Expressing cation exchange capacity in milliequivalents per 100 grams and in SI units[1]

John P. Reganold and James B. Harsh[2]

ABSTRACT

Many students in introductory soil science and soil chemistry courses have difficulty understanding the chemical concepts that are associated with expressing cation exchange capacity in either equivalent units or the International System of Units (SI). This paper is intended as a handout to help beginning soils students understand these chemical concepts using a step-by-step review of chemical units. The handout incorporates Avogadro's concept into the definitions of equivalent and gram-equivalent-weight in order to give the student a logical basis for understanding equivalents and their application to cation exchange. It also clarifies the use of SI units in expressing cation exchange capacity. Sample problems and solutions are provided to give students practice in this application. Although cation exchange capacity is expressed in milliequivalents per 100 grams (units which are still used in practically all introductory soil science texts), conversion of cation exchange capacity values in milliequivalents per 100 grams to SI units is relatively easy for the student once the concept of equivalent is learned.

Additional index words: **Equivalent, Gram-equivalent-weight, Soil chemistry.**

WE HAVE found that many students in introductory soil science and in soil chemistry courses have difficulty understanding the concept of equivalent and applying it to express cation exchange capacity in milliequivalents per 100 grams. Seven recently published introductory soil texts (1, 4, 5, 6, 7, 10, 14) and two soil chemistry texts (2, 3) do not explain this concept and these units in terms that many beginning soils students can easily comprehend. Brady (4) eschews equivalent units in favor of the current International System of Units (SI); his book is the only introductory soils text thus far that uses SI units. Some of these texts use the conventional definition of equivalent in terms of acid/base and redox reactions which are not particularly relevant to cation exchange reactions.

Although university chemistry is required prior to taking introductory soils at Washington State University, these chemistry classes also use definitions foreign to what is needed to define cation exchange capacity in soils classes. For acid/base and redox reactions, one equivalent is defined as the amount of substance that will react with Avogadro's number of hydrogen ions or with Avogadro's number of electrons, respectively, in a given chemical reaction. As a result, the definition of equivalent depends not only on the type of reaction (acid/base or redox) but on the specific reactants and products (2). For example, one *mole* of Hg can be considered to be either one or two *equivalents* of Hg depending on whether it is oxidized to Hg^+ or Hg^{2+}, respectively.

The inherent ambiguity in this treatment of the term causes general confusion among freshman chemistry students, and several recent introductory chemistry texts have dropped the term altogether (G. Crosby, personal communication, Dep. of Chemistry, Washington State University). No such ambiguity exists in the use of equivalents in cation exchange reactions if the definition is based on Avogadro's number (one mole) of charge without reference to hydrogen ions or electrons. We have, thus, developed a handout which teaches the student to understand and use equivalents to define cation exchange capacity (CEC) independent of what the student *may* have learned from freshman chemistry.

We have used the handout in the introductory soils class at Washington State University for the past two semesters. The students have responded well to the handout, and most of them could adequately answer similar CEC problems (to those on the handout) by semester's end as well as general questions on the important topic of cation exchange and cation exchange capacity. No comparison of the students' understanding of such CEC problems between the last two semesters (academic year 1983–1984) and any semester that preceded these last two was made because (i) a different instructor taught the course pre-academic year 1983–1984 and (ii) such CEC problems as on the handout were not asked of the students before the academic year 1983–1984. However, we have documented the usefulness of the handout through a student questionnaire and included the results of the questionnaire at the end of this paper.

The handout serves two purposes. First, it is intended to help the student understand conceptually why cation exchange capacity is measured in units of equivalents per unit mass, and then in SI units. Secondly, it provides a method for calculating the number of equivalents of an ion from the mass of a mole of the ion (gram-atomic-weight) and its ionic valence. Avogadro's number is used to develop the conceptual framework, but its use is avoided in the calculations because it is unnecessarily cumbersome.

---

[1] Contribution from the Dep. of Agronomy and Soil Science, Washington State Univ., Pullman, WA 99164-6420. Scientific Paper No.: SP 6728.

[2] Assistant professors of soil science, Washington State Univ., Pullman.

An argument for using Avogadro's concept to teach students how and why equivalents are used to define cation exchange capacity was developed by Thien (12). The success of this method was indicated by the students' dramatic improvement in handling cation exchange problems during examinations (12). Thien's method involves defining an equivalent as Avogadro's number (6.023×10^{23}) of charges. Conversions from equivalents to grams are then made by multiplying equivalents by 6.023×10^{23}, dividing the result by the number of charges per ion, and, finally, multiplying by the mass (in grams) per ion.

Thien avoids the use of equivalent weight, present in many introductory soil science textbooks, because obtaining equivalent weight in grams involves dividing atomic weight by valence, two "essentially unitless" relations. And yet, he presumably obtains his "charge per ion" term from the ionic valence and his "gram per ion" term by dividing atomic weight by Avogadro's number, two essentially unitless relations.

Furthermore, he argues that the use of equivalent weight is confusing because it must be explained to the student that ionic valence can only be used in its calculation if there are no redox reactions. Yet, this disclaimer is also required in his definition of equivalent. As a result, Thien (12) has not avoided the conceptual problems he set out to eliminate.

It is the purpose of this paper to suggest an alternative method to Thien's using the following definitions:

1. A mole of atoms, ions, molecules, or charges is 6.023×10^{23} atoms, ions, molecules, or charges.
2. Gram-atomic-weight is the mass in grams of a mole of atoms.
3. An equivalent is the amount of an ion containing a mole of charges.
4. Gram-equivalent-weight is the mass in grams of an equivalent of ions.

The term gram-equivalent-weight can then be used to convert from grams to equivalents without recourse to Avogadro's number. Since most students are already familiar with, for example, converting from grams to moles using gram-atomic-weight, this presents a logical analogy. No conceptual difficulty arises since the use of unitless terms has been avoided by defining gram-equivalent-weight and gram-atomic-weight in terms of the mass of a mole of ions or atoms (8).

The suggestion by Thien (12) that Avogadro's concept be used to explain equivalents to students grappling with the units and stoichiometry of cation exchange is an excellent one. The student handout below uses the concept repeatedly in taking the student through the chemical definitions to arrive at a simple formula for expressing cation exchange capacity and in explaining the value of the equivalent unit. This approach is offered as an alternative to requiring students to make all calculations on a per ion basis as suggested by Thien (12).

To summarize, our definitions and method of calculating CEC improve on those from traditional chemistry and soil science textbooks by:

1. Eliminating definitions from traditional chemistry based on electrons or protons which are relevant primarily to redox and acid-base reactions, respectively;
2. Eschewing unitless terms used by Thien (8) by employing gram-atomic- and gram-equivalent-weight definitions; and
3. Using a formula for calculating CEC which is based conceptually on Avogadro's number, but does not employ 6.023×10^{23} in the actual calculation.

One may argue whether "equivalent" should be used at all in an introductory soils course, given that some journals (e.g. *Soil Science Society of America Journal*) now permit only SI units in submitted papers and that the current trend in general chemistry is away from the unit. We would argue that as long as the term is in common usage in soil science, it should be taught at the introductory level. There are still journals which allow and even encourage the use of equivalents in defining CEC (e.g. *Clays and Clay Minerals*), and the term is incorporated into some of the most widely used cation selectivity coefficient expressions (11). We also feel that once students have mastered the expression of CEC in meq/100 g, teaching them to become equally conversive in SI units is relatively easy (12).

STUDENT RESPONSE TO THE HANDOUT

We documented the usefulness of the handout in Introductory Soil Science at Washington State University through a student questionnaire, which gave us an idea of the students' chemistry background and response to the handout. We found that although 83% of the 96 students that responded had taken introductory chemistry, 35% of them had been given a traditional chemistry definition of equivalent (i.e., based on acid-base or redox reactions), and 51% of them did not remember if they had been given a definition. Of the 35% of the students who had been given the traditional chemistry definition, 84% found the definition on our handout to be "far easier" or "somewhat easier" to understand. Ninety percent of all the students (including those who had not had introductory chemistry) rated the handout as being "very helpful" or "somewhat helpful" with regard to understanding CEC; only 10% found it "not helpful" or "confusing."

Four of the 27 students in upper division Soil Chemistry requested a copy of the handout to review their chemistry, so we also gave them the questionnaire. All four students had taken introductory chemistry, all found our definition on the handout "far easier" to understand than the chemistry definition, and all rated the approach on the handout with regard to understanding CEC and related calculations as "very helpful." In view of the straightforward approach to defining and calculating CEC and the favorable student response, we recommend the use of this handout to our peers teaching introductory soils courses. The handout will also be useful to any students needing to strengthen their background in use of basic chemical units.

THE STUDENT HANDOUT

Expressing Cation Exchange Capacity in Milliequivalents/100 Grams and in SI Units

The *cation exchange capacity* (CEC) of a soil is a measure of the negative charge of the solid phase of a soil balanced by exchangeable cations. This negative charge is usually expressed in milliequivalents per 100 grams (meq/100 g) of soil. The CEC of a silt loam soil, for example, might be 18 meq/100 g. To get a better understanding of how and why these units are used in expressing CEC, let's review our chemical units.

Part 1: Mole

The term *mole* is a quantity measurement of atoms, ions, molecules, or charge, and is equal to 6.023×10^{23} atoms, ions, molecules, or charges; e.g., one mole of H^+ equals 6.023×10^{23} H^+ ions or one mole of Ca^{2+} equals 6.023×10^{23} Ca^{2+} ions. So, one mole of H^+ has the same number of ions as one mole of Ca^{2+}; but one mole of H^+ has a *different mass* than one mole of Ca^{2+} because H^+ and Ca^{2+} have different atomic weights.

The Bottom Line: One mole of an ion equals 6.023×10^{23} ions.

Part 2: Gram-Atomic-Weight

The *gram-atomic-weight* of an atom is the mass of one mole of that atom expressed in grams. One mole of hydrogen weighs 1 g or 6.023×10^{23} hydrogen atoms weigh 1 g; so the gram-atomic-weight of H is 1 g. One mole of calcium weighs 40 g, so the gram-atomic-weight of Ca is 40 g. Since the mass of an electron is so small, the gram-atomic-weight of an ion[3] is no different than the mass of the element. Therefore, a mole of Ca^{2+} ions also weighs 40 g.

The Bottom Line: The gram-atomic-weight of an ion is the mass of one mole of that ion.

Part 3. Gram-Formula-Weight

The *gram-formula-weight* of a chemical compound or molecule is simply the mass of one mole of the compound or molecule or the sum of the gram-atomic-weights of the elements in its chemical formula. For example, the salt, $CaCl_2$, has a gram-formula-weight equal to the gram-atomic-weight of Ca plus two times the gram-atomic-weight of Cl (since there are two Cl^- ions in the formula). Thus, the gram-formula-weight of $CaCl_2$ is $40 + (2 \times 35) = 110$ g per mole of $CaCl_2$.

The Bottom Line: The gram-formula-weight of a chemical compound or molecule is simply the sum of the gram-atomic-weights of the elements or ions in its chemical formula.

Part 4: Charge and Ionic Valence

The *charge* of an ion is represented by its *ionic valence.* H^+ has a valence of "1+" and, therefore, one positive charge; Ca^{2+} has a valence of "2+" and, therefore, two positive charges. The number of charges associated with one mole of ions is obtained by multiplying its ionic valence by 6.023×10^{23}. So, one mole of H^+ has 6.023×10^{23} ions times one charge per ion $= 6.023 \times 10^{23}$ charges or one mole of charge. One mole of Ca^{2+} has 6.023×10^{23} ions times two charges per ion $= 12.046 \times 10^{23}$ charges or two moles of charge.

The Bottom Line: The amount of charge associated with one mole of an ion equals 6.023×10^{23} ions times its ionic valence (charge per ion).

Part 5: Equivalent

For the purpose of expressing cation exchange capacity, an *equivalent* of an ion may be defined as the quantity of that ion that contains one mole of charge (i.e., 6.023×10^{23} charges). For example, the quantity of H^+ that contains 6.023×10^{23} charges is 6.023×10^{23} ions or one mole of H^+. So, one equivalent of H^+ equals one mole of H^+.

The quantity of Ca^{2+} that contains 6.023×10^{23} charges is 6.023×10^{23} ions/2 or 1/2 mole of Ca^{2+}. (Remember that for every ion of Ca^{2+} there are two charges.) So, one equivalent of Ca^{2+} equals 1/2 mole of Ca^{2+}.

The relationship between equivalents and moles may now be expressed as follows: one equivalent of an ion is equal to one mole of that ion divided by its valence. As a final example, one equivalent of Al^{3+} equals one mole of Al^{3+} divided by 3; so, one equivalent of Al^{3+} equals 1/3 mole of Al^{3+}.

The Bottom Line: An equivalent of an ion is the quantity of that ion containing one mole of charge (i.e., 6.023×10^{23} charges).

Part 6: Gram-Equivalent-Weight

The *gram-equivalent-weight* of an ion is simply the mass of one equivalent of that ion. For example, the mass of one equivalent of H^+ is the same as the mass of one mole of H^+, since one equivalent of H^+ equals one mole of H^+ (from Part 5). The mass of one mole of H^+ is its gram-atomic-weight or 1 g. Thus, the gram-equivalent-weight of H^+ is 1 g.

The mass of one equivalent of Ca^{2+} is the same as the mass of 1/2 mole of Ca^{2+}, since one equivalent of Ca^{2+} equals 1/2 mole of Ca^{2+}. The mass of 1/2 mole of Ca^{2+} is 1/2 its gram-atomic-weight or 40 g/2 = 20 g. Thus, the gram-equivalent-weight of Ca^{2+} is 20 g.

The relationship between gram-equivalent-weight and gram-atomic-weight may be expressed as follows: the gram-equivalent-weight of an ion or molecule is equal to

---

[3] An ion is an atom that has gained or lost an electron(s) resulting in a negative or positive charge.

its gram-atomic-weight divided by its valence. Further examples of calculating gram-equivalent weight are listed below.

1. The gram-equivalent-weight of an element forming a simple ion (e.g., Ca^{2+} or K^+) is equal to its gram-atomic-weight divided by its valence (charge of the ion).

   Example: Al^{3+}, atomic weight = 27 g

   $$\text{Gram-equivlent-weight} = \\ = \frac{\text{Gram-atomic-weight}}{\text{Valence}} = \frac{27\text{ g}}{3} = 9\text{ g}$$

2. The gram-equivalent-weight of a complex ion (e.g., NH_4^+, NO_3^-, or SO_4^{2-}) is equal to its gram-formula-weight divided by the valence (charge of the complex ion).

   Example: NH_4^+, gram-formula-weight = 14 g + 4(1 g) = 18 g

   $$\text{Gram-equivalent-weight} \\ = \frac{\text{Gram-formula-weight}}{\text{Valence}} = \frac{18\text{ g}}{1} = 18\text{ g}$$

3. The gram-equivalent-weight of a compound (e.g., $CaCO_3$, K_2SO_4, $CaCl_2$) is often expressed as the gram-formula-weight divided by the total number of cation (+) *or* anion (−) charges associated with the chemical formula. For example, $CaCl_2$ contains a Ca^{2+} cation with two positive charges and two Cl^- anions with one negative charge each. Thus, the compound contains two positive and two negative charges.[4]

   Example: $CaCl_2$, gram-formula-weight = 40 g + 2(35) = 110 g

   $$\text{Gram-equivalent weight} \\ = \frac{\text{Gram-formula-weight}}{\text{Valence}} = \frac{110\text{ g}}{2} = 55\text{ g}$$

   It can be seen that the gram-equivalent-weight of a compound is based on the number of equivalents of cations *or* anions it will produce when completely dissolved in solution.

The Bottom Line: The gram-equivalent-weight of an ion or molecule is equal to its gram-atomic-weight divided by its valence.

Part 7: Milliequivalent and Gram-Milliequivalent-Weight

Since an equivalent is a large unit for clays, humus, and soil, it is more convenient to use a smaller unit, the milliequivalent. A *milliequivalent* (meq) equals 1/1000 of an equivalent. Also, the *gram-miliequivalent-weight* of an ion equals 1/1000 of a gram-equivalent-weight of that ion; e.g., Ca^{2+} has a gram-equivalent-weight of 20 g and a gram-milliequivalent-weight of 0.020 g (20/1000). Thus, while the gram-equivalent-weight of an ion yields 6.023×10^{23} charges, its gram-milliequivalent-weight yields 6.023×10^{20} charges.

Table 1. Gram-equivalent- and gram-milliequivalent-weights of the more important cations and anions in soils and of two compounds.

Cation or compound	Gram-atomic-weight or gram-formula-weight	Valence or total number of cation charges in compound	Gram-equivalent-weight	Gram-milliequivalent-weight†
	g		g	
H^+	1	1	1.0	0.001
Na^+	23	1	23.0	0.023
K^+	39	1	39.0	0.039
NH_4^+	18	1	18.0	0.018
Ca^{2+}	40	2	20.0	0.020
Mg^{2+}	24	2	12.0	0.012
Al^{3+}	27	3	9.0	0.009
NO_3^-	62	1	62.0	0.062
$H_2PO_4^-$	97	1	97.0	0.097
SO_4^{2-}	96	2	48.0	0.048
$CaCO_3$	100	2	50.0	0.050
$CaCl_2$	110	2	55.0	0.055

† Or one milliequivalent of an ion or compound weighs in grams.

Examples of gram-equivalent- and gram-milliequivalent-weights of the more important cations and anions in soils and of two compounds are shown in Table 1.

The Bottom Line: The gram-milliequivalent-weight of an ion equals 1/1000 of the gram-equivalent-weight of that ion.

Part 8: Milliequivalents/100 Grams of Soil

From the principle of electrostatic neutrality, we know that each negative charge on a soil particle must be balanced by a positive charge from an adsorbed or dissociated cation.[5] The cation exchange capacity is a measure of adsorbed cations that can be displaced by exchange with other cations. The CEC of a soil is expressed in units of milliequivalents per 100 grams of a soil which results in a number, usually between 1 and 100 meq/100 g soil.

Milliequivalents of cations are used instead of moles or grams (weight) of cations because milliequivalents directly measure the number of negative sites balanced by exchangeable cations in a given 100 gram soil sample. Therefore, they give the same value of the cation exchange capacity regardless of the cations being adsorbed.[6] One milliequivalent of cation "X" (e.g., Na^+) neutralizes the same number of cation exchange sites as one milliequivalent of cation "Y" (e.g., Ca^{2+}).

The number of moles of any cation per 100 g of soil that would balance a given number of negative sites

---

[4] For any chemical compound, the number of cation charges must equal the number of anion charges according to the principle of electrostatic neutrality.

[5] Dissociated cations are separated from the clay surface by several layers of water, yet they can contribute to balancing the negative charges on a soil particle.

[6] Sometimes there are experimental difficulties in obtaining exactly the same CEC with different cations but these have nothing to do with the units used.

would not be the same for any cation because different cations may exhibit different charges (valences). For example, 100 g of the above soil, if saturated with Na^+, would adsorb 50 millimoles (1/1000 of a mole) of exchangeable Na^+ because 50 millimoles of Na^+ equals 50 meq of Na^+. However, 100 g of this same soil, if saturated with Ca^{2+}, would adsorb only 25 millimoles of exchangeable Ca^{2+} because 25 millimoles of Ca^{2+} equals 50 meq of Ca^{2+}.

Likewise, the number of grams of any exchangeable cation per 100 g of soil would not be the same for any cation because different cations have different gram-atomic-weights. If gram-atomic-weights were used, 1 g of cation "X" (e.g., Na^+) would *not* neutralize the same number of cation exchange sites as one gram of cation "Y" (e.g., Ca^{2+}). Measuring the CEC in meq of cations per 100 g of soil keeps the CEC value the same regardless of what cations neutralize the site.

The Bottom Line: The CEC of a soil is expressed in terms of milliequivalents (meq) of exchangeable cations per 100 g of soil.

Part 9: Expressing CEC in Terms of the International System of Units

The International System (SI) of Units was introduced in science to provide a self-consistent system that would eliminate the problems associated with scientists in different fields and from different parts of the world using disparate units (13). Recently, several journals (e.g., *Soil Science Society of America Journal*) have begun to require that only SI units be used in research publications. The CEC of a soil is expressed in SI units in terms of the amount of charge per unit mass of soil. The equivalent unit is not used in the SI. Instead, we express the amount of charge in terms of the mole (abbreviated mol). For the convenience of being able to express CEC so that it is numerically equivalent to meq/100 g, we usually use cmol (+) kg^{-1} of positive charge. The "+" refers to the charge on a proton and, thus, specifies *positive* charge. Likewise, units of negative charge are designated (−) or the charge on an electron. Note that the mass unit used, by convention, is the kilogram (kg) and that the slash ("/") signifying "per" has been eliminated in favor of the superscript "−1".

From Part 1, one mole of charge is provided by 1 mole of H^+, NH_4^+, or any other monovalent cation, by 1/2 mole of Ca^{2+}, Mg^{2+}, or other divalent cation, and by 1/3 mole of Al^{3+} or other trivalent cation. Thus, if a soil has a CEC of 15 cmol (+) kg^{-1}, 1 kg of this soil is capable of adsorbing 15 cmol of H^+ ion, for example, and of exchanging it with 15 cmol of another monovalent cation (e.g., NH_4^+ or K^+), or with 7.5 cmol of a divalent cation (e.g., Ca^{2+} or Mg^{2+}), or with 5 cmol of a trivalent cation (e.g., Al^{3+}). In each situation, the 15 cmol of negative charge associated with 1 kg of soil is attracting 15 cmol of positive charge, whether they come from 15 cmol of monovalent cations, from 7.5 cmol of divalent cations, or from 5 cmol of trivalent cations.

In order to maintain consistency in the amount of charge irrespective of the cation used, we always refer to *the fraction of the ion that possesses one mol of charge.* For example, one-half mol of Mg^{2+} possesses one mol of charge, so we refer to the amount of Mg^{2+} on exchange sites in terms of moles of 1/2 Mg^{2+} or mol (1/2 Mg^{2+}). Therefore, 15 meq/100 g of exchangeable Mg^{2+} would be expressed as 15 cmol (1/2 Mg^{2+}) kg^{-1}. To express meq/100 g as cmol kg^{-1}, you need only change meq M^{n+} to cmol (1/n M^{n+}). For examples:

$$10 \text{ meq } K^+/100 \text{ g} = 10 \text{ cmol } (K^+) \text{ kg}^{-1}$$
$$10 \text{ meq } Ca^{2+}/100 \text{ g} = 10 \text{ cmol } (1/2\ Ca^{2+}) \text{ kg}^{-1}, \text{ and}$$
$$10 \text{ meq } Al^{3+}/100 \text{ g} = 10 \text{ cmol } (1/3\ Al^{3+}) \text{ kg}^{-1}.$$

Table 2 lists representative values and common ranges of cation exchange capacities in both meq of cations/100 g of soil and cmol of positive charge (+) kg^{-1} of soil for clay minerals and humus.

Table 3 lists representative cation exchange capacities and amounts of individual exchangeable cations of a variety of soils in the United States (9). Nine of the 10 different U.S. taxonomic orders are represented; only

Table 2. Representative values and common ranges of cation exchange capacities of clay minerals and humus.

Clay mineral or humus	Cation Exchange Capacity Representative value	 Common range
	meq/100 g or cmol (+) kg^{-1}	
Kaolinite†	8	3–15
Chlorite	30	15–40
Illite	30	15–40
Montmorillonite	80	60–100
Allophane†	100	50–200
Vermiculite	125	80–150
Humus†	200	100–300

† The actual CEC value will be dependent on the pH of the solution in which the clay mineral or humus is being analyzed.

Table 3. Representative cation exchange capacities and amounts of individual exchangeable cations in surface horizons of a variety of soils in the United States.†

Soil	CEC	Ca^{2+}	Mg^{2+}	Na^+	K^+	Al^{3+}, H^+
	meq of cations/100 g or cmol (+) kg^{-1} of soil					
Mollic Haploxeralf, sandy loam, California	16.1	8.8	4.2	0.5	0.6	2.0
Typic Natrargid, fine sandy loam, Arizona	8.2‡	16.8	1.6	2.0	1.0	--
Typic Ustipsamment, sand, Kansas	5.2	1.9	1.2	trace	0.3	1.8
Typic Dystrochrept, silt loam, West Virginia	23.4	6.5	1.6	<0.1	0.6	14.7
Typic Cryoboroll, clay loam, Montana	52.4	28.5	6.0	--	2.1	15.8
Typic Torrox, silty clay, Hawaii	23.5	6.0	3.0	0.3	0.4	13.8
Typic Haplorthod, fine sandy loam, New Hampshire	25.7	2.9	0.2	trace	trace	22.6
Typic Albaquult, sandy loam, Georgia	14.6	1.8	0.9	0.1	0.1	11.7
Entic Pelludert, clay, Texas	36.9	15.7	6.0	1.2	0.4	13.6

† These data were gathered from the USDA Agric. Handb. No. 436 (9).

‡ The measured CEC may differ under certain conditions including variable pH, the presence of soluble minerals, the fixation of some cations, and the existence of exchangeable complexes (e.g., $CaCl^+$).

the order, Histosols (organic soils), is excluded. Table 3 illustrates that Ca^{2+} ions are usually the dominate exchangeable cation. Although Al^{3+} and H^+ ions are placed together (as they were in the original USDA data), the Al^{3+} ions are in much greater concentration on the exchange complex than the H^+ ions.

The Bottom Line: To convert to SI units (cmol kg^{-1}) from meq/100 g for any exchangeable cation (M^{n+}), change meq M^{n+} to cmol (1/n M^{n+}).

Sample Problems and Solutions

1. What is the gram-equivalent-weight and gram-milli-equivalent-weight of HPO_4^{2-} and KCl?
Solution:

	Gram-atomic- or gram-formula-weight	Valence	Gram-equivalent-weight	Gram-milli-equivalent-weight
HPO_4^{2-}	96 g/mole	2	96/2 = 48 g/equiv.	48/1000 = 0.048 g/meq
KCl	74 g/mole	1	74/1 = 74 g/equiv.	74/1000 = 0.074 g/meq

2. 100 g of a soil has the following cations on the exchange sites:

1 meq H^+ 6 meq Ca^{2+} 1 meq Na^+
5 meq Al^{3+} 2 meq Mg^{2+} 1 meq Na^-

a) What is the CEC of this soil in meq/100 g soil?
Solution: Since we have 100 g of soil, simply adding the milliequivalents of exchangeable cations equals the CEC as follows: 1 + 5 + 6 + 2 + 1 + 1 = 16. So, the CEC is 16 meq/100 g soil.

b) What is the CEC of this soil in cmol kg^{-1} soil?
Solution: 16 meq/100 g soil = 16 cmol (+) kg^{-1} soil.

c) What is the percentage base saturation of the soil?
Solution: H^+ and Al^{3+} are acid-forming cations which total 6 meq. Ca^{2+}, Mg^{2+}, K^+, and Na^+ are basic-forming cations which total 10 meq.

$$\begin{aligned}\text{\% base saturation} &= \frac{\text{amount of exchangeable bases}}{\text{CEC}} \times 100\% \\ &= \frac{10\text{ meq}/100\text{ g}}{16\text{ meq}/100\text{ g}} \times 100\% = 62.5\%.\end{aligned}$$

d) How many grams of Mg^{2+} are in this 100 g soil sample?
Solution: There are 2 meq Mg^{2+} in this 100 g soil sample. From Table 1 we find that 1 meq Mg^{2+} weighs 0.012 g. So, 2 meq Mg^{2+} weighs 0.024 g. Thus, there are 0.024 g of Mg^{2+} in this 100 g soil sample.

e) How many pounds of Mg^{2+} are in one acre-furrow slice[7] of this soil? (Note: for mineral soils, there are approximately 2 million lb of soil per acre-furrow slice.)
Solution:

$$\frac{0.024\text{ g }Mg^{2+}}{100\text{ g soil}} = \frac{X\text{ lb }Mg^{2+}}{2\,000\,000\text{ lb soil}}\ .$$

Thus,

$$X = \frac{(2\,000\,000)\,(0.024)}{100} = 480\text{ lb }Mg^{2+}.$$

There are 480 lb Mg^{2+}/acre-furrow slice.

3. If 100 g of a mineral soil has 15% montmorillonite clay, 5% illite clay, and 4% humus, what would be the "approximate" CEC of the soil in cmol (+) kg^{-1}?
(Assume from Table 2 that the CEC's of montmorillonite, illite, and humus are 80, 30, and 200 cmol (+) kg^{-1}, respectively.)
Solution: Montmorillonite → 0.15 × 80 cmol (+) kg^{-1} = 12.0 cmol (+) kg^{-1}
Illite → 0.05 × 30 cmol (+) kg^{-1}
= 1.5 cmol (+) kg^{-1}
Humus → 0.04 × 200 cmol (+) kg^{-1}
= 8.0 cmol (+) kg^{-1}

Adding CEC contributions from montmorillonite, illite, and humus: 12.0 + 1.5 + 8.0 = 21.5 cmol (+) kg^{-1}. The approximate CEC of the soil is 21.5 cmol (+) kg^{-1} soil.

4. A farmer, wanting to know if potassium (K^+) fertilizer is necessary for the soil, has several surface soil samples analyzed for potassium. The laboratory analyses result in an average exchangeable potassium value of 0.12 cmol (K^+) kg^{-1} soil. Assuming the farmer is planting corn (*Zea mays* L.) and will need at least 160 kg of exchangeable K^+ per hectare to a 15-cm depth to get a good yield, will she/he need to add K^+ fertilizer to get this "good" yield? (Note: Assume for mineral soils that there are 2 million kg of soil per hectare-15 cm depth.)
Solution: We know how much K^+ we have in 1 kg of soil → 0.12 cmol (K^+) kg^{-1} soil. We need to find out how much K^+ in kilograms is present in a hectare to a 15-cm depth. If it's less than 160 kg/ha-15 cm, then we need to add some K^+ fertilizer.
Step 1: We need to convert 0.12 cmol (K^+) to kilograms K^+. From Table 1, we find that 1 meq K^+ = 0.039 g K^+. We also know that 1 meq K^+ = 1 mmol (K^+) = 0.1 cmol (K^+). So, 0.1 cmol (K^+) = 0.039 g. But we have 0.12 cmol (K^+); so

$$\frac{0.1\text{ cmol }(K^+)}{0.039\text{ g}} = \frac{0.12\text{ mmol }(K^+)}{X\text{ g }K^+}.$$

---

[7] The furrow slice is that portion of the soil that is turned or "sliced" when the soil is plowed and cultivated. One acre-furrow slice is a volume measurement and means 1 acre of land to a depth of about 6⅔ inches.

Thus,

$$X = \frac{(0.12)(0.039)}{0.1} = 0.047\text{ g}.$$

So, we have 0.047 g K^+ kg^{-1} soil, or 4.7×10^{-5} kg K^+ kg^{-1} soil.

Step 2: Let's convert kg K^+/kg soil to kg K^+/ha-15 cm depth soil. (Remember that 2 million kg of soil = 1 ha-15-cm depth.)

$$\frac{4.7 \times 10^{-5}\text{ kg K}^+}{\text{kg soil}} = \frac{Y\text{ kg K}^+}{2 \times 10^6\text{ kg of soil}}$$

Thus,

$$Y = \frac{(2 \times 10^6)(4.7 \times 10^{-5})}{1} = 94\text{ kg K}^+.$$

There are 94 kg exchangeable K^+ per hectare to a 15 cm depth. 94 kg exchangeable K^+ < 160 kg exchangeable K^+; thus, add K^+ fertilizer.

5. A soil has a percentage base saturation (% BS) of 70 and a cation exchange capacity of 28 meq/100 g of soil. To raise the percentage base saturation to 95, how many pounds of $CaCO_3$ should be added per acre-furrow slice? (Assume that the CEC is not a function of pH for this calculation and that 100% of the $CaCO_3$ is soluble; i.e., all of the $CaCO_3$, when added to the soil, will eventually dissolve to form Ca^{2+} ions and CO_3^{2-} ions.)

   Solution: To raise the % BS from 70 to 95, we need to replace with Ca^{2+} from $CaCO_3$ that portion of the cation exchange sites holding Al^{3+} and H^+. That portion is equal to 25% of the cation exchange sites or capacity, because 95% − 70% = 25%. A total of 25% of the CEC = (0.25) (28 meq/100 g soil) = 7 meq/100 g soil.

   So, 7 meq Al^{3+} and H^+/100 g soil need to be replaced by Ca^{2+} from $CaCO_3$ to bring the % BS up from 70 to 95. And 1 meq of $CaCO_3$ weighs 0.050 g; so, 7 meq of $CaCO_3$ weigh 0.35 g. Thus, 0.35 g $CaCO_3$/100 g soil will replace 7 meq H^+ and Al^{3+}/100 g.

   However, we want our answer in pounds of $CaCO_3$ per acre-furrow slice. (Remember 1 acre-furrow slice = 2×10^6 lb soil.)

$$\frac{0.35\text{ g CaCO}_3}{100\text{ g soil}} = \frac{X\text{ lb CaCO}_3}{2 \times 10^6\text{ lb of soil}}.$$

Thus,

$$X = \frac{(2 \times 10^6)(0.35)}{100} = 7000\text{ lb CaCO}_3.$$

We need to add 7000 lb $CaCO_3$.

REFERENCES

1. Berger, K. C. 1965. Introductory soils. MacMillan Co., New York. p. 84.
2. Bohn, H. L., B. L. McNeal, and G. A. O'Connor. 1979. Soil chemistry. John Wiley and Sons, New York. p. 18–24.
3. Bolt, G. H., and M. G. M. Bruggenwert. Ed. 1976. Soil chemistry a. basic elements. Elsevier Scientific Publishing Co., Amsterdam. p. 55–56.
4. Brady, N. C. 1984. The nature and properties of soils. 9th ed. MacMillan Co., New York. p. 175–179.
5. Donahue, R. L., R. W. Miller, J. C. Shickluna. 1983. Soils, an introduction to soils and plant growth. 5th Ed. Prentice-Hall, Inc., Englewood Cliffs, NJ. p. 99–106.
6. Foth, H. D. 1984. Fundamentals of soil science. 7th ed. John Wiley & Sons, New York. p. 192–196.
7. Hausenbuiller, R. L. 1985. Soil science, principles and practices. 3rd Ed. W. C. Brown Co., Dubuque, IA. p. 148–152.
8. Pauling, L. 1970. General chemistry. 3rd ed. W. H. Freeman, San Francisco. p. 96.
9. Soil Survey Staff. 1975. Soil taxonomy, a basic system of soil classification for making and interpreting soil surveys. USDA Soil Conservation Service. Agric. Handb. No. 436. U.S. Government Printing Office, Washington, DC.
10. Sopher, C. D., and J. V. Baird. 1978. Soils and soil management. Reston Publishing Co., Reston, VA. p. 81–82.
11. Sposito, Garrison. 1981. Cation exchange in soils: an historical and theoretical perspective. *In* D. E. Baker et al. (ed.) Chemistry in the soil environment. Soil Science Society of America, Inc., Madison, WI.
12. Thien, S. J. 1977. Avogadro's concept of equivalents for teaching cation exchange capacity. J. Agron. Educ. 6:35–37.
13. ----, and J. D. Oster. 1981. The international system of units and its particular application to soil chemistry. J. Agron. Educ. 10:62–70.
14. Thompson, L. M., and F. R. Troeh. 1973. Soil and soil fertility. 3rd ed. McGraw-Hill Co., New York. p. 152–155.