Cation Exchange Capacity (CEC)

CEC[1] is a calculated value that estimates the soils ability to attract, retain, and exchange nutrients with a positive electrical charge (cations). For a plant to absorb nutrients, they must be dissolved in the soil solution. When nutrients are dissolved, they are in a form called "ions". This simply means that they have electrical charges. As an example, table salt is sodium chloride ($NaCl$), when it dissolves it becomes two ions; one of sodium (Na^+) and one of chloride (Cl^-). The small + and - signs with the Na and the Cl indicate the type of electrical charges associated with these ions. In this example, the sodium has a plus charge and is called a "cation". The chloride has a negative charge and is called an "anion". Since, in soil chemistry, "opposites attract" and "likes repel", nutrients in the ionic form can be attracted to any opposite charges present in soil.

Clay and organic matter have a large number of negative charges on their surfaces, thus they attract positively charged cations. The total number of negatively charged sites comprises the Cation Exchange Capacity (CEC). Clay and organic matter are the contributors to higher CEC soils. At the same time, the negatively charged sites also repel negatively charged anion nutrients. The CEC of a soil is relatively constant unless large amounts of organic matter are added.

Some important elements with a positive electrical charge in their plant-available form include potassium (K^+), ammonium (NH_4^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), sodium (Na^+), zinc (Zn^+), manganese (Mn^{2+}), iron (Fe^{2+}), copper (Cu^+), Aluminium (Al^{3+}) and hydrogen (H^+). While hydrogen is not a nutrient, it affects the degree of acidity (pH) of the soil, therefore it is important. Aluminium and Sodium are also not nutrients but can be toxic or detrimental to balanced nutrient uptake.

Ca^{2+} Calcium (Ca^{++})
Mg^{2+} Magnesium (Mg^{++})
K^+ Potassium (K^+)
Na^+ Sodium (Na^+)
H Hydrogen (H^+)
Al Aluminium (Al^{+++})

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[1] AgVita reports the effective CEC = CECe. It is measured at actual soil pH, not at pH 8.2 as for CEC.
Both CEC measurements may pick up cations in solution as well as cations on exchange sites at pH > 7.2

When water is added to soil, cations can move into solution. They will still be attracted to the clay particle or organic matter surface and, as a result, 'swarm' around them. Positively charged ions capable of being readily substituted from the soil solution and onto the surface of a negatively charged soil particle, and vice-versa, are termed exchangeable cations. The exchangeable cations of most importance are shown in the table on the previous page. The size of the hydrated cation is indicated by the size of the circle containing the symbol, and the charge is indicated by the number of plus signs after the chemical symbol for the element (in brackets after the name).

The mechanism of adsorption and desorption (exchange) is important, even though less than 1% of cations may do this at any one time. This is because desorbed cations become available to plants. Cations such as Ca^{2+}, Mg^{2+}, K^+ and Na^+ maintain an equilibrium between adsorption to the negative sites and solution in the soil water (desorption). This equilibrium produces exchanges when one cation detaches from a site (leaving it free), another cation attaches to it. When adsorbed to soil particles, the leaching of these plant available nutrients is reduced.

The number of cation adsorption sites per unit weight of soil or the sum total of exchangeable cations that a soil can absorb, CEC, is expressed in milliequivalents (meq) per 100 g of oven dry soil.

$$\text{Equivalent weight} = \frac{\text{molecular or atomic wt (g)}}{\text{valence or charges per formula}}$$

To become available to a plant, a cation adsorbed on a clay particle must be replaced by a cation present in the soil solution. Plant roots facilitate this process by excreting a H^+ ion into the soil solution in order to exchange this for a cation (eg potassium - K^+). The cumulative effect of a hydrogen (H^+) ions being given up by a plant leads to soil acidification if the cation (e.g. K^+) is not replaced (e.g. via fertiliser).

The process of substitution or cation exchange occurs only when a cation in the soil solution moves into the hemisphere of motion of a cation located on the surface of a negatively charged particle. The charge of the cation and the size of the hydrated cation essentially govern the preferences of cation exchange equilibria. In summary, highly charged cations tend to be held more tightly than cations with less charge and secondly, cations with a small hydrated radius are bound more tightly and are less likely to be removed from the exchange complex.

Larger CEC values indicate that a soil has a greater capacity to hold cations. Therefore, it requires higher rates of fertiliser or lime to change a high CEC soil. When a high CEC soil has high cation levels, it offers a large nutrient reserve. However, when levels are poor, it can take a large amount of fertiliser or lime to correct this. A high CEC soil requires a higher absolute soil cation level to provide adequate crop nutrition than a low CEC soil. Low CEC soils hold fewer nutrients and will most likely be subject to leaching of mobile "anion" nutrients. They benefit from split applications of most nutrients. A particular CEC is neither good nor bad in itself. However, knowing what the CEC is can be a valuable management tool in regard to fertiliser amounts and timings.

Element	**Na^+**	**K^+**	**Ca^{2+}**	**Mg^{2+}**
Valence	1	1	2	2
Atomic weight	23	39	40	24
Equivalent weight	23/1=23	39/1=39	40/2=20	24/2=12
Meq wt	0.23	0.39	0.2	0.12

The average CEC for organic matter is:	200 meq/100g
The average CEC for clay is:	50 meq/100g

The CEC may be estimated from organic matter (OM) and clay content of a soil as follows:

$$\text{CEC} = (\%\ \text{OM} \times 200) + (\%\ \text{Clay} \times 50)$$

Typical CEC values are:

Sand = 0 - 3 meq/100 g
Loamy Sand to Sandy Loam = 3-10 meq/100 g
Loam = 10 - 15 meq/100 g
Clay Loam = 10 - 30 meq/100 g
Clay = > 30 (depends on type of clay)

- A high CEC value (>25) is a good indication that a soil has a high clay and / or organic matter content and can hold a lot of cations.
- A low CEC value (<5) is a good indication that a soil is sandy with little or no organic matter, thus cannot hold many cations.

Base Saturation and pH

The percentage Base Saturation describes the proportion of alkaline (or basic) cations in milliequivalents (meq bases[1]/CEC x 100).

The total acidity refers to the proportion of acidic cations[2] in milliequivalents (meq Saturation - meq H/CEC x100

Both together form the total cation saturation or CEC.

Example for CEC = 27 meq/100g (sum of cations):

Cation	**H^+ & Al^{3+}**	**Ca^{2+}**	**Mg^{2+}**	**K^+**	**Na^+**
meq/100g	9.4	14	3	0.5	0.1
% saturation or CEC	34.8	51.9	11	1.9	0.4
Base saturation %		65.2			
Total acidity %	34.8				

The base saturation and acidity information gives another tool to predict a soils ability to provide adequate crop nutrients, and indicate fertiliser or lime requirements

When the soil pH is above pH 7.2, there is "free" solution Ca, Mg, and/or Na (unattached to the soil exchange complex) in the soil that is unavoidably extracted by the soil testing process. Then the sum of the measured cation saturation's could add up to more than 100%. In the **expressSoil®** test the base saturation will show 100%, but the CEC value may be inflated.

Optimum Percent Saturation Ranges

There is some disagreement about the value of using "optimum" percent saturation ranges of soil cation nutrients. One school of thought is that it is very important for the soil to have a specific saturation, or ratio of saturations for each of the major cation nutrients (Ca, Mg, K). Practitioners of this approach will make recommendations designed to adjust the soil to specific saturation levels. The opposing view is that there can be a wide range of saturation for each of these major cations, with no significant benefit to having particular saturation levels or ratio of saturation levels as long as Sodium (Na) is not in excess. Evidence exists that the primary need is for the availability of an adequate absolute amount of each

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[1] Bases (basic cations): Calcium (Ca), Potassium (K), Magnesium (Mg), Sodium (Na),
Other cations: Iron (Fe^{2+}), Manganese (Mn^{2+}), Copper (Cu^{2+}), Zinc (Zn^{2+}) others

[2] Acidic cations: Hydrogen (H^+), Aluminium (Al^{3+})

nutrient, regardless of the resulting percent saturation, and that the desired cation saturation range can be quite broad. It has to be considered that an "ideal" percent saturation range or ratio of cations, will be affected by several other factors such as any unique characteristics of a plant species, the intended use of the plants, the nature of the soil itself, and others. We believe that both the ‘kg/ha’ or ‘mg/kg’ and the "percent saturation" approaches have some merit in different situations, and both should be considered in making recommendations, remembering that most plants tolerate a reasonably wide range of soil calcium to magnesium or potassium to magnesium ratios.

When the soil CEC is between 0 and about 3, the percent saturation has little agronomic meaning. The reason is that the holding power of the soil is so low that even a deficient amount of a cation could result in a relatively high saturation. In those cases, the soil test is telling us that we should consider making multiple split applications of relevant cations needed in large amounts, because the soil is unable to retain any significant amount from a single application.

Anion exchange capacity

Some nutrients have a negative electrical charge in their plant-available form. They are called anions and include nitrate (NO_3^-), phosphate ($H_2PO_4^-$ and HPO_4^{2-}), sulfate (SO_4^-), borate (BO_3^-), and molybdate (MoO_4^{2-}). Phosphates are unique among the negatively charged anions, as they are not mobile in the soil. They are highly reactive, and nearly all phosphorus (P) forms will combine with various elements or compounds in the soil other than clay and organic matter. The resulting compounds (e.g. ironphosphates, aluminium-phosphates or calcium-phosphates) are not soluble, thus they precipitate out of the soil solution. In this precipitated state, they are unavailable to plants and form the phosphorus "reserve" in the soil (P-fixing).

Soils in which the predominant colloids are oxides of Fe and Al (e.g. Ferrosols) may have a net positive charge. This creates opportunities for anion adsorption and exchange.

At sufficiently high pH, Fe and Al oxides can contribute to cation exchange capacity by acquiring extra hydroxyl (OH) groups. However, most soils abundant in Fe and Al oxides are naturally acidic and as such contribute to Anion Exchange Capacity.