Calculating Cation Exchange Capacity, Base Saturation, and Calcium Saturation

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The purpose of this fact sheet is to define soil cation exchange capacity, base saturation and calcium saturation, and demonstrate how these values are calculated in soil test reports.

Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC) is a fundamental soil property used to predict plant nutrient availability and retention in the soil. It is the *potential* of available nutrient supply, not a direct measurement of available nutrients. Soil CEC typically increases as clay content and organic matter increase because cation exchange occurs on surfaces of clay minerals, organic matter, and roots. Soils in Ohio can encompass a wide CEC range, but typically fall somewhere between 5 to 25 meq/100 g soil (Table 1). Values over 25 meq/100 g soil are found with heavy clay soils, organic, or muck soils.

Table 1. The relationship between soil texture and CEC

Soil Texture	**Typical CEC (meq/100 g soil)**
Sands	3-5
Loams	10-15
Silt loams	15-25
Clay and clay loams	20-50
Organic soils	50-100

Cation exchange capacity is defined as a soil's total quantity of negative surface charges. It is measured commonly in commercial soil testing labs by summing cations (positively charged ions that are attracted to the negative surface charges in soil). Exchangeable cations include base cations, calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and sodium (Na^{+}), as well as acid cations such as hydrogen (H^{+}), aluminum (Al^{3+}) and ammonium (NH_4^{+}).

$$\text{CEC} = \textit{Base cations} + \text{Acid cations}$$

$$(Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}) + (\mathrm{H}^{+} + \mathrm{Al}^{3+} + \mathrm{NH}_4^{+})$$

Figure 1 illustrates a low CEC soil, with a small number of negative charges and associated cations (left) and a high CEC soil with a larger amount of negative charges, occupied by a greater number of total cations (right).

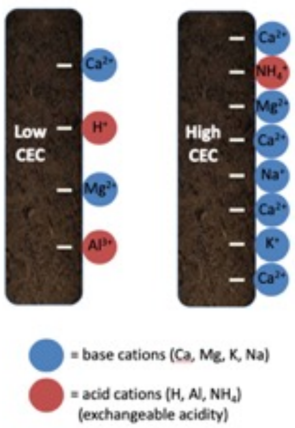

Figure 1. Soils with different CEC values.

Base Saturation

Base saturation is calculated as the percentage of CEC occupied by base cations. Figure 2 shows two soils with the same CEC, but the soil on the right has more base cations (in blue). Therefore, it has a higher base saturation. Base saturation is closely related to pH; as base saturation increases, pH increases.

$$\text{Base Saturation (\%)} = (\textit{Base cations/CEC})\ x\ 100$$

Similarly, we can calculate the base saturation for each individual base cation. Calcium base saturation is calculated as the percentage of CEC occupied by calcium cations. In Figure 2, the soil on the right has twice as many calcium cations (Ca^{2+}), thus a higher calcium saturation.

$$\text{Calcium Saturation (\%)} = (\textit{Calcium cations/CEC})\ x\ 100$$

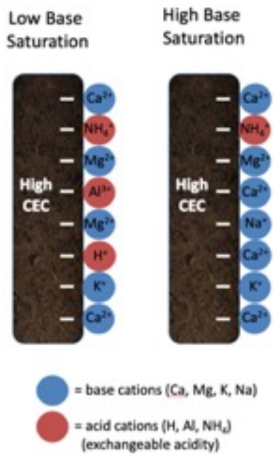

Figure 2. Soil with differences in base saturation.

Calculating CEC from a Soil Test

CEC is reported as milliequivalents per 100 grams of soil (meq/100g), or charge per weight of soil. Milliequivalents are used instead of weight because charge is more useful when talking about ion exchange.

So, how do we take the concentration of nutrients in a soil test (ppm) and convert to charges (meq/100g soil)? Soil testing laboratories often provide these values already on the soil test report, or will provide them upon request. However, to gain a better understanding of the relationships, the steps to perform these calculations are outlined below.

Step 1: Determine the gram equivalent weight of each base cation. Each base cation has an atomic weight and valence number (charge) in the periodic table of elements. Figure 3 shows the base cations. For calcium, the atomic weight is ~40 grams per mole and the charge is 2. We divide each atomic weight (40) by the charge (2) to calculate the gram equivalent weight (20). The value for each base cation is outlined in Table 2.

Figure 3. Basic cations from the periodic table.

Step 2. Convert gram equivalent weight into charge per weight of soil (meq/100g soil).

$$\text{equivalent} \times \frac{1000\ \text{milliequivalent}}{1\ \text{equivalent}} \times \frac{1}{100\ \text{g soil}} = \frac{10\ \text{meq}}{\text{g soil}}$$

Step 3. Multiply the gram equivalent weight by 10 to convert to meq/100g of soil. Again, for calcium, the gram equivalent weight of 20 grams multiplied by 10 gives us 200 meq/100 g soil. This meq/100g soil value is used as a conversion factor for the nutrient concentration values (ppm) received in a soil test. The bolded values in the last column in Table 2 can be used as a conversion factor each time and will not change.

Table 2. The meq/100g soil constants for the base cations Ca, Mg, K, and Na.

Base Cation	**Atomic Weight**	**Charge (Valence)**	**Gram Equivalent Weight (g)**	**Milliequivalent/ 100 g soil**
Calcium (Ca)	40	2	20	**200**
Magnesium (Mg)	24	2	12	**120**
Potassium (K)	39	1	39	**390**
Sodium (Na)	23	1	23	**230**

Step 4. Convert soil test nutrient concentration to charge. Table 3 provides an example of typical soil test levels in Ohio (in ppm). We can calculate the collective charge each cation occupies on the exchange sites by taking the values calculated in Table 2 (last column) and dividing them by the soil test levels. For calcium, a soil test level of 2000 ppm, divided by 200 equals 10.0 meq/100 g soil. This is done for each cation individually.

Step 5. Calculate collective charge from base cations. Next, we add up the charges of each base cation. For this example, the sum of base cations equals 12.4 meq/100g soil (Table 3).

Step 6. Calculate exchangeable acidity, using the buffer pH with the empirically derived conversion equation (Table 3). If the soil has a pH greater than 7.0, you essentially have no exchangeable acidity and CEC is just the sum of base cations. A soil with a buffer pH of 6.6 indicates that acidic cations occupy 4.8 meq per 100 grams of soil.

Table 3. Conversion of soil test values (ppm) to meq/100 g soil for base and acid cations to determine CEC.			
Base Cation	**Soil test level (ppm)**	**Milliequivalent/ 100 g soil**	**meq/100 g soil**
Calcium (Ca^{2+})	2000	200	10.0
Magnesium (Mg^{2+})	240	120	2.0
Potassium (K^{+})	100	390	0.26
Sodium (Na^{+})	20	230	0.09
Subtotal			**12.4**
Acid Cation	**Buffer pH**	**Conversion Equation**	**meq/ 100 g soil**
Exchangeable acidity (H^{+}, $Al_3{}^{+}$, $NH_4{}^{+}$)	6.6	12 x (7.0 – 6.6)	**4.8**
*If soil test values are in pound per acre, then first convert pound per acre to ppm by dividing soil test values by 2.			
**If buffer pH is 7 or above, then you have no exchangeable acidity (CEC = sum of base cations).			

Step 7. Calculate CEC by adding the base cations and acid cations:

Cation exchange capacity (CEC) = *Base cations* + Acid cations

$$= 12.4 + 4.8$$

= 17.2 *meq*/100 *g*

With CEC, we can calculate the following (multiplying by 100 to get a percentage):

Base Saturation (%) = (*Base cations/CEC*) x 100

= (*12.4*/17.2) x 100

= **72**%

Calcium Saturation (%) = (*Calcium cations/CEC*) x 100

$$= (10/17.2)\ x\ 100$$

$$= \mathbf{58}\%$$

$$\text{Magnesium Saturation (\%)} = (\textit{Magnesium cations/CEC})\ x\ 100$$

$$= (2.0/17.2)\ x\ 100$$

$$= \mathbf{12}\%$$

Summary

Cation exchange capacity and base saturation are important soil measurements that help determine how a soil is managed and fertilized. While standard soil testing laboratories commonly calculate and report these values in soil test reports, it is helpful to have a solid understanding of CEC and base saturation calculations.

References

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