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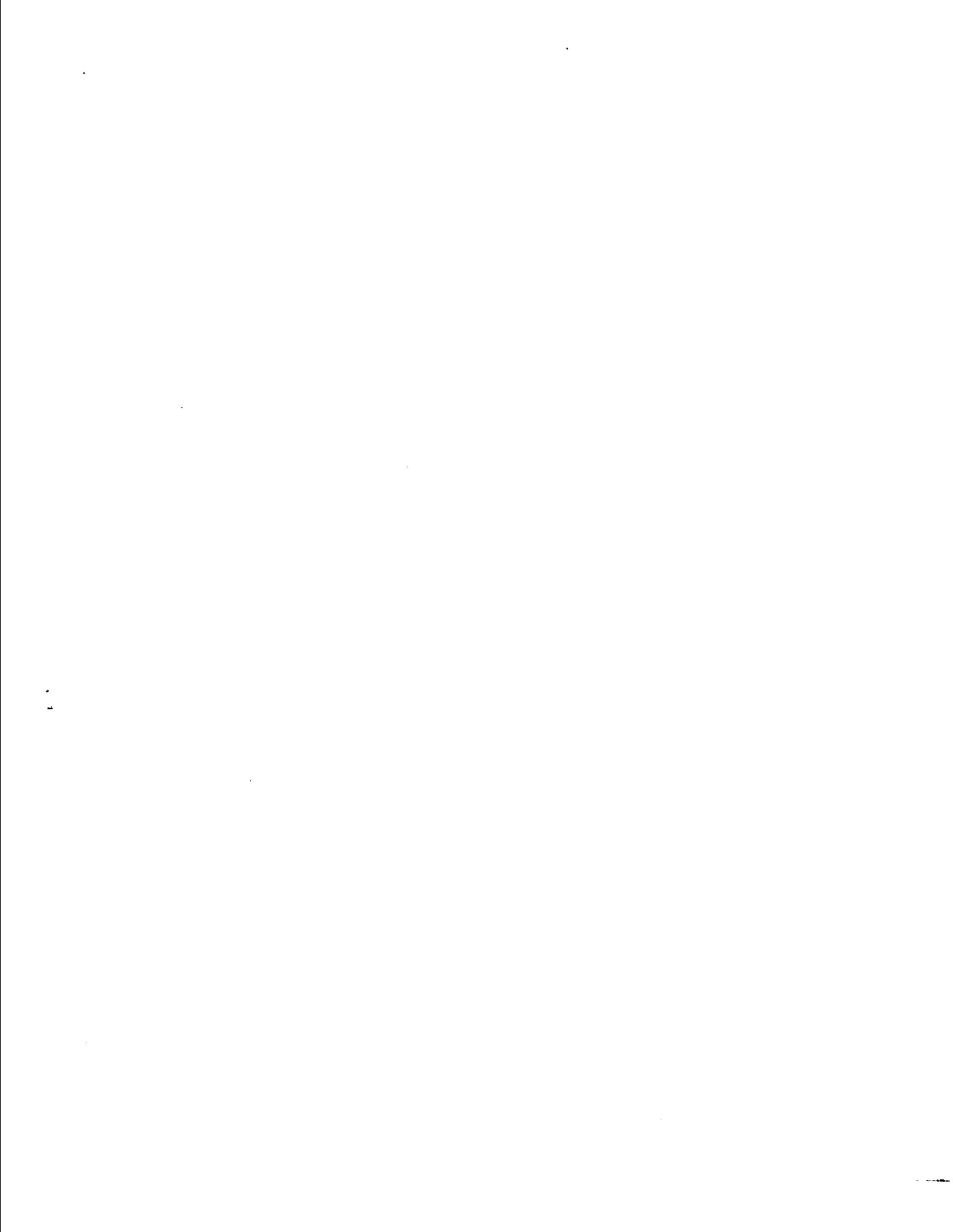
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Spectral reflectance measurements of salt-affected soil

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The University of Arizona, 1987

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SPECTRAL REFLECTANCE MEASUREMENTS
OF SALT-AFFECTED SOIL

by

Saud Abdulaziz Amer

A Thesis Submitted to the Faculty of the
DEPARTMENT OF SOIL AND WATER SCIENCE
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE

In the Graduate College
THE UNIVERSITY OF ARIZONA

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TABLE OF CONTENTS

	Page
LIST OF ILLUSTRATIONS	v
LIST OF TABLES	vi
ABSTRACT	viii
1. INTRODUCTION	1
2. LITERATURE REVIEW	2
Saline and Alkali Soils: Their Origin and Nature	2
Definition	2
Effects of Soluble Salts on Plants	5
Salinization	6
Alkalization	7
Influence of Soil Parameters on Spectral Reflectance Characteristics of Soils.	8
Salinity	8
Moisture Content	15
Organic Matter	17
3. METHODS AND MATERIALS	19
Soil Characteristics	19
The 1985 Experiment	19
Data Acquisition	19
Reflectance Measurements	21
The 1986 Experiment	23
4. RESULTS AND DISCUSSION	24
The 1985 Experiment	24
The 1986 Experiment	37
5. CONCLUSIONS AND RECOMMENDATIONS	55
APPENDIX I. REFLECTANCE VALUES AND SOIL ANALYSIS FOR THE 1985 EXPERIMENT	57
APPENDIX II. REFLECTANCE VALUES AND SOIL ANALYSIS FOR THE 1986 EXPERIMENT	62
REFERENCES	65

LIST OF ILLUSTRATIONS

Figure		Page
1	The Electromagnetic Spectrum	12
2	Landsat Satellite	13
3	Typical Landsat Daily Orbit Pattern (Daylight passes only).	14
4	Spectral Curve at Air Dry Moisture Condition.	25
5	Spectral Curve at Air Dry Moisture Condition.	26
6	Spectral Curve at Air Dry Moisture Condition.	27
7	Spectral Curve at Wet Moisture Condition	29
8	Spectral Curve at Wet Moisture Condition	30
9	Spectral Curve at Wet Moisture Condition	31
10	Spectral Curve at Dry Moisture Condition (24-hr after wetting)	32
11	Spectral Curve at Dry Moisture Condition (24-hr after wetting)	33
12	Spectral Curve at Dry Moisture Condition (24-hr after wetting)	34
13	Relationship Between Electrical Conductivity and Concentration of the Cation Sodium	38
14	Relationship Between Reflectance (from TM4) and Electrical Conductivity (EC) for the Sodium Salts	39
15	Relationship Between Reflectance (from TM3) and Sodium Adsorption Ratio (SAR)	40
16	Spectral Curve at Air Dry Moisture Condition.	42
17	Spectral Curve at Air Dry Moisture Condition.	43
18	Spectral Curve at Air Dry Moisture Condition.	44

LIST OF ILLUSTRATIONS--Continued

Figure		Page
19	Spectral Curve at Wet Moisture Condition	45
20	Spectral Curve at Wet Moisture Condition	46
21	Spectral Curve at Wet Moisture Condition	47
22	Spectral Curve at Dry (24-hr after wetting) Moisture Condition	48
23	Spectral Curve at Dry (24-hr after wetting) Moisture Condition	49
24	Spectral Curve at Dry (24-hr after wetting) Moisture Condition	50

LIST OF TABLES

Table		Page
1	Some Physical and Chemical Properties of the 0 to 30 cm Layer of the Soil Used in Study	20
2	Chemical Analysis of Soil Samples	36
3	Relationship Between Reflectance With (a) Electrical Conductivity, (b) Sodium Adsorption Ratio and (c) Exchangeable Sodium Percentage	41
4	Chemical Analysis of Soil Samples	53
5	Relationship Between Reflectance With (a) Electrical Conductivity (EC), (b) Sodium Adsorption Ratio (SAR) and (c) Exchangeable Sodium Percentage	54

ABSTRACT

Salt-affected soils have undermined the effectiveness of agricultural development of considerable areas of the world, especially in the arid and semi-arid regions.

This research is set out for the direct measurement of salt-affected soil. Two experiments were conducted to study the influence of different salt types and concentrations on spectral reflectance of soil. In the first experiment, five different salts (Na_2SO_4 , NaHCO_3 , CaCO_3 , CaCl_2 and NaCl) were mixed individually with Gila soil at 0.51, 1.51 and 3.0% by weight. The second experiment was conducted to examine the spectral response of sodium sulfate and sodium bicarbonate (individually and in combination) in Gila soil at 3.0 and 6.0% by weight.

Reflectance measurements were made over all soil treatments under different moisture conditions. Upon drying (24-hour after wetting), different salt types and concentrations showed different spectral response.

The chemical analysis of soil samples have indicated some important relationships which influenced, directly and indirectly, the spectral reflectance of soil surfaces.

INTRODUCTION

Saline and alkali soil conditions are considered, among many other associated factors, to be the most influential direct factor in reducing the value and productivity of considerable areas in the world.

The arid and semi-arid regions are characterized by evaporation rate which greatly exceeds the precipitation rate. Salts then accumulate on the soil surface, deteriorating the chemical and physical properties of the soil and reducing yield due to water stress for a significant period of time.

Salinization and alkalization of fertile areas in many parts of the arid and semi-arid regions of the world started in the very early days and have destroyed many ancient civilizations. Even though the problem is well known and the literature is rich with information on this subject, that saline and alkali soil formation caused either by an excessive concentration of soluble salts or a high percentage of exchangeable sodium, or both, the complexity of the chemical and physical processes forming such soils is still not well understood (U.S. Salinity Lab., 1954; Adrien et al., 1982).

Too often, preventive measures to reduce the level of salt accumulation have been applied only after the problem has become a serious threat to agricultural production. Such an accumulation, which is often detectable by human eye, may cause significant differences in the

absorption and reflectance of light from the soil surface and therefore, be evident by remote sensing.

One of the broad objectives of remote sensing is measuring the earth resources and their rates of change. The reflected radiant energy from the surface of the earth is contributed to by different components such as soil, vegetation, moisture and salinity. If early detection of tonal differences of salt affected soils can be obtained by analysis of spectral reflectance measurements, a valuable tool and cost-effective method that can save time and effort will be available for characterizing these soils.

The objectives of this study are to (1) study the spectral reflectance characteristics of soil of different salt types and salt concentrations, (2) study the influence of the salt-water interaction upon reflectance, and (3) study the effect of moisture on the spectral reflectance curves of soil surface in four wavelength bands by radiometer.

In order to achieve these objectives, a field study was conducted to assess the suitability of remotely sensed data in detecting soil of different salts and concentrations at different moisture conditions.

LITERATURE REVIEW

Salt-affected areas are presently estimated at more than 400 million ha on global basis (Adrien et al., 1982). The various concentrations of salts usually affect plant growth due to their osmotic effect. As salt concentration increases, the total suction (matrix plus osmotic) holding water in the soil increases and makes it more difficult for plant roots to extract the water. High salt concentrations, during dry periods, may kill plants by extracting water from them (exosmosis)(Donahue et al., 1977). The detection for avoidance of salinity or reclamation of salt-affected soils is of great importance for agricultural production.

Saline and Alkali Soils: Their Origin and Nature

Definition

A saline soil may be defined as one which contains sufficient soluble salts to impair its productivity (U.S. Salinity Lab, 1954)., It is not easy to draw a rigid line between saline and non-saline soils. This line is a function of many factors, among which are soil physical and chemical properties, topography, quantity and quality of water and crop tolerance.

The salinity problem is due to salts that are water soluble and readily transported by water (FAO, 1985). The original source of all the salts is the weathering of primary minerals found in soils. The chemical characteristics of soils classed as saline are mainly determined

by the kinds and amounts of salts present. The principle soluble salts that occur in soils consist of various concentrations of the cations calcium, sodium and magnesium, and the anions chloride and sulfate. The cation potassium and the anions carbonate, bicarbonate, and nitrate constituents, are found in lesser amounts (Adrien et al., 1982, U.S. Salinity Lab., 1954).

Generally, it is agreed that the term of saline soils is used in connection with soils in which the saturation extract has an electrical conductivity of more than 4 mmhos/cm (or dS/m) at 25°C, an exchangeable sodium percentage (ESP) of less than 15%, and the pH of less than 8.5 (U.S. Salinity Lab, 1954).

On the other hand, the term alkali soils is applied to soils with ESP of more than 15%, the conductivity of the saturation extract of less than 4 mmhos/cm (or dS/m) at 25°C, and the pH reading is equal to or greater than 8.5 (U.S. Salinity Lab., 1954).

Alkali soils have relatively low soluble salts in solution. The removal of excess salts in such soils tends to increase the rate of hydrolysis of exchangeable sodium and often causes the soil pH to rise. Organic matter is nearly insoluble in water but soluble in alkali solutions. Dispersed and dissolved organic matter present in an alkali soil solution causes black alkali when deposited on the soil surface by evaporation (U.S. Salinity Lab., 1954; and Donahue et al., 1977).

Effects of Soluble Salts on Plants

The salinity problem of principle economic importance arises when previously non-saline soils become saline and causes a loss in yield because much money has been spent to develop the land-irrigation system, buildings, transportation facilities, etc.

Salinity affects plant uptake and translocation of nutritional ions such as K^+ and Ca^{++} . Salt tolerance of the plants is reduced under conditions of low nutrient availability (Staples and Toenniessen, 1984). The plant exerts its absorptive force throughout the roots and takes water-borne nutrients from wherever the water is most readily available. This force must be greater than that which holds the water to the soil (Chapman, 1966; FAO, 1985). As the salt concentration in the soil-water increases, the force the plant must exert to extract water increases and this additional force is referred to as the osmotic effect or osmotic potential. This effect appears to divert energy from growth processes to maintain the osmotic differential (Bohn et al., 1979). The additional energy (osmotic potential) required to absorb water from salty soil is additive to the energy required to absorb water from a salt-free soil (soil-water potential) and the cumulative effect results in an important reduction in water availability to plants as salinity increases (Staples and Toenniessen, 1984; Russell and Barber, 1960; FAO, 1985).

Salt-affected soils are often recognized by the presence of white crusts of salts, dark brown-oily looking surfaces, by impeded growth of plants with considerable variability in size and deep blue-green foliage,

and sometimes by tipburn of the margins of leaves (U.S. Salinity Lab., 1954; Strogonov, 1964; Bernstein, 1962; Bresler et al., 1982).

Salinization

Salinization of soils occurs under conditions which favor the accumulation of soluble salts. There are three principle factors responsible for the salinization of soils; arid climate, poor drainage, and irrigation (U.S. Salinity Lab., 1947).

Saline soils occur mostly in arid and semi-arid regions where the evaporation rate exceeds the precipitation rate. Leaching and transportation of soluble salts downward in the soil profile is not so complete as in humid regions. In arid and semi-arid regions leaching is usually local in nature and soluble salts may not be transported far (U.S. Salinity Lab., 1954). The soluble salts content tends to build up in the soil profile, especially on the surfaces, because there is less precipitation to leach the salts away and because of the high evaporation rates characteristic of arid climates. Under humid conditions, soluble salts are carried into ground water and ultimately by streams to oceans because salt removal by leaching is equal to or exceeds the salt addition from applied water and those formed by weathering of soil minerals, and because the rates of evaporation are much lower than those of arid climates (U.S. Salinity Lab., 1954; FAO, 1985; International Institute for Reclamation, 1972).

Alkalization

Alkalization is the accumulation of exchangeable sodium in soils. The electrical charges at the surface of the soil particles are responsible for adsorption and exchange of cations. Soil colloids (i.e. clay and organic matter) adsorb and retain cations such as sodium, calcium, and magnesium on their surfaces (U.S. Salinity Lab., 1954).

Cation adsorption, being a surface phenomenon, involves mainly the fine silt, clay and organic matter fractions of soils. Each soil has a rather definite cation adsorption or exchange capacity depending upon the content of those fractions of soils. Calcium and magnesium are the primary cations found in the soil solution and hence on the exchange complex of normal soils in arid regions (U.S. Salinity Lab., 1947). When these soils are subjected to excess soluble salts, sodium frequently becomes the dominant cation in the soil solution. Sodium may become the predominant cation not only in the soil solution but also in the upper horizons and surfaces of the soil, owing to the precipitation of calcium and magnesium compounds (U.S. Salinity Lab., 1954). As the soil solution concentrates through high evaporation in arid regions or water absorption by plants, the solubility limits of calcium sulfate and calcium carbonate are often exceeded, in which case they precipitate out of the soil solution with a corresponding increase in the relative proportion of sodium (U.S. Salinity Lab., 1954). Such soils frequently crust badly and the clay particles disperse and plug soil water flow channels, greatly decreasing the hydraulic conductivity (Bohn, et al., 1979).

In general, sodium must be half or more of the soluble cations before appreciable amounts are adsorbed by the soil colloids. The process whereby the relative amount of sodium in the soil solution and that adsorbed by the exchangeable complex increases has been termed alkalinization (U.S. Salinity Lab., 1954; Sigmond, 1938).

Soils which contain mostly sodium chloride and sodium sulfate as the precipitated salts are sometimes called "white alkali." Soils are named "black alkali" if the soluble salts are mostly sodium carbonates and bicarbonates. Black alkali soils commonly show a discoloration of the soil surface induced by the dispersed humus deposited on the soil surface by evaporation (Brady, 1974; UNESCO, 1961).

Influence of Soil Parameters on Spectral Reflectance Characteristics of Soils

The sun is the primary source in passive remote sensing. The incident radiant flux (irradiance) from the sun is partially absorbed by the soil surface and transformed mainly into heat. A small part of it is diffusely reflected. Numerous soil properties, among which are salinity, moisture content, and organic matter affect reflection and emission of electromagnetic energy in the visible and infrared regions of the electromagnetic spectrum.

Salinity

Most remote sensing literature deals with detecting the effect of salinity stress on vegetation as an indirect procedure of an early detection and determination of salt affected soils. Only a few studies

consider detection of salt affected soils per se: when salt crusts are observed on the soil surface.

In a series of greenhouse experiments, Ward (1978) studied changes in spectral reflectance of the upper surface of sugar maple leaves, induced by drought and salinity soil conditions. The instrument used was a Beckman DK-2A Spectroreflectometer, operating over the range of wavelength from 0.5 to 2.6 micrometers. The best detection, even before visible symptoms were obvious, of drought or salinity affected plants were at 1.43, 1.94, and 2.19 micrometer wavelength. Satterwhite and Eastes (1982), evaluating spectroradiometric measurements in the range of 0.4 to 1.1 micrometer of the spectrum on halophytic and non-halophytic plants as an indirect detection of salinity, concluded that the degree of salinity, especially in the infrared region, could be estimated on a species by species basis.

Harker (1981) conducted a study in Canada, with color photographs and compared panchromatic black and white photographs with black and white infrared photographs to assess salinity and salinization. The panchromatic black and white photographs at scale of 1:20,000 demonstrated the most effective and acceptable results when accompanied by ground data. Black and white infrared photography was used for identifying and mapping soil limitations, including alkalinity and salinity (Frazee et al., 1971). A density slicing system was used to analyze the variations in tone of the photographic transparencies and displayed the color encoded density levels on a color television screen. The study indicated that a color density slicing system has great potential not only for

identifying and mapping soil limitations, but also for indicating the percentage composition of an area.

Color infrared photographs were used in mapping different salinity levels in the Oahe irrigation project in South Dakota (Myers et al., 1966). The variations in tone made it possible to group the soils of the area into different salinity levels. Everitt et al. (1981) have used microdensitometry on 70 mm color-infrared (CIR) aerial film to distinguish saline from nonsaline sites on a rangeland in Starr County, Texas. Film density readings were made on CIR film with microdensitometer equipped with an automatic scanning attachment. Density readings were made with four different light sources: white (no filter), red (Wratten 92 filter), green (Wratten 93 filter), and blue (Wratten 94 filter). This study concluded that the microdensitometric readings on CIR aerial film could be used successfully to separate saline from nonsaline range sites, mainly based on differences in plant cover. Other researchers have evaluated color infrared photography and thermal infrared imagery for detecting saline seeps at different stages: (1) emergent or incipient; (2) intermediate, indicated by salt tolerant vegetation; (3) mature, wet saline with bare salt crust (Dalsted and Worcester, 1979). The study indicated that color infrared photography was helpful in identifying stages two and three. Thermal imagery appeared to have potential for locating incipient seeps (stage one).

Skylab Satellite imagery at scale of 1:3,000,000 was used to test the feasibility of distinguishing between saline and non-saline rangelands (Everitt et al., 1977). The saline and non-saline rangelands

could be differentiated by using microdensitometry on black and white Skylab imagery.

The launch of a series of Earth Resources Technology Satellites (ERTS)¹, opened a new era in space technology for application possibilities of remote sensing in soil mapping in the 1970's. Landsat satellites were placed in a circular near-polar, sun-synchronous orbit. They are equipped with multispectral scanner sensor systems (MSS) which measure reflectance characteristics of earth surface features in both visible and infrared region of the electromagnetic spectrum, Figs. 1, 2 and 3 (Lillesand and Kiefer, 1979; Paine, 1981; NASA, 1979).

Landsat MSS data have been evaluated in a study conducted in India, for delineation and mapping of agricultural soil limitations and hazards including salinity and alkalinity (Venkataratnam, 1980). Two degrees of soil salinity and alkalinity were separated in addition to normal soils. The study also concluded that the Landsat MSS data could be used for delineating various levels of soil limitations and hazards. Venkataratnam (1983) conducted another study in Indo-Gangetic Plains of northwestern India, for monitoring changes in soil salinity and alkalinity levels. Multidate Landsat MSS data were used. Landsat MSS data were collected at different dates and seasons while reclamation efforts were vigorously employed. The data were analyzed on computer-aided Bendix MDAS (Multispectral Data Analysis System). The Landsat MSS data could

¹As of January 1975, NASA officially renamed the ERTS program the "Landsat Program" to distinguish it from the planned Seasat Oceanographic Satellite Program (Lillesand and Kiefer, 1979).

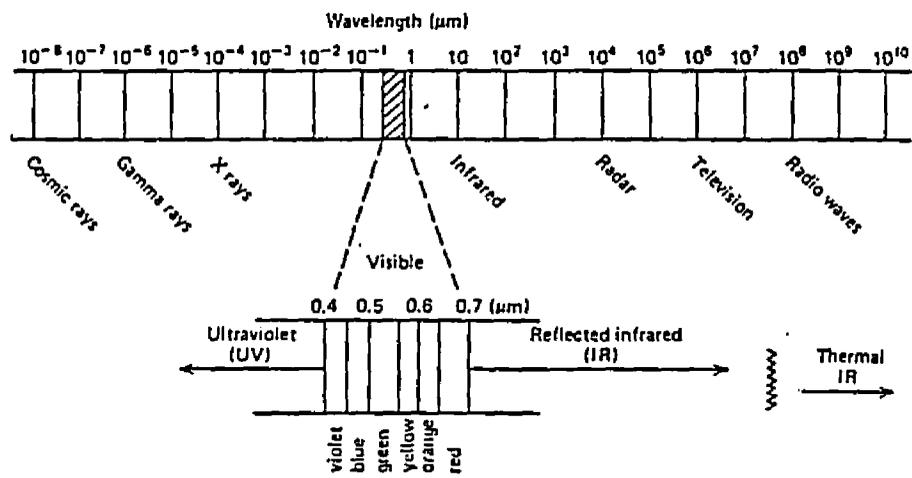


Fig. 1. The Electromagnetic Spectrum.

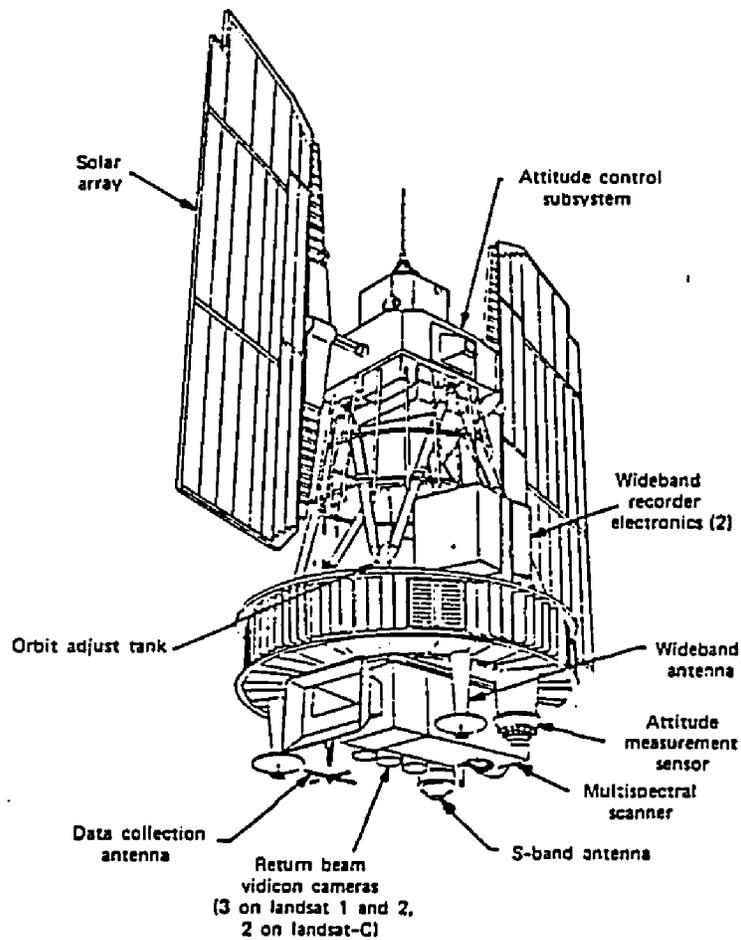


Fig. 2. Landsat Satellite.

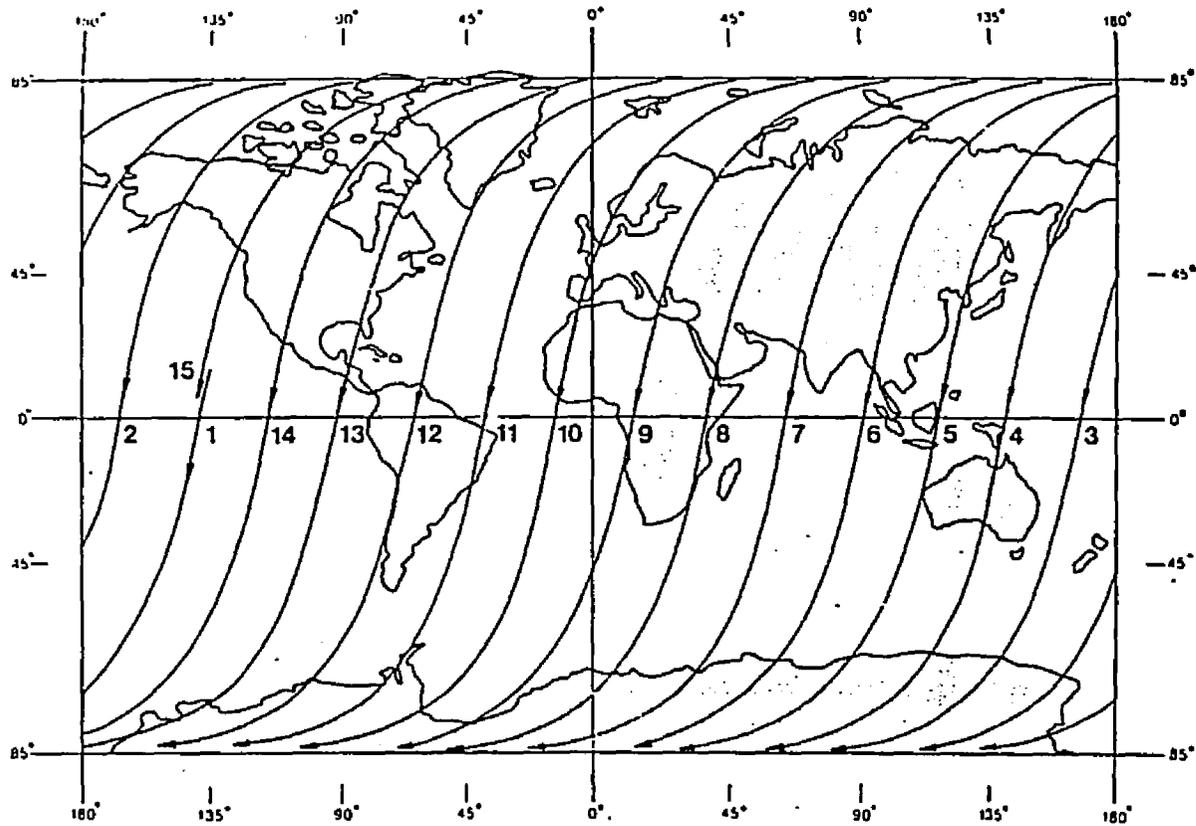


Fig. 3. Typical Landsat Daily Orbit Pattern (Daylight passes only).

monitor changes in the soil salinity and alkalinity levels even in small areas when accompanied by sufficient ground data.

Moisture Content

Surface moisture content has a distinct influence on reflection and/or emission of electromagnetic energy and hence increases or decreases soil reflectance.

In a series of field and laboratory experiments, the influence of soil moisture content and aggregation on reflectivity was studied in the visible part of the spectrum from 0.4 to 0.75 micrometer (Obukhov and Orlov, 1964; Silva et al., 1971). The dry soil samples reflected more of the incident radiation than did the corresponding wet soil samples. The authors also concluded that reflectivity increases with wavelength and the greatest difference was observed in the red band of the spectrum. The red region of the spectrum is superior because the total amount of energy absorbed by the soils of various natural zones is not determined by reflectivity alone, but also by the intensity of solar radiation and the spectral composition of this radiation that reaches the soil surface, whose maximum shifts toward the yellow region of the spectrum as the height of the sun above the horizon increases. This fact correspondingly changes the actual spectral composition of reflected light (Obukhov and Orlov, 1964).

In a laboratory experiment, spectroradiometric measurements were made in the visible and infrared regions of the spectrum from 0.52 to 2.32 micrometer to determine the effects of soil parameters, including moisture, on the reflectance properties of soils (Stoner et al., 1980).

Reflectance measurements were taken over 251 soils, representing a wide range of soil-forming conditions. Increased soil moisture content decreased soil reflectance at all wavelengths. Strong water absorption bands at 1.45 and 1.95 micrometer were present in all of the spectral curves. The authors also concluded that the actual soil moisture content was most highly correlated with soil reflectance in the 2.08 to 2.32 um region of the spectrum.

Bowers and Smith (1972) noticed a linear relation between absorbance at 1.94 um and percentage of soil moisture ranging from air dry to the moisture equivalent. Conventional color aerial imagery, through ratio analysis of image photometric information, were evaluated to extract information on relative soil moisture and texture patterns (Piech and Walker, 1974). The ratios between the reflectance of a soil element in the red and blue spectral bands can discriminate and delineate soil moisture and texture variations.

Cipra et al. (1971) evaluated reflectance measurements from samples of seven Indiana soil series in a spectral range from 0.43 to 0.73 micrometers. Dry soil samples reflected more of the incident energy than did the corresponding wet soil samples.

Other researchers have estimated soil moisture remotely using the 0.4 to 14.0 um (visible, near infrared and thermal infrared) wavelength region of the spectrum (Blanchard et al., 1974). The spectral reflectance measurements, in the visible and near infrared regions, revealed that reflectance decreases as soil moisture increases for the wavelengths from 0.4 to 1.3 um of the spectrum. It also showed that

reflectance differences were greater in the near-infrared region of the spectrum than in the visible part and became more pronounced at the 1.4 and 1.9 μm water absorption bands. In the same study, the soil temperature measurements, in the thermal infrared region, showed that differences between daytime and nighttime soil temperatures decrease as moisture content increases for a given soil. Angstrom (1925) explained the low reflectance (darkening) effect of moisture in soils on the basis of internal total reflections within the thin water film covering the soil surface.

Organic Matter

Under virgin conditions, the organic matter content of arid and semi-arid regions is usually low. Organic matter additions tend to counteract the unfavorable effects of exchangeable sodium on soils (U.S. Salinity Lab., 1954). Many investigators reported that peat and muck soils with appreciable amounts of exchangeable sodium have good physical properties (Campbell and Richards, 1950). The organic matter content and the composition of the organic constituents also affect the soil reflectance properties. Many workers have found that soil reflectance decreases as organic matter content increases in the spectral range from 0.4 to 2.6 μm (Baumgardner et al., 1970).

Baumgardner et al. (1970), using digital analysis for processing airborne optical-mechanical scanner data, were able to delineate five different levels of organic matter content for approximately 200 surface soil samples which contained from 1.5 to 7% organic matter. The same study also showed that organic matter content played a major role in

bestowing spectral properties on soils when the organic matter exceeded 2.0% level. The authors also found that as the organic matter dropped below the 2.0% level, it became less effective in masking out the effects on spectral response of other soil constituents such as iron or manganese.

Other studies have indicated that organic constituents such as humic and fulvic acids showed a strong influence on reflectivity and color of soils in the visible part (0.4 - 0.75 μm) of the spectrum (Obukhov and Orlov, 1964). Fulvic acids differ from humic acids in that they have higher reflection coefficients in the green and red bands of the spectrum (Obukhov and Orlov, 1964). The authors also found that a drop in the humic acids content to 0.2% leads to a sharp decrease in light absorption and to an increase in soil reflectivity, which approaches the reflectivity of the soil-forming material.

Obukhov and Orlov (1964) concluded that there is the possibility of quantitative determination of humus content in soils from reflection spectra. Other researchers have reported that the oxidation of soil organic matter with hydrogen peroxide (H_2O_2) resulted in an increase in soil reflectance in the wavelength range from 0.4 to 2.4 micrometer of the spectrum (Bowers and Hanks, 1965).

METHODS AND MATERIALS

Two experiments were conducted, to examine the spectral response of salt-affected soil, during the summer of 1985 and the spring of 1986 at the University of Arizona Campus Agricultural Center, Tucson, Arizona (32° 17' N, 110° 57' W) to test the effects of soluble salts on soil reflectance.

Soil Characteristics

The soil selected for this study is Gila fine sandy loam. Gila soils are coarse-loamy, mixed (calcareous), thermic typic Torrifuvent. These soils are entisols formed from water-deposited sediments on flood plains and alluvial fans. This soil series consists of nearly level to gently sloping soils (0-3% slope), mostly brownish, loamy to sandy loam soils, deep, well drained, high water-holding capacity, moderately permeable to water and penetrable by roots to more than 1.5 meters. Elevation reaches more than 935 m, and the annual rainfall is 23-31 cm (USDA, 1972). Some physical and chemical properties of the 0 to 30 layer of this soil are shown in Table 1.

The 1985 Experiment

Data Acquisition

A preliminary study, to test the spectral reflectance curves of salt-affected soil, was conducted by mixing the Gila soil with five

Table 1. Some Physical and Chemical Properties of the 0 to 30 cm Layer of the Soil Used in Study.

Soil Series	:	Gila
Textural Class	:	Fine sandy loam
Particle Size Distribution	:	Gravel (% of total weight) 5.0 Sand (% of total weight) 51.9 Silt (% of total weight) 35 Clay (% of total weight) 8.1
Bulk Density g cm ⁻³	:	1.19
Organic Matter %	:	1.5
Extractable Iron %	:	0.5
Calcium Carbonate %	:	6.0
Available Water mm/m	:	111
Munsell Color	:	10YR 6/3 Dry 10YR 4/3 Wet

different salts: (1) calcium carbonate (CaCO_3); (2) sodium bicarbonate (NaHCO_3); (3) sodium sulfate (Na_2SO_4); (4) calcium chloride (CaCl_2); and (5) sodium chloride (NaCl). Three salts (NaHCO_3 , Na_2SO_4 and CaCO_3), which showed the most variations in spectral response, will be discussed in the text. The complete set of data of the other two salts (NaCl and CaCl_2) are found in the Appendix.

The soil was passed through a 2 mm sieve. Salt treatments were prepared at three concentrations (0.5, 1.5 and 3.0% by weight). The salts were added individually and mixed thoroughly with 7 kg of soil using an electrical V-shaped soil mixer. Non-treated soil treatment "control" was used for comparison.

The soil-salt mixtures were placed inside 40 cm x 40 cm x 3 cm black wooden boxes. The soil surface was leveled by striking off the excess soil with a straight edge. Two boxes were used for each treatment (one for reflectance measurements and the second one for sampling), and all boxes were set on a support frame.

Reflectance Measurements

A portable Exotech Model 100 AX radiometer was used to measure reflected solar radiation simultaneously in four wavebands. The Exotech radiometer has a 15° field of view (FOV) with bandpass intervals that match the thematic mapper (TM) bands 1 through 4 (0.45-0.52, 0.52-0.60, 0.63-0.69, and ,0.76-0.90 μm).

The radiometer was hand-held during all measurements to obtain an air view from a height of 50 cm above the target surface, which

corresponds to a circular area of about 13 cm in diameter at 50 cm elevation.

Spectral response was measured over all treatments under air dry, wet (after adding 170 ml of deionized water) and dry (24-hr after wetting, natural air-drying) moisture conditions. Spectral measurements under wet conditions were taken a few seconds (to avoid specular reflection) after spraying the upper centimeter of the surface with a hand sprinkler using deionized water. All treatments then were allowed to dry in the air (dry condition) for 24 hr before another series of spectral measurements were made.

Four readings were taken per treatment. Readings from a standard, barium sulfate-coated reference plate were obtained before and after short periods of time of the target (treatment) readings. Measurements were taken during sunny, cloud-free days between 9:00 and 11:30 A.M. The reflectance was then calculated by dividing the average of four target radiance measurements to the plate radiance, both corrected for dark-level instrument offset, and multiplied by the plate reflectance factor corrected for sun angle.

Soil samples were collected for laboratory analysis. A 1:1 soil:water ratio was prepared, and electrical conductivity (EC:dS/m) at 25°C and soluble cations (Na, K, Ca and Mg) were measured on all soil samples using the conductivity bridge and the atomic absorption spectrometry, respectively.

The 1986 Experiment

The spectral reflectance of sodium sulfate (Na_2SO_4) and sodium bicarbonate (NaHCO_3) in soil were examined individually and in combination at 3.0 and 6.0% by weight. Gila fine sandy loam soil was again used at the same three moisture conditions: (1) air dry; (2) wet (170 ml of deionized water added); and (3) dry (24 hr after wetting, natural air drying).

The experimental procedure for data acquisition and reflectance measurements described for the 1985 experiment was exactly followed for this experiment.

RESULTS AND DISCUSSION

The 1985 Experiment

Spectral curves are the most common method of displaying variations in the spectral response of soils. They are simply plots of percent reflectance vs. wavelength in micrometers or nanometers.

Figures 4, 5 and 6 show the spectral response of the Gila soil at all three salt treatments at each concentration level (0.5, 1.5 and 3.0%) as compared to the control (untreated soil treatment), under air dry moisture condition. All soil treatments showed high spectral reflectance values. It can be seen that it is difficult to quantify the effect of different salts on the spectral response of soil surface. The spectral distribution of radiant energy reflected by all soil treatments behaved similarly except for the sodium sulfate treatment. The variation in the spectral reflectance behavior of the sodium sulfate is observed only at the red region (TM3) of the electromagnetic spectrum. At 0.5% salt concentration, Fig. 4, the soil Na_2SO_4 mixed had the lowest reflectance value at the TM3 band. The trend was more pronounced at the 1.5 and 3.0% concentrations, Figs. 5 and 6. This variability is suspected to be due, at least in part, to the arrangement of salt particles at the soil surface.

The spectral response curves of the four soil treatments (3 salt treatments and control) at the wet moisture condition are shown in

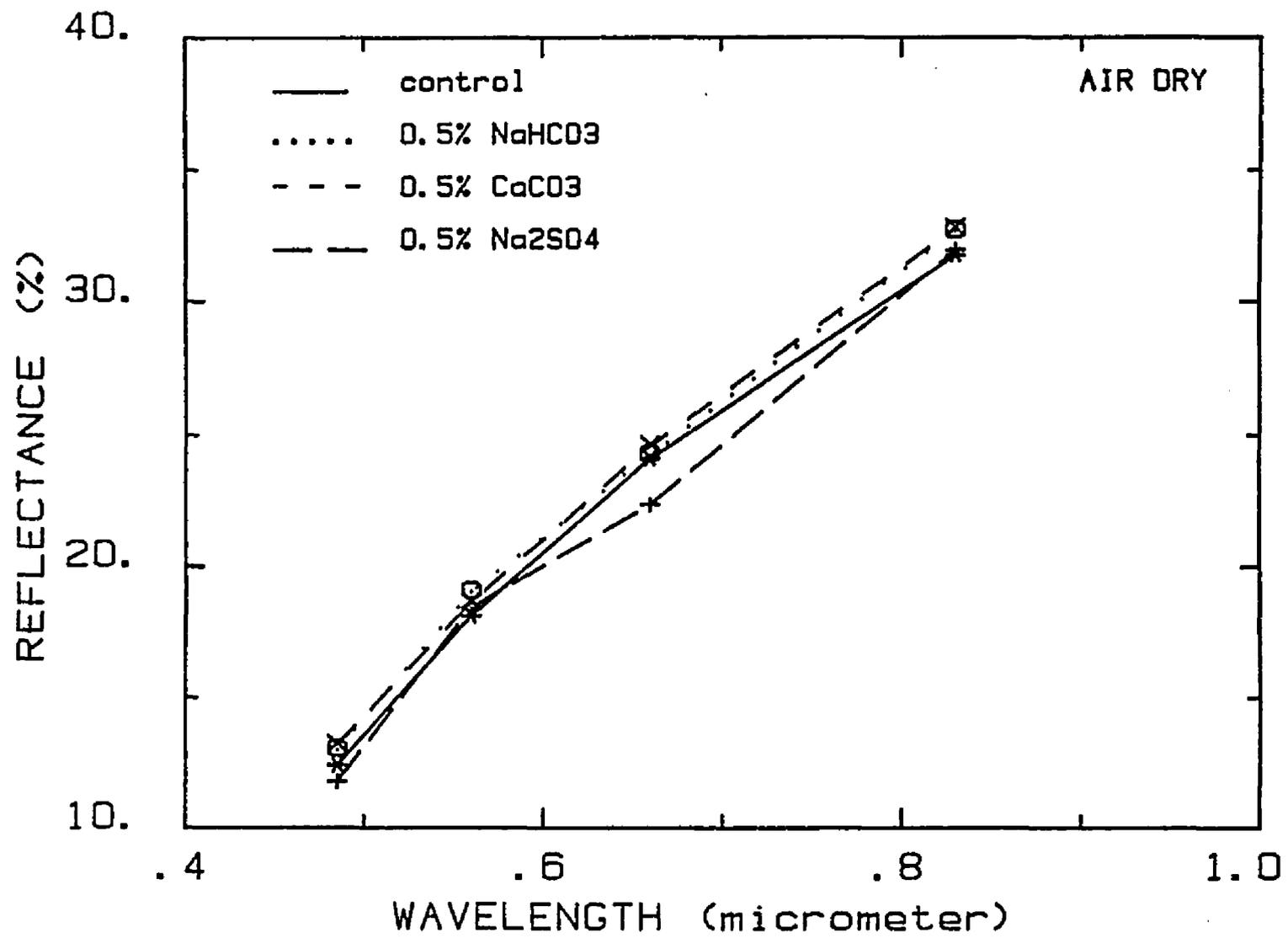


Fig. 4. Spectral Curve at Air Dry Moisture Condition.

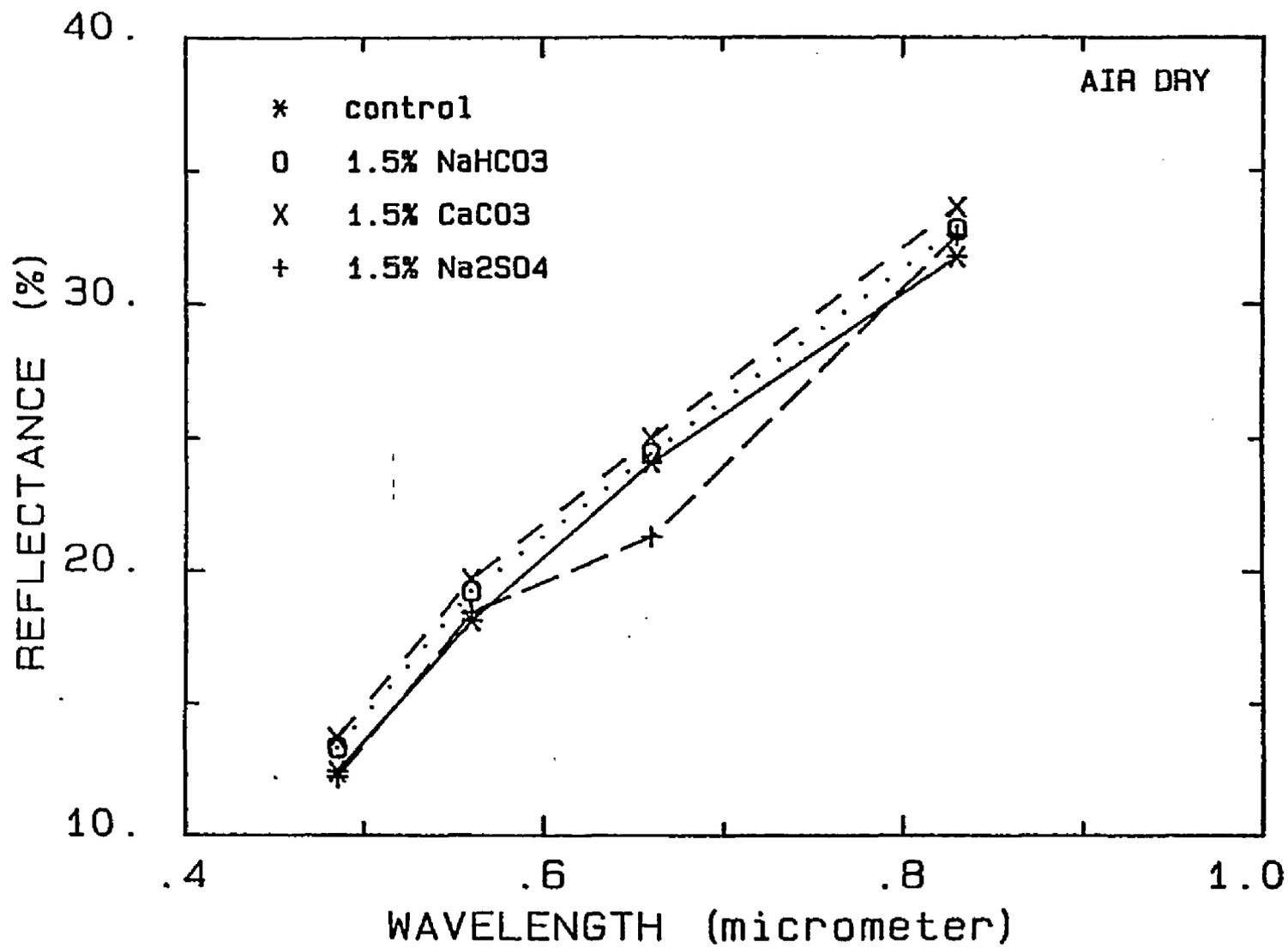


Fig. 5. Spectral Curve at Air Dry Moisture Condition.

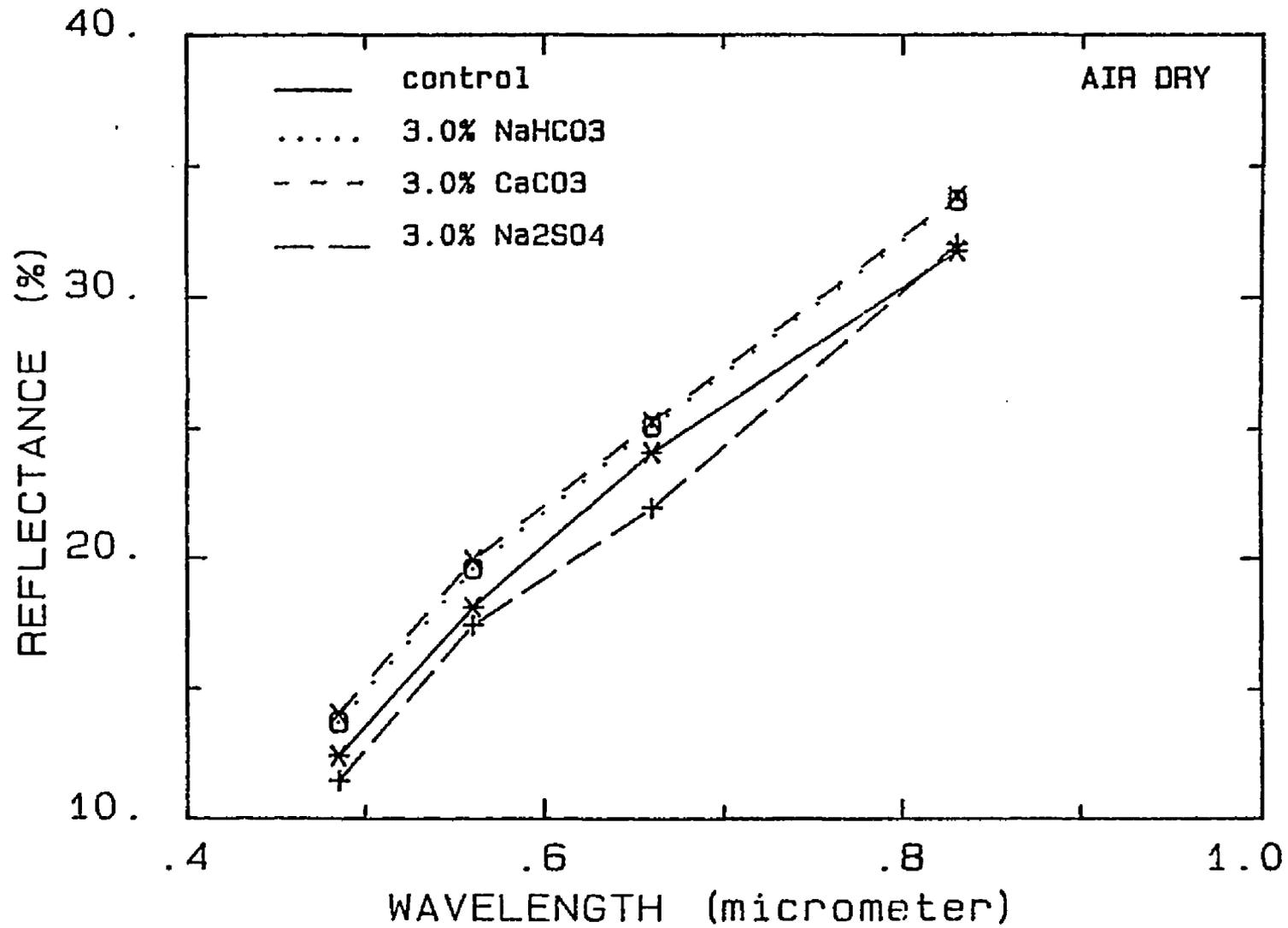


Fig. 6. Spectral Curve at Air Dry Moisture Condition.

Figs. 7, 8 and 9. These curves show that wetting strongly decreased the spectral reflectance values of the soil at all salt concentrations (0.5, 1.5 and 3.0%) in the entire visible and near-infrared (NIR) regions of the electromagnetic spectrum. Generally, soils appear darker when wet than when dry due to the internal total reflections within the thin water film covering the soil particles (Angstron, 1925).

Upon drying the salt-treated soil for 24 hours after wetting (natural air-drying), the spectral reflectance values increased, Figs. 10, 11 and 12. Spectral differentiation among the salt treatments differed spectrally from the control only at the 1.5 and 3.0% salt concentrations, Figs. 11 and 12. The variations in reflectance are due to the evaporation of water from the soil surface, hence the upward capillary movement transports dissolved salts and organic matter from the soil solution to the surface.

Figure 11 at 1.5% salt shows variations in spectral reflectance among soil treatments. In comparison to the control treatment, the accumulation of organic matter on the surface of the NaHCO_3 treatment has the strongest influence on soil reflectance and color. This determines the darkness of the color and hence, had the lowest reflectance values. On the other hand, the CaCO_3 treatment showed the highest reflectance values due to the formation of a white crust on the soil surface. The sodium sulfate treatment showed lower reflectance values than that of the control.

Upon increasing the salt concentrations from 1.5 to 3.0%, Fig. 12, the reflectance values changed slightly. A comparison with the

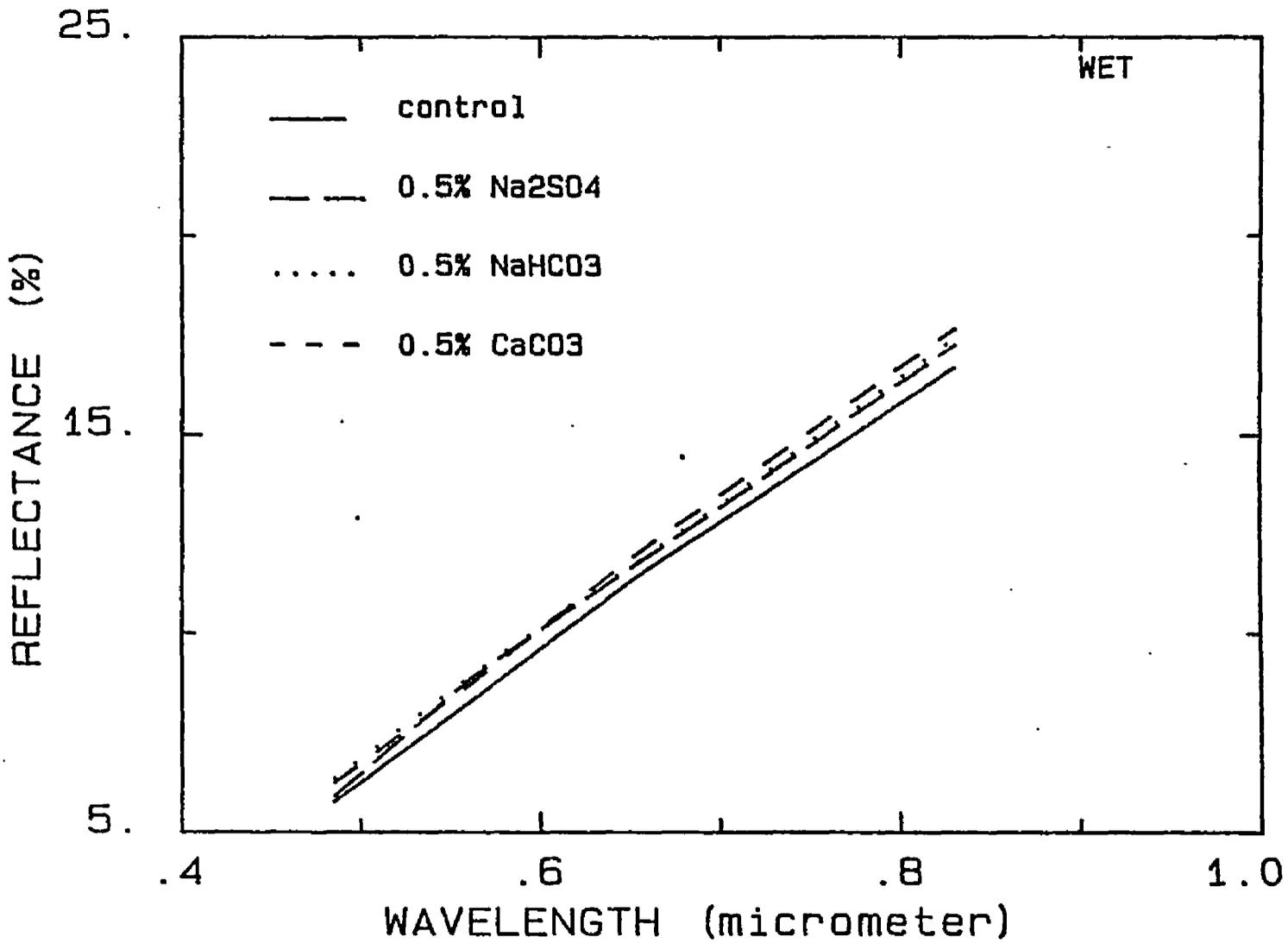


Fig. 7. Spectral Curve at Wet Moisture Condition.

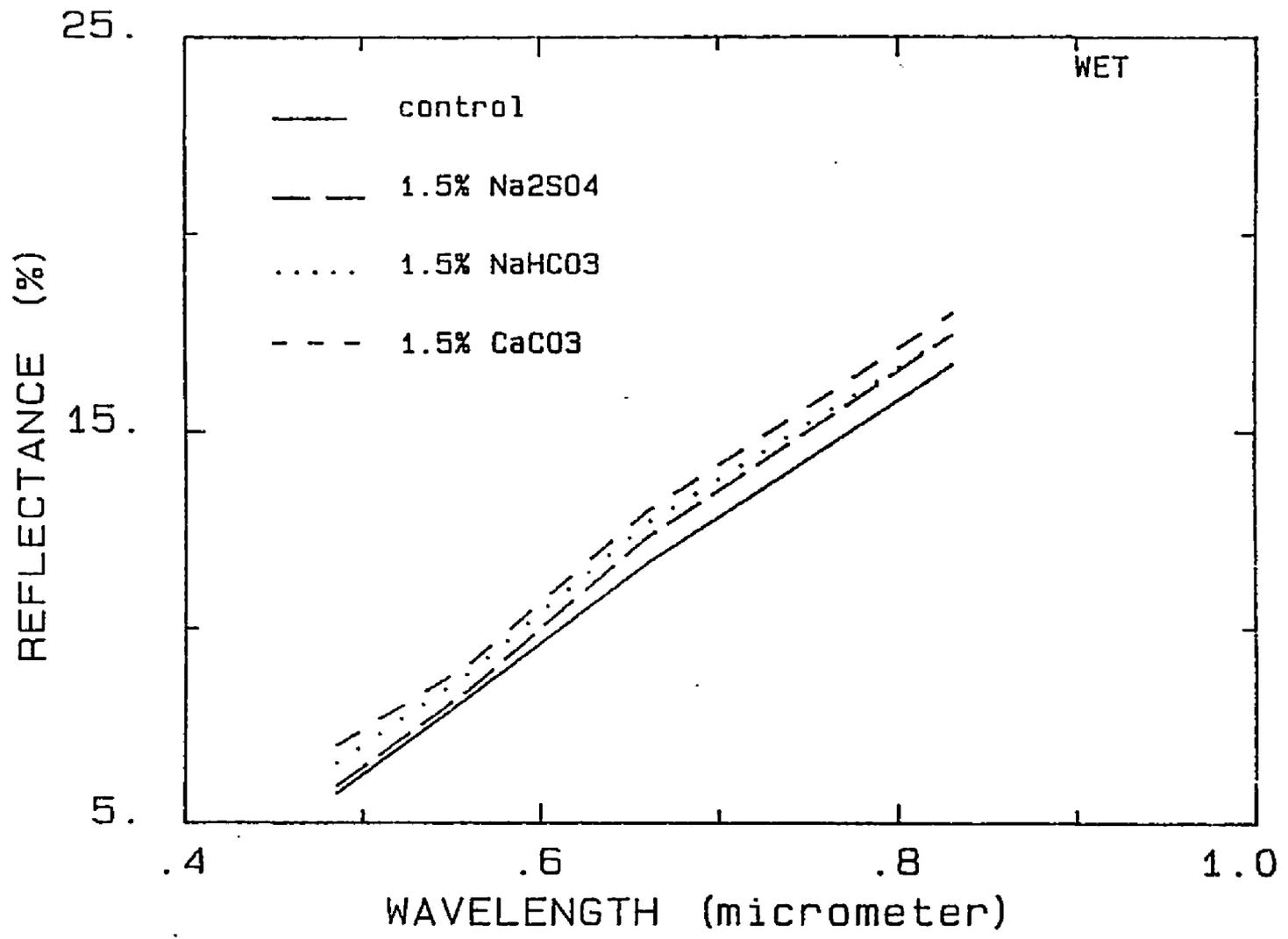


Fig. 8. Spectral Curve at Wet Moisture Condition.

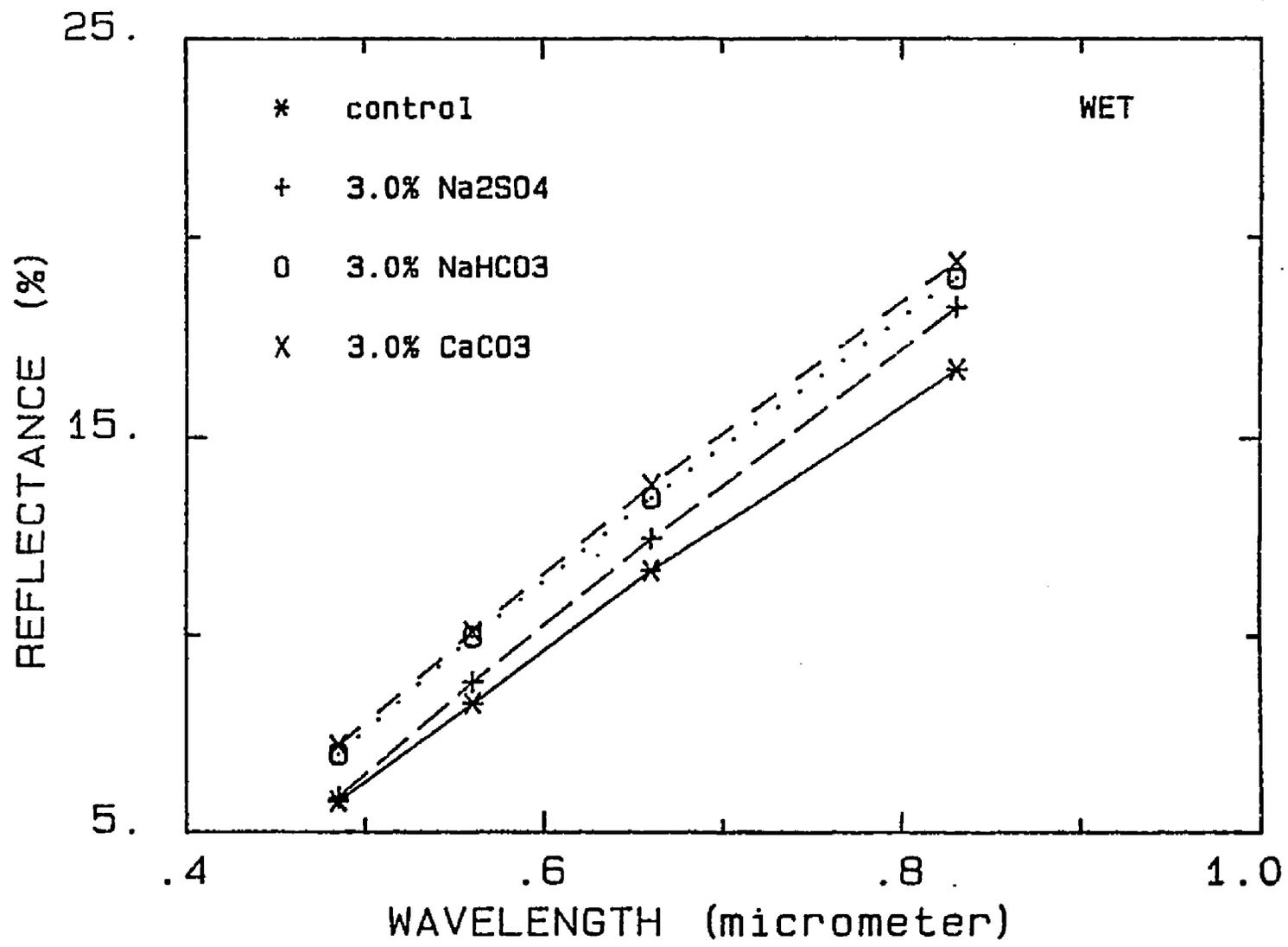


Fig. 9. Spectral Curve at Wet Moisture Condition.

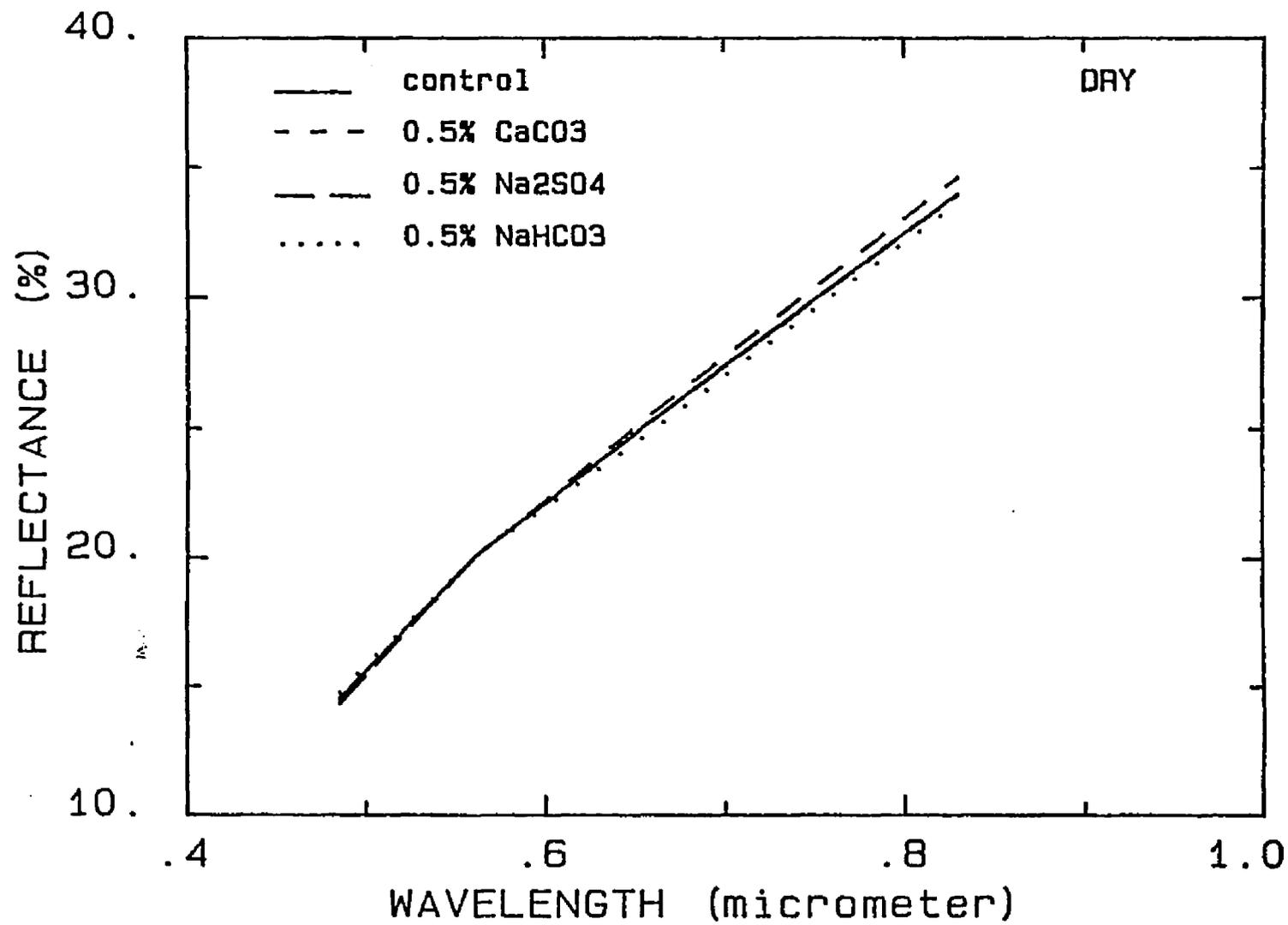


Fig. 10. Spectral Curve at Dry Moisture Condition (24-hr after wetting).

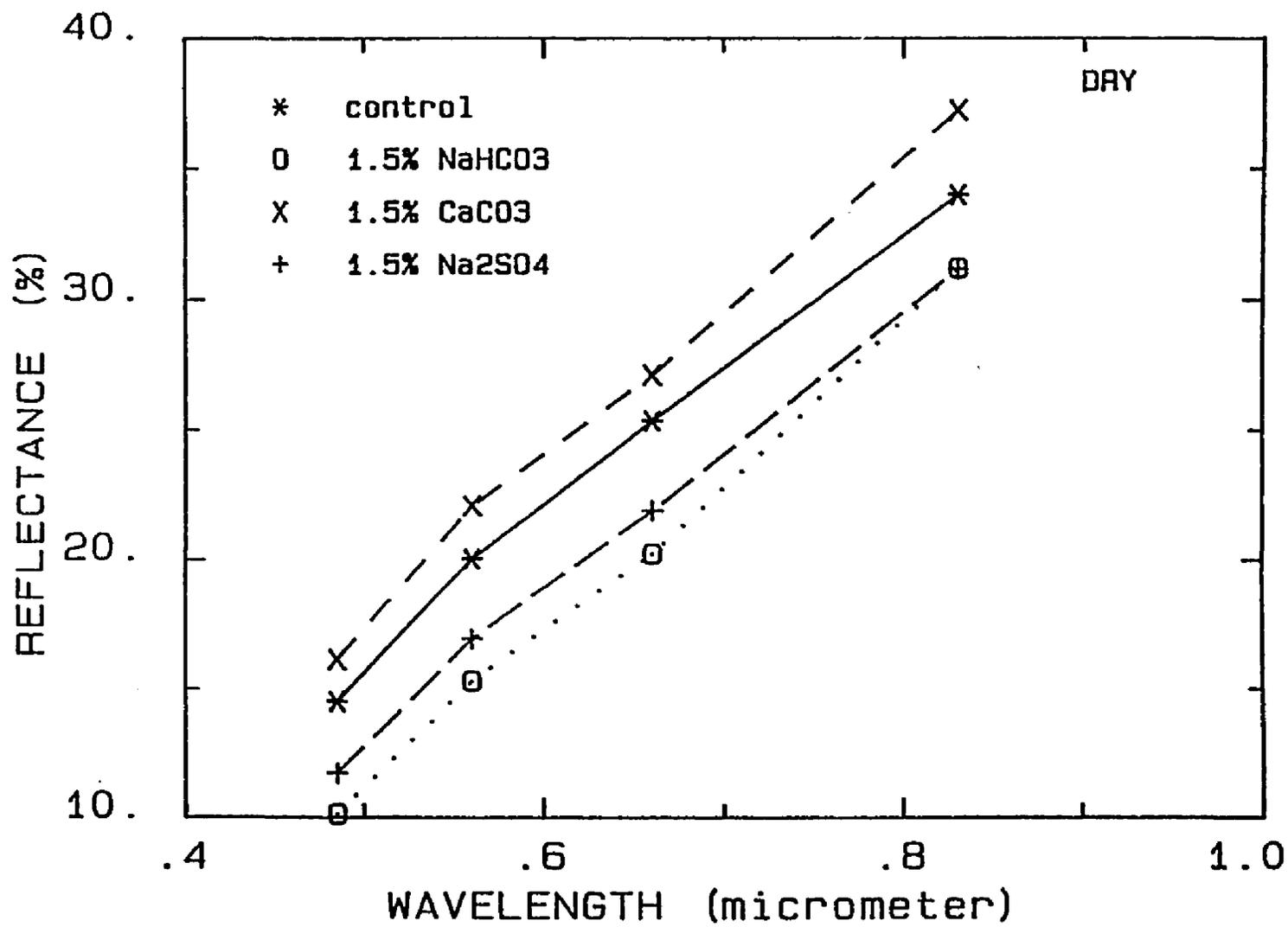


Fig. 11. Spectral Curve at Dry Moisture Condition (24-hr after wetting).

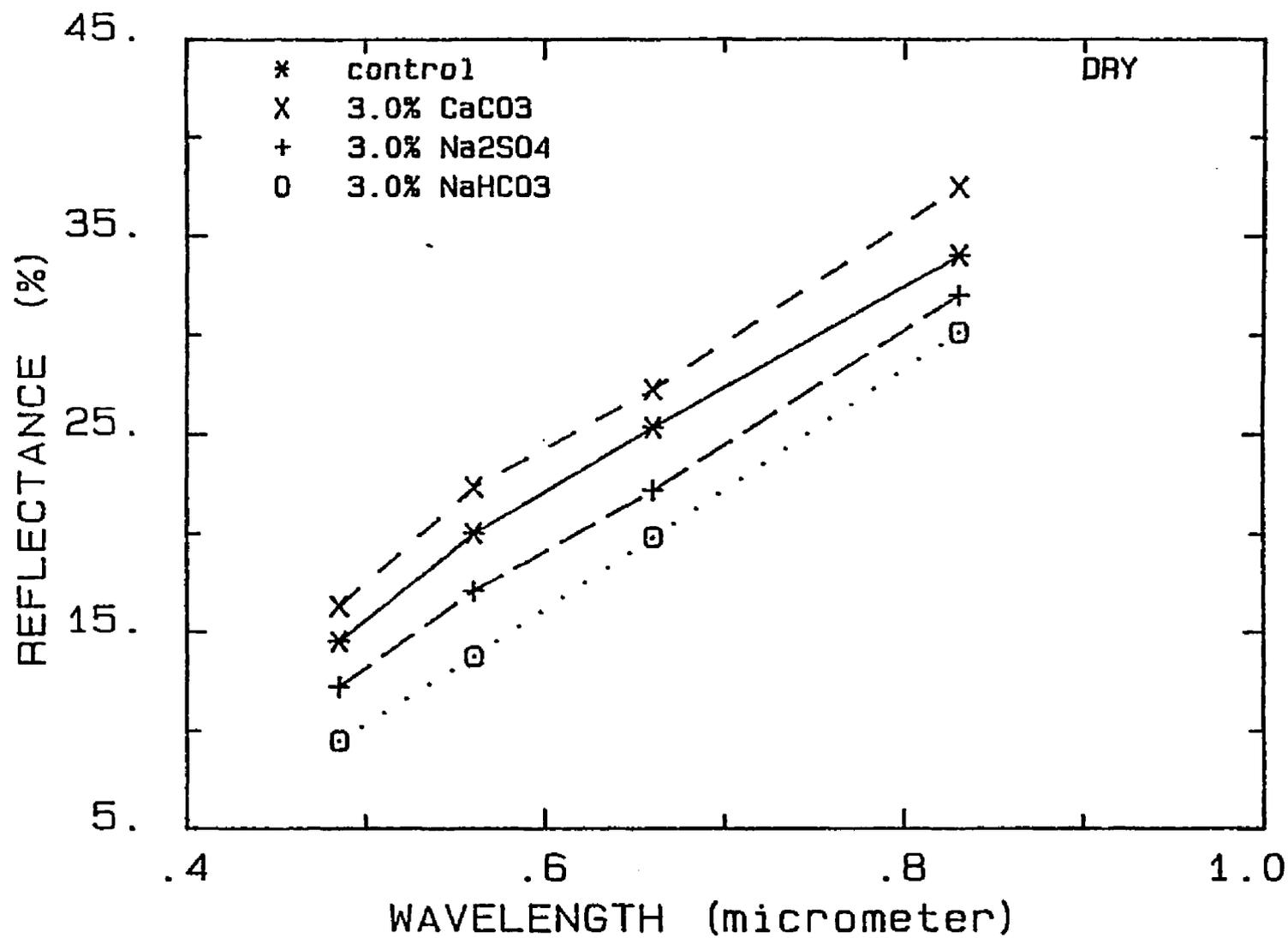


Fig. 12. Spectral Curve at Dry Moisture Condition (24-hr after wetting).

reflectance values obtained from the 1.5% concentration, the Na_2SO_4 showed a slight increase in reflectance while the NaHCO_3 showed a slight decrease in the reflectance values. The spectral response of the CaCO_3 treatment remained almost constant which suggests that excess concentration has no effect on the reflectance. Thin cracks occurred in all treatments as a result of the soil shrinkage upon drying.

The major reason behind these variations in spectral response is the attraction of atmospheric moisture by salts. At mid-day, the high evaporation rates characteristic of arid and semi-arid climates increases the upward capillary movement which tends to concentrate the salts at soil surface. During the night when the evaporation rate is lower and humidity is higher, the salts attract atmospheric moisture. Both the ion charge and the ionic radius determine the strength of such interaction; the higher the charge and the smaller the ionic radius, the greater the interaction of the ions with the dipole H_2O molecule.

For the sake of further relationships, another approach to the evaluation of spectral differentiation was investigated. The chemical analysis of the soil samples, Table 2, indicated some important properties which influenced, directly and indirectly, the spectral response of the soil surface. These relationships were: (1) the sodium cation (Na^+) has a great influence on electrical conductivity (EC); (2) generally, the electrical conductivity (EC) has a clear influence on the reflectance; (3) at a given electrical conductivity (EC) value the sodium sulfate shows higher reflectance value than that of the sodium bicarbonate; and (4) reflectance was linearly related to (a) sodium adsorption ratio

Table 2. Chemical Analysis of Soil Samples.

Sample	EC ds/m	Ca	Mg	Na	K
		-----meq/l			
Control	0.57	2.91	0.36	0.83	0.76
0.5% NaHCO ₃	1.5	6.31	1.49	10.43	0.88
1.5% NaHCO ₃	9.3	5.33	0.48	57.00	1.10
3.0% NaHCO ₃	25.0	2.81	0.61	140.00	1.67
0.5% CaCO ₃	0.55	2.65	0.34	0.75	0.95
1.5% CaCO ₃	0.52	2.44	0.27	0.71	0.71
3.0% CaCO ₃	0.45	2.55	0.35	0.73	0.77
0.5% Na ₂ SO ₄	5.5	12.38	1.30	38.13	1.73
1.5% Na ₂ SO ₄	23.0	25.45	2.17	114.30	2.33
3.0% Na ₂ SO ₄	42.0	18.06	2.39	172.61	3.08

(SAR) and (b) exchangeable sodium percentage (ESP), Figs. 13, 14 and 15, and Table 3. These relationships are in addition to the chemical-physical properties which characterized salt-affected soils.

The 1986 Experiment

As indicated earlier, no significance in the spectral response of soil-salt mixtures was found at air dry and wet moisture conditions. All soil treatments showed high reflectance values at air dry condition, Figs. 16, 17 and 18, while these values decreased strongly when the soil was wetted, Figs. 19, 20 and 21. The variation in spectral response of the NaHCO_3 treatments, Figs. 19 and 20, is thought to be due to interference of an object other than the soil surface within the viewing area of the radiometer (the radiometer off-mounted when the measurements were taken) or the arrangement or orientation of the salt particles. As would be expected, the more pronounced influence of surface soil of different salts and concentrations on reflectance is shown at the dry moisture condition (after wetting), Figs. 22, 23 and 24.

Figure 22 shows the effect of Na_2SO_4 and NaHCO_3 at 3.0% concentration level on the reflectance of surface soil. Compared to the control treatment, the sodium bicarbonate treatment showed lower reflectance while the sodium sulfate treatment indicated higher reflectance values. At the 6.0% concentration (Fig. 23), the sodium bicarbonate showed lower reflectance values than at 3.0% concentration, while the Na_2SO_4 treatment maintained high reflectance.

As indicted by the 1985 experiment, the low reflectance of the NaHCO_3 treatment, attributed to the dispersed and dissolved organic

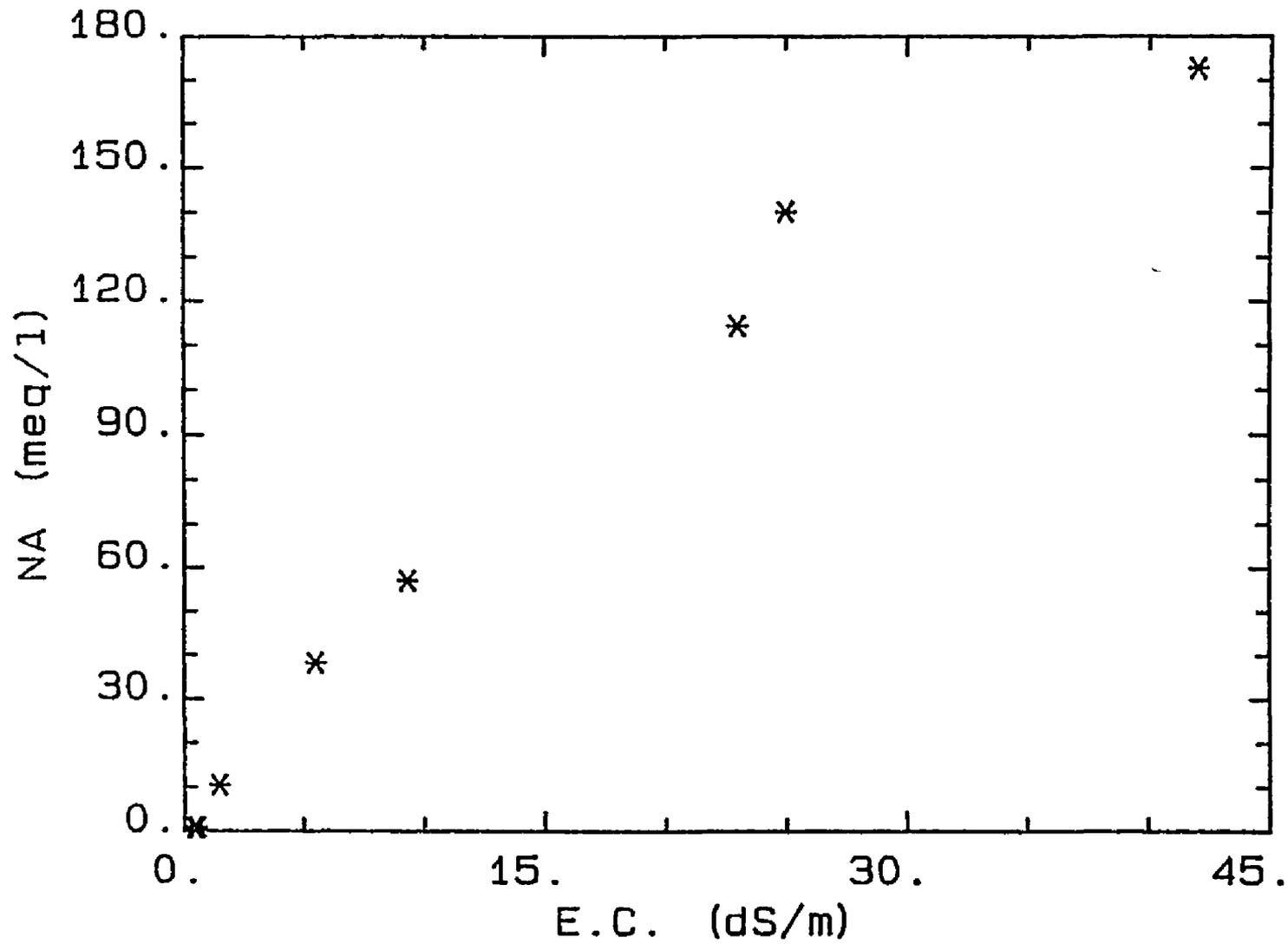


Fig. 13. Relationship Between Electrical Conductivity and Concentration of the Cation Sodium.

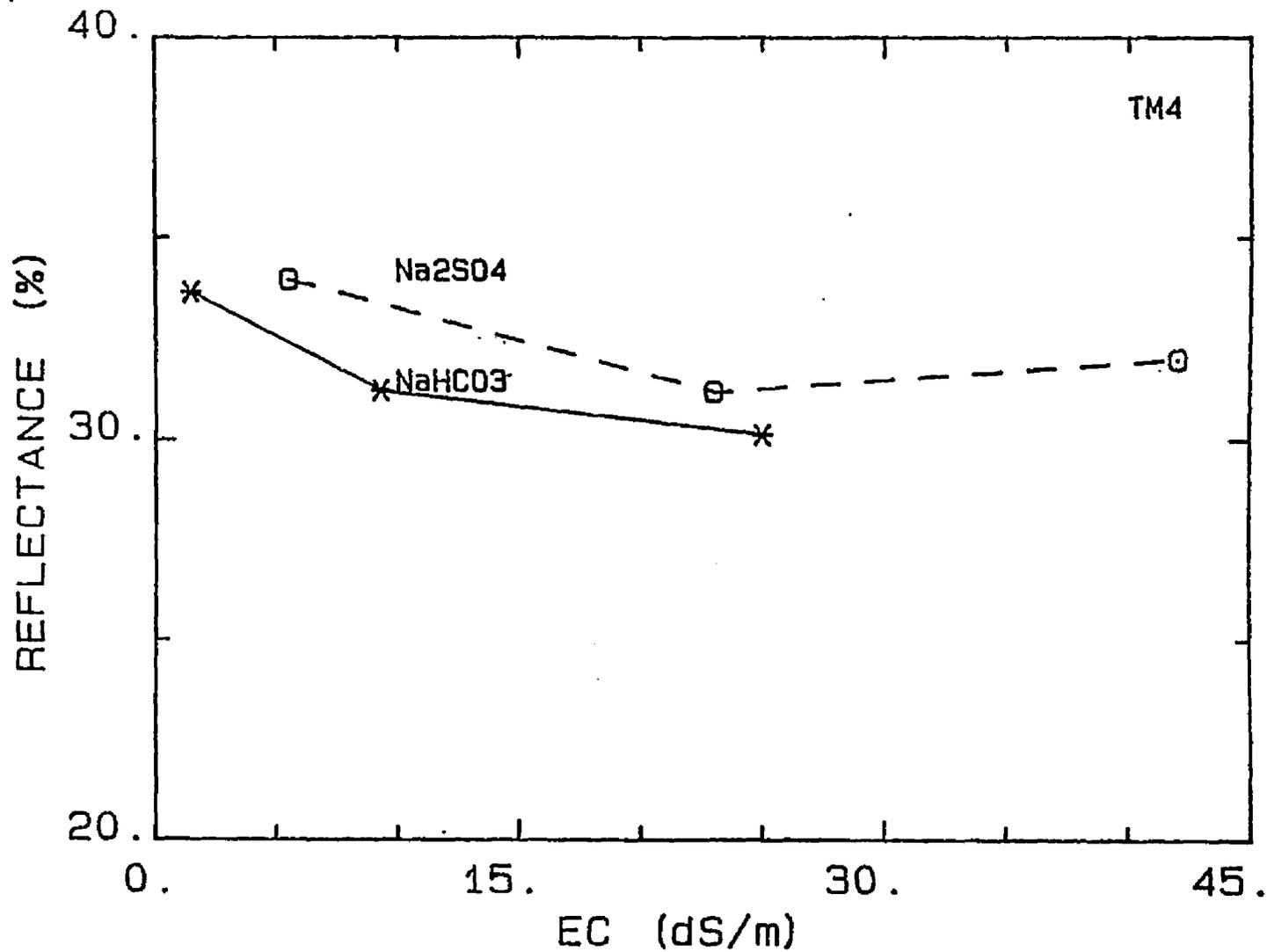


Fig. 14. Relationship Between Reflectance (from TM4) and Electrical Conductivity (EC) for the Sodium Salts.

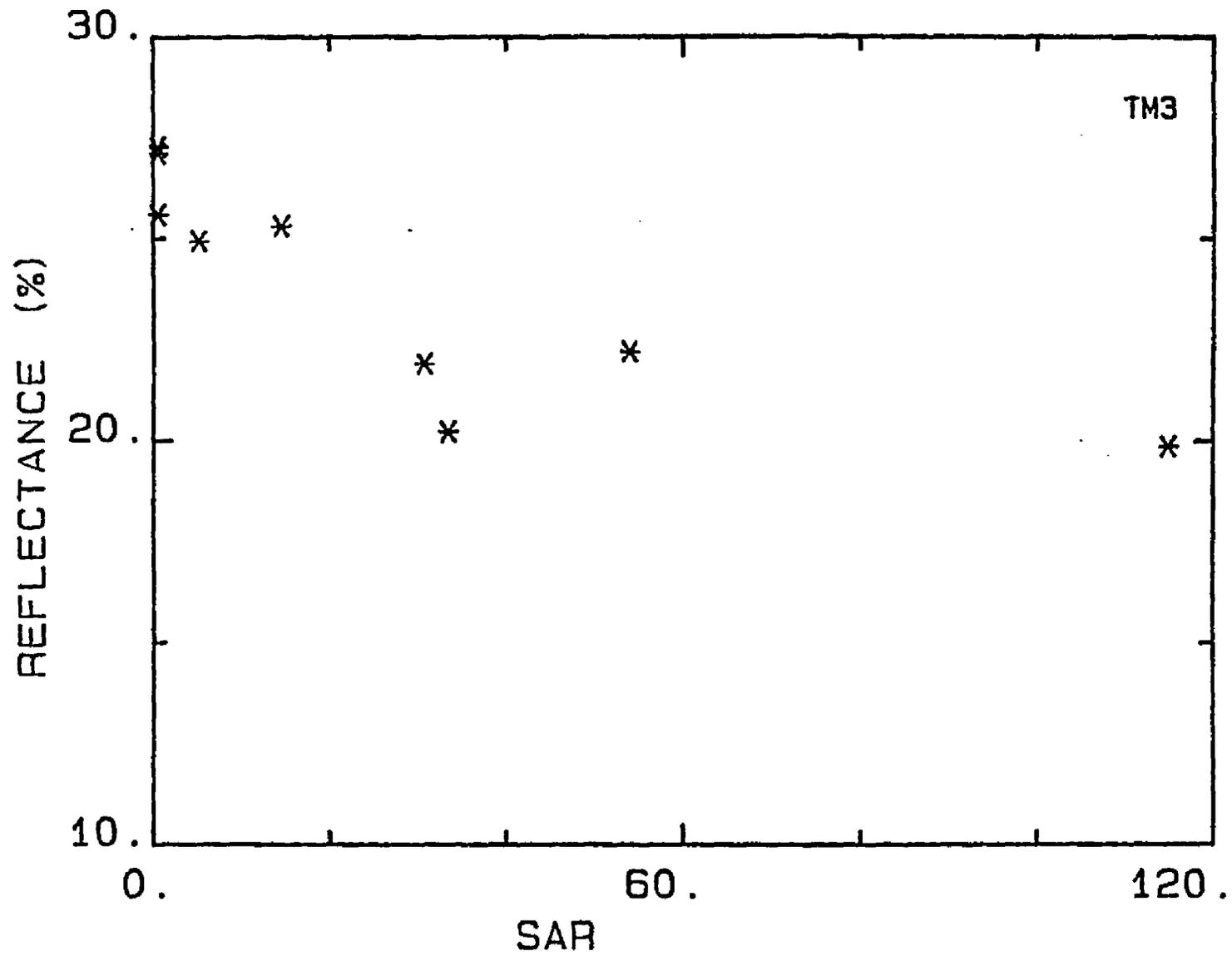


Fig. 15. Relationship Between Reflectance (from TM3) and Sodium Adsorption Ratio (SAR).

Table 3. Relationship Between Reflectance With (a) Electrical Conductivity, (b) Sodium Adsorption Ratio and (c) Exchangeable Sodium Percentage.

Salt Concentration %	Treatment	EC ds/m	SAR	ESP*	TM1	TM2	TM3	TM4
					--- Reflectance % ---			
0	Control	0.57	0.65	0	14.51	20.03	25.34	34.00
0.5	CaCO ₃	0.55	0.61	0	14.49	20.58	25.58	34.63
1.5	CaCO ₃	0.52	0.61	0	16.11	22.09	27.09	37.22
3.0	CaCO ₃	0.45	0.61	0	16.31	22.36	27.25	37.45
0.5	NaHCO ₃	1.5	5.25	6.09	14.73	20.02	24.93	33.64
1.5	NaHCO ₃	9.3	33.44	32.46	10.14	15.30	20.22	31.21
3.0	NaHCO ₃	25.0	114.89	62.71	9.48	13.75	19.85	30.13
0.5	Na ₂ SO ₄	5.5	14.53	16.79	14.31	20.01	25.30	33.95
1.5	Na ₂ SO ₄	23.0	30.76	30.61	11.72	16.92	21.90	31.18
3.0	Na ₂ SO ₄	42.0	53.98	43.93	12.20	17.01	22.20	31.98

*Negative ESP values are set to zero.

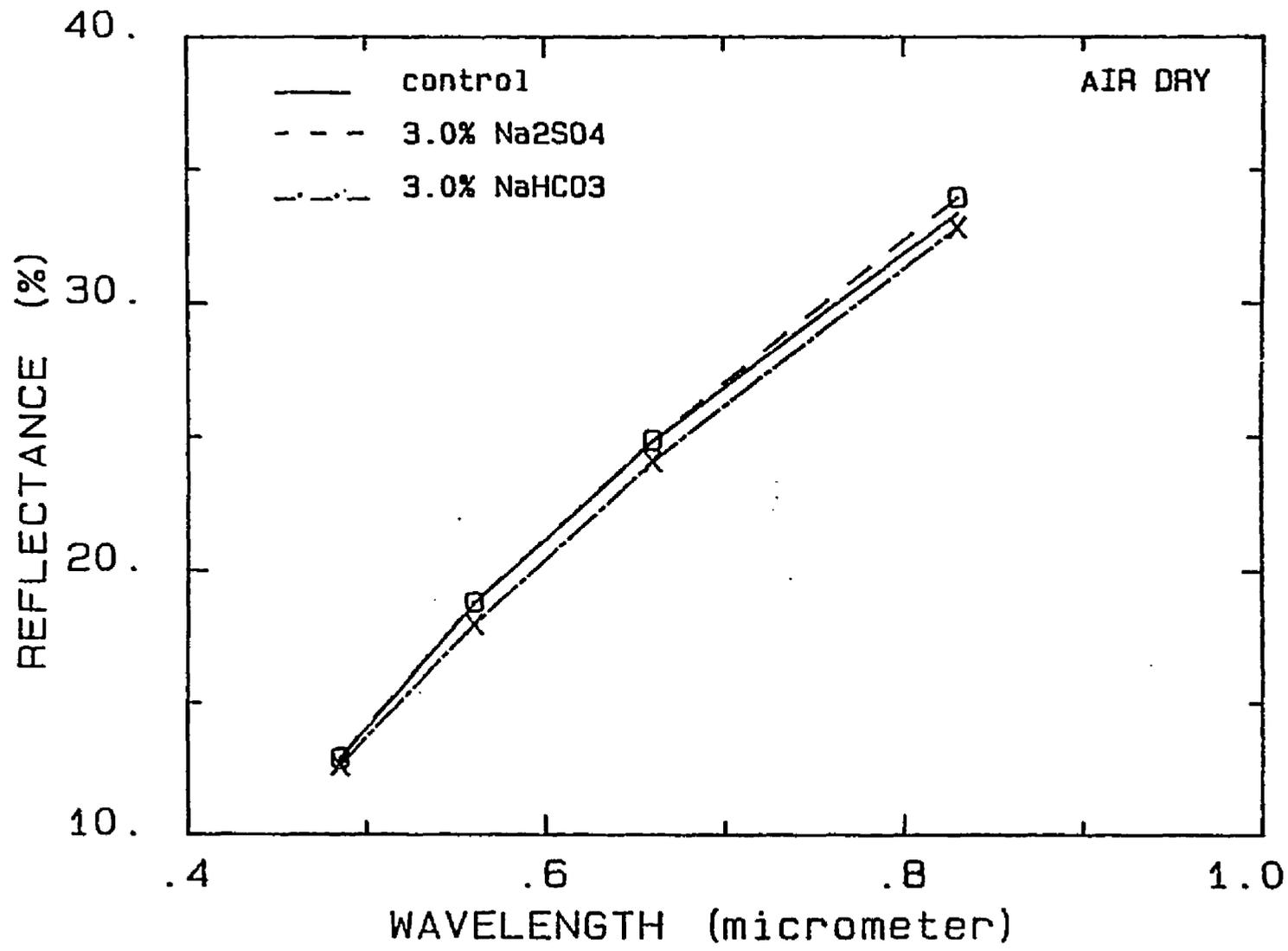


Fig. 16. Spectral Curve at Air Dry Moisture Condition.

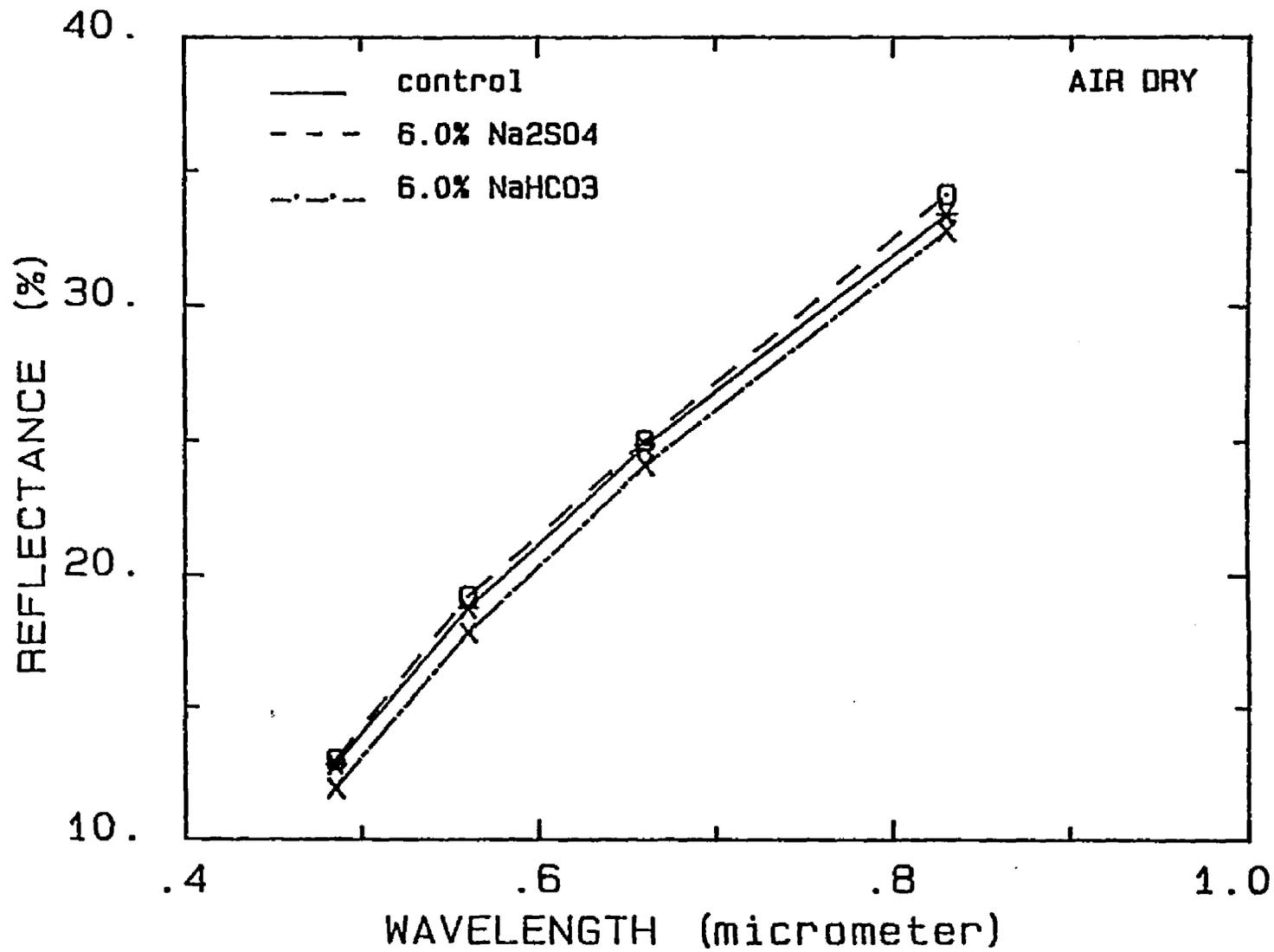


Fig. 17. Spectral Curve at Air Dry Moisture Condition.

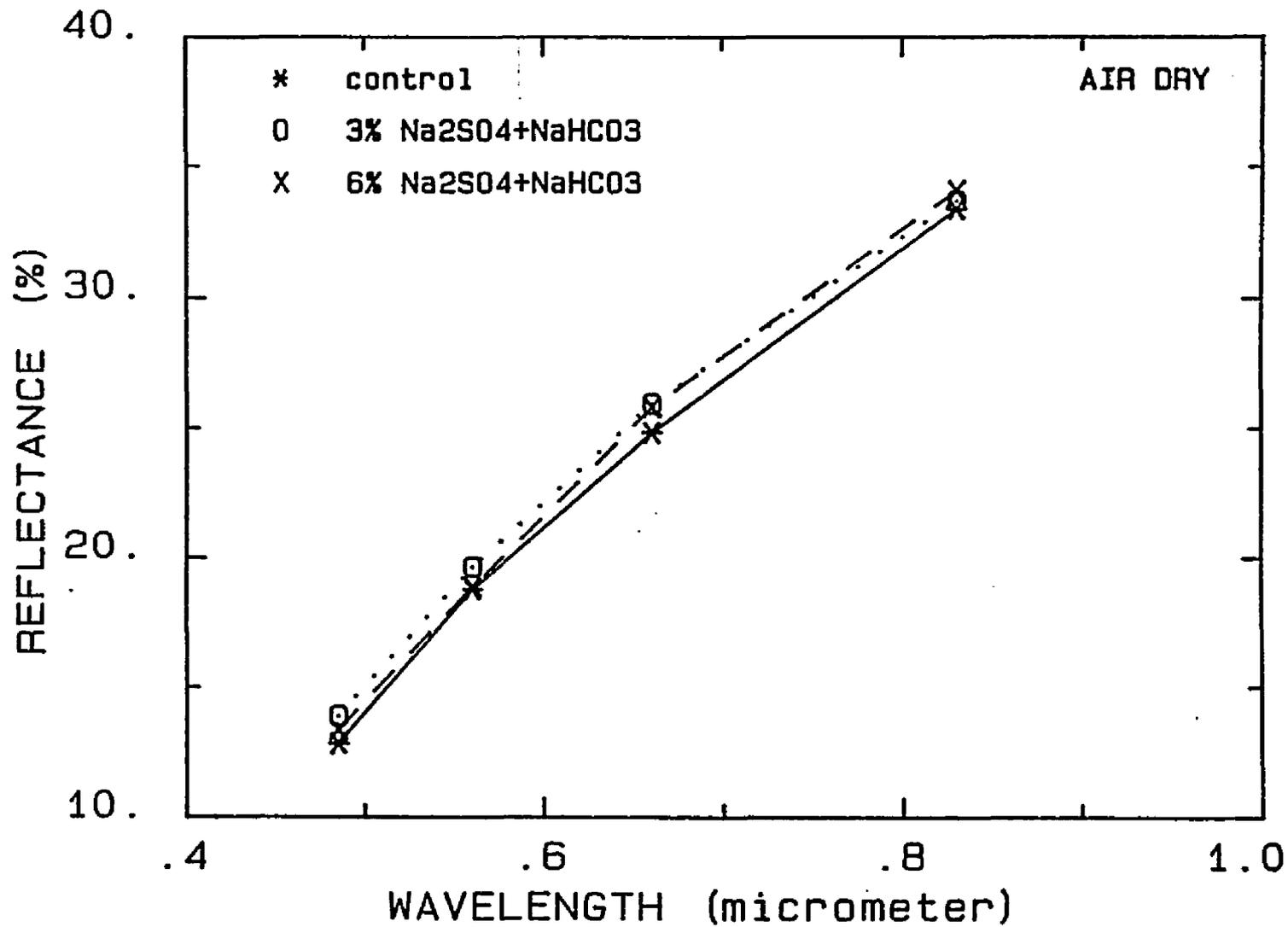


Fig. 18. Spectral Curve at Air Dry Moisture Condition.

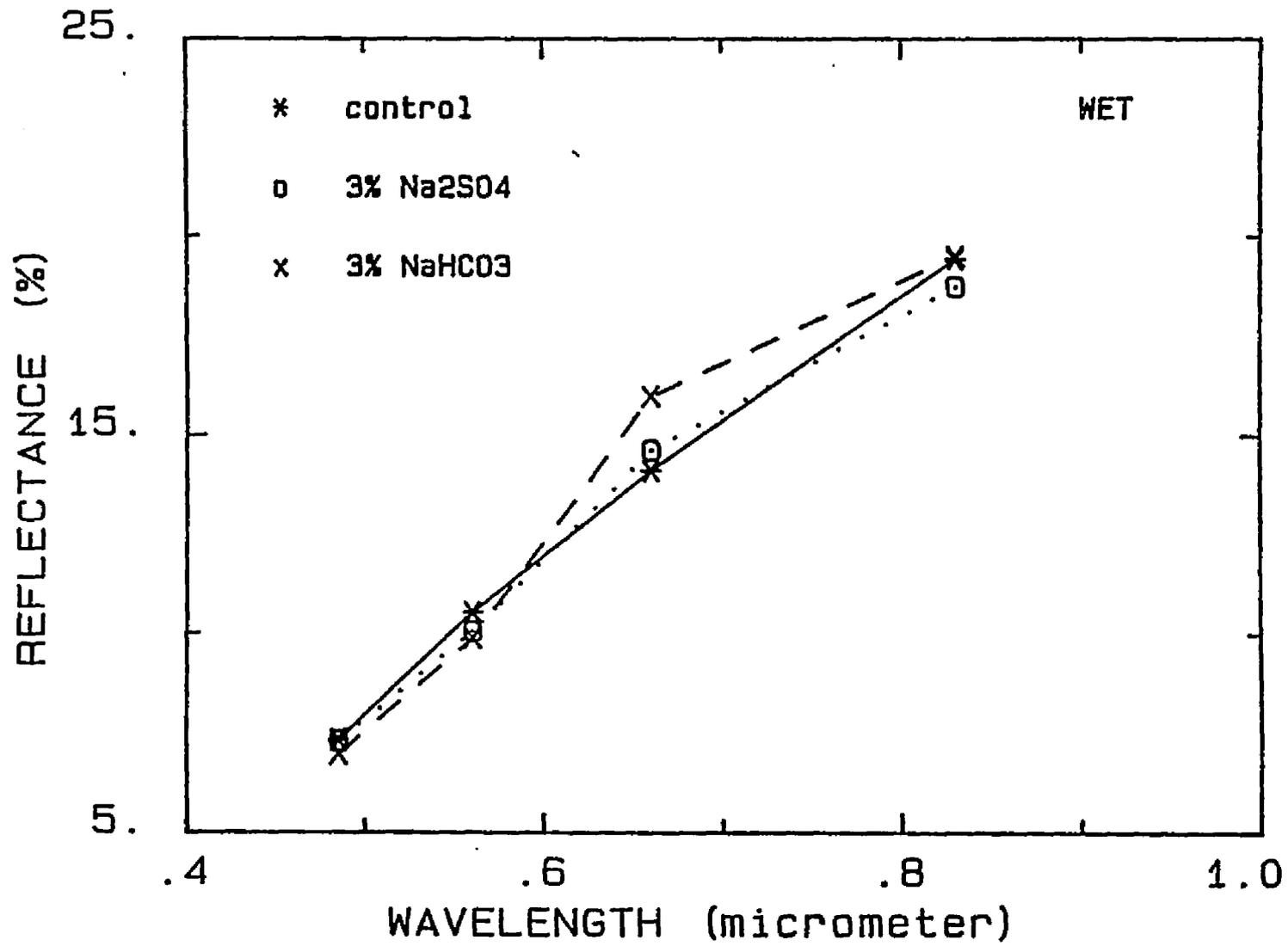


Fig. 19. Spectral Curve at Wet Moisture Condition.

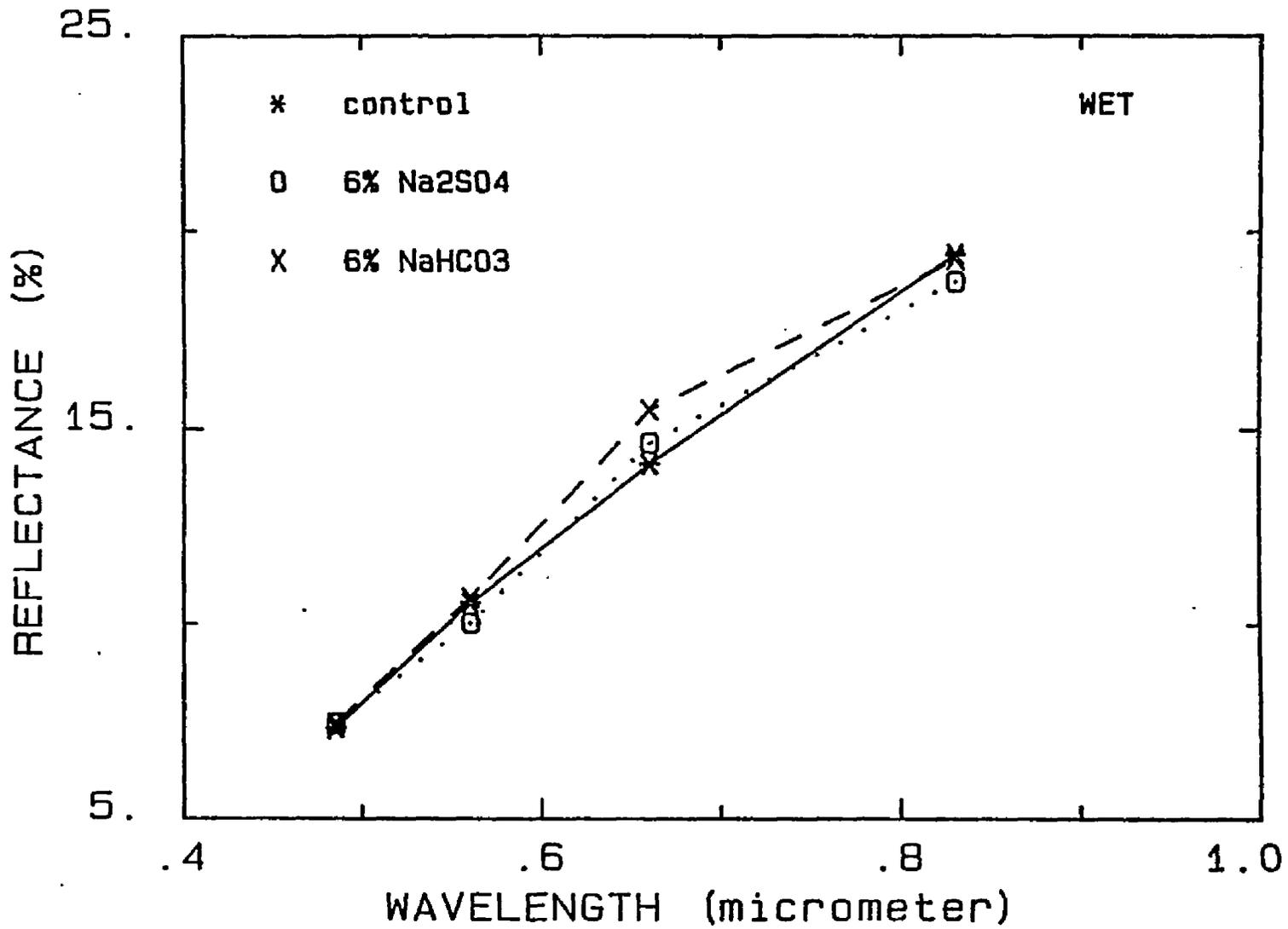


Fig. 20. Spectral Curve at Wet Moisture Condition.

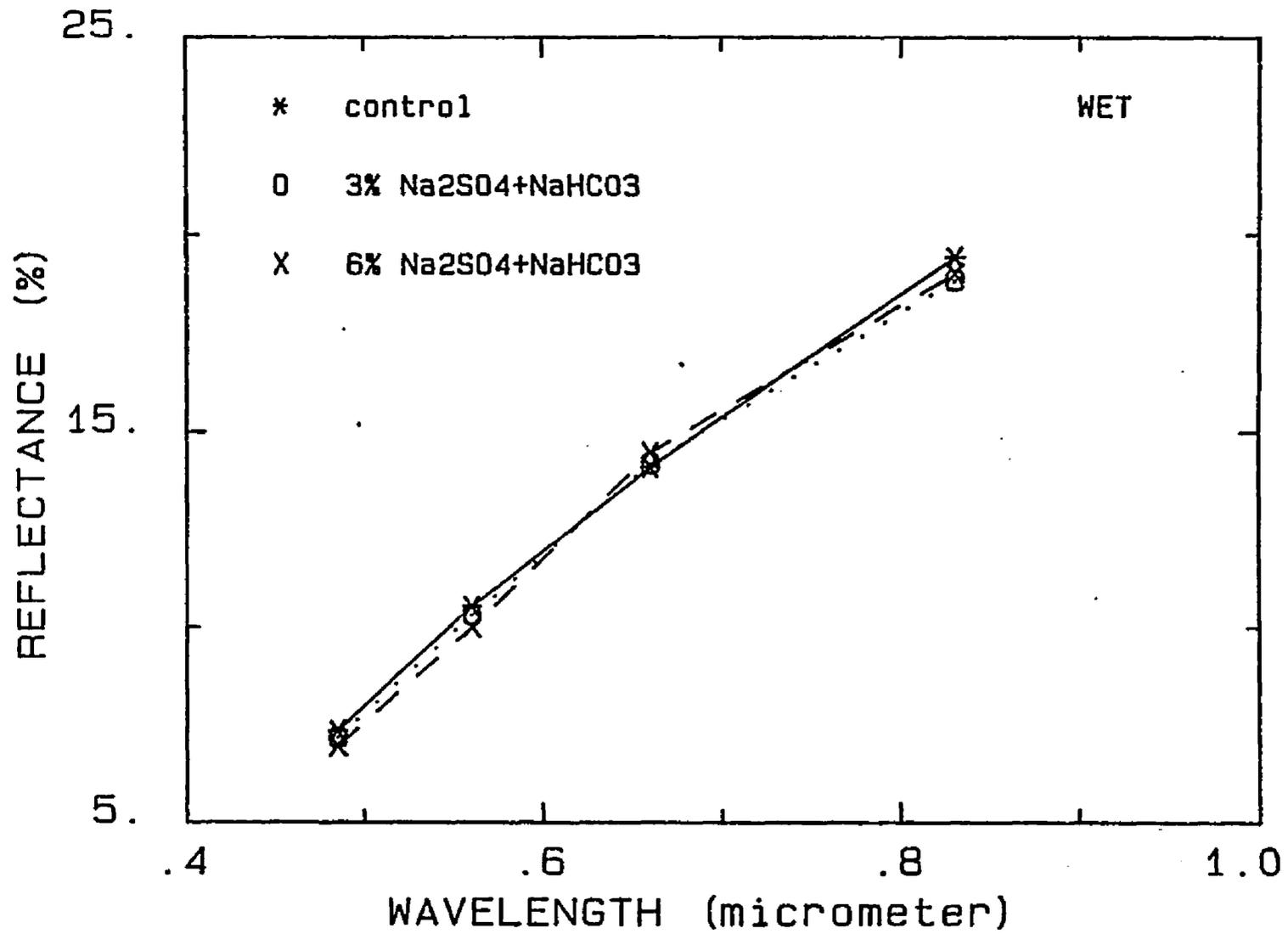


Fig. 21. Spectral Curve at Wet Moisture Condition.

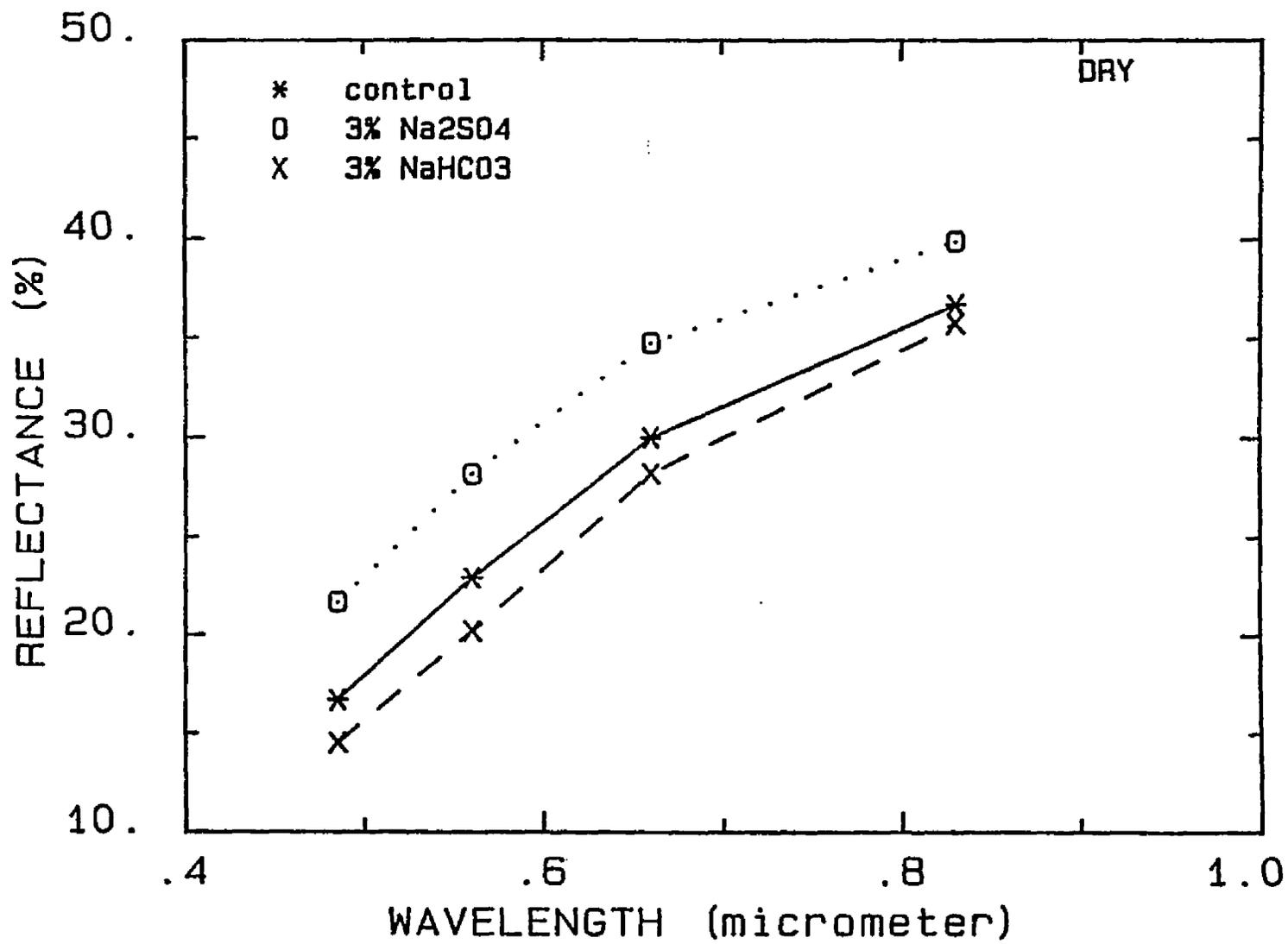


Fig. 22. Spectral Curve at Dry (24-hr after wetting) Moisture Condition.

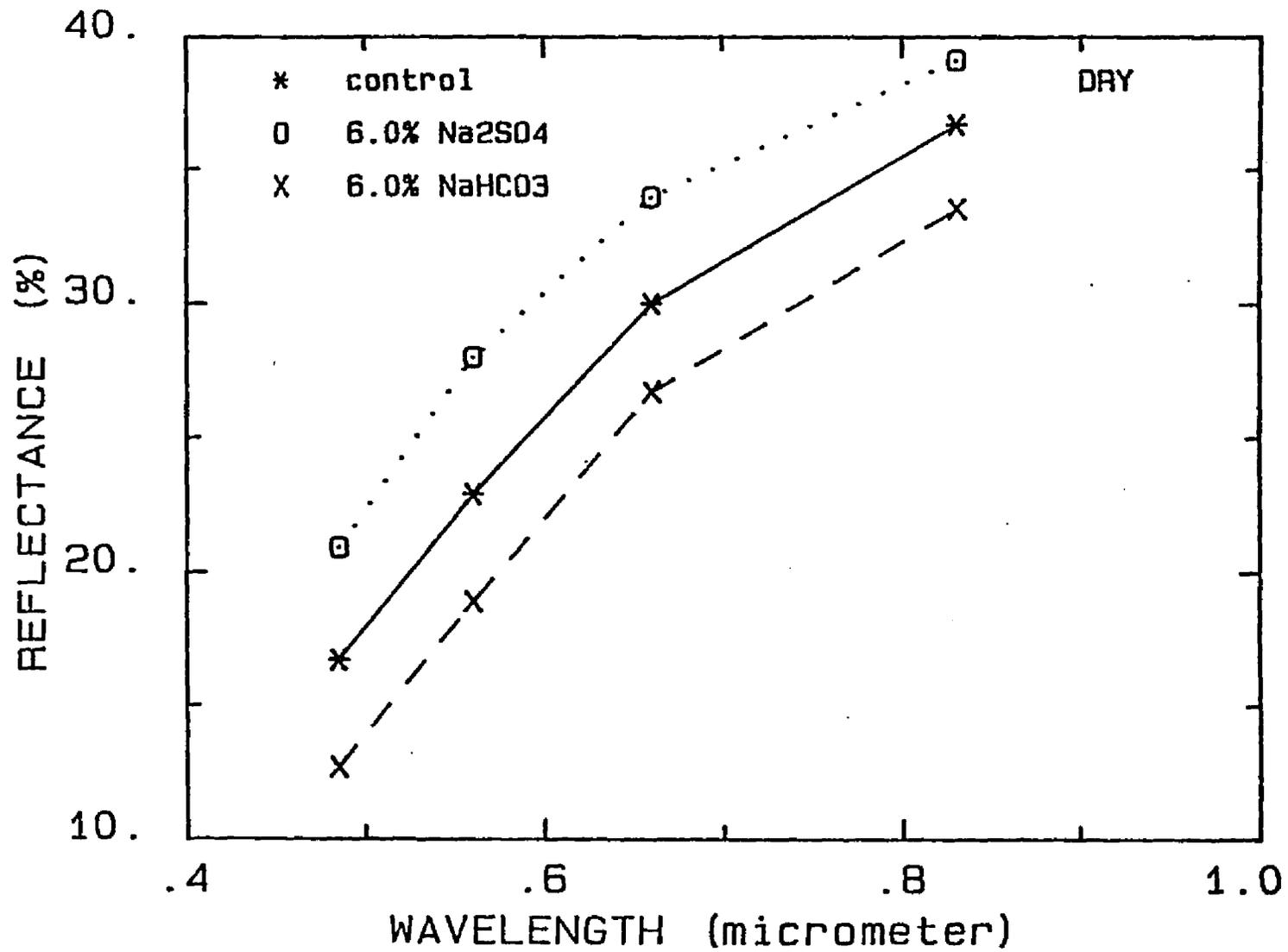


Fig. 23. Spectral Curve at Dry (24-hr after wetting) Moisture Condition.

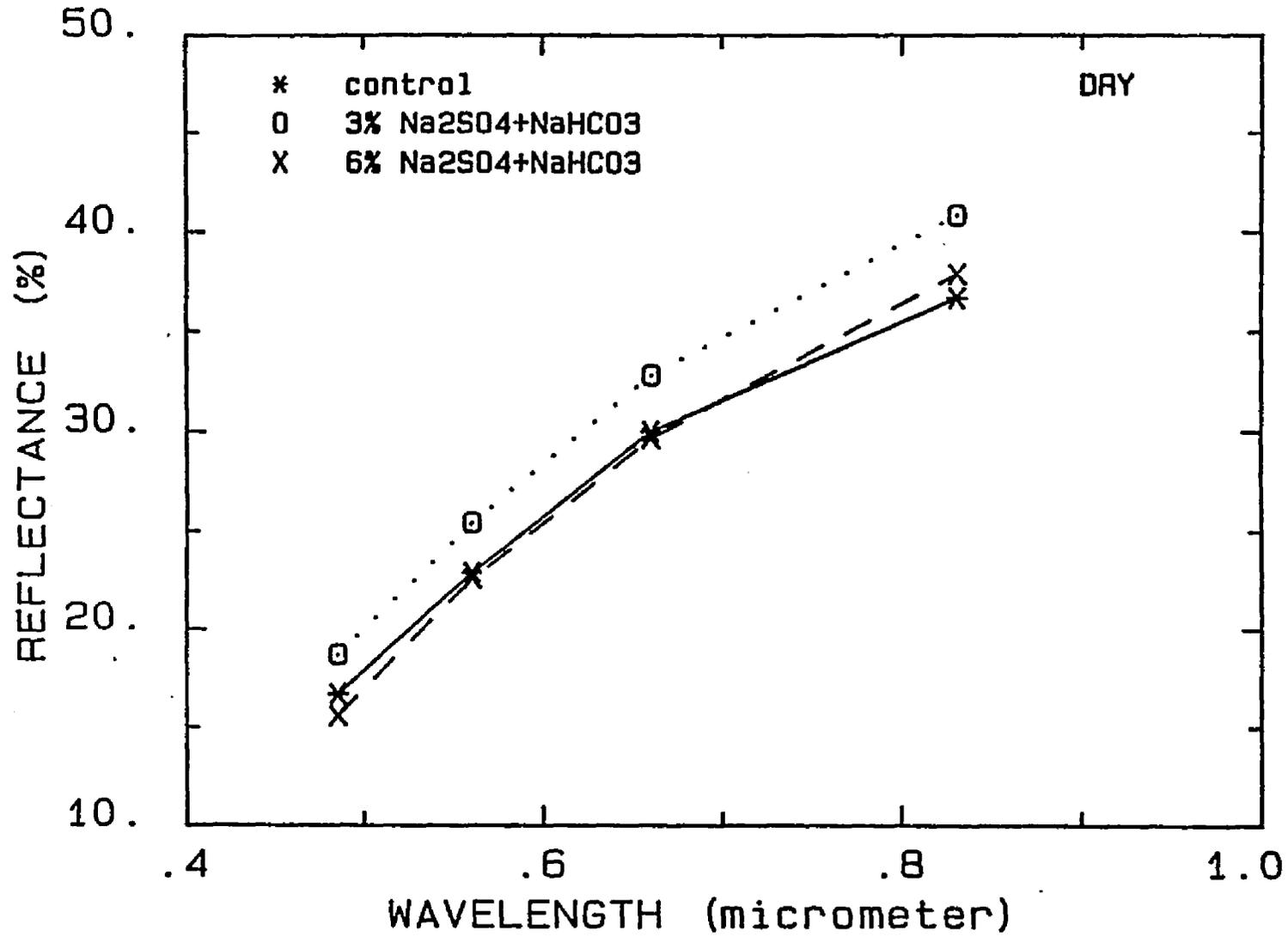


Fig. 24. Spectral Curve at Dry (24-hr after wetting) Moisture Condition.

organic matter in alkali soil solution and deposited on the soil surface by evaporation, caused the surface to darken.

The study showed that the higher the concentration of NaHCO_3 in the soil, the lower the reflectance values. On the other hand, the high reflectance values observed in the Na_2SO_4 treatments were due to the precipitation of a white salt crust on the soil surface. The same study showed that increasing the concentration levels of the Na_2SO_4 from 3.0 to 6.0% had almost no affect on the reflectance, Figs. 22 and 23. This behavior may be related to: (a) higher salt concentration (6.0%) causes slower release of moisture upon drying; (b) the amount of water added to the 6.0% treatment was not enough to dissolve the total amount of salt (Na_2SO_4); or (c) the increased salt concentration has no influence on reflectance.

Figure 24 shows the behavior of three spectral reflectance curves: (1) control; (2) a mixture of sodium sulfate and sodium bicarbonate at 3.0% concentration; and (3) the same mixture of 6.0% concentration level. The reflectance behavior observed can be interpreted as the combined influence of two opposite effects of salt-water interaction on reflectance. The first effect is attributed to the precipitation of white crust, due to the sodium sulfate, on the surface soil which tends to increase the reflectance. The second effect is related to the formation of black alkali, presence of NaHCO_3 , which tends to reduce the reflectance. A comparison of spectral curves for Figs. 22, 23 and 24 reveals that the increase in reflectance values observed in Fig. 24 can be attributed to dominance of the first effect over the second one.

A close look to spectral data obtained from both experiments indicate that there are variations in spectral response behavior of the sodium sulfate and sodium bicarbonate. These variations are suspected to be due to variations in (a) sun angle altitude, (b) moisture content, (c) time of year (influence to some extent chemical-physical properties of soil), and/or (d) source of salt.

The chemical analysis of soil samples (Table 4) has shown the same relationships mentioned earlier (in the 1985 experiment). These relationships are: (1) the sodium cation (Na^+) has a great influence on electrical conductivity (EC); (2) the electrical conductivity (EC) has a clear influence on reflectance; and (3) a linear relationship exists between reflectance with (a) sodium adsorption ratio (SAR) and (b) exchangeable sodium percentage (ESP) (Tables 4 and 5).

Table 4. Chemical Analysis of Soil Samples.

Sample	EC ds/m	Ca	Mg	Na	K
		-----meq/l-----			
Control	.35	3.56	.68	.51	.41
3.0% Na ₂ SO ₄	40	20.23	1.76	121.30	3.49
6.0% Na ₂ SO ₄	72	28.62	2.47	376.52	5.38
3.0% NaHCO ₃	26	1.92	.40	139.13	2.35
6.0% NaHCO ₃	55	.40	.50	330	4.32
3.0% Na ₂ SO ₄ + NaHCO ₃	34	2.36	.63	130.39	2.50
6.0% Na ₂ SO ₄ + NaHCO ₃	65	.51	.35	293.48	4.49

Table 5. Relationship Between Reflectance With (a) Electrical Conductivity (EC), (b) Sodium Adsorption Ratio (SAR) and (c) Exchangeable Sodium, Percentage (ESP).

Salt Concentration %	Treatment	EC ds/m	SAR	ESP	--- Reflectance % ---			
					TM1	TM2	TM3	TM4
0	Control	.35	.35	0	16.69	22.92	29.98	36.67
3.0	Na ₂ SO ₄	40	36.58	34.51	21.67	28.17	34.77	39.88
6.0	Na ₂ SO ₄	72	95.50	58.26	20.93	27.98	33.95	39.11
3.0	NaHCO ₃	26	125.18	65.43	14.52	20.20	28.20	35.73
6.0	NaHCO ₃	55	491.93	87.87	12.70	18/90	26.70	33.52
3.0	Na ₂ SO ₄ + NaHCO ₃	34	106.64	60.94	18.70	25.44	32.18	40.82
6.0	Na ₂ SO ₄ + NaHCO ₃	65	447.55	86.82	15.58	22.61	29.66	37.87

CONCLUSIONS AND RECOMMENDATIONS

The spectral figures of all soil treatments have shown that the presence of moisture reduced the reflectance at all TM bands (visible and NIR). All TM bands showed similarly the same general relationships between reflectance and soil properties (i.e. moisture, EC).

Reflectance values varied from one soil treatment to another depending upon type and concentration of salts, soil color and moisture. Upon drying (salt-water interaction takes place), different salt types could be separated. Calcium carbonate treatments show the highest spectral reflectance, then in order come sodium sulfate and finally sodium bicarbonate treatments having the lowest reflectance.

Spectral differentiation at 0.5% salt concentrations was not possible. Variations in spectral response were found at higher concentrations (i.e. 1.5, 3.0%). The relationships found in this study which influenced, directly and indirectly, the spectral response of soil surface can be a helpful tool to use along with the spectral curves in detecting salt-affected soils.

Since amount of water stored in the surface soil has a clear influence on the reflectance characteristics and the retention and release of that water affected by several parameters including salt types and concentrations, similar studies should be carried out using extended wavelength field spectroradiometry. This spectral instrument should include the water absorption bands at 1.45, 1.95 and 2.2 micrometers.

Also, the study should be carried out under different water application rates. Field study (in situ) of salt affected soils should be conducted and relate their reflectance characteristics to the ones obtained in this research. Such comparison may help further and advance application of reflectance characteristics of salt-affected soils. An attempt to study the spectral reflectance behavior from sodium sulfate and sodium bicarbonate treatments should be made for better understanding the variations observed in our study.

However, even though there are still questions to be answered, this study showed that the remote sensing technique can be used as a tool in detecting salt-affected soils, provided sufficient ground truth and related data are available.

APPENDIX I

REFLECTANCE VALUES AND SOIL ANALYSIS
FOR THE 1985 EXPERIMENT

Reflectance Values

Location: University of Arizona Campus Agricultural Center, Tucson.

LAT: 30° 17' N
LONG: 110° 57' W

Condition: Air Dry

Salt Concentration %	Treatment	TM1	TM2	TM3	TM4
-----	Control	12.41	18.11	24.09	31.74
0.5	NaHCO ₃	12.98	19.02	24.23	32.65
0.5	CaCO ₃	13.16	18.63	24.56	32.73
0.5	NaSO ₄	11.78	18.43	22.35	31.92
0.5	NaCL	13.40	19.30	25.00	33.37
0.5	CaCL ₂	11.69	17.40	22.60	31.15
1.5	NaHCO ₃	13.32	19.23	24.43	32.77
1.5	CaCO ₃	13.68	19.67	25.00	33.61
1.5	NaSO ₄	12.20	18.41	21.29	32.54
1.5	NaCL	12.58	18.67	24.13	32.28
1.5	CaCL ₂	11.65	17.21	22.45	30.69
3.0	NaHCO ₃	13.70	19.58	25.09	33.69
3.0	CaCO ₃	19.91	25.26	33.83	11.45
3.0	NaSO ₄	11.45	17.43	21.93	32.00
3.0	NaCL	12.77	18.65	24.11	32.23
3.0	CaCL ₂	11.77	17.30	22.79	31.07

Condition: Wet (adding 170 ml of deionized water).

Salt Concentration %	Treatment	TM1	TM2	TM3	TM4
-----	Control	5.78	8.27	11.66	16.68
0.5	NaHCO ₃	63.45	8.91	12.01	17.38
0.5	CaCO ₃	6.25	8.71	12.25	17.63
0.5	NaSO ₄	5.905	8.847	11.98	17.23
0.5	NaCL	6.395	9.775	12.87	19.09
0.5	CaCL ₂	6.128	8.765	12.83	18.76
1.5	NaHCO ₃	6.542	8.875	12.67	17.45
1.5	CaCO ₃	7.08	9.17	12.99	17.98
1.5	NaSO ₄	5.955	8.45	12.32	17.44
1.5	NaCL	7.06	10.35	13.78	20.36
1.5	CaCL ₂	5.792	08.49	11.90	17.70
3.0	NaHCO ₃	6.977	9.967	13.50	18.95
3.0	CaCO ₃	7.195	10.08	13.82	19.36
3.0	NaSO ₄	5.868	8.81	12.46	18.27
3.0	NaCL	7.025	9.837	13.75	19.02
3.0	CaCL ₂	5.857	8.315	12.35	17.45

Condition: Dry (24-hr after wetting).

Salt Concentration %	Treatment	TM1	TM2	TM3	TM4
-----	Control	14.51	20.03	25.34	34.00
0.5	NaHCO ₃	14.73	20.02	24.93	33.64
0.5	CaCO ₃	14.49	20.01	25.58	34.63
0.5	NaSO ₄	14.31	20.01	25.30	33.95
0.5	NaCL	14.72	20.40	26.02	35.48
0.5	CaCL ₂	12.98	18.47	22.62	32.54
1.5	NaHCO ₃	10.14	15.30	20.22	31.21
1.5	CaCO ₃	16.11	22.09	27.09	37.22
1.5	NaSO ₄	11.72	16.92	21.90	31.18
1.5	NaCL	14.55	20.41	25.54	35.45
1.5	CaCL ₂	12.38	17.23	22.70	31.34
3.0	NaHCO ₃	9.48	13.75	19.85	30.13
3.0	CaCO ₃	16.31	22.36	27.25	37.45
3.0	NaSO ₄	12.20	17.10	22.20	31.98
3.0	NaCL	14.62	20.46	25.51	35.39
3.0	CaCL ₂	11.71	16.62	22.08	30.71

Soil Analysis

Salt Concentration %	Treatment	EC ds/m	Ca	Mg meq/l	Na	K
----	Control	0.57	2.91	0.36	0.83	0.76
0.5	NaHCO ₃	1.5	6.31	1.49	10.43	0.88
1.5	NaHCO ₃	9.3	5.33	0.48	57	1.10
3.0	NaHCO ₃	25	2.81	0.61	140	1.67
0.5	CaCO ₃	0.55	2.65	0.34	0.75	0.95
1.5	CaCO ₃	0.52	2.44	0.27	0.71	0.71
3.0	CaCO ₃	0.45	2.55	0.35	0.73	0.77
0.5	Na ₂ SO ₄	5.5	12.38	1.39	38.13	1.73
1.5	Na ₂ SO ₄	23	25.45	2.17	114.3	2.33
3.0	Na ₂ SO ₄	42	18.06	2.39	127.61	3.08
0.5	NaCl	8.0	11.11	1.12	51.57	1.96
1.5	NaCl	29	10.63	01.56	127.91	3.70
3.0	NaCl	54	22.21	2.24	291.74	3.70
0.5	CaCl ₂	11	60.13	3.28	1.12	2.46
1.5	CaCl ₂	25.9	126.25	4.69	1.25	2.75
3.0	CaCl ₂	47	247.00	4.01	1.25	3.59

APPENDIX II

**REFLECTANCE VALUES AND SOIL ANALYSIS
FOR THE 1986 EXPERIMENT**

Reflectance Values

Location: University of Arizona Campus Agricultural Center, Tucson.

LAT: 30° 17' N
LONG: 110° 57' W

Condition: Air Dry

Salt Concentration %	Treatment	TM1	TM2	TM3	TM4
-----	Control	12.84	18.76	24.82	33.36
3.0	NaSO ₄	11.78	18.43	22.35	31.92
3.0	NaHCO ₃	13.40	19.30	25.00	33.37
6.0	NaSO ₄	13.8	19.2	25.0	34.1
6.0	NaHCO ₃	11.94	17.83	24.1	32.75
6.0	NaSO ₄ + NaHCO ₃	13.89	19.65	25.93	33.67
6.0	NaSO ₄ + NaHCO ₃	13.35	18.86	25.79	34.06

Condition: Wet (adding 170 ml of deionized water).

-----	Control	7.33	10.54	14.12	19.41
3.0	NaSO ₄	7.30	10.05	14.62	18.72
3.0	NaHCO ₃	6.97	9.87	15.96	19.48
6.0	NaSO ₄	7.43	10.02	14.65	18.73
6.0	NaHCO ₃	7.44	10.67	15.48	19.28
6.0	NaSO ₄ + NaHCO ₃	7.16	10.31	14.21	18.83
6.0	NaSO ₄ + NaHCO ₃	6.94	9.98	14.48	18.99

(Continued)

Condition: Dry (24-hr after wetting).

Salt Concentration %	Treatment	TM1	TM2	TM3	TM4
-----	Control	16.69	22.92	29.98	36.67
3.0	NaSO ₄	21.67	28.17	34.77	39.88
3.0	NaHCO ₃	14.52	20.20	28.20	35.73
6.0	NaSO ₄	20.93	27.98	33.95	39.11
6.0	NaHCO ₃	12.70	18.90	26.70	33.52
6.0	NaSO ₄ + NaHCO ₃	18.70	25.44	32.81	40.82
6.0	NaSO ₄ + NaHCO ₃	15.58	22.61	29.66	37.87

Soil Analysis

Concentration %	Treatment	EC ds/m	Ca ----- meq/l	Mg -----	Na -----	K -----
----	Control	0.35	3.56	0.68	0.51	0.40
3.0	NaSO ₄	40	20.23	1.76	121.30	3.49
3.0	NaHCO ₃	72	28.62	2.47	376.52	5.38
6.0	NaSO ₄	26	1.92	0.40	139.13	2.35
6.0	NaHCO ₃	55	0.40	0.5	330	4.32
6.0	NaSO ₄ + NaHCO ₃	34	2.36	0.63	130.39	2.50
6.0	NaSO ₄ + NaHCO ₃	65	0.51	0.35	293.48	4.49

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