1561, Test for Compaction of Test Specimens of Bituminous Mixtures by Means of California Keading Compactor, or Method D3387, Test for Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Corps of Engineers Gyratory Testing Machine, will be followed in preparing the loose mixtures and in molding and curing the test specimens.

4. <u>Grouping, Vacuum Saturation, and Determination of Bulk Density and Permeable Voids of Test Specimens</u>

4.1 Allow each set of nine test specimens to cool at room temperature for at least 24 hours after completion of specimen fabrication and curing described in Methods: D1559, D1561, D3387. Label each specimen with waterproof identification and obtain the dry weight of each specimen to the nearest .1 g.

4.2 Randomly select a subset, I, of three specimens from the set of nine test specimens. Maintain subset I specimens in a dry condition. Place subset I specimens in metallic jars and then place the jars in a water bath at the selected mechanical test temperature (see Note 1) of 55 $\pm$ 1.8 F (12.8 $\pm$ 1 C) or 73 $\pm$ 1.8 F (22.8 $\pm$ 1 C) for 5 h maintaining the top lip of the jars above the water level of the bath. Place an insulating stuffing in the top of the jars, making contact with the top specimen's surface and with the jar walls, then proceed with the mechanical testing of subset I as described in sections 6-9.

4.3 The six remaining test specimens will be vacuum saturated as follows. Place a porous spacer seat on the bottom of a vacuum jar and then place two or more of the specimens, depending on jar height, horizontally in the jar using another porous spacer seat between the specimens. Put distilled water, or water treated to eliminate electrolytes, at 73 F (22.8 C) in the jar to about 1 in (2.5 cm) above the upper specimen's surface. Place a dampened donut gasket and a stiff metallic plate on top of the jar. Attach a vacuum hose from

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<u>Note 1.</u> Refer to section 6 for information on the selection of mechanical test temperature.

the plate receptacle to the vacuum pump. Apply a vacuum of 26 in (66 cm) of mercury to the jars for a duration of 30 min, gently agitating the jar wall. Remove the vacuum and leave the six specimens submerged in the jars at atmospheric pressure for 30 minutes.

4.4 Remove each of the six specimens from the vacuum jars, quickly surface dry the specimens by towel blotting and weigh immediately in air and then weigh submerged in room-temperature water at approximately 73 F (22.8 C). Immediately after weighing each submerged specimen, return the specimens to the water-filled vacuum jars and submerge each specimen under the water at atmospheric pressure.

4.5 Calculate the bulk density and permeable voids of each of the six vacuum saturated test specimens as follows:

$$\text{Bulk density} = \frac{AD}{B-C},$$

$$\text{Permeable voids, \%} = \frac{100\ (B-A)}{B-C}, \qquad \text{where}$$

A = weight of dry specimen in air, g,

B = weight of surface-dry (blotted) vacuum saturated specimen in air, g,

C = weight of vacuum saturated specimen submerged in water, g, and

D = density of water at 73 F (22.8 C), g/cc.

4.6 Sort and assign each of the six vacuum saturated test specimens into two subsets, II and III, consisting of three specimens each so that the average permeable voids (or average bulk density) is essentially the same in each subset. Immerse subset II specimens into a water bath at the selected mechanical test temperature of 55 ± 1.8 F (12.8 ± C) or 73 ± 1.8 F (22.8 ± 1 C) for 3 h and then proceed with the mechanical testing of this subset described in sections 6-9. Condition the subset III specimens by using the procedure described in section 5.

5. Accelerated Conditioning Procedure

5.1 Maintain specimen surface dampness and internal saturation, and wrap tightly each of the three specimens of subset III with two layers of plastic film using masking tape to hold the wrapping if necessary. Place each wrapped specimen into a leak-proof plastic bag, and seal the bag with a tie or tape.

5.2 Immerse each of the three individually wrapped and bagged specimens of subset III into an air bath freezer for 15 h at -.4 ± 3.6 F (-18 ± 2 C). (If this step begins at 5 pm, specimens can then be removed from the freezer at 8 am the following day).

5.3 Remove the three wrapped and bagged specimens of subset III from the freezer and immerse them immediately into a water bath at 140 ± 3.6 F (60 ± 2 C) for 24 h. (After 1/2-1 h of immersion, when specimen surface thaw takes place, carefully remove the bag and wrapping from the specimens and reimmerse the specimens in the water bath).

5.4 Carefully remove the three unwrapped specimens of subset III from the water bath, immerse the specimens in a water bath at the selected mechanical test temperature of 55 ± 1.8 F (12.8 ± 1 C) or 73 ± 1.8 F (22.8 ± 1 C) for 3 h, and then proceed with the mechanical testing of this subset as described in sections 6-9.

6. Selection of Mechanical Test Temperature

6.1 The selection of the mechanical test temperature for the nine specimen set is based on the type of mechanical test desired for measurement of the effects of the water-related conditioning. Diametral (tensile) resilient modulus may be performed at either 55 $\pm$ 1.8 F (12.8 $\pm$ 1 C) or 73 $\pm$ 1.8 F (22.8 $\pm$ 1 C). Diametral tensile strength is performed at 55 $\pm$ 1.8 F (12.8 $\pm$ 1 C). If low to moderate stresses are applied to the specimens in the diametral (tensile) resilient modulus test, then this test can be considered nondestructive and the same specimens can be also tested using the diametral tensile strength test, therefore providing additional mechanical properties data. If this is to be done, then specimens must be reimmersed in the water bath at selected test temperature for 1 h after diametral (tensile) resilient modulus testing prior to the diametral tensile strength testing.

7. Specimen Handling in the Mechanical Testing Procedures

7.1 Each specimen subset will be tested rapidly following the completion of their respective test-temperature water-bath soak times as prescribed in section 4.2 for subset I, section 4.6 for subset II, and section 5.4 for subset III.

7.2 Remove a subset specimen from the water bath at the test temperature, surface dry by blotting with a towel (necessary for specimens from subsets II and III), measure and record the specimen height (thickness) and identification, and place the specimen with circular ends vertical (specimen on edge) into the appropriate mechanical loading device. Test one specimen at a time, leaving the remaining untested specimens in the water bath. Proceed with testing as rapidly as possible since the mechanical testing will expose the specimen to air temperature which may be different than the test temperature. Test the specimens by either one or both of the procedures described in sections 8 and 9.

8. Test and Calculation Procedure for Diametral (Tensile) Modulus

8.1 Place the transducers of the Resilient Modulus Apparatus on the specimen at test temperature and proceed quickly with diametral loading at 0.1 sec. load duration time, following the procedures described in the instruction manual provided by the manufacturer. Record load and horizontal deformation. Rotate the specimen 90° and repeat.

8.2 Calculate the specimen's diametral resilient modulus for each of the two 90° rotations as follows:

$$M_R = \frac{P\ (\nu + 0.2734)}{L\ \Delta},$$ where

M_R = diametral resilient modulus, psi (k Pa),

P = load magnitude applied to specimen, lb (dN),

ν = Poissons ratio of specimen (use .35 unless measured specifically),

.2734 = dimensionless strain integration constant for 4 in. (10.2 cm) diameter specimens,

L = thickness of specimen, in. (cm), and

Δ = horizontal deformation magnitude of specimen, in. (cm).

The average of the two 90° resilient modulus values is calculated for this specimen and test temperature. Return specimen to water bath if a diametral tensile strength test is also to be performed on the same specimen.

8.3 Repeat by testing the two remaining specimens in the subset, and calculate the overall average diametral resilient modulus for the subset of three specimens.

8.4 Repeat procedure and calculations described in sections 8.1-8.4 for the remaining two subsets of three specimens.

8.5 Proceed to section 10, calculation.

9. Test and Calculation Procedure for Diametral Tensile Strength

9.1 Place and center a subset specimen at test temperature under the flat loading head of the compression test machine, and proceed quickly with diametral loading at a vertical deformation rate of .065 in per min (.165 cm per min). (The specimen is placed on its edge without support blocks or loading strips). Record the maximum compressive load. Immediately decrease load to zero, remove specimen and measure specimen edge or side flattening to nearest 0.1 in (.25 cm). This can be accomplished easily by stroking the top flattened edge (side) with a piece of chalk held lengthwise to delineate the flattened width, and then using a scale to measure the average maximum width of the flattened edge. Record this width.

9.2 Replace the specimen in the compression test machine with its original orientation (flattened edges top and bottom) and redeform the specimen at .065 in per min (.165 cm per min) until a definitive vertical crack appears and opens. Decrease load to zero, remove specimen and slowly pull apart the two sides of the specimen at the crack. The internal surface may then be observed for stripping, and recorded qualitatively.

9.3 Calculate the specimen's diametral tensile strength as follows:

$$S_t = \frac{S_{10} P}{10,000 L} ,$$ where

S_t = diametral tensile strength, psi (k Pa),

S_{10} = maximum tensile stress, psi (k Pa), obtained by calculating: $1591 + 437a - 1389 a^2 + 2854 a^3 - 2474 a^4 + 885 a^5$, where a = flattening width, in., based on a 4 in (10.2 cm) diameter solid cylinder loaded at 10,000 lb (22 kg) per inch (cm) thickness (see note 2),

P = maximum compressive load on specimen, lb. (N),

10,000 = load constant: 10,000 lb per in of thickness (17,512 N per cm of thickness), and

L = thickness of specimen, in (cm).

9.4 Repeat by testing the two remaining specimens in the subset, and calculate the overall average diametral tensile strength for the subset of three specimens.

9.5 Repeat procedure and calculations described in sections 9.1-9.4 for the remaining two subsets of three specimens each.

9.6 Proceed to section 10, Calculation.

10. Calculation

10.1 Calculate the numerical indices of the effects of vacuum saturation and accelerated conditioning as the ratios of the mechanical properties of subsets II and III to the mechanical properties of subset I for the specified test temperature as follows:

$$M_R R_1 = \frac{M_R \text{ (II)}}{M_R \text{ (I)}} \quad \text{and} \quad M_R R_2 = \frac{M_R \text{ (III)}}{M_R \text{ (I)}}, \quad \text{where}$$

$M_R R_1$ = diametral resilient modulus ratio of saturation,

$M_R R_2$ = diametral resilient modulus ratio of accelerated conditioning,

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Note 2. To calculate S_{10} in SI units, first calculate S_{10} in U.S. Customary units of psi using the polynomial constants as shown, with a in inches, then convert psi to k Pa using 1 psi = 6.895 k Pa.

M_R (I) = average diametral resilient modulus of specimen subset I, psi (k Pa),

M_R (II) = average diametral resilient modulus of specimen subset II, psi (k Pa), and

M_R (III) = average diametral resilient modulus of specimen subset III, psi (k Pa).

$$TSR_1 = \frac{S_t\ (II)}{S_t\ (I)} \quad \text{and} \quad TSR_2 = \frac{S_t\ (III)}{S_t\ (I)}, \quad \text{where}$$

TSR_1 = diametral tensile strength ratio of saturation,

TSR_2 = diametral tensile strength ratio of accelerated conditioning,

S_t (I) = average diametral tensile strength of specimen subset I, psi (k Pa),

S_t (II) = average diametral tensile strength of specimen subset II, psi (k Pa), and

S_t (III) = average diametral tensile strength of specimen subset III, psi (k Pa).

Ratios will be reported to the nearest hundredth.

10.2 Ratios may be interpreted as follows. M_RR_1 and TSR_1 are related to short-term pavement performance, eg. 2 yr. M_RR_2 and TSR_2 are related to long-term pavement performance, eg. 8 yr. Low ratios are associated with the mixture's inability to resist moisture effects.

11. Precision

11.1 Single-Operator Precision - The single operator standard deviation has been found to be 11% for M_RR and 10% for TSR (see Note 3). Therefore, results of two properly conducted tests by the same operator on the

Note 3. These numbers represent, respectively, the (IS) and (D2S) limits as described in ASTM Recommended Practice C 670, for Preparing Precision Statements for Test Methods for Construction Materials.

same material should not differ by more than 28% for M_RR and 31% for TSR.

11.2 Multilaboratory Precision - The multilaboratory standard deviation has been found to be % for M_RR and % for TSR (see Note 3). Therefore, results of two properly conducted tests from two different laboratories on identical samples of the same material should not differ by more than % for M_RR and % for TSR.

APPENDIX B

MOISTURE DAMAGE TRENDS MEASURED BY TENSILE STRENGTH RATIO at 55F (13C)

Explanation of moisture damage prediction codes in the figures, examples:

C - 0	initial cores tested at zero month storage time
C - 12	initial cores tested at 12 month storage time
L - 5	laboratory specimens tested at 5 month storage time
LR - 0	laboratory specimens at reduced voids tested at zero month storage time
SAT	vacuum saturated only
COND	vacuum saturated plus accelerated conditioned

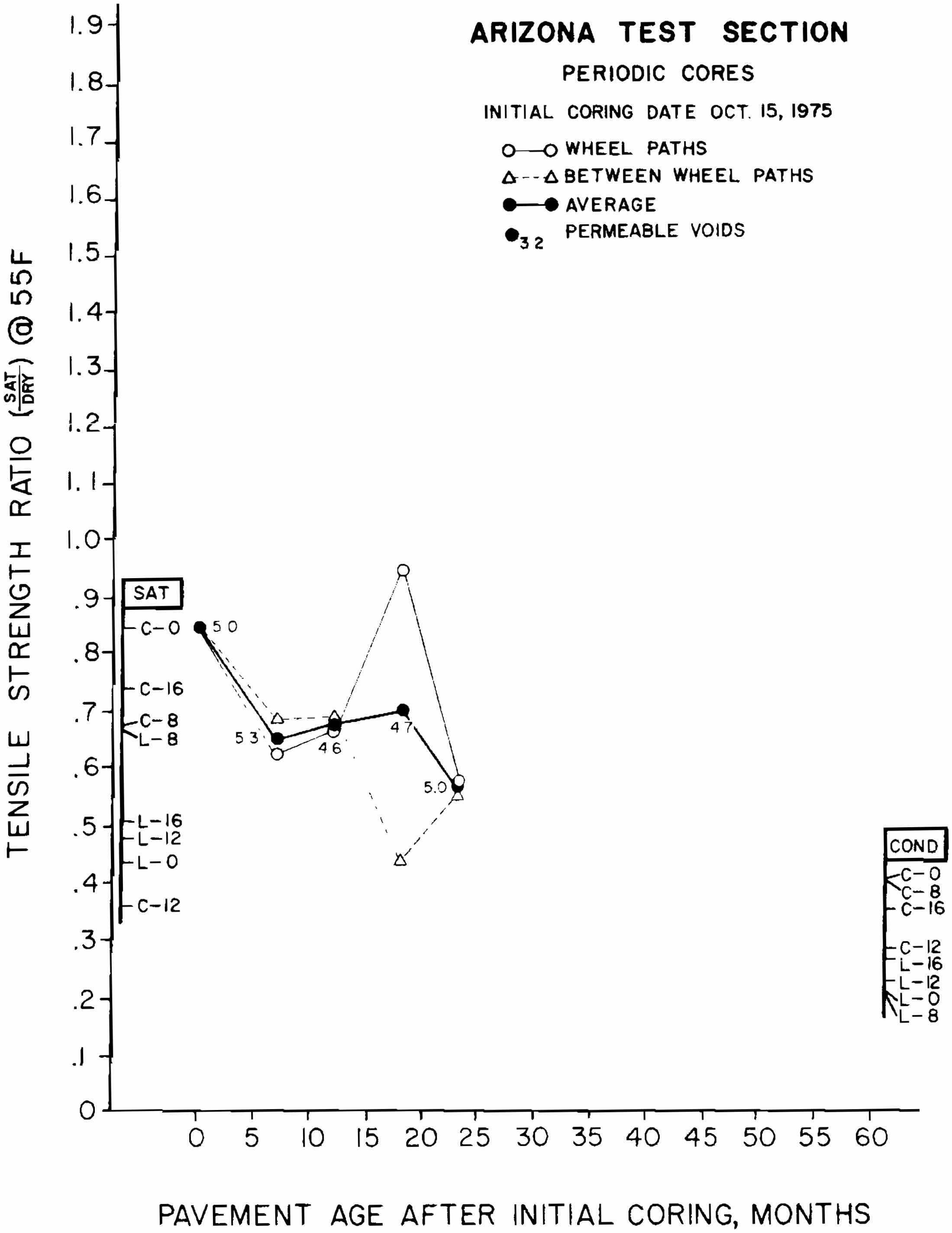

Figure B-?. Tensile Strength Ratio Trends with Pavement Age and Predictions, 55F (13 C) for Arizona.

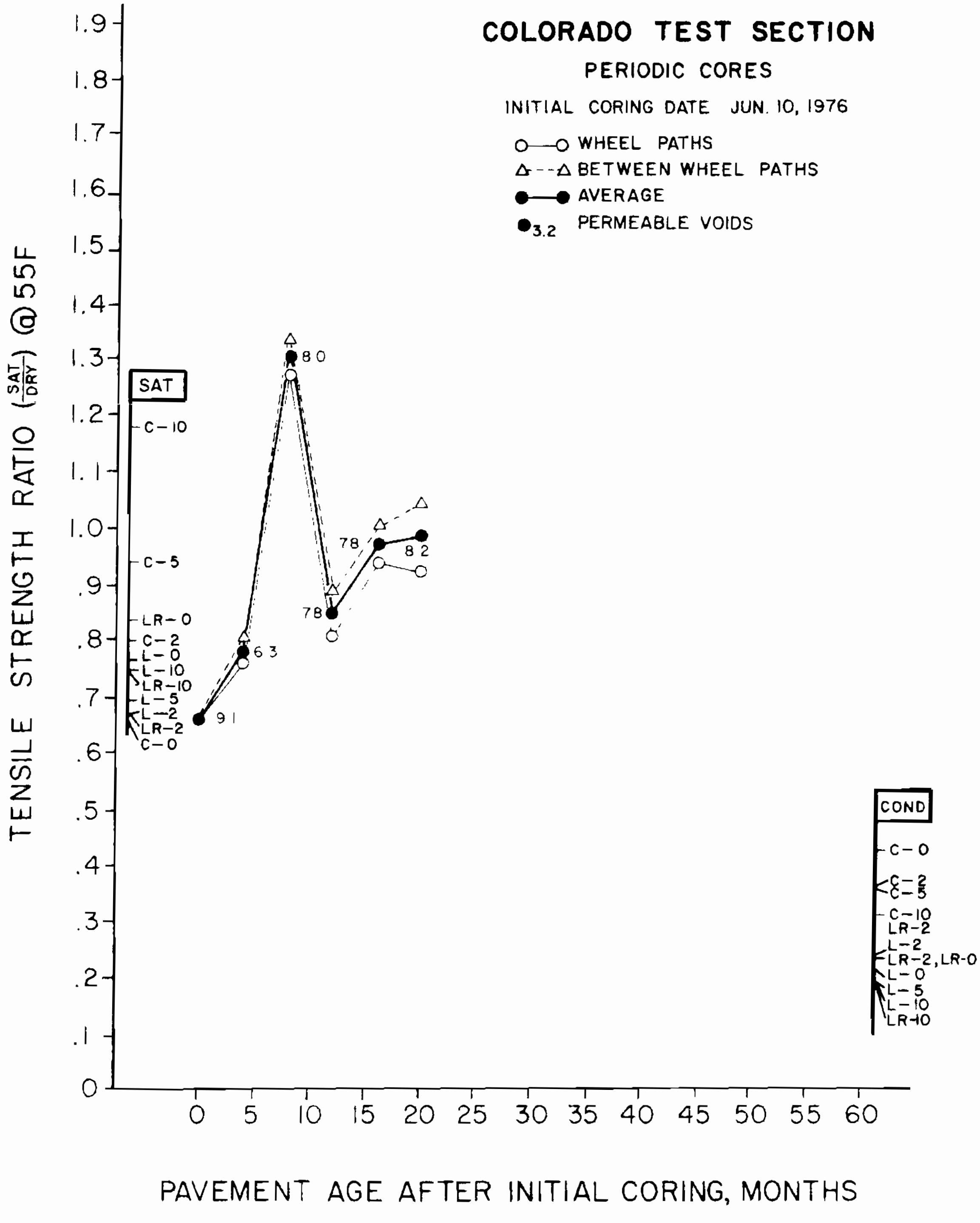

Figure B-2. Tensile Strength Ratio Trends with Pavement Age and Predictions, 55F (13 C) for Colorado.

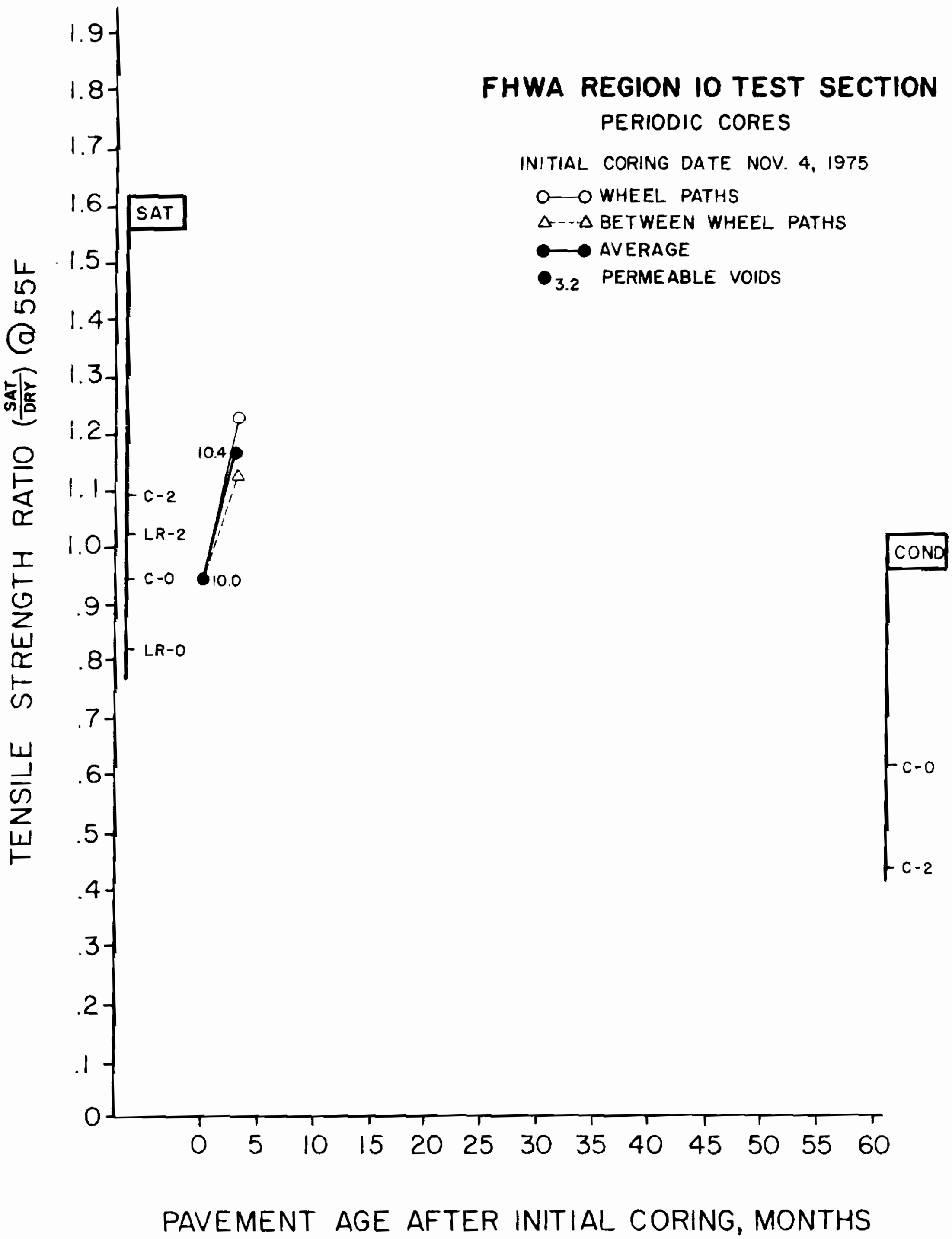

Figure B-3. Tensile Strength Ratio Trends with Pavement Age and Predictions, 55F (13 C) for FHWA 10.

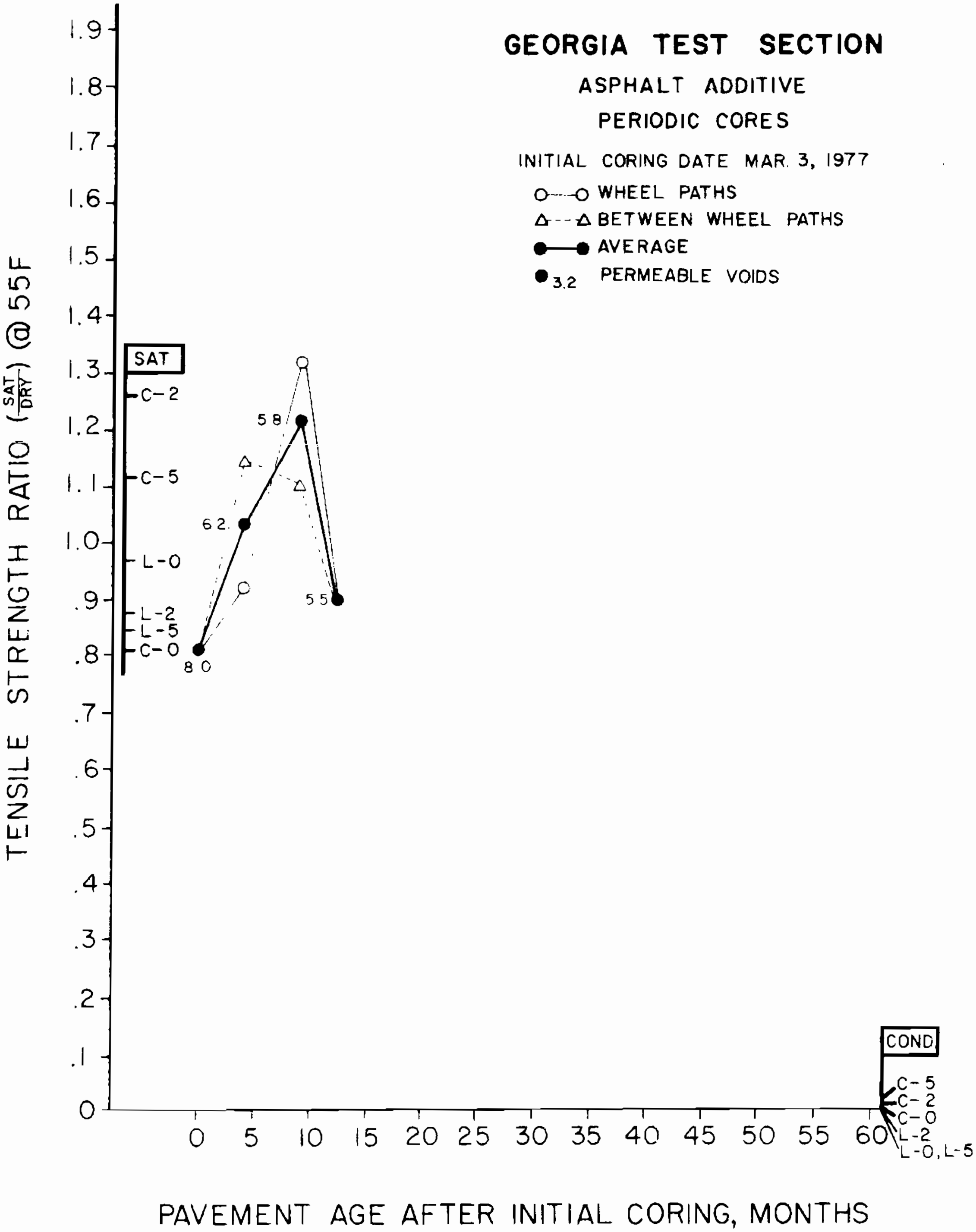

Figure B-4. Tensile Strength Ratio Trends with Pavement Age and Predictions, 55F (13 C) for Georgia (add.)

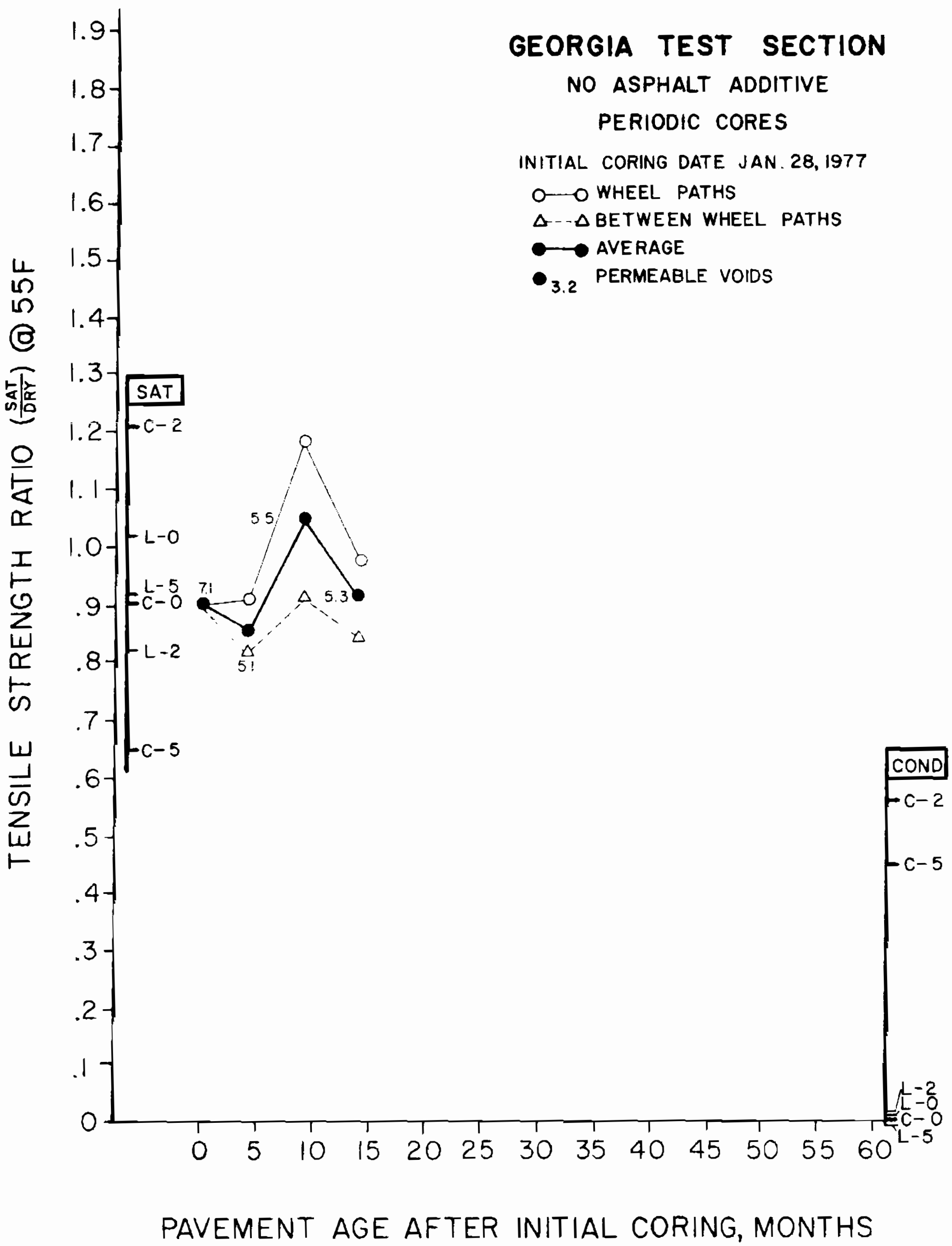

Figure B-5. Tensile Strength Ratio Trends with Pavement Age and Predictions, 55F (13C) for Georgia (no add.)

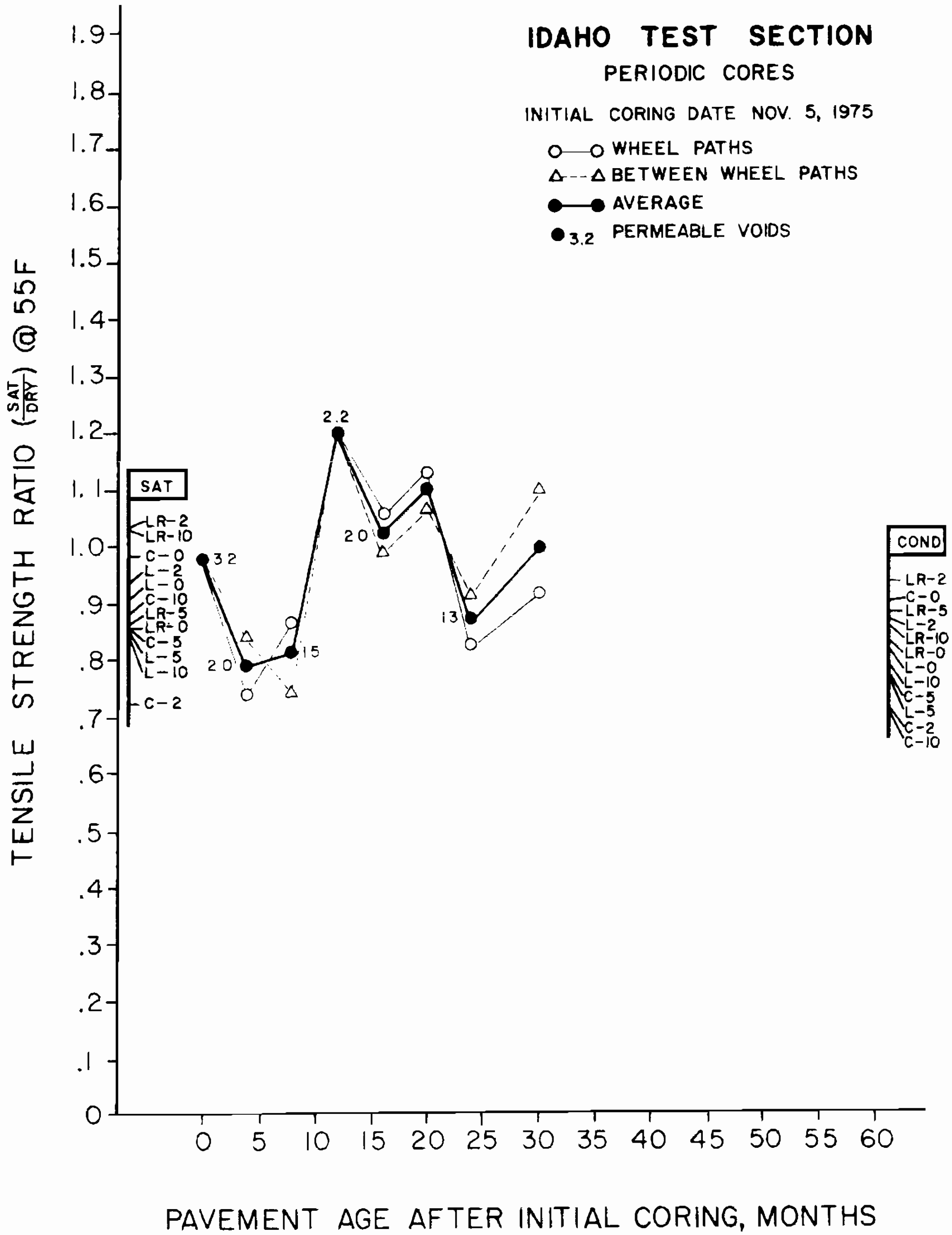

Figure B-6. Tensile Strength Ratio Trends with Pavement Age and Predictions, 55F (13C) for Idaho.

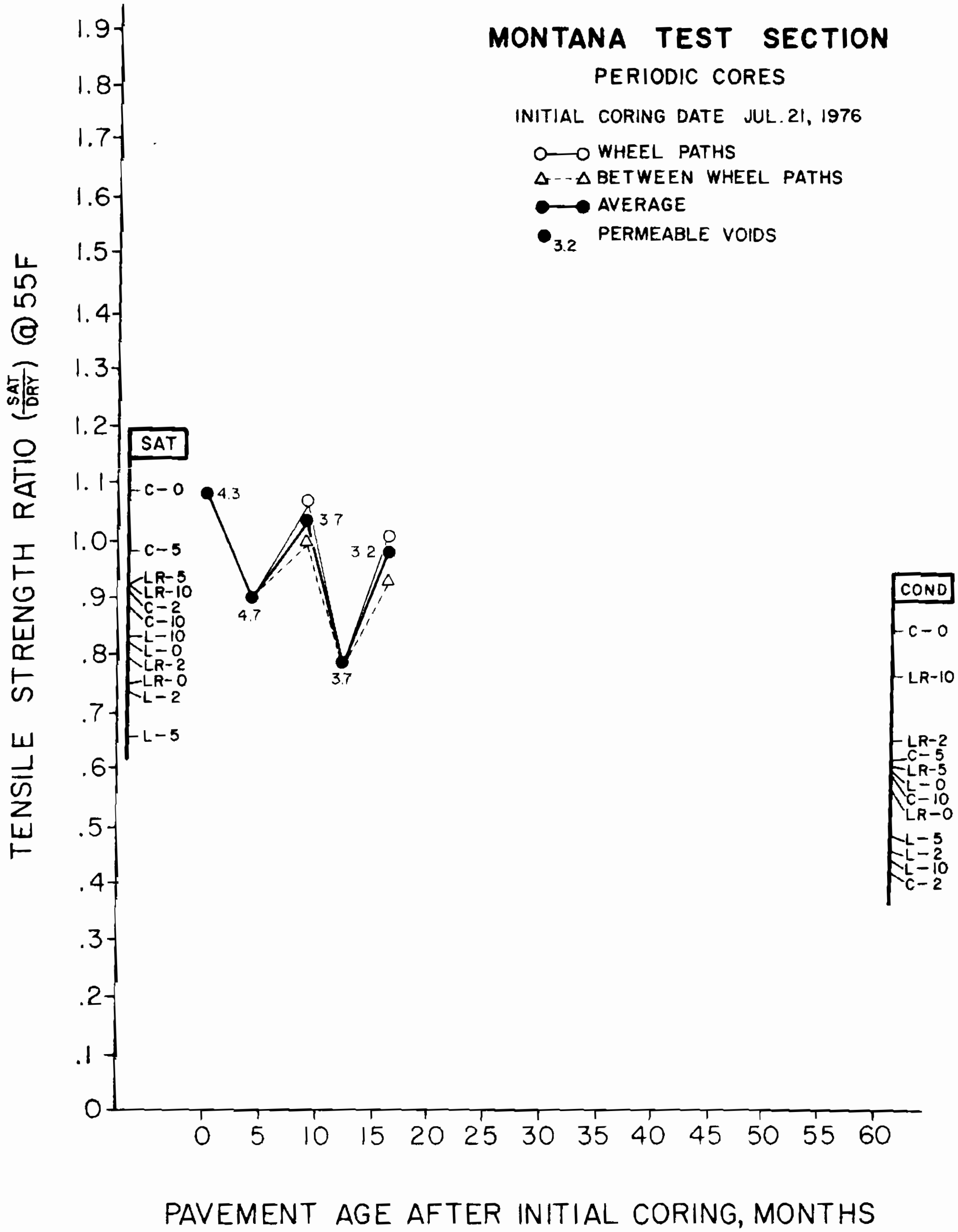

Figure B-7. Tensile Strength Ratio Trends with Pavement Age and Predictions, 55F (13 C) for Montana.

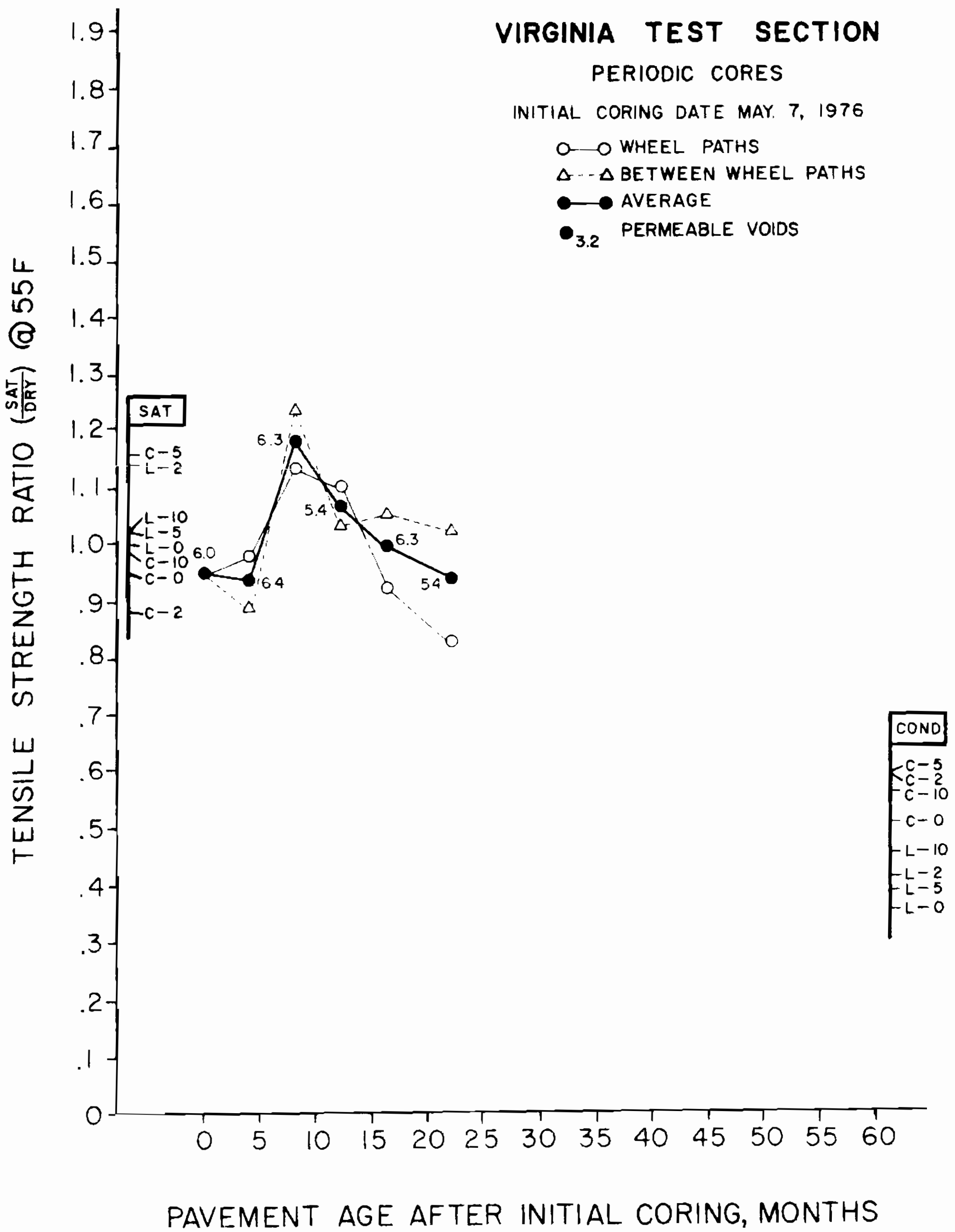

Figure B-8. Tensile Strength Ratio Trends with Pavement Age and Predictions, 55F (13 C) for Virginia.

APPENDIX C

MOISTURE DAMAGE TRENDS MEASURED BY RESILIENT MODULUS RATIO at 73F (23C)

Explanation of moisture damage prediction codes in the figures, examples:

C - 0 initial cores tested at zero month storage time

C - 12 initial cores tested at 12 month storage time

L - 5 laboratory specimens tested at 5 month storage time

LR- 0 laboratory specimens at reduced voids tested at zero month storage time

SAT vacuum saturated only

COND vacuum saturated plus accelerated conditioned

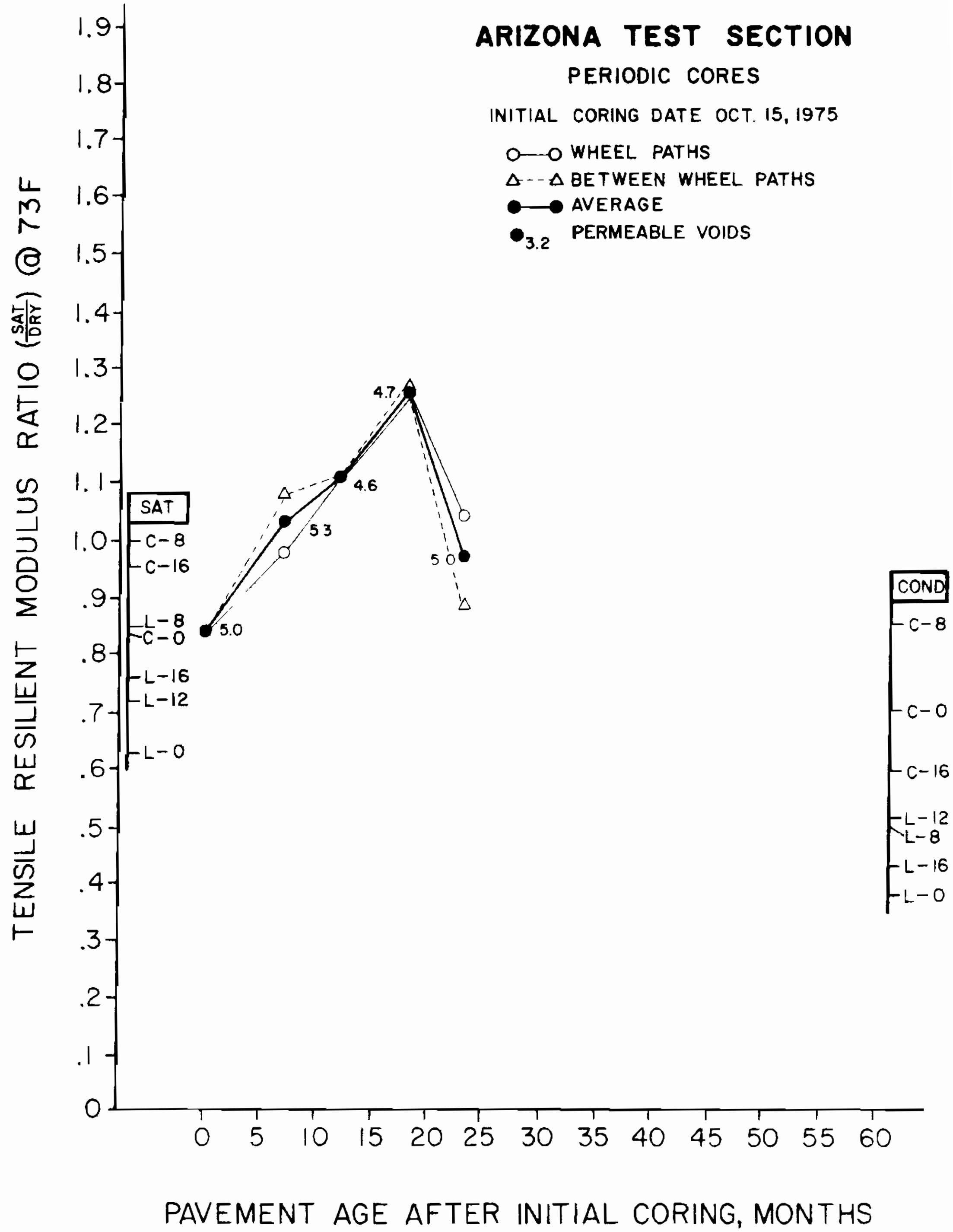

Figure C-1. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 73F (23 C) for Arizona.

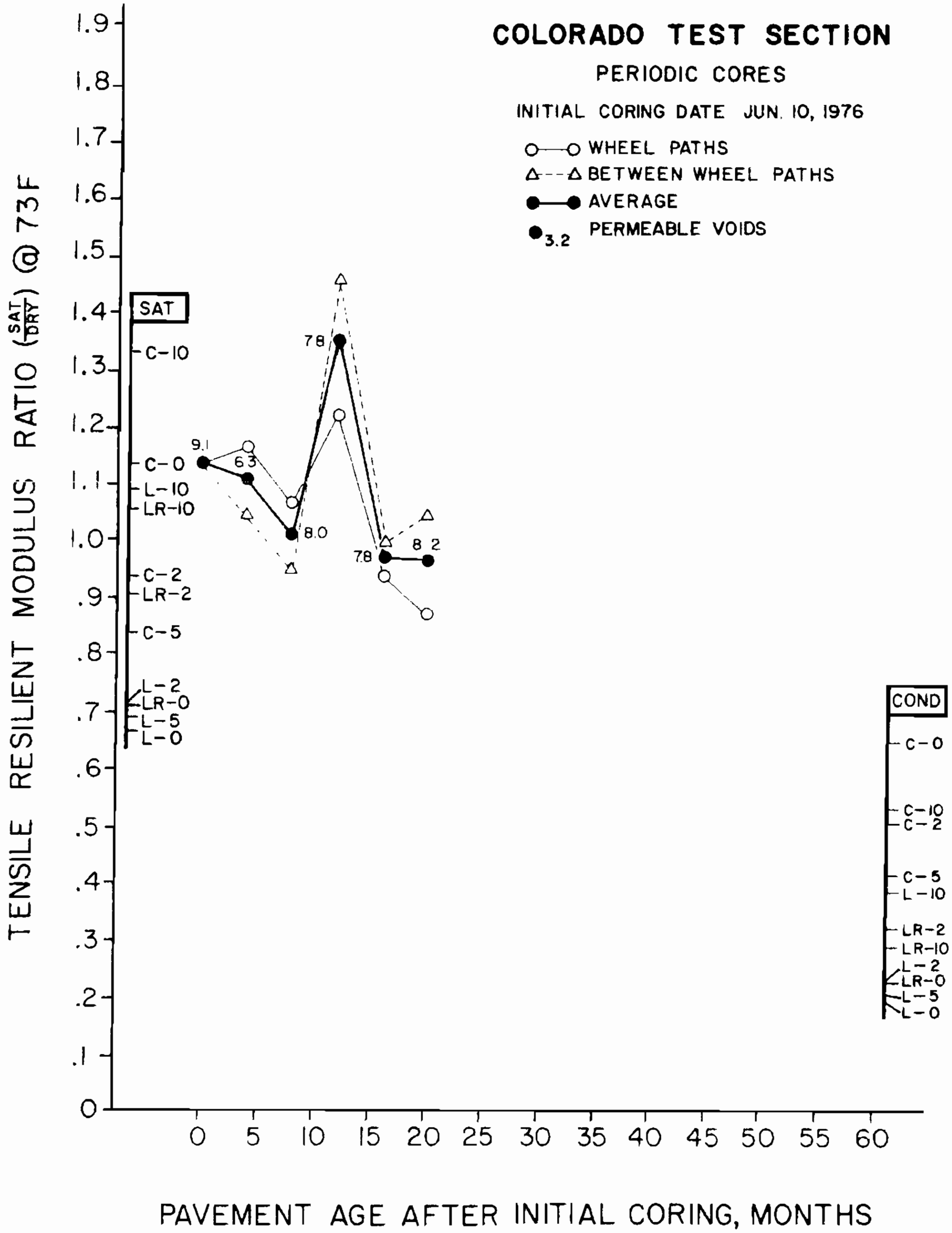

Figure C-2. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 73F (23 C) for Colorado.

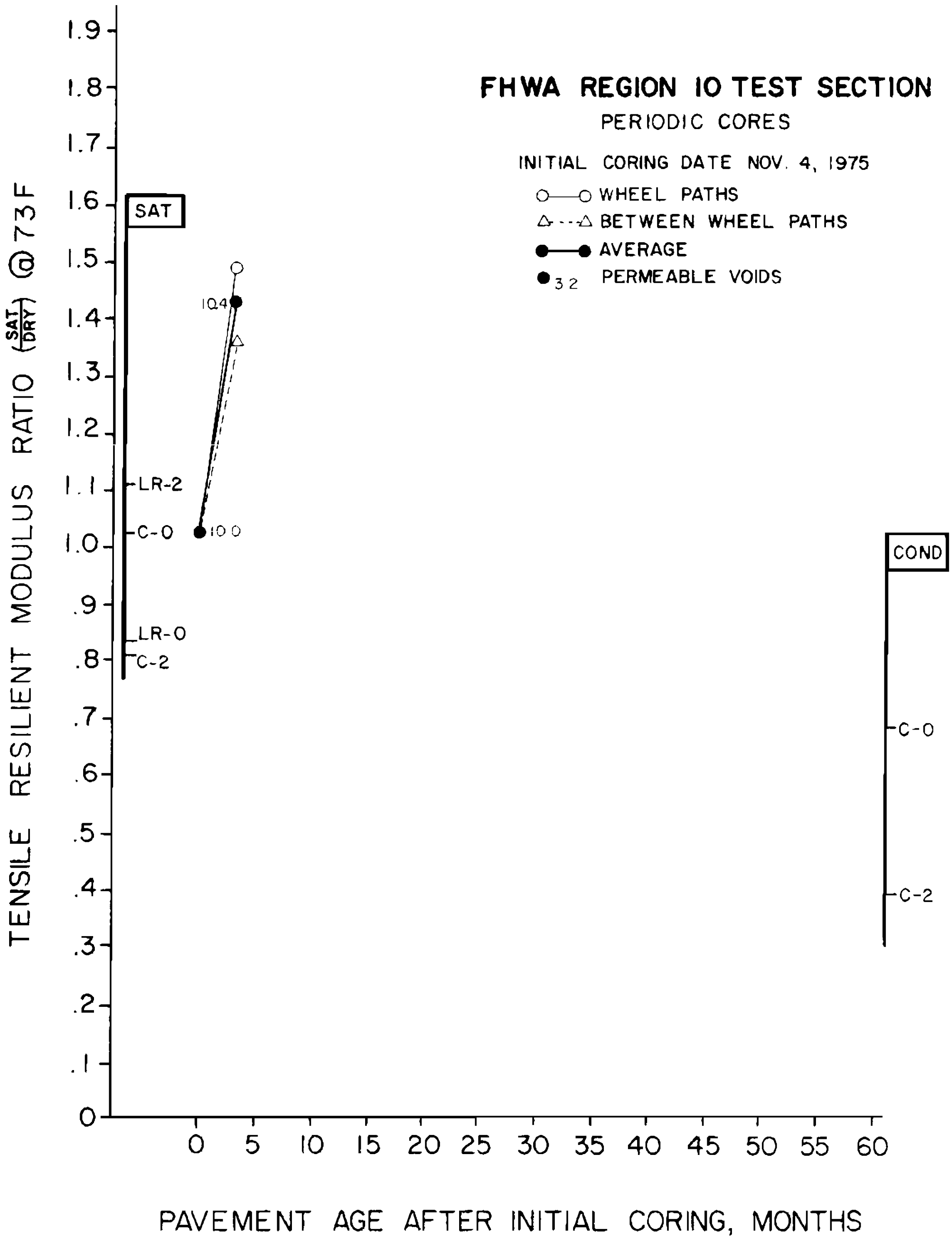

Figure C-3. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 73F (23 C) for FHWA 10.

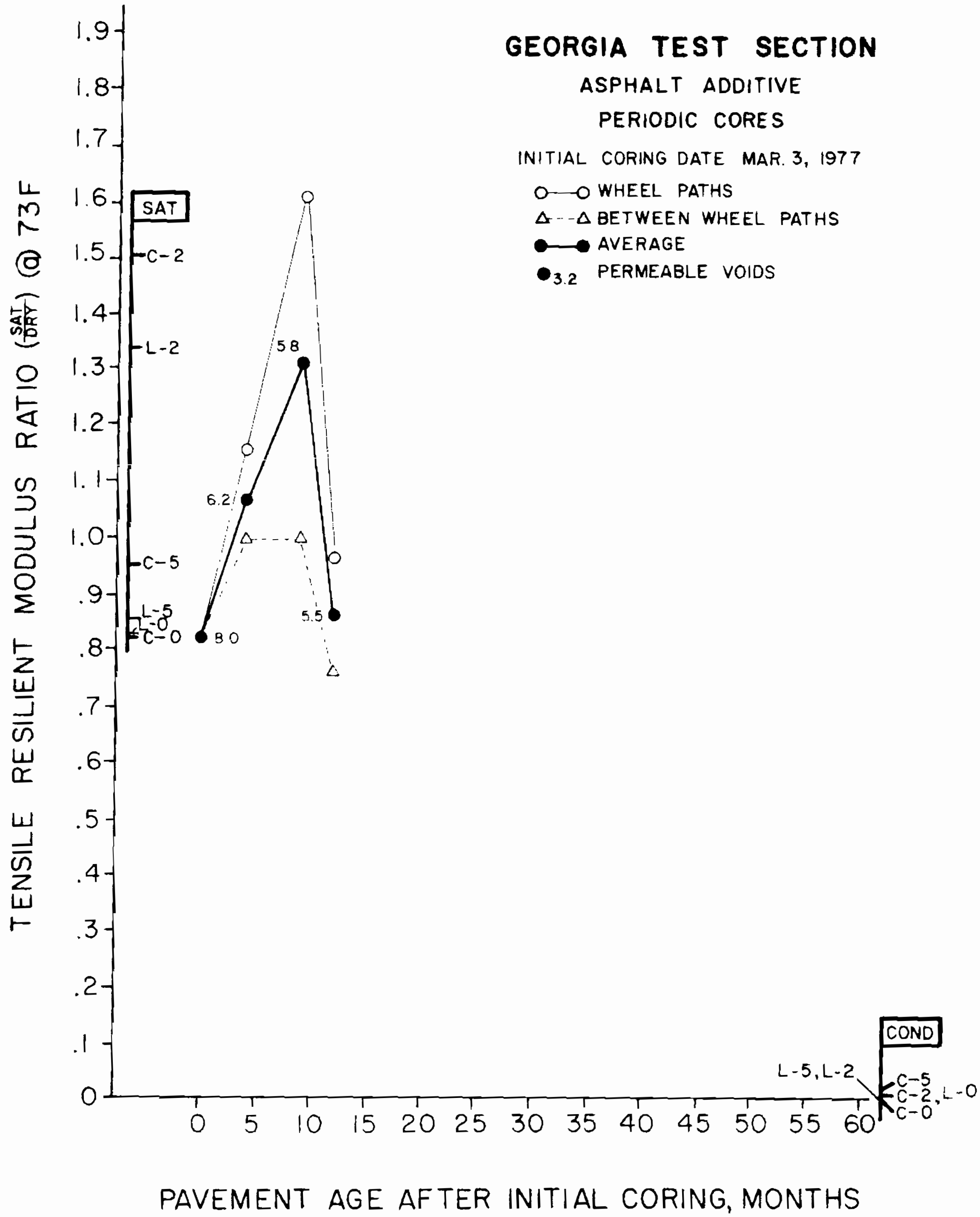

Figure C-4. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 73F (23 C) for Georgia (add.)

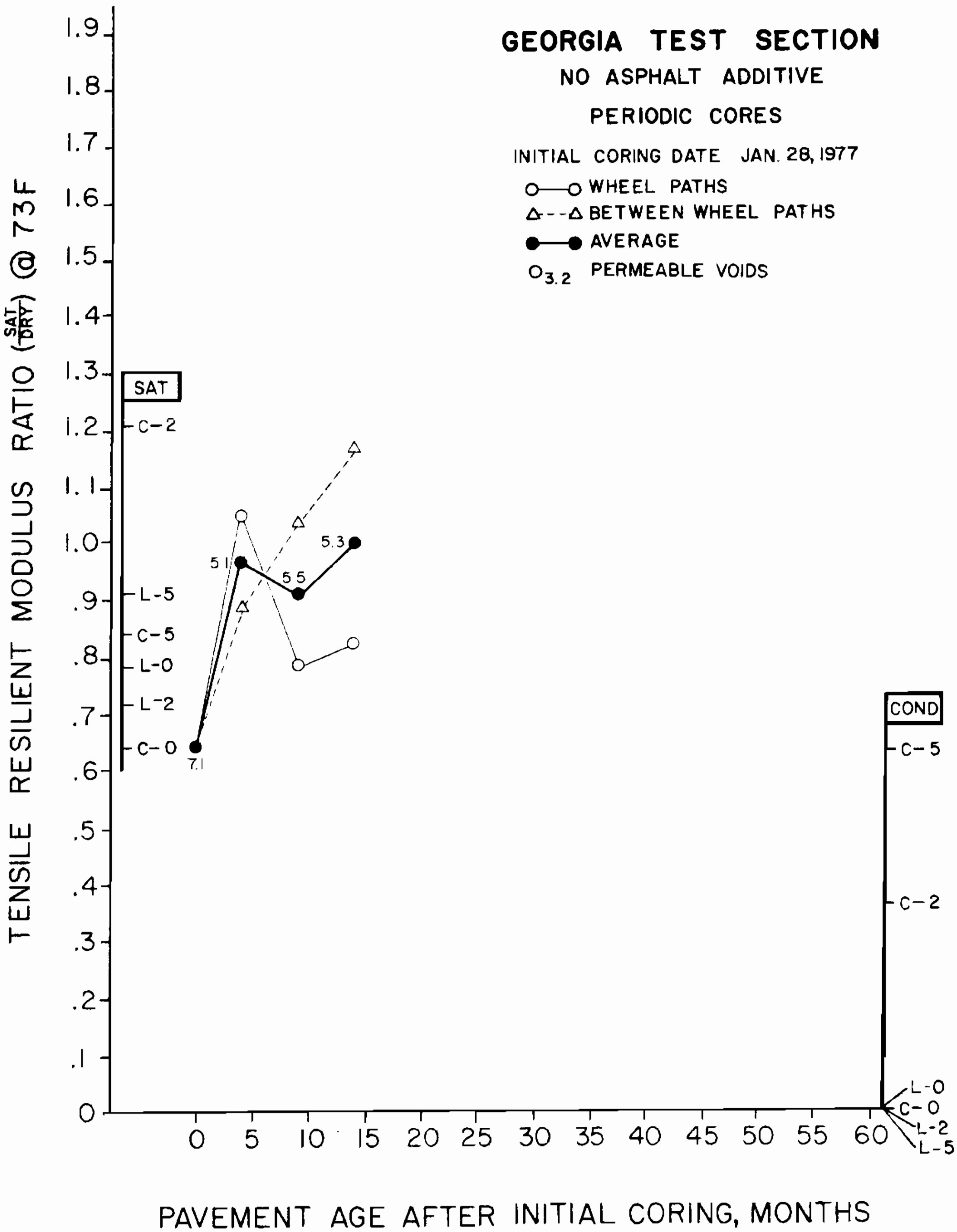

Figure C-5. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 73F (23 C) for Georgia (no add.)

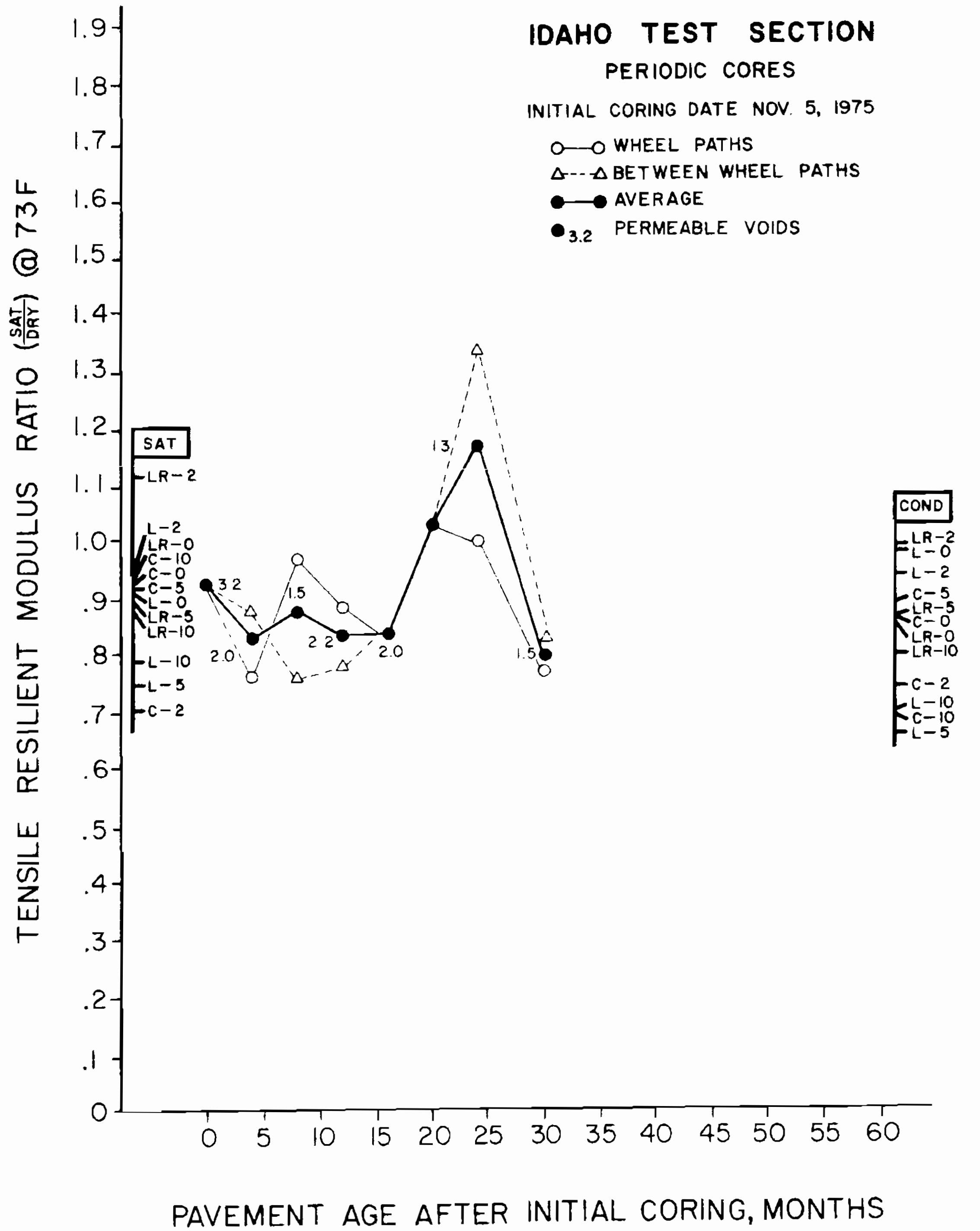

Figure C-6. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 73F (23 C) for Idaho.

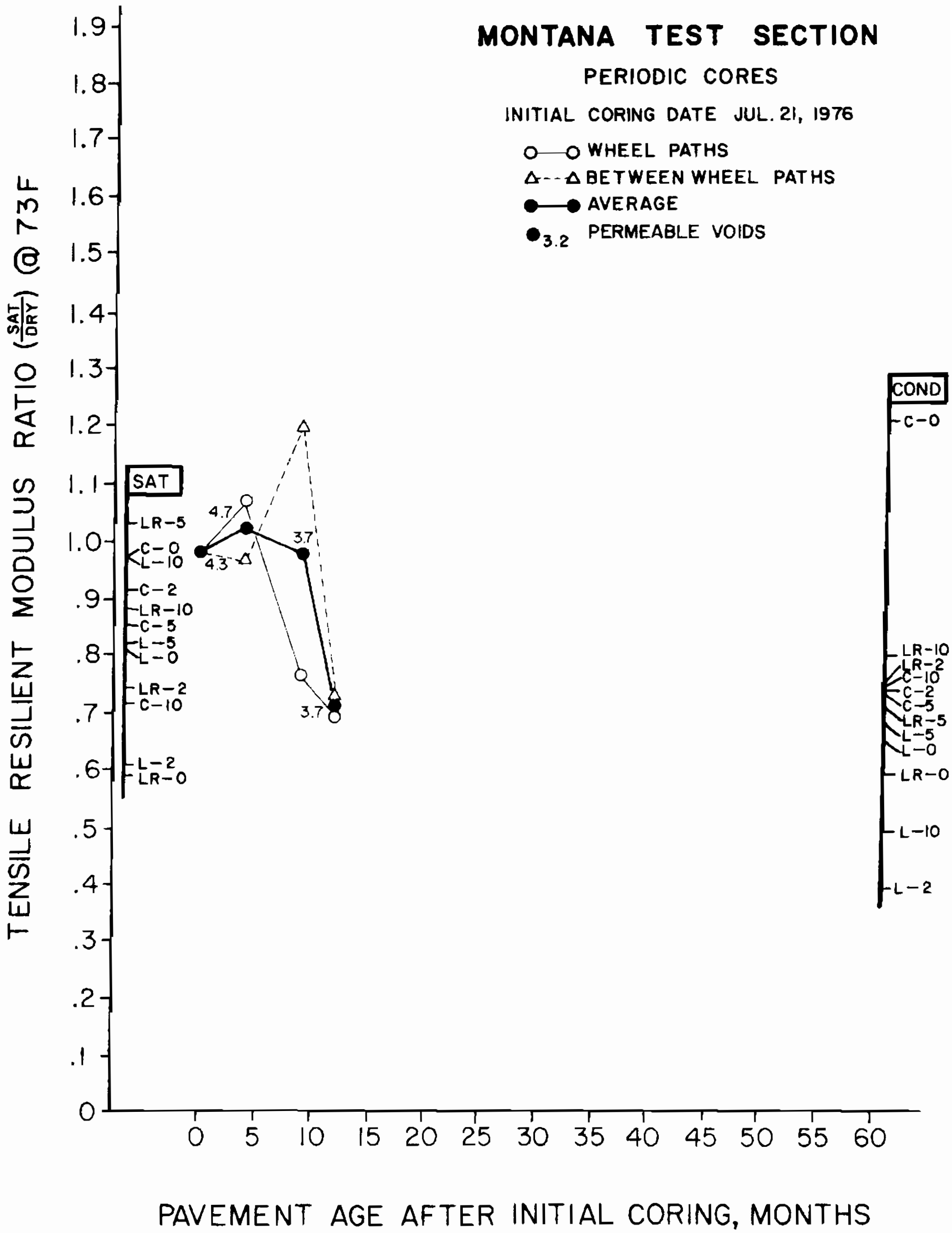

Figure C-7. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 73F (23 C) for Montana.

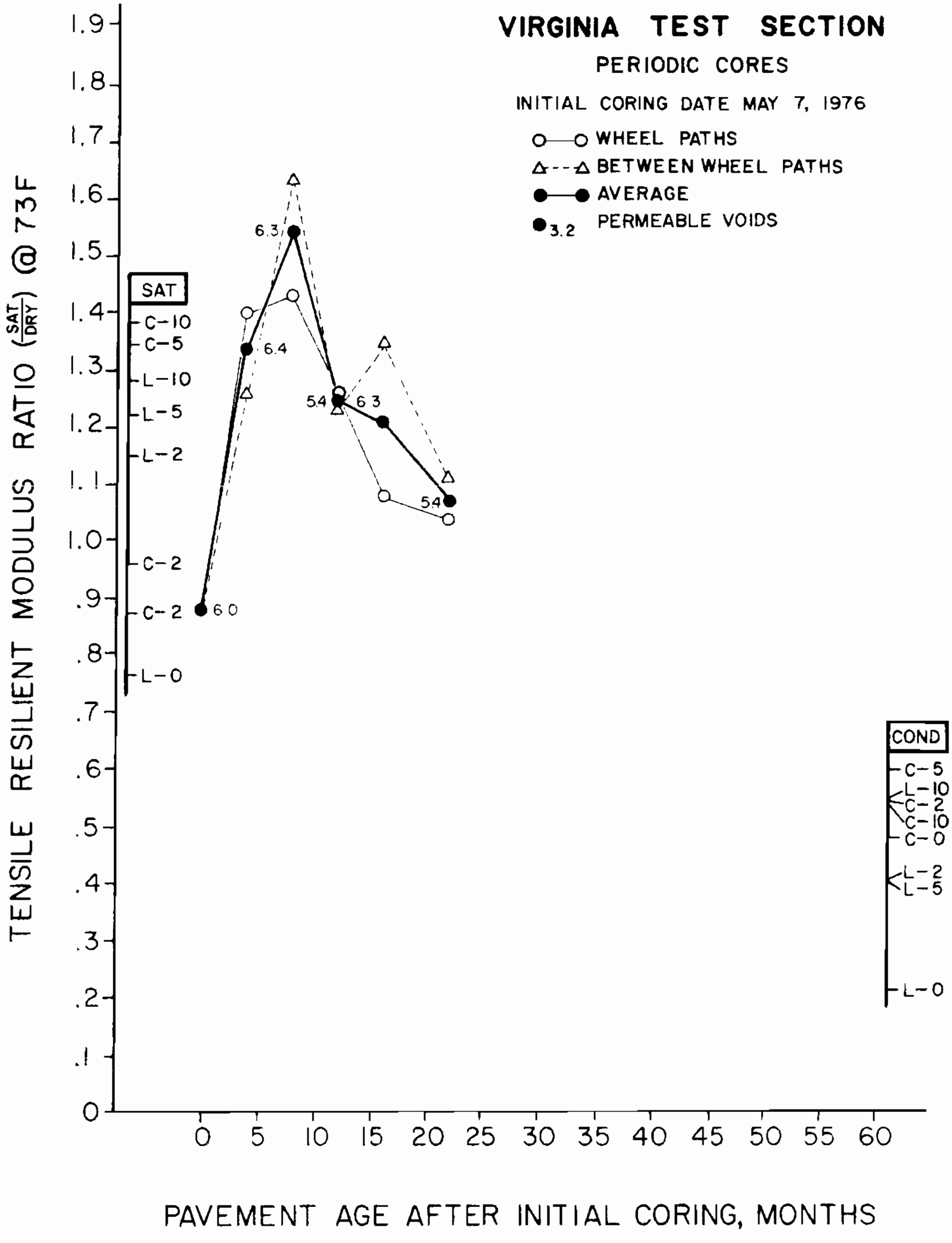

Figure C-8. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 72F (23 C) for Virginia.

APPENDIX D

MOISTURE DAMAGE TRENDS MEASURED BY RESILIENT MODULUS RATIO at 55F (13C)

Explanation of moisture damage prediction codes in the figures, examples:

C - 0 initial cores tested at zero month storage time

C - 12 initial cores tested at 12 month storage time

L - 5 laboratory specimens tested at 5 month storage time

LR - 0 laboratory specimens at reduced voids tested at zero month storage time

SAT vacuum saturated only

COND vacuum saturated plus accelerated conditioned

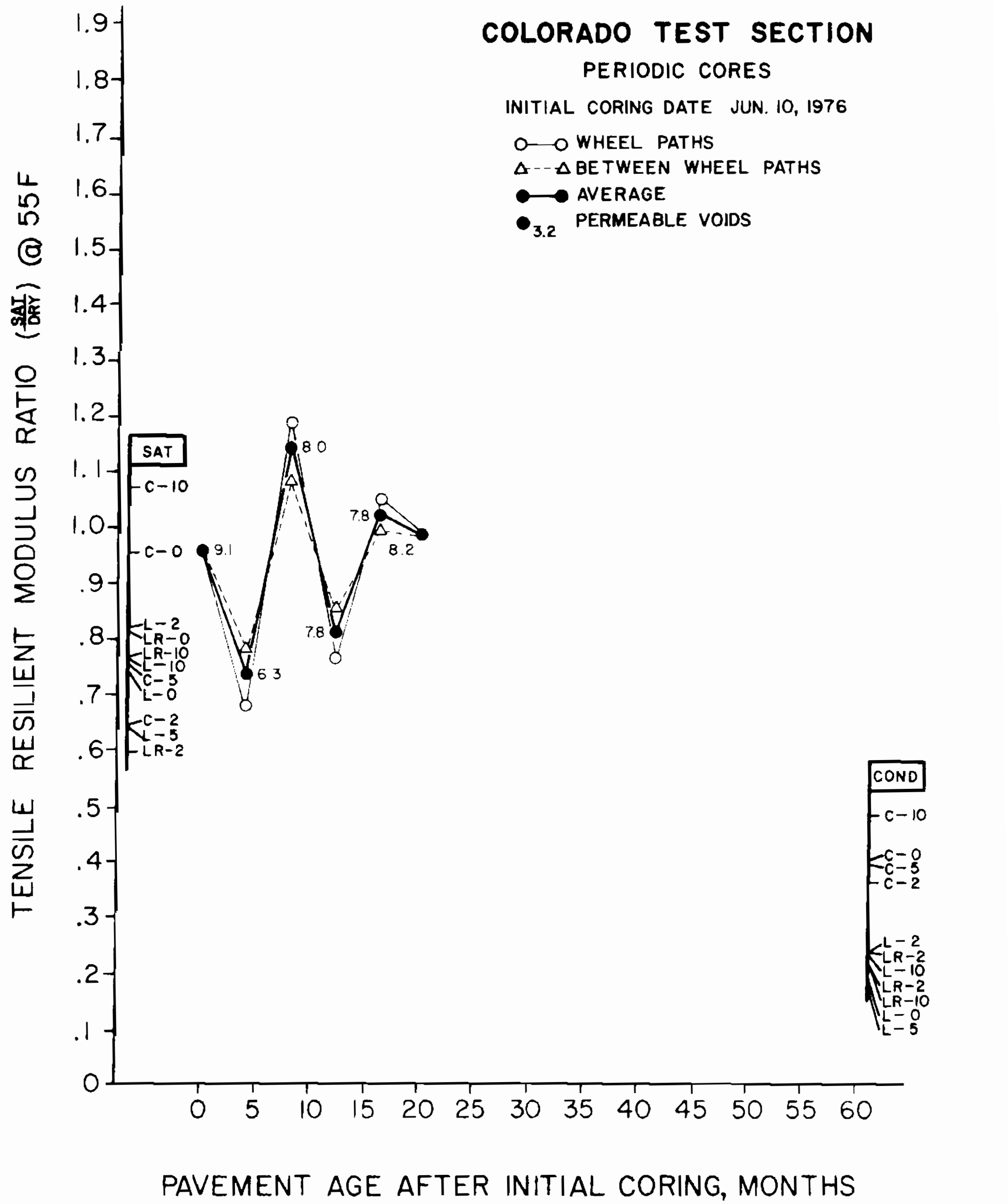

Figure D-1. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 55F (13 C) for Colorado.

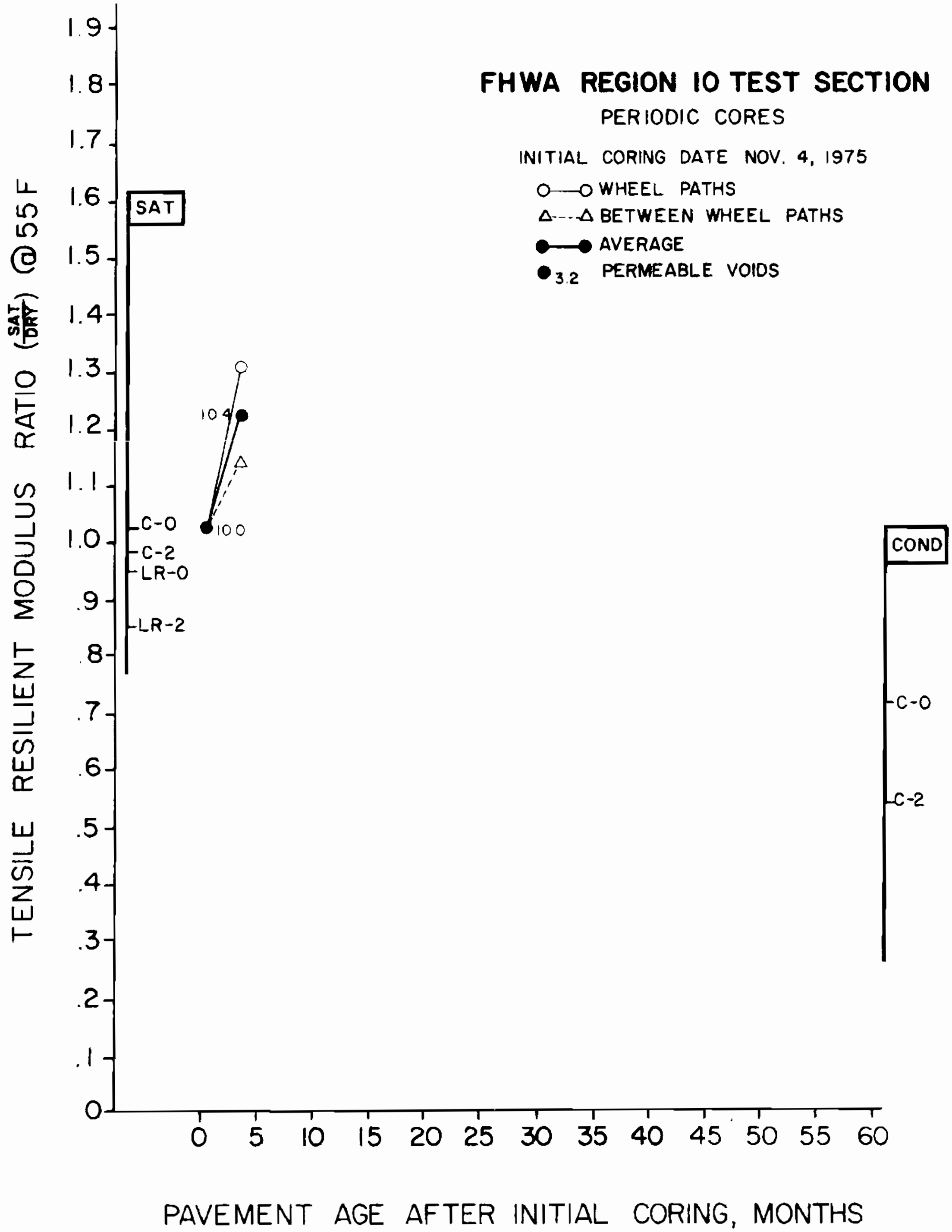

Figure D-2. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 55F (13 C) for FHWA 10.

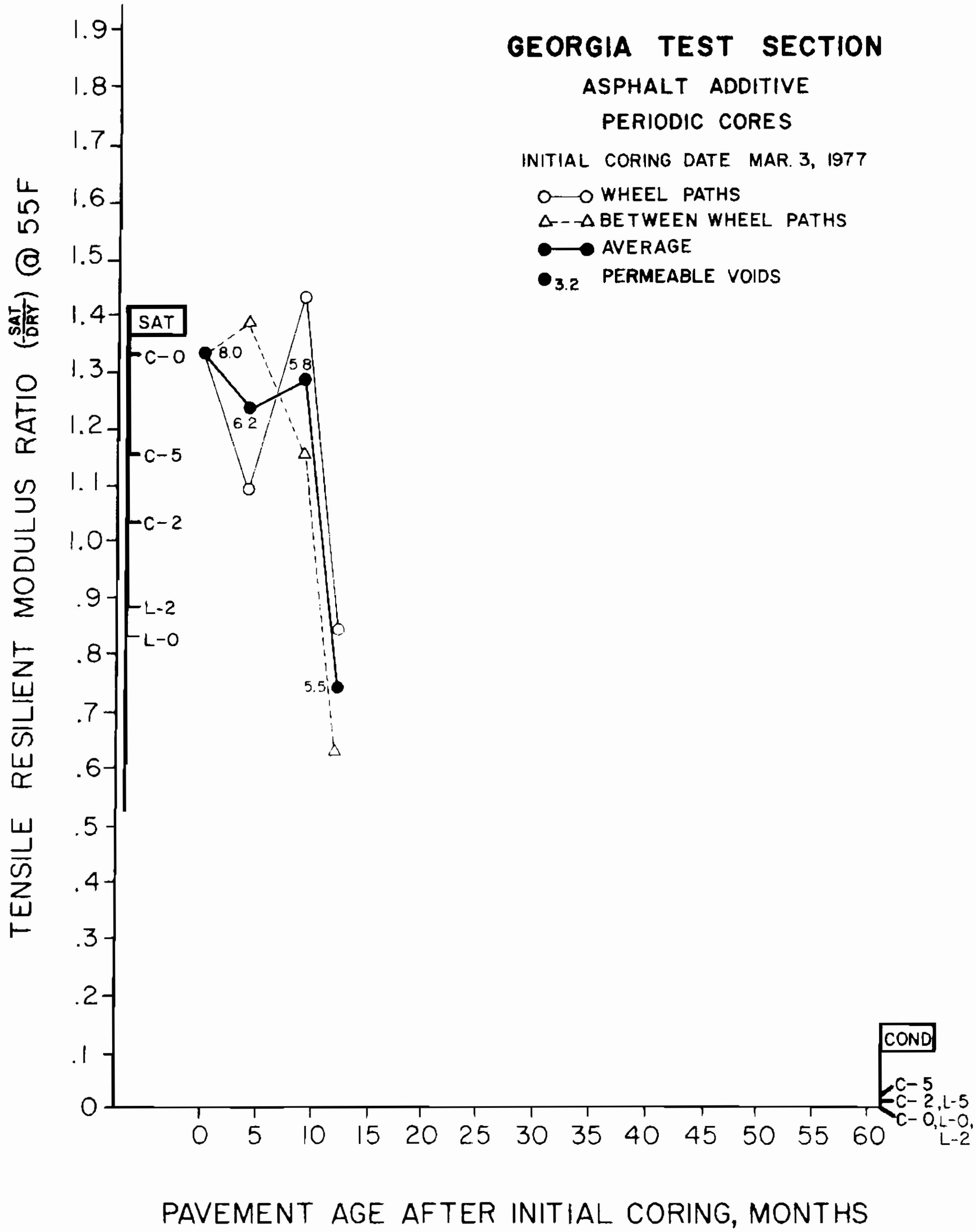

Figure D-3. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 55F (13 C) for Georgia (add.)

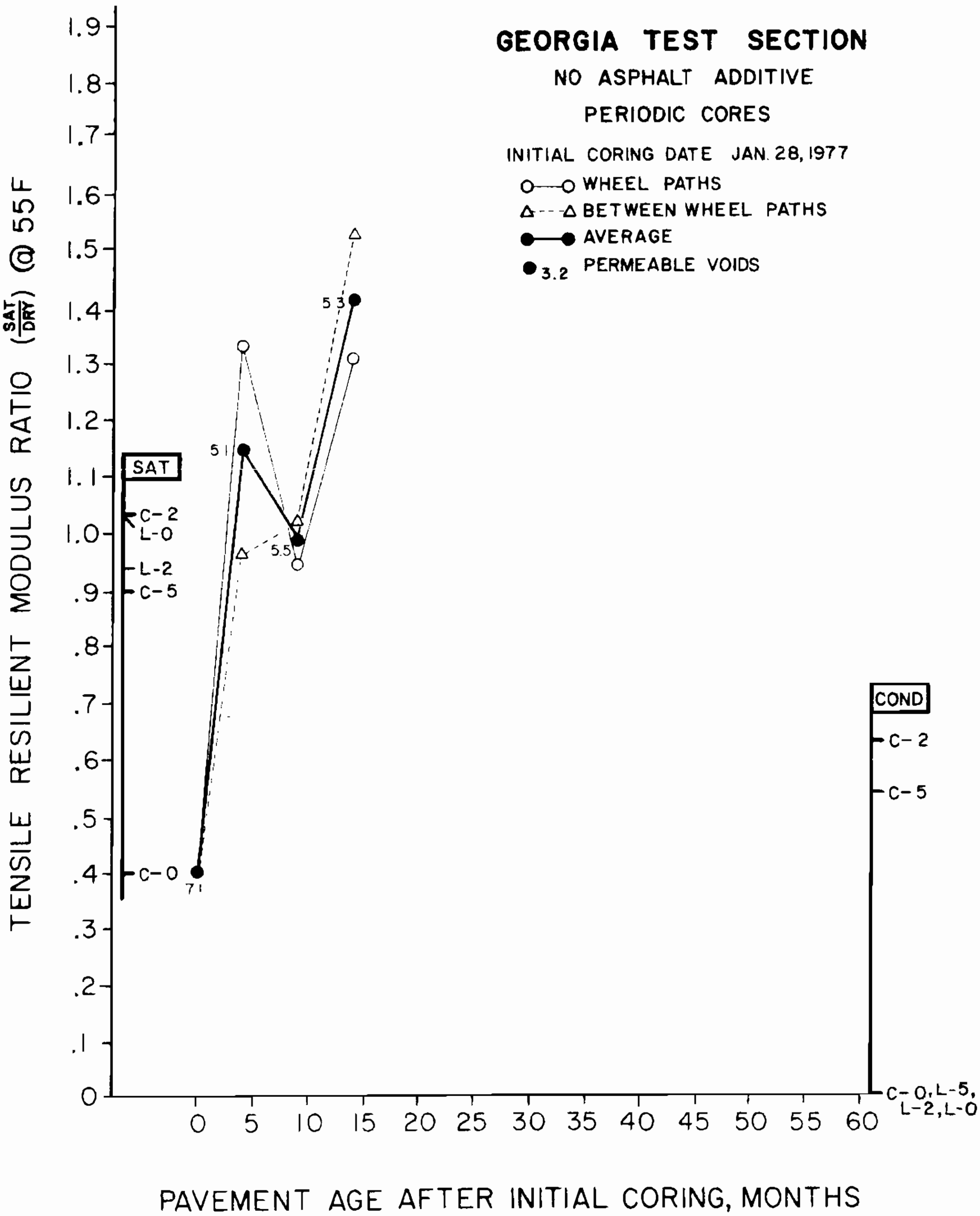

Figure D-4. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 55F (13 C) for Georgia (no add.)

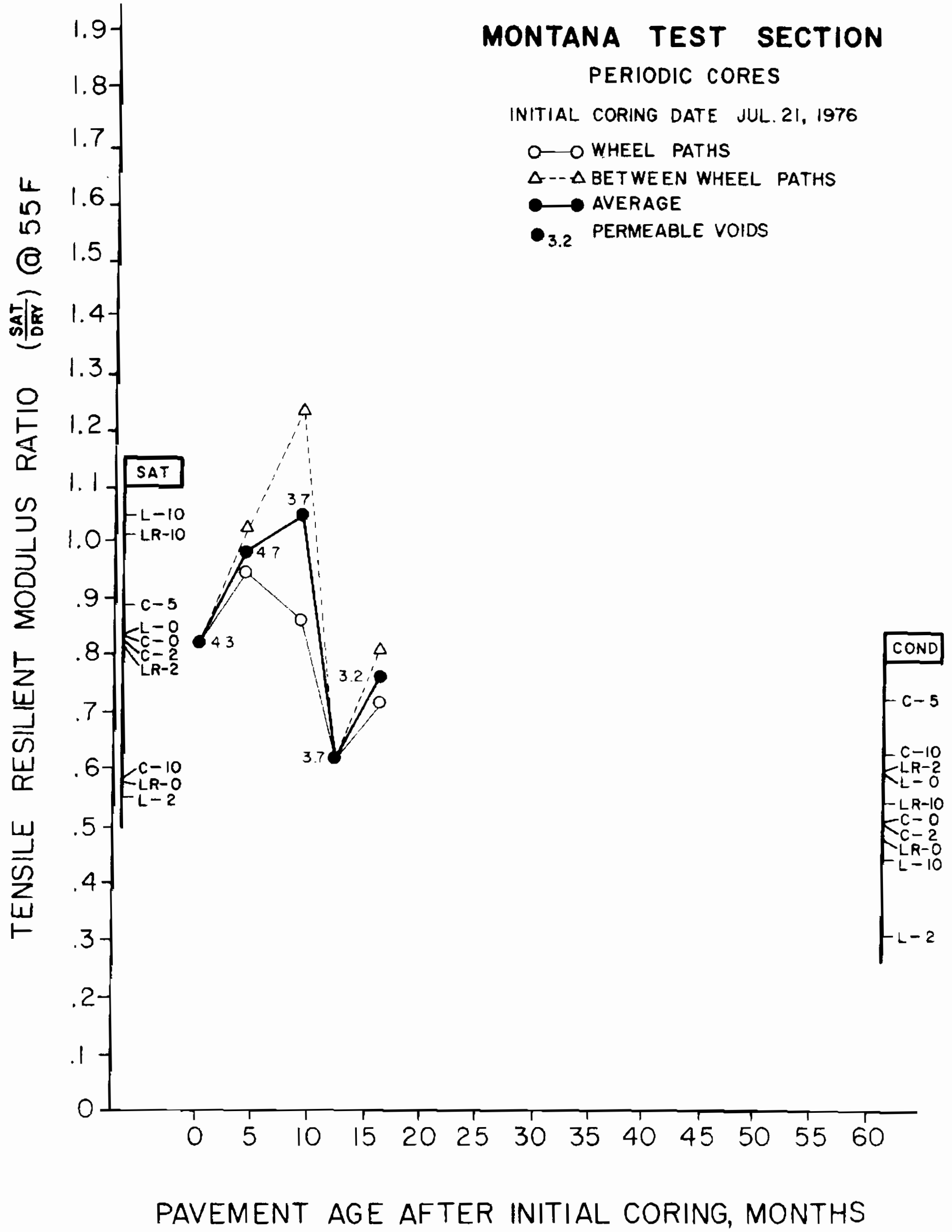

Figure D-5. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 55 F (13 C) for Montana.

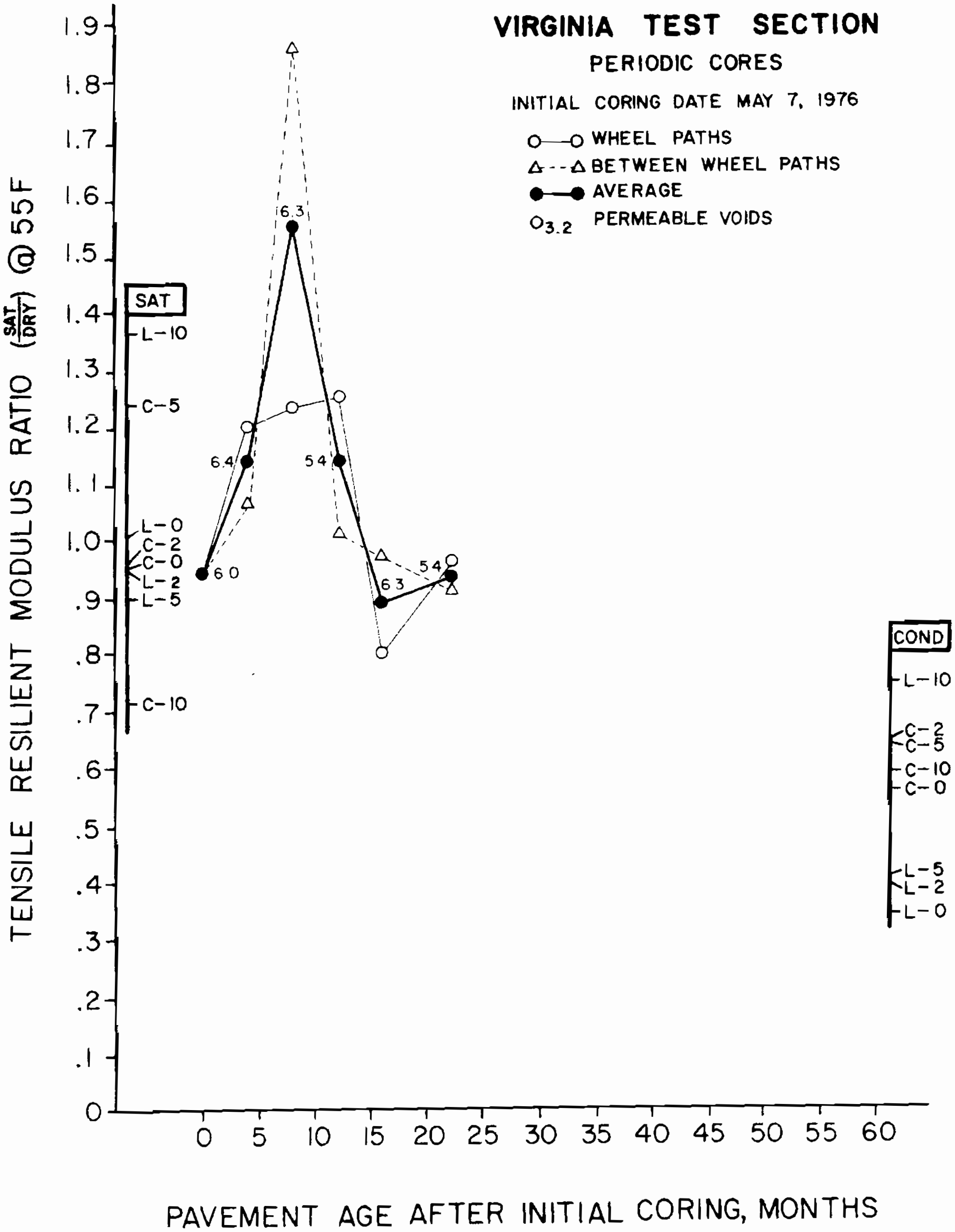

Figure D-6. Tensile Resilient Modulus Ratio Trends with Pavement Age and Predictions, 55F (13 C) for Virginia.

APPENDIX E

RELATIVE CHANGE OF TENSILE STRENGTH at 55F (13C) WITH PAVEMENT AGE

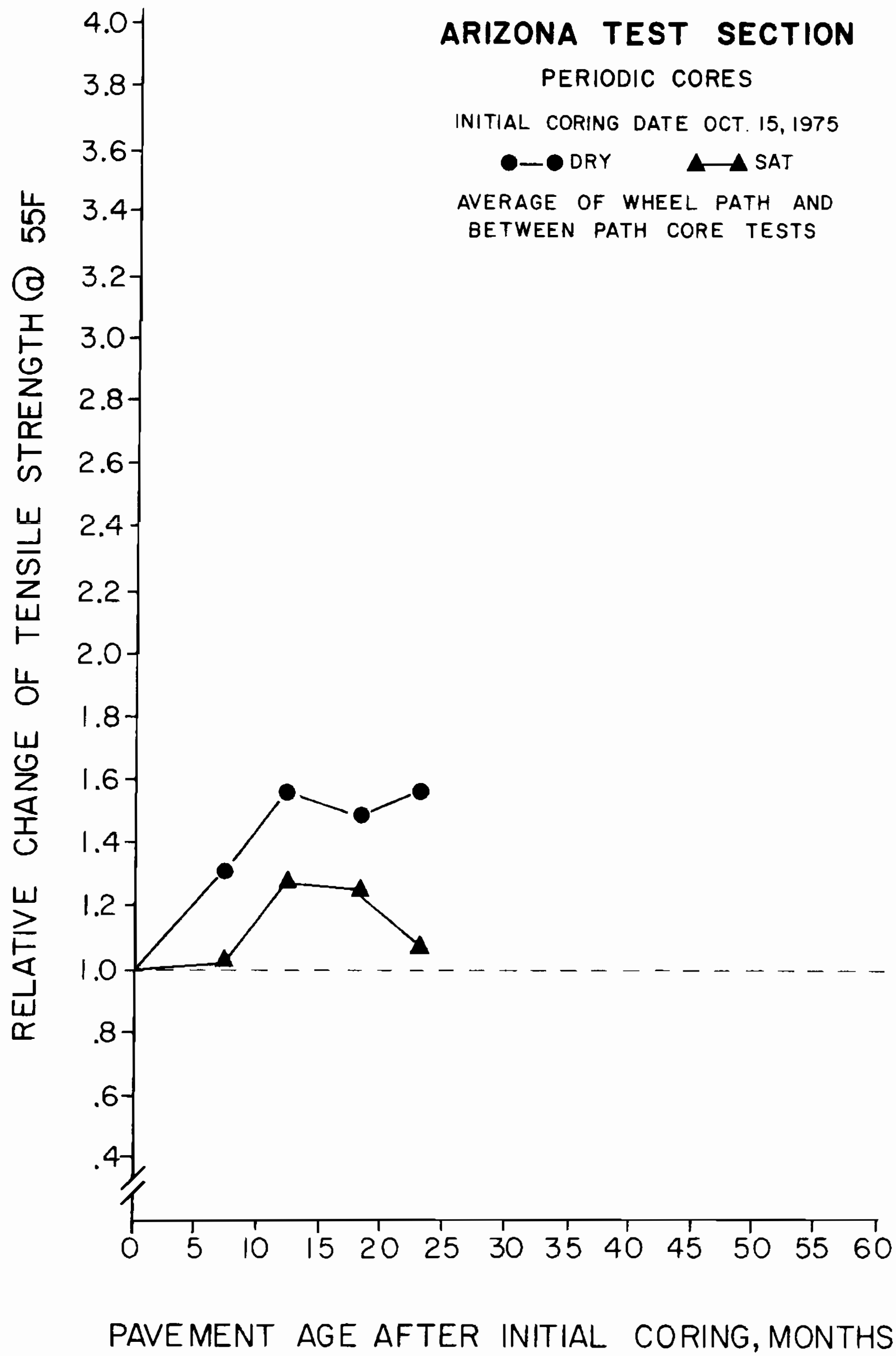

Figure E-1. Relative Increase of Tensile Strength with Pavement Age, 55F (13 C) for Arizona.

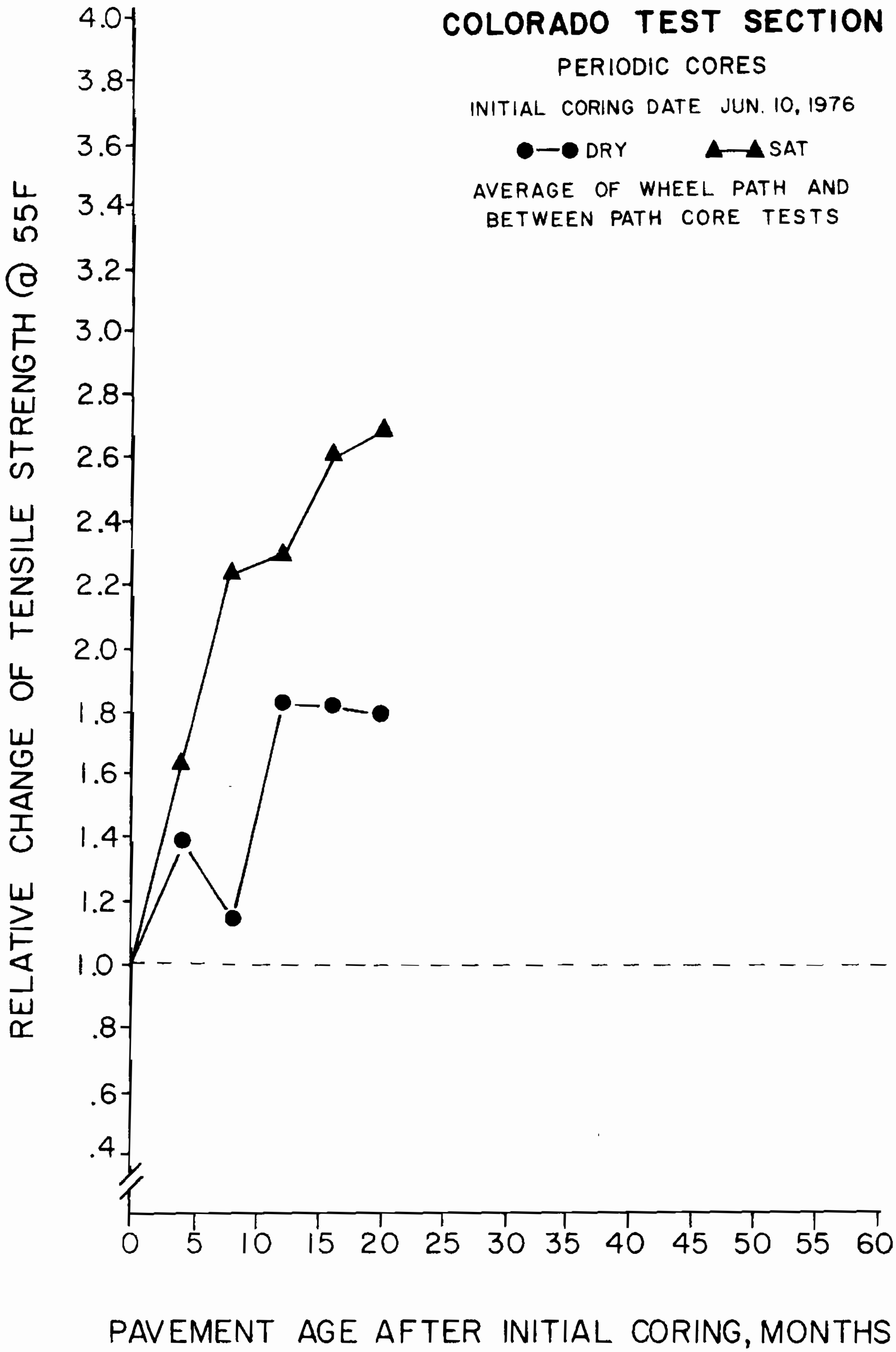

Figure E-2. Relative Increase of Tensile Strength with Pavement Age, 55F (13 C) for Colorado.

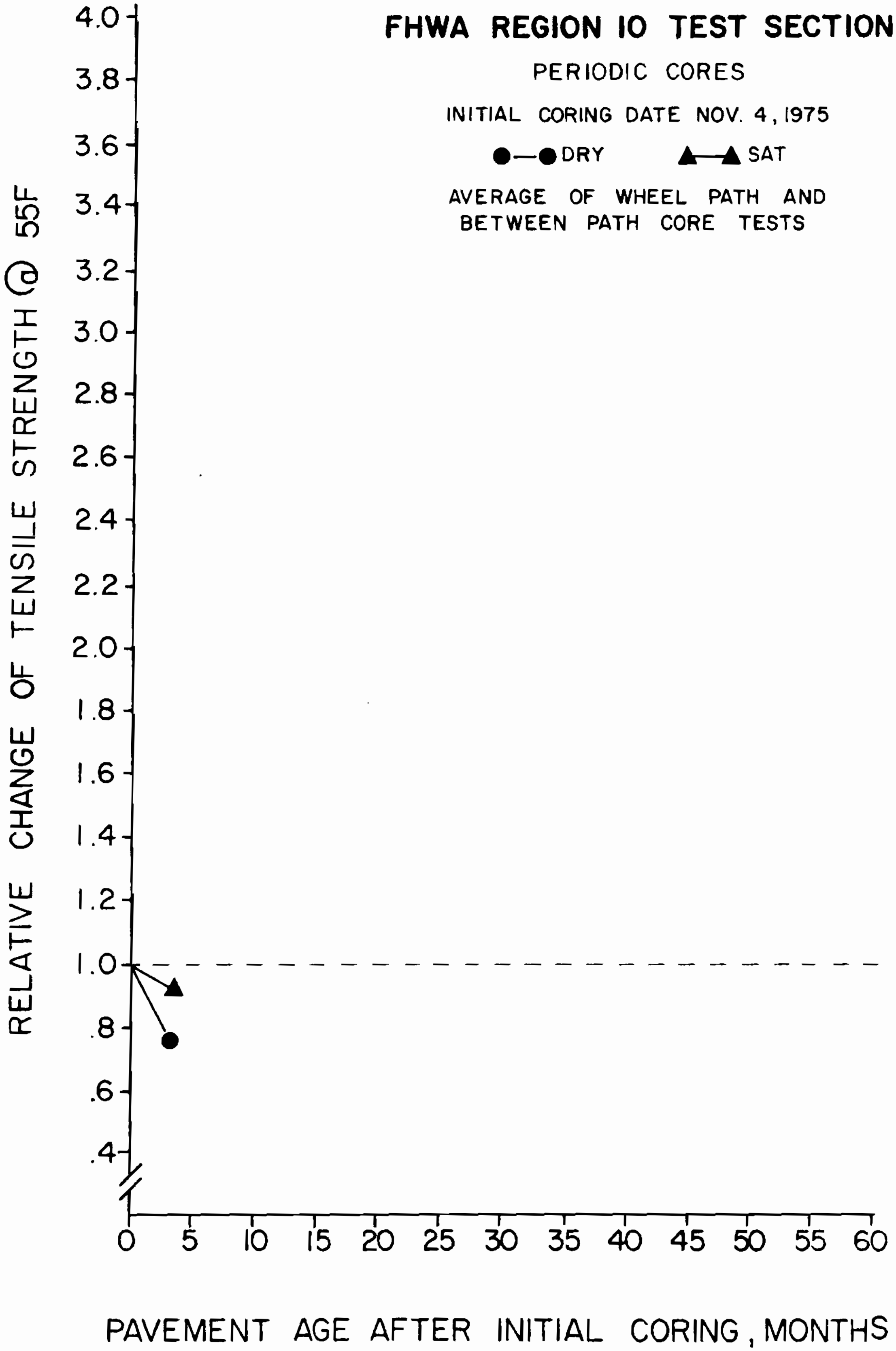

Figure E-3. Relative Increase of Tensile Strength with Pavement Age, 55F (13 C) for FHWA 10.

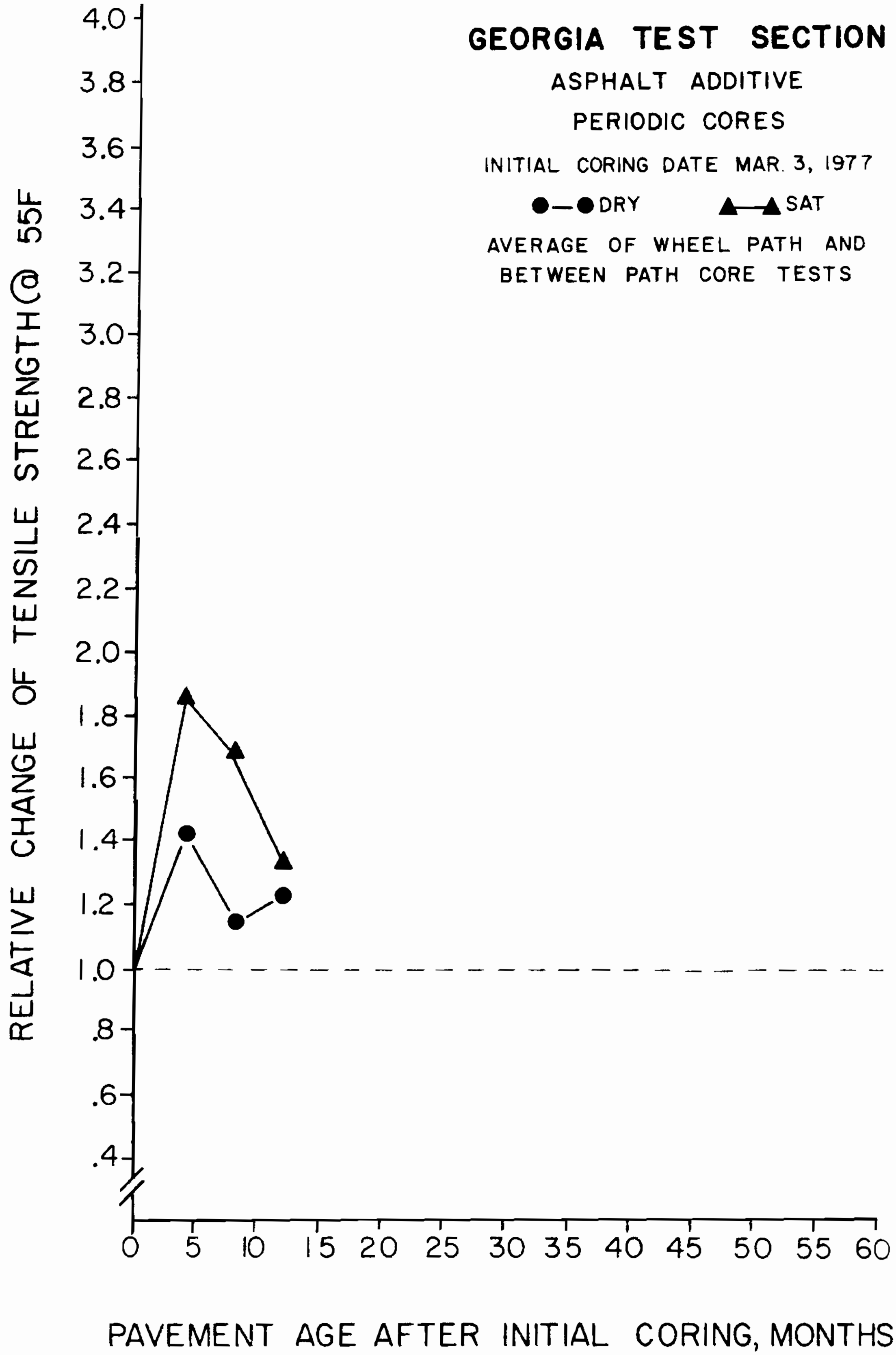

Figure E-4. Relative Increase of Tensile Strength with Pavement Age, 55F (13 C) for Georgia (add.)

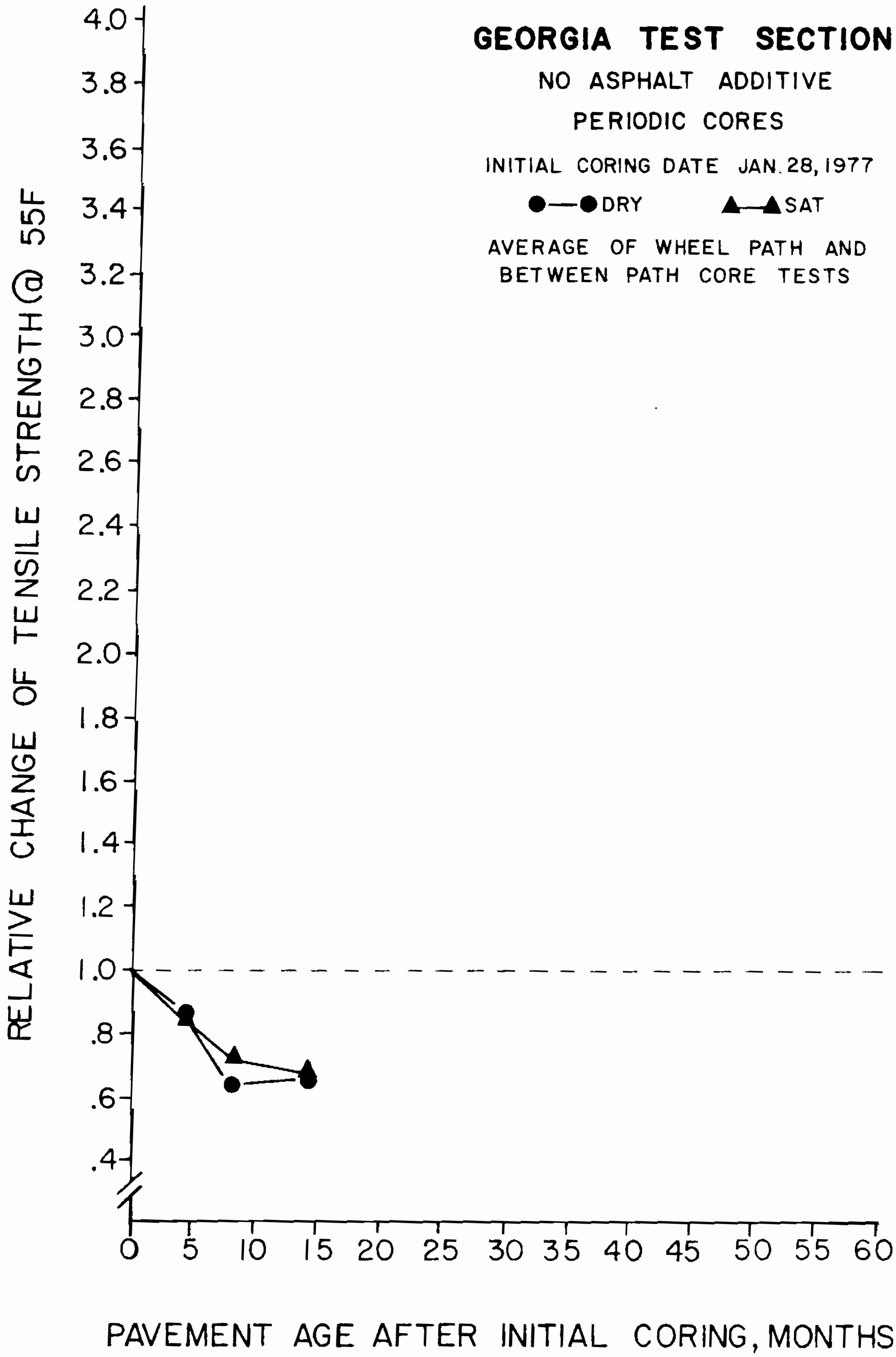

Figure E-5. Relative Increase of Tensile Strength with Pavement Age, 55F (13 C) for Georgia (no add.).

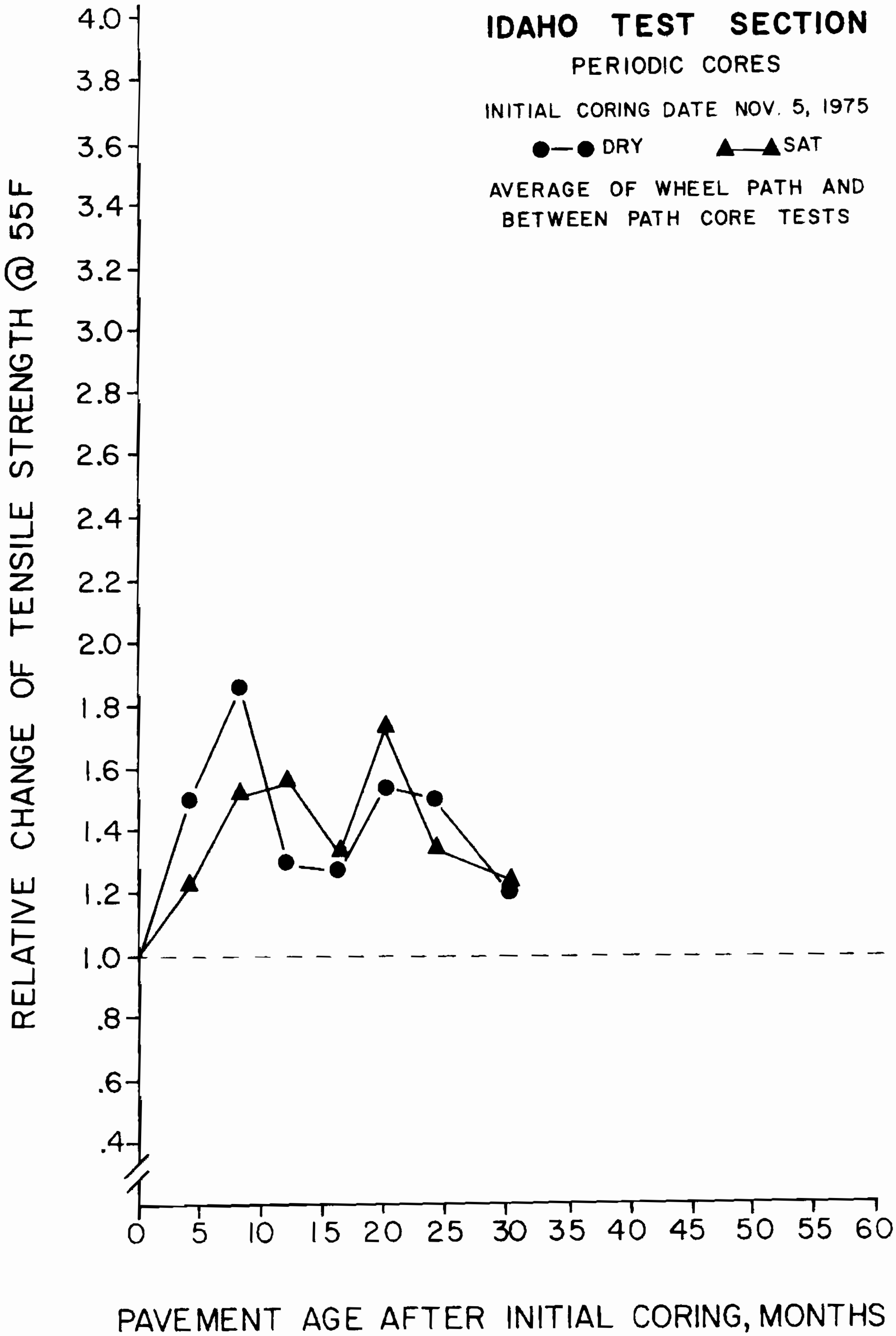

Figure E-6. Relative Increase of Tensile Strength with Pavement Age, 55F (13 C) for Idaho.

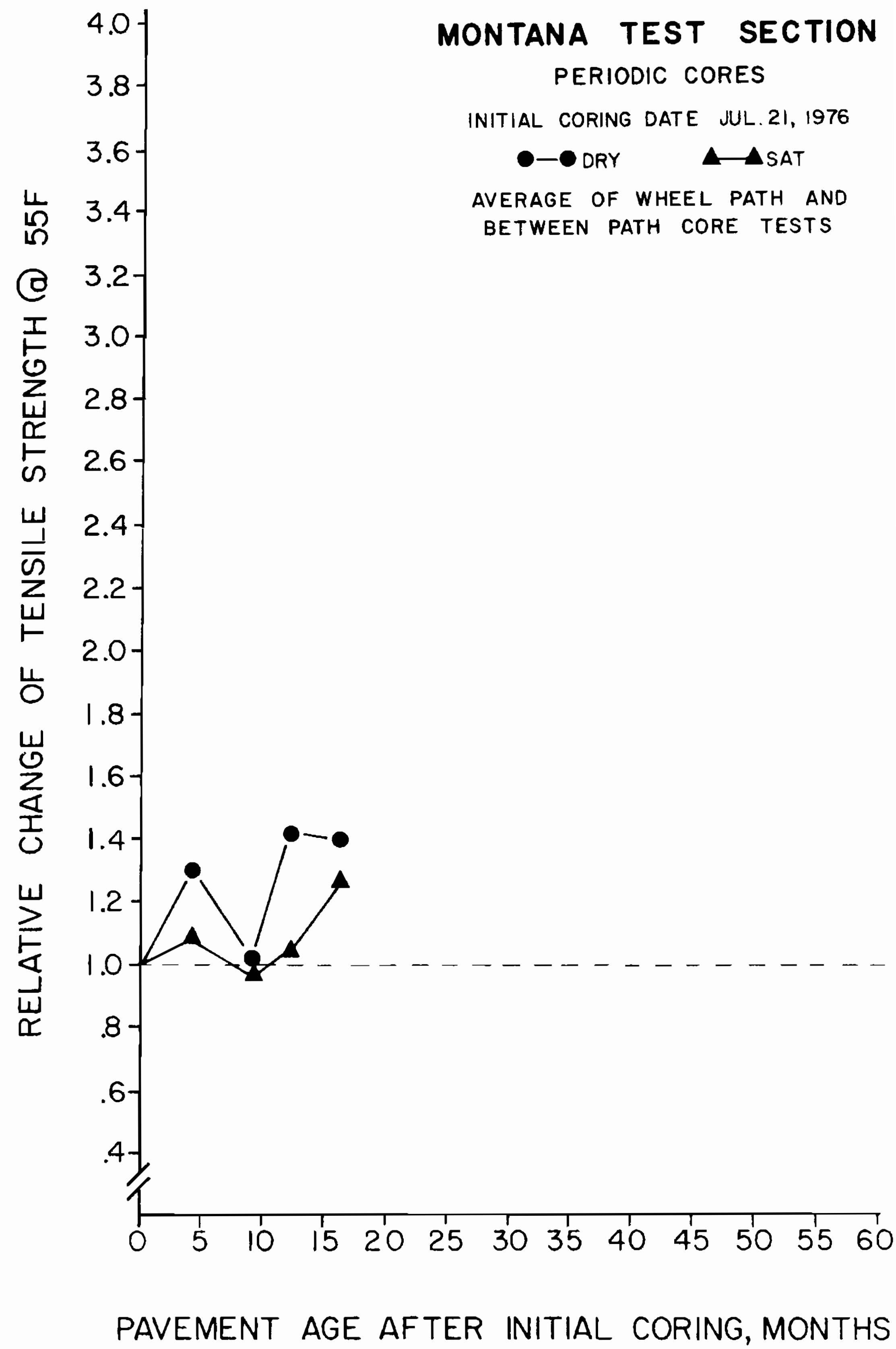

Figure E-7. Relative Increase of Tensile Strength with Pavement Age, 55F (13 C) for Montana.

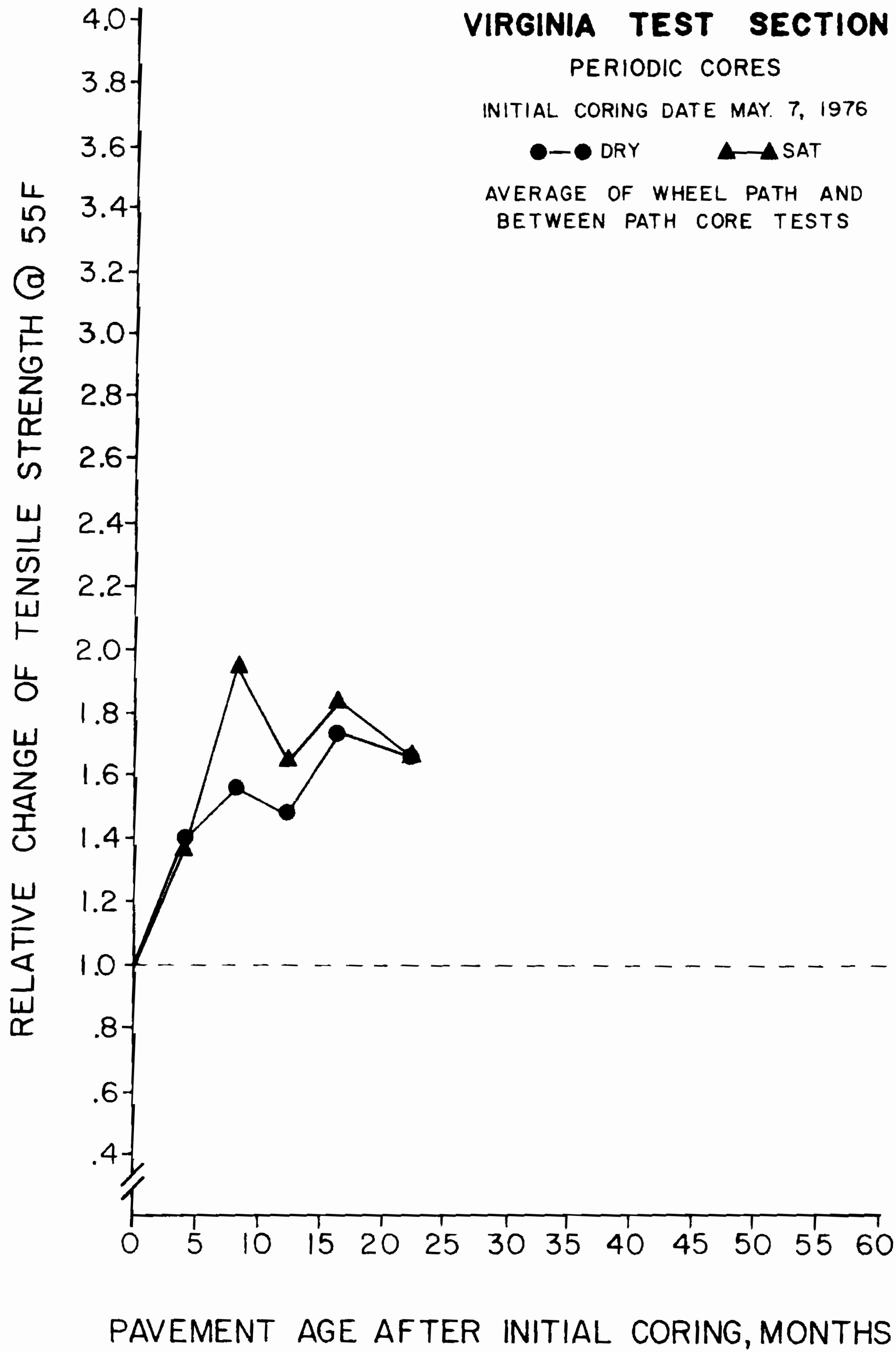

Figure E-8. Relative Increase of Tensile Strength with Pavement Age, 55F (13 C) for Virginia.

APPENDIX F

RELATIVE CHANGE OF RESILIENT MODULUS at 73F (23C) with PAVEMENT AGE

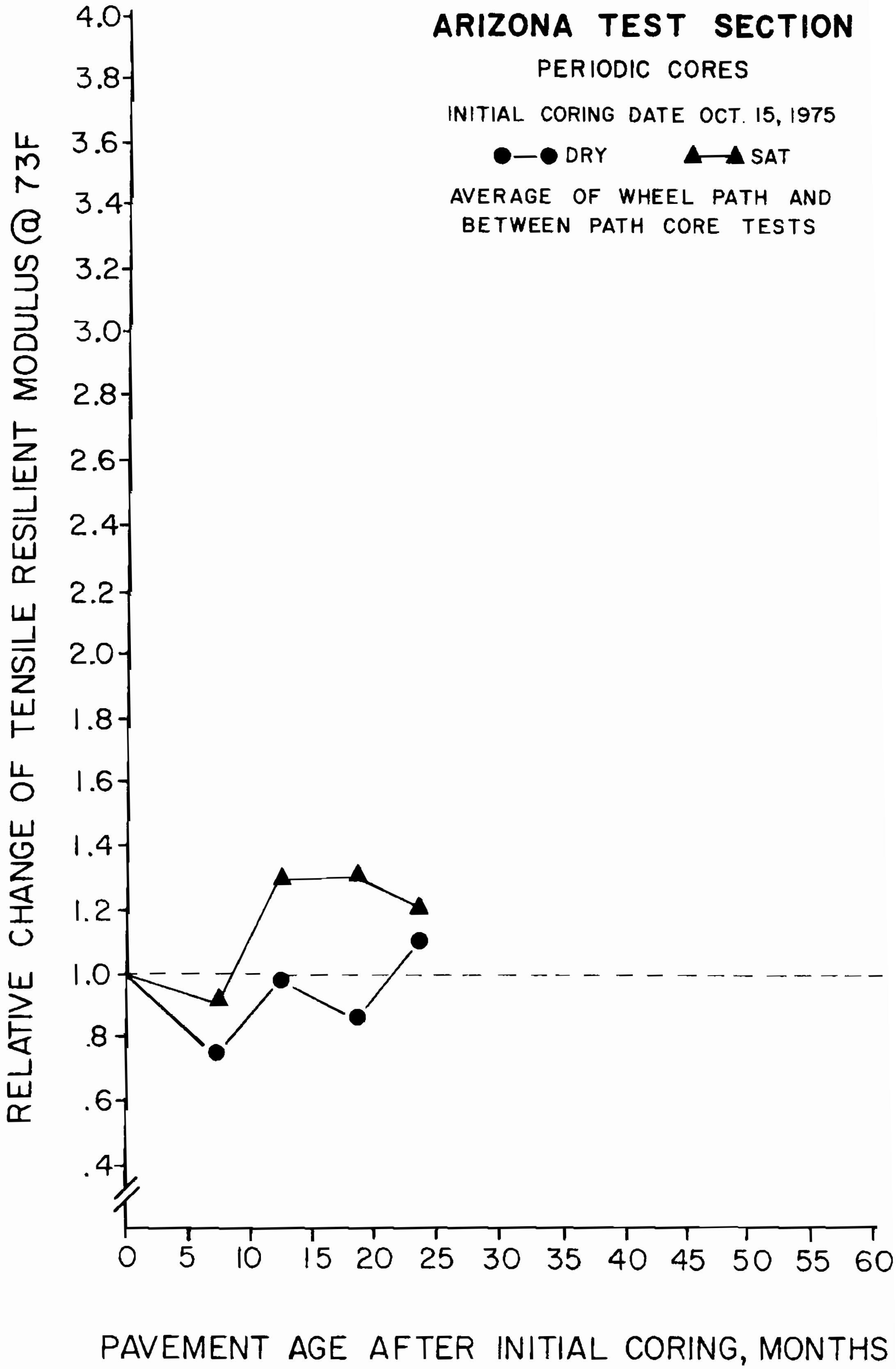

Figure F-1. Relative Increase of Tensile Resilient Modulus with Pavement Age, 73F (23 C) for Arizona.

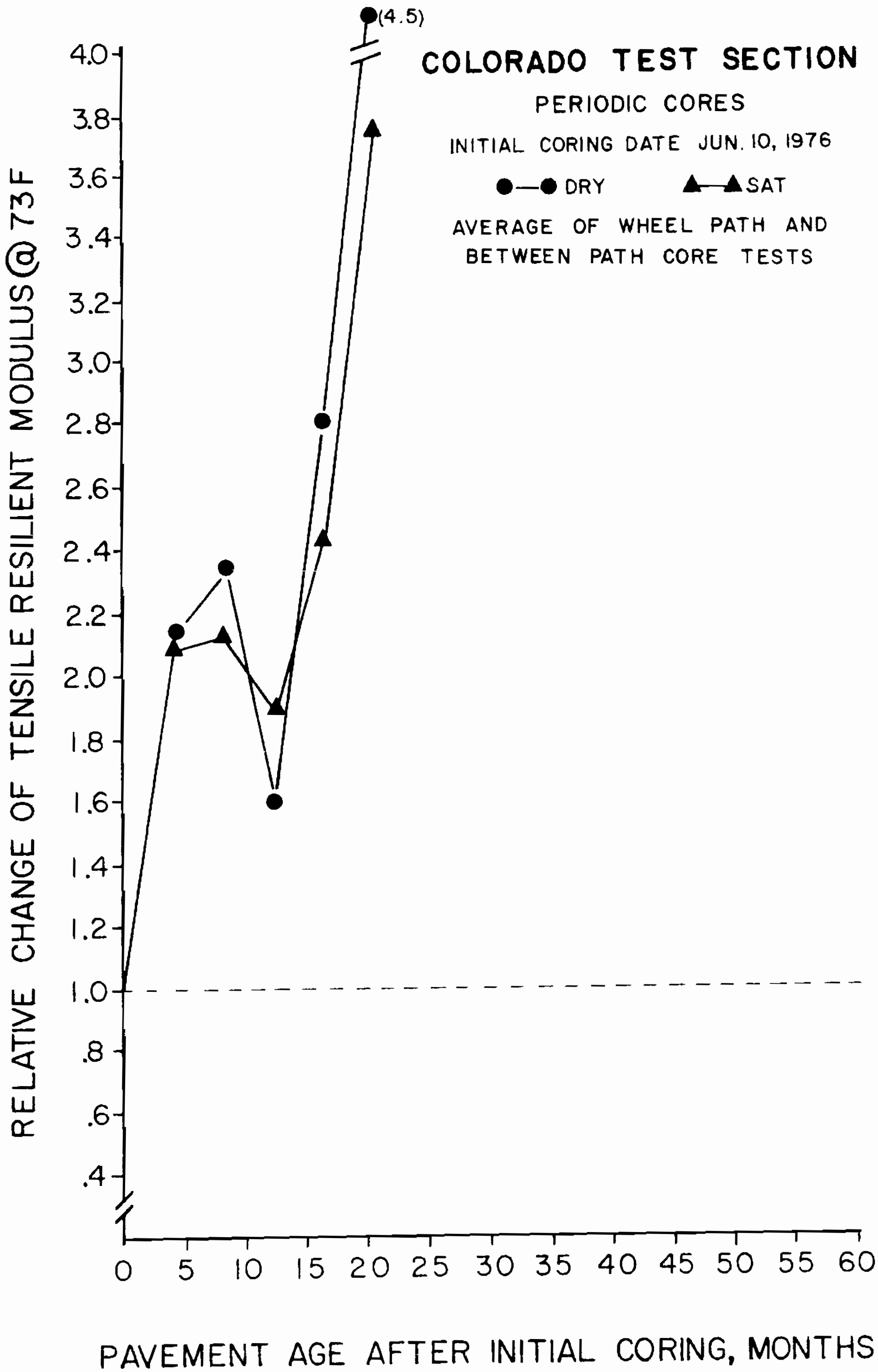

Figure F-2. Relative Increase of Tensile Resilient Modulus with Pavement Age, 73F (23 C) for Colorado.

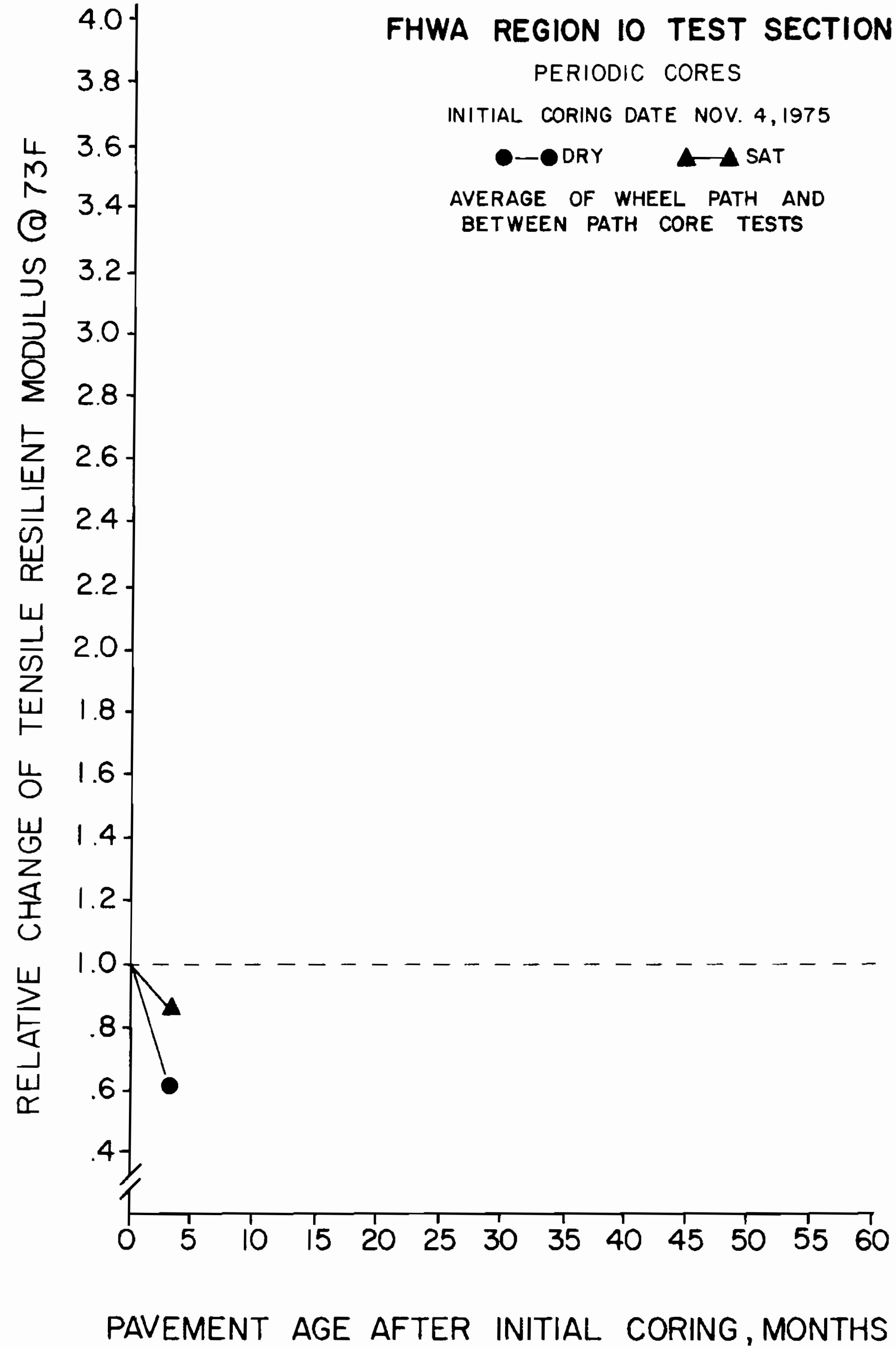

Figure F-3. Relative Increase of Tensile Resilient Modulus with Pavement Age, 73F (23 C) for FHWA 10.

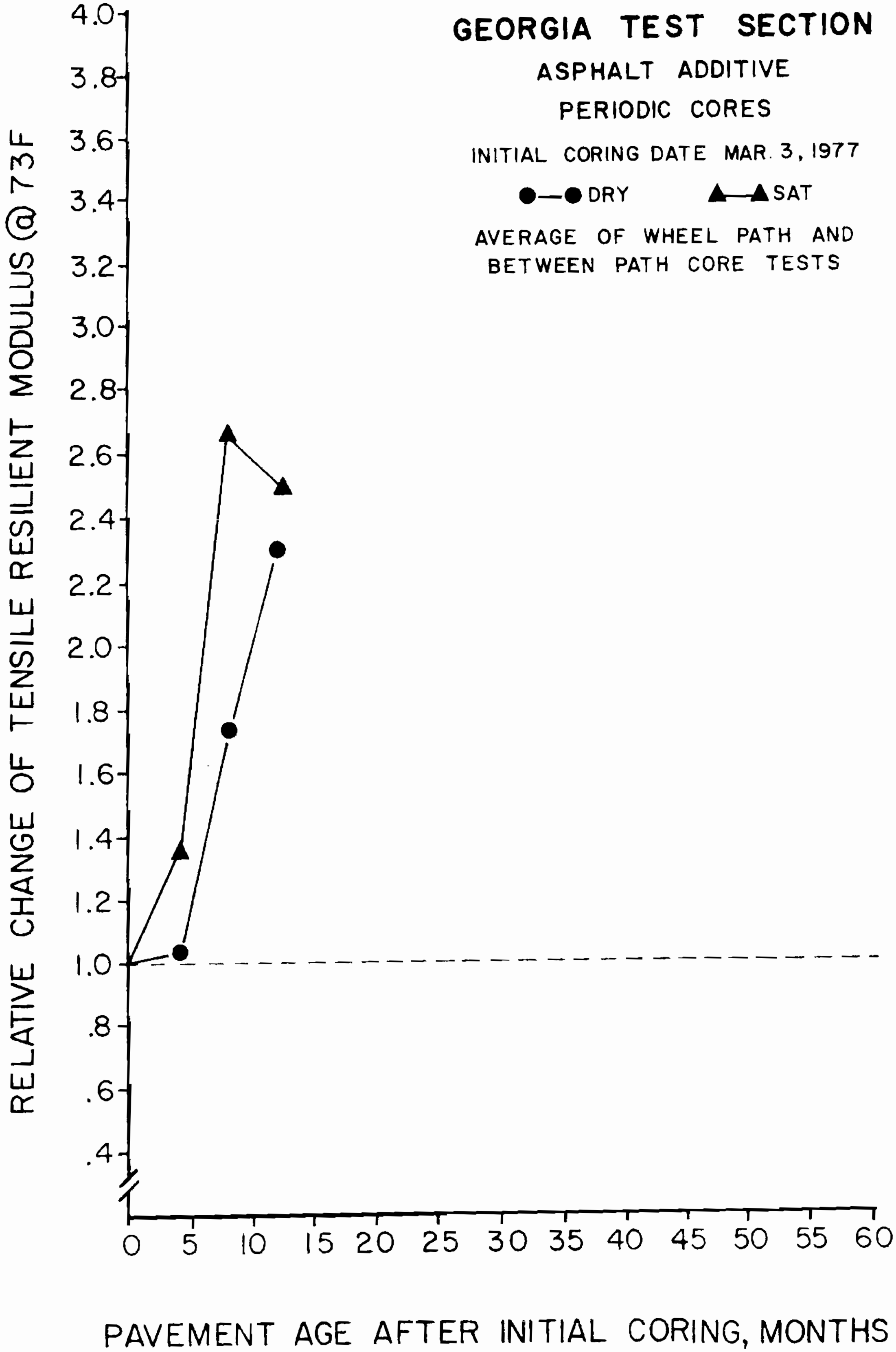

Figure F-4. Relative Increase of Tensile Resilient Modulus with Pavement Age, 73 F (23 C) for Georgia (add.)

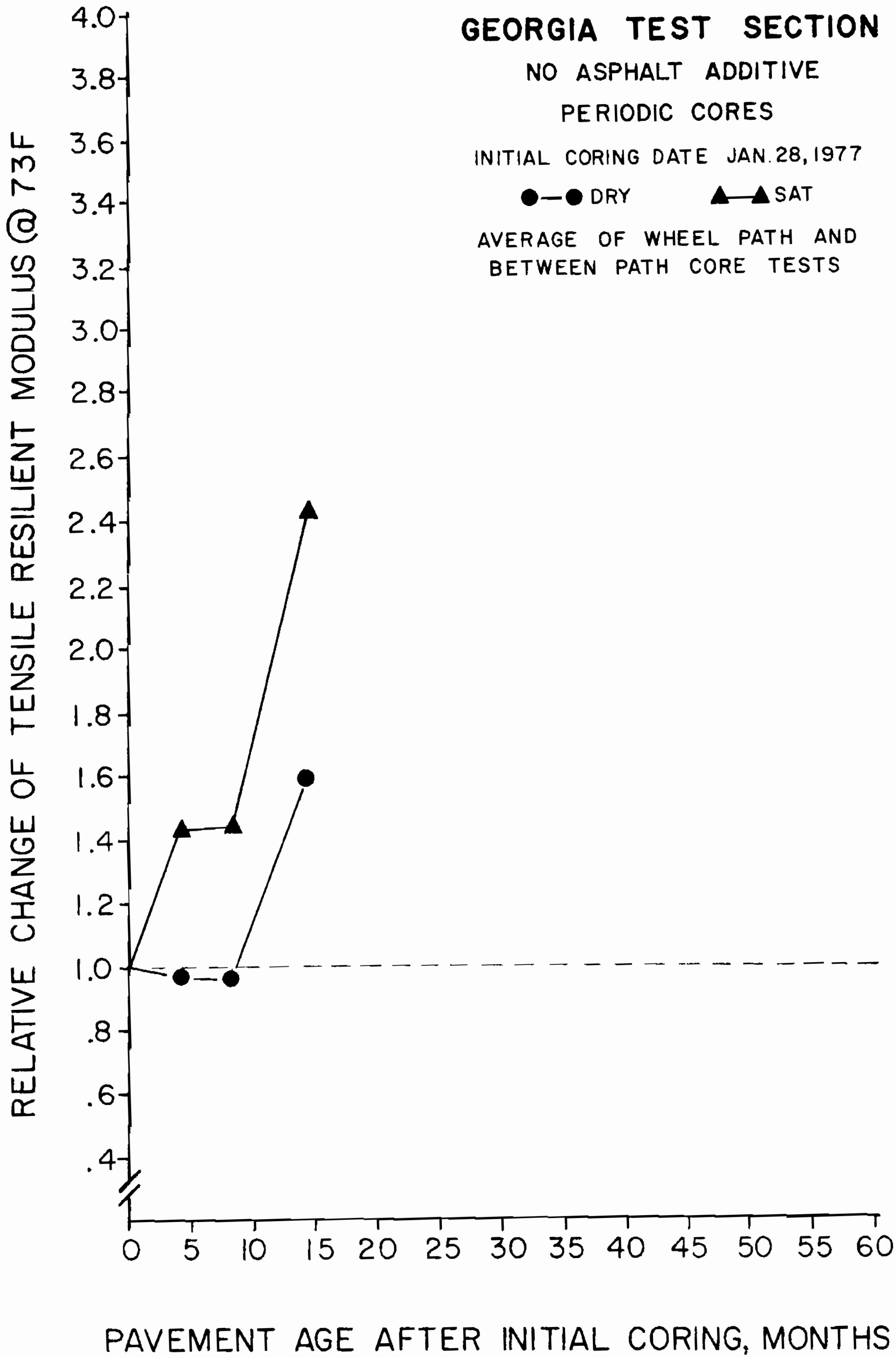

Figure F-5. Relative Increase of Tensile Resilient Modulus with Pavement Age, 73F (23 C) for Georgia (no add.)

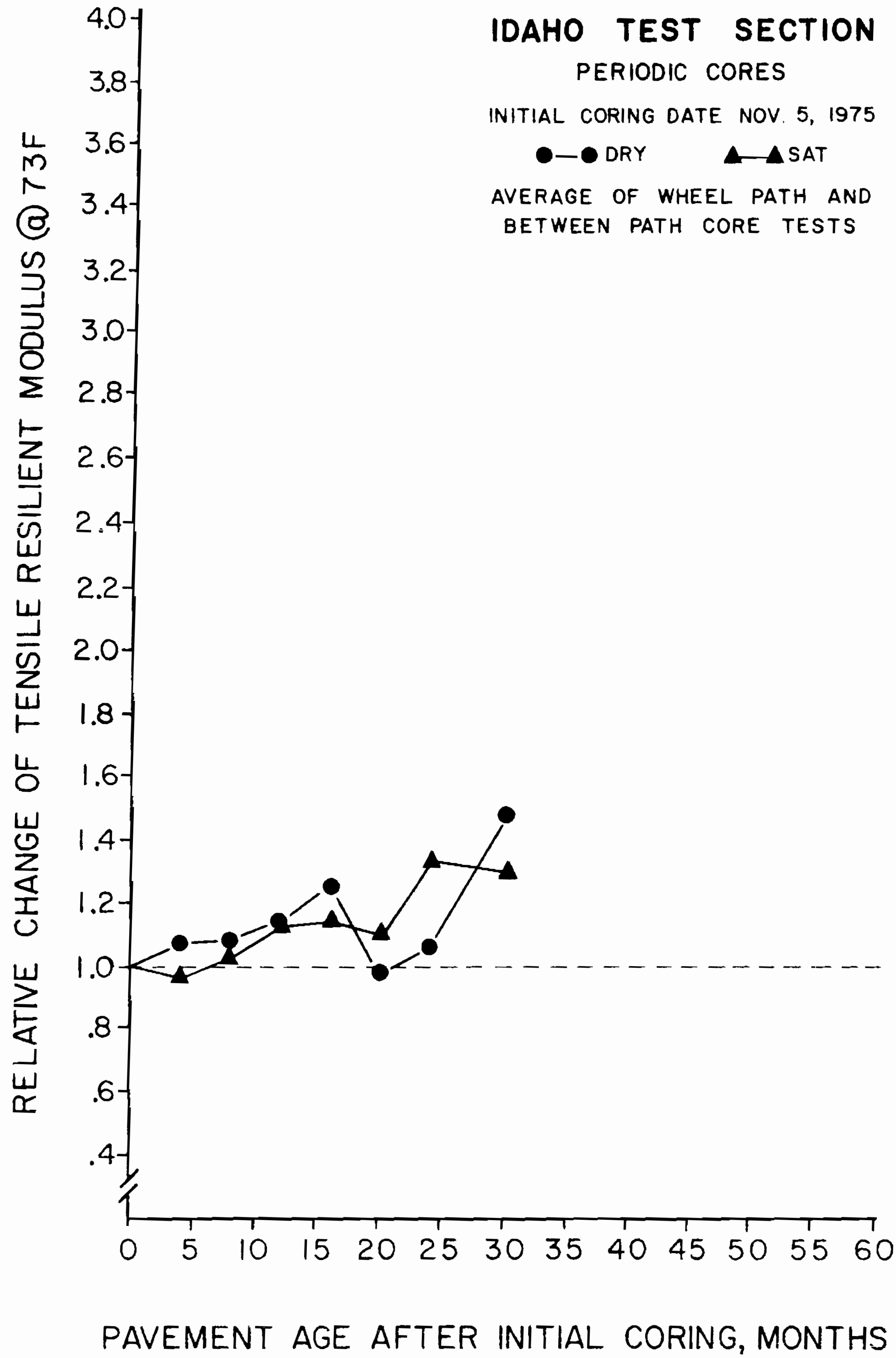

Figure F-6. Relative Increase of Tensile Resilient Modulus with Pavement Age, 73F (23 C) for Idaho.

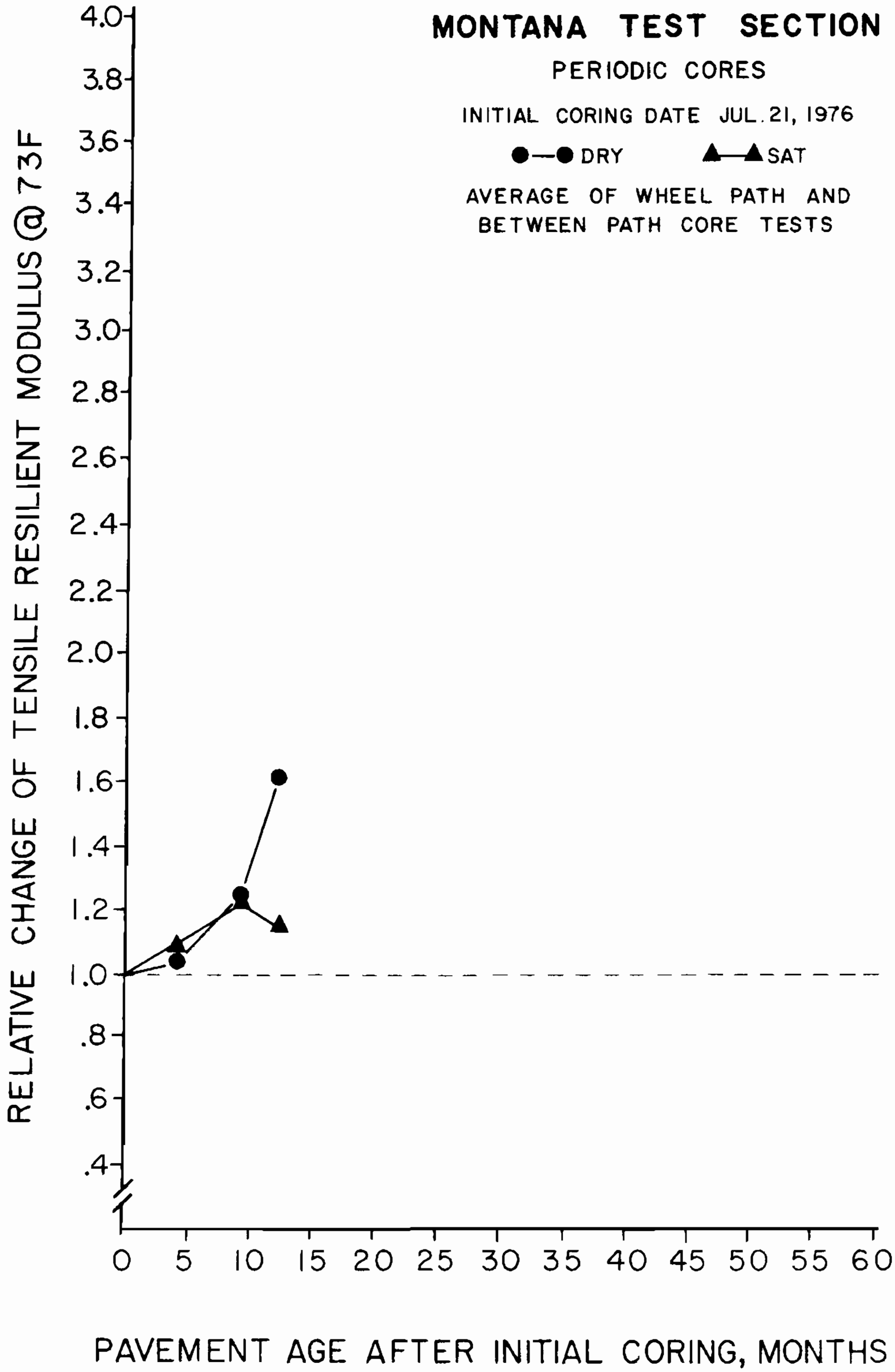

Figure F-7. Relative Increase of Tensile Resilient Modulus with Pavement Age, 73F (23 C) for Montana.

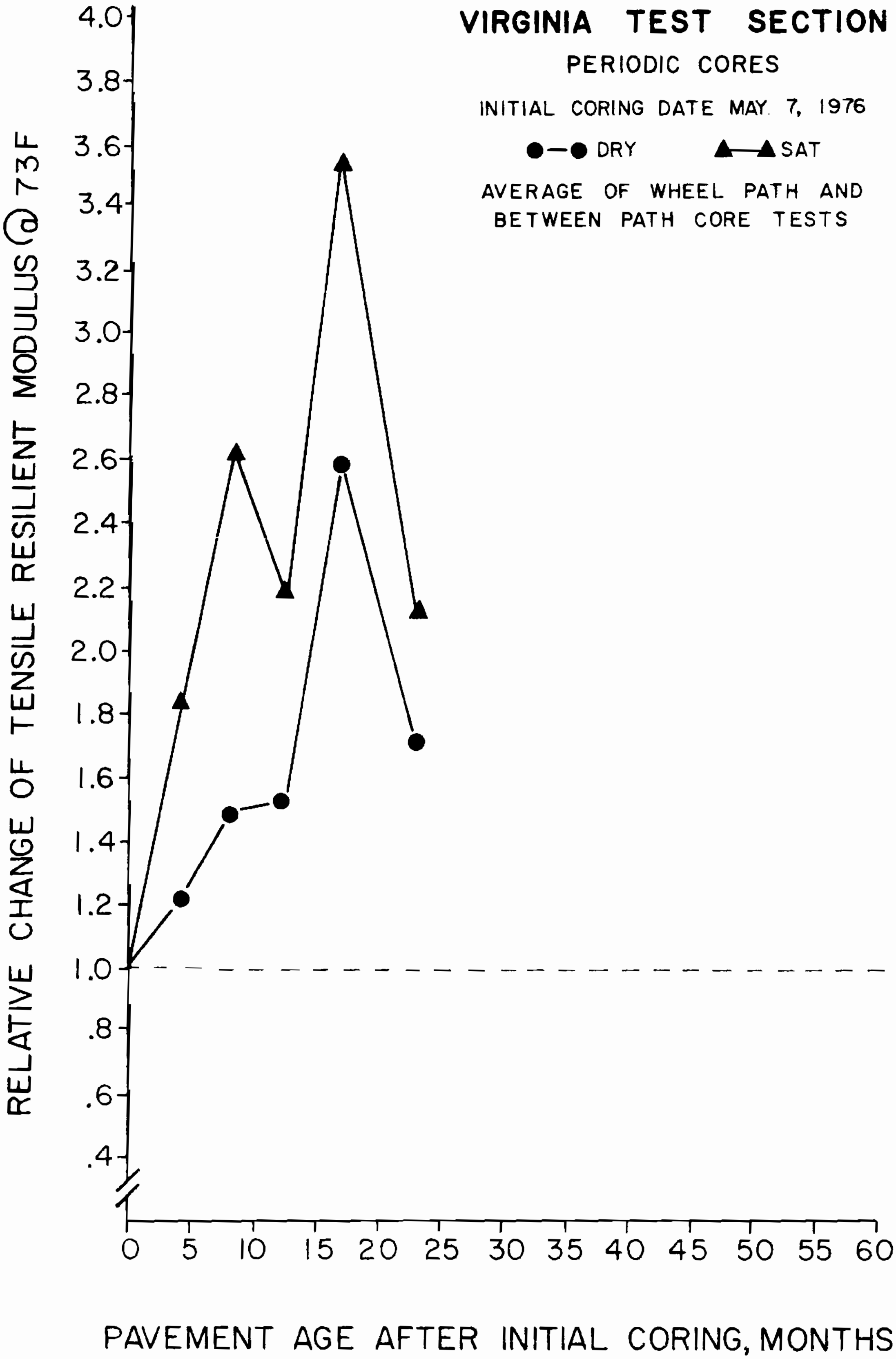

Figure F-8. Relative Increase of Tensile Resilient Modulus with Pavement Age, 73 F (23 C) for Virginia.

APPENDIX G

RELATIVE CHANGE OF RESILIENT MODULUS at 55F (13C) with PAVEMENT AGE

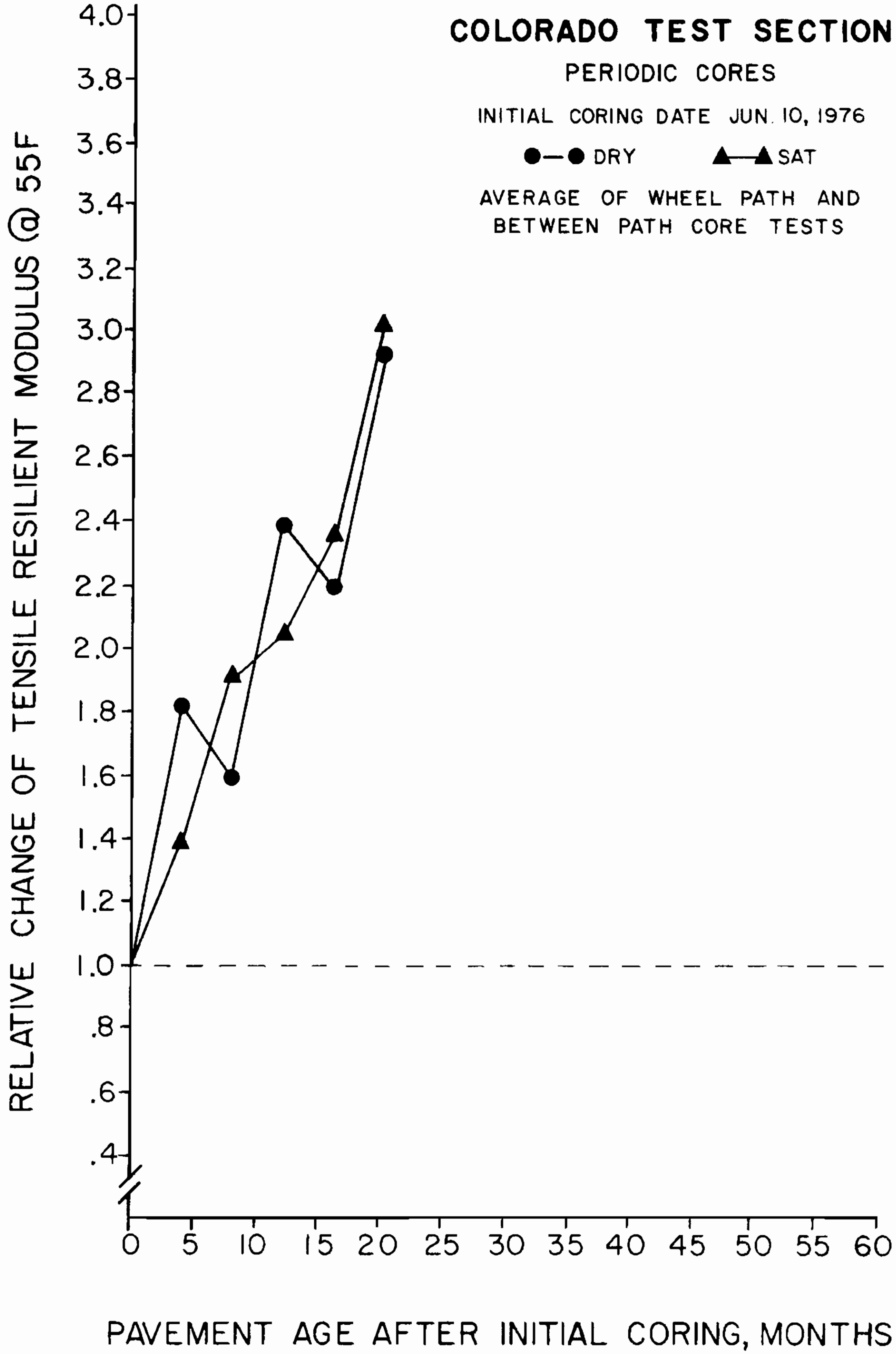

Figure G-1. Relative Increase of Tensile Resilient Modulus with Pavement Age, 55F (13 C) for Colorado.

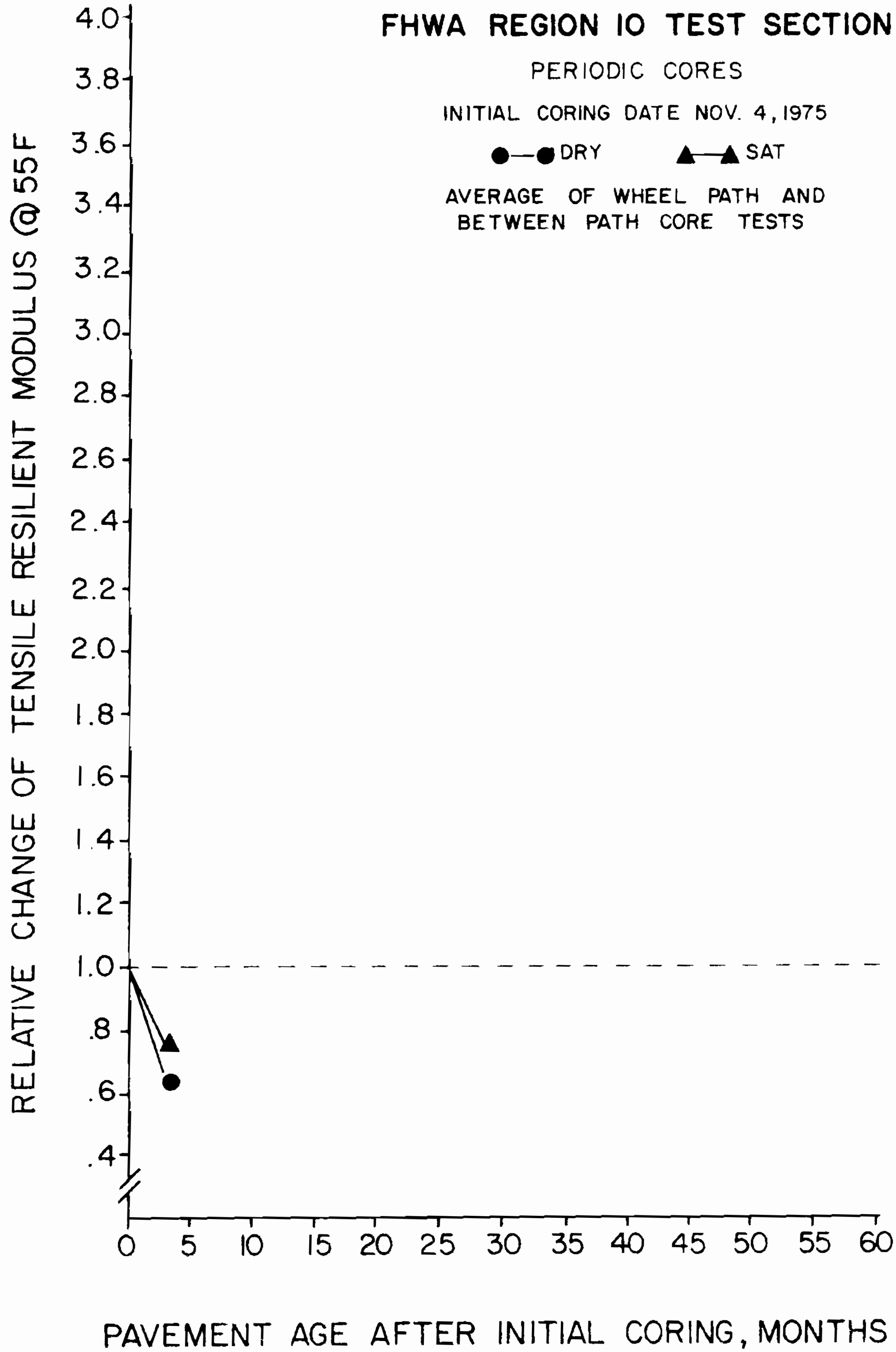

Figure G-2. Relative Increase of Tensile Resilient Modulus with Pavement Age, 55F (13 C) for FHWA 10.

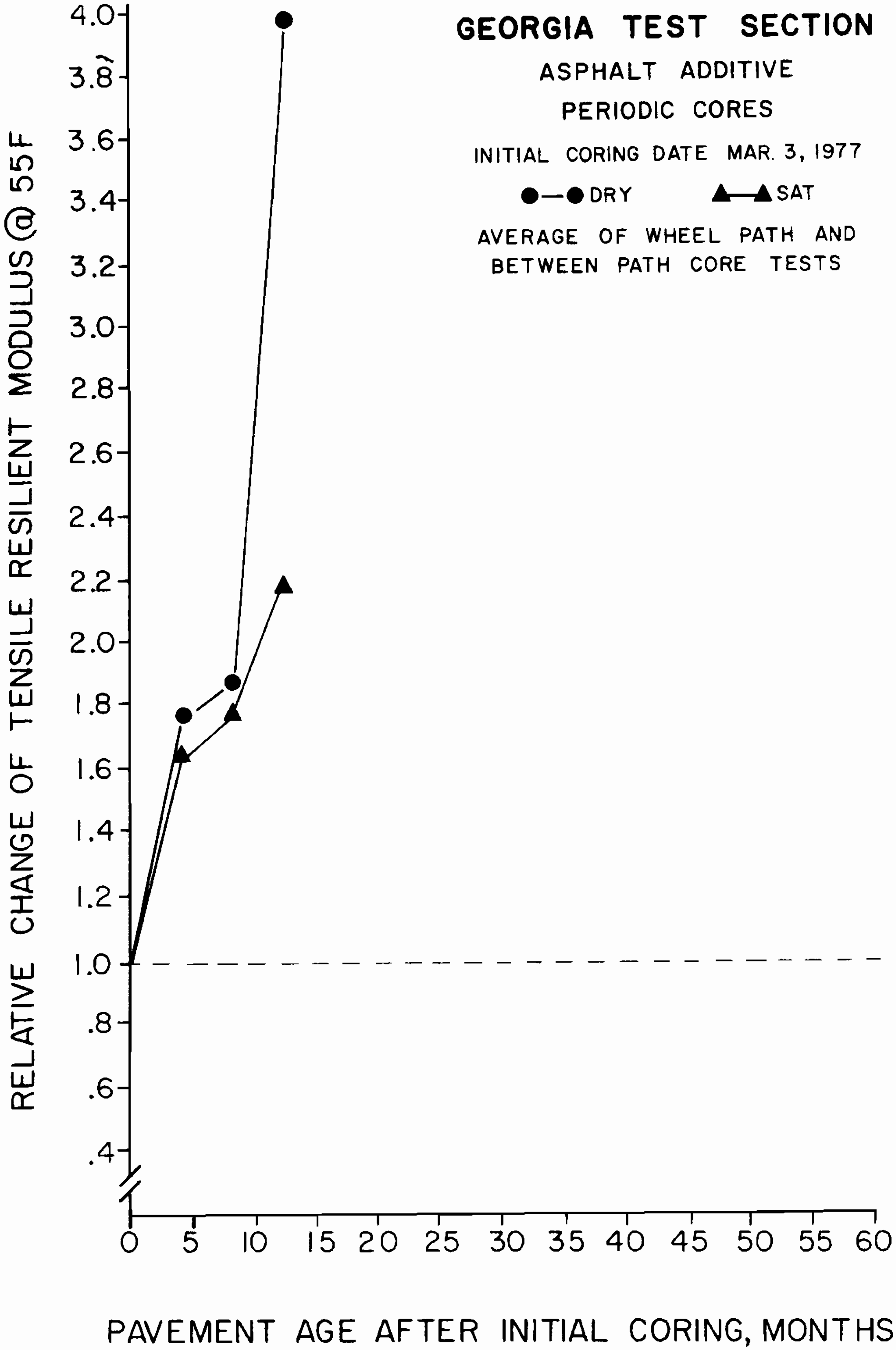

Figure G-3. Relative Increase of Tensile Resilient Modulus with Pavement Age, 55F (13 C) for Georgia (add.)

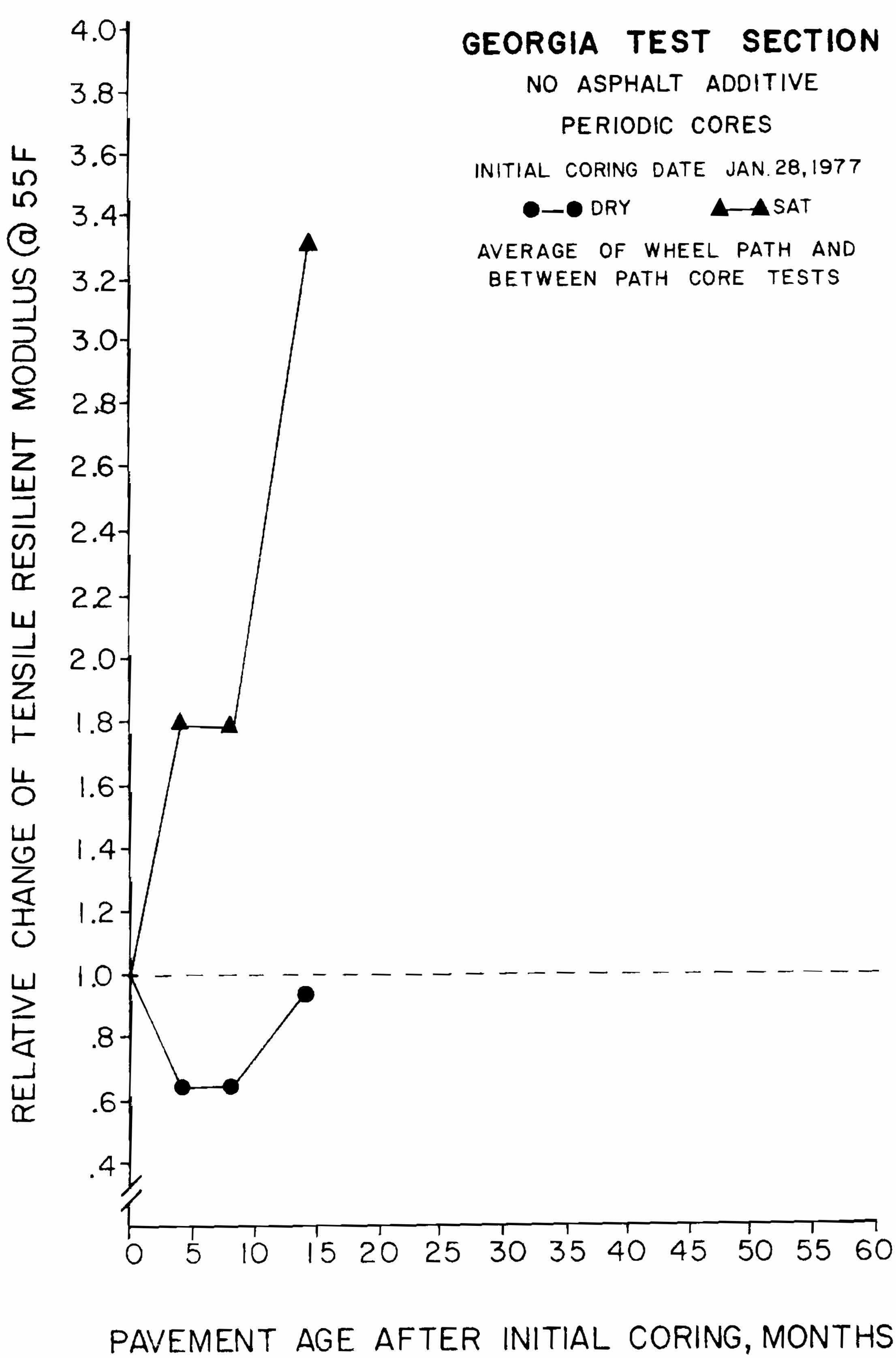

Figure G-4. Relative Increase of Tensile Resilient Modulus with Pavement Age, 55 F (13 C) for Georgia (no add.)

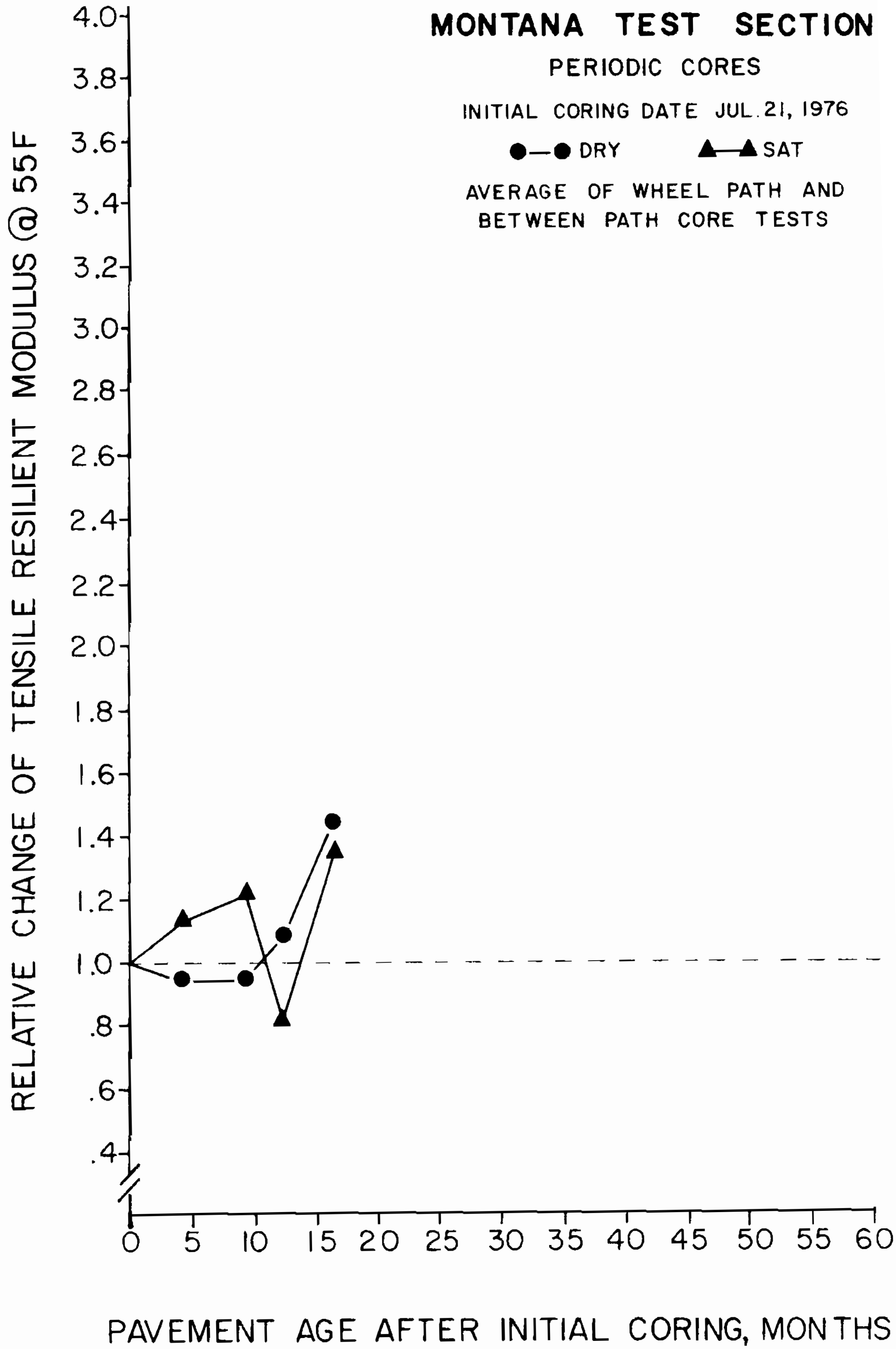

Figure G-5. Relative Increase of Tensile Resilient Modulus with Pavement Age, 55F (13 C) for Montana.

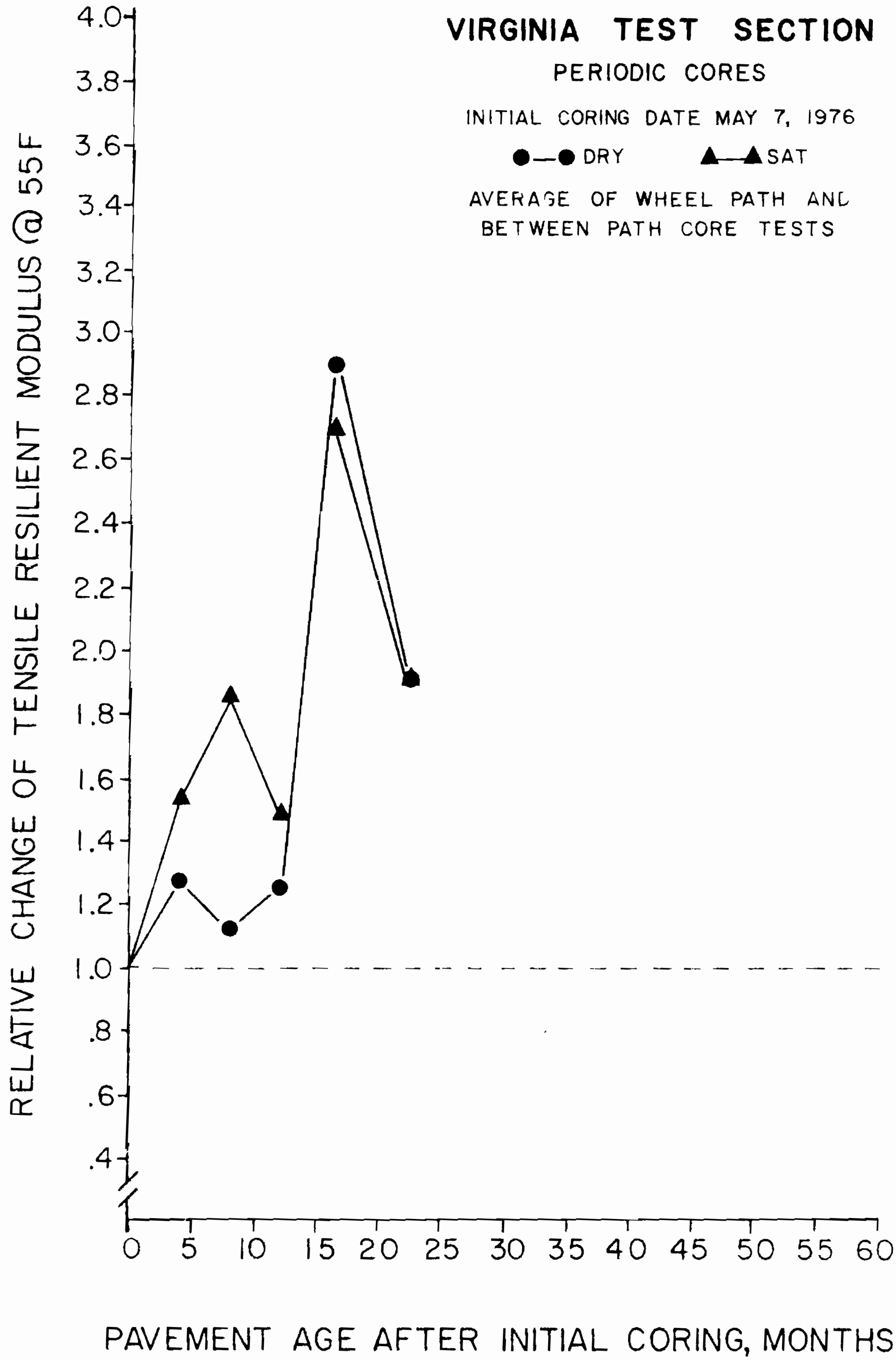

Figure C-6. Relative Increase of Tensile Resilient Modulus with Pavement Age, 55F (13 C) for Virginia.

APPENDIX H

MECHANICAL PROPERTIES OF INITIAL PAVEMENT CORES AND LABORATORY SPECIMENS AT ZERO STORAGE/TIME

TABLE II-1
MECHANICAL PROPERTIES OF INITIAL PAVEMENT CORES AND LABORATORY SPECIMENS AT ZERO MONTH STORAGE/TIME

Agency/Test Pavement Location	Mechanical Property[1]: Tensile Strength, psi[2] at 55 F (13C): Initial Cores: Dry	Sat.[3]	Cond.[4]	Laboratory Specimens: Dry	Sat.	Cond.	Resilient Modulus, 1000 psi at 73 F (23C): Initial Cores: Dry	Sat.	Cond.	Laboratory Specimens: Dry	Sat.	Cond.	Resilient Modulus, 1000 psi at 55 F (13C): Initial Cores: Dry	Sat.	Cond.	Laboratory Specimens: Dry	Sat.	Cond.
Arizona	97	82	29	222	97	47	407	343	290	765	479	292	n.a.[5]	n.a.	n.a.	n.a.	n.a.	n.a.
Colorado	36	24	16	41 (65)[a]	56 (58)	9 (16)	127	144	83	322 (474)	215 (335)	63 (111)	475	456	196	940 (1281)	693 (1046)	186 (303)
FHWA 10	74	70	46	(162)	(131)		229	284	129	(553)	(464)		997	1023	720	(1672)	(1590)	
Georgia (additive)	59	48	0	87	84	0	149	123	0	236	190	0	246	324	0	456	379	0
Georgia (no additive)	110	99	0	85	87	0	205	139	0	288	224	0	798	316	0	375	390	0
Idaho	52	51	47	83 (103)	75 (90)	63 (86)	167	153	146	294 (402)	267 (383)	287 (349)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Montana	47	53	40	74 (66)	61 (50)	44 (38)	99	97	121	159 (150)	128 (89)	106 (89)	599[b]	493[b]	314[b]	785 (655)	648 (501)	471 (415)
Virginia	47	45	24	56	56	20	163	143	79	236	182	51	465	439	262	668	666	227

NOTES:

1. Mechanical properties are rounded off to nearest whole number
2. 1psi - 6.895 kpa
3. vacuum saturated
4. Vacuum saturated plus accelerated conditioned
5. n.a. (not available). Not programmed by agency due to early start-up of laboratory tests.

a. Numbers in parentheses represent mechanical properties of laboratory specimens at reduced permeable voids.
b. Resilient moduli @ 55 F represent initial cores at 2 months storage because these moduli were not determined for zero month storage time.