Predicting Subgrade Moisture Under Aggregate Surfacing

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Methods and results of monitoring subgrade moisture under seven aggregate-surfaced roads in northern Idaho are presented. Data were collected over a 5-year period from 1978 to 1982. The data were collected to predict subgrade moisture for consideration of seasonal variations in subgrade strength in aggregate thickness design. One hundred forty-six specially calibrated electrical resistance moisture-temperature cells and 100 nuclear depth probe tubes were installed in the roads' subgrades. About 9,100 electrical cell observations were analyzed. Electrical cell measurements were within about 1 to 2 percent saturation of gravimetric (oven-dry) tests. Comparison between nuclear depth-probe measurements and gravimetric-volumetric tests was poor, and the method was abandoned about midway through the project. Saturation decreased from a maximum of about 95 percent in early spring to a minimum of about 65 percent in early fall, and then increased until freeze-up. Two regression equations for percent saturation that are based on electrical cell readings are given: one as a cosine function of time ($R^2 = 0.76$) and the other as a function of antecedent precipitation index ($R^2 = 0.78$).

The methods and results of field monitoring studies by the USDA Forest Service on subgrade moisture under typical aggregate-surfaced logging roads in northern Idaho are described. The general purpose of the studies was to find a method of predicting subgrade moisture to allow consideration of seasonal variations in subgrade strength for aggregate thickness design. In order to determine the validity of data, the studies included an assessment of the instrumentation accuracy. Once subgrade moisture is predicted, soil strength tests such as the California bearing ratio (CBR) can be run in the laboratory to simulate field conditions.

Many Forest Service logging roads are used only during a limited haul season. Typically, in the northern part of the country and in high mountainous areas, logging roads are closed during the winter and during the spring breakup period. The Forest Service Aggregate Surfacing Design Guide (*1*), which was adopted in 1990, uses varying subgrade soil strengths for increments of time within the design season. A similar procedure was developed in Region 1 of the Forest Service in 1980.

Data were collected from 1978 through 1982 in two study areas; Horse Creek in the Nezperce Forest and the St. Maries area of the Idaho Panhandle National Forests. The Horse Creek and the St. Maries studies differed in the intensity of instrumentation. The Horse Creek study was heavily instrumented over a 1.2-mi road segment. The St. Maries study was less heavily instrumented, but represented a wider variety of soil and climatic conditions on six roads totaling 31 mi.

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STUDY AREAS

St. Maries

The St. Maries project area is approximately 65 air miles southeast of Spokane, Washington, as shown in Figure 1. The roads are identified as Staples, Christmas, Merry, Gold, Emerald, and Elk. The majority of the test roads were constructed and surfaced with aggregate in the 1970s.

Topographic and climatic characteristics at the St. Maries test area are as follows:

- Elevation—2,800 to 5,000 ft above sea level;
- Topography—0 to 70 percent side slopes in mountainous terrain;
- Temperature—Average annual temperature is 48°F, average mean daily temperature is 68°F in July, and average mean daily temperature is 28°F in January;
- Precipitation—Average annual precipitation is 41 in. with 50 percent occurring as snow; and
- Vegetation—Moderately heavy fir and pine forest.

The roads are single-lane, aggregate-surfaced, logging roads with varying top widths. The aggregate surfacing was good-quality, dense-graded, crushed rock with depths of 4 to 12 in. Road grades ranged from 1 to 9.5 percent. The roads represent all four aspects. Major traffic on the roads is related to timber haul.

Subgrade soils are residual nonplastic silts and silty sands derived from the weathering of the underlying mica schists and quartzites. Mean index properties are presented in Table 1. Figure 2 shows an example of the results of laboratory tests run to determine the relationship between CBR and percent saturation to relate field data to seasonal changes in subgrade strength. A groundwater table does not exist in the soil layer overlying the bedrock. Groundwater is limited to seeps and springs at the surface and some fractured areas in the bedrock.

Horse Creek

The Horse Creek study was a satellite project identified as "Study Plan 6" within the Forest Service's Horse Creek Administrative Research Project. The overall research project is a long-term monitoring program begun in 1965 to deter-

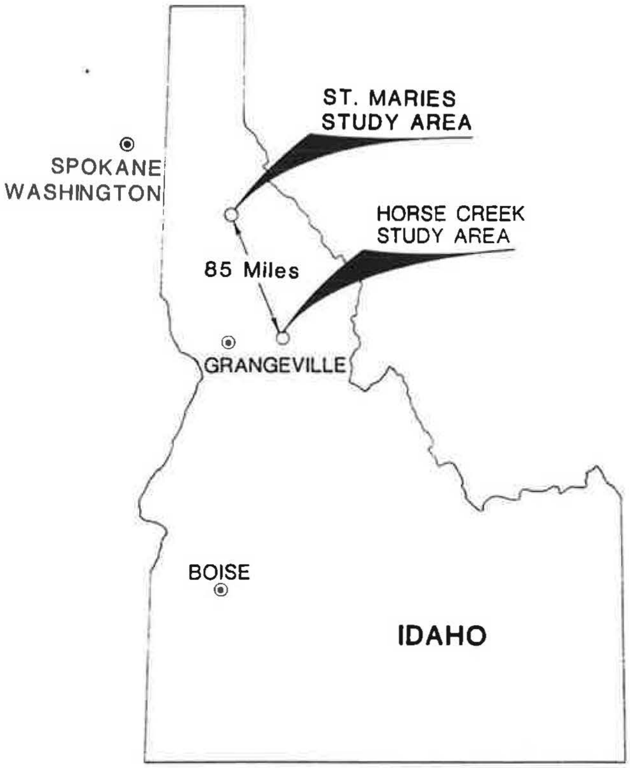

FIGURE 1 Project location.

mine the effects of logging and road building on water quality. The need for aggregate surfacing research was recognized in the late 1970s. It was decided to use similar techniques as developed at St. Maries and expand that effort because road construction and timber-hauling activities were carefully controlled, related weather data was being collected, and research personnel were available.

The test road is about 35 air miles east of Grangeville, Idaho, as shown in Figure 1.

Topographic and climatic characteristics at the Horse Creek test area are as follows:

- Elevation—5,500 ft above sea level;
- Topography—10 to 45 percent sideslopes near top of a ridge in mountainous terrain;
- Temperature—Average annual temperature is 37°F, average mean daily temperature is 60°F in July, average mean daily temperature is 23°F in January;
- Precipitation—Average annual precipitation is 49 in. with 72 percent occurring as snow; and
- Vegetation—Moderately heavy fir and pine forest.

The road is a single-lane, aggregate-surfaced logging road with a 12-ft top width. The 1.2-mi road was surfaced in three segments with 4, 8, and 12 in. of good-quality, dense-graded, crushed rock. Road grades range from −6.4 to +5.6 percent. Major traffic on the test road is related to timber haul.

Subgrade soil is nonplastic silty sand derived from metamorphic rocks of the Idaho Batholith border zone. It is locally called "decomposed granite." Soil is above the groundwater table. Mean index properties are presented in Table 1.

STUDY PLAN

St. Maries

At the St. Maries project area, 81 electrical resistance moisture-temperature cells (Soiltest Model MC-300B) were installed with the top of the cell approximately 4 in. below the top of the subgrade. All cells were installed in roads with existing aggregate surfacing. The cells were placed on the inside and outside wheel tracks. Moisture contents and soil temperatures

TABLE 1 MEAN SUBGRADE SOIL PROPERTIES (STANDARD DEVIATIONS IN PARENTHESES)

ROAD	Horse Crk	Staples	Xmas	Merry	Gold	Emerald	Elk
No. Samples	24	12	8	12	8	30	12
% - No. 4	89 (6)	92 (12)	85 (11)	88 (10)	88 (12)	91 (8)	93 (3)
% - No. 200	32 (6)	56 (15)	46 (12)	50 (8)	49 (9)	51 (18)	46 (6)
PI	NP	NP	NP	NP	NP	NP	NP
Unified Clas.	SM	ML	SM	SM-ML	SM	ML	SM
S.G	2.78 (.09)	2.69 (.03)	2.64 (.03)	2.63 (.05)	2.63 (.05)	2.71 (.08)	2.67 (.07)
AASHTO T-99 MAX Dens, PCF	113 (7)	112 (4)	110 (8)	102 (10)	104 (9)	107 (9)	105 (7)
Opt. Moist., %, AASHTO T99	16 (3)	15 (2)	15 (3)	18 (5)	17 (4)	16 (5)	16 (3)
In-Place Density, PCF	118 (8)	110 (7)	106 (12)	103 (15)	104 (12)	113 (12)	106 (7)
% T99 Max.	106 (6)	98 (4)	96 (8)	101 (7)	101 (4)	106 (11)	101 (4)

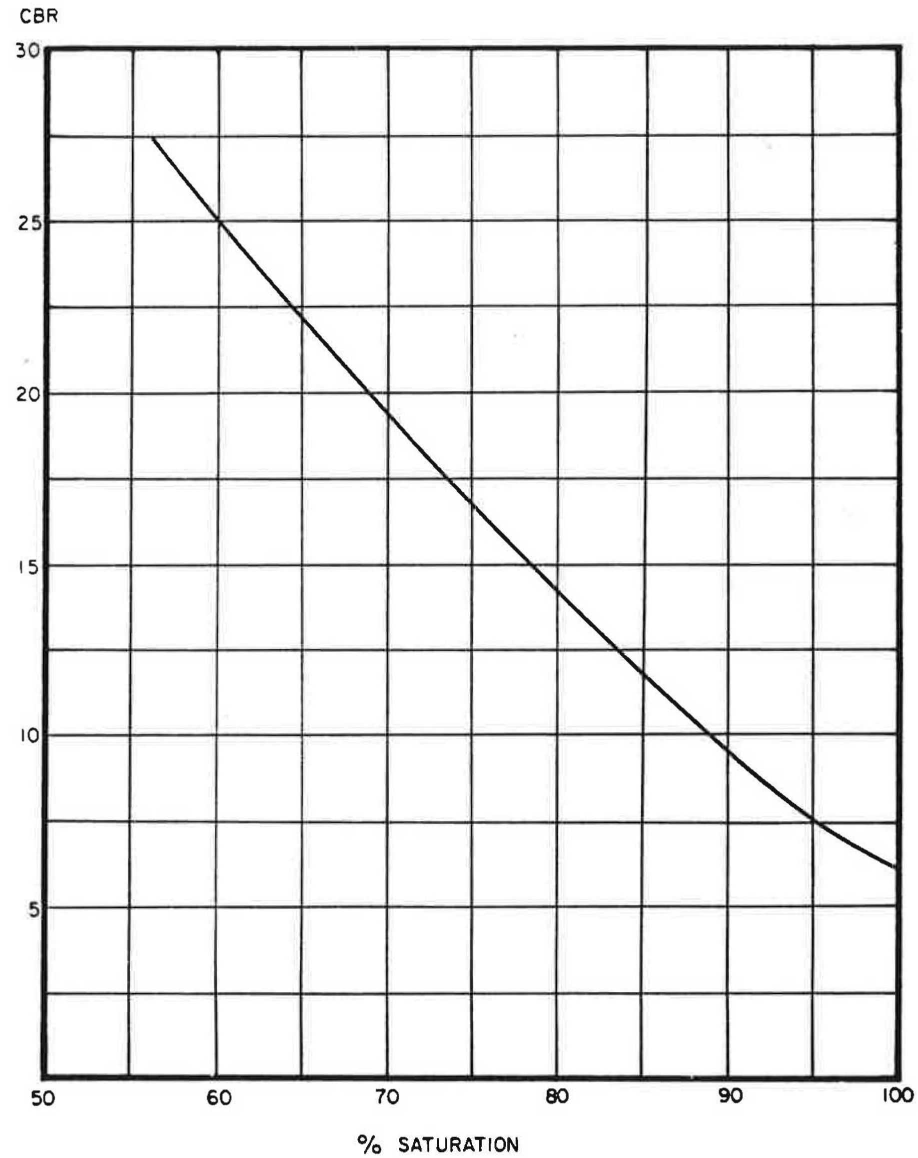

FIGURE 2 Example of a range of subgrade strength (CBR) values from a soil tested at varying moisture conditions.

were measured weekly during the April to November field season from 1979 through 1981 and less frequently in 1982. Approximately 3,620 observations were made.

Eighty-two nuclear depth probe tubes were installed in 1978, 1979, and 1980. The tubes were installed on the inside and outside wheel tracks within a few feet of the electrical cells. The subgrade was uncovered and readings taken with a Campbell Nuclear Pacific Model 501/504 nuclear gauge at 1.0, 1.5, 2.0, and 2.5 ft below the top of the subgrade. The readings were taken two to four times during field seasons.

Measurements of in-place density at the top of the subgrade were attempted in 1978, by digging out the overlying aggregate and using a direct-transmission nuclear gauge. However, the data were erratic, apparently because of the boundary effect of the aggregate walls of the hole. Eighty-one in-place densities were then taken volumetrically using a ring densometer (similar to a Washington densometer).

Horse Creek

At the Horse Creek area, 65 electrical resistance moisture-temperature cells were installed in the subgrade before the aggregate surfacing was placed. The cells were placed in groups of three or four in the vicinity of each of the 18 nuclear tubes discussed below and also in groups of two at 10 intermediate stations. Moisture contents and soil temperatures were measured weekly from 1978 through 1980, and less frequently during 1981 and 1982. Approximately 5,490 observations were made.

Eighteen nuclear depth probe tubes were installed in the subgrade soil at the end of construction in 1978. The locations were chosen to represent various conditions of road geometry. The subgrade was uncovered and readings of moisture and density taken at 0.5, 1.0, 1.5, 2.0, and 2.5 ft below the top of the subgrade at monthly intervals during the field season.

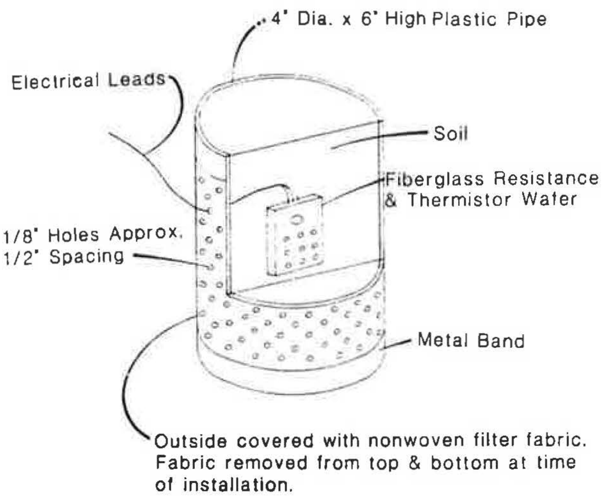

FIGURE 3 Electrical cell details.

Samples of the top 4 in. of subgrade were taken approximately monthly during the first 2 years of monitoring from the vicinity of the nuclear tubes for gravimetric (oven-dry) moisture contents.

Measurements of in-place density at the top of the subgrade were attempted in 1979 by digging out the overlying surfacing and using a direct-transmission nuclear gauge. The data were erratic and similar to the St. Maries experience. In-place densities were then taken volumetrically with a Washington densometer.

INSTRUMENTATION

Electrical Cells

The electrical cells are fiberglass wafer resistance devices calibrated to measure moisture content. The wafer also contains a thermister for measuring soil temperature. The devices had to be carefully calibrated in the laboratory in soil of the same type and density as exists in the field. Schematic diagrams of typical cell configuration and field installation are shown in Figures 3 and 4, respectively.

The calibration procedure for electrical moisture cells was as follows.

- The cells were saturated in water;
- While air drying, the cells were weighed periodically to determine moisture content and the corresponding resistance reading taken; and
- The saturation-drying cycle was repeated at least three times or until the calibration plot of resistance versus moisture content repeated itself.

To determine accuracy, a comparison was made of available gravimetric and electrical cell moisture data by paired t-tests. At Horse Creek, 250 gravimetric samples were taken at the top of subgrade in conjunction with electrical cell readings. Sixty-five gravimetric measurements of moisture taken at St. Maries during the initial stages of the project for in-place density determination were compared with the average percent saturation at the same site, on the same date (± 3 days), in subsequent years. The results of the paired t-tests are as follows:

	Number of Pairs	*Mean Difference, Electrical Minus Gravimetric Measurements, Percent Saturation*	*Standard Error of Difference*	*Probability Level*
Horse Creek	250	−0.6	1.0	0.58
St. Maries	65	−0.01	2.0	0.996

The probability level is the probability of no difference between gravimetric and electrical readings. In general, electrical cell readings are within about 1 to 2 percent saturation compared to gravimetric measurements.

Nuclear Depth Probes

The configuration of the nuclear depth probes is shown in Figure 5. The aluminum tube holes were drilled with a truck-mounted rotary drill using a 2-in.-diameter saw-tooth bit on the end of a standard penetration test split spoon. The tube was a tight fit and normally required gentle pushing into place with the hydraulic action of the drill chuck.

At Horse Creek, a comparison of nuclear and gravimetric/volumetric measurements was made by digging out two of the tubes immediately after taking nuclear readings. Gravimetric moisture contents and volumetric in-place densities using a Washington densometer were determined from 0.5 to 2.5 ft below subgrade at each 0.5-ft interval corresponding to the nuclear measurements. A paired t-test was made of the difference between the nuclear and the gravimetric/volumetric measurements, with the following results.

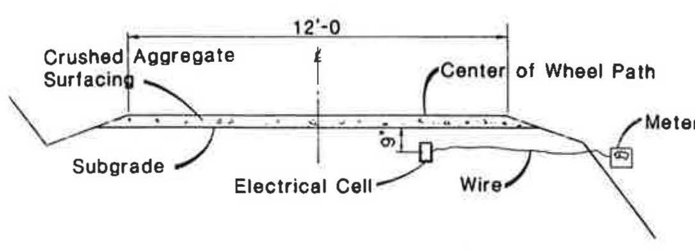

FIGURE 4 Electrical cell field installation.

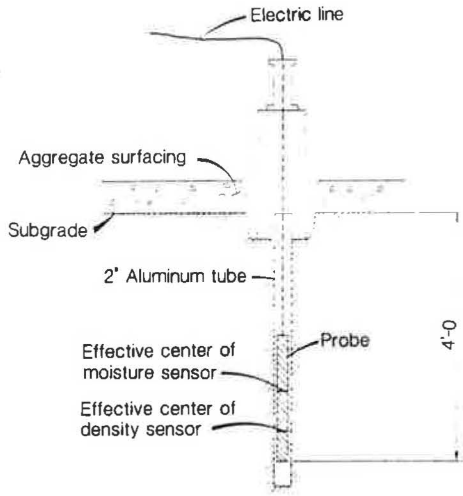

FIGURE 5 **Nuclear depth probe schematic.**

	Number of Pairs	*Mean Difference, Nuclear Minus Gravimetric/ Volumetric Measurements*	*Standard Error of Difference*	*Probability Level*
Percent saturation	10	−21.0	11.2	0.10
Density, lb/ft^3	10	7.4	6.3	0.27

The probability level indicates a low probability of difference between the nuclear and gravimetric measurements. In other words, there is a poor correlation.

RESULTS

Electrical Cell Measurements

The results of field electrical cell measurements are shown in Figures 6–14. Moisture contents are converted to percent saturation to provide uniformity between various soil properties. Each point on the graphs represents the average of the cell readings on a road for a particular date.

Moisture variations followed similar annual trends. In general, moisture contents decreased with increasing temperature and increased with precipitation. There was a lag of 1 to 2 weeks before rainfall affected the cells. The increase in percent saturation from precipitation was generally small and storms with less than about 0.2 in. of rain per day did not seem to affect cell moisture.

Subgrade soil temperature closely paralleled mean daily air temperature, and air temperature turned out to be a better prediction tool because it is more readily available. Subgrade soil temperature readings were particularly useful to determine if the soil was frozen.

Nuclear Depth Probes

The average and standard deviations of density and moisture content at the 18 nuclear depth probe stations at Horse Creek in 1980 are presented in Table 2. Data for other years both from Horse Creek and St. Maries are similar. The nuclear depth probe measurements were discontinued after 1980 because of apparent scatter in data and the results of field accuracy comparison tests.

The 0.5-ft moisture readings showed greater variations in time than the deeper readings, and they compare roughly with the electrical cell data.

The average density for all 0.5-ft readings is 120.1 lb/ft^3 compared to the average of all Washington densometer tests taken on top of the subgrade of 117.6 lb/ft^3. Higher nuclear densities were also observed in the accuracy comparison tests at various depths.

Subgrade soil densities were higher than anticipated. One reason is the in-place soil derived from metamorphic rocks that gradually grades into weathered bedrock. High densities would be expected in deeper cut sections. Traffic compaction may also have contributed to high densities.

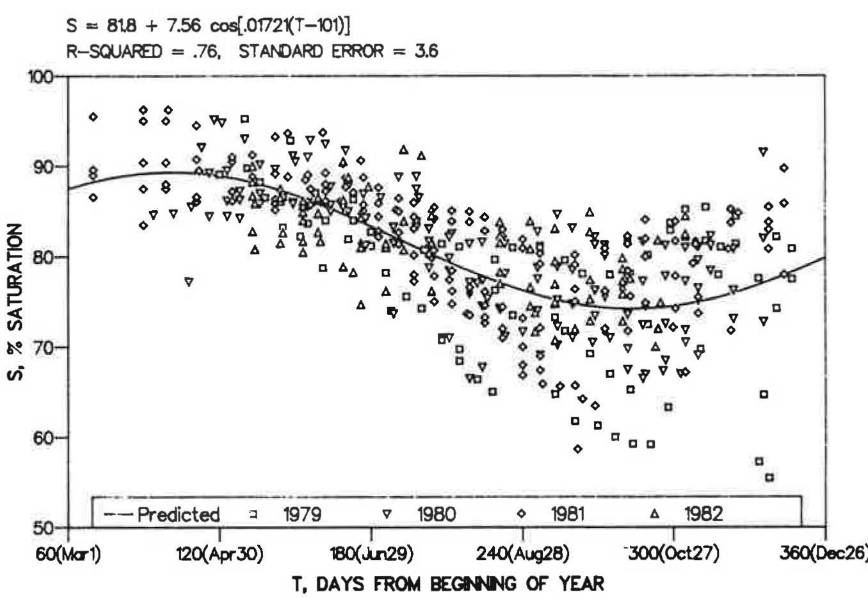

FIGURE 6 **Total electrical cell data, cosine prediction.**

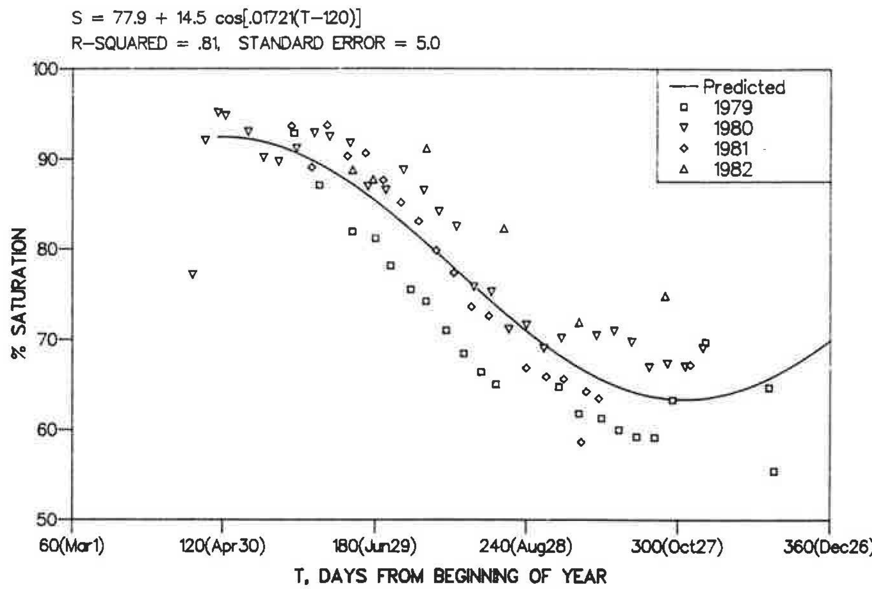

FIGURE 7 Horse Creek electrical cell data, cosine prediction.

ANALYSIS

Electrical Cell Percent Saturation

The electrical cell data were analyzed to find a practical model for prediction of percent saturation at various times during the year. The analysis was directed toward the period from spring thaw to snow closure in the late fall because these roads are normally closed during the winter months. The 1978 data were excluded from the analysis because of erratic data until the cells reached equilibrium with the surrounding soil. The following 21 variables were analyzed:

- Time;
- Precipitation;
- Cumulative precipitation;
- Antecedent precipitation index (defined below);
- Air temperature;
- Subgrade soil temperature;
- Aspect (facing direction of the topographic slope);
- In-place subgrade soil density;
- Maximum density, AASHTO T-99;
- Optimum moisture content, AASHTO T-99;
- Percent passing No. 4 sieve;
- Percent passing No. 200 sieve;
- Specific gravity;
- Unified soil classification;
- Type cross section such as through cut, through fill, or cut-fill combination;
- Inside or outside wheel track;

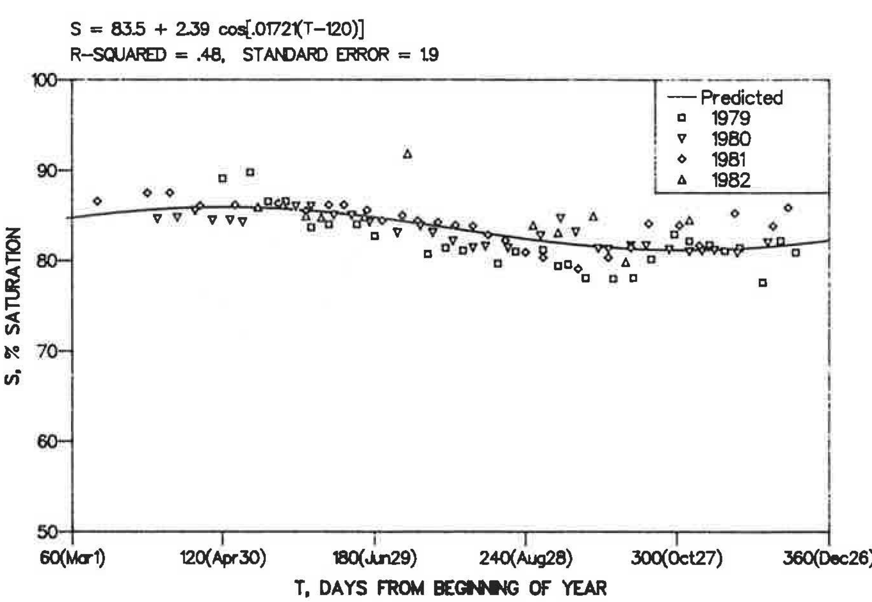

FIGURE 8 Staples electrical cell data, cosine prediction.

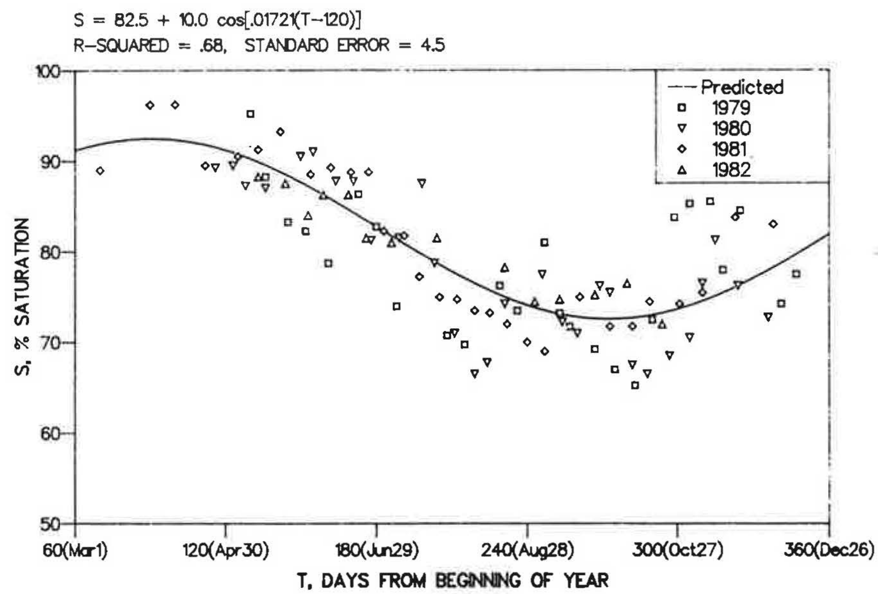

FIGURE 9 Xmas electrical cell data, cosine prediction.

- Side slope above road;
- Side slope below road;
- Longitudinal road grade;
- Depth of cut or fill; and
- Aggregate thickness.

Various transformations and combinations of variables were used.

Scatter plots, partial correlation analysis, and regression analyses, including nonlinear techniques, were made using the Number Cruncher Statistical System computer program (*2*) to identify significant variables and develop models. The best two models involved just one variable; either time or antecedent precipitation index. A number of functions involving precipitation, including a correction for the observed lag time between precipitation and soil moisture occurrence, were attempted. Attempts were also made to combine the time and precipitation functions, but the various mathematical combinations were no better than models with just one of the variables. None of the other variables or their transformations increased the R^2 value by more than 0.02, and the best total increase, using all significant variables, was less than 0.06. The most significant of the minor variables were air temperature, subgrade soil temperature, percent passing the No. 200 sieve, aspect, and elevation.

The data were analyzed by road for each year, by road using the data for all years, and for all data from all roads together. Once the minor variables were eliminated, the average percent saturation for each road on a particular date was used as the dependent variable.

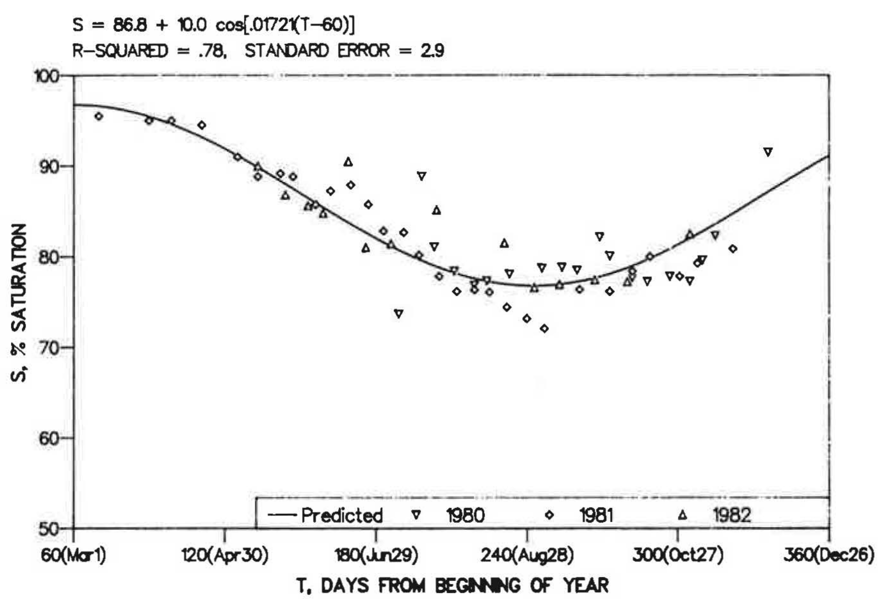

FIGURE 10 Merry electrical cell data, cosine prediction.

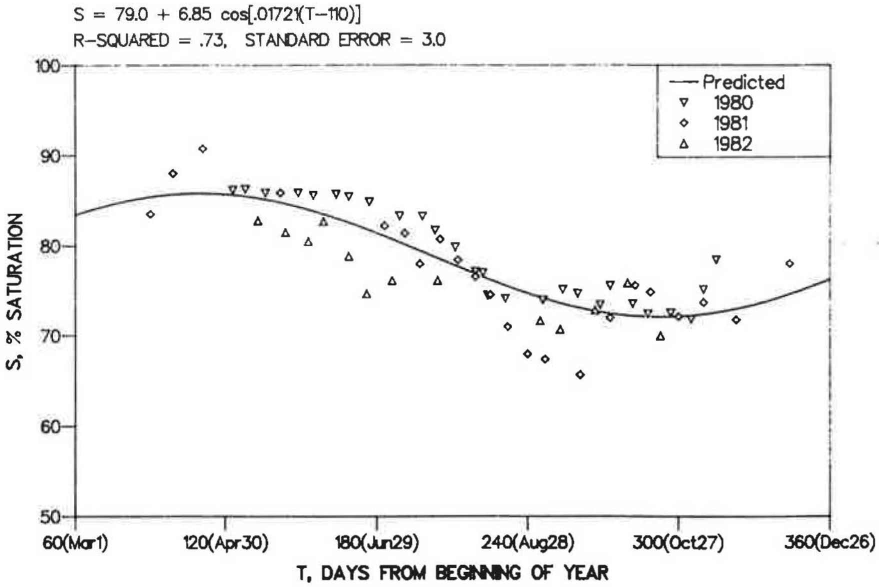

FIGURE 11 Gold electrical cell data, cosine prediction.

The best model found that involved time used a cosine function of time as the independent variable:

$$S = B + A \cos\left[\frac{\pi}{L}(T - T_0)\right] \quad (1)$$

where the quantity in brackets is expressed in radians and

S = percent saturation;
B = average percent saturation throughout the predicted period, (Max + Min)/2;
A = variation of percent saturation, (Max − Min)/2;
L = length of dry season (days), from spring thaw to the driest time during summer or fall;
T = time (days) from January 1 to the date of prediction; and
T_0 = time (days) from January 1 to the beginning of spring thaw.

Considering all data together, the best result was with L = 182.5 days (half a year), resulting in an annual cyclic function. The average date of spring thaw was Day 101 (April 11). A and B were solved by regression, resulting in the following equation:

$$S = 81.8 + 7.56 \cos[0.01721(T - 101)] \quad (2)$$

R^2 = 0.76, Standard Error = 3.6.

A plot of the prediction equation with the observed field data is shown in Figure 6. The results of similar analyses on each of the individual roads are shown in Figures 7–13.

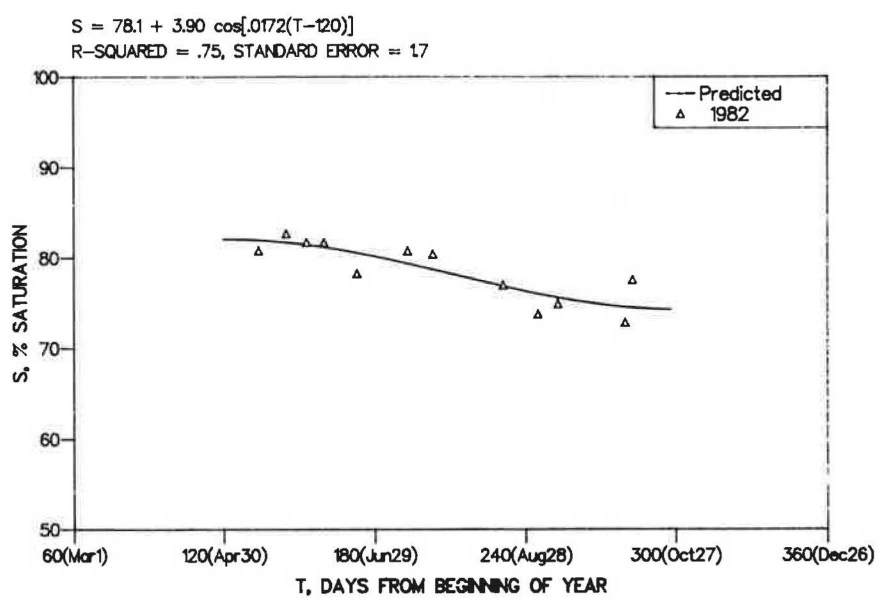

FIGURE 12 Emerald electrical cell data, cosine prediction.

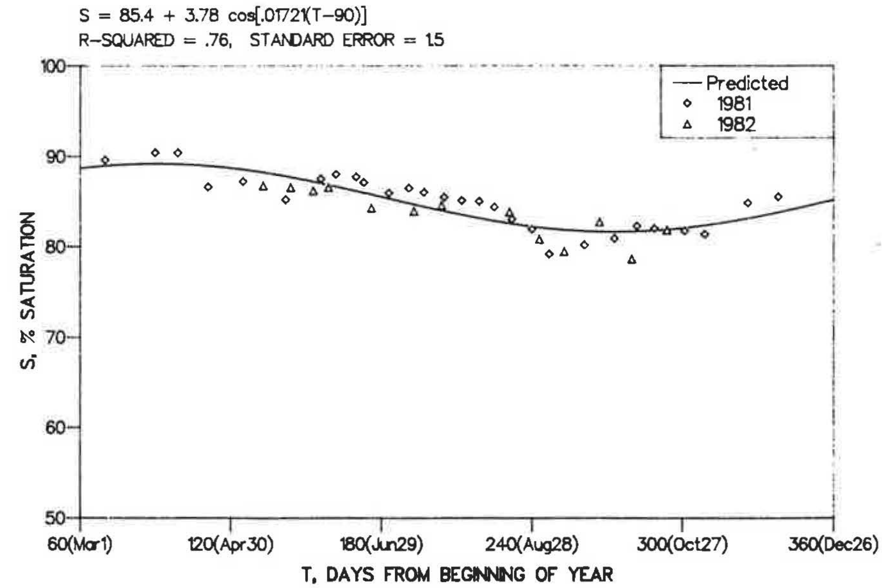

FIGURE 13 Elk electrical cell data, cosine prediction.

The preceding time model requires some knowledge of local conditions. The data shown in the figures should provide some guidance for selecting the parameters under similar site conditions.

The other successful model uses the antecedent precipitation index (API), that has been found useful in rainfall-runoff correlations to account for soil moisture (*3*).

A satisfactory relationship between percent saturation and API was developed for the Horse Creek data, but not for the St. Maries data. The reason appears to be the quality of precipitation data available. At Horse Creek, a weather station was available within 0.5 mi of the site. The nearest weather station for the St. Maries roads was the Clarkia Ranger Station, about 8 mi from the sites, which has an elevation difference of up to 2,100 ft. In mountainous areas, precipitation can vary drastically over short distances. Therefore, this model may only apply where accurate precipitation records are available close by.

The basic concept of API is illustrated by the formula

$$\mathrm{API}_n = K(\mathrm{API}_{n-1}) + P_n \tag{3}$$

where

API_n = antecedent precipitation index on the current date,
K = constant,
API_{n-1} = antecedent precipitation index on the previous date, and
P_n = precipitation occurring between Dates $n - 1$ and n.

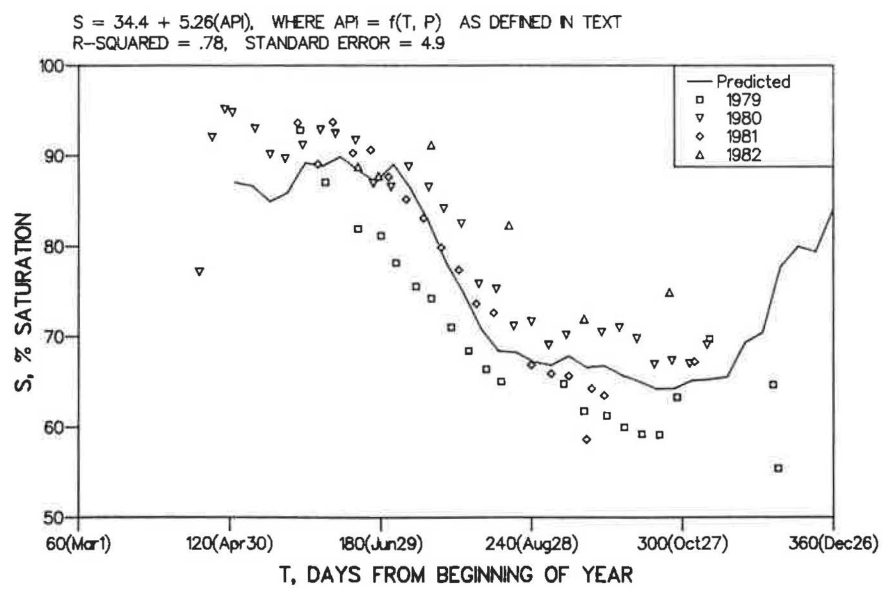

FIGURE 14 Horse Creek electrical cell data, API prediction.

TABLE 2 NUCLEAR DEPTH PROBE MOISTURE CONTENTS AND DRY DENSITIES, HORSE CREEK, 1980

	DATE					
Depth below Subgrade, ft.	5/4/80	5/27/80	7/3/80	8/3/80	8/31/80	9/28/80
0.5	14.2 (2.8) 116.7 (7.0)	13.7 (2.6) 119.2 (6.7	13.9 (3.6) 117.4 (9.7)	12.8 (2.8) 118.2 (9.8	13.1 (3.5) 122.0 (12.7)	11.7 (3.4) 122.1 (8.6)
1.0	14.7 (3.0) 116.4 (6.4)	14.5 (2.1 117.1 (5.9)	15.2 (3.3) 114.3 (8.4	14.0 (2.9) 118.4 (8.0)	13.1 (2.6) 121.1 (9.7)	13.6 (2.7) 116.0 (5.7)
1.5	14.0 (2.7) 117.7 (5.4)	14.5 (2.8) 116.1 (5.8)	14.2 (3.2) 117.3 (8.1)	13.9 (4.2) 116.5 (9.7)	13.2 (3.7) 120.1 (8.5)	13.3 (4.3) 116.5 (9.5)
2.0	14.5 (4.2) 116.2 (11.3)	14.3 (4.0) 117.4 (10.2)	14.2 (4.2) 118.0 (10.2)	13.9 (3.9) 118.8 (8.2)	13.4 (4.0) 118.9 (9.2)	13.6 (4.2) 116.8 (9.6)
2.5	14.6 (6.9) 117.1 (13.1)	14.5 (3.5) 116.1 (10.5)	14.3 (3.6) 117.1 (10.7)	13.4 (3.4) 120.4 (9.4)	13.0 (3.4) 122.5 (9.6)	13.2 (3.2) 116.9 (8.6)

Note: Top number in each set is % moisture content and lower number is dry density in pcf. Numbers in parentheses are standard deviations.

Various precipitation time periods, initial starting values of API, and K values were analyzed. The best correlations resulted from average weekly precipitation, API starting value = 10.0, K = 0.9, and time beginning at spring thaw. The weekly precipitation data were based on the average over a 5-year period. The calculation of API is tabulated below for the Horse Creek data.

Date	*Previous Week's API × 0.9*	*Previous Week's Precipitation (in.)*	*API, This Date*
May 2	–	–	10.00
May 9	9.00	0.92	9.92
May 16	8.93	0.66	9.59
May 23	8.63	1.15	9.78
May 30	8.80	1.60	10.40

The API regression equation for Horse Creek is

$$S = 34.4 + 5.26(\text{API}) \quad (4)$$

R^2 = 0.78, Standard Error = 4.9

where

S = percent saturation, and
API = weekly antecedent precipitation index.

A plot and observed data are shown in Figure 14.

Nuclear Depth Probe Data

Regression analyses were run on the nuclear depth probe data both with moisture and density as functions of depth, time, and the other variables analyzed with electrical cell data. The analyses were inconclusive and significant correlations were not found. The problem appears to be scatter in the data as discussed earlier.

CONCLUSIONS

Conclusions for the specific site conditions at the Horse Creek and St. Maries study areas were as follows:

- There are significant seasonal variations in subgrade moisture under aggregate surfacing that need to be considered in laboratory testing and thickness design.
- The accuracy of electrical resistance cells for measuring percent saturation is about 1 to 2 percent as compared to the gravimetric (oven-dry) method.
- Nuclear depth-probe percent saturation and in-place densities between 0.5 and 2.5 ft below subgrade indicate little change with depth or time, although the accuracy of nuclear depth-probe measurements in this study is poor.
- Soil test results and field moisture observations showed wide variations, indicating the need for large numbers of tests and observations to provide statistically meaningful results in a study of this kind.
- The degree of saturation of shallow subgrade soil, as measured by electrical resistance moisture cells, could be predicted from the cosine function of time given in Equation 1.
- When good weather station data are available close to the site, the degree of saturation could be predicted as a function of the antecedent precipitation index by Equation 4.

RECOMMENDATIONS

- Conduct additional studies in areas of different climates, topography, and soils to verify or modify the results given herein.
- Perform additional research to improve and develop instrumentation for monitoring subgrade moisture.

ACKNOWLEDGMENT

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