FIG. 1. Map of the United States showing locations where soil samples were collected.

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The Spectral Reflectance of American Soils

The characteristic can be predicted with sufficient accuracy from measurements made at only five wavelengths.

INTRODUCTION

MUCH INTEREST has been expressed recently in the identification of terrestrial features in aerial photography, and it is well known that the government is sponsoring several research projects pertaining to this endeavor. Most of the land area of the earth's surface consists of soils and their color represents a basic characteristic for use in their identification. Therefore, spectrophotometric curves of soil reflectance should be of particular interest in studies relating to the use of aerial photography in the Earth Resources Survey to be sponsored by NASA and other agencies. To assist in this project, spectral reflectances extending from 320 to 1,000 nanometers have been obtained from a large proportion of the 285 samples of surface soils (to a depth of about two inches) collected from 36 states. These samples represent a wide variation in both color and reflectance. The locations where they were collected are shown in Figure 1. In most instances the samples collected were representative of the soil most prominently evident in that particular area.

ABSTRACT: *Spectral reflectances extending from 320 to 1,000 nanometers have been obtained for 160 soil samples collected from 36 states. Measurements were made of both wet and dry samples, which vary widely in color and reflectance. An examination of the 160 sets of curves indicates that they can be classified into three general types with respect to their curve shape. A characteristic vector analysis was made of the spectral reflectance data; it showed that by linear combinations of four vectors and the mean curve, each set of data could be reconstituted to a high degree of accuracy. Theoretically then, the reflectance data for all wavelengths should be predictable from measurements made at as few as four wavelengths. Empirical regression equations have been derived which relate spectral reflectance data at 35 wavelengths spaced at 20-nanometer increments to measurements made at only five specially selected wavelengths. To the extent that soils may be identified by their reflectance characteristics, this abridged technique seems to have sufficient accuracy for the 160 samples which have been measured.*

MEASUREMENTS

Measurements extending from 320 to 800 nm were made with a Cary Recording Spectrophotometer Model 14 equipped with an attachment for the measurement of diffuse reflectance. Measurements were extended from 800 to 1,000 nm by use of a manually operated Beckman DU Spectrophotometer, also equipped with an attachment for making diffuse reflectance measurements. With both instruments the sample was illuminated at normal incidence, measurements being made at an angle of 45°.

Each sample was measured in both a wet and a dry condition. Wetting was accomplished by adding a fine spray of water to the sample until it was almost—but not quite—saturated, after which spectral reflectances were determined. The sample was then oven dried at 110°F and another set of measurements were made.

All soil samples were thoroughly dried before they were prepared for measurement. In some instances the soil dried in the form of clumps or aggregates which were reduced in size by placing them in a mortar and pressing the pestle against them with sufficient pressure to separate the aggregates into individual and small groups of particles. The samples were placed in holders containing a circular cavity $1\frac{1}{2}$ inches in diameter and 3/8 inch in depth. The surface texture was made relatively smooth by first applying a moderate amount of pressure to the sample by means of a flat piece of Plexiglas followed by sliding the Plexiglas across the top of the holder.

CLASSIFICATION BY CURVE SHAPE

An examination of the 160 sets of curves thus far obtained indicates that the general shape of the curves can be classified into three types. Type 1, represented by the spectral reflectance of a chernozem-type soil collected 20 miles east of Lincoln, Nebraska, is illustrated in Figure 2. The distinguishing feature of these curves is that over any range of wavelengths the slope, with minor exceptions, either increases or is nearly constant. In the majority of examples of this type the slope increases throughout the whole spectral range from 320 to 1,000 nm, as is shown in Figure 2. In the other examples the slope increases in the ultraviolet, blue and green region but is nearly constant in the red and infrared region. Most samples having Type 1 general shape are those with rather low reflectances.

Type 2 is represented by the curves shown in Figure 3, which are from a pedalfer-type silt collected 15 miles southeast of Hot Springs, Arkansas. In this type the reflectance increases fairly rapidly, especially for the dry curve, from 320 to about 450 nm, where a

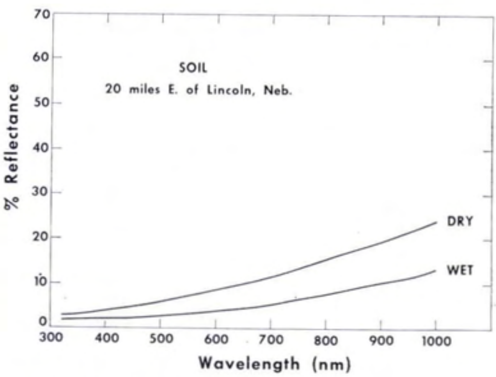

FIG. 2. Type 1 curves for a sample of chernozem-type soil.

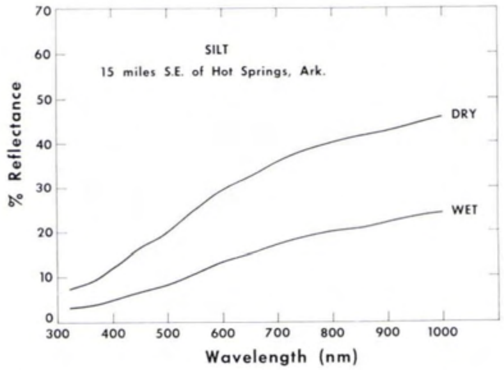

FIG. 3. Type 2 curves for a sample of pedalfer-type silt.

slight or even moderate dip in the slope occurs, followed by an incresae in the slope at about 480 nm. At about 580 nm another decrease in the slope occurs. From 600 to about 700 nm a slight-to-moderate dip in the slope is generally present. At about 750 nm the slope decreases again. Beyond 780 nm the slope usually changes very little with increasing wavelength. A few examples have been found where the decrease in the slope at 750 nm is completely absent.

Type 3, illustrated in Figure 4, is from a red quartz and calcite sand collected from Monument Valley, Utah. In this type the slope of the curve increases at a moderate rate from the ultraviolet region to about 530 nm, then rises sharply to about 580 nm, where a definite decrease in the slope occurs. From about 620 to about 740 nm a slight-to-moderate dip in the slope is usually present. At 740 nm another definite decrease in the slope occurs, often dropping to or near zero. In about half of the 33 sets of curves thus far obtained which represent this type of curve shape, the slope was found to rise again at longer wavelengths, as illustrated in Figure 4. In the other sets of curves of this type there occurred a decrease not only in slope but in reflectance from 760 to about 880 nm. Beyond 880 nm the slope increased with increasing wavelength. Such an example is illustrated in Figure 5, which is the spectral reflectance of a laterite-type soil collected 5 miles north of Charlottesville, Virginia. The curves given in this figure and in Figure 4 are quite similar in shape from 320 to about 750 nm, particularly in the case of the dry samples. But, as shown in Figure 5, the reflectance decreased from 760 to 880 nm with an increase in reflectance occurring from 880 to 1,000 nm. The necessity for extending the spectral reflectance measurements to at least 1,000 nm can be seen from the fact that while the two samples are quite similar through the ultraviolet and visible regions of the spectrum, they are quite different in the infrared.

A numerical value of the difference in curve shape between Type 2 and Type 3 may be obtained by comparing the ratio in reflectance measured at 760 and 500 nm of the dry and wet curves for each type. From measurements made of 100 Type 2 curves the lowest ratio for the dry curves (reflectance at 760 nm divided by reflectance at 500 nm) was found to be 1.2 the highest was 2.8, and the average was 2.0. In the occurrence of the 33 Type 3 curves, the lowest ratio was found to be 2.9, the highest, 7.3, and the average 4.6. Note that the lowest ratio for the Type 3 curves is higher than the highest ratio for the Type 2 curves.

For the wet curves, the lowest ratio for Type 2 curves was found to be 1.2, the high-

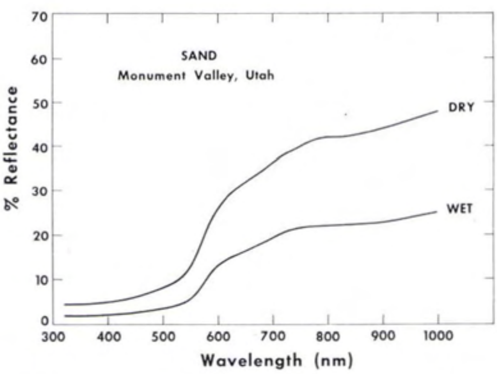

FIG. 4. Type 3 curves for a sample of red quartz and calcite sand.

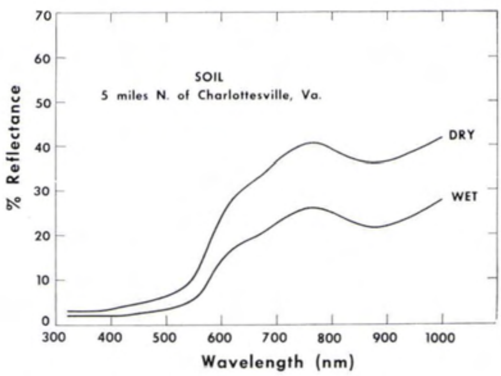

FIG. 5. Type 3 curves for a sample of laterite-type soil.

est was 3.7, and the average 2.4. The lowest ratio for the Type 3 curves was 3.8, the highest 8.2, and the average, 5.3. Again, the lowest ratio for the Type 3 curves is higher than the highest ratio for the Type 2 curves.

Abridged Technique of Spectrophotometry

At an early stage in this study it became evident that the measurement of the spectral reflectance of soils by means of aerial photography would be greatly simplified if the reflectance data at all 35 wavelengths (data were digitized at 20-nm increments) could be predicted from measurements made at only a few wavelengths. The application of characteristic vector analysis to photographic and optical response data as described by Simonds,[1] of the Kodak Research Laboratories, was used in this study. For this analysis 200 spectral reflectance curves from 100 samples were selected, and from these, the mean spectral reflectance data and four vectors were extracted. These curves are shown in Figure 6. A measure of the variability of the reflectance data is given in the trace, i.e., the sum of the diagonal elements of the covariance matrix computed from the original data. Characteristic vector analysis of these data has shown that, in linear combination with the mean curve, one vector can account for 93.67 percent of the trace. Two vectors can explain 98.72 percent; three vectors, 99.60 percent; and four vectors, 99.92 percent of the trace. The value of the empirical eigenvector analysis lies in its finding that the

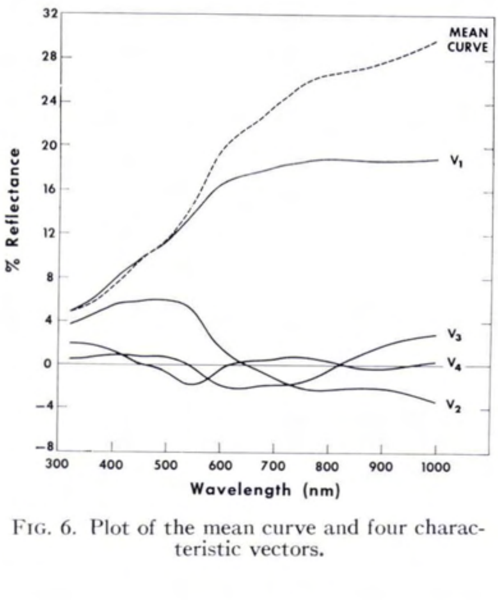

Fig. 6. Plot of the mean curve and four characteristic vectors.

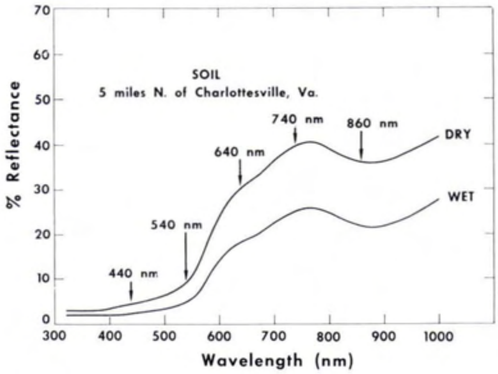

Fig. 7. Location of the five selected wavelengths with respect to the curve shape of one of the soil samples.

dimensionality of the data variability is small; it seems evident that reflectance data at all wavelengths can be accurately predicted from measurements made at only a few selected wavelengths.

From an examination of the eigenvectors from the covariance matrix, several possible wavelengths were selected. Linear stepwise regression analysis was used to find the best linear combination of a specified number of predictor variables. These are *best* in the sense that the particular combination gives a minimum standard error of estimate of data reconstitution. This analysis revealed that reflectance measurements made at only 5 wavelengths should be required to predict with sufficient accuracy the reflectance at the other 30 wavelengths. Ideally the selected wavelengths should be 400, 540, 640, 740, and 920 nm.

The energy reflected by the sample at these wavelengths can be measured either photoelectrically or photographically. If one uses the latter technique, the soil, along with a target of known spectral reflectance, would be photographed through five interference filters whose peak transmittances correspond with the five wavelengths. Knowledge of the spectral sensitivity characteristics of the film allows one to determine the energy reflected at the five wavelengths by the standard methods of photographic photometry. From these energy measurements, the percent reflectance of the sample at these wavelengths can be obtained. Unfortunately, the aerographic film most suited for this work—KODAK Infrared AEROGRAPHIC Film 2424 (ESTAR Base)—has, for all practical purposes, no sensitivity at 920 nm. Inspection of the film's spectral sensitivity curve indicates

TABLE 1. WAVELENGTH-DEPENDENT ADDITIVE TERM AND REGRESSION COEFFICIENTS

Wavelength (nm)	*Wavelength-Dependent Additive Term* a_0	*Regression Coefficients* a_1	a_2	a_3	a_4	a_5
320	0.6670	1.2289	−0.7553	0.5264	−0.3616	0.0589
340	0.5448	1.3231	−0.7552	0.4587	−0.2967	0.0371
360	0.3545	1.3876	−0.7145	0.3579	−0.2241	0.0293
380	0.2008	1.3910	−0.6090	0.2414	−0.1423	0.0183
400	0.0823	1.3363	−0.4358	0.1132	−0.0492	−0.0005
420	0.0232	1.2159	−0.2490	0.0236	−0.0002	−0.0009
440	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
460	−0.0260	0.8972	0.1355	−0.0004	−0.0067	0.0026
480	−0.1005	0.8446	0.2020	0.0145	−0.0562	0.0450
500	−0.0870	0.6537	0.3990	0.0049	−0.0623	0.0532
520	−0.0738	0.3584	0.6879	−0.0072	−0.0433	0.0385
540	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
560	0.0062	−0.2325	0.9766	0.3661	−0.1742	0.0300
580	0.0522	−0.2073	0.5690	0.9328	−0.3901	0.0666
600	0.1068	−0.0936	0.2150	1.1539	−0.3199	0.0248
620	0.0329	−0.0331	0.0669	1.1094	−0.1412	−0.0085
640	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
660	−0.0793	−0.0073	−0.0017	0.8295	0.1558	0.0221
680	−0.1054	0.0073	−0.0235	0.6405	0.3405	0.0355
700	−0.0788	0.0115	−0.0243	0.4242	0.5852	0.0098
720	−0.0283	0.0034	−0.0131	0.1941	0.8314	−0.0155
740	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
760	0.0020	−0.0224	0.0182	−0.0809	0.9911	0.0936
780	0.0344	−0.0404	0.0374	−0.1102	0.8630	0.2450
800	0.0579	−0.0520	0.0465	−0.0657	0.6233	0.4379
820	−0.0461	−0.0540	0.0498	−0.0352	0.3953	0.6355
840	−0.0567	−0.0372	0.0326	−0.0066	0.1759	0.8296
860	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
880	0.0467	0.0455	−0.0402	−0.0173	−0.1138	1.1330
900	0.0890	0.0981	−0.0817	−0.0884	−0.1375	1.2247
920	0.1465	0.1638	−0.1472	−0.1558	−0.1435	1.3069
940	0.1709	0.2329	−0.2117	−0.2637	−0.0817	1.3587
960	0.2361	0.2878	−0.2637	−0.3774	−0.0095	1.4034
980	0.3094	0.3437	−0.3171	−0.4999	0.1017	1.4195
1,000	0.4297	0.3911	−0.3634	−0.6271	0.2334	1.4179

that the measurement in the infrared region should be made at a wavelength no longer than 860 nm. In addition, since atmospheric haze is generally very high in the ultraviolet and far blue region of the spectrum, the measurement at 400 nm should be shifted to 440 nm. A shift of these two wavelengths will, in some instances, lead to less accurate predictions in the regions of 320 to 380 nm and from about 920 to 1,000 nm. In summary then, the final choice of five wavelengths to be used in this abridged technique of spectrophotometry was 440, 540, 640, 740, and 860 nm. The location of these selected wavelengths, with respect to curve shape of one of the soil samples, is shown in Figure 7.

From the 200 sets of measurements made at the five selected wavelengths, regression coefficients and wavelength-dependent additive terms were obtained, by a standard least-squares regression analysis, for use in predicting the reflectance data at each of the other 30 wavelengths. This empirical deviation indicates that, to determine the full spectral reflectance curve for a soil sample, one need only measure the reflectances at 440, 540, 640, 740, and 860 nm and insert them into linear regression equations of the form:

$$R_\lambda = a_{0,\lambda} + a_{1,\lambda}R_{440} + a_{2,\lambda}R_{540} + a_{3,\lambda}R_{640} + a_{4,\lambda}R_{740} + a_{5,\lambda}R_{860}.$$

The wavelength-dependent additive term, $a_{0,\lambda}$, and the regression coefficients, $a_{1,\lambda}$, $a_{2,\lambda}$, $a_{3,\lambda}$, etc., for each of the 30 prediction equations, plus the five equations corresponding to the wavelength at which the reflectance measurements were made, are listed in Table 1. Applying these regressions to the original data yields low errors in predicting the reflectance data in this abridged manner. The standard error of estimate, expressed in terms of per cent reflectance, is tabulated for each wavelength in Table 2. It should be pointed out, however, that this abridged technique is applicable only for materials whose spectral

TABLE 2. STANDARD ERROR OF ESTIMATE

Wavelength (nm)	*Standard Error of Estimate (% Reflectance)*
320	1.07
340	.89
360	.68
380	.48
400	.32
420	.24
440	.00
460	.21
480	.34
500	.30
520	.24
540	.00
560	.30
580	.41
600	.33
620	.21
640	.00
660	.12
680	.16
700	.17
720	.11
740	.00
760	.15
780	.19
800	.24
820	.20
840	.16
860	.00
880	.18
900	.31
920	.47
940	.66
960	.82
980	.99
1,000	1.17

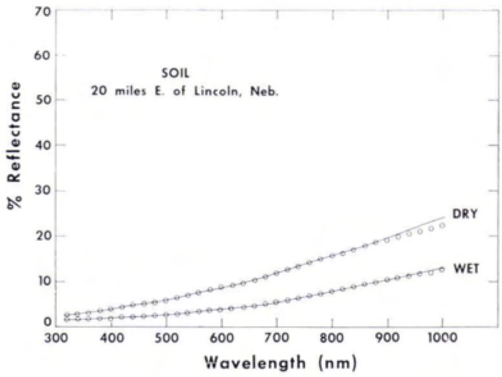

FIG. 8. Type 1 curves for a sample of chernozem-type soil. Measured values are shown by lines; predicted values by a series of circles.

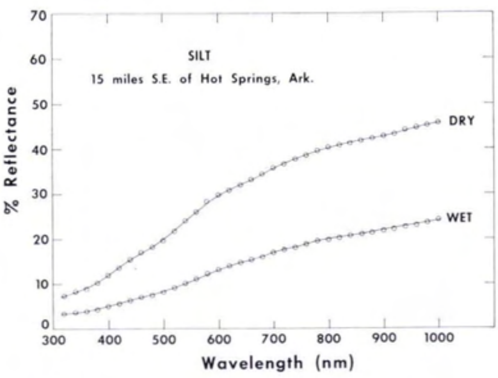

FIG. 9. Type 2 curves for a sample of pedalfer-type silt. Measured values are shown by lines; predicted values by a series of circles.

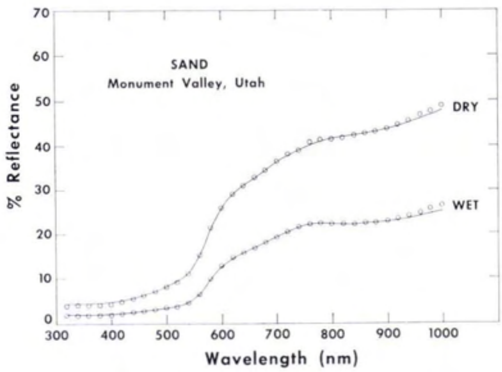

FIG. 10. Type 3 curves for a sample of red quartz and calcite sand. Measured values are shown by lines; predicted values by a series of circles.

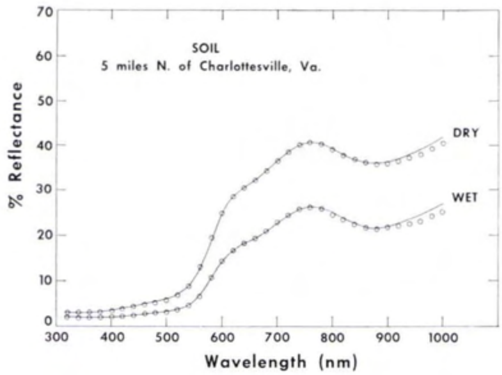

FIG. 11. Type 3 curves for a sample of laterite-type soil. Measured values are shown by lines; predicted values by a series of circles.

reflectance distributions lie within the domain of variability spanned by the characteristic vectors derived in this experiment.

Let us now see how well this abridged technique of spectrophotometry has been able to predict the curves given in Figure 2 to 5. These same curves are shown again in Figure 8 to 11. The actual measurements are shown by the solid line; the predicted values are represented by the circles. It will be noted that except for the measurements from about 940 to 1,000 in Figure 8, 10, and 11, the predicted values are extremely accurate.

Spectral Reflectance Curves

In the section which follows, figures show spectral reflectances for various soil samples. The soil samples, in each of the various curve type groups, are presented in order of increasing reflectance of their dry curve at 700 nm, which is about the midpoint of the spectral range covered in this study.

It has been found that any lack of a match

TABLE 3. EVALUATION OF THE MATCH BETWEEN PREDICTED AND MEASURED SPECTRAL REFLECTANCE DATA

Fig. No.	*320–380-nm Region*		*400–900-nm Region*	*920–1,000-nm Region*	
	Dry Curve	*Wet Curve*	*Dry and Wet Curves*	*Dry Curve*	*Wet Curve*
8	Excellent	Excellent	Excellent	Fair	Excellent
9	Excellent	Excellent	Excellent	Excellent	Excellent
10	Very good	Excellent	Excellent	Very good	Good
11	Excellent	Excellent	Excellent	Good	Fair
12	Excellent	Excellent	Excellent	Fair	Good
13	Excellent	Excellent	Excellent	Very good	Good
14	Very good	Excellent	Excellent	Good	Fair
15	Good	Excellent	Excellent	Good	Excellent
16	Very good	Excellent	Excellent	Good	Very good
17	Excellent	Excellent	Excellent	Excellent	Excellent
18	Excellent	Very good	Excellent	Very good	Excellent
19	Poor	Poor	Excellent	Excellent	Excellent
20	Fair	Fair	Excellent	Good	Excellent
21	Poor	Poor	Excellent	Very good	Excellent
22	Poor	Poor	Excellent	Fair	Fair
23	Very good	Excellent	Excellent	Excellent	Fair
24	Excellent	Excellent	Excellent	Excellent	Excellent
25	Excellent	Excellent	Excellent	Excellent	Excellent
26	Poor	Poor	Very good	Very good	Fair
27	Very good	Excellent	Excellent	Very good	Excellent
28	Poor	Poor	Excellent	Very poor	Very poor
29	Poor	Excellent	Excellent	Very good	Very poor
30	Excellent	Excellent	Excellent	Good	Good
31	Excellent	Excellent	Excellent	Poor	Fair
32	Good	Good	Excellent	Excellent	Very good
33	Excellent	Excellent	Excellent	Fair	Good
34	Excellent	Excellent	Excellent	Fair	Fair
35	Excellent	Excellent	Excellent	Fair	Excellent
36	Very good	Excellent	Excellent	Excellent	Excellent
37	Excellent	Excellent	Excellent	Excellent	Fair

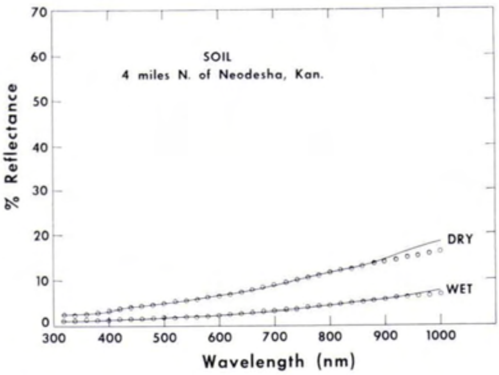

FIG. 12. Type 1 curves for a sample of chernozem-type soil. Measured values are shown by lines; predicted values by a series of circles.

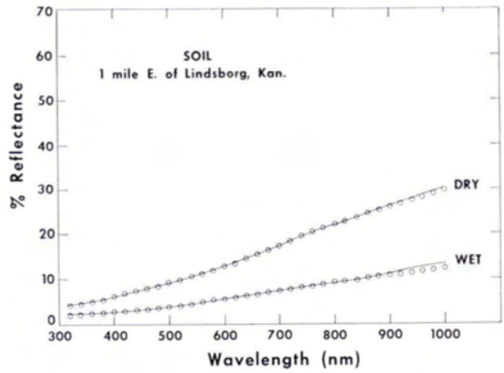

FIG. 13. Type 1 curves for a sample of chernozem-type soil.

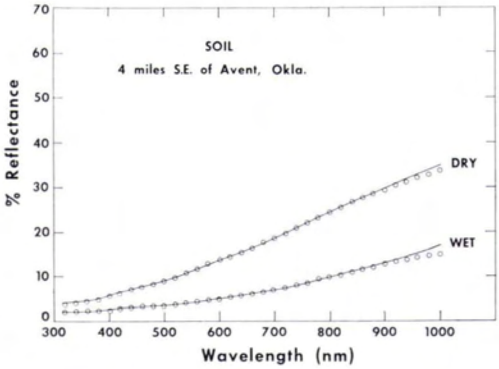

FIG. 14. Type 1 curves for a sample of chernozem-type soil

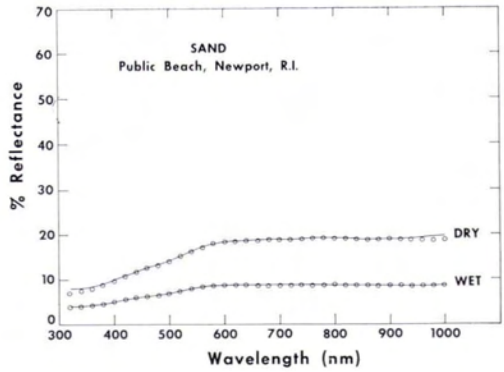

FIG. 15. Type 2 curves for a sand sample containing quartz, rock fragments, and shell fragments. The unusual feature of these curves is that they are flat over such a long wavelength span: 600 to 1,000 nm.

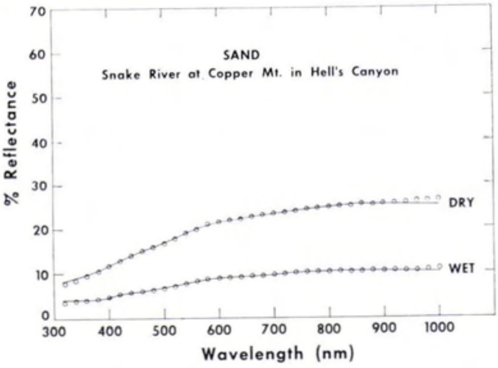

FIG. 16. Type 2 curves for a sample of quartz and rock-fragment sand.

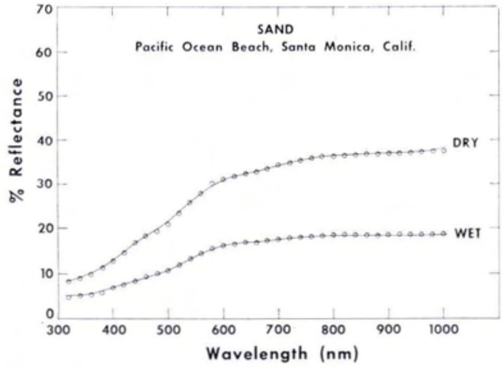

FIG. 17. Type 2 curves for a sample of quartz and rock-fragment sand.

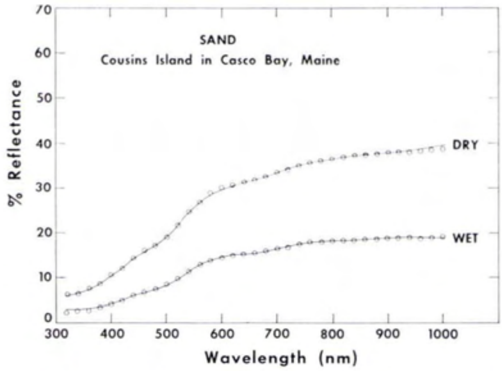

FIG. 18. Type 2 curves for a sample of quartz and rock-fragment sand.

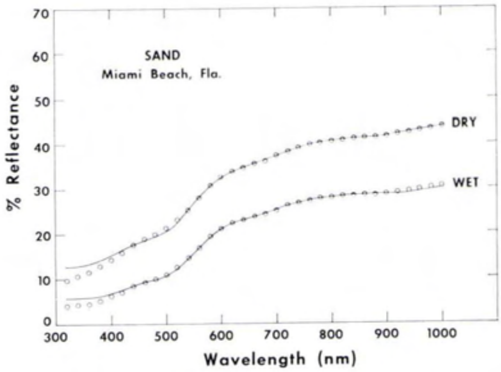

FIG. 19. Type 2 curves for a sample of quartz and carbonate sand.

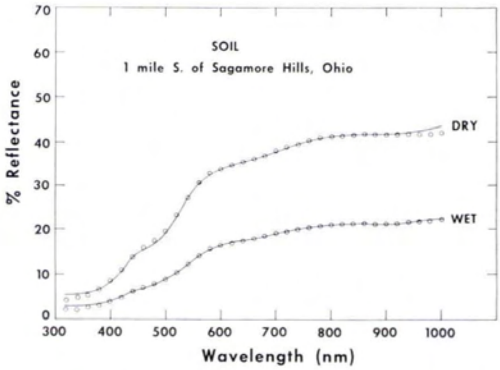

FIG. 20. Type 2 curves for a pedocal-type soil sample.

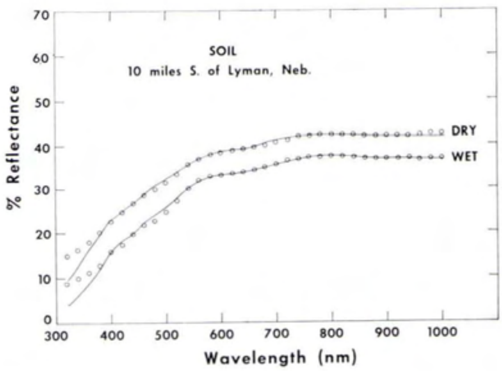

FIG. 21. Type 2 curves for a pedocal-type soil sample. Note the small difference in reflectance between the dry and wet curves.

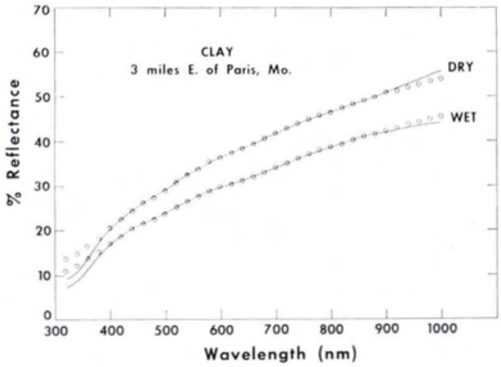

FIG. 22. Type 2 curves for a clay sample. Note that the difference in reflectance between the dry and wet curves in this figure is fairly small.

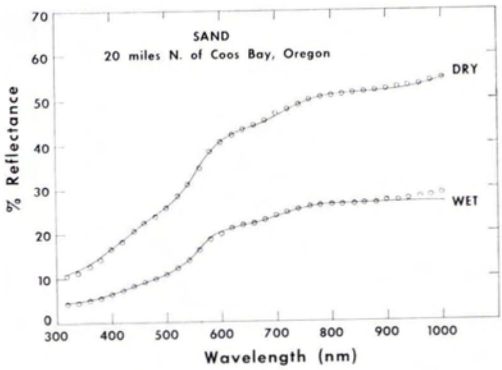

FIG. 23. Type 2 curves for a sample of quartz sand.

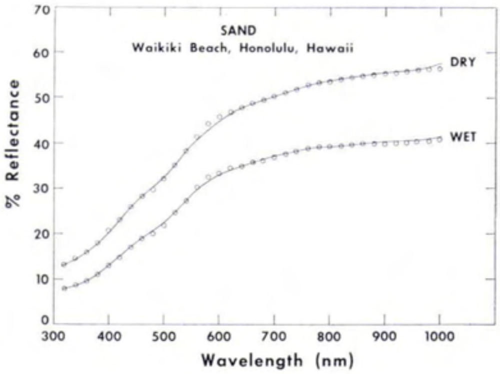

FIG. 24. Type 2 curves for a carbonate sand sample.

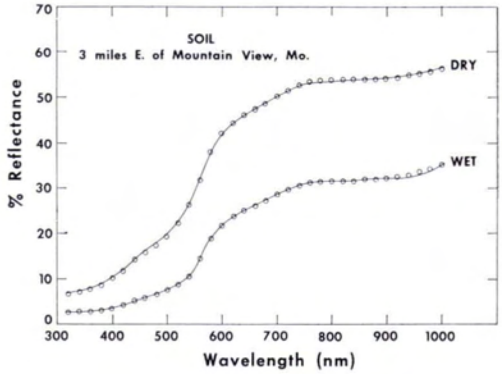

FIG. 25. Type 2 curves for a pedalfer-type soil sample.

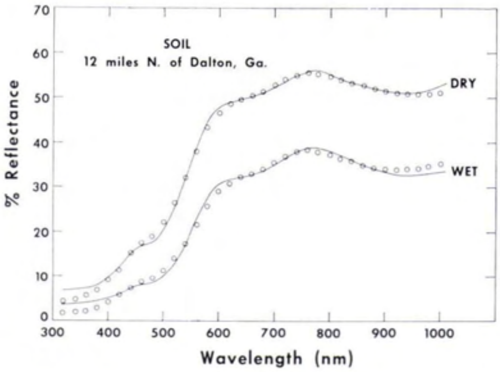

FIG. 26. Type 2 curves for a sample of a pedalfer-type soil. The curves shown in this figure are difficult to classify. Portions of the curves more nearly resemble the Type 3 shape but they were placed in the Type 2 classification because of the rapid rise in reflectance in the region from 320 to 500 nm, which is particularly characteristic of the Type 2 curves. This is one of only two such Type 2 curves thus far obtained in which the reflectance decreases by any appreciable amount in the region beyond 760 nm.

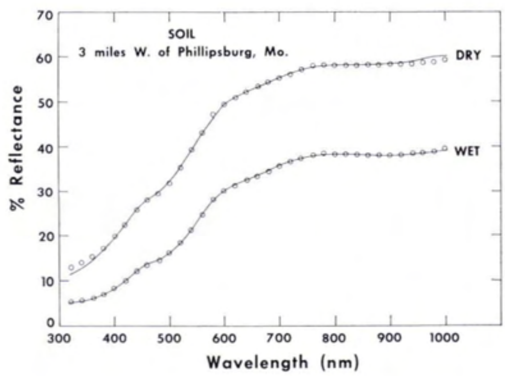

FIG. 27. Type 2 curves for a pedocal-type soil sample of very high reflectance.

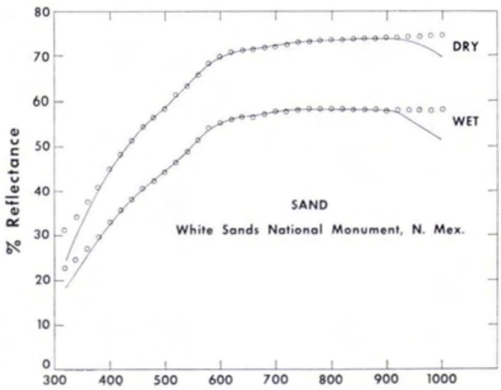

FIG. 28. Type 2 curves for a sample of gypsum sand. Note that beyond 920 nm there is a sharp decrease in the reflectance for both the wet and dry curves, the abridged technique was unable to predict correctly values beyond 920 nm.

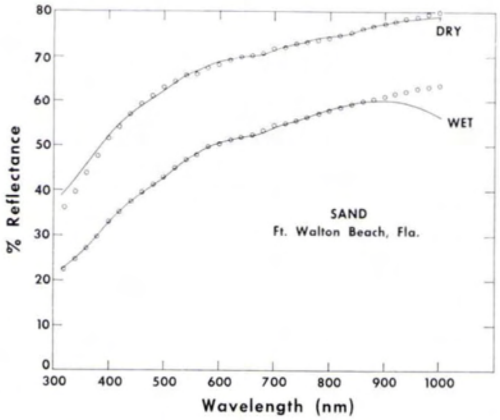

FIG. 29. Type 2 curves for a sample of quartz sand, collected at Ft. Walton Beach, Florida. This sample was found to have the highest spectral reflectance of any thus far measured, reaching a value of 79 percent at 1,000 nm.

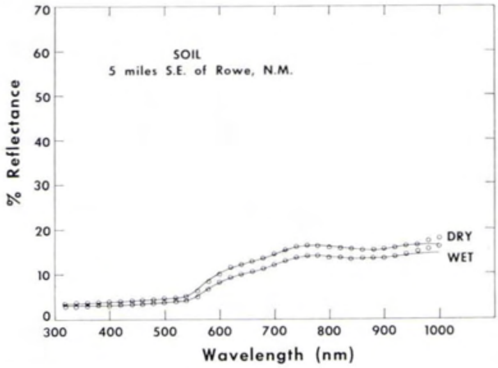

FIG. 30. Type 3 curves for a sample of a very low reflectance, pedalfer-type soil. Note the very small difference in reflectance in the wet and dry curves.

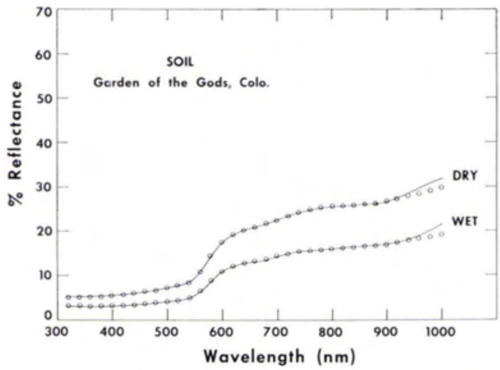

FIG. 31. Type 3 curves for a sample of a pedalfer-type soil.

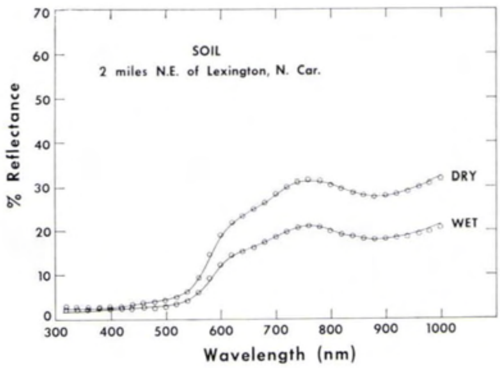

FIG. 32. Type 3 curves for a sample of a laterite-type soil.

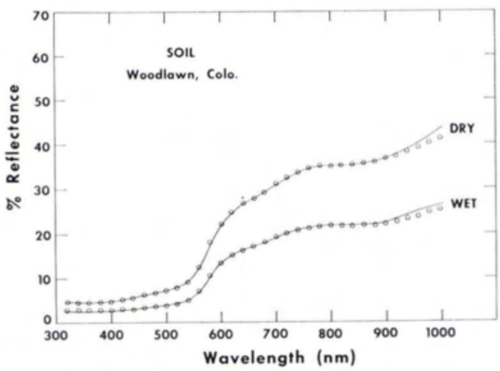

FIG. 33. Type 3 curves for a sample of a pedalfer-type soil.

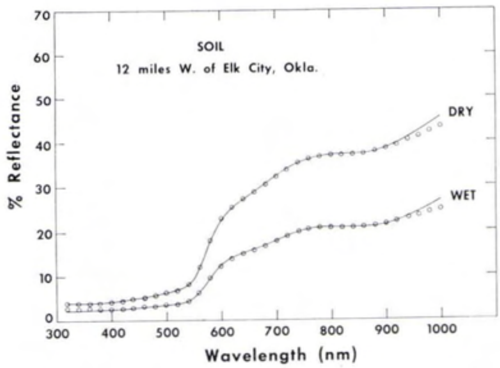

FIG. 34. Type 3 curves for a sample of a pedocal-type soil sample.

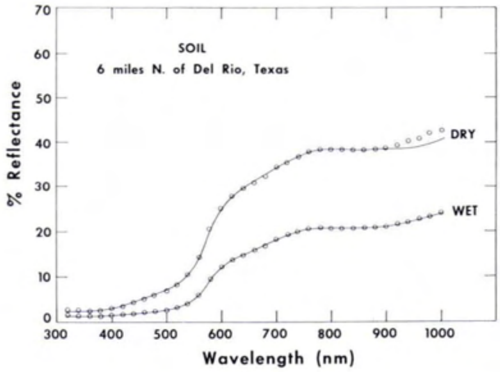

FIG. 35. Type 3 curves for a sample of a pedalfer-type soil.

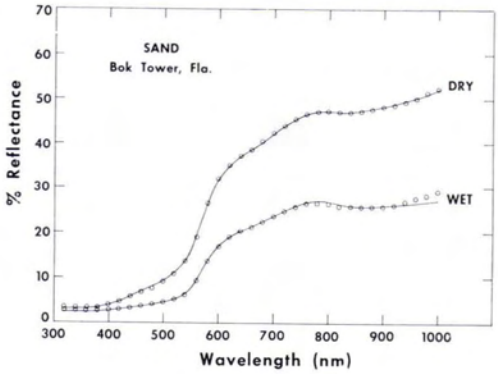

FIG. 37. Type 3 curves for a sample of quartz sand with a hematite stain.

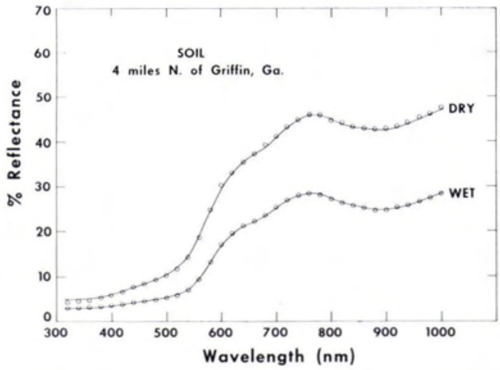

FIG. 36. Type 3 curves for a sample of a pedalfer-type soil.

between predicted and measured values of spectral reflectance usually occurs in the regions from 320 to 380 nm and 920 to 1,000 nm. In Table 3 is given an evaluation of how well the predicted values match the measured values in these two regions as well as in the region from 400 to 900 nm for the 30 samples discussed in this paper.

Figures 12 to 14 reproduce Type 1 curves, Figure 15 to 29 show Type 2 curves, and the remaining figures (30 to 37) show Type 3 curves for representative soil samples examined.

Of the 30 sets of curves presented in this paper, 18 were from the 100 sets used in the characteristic vector analysis. They are shown in Figure 8–12, 15–18, 21–24, 26, 27, 32, 35, and 37. The curves not included in the analysis are shown in Figure 13, 14, 19, 20, 25, 28–31, 33, 34, and 36. It is important to note that no significant difference exists between the two groups with respect to the accuracy with which the abridged technique was able to predict spectral reflectance values.

CONCLUSIONS

From a study of the degree to which the predicted spectral reflectance data matched the measured values, it seems evident that the spectral reflectance of a wide variety of soils (a basic characteristic in their identification) can be predicted with sufficient accuracy from measurements made at only five wavelengths.

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REFERENCE

1. Simonds, J. L., "Application of Characteristic Vector Analysis to Photographic and Optical Response Data," *J. Opt. Soc. Am.* 53: 968–974, August 1963.