

RELATION OF CATION EXCHANGE CAPACITY TO CLAY AND ORGANIC CARBON CONTENTS OF INDIANA SOILS

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ABSTRACT: Soil cation exchange capacity (CEC) is a measure of the cations adsorbed on negative sites of solid soil particles. It is important in determining the ability of a soil to retain nutrient cations and to prevent them from getting into surface water and groundwater. Thus, to properly manage soils, we must know their CEC. It has been determined for many soils, but not for many others. The objective of this study was to summarize the relationships of CEC to clay and organic matter contents, which are more commonly determined, so that these relationships can be used to predict CEC for soils with no CEC data. On average for all soils of the state, 100 grams of clay contributes 59 me CEC and 100 grams of organic matter contributes 208 me CEC measured at pH 8.2. This CEC is about 15% higher than CEC measured at pH 7.0. Soil pH can be used to predict base saturation with moderate accuracy. CEC can also be predicted from soil texture and Munsell color designation which can be estimated in the field and which are recorded in many soil pedon descriptions.

INTRODUCTION

The cation exchange capacity (CEC) of a soil is a measure of the cation charge that can be desorbed from a soil at a given pH. It arises from an excess of negative charges at the surfaces of solid particles in the soil. Solid-particle surfaces develop electrical charges in two principal ways: from isomorphous substitutions among ions of differing valence in soil minerals, and from the reactions of surface functional groups with ions in the soil solution. The kind of isomorphous substitution important in clay minerals is the substitution of a cation with lower positive charge (e. g., Al^{3+}) for a similar size ion with higher charge (Si^{4+}). This substitution results in *permanent structural charge* (Sposito, 1989) that is not affected by the pH of the soil.

Some charge is less permanent and is called *net proton charge* (Sposito, 1989). It is the difference between the number of protons and the number of hydroxide ions complexed by surface functional groups in soils. Most of these groups are on organic matter, hydrous oxides (especially of Fe and Al), and 1:1 aluminosilicates such as kaolinite. At higher pH, greater OH^- activity, more OH^- groups are complexed at the surface and the surface negative charge is increased. At lower pH, smaller OH^- activity, fewer OH^- groups are complexed at the surface and the surface negative charge is decreased. Thus, a higher measured CEC is expected at higher pH values.

The negative charge on the surfaces of solid particles are balanced by adsorbed cations such as Ca^{2+} , Mg^{2+} , Na^+ , and K^+ ('bases') and H^+ and Al-compounds

("exchange acidity"). In one method of determining CEC, the charges from these bases and exchangeable acidity are added together to give CEC. In another method, all the adsorbed cations are replaced in the laboratory by a cation such as NH_4^+ and the amount of this adsorbed cation is determined. CEC is commonly expressed as milliequivalents of positive charge per 100 grams of soil (me/100g). Base saturation (BS) is the percentage of the total CEC that is comprised of bases.

CEC is an important soil property because it determines the ability of a soil to retain nutrient cations for use by plants and to keep these cations and others from leaching through the soil. Thus, soil CEC greatly influences the fertility of a soil and the chemical composition of the water that leaches through it. It is used, for example, to determine the optimum levels of fertilizer (Mengel, 1980) or sludge (Sommers et al., 1980) to apply.

CEC and BS have been measured for a number of Indiana soils, but for many other soils there is no data available. It is possible, however, to estimate CEC and BS from other laboratory data that is more readily available and from morphological properties that can be estimated in the field if these relationships are known. The objectives of this study were: 1) to determine the relationship of CEC to clay and organic matter contents, 2) to determine the relation of CEC determined at pH 8.2 to CEC determined at pH 7.0, 3) to determine the relationship of BS to soil pH, and 4) to determine the relationship of CEC to texture class and soil color, which are estimated in the field.

METHODS AND MATERIALS

During the course of the Indiana Cooperative Soil Survey, field soil scientists collected samples from a number of pedons (profiles) in each county for analysis in the Purdue Soil Characterization (PSCL) Laboratory or the National Soil Survey Laboratory (NSSL). Data from the PSCL were published in a series of 10 reports culminating with Indiana Soil Survey Staff (1988), and they are also stored in a data base management system. Data from the NSSL are not published, but most of it is stored on a computer, and we also entered that data into our data base management system. Several thousand samples were analyzed for CEC in the two laboratories.

Laboratory methods are described in the methods manuals of the laboratories, Franzmeier et al. (1977) for the PSCL and Soil Conservation Service (1984) for the NSSL. For each determination, the methods used in the two laboratories are very similar and give essentially the same results.

Cation exchange capacity (CEC) was determined at two pH levels. In the sum of cations method (CEC8), "basic" cations, Ca^{2+} , Mg^{2+} , Na^+ , and K^+ , were extracted with ammonium acetate solution, and extractable acidity was determined by the barium chloride-triethanolamine method at pH 8.2 (NSSL method 6H, PSCL pages 18-19). In the direct replacement method (CEC7), all cations in the soil were replaced by an excess of NH_4^+ ions from ammonium acetate at pH 7.0, NH_4^+ ions in solution were removed, and adsorbed NH_4^+ was determined (NSSL 5A8). Base saturation (BS) was calculated by dividing the sum of Ca^{2+} , Mg^{2+} , K^+ , and Na^+ extracted with ammonium acetate by CEC8 and multiplying by 100 to give percentage values.

Particle-size distribution was determined by the pipet method after destruction of organic matter by hydrogen peroxide in both laboratories (NSSL 3A, PSCL p. 14-15). Organic carbon was determined by wet oxidation with potassium dichromate and sulfuric acid by the Walkley-Black method, with no external heat, in the NSSL (6A1), and by

the Mebius method, with external heat, in the PSCL (page 19-20). Statistical analyses were done with the SAS system (SAS Institute 1985).

RESULTS AND DISCUSSION

Using data from both the PSCL and the NSSL, the relationships of CEC8 to clay and organic carbon contents listed below were derived.

A and E horizons, 1229 samples, $R^2 = 0.81$:

$$\text{CEC8} = -0.177 + 0.599 \text{ Clay} + 3.65 \text{ OC.}$$

B horizons, 1316 samples, $R^2 = 0.76$:

$$\text{CEC8} = 0.936 + 0.561 \text{ Clay} + 4.70 \text{ OC.}$$

Other horizons (mainly C), 180 samples, $R^2 = 0.79$:

$$\text{CEC8} = 2.21 + 0.547 \text{ Clay} + 3.56 \text{ OC.}$$

All horizons, 2725 samples, $R^2 = 0.79$

$$\text{CEC8} = 0.515 + 0.588 \text{ Clay} + 3.58 \text{ OC.}$$

For all horizons, 100 grams of clay provides 59 milliequivalents (me) of cation exchange sites, and 100 grams of organic matter provides 208 me of exchange sites (assuming that one gram of organic carbon is equivalent to 1.72 g of organic matter). For comparison, Brady (1984) gives average values of 50 to 100 me CEC per 100 g of clay for soils of the Midwest, and 200 me for 100 g of organic matter.

The measured CEC depends, in part, on the pH at which the determination was made. Using NSSL data, the CEC measured at pH 8.2 (CEC8) was correlated with the CEC measured at pH 7.0 (CEC7) to give the relationship (Figure 1),

$$\text{CEC7} = -1.24 + 0.869 \text{ CEC8 (582 samples, } R^2 = 0.94).$$

Soils with higher base saturation usually have a higher pH than those with lower BS. In the PSCL, pH was measured in three solutions, distilled water, 0.01 M CaCl_2 , and 1 M KCl. Measured pH decreases with greater salt concentration because the cations replace adsorbed protons. The relationships below were obtained from the correlation of BS and pH.

pH in H_2O , 6506 samples, $R^2 = 0.54$

$$\text{pH} = 3.82 + 0.0347 \text{ BS.}$$

pH in 0.01 M CaCl_2 solution, 6292 samples, $R^2 = 0.64$:

$$\text{pH} = 3.22 + 0.0370 \text{ BS.}$$

pH in 1 M KCl, 5715 samples, $R^2 = 0.56$:

$$\text{pH} = 2.69 + 0.0351 \text{ BS.}$$

Of the three methods, the CaCl_2 method gave the best correlation, but even this relationship showed much scatter (Figure 2). A BS of 35% is used to separate some soils in Soil Taxonomy. This corresponds to a pH in water of 5.0 and a pH in CaCl_2 of 4.5.

CEC8 values were also sorted by field-observable characteristics, texture class and Munsell color designation (Table 1). CEC increases with higher clay content and with darker colors (smaller numbers in the value/chroma designation).

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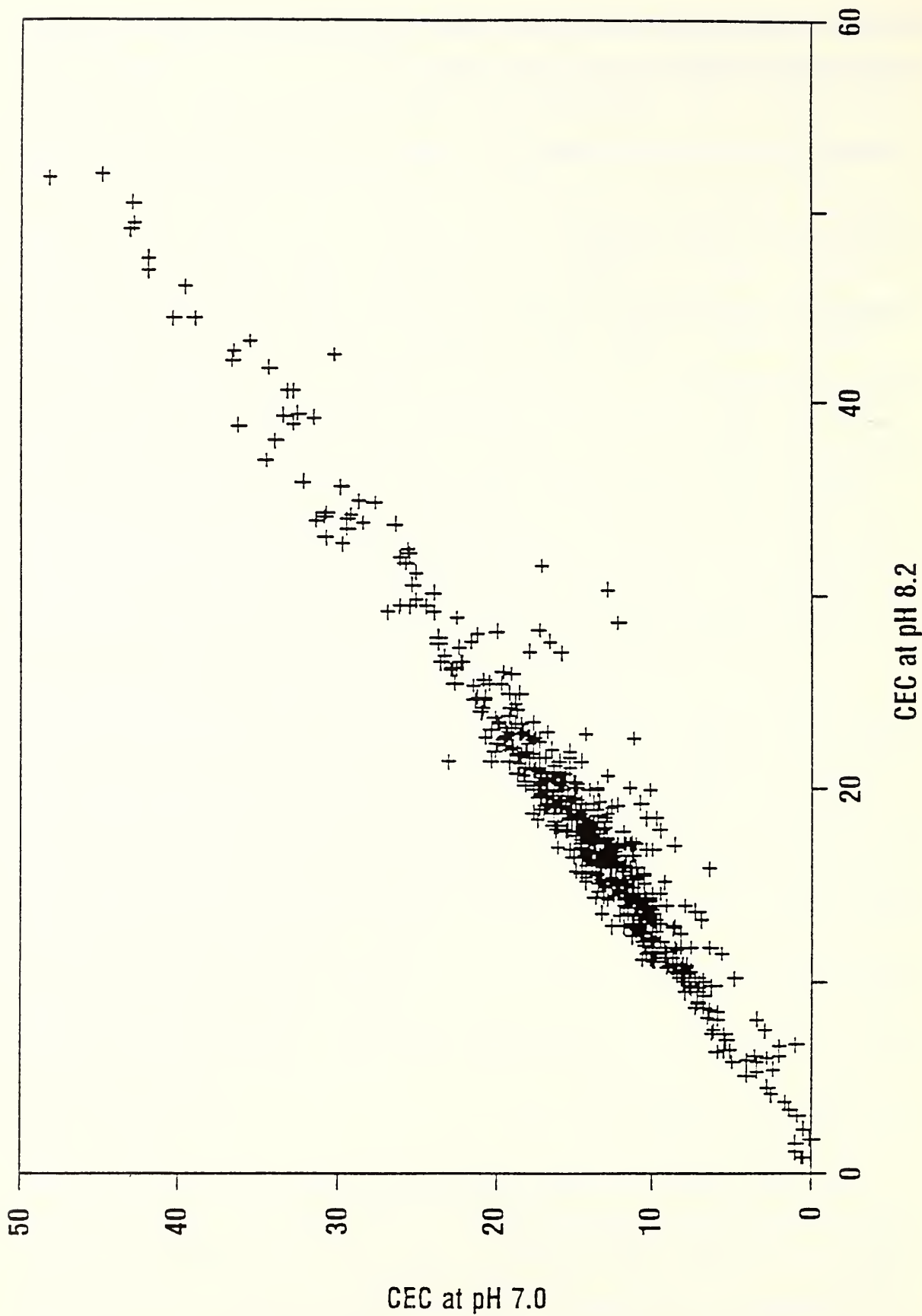


Figure 1. Relation of CEC determined at pH 7.0 to CEC determined at pH 8.2.

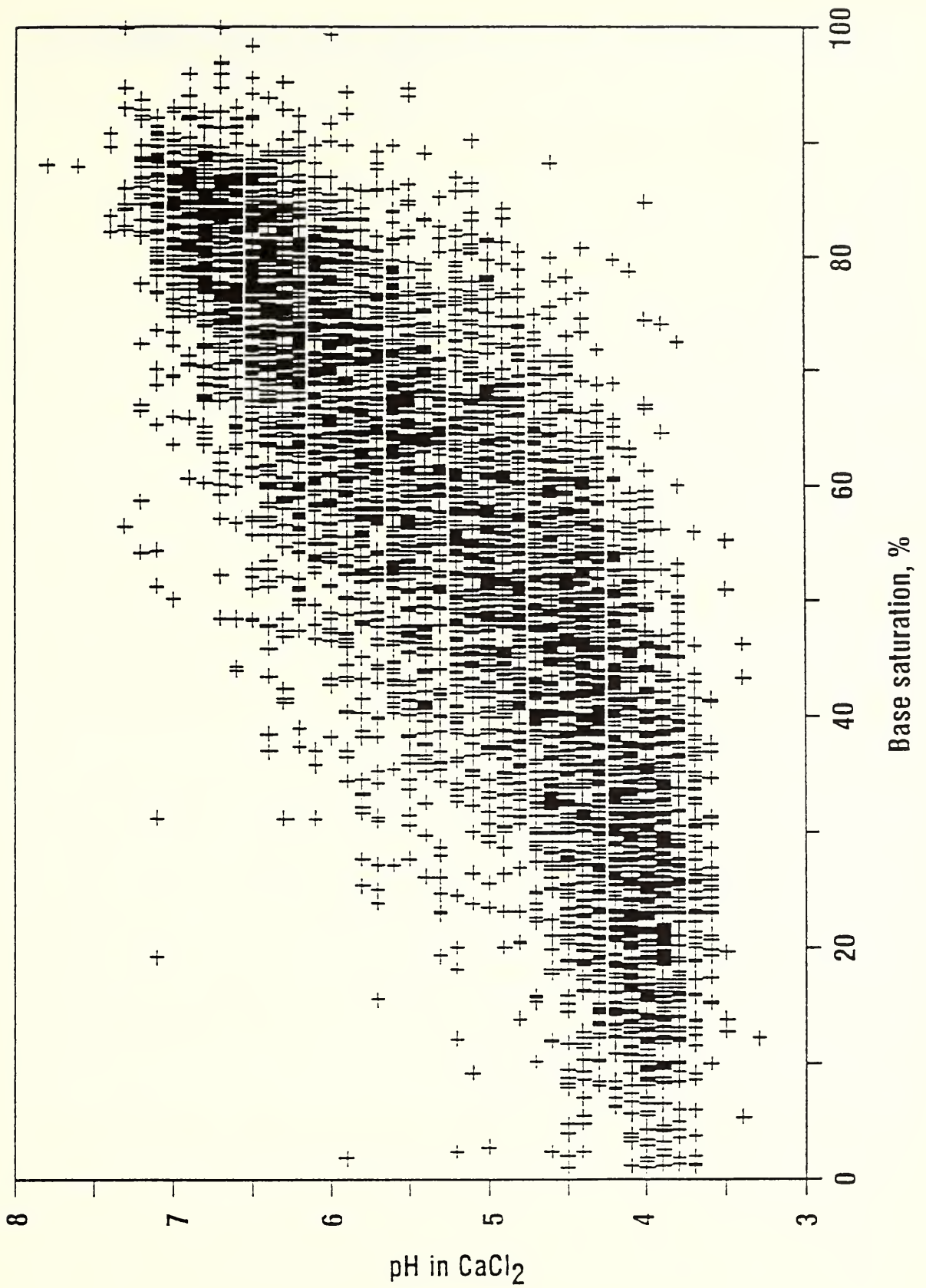


Figure 2. Relation of pH in 0.01 M CaCl₂ to base saturation.

Table 1. Cation exchange capacity (CEC8) by soil color and texture groups.

Texture classes		Munsell value/chroma (10YR hue), A and E horizons ¹						B horizons ²	
		2/1	3/1	3/2	3/3	4/1 4/2	4/3 4/4	All others	
Sand, fine sand, loamy sand, and loamy fine sand	\bar{x} ³	19.2	9.0	8.7	6.0	7.2	5.3	4.9	7.1
	SD	6.9	2.7	4.7	1.6	1.6	2.1	3.2	5.6
	<i>n</i>	5	6	16	14	10	27	50	215
Sandy loam and fine sandy loam	\bar{x}	19.8	14.3	12.5	8.3	11.2	8.1	9.7	10.8
	SD	7.4	4.6	3.0	2.4	4.0	2.6	4.9	4.5
	<i>n</i>	11	20	16	11	31	40	47	383
Loam and silt loam	\bar{x}	31.0	24.6	22.2	19.5	15.6	13.4	13.8	15.0
	SD	8.9	7.6	7.8	6.9	5.3	3.6	6.5	5.0
	<i>n</i>	29	59	92	37	160	258	292	1439
Clay loam and silty clay loam	\bar{x}	35.9	33.7	31.6	29.3	25.9	22.7	27.2	22.1
	SD	9.1	7.7	7.4	4.8	7.7	6.9	8.4	6.4
	<i>n</i>	39	45	31	8	22	11	23	1327
Silty clay and clay	\bar{x}	54.7	41.4	36.5	33.8				29.7
	SD	6.5	7.4	4.6	3.1				9.9
	<i>n</i>	5	8	5	2				406

¹Purdue Soil Characterization Laboratory (SCL) data.

²National Soil Survey Laboratory and SCL data.

³ \bar{x} = mean, SD = standard deviation, me/100g; *n* = number of samples.

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