

# Calculation of the Dielectric Properties of Temperate and Tropical Soil Minerals from Ion Polarizabilities using the Clausius–Mosotti Equation

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## ABSTRACT

Soil dielectric properties are commonly used to estimate soil water content, however, the relative permittivity of common soil minerals is often unknown or estimated to be 5, similar to quartz (4.6). In this study, the Clausius–Mosotti model is used to estimate mineral relative permittivity from atomic polarizability for common soil minerals. Atomic polarizabilities are used to calculate the average mineral polarizability using the oxide additivity rule. Results of these calculations are compared with measurements found in the literature for rock and mineral samples. Predictions correspond well with measurements on single crystals or obtained using the immersion method to determine relative permittivity (better than 10%). The application of this simple calculation technique allows estimates of relative permittivity to be obtained for minerals for which it is difficult to measure relative permittivity directly, such as soil clay minerals.

ELECTROMAGNETIC measurement techniques have become popular for obtaining estimates of soil water content. Time domain reflectometry is commonly used for sample scale measurements in the laboratory and field (Topp et al., 2002; Robinson et al., 2003) and techniques such as ground penetrating radar are being used to obtain two-dimensional estimates of profile soil water content in field applications (Binley et al., 2001; Huisman et al., 2001). Such techniques measure the propagation velocity of electromagnetic waves, which are closely related to the relative permittivity, referred to here after simply as the permittivity, of the medium through which they travel:

$$v_p = \frac{1}{\sqrt{\mu_0 \mu_r \epsilon_0 \epsilon_r}} = \frac{c}{\sqrt{\mu_r \epsilon_r}} \quad [1]$$

where  $c$  is the velocity of light ( $3 \times 10^8 \text{ ms}^{-1}$ ),  $\epsilon_0$  is the permittivity of vacuum ( $8.854 \text{ pF m}^{-1}$ ),  $\epsilon_r$  is the relative permittivity,  $\mu_0$  is the magnetic permeability of vacuum ( $1.257 \times 10^{-6} \text{ H}$ ), and  $\mu_r$  is the relative magnetic permeability.

A strong relationship between the permittivity measured by these methods and water content of soils arises due to the difference between the permittivity of the soil constituents and water. Air has a permittivity of 1, water is 78.5 at atmospheric pressure and 25°C, and soil minerals commonly fall in the category of 4.5 to 10. To obtain the best determination of water content, grain scale models are being developed and tested that predict the permittivity of porous media and soils based on the soil constituents and their geometrical arrangement

(Sen et al., 1981; Friedman, 1998; Jones and Friedman, 2000; Robinson and Friedman, 2002a). An important input for these models is the value of the permittivity of the mineral phase. An average value is difficult to measure directly and thus the mineral permittivity is often assigned a value of 5 based on reported values of rock permittivity (Friedman, 1998). Hence the mineral permittivity essentially remains a fitting parameter, which is undesirable for testing models.

A recent application of electromagnetic sensors has been to search for and locate buried objects such as unexploded ordnance (UXO). In this application, techniques such as ground penetrating radar exploit the contrast between the dielectric properties of a target and the dielectric properties of the background soil, usually under wet conditions (Das et al., 2001). In temperate soils dominated by quartz, standard calibrations between permittivity and water content may suffice to indicate dielectric contrast. However, in tropical soils where metal oxides may be dominant these relationships may need adjustment. To place bounds on the possible adjustment that might be required an initial step is to estimate permittivity values of oxide minerals often found in tropical soils; in this paper we provide such estimates.

## MATERIALS AND METHODS

### Methods of Measuring Mineral Dielectric Permittivity

A variety of methods exist for measuring the permittivity of minerals. These are in increasing order of accuracy, repacked granular sample (Nelson, 1992), dielectric immersion (Schmidt, 1902; Andeen et al., 1970; Robinson and Friedman, 2003), the three-terminal guarded electrode method (Lowndess and Martin 1969), and the two-terminal method (Subramanian et al., 1989). The repacked granular sample method is fast. However, it relies on the use of a dielectric mixing model to estimate the permittivity of a granular sample packed in air, by extrapolating the permittivity values back to zero porosity. This method is undesirable as the accuracy can vary depending on the choice of model (Robinson and Friedman, 2003). The immersion technique has been found to have accuracies of about 10% and better for coarse-grained materials according to Robinson and Friedman (2003). Measurement becomes difficult in clays due to adsorption of the immersion dielectric on the clay surfaces and its reduced permittivity, air entrapment in samples can also create difficulties (Robinson, 2004). Smectites present a particular problem as the immersion dielectric fluid can be adsorbed onto the internal surface of the mineral and so have its permittivity reduced. The assumption of a bulk permittivity for the liquid then becomes invalid. Accuracies of the three terminal and two terminal methods have been found to be 0.5 and 0.01%, respectively (Bussey et al., 1964; Andeen et al., 1970). These techniques however, are only suited to single crystal samples that are cut and pre-

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pared for direct measurement. This technique cannot be used to measure the permittivity of clay minerals for example.

### Minerals in Soils

Soils tend to pose two distinct problems for the determination of mineral permittivity. The mineralogy is often fine grained and is usually a mixture of different minerals. As previously discussed clay minerals can present particular problems for dielectric measurement methods. In the case of the second problem, results indicate (Robinson and Friedman, 2002b) that the effective permittivity of the mineral phase of a soil can be predicted using the arithmetic average of the mineral components, and their permittivities, so long as the mineral permittivity contrast is less than about 4.

### Tectosilicates

The silica group exists as seven distinct polymorphs in nature (Drees et al., 1989). Quartz is the most dominant form in soils, especially in temperate zone soils. Disordered cristobalite is also found in some soils. Measurements of the permittivity of quartz appear to range in the geology literature between 4.19 and 5.0 (Keller, 1989). Due to its importance in soils a number of calculations are performed from data for silica minerals. Calculations are also performed for orthoclase feldspar. Feldspar is a primary mineral but often found in many soils inherited from parent materials (Huang, 1989).

### Phyllosilicates

Phyllosilicates found in soils are in the mineral groups of kaolin (kaolinite, dickite, and nacrite), mica (muscovite, biotite, phlogopite, and illite), and the smectites (montmorillonite, beidellite, and nontronite) (Allen and Hajek, 1989). Other phyllosilicates found occasionally in soils include, talc and pyrophyllite. Literature permittivity values for the clay minerals vary greatly with reported values between 5 and 10 (Olhoeft, 1981). The variation in these values is most likely due to poor measurement method and the effects of hygroscopic water contained in samples; this raises observed values of permittivity. Calculations are performed on a range of phyllosilicates to give a feel for expected permittivity values.

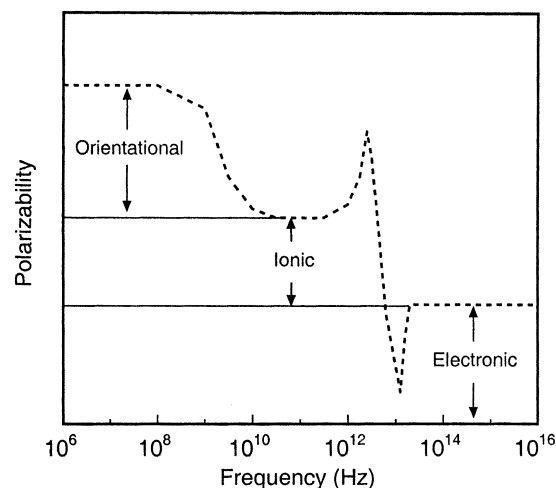
### Oxides and Hydroxides

Oxides and hydroxide minerals are an important component of many tropical soils (Allen and Hajek, 1989). The aluminum oxide gibbsite and the iron oxide goethite are considered the most common oxide minerals found in soils. Lepidocrocite tends to be associated with gley soils where as hematite tends to be found in well-drained soils in warmer climates. Other oxides including, magnetite, ilmenite, and anatase can also be found in soils but tend to result from weathering of parent material that contains those minerals.

## THEORETICAL CONSIDERATIONS

### Polarization

Polarization mechanisms in solids can be divided into three major categories: electronic, ionic, and orientational; the frequency range in which these mechanisms primarily operate is presented in Fig 1. In the radio and microwave frequency bandwidths all these mechanisms can operate. Orientational polarization is assumed to be negligible in dehydrated soil minerals as it arises due to the presence of permanent dipoles. It is a mechanism associated with water and other polar liquids.



**Fig. 1. A schematic diagram of the major polarization mechanisms in the frequency spectrum. The contribution to mineral permittivity comes mostly from electronic and ionic polarizability. Relaxation of orientational polarization usually occurs in the microwave frequency region or lower ( $10^{10}$  Hz) and ionic relaxation usually takes place in the infrared ( $10^{13}$  Hz).**

It is thus the combination of electronic and ionic polarizabilities that is of most interest to determine the mineral polarizability. The link between the mineral dielectric polarizability,  $\alpha_D$ , and the measured real part of the relative permittivity,  $\epsilon'_r$ , is given by the Clausius–Mosotti equation:

$$\alpha_D = \frac{1}{b} \left[ \frac{V_m(\epsilon'_r - 1)}{\epsilon'_r + 2} \right] \quad [2]$$

Where  $V_m$  is the molar volume in cubic angstroms,  $b$  is defined as  $4\pi/3$ , and  $\epsilon'_r$  is the real part of the complex dielectric permittivity (Shannon, 1993). The model assumes an isotropic distribution of spherical atoms in space and all the calculated values of permittivity are average values, taking no account of crystal orientation. This value is sufficient for granular materials where the assumption of isotropy at the sample scale is reasonable. The molecular volume  $V_m$  can be calculated by dividing the molar volume by Avogadro's number. Molar volumes for many minerals can be found in Weast (1984) for example. This method of calculating mineral permittivity has been used with some success to predict the permittivity of a variety of oxide minerals (Shannon et al., 1991a, 1991b, 1992; Shannon and Rossman, 1992).

### The Additivity Rule

The additivity rule allows the summation of molecular (Heydweiller, 1920) or ion (Shannon, 1993) polarizabilities to give the substance dielectric polarizability. Conversely, complex solids can be broken down to reveal molecular polarizabilities:

$$\alpha_D(M_2M'X_4) = 2\alpha_D(MX) + \alpha_D(M'X_2) \quad [3]$$

where  $M$  and  $M'$  represent cations and  $X$  represents the complementary anion in the substance, for instance  $\alpha_D(\text{Mg}_2\text{SiO}_4) = 2\alpha_D(\text{MgO}) + \alpha_D(\text{SiO}_2)$ . Chemical formulae can be further subdivided into individual ion polarizabilities,  $\alpha$ :

$$\alpha_D(M_2M'X_4) = 2\alpha(M^{2+}) + \alpha(M'^{4+}) + 4\alpha(X^{2-}) \quad [4]$$

So that  $\alpha_D(\text{Mg}_2\text{SiO}_4) = 2\alpha(\text{Mg}^{2+}) + \alpha(\text{Si}^{4+}) + 4\alpha(\text{O}^{2-})$ . Most recently Shannon (1993) used measurements of the permittivity of high quality crystals of known orientation to develop a data set of ion polarizabilities. This data set was then used to

**Table 1. The polarizability of ions based on data taken from Shannon (1993).**

Ion polarizabilities from oxides and fluorides (data from Shannon [1993])											
Cations ( $\alpha$ cubic angstroms)									Anions ( $\alpha$ cubic angstroms)		
+1		+2		+3		+4		+5		-1	
Li	1.20	Be	0.19	B	0.05	Si	0.87	P	1.22	F	1.62
Na	1.80	Mg	1.32	Al	0.79	Ge	1.63	As	1.72	OH	2.27
K	3.83	Zn	2.04	Ga	1.50	Ti	2.93	V	2.92		
Rb	5.29	Ni	1.23	Cr	1.45	Sn	2.83	Nb	3.97		
Cs	7.43	Co	1.65	Fe	2.29	Zr	3.25	Ta	4.73	-2	
Tl	7.28	Fe	2.23	In	2.62	Ce	3.94			O	2.01
		Cu	2.11	Sc	2.81	U	4.45				
		Mn	2.64	Y	3.81	Th	4.92				
		Ca	3.16	Lu	3.64	Te	5.23				
		Sr	4.24	Yb	3.58						
		Ba	6.40	Tm	3.82						
		Cd	3.40	Er	3.81						
		Pb	6.58	Ho	3.97						
		Eu	4.83	Dy	4.07						
				Tb	4.25						
				Gd	4.37						
				Eu	4.53						
				Sm	4.74						
				Nd	5.01						
				Pr	5.32						
				La	6.07						
				Ce	6.15						
				Sb	4.27						
				Bi	6.12						

predict the permittivity of minerals of known composition and structure. The approach proved accurate for simple oxides allowing permittivity calculation to within 2 to 3% of measured values. This level of accuracy is better than can be measured using techniques such as immersion or repacking of granular samples. Shannon (1993) used deviation between measured and modeled results to gain insight into polarization mechanisms in minerals that weren't described by the Clausius–Mosotti model.

## RESULTS AND DISCUSSION

The values of ion polarizabilities presented in Table 1 were used in the Clausius–Mosotti equation to predict mineral permittivity of a range of soil minerals according to:

$$\epsilon'_i = \frac{(3V_m + 8\pi\alpha_D)}{(3V_m - 4\pi\alpha_D)} \quad [5]$$

### Tectosilicates

Calculations of the permittivity of SiO<sub>2</sub> group minerals and orthoclase feldspar are presented in Table 2. The values for  $\alpha$ -quartz can be compared with measurements made with single crystals using a capacitance technique. Values of 4.5208 and 4.6368 were reported by Fontanella

et al. (1974) for the different axial directions. Thus an average value between these limits is to be expected for crystalline samples with a density of 2.65 g cm<sup>-3</sup>. This compares very favorably with the modeled permittivity value of 4.6, which does fall within these values. Measured values of 4.09 and 4.27 are given for bipyramidal quartz in Carmichael (1982), again close to the calculated value of 4.3. Measured values for cristobalite couldn't be found in the literature. However, the indication from this data and the modeling is that the more open structures would lead to lower permittivity values. The value of 4.6 estimated for orthoclase feldspar can be compared with values presented in Carmichael (1982). These values were, 5.55, 5.80, and 4.5 for the a, b, and c axial directions, respectively. A value of 4.6 appears a little low but corresponds within the bounds of these measured values.

### Phyllosilicate Minerals

Measurements of the permittivity of the clay minerals are uncommon in the literature. This is possibly because of the difficulty associated with obtaining reliable measurements. Table 3 presents a collection of values obtained from the literature from a number of sources. The values presented in Column G (Robinson, 2004)

**Table 2. Tectosilicates, values used for the molar volume,  $V_m$ , and mineral polarizability,  $\alpha_D$ .**

Mineral name	Mineral formula	X-ray density	$V_m$	$\alpha_D$	Estimated permittivity
		g cm <sup>-3</sup>			
		<u>SiO<sub>2</sub> group</u>			
$\alpha$ -quartz	SiO <sub>2</sub>	2.6483	37.674	4.89	4.6
$\beta$ -quartz	SiO <sub>2</sub>	2.533	39.389	"	4.3
$\alpha$ -cristobalite	SiO <sub>2</sub>	2.3344	42.740	"	3.8
$\beta$ -cristobalite	SiO <sub>2</sub>	2.1944	45.467	"	3.5
		<u>Feldspar group</u>			
Orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>	2.570	179.837	23.31	4.6

Table 3. Average permittivity values of minerals found in the literature.†

Mineral name	A 100 Hz	B 1 MHz	C 2.5 MHz	D Radio frequencies	E 1Ghz	F Not given	G ~500MHz
<u>Smectite group</u>							
Montmorillonite		207	10.41				5.5
Beidellite		17.4					
Nontronite							
<u>Mica group</u>							
Muscovite		7.6		6.19–8.00	8.85		
Biotite		6.3		6.19–9.30			6.0
Phlogopite	6.35	7.6		5.90–6.50	10.59		5.8
Illite		10	8.44				5.8
<u>Kaolin group</u>							
Kaolinite		11.8	5.24				5.1
Dickite		4.6					
Nacrite							
<u>Pyrophyllite-Talc group</u>							
Pyrophyllite		6.3					
Talc		5.8				5.8	5.3

† A–Jones and Friedman (2000), B–Olhoeft (1981), C–Ficai (1959), D–Carmichael (1982), E–Nelson et al. (1989), F–Clarke (1966), G–Robinson (2004).

were collected using the immersion method and are perhaps the more reliable values. The data presented in Column B (Olhoeft, 1981) were collected using the repacking method and are less reliable due to the possible presence of hygroscopic water and the requirement of a model to predict permittivity values. The value of 207 for montmorillonite was for a wet sample and should not be considered as close to the permittivity of the dehydrated montmorillonite quasi-crystal. The other values presented come from a number of sources (Jones and Friedman, 2000; Ficai, 1959; Carmichael, 1982; Nelson et al., 1989; Clark, 1966), the methods by which they were obtained are not certain. Clearly the table demonstrates that there is a scarcity of reliable data in the literature for these minerals that are of considerable importance in soils.

Calculated values for dehydrated samples of all the minerals presented in Table 3 are presented in Table 4. The values for the smectite group range between 3.2

and 6.1. The predicted values for beidellite and nontronite are low due to the low particle density. A value of 5.5 was obtained by Robinson (2004) for a dehydrated montmorillonite with a particle density of 2.71. Assuming this value, the model predicts a value of 5.0. Within half a permittivity unit, which is good considering the actual chemical composition of the sample was unknown.

The values for the mica group were calculated between 4.8 and 5.8. Reported values for the phlogopite, biotite, and muscovite range between 5.9 and 9.3 with a number of values around 6. The calculated values for the illite are in good agreement with the value of 5.8 measured using the immersion method. Previously reported values of approximately 10 appear too high. This, we suggest, is due to inaccuracies in the method of repacking samples to estimate permittivity. A little hygroscopic water could be the cause of these higher estimates. The calculated numbers in general appear very reasonable and in comparison with measured values.

Table 4. Calculated values of permittivity of dehydrated phyllosilicates based on the chemical formula and density data presented in Weast (1984) and McClune (1980). The density range for Montmorillonite is non X-ray density data from Weast (1984).

Mineral name	Mineral formula used for calculation	X-ray density	$V_m^\dagger$	$\alpha_D^\ddagger$	Estimated permittivity
<u>g cm<sup>-3</sup></u>					
<u>Smectite group</u>					
Montmorillonite	$Si_4Al_{1.5}Mg_{0.5}O_{10}(OH)_2Ca_{0.25}$	2–3*	204.244	30.76	3.2–6.1
Beidellite	$Si_{3.5}Al_{0.5}Al_2O_{10}(OH)_2Ca_{0.25}$	1.509	406.917	30.45	2.4
Nontronite	$Si_{3.5}Al_{0.5}Fe_2O_{10}(OH)_2Ca_{0.25}$	2.30	308.653	33.45	3.5
<u>Mica group</u>					
Muscovite	$KAl_2[AlSi_3O_{10}](OH)_2$	2.831	233.630	33.45	5.5
Biotite	$KFe_3[AlSi_3O_{10}](OH)_2$	3.25	261.536	38.56	5.8
Phlogopite	$KMg_3[AlSi_3O_{10}](OH)_2$	2.784	248.878	35.83	5.6
Illite 2M <sub>1</sub>	$KAl_2[AlSi_3O_{10}](OH)_2$	2.82	234.541	33.45	5.5
Illite 2M <sub>2</sub>	$K_{0.7}Al_{2.1}[Si_4O_{10}](OH)_2$	2.655	244.159	32.46	4.8
<u>Kaolin group</u>					
Kaolinite	$Al_2Si_2O_5(OH)_4$	2.594	165.260	22.45	5.0
Dickite	$Al_2Si_2O_5(OH)_4$	2.600	164.879	22.45	5.0
Nacrite	$Al_2Si_2O_5(OH)_4$	2.602	164.752	22.45	5.0
<u>Pyrophyllite-Talc group</u>					
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	2.863	208.982	29.7	5.4
Talc	$Mg_3Si_4O_{10}(OH)_2$	2.784	226.216	32.08	5.4

† Molar volume.

‡ Mineral polarizability.

The value calculated for kaolinite of 5.0 is in close agreement with the immersion measurement value of 5.1. The predicted value for Talc of 5.4 is also very close to the immersion-measured value of 5.3. The modeled results are exceptionally encouraging for the phyllosilicates. The general trend would indicate that the modeled permittivity values of these minerals fall into a permittivity range between approximately 3 and 6, with the more common soil minerals falling into a range between 5 and 6. This corresponds well with the measurements of Robinson (2004) who also found that values tended to fall in the 5 to 6 range. Clearly, the mineral composition is important and more refined tests might be conducted based on known mineral composition.

### Oxides and Hydroxides

Metal oxides and hydroxides of Fe and Al are found predominantly in highly weathered tropical soils. As a result there has been much less focus on the dielectric properties of these soils by scientists working predominantly in the more temperate zones. However, the results (Table 5) would indicate that these minerals are likely to have permittivity values two to five times higher than quartz. Literature values for these minerals are again scarce, however some can be compared. In the case of the Fe minerals permittivity estimates between 18.9, (Nelson et al., 1989) and 25 (Olhoeft, 1981) have been presented for Hematite, in close agreement with our value of 23.9. Nelson et al. (1989) also presented a value of 13.6 for a goethite and Olhoeft (1981) presented a value of 11.7, both of which are close to our calculated value of 12.7. A value of 20 for magnetite has been presented by Jantzen (1963, as cited by Young and Frederikse, 1973). The measured value for magnetite is higher but this may have something to do with the magnetic properties of the magnetite affecting the measurement.

Accurate measurements of permittivity are available for Bohemite. The single crystal value of 8.44 was obtained as the average of the three axial directions: a, 8.33; b, 9.15; and c, 7.85; taken from Shannon (1993). This value of 8.44 was close to the estimated value of 8.75. No values for the permittivity of gibbsite could be found in the literature. However, the predicted value suggests that gibbsite won't increase soil permittivity above values obtained for temperate soils. Titanium

minerals are often found in small quantities in many soils (<1%) tending to be remnants from the weathering of parent materials. Sherman (1952) however, found that certain size fractions from some Hawaiian soils could contain as much as 25% TiO<sub>2</sub>. Nelson et al. (1989) presented a value of 30.7 for ilmenite at 1 GHz using the repacking method to measure the permittivity. Robinson et al. (1995) also demonstrated that 10% ilmenite increased time domain reflectometry waveform travel time significantly in a quartz ilmenite mixture. The ilmenite appearing to have a greater impact under saturated conditions. The value estimated by Nelson et al. (1989) is about 15% higher than the calculated value and is perhaps a reflection of the effect of conduction or magnetism on the permittivity measurement. Again the predicted values of permittivity are in reasonable agreement with measurements and estimates taken from the literature.

Despite the assumptions about chemical composition and mineral density the predicted values tended to be within 20% of the best available measured values for these minerals in the literature. In general it appeared that the calculated values formed a lower bound for the expected mineral permittivity. The method of calculating mineral permittivity values from ion polarizabilities appears to work well for the soil minerals presented. This modeling approach is a useful tool for estimating the permittivity of minerals that can be particularly difficult to measure such as the Smectites. Improved testing of the reliability of this method could be achieved using better-defined mineral samples for measurements.

### CONCLUSIONS

Permittivity values are calculated from ion polarizabilities for a selection of minerals commonly found in soils. The calculated values are in excellent agreement with values measured for single crystals or using the immersion method. The calculated values tend to be within 10% of measured values. This is good considering the exact mineral compositions for many of the measured minerals are not known exactly. The agreement between permittivity values estimated using repacked samples and those calculated can differ by as much as 100%. Poorer agreement is ascribed to the poor accuracy of the permittivity estimates, obtained using this

**Table 5. Calculated permittivity values for metal oxide and hydroxide minerals.**

Mineral name	Mineral formula	X-ray density g cm <sup>-3</sup>	V <sub>m</sub> †	α <sub>D</sub> ‡	Estimated permittivity
<b>Iron minerals</b>					
Goethite	α-FeOOH	4.269	34.562	6.57	12.7
Hematite	α-Fe <sub>2</sub> O <sub>3</sub>	5.2749	50.271	10.61	23.9
Lepidocrocite	γ-FeOOH	3.973	37.137	6.57	9.6
Magnetite	FeFe <sub>2</sub> O <sub>3</sub>	5.2003	73.934	14.85	16.9
<b>Aluminum minerals</b>					
Boehmite	γ-AlOOH		29.51	5.02	8.75
Gibbsite	γ-Al(OH) <sub>3</sub>	2.441	53.063	7.6	5.5
<b>Titanium minerals</b>					
Anatase	TiO <sub>2</sub>	3.893	34.080	6.95	18.6
Ilmenite	FeTiO <sub>3</sub>	4.784	52.671	11.19	25.3

† Molar volume.

‡ Mineral polarizability.

repacking method, the calculations are considered to be more accurate. This method of calculating permittivity provides a useful tool for estimating the permittivity of minerals that due to size, shape, and layer charge can be hard to measure.

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### REFERENCES

- Allen, B.L., and B.F. Hajek. 1989. Mineral occurrence in oil environments. p. 199–278. *In* J.B. Dixon and S.B. Weed (ed.) Minerals in soil environments. SSSA Book Series No. 5. SSSA, Madison, WI.
- Andeen, C., J. Fontanella, and D. Schuele. 1970. Accurate determination of the dielectric constant by the method of substitution. *Rev. Sci. Instrum.* 41:1573–1576.
- Binley, A.P., P. Winship, R. Middleton, M. Pokar, and L.J. West. 2001. High-resolution characterisation of vadose zone dynamics in the Sherwood sandstone using cross-borehole radar. *Water Resour. Res.* 37, 11: 2639–2652.
- Bussey, H.E., J.E. Gray, E.C. Bamberger, E. Rushton, G. Russell, B.W. Petley, and D. Morris. 1964. International comparison of dielectric measurements. *IEEE Trans Instrum. Meas.* IM-13:305–311.
- Carmichael, R.S. 1982. Handbook of physical properties of rocks. CRC Press, Boca Raton, FL.
- Clark, S.P. 1966. Handbook of physical constants. The Geographical Society of America, New York.
- Das, B.S., J.M.H. Hendrickx, and B. Borchers. 2001. Modelling transient water distributions around landmines in bare soils. *Soil Sci.* 166:163–173.
- Drees, R.L., L.P. Wilding, N.E. Smekc, and A.L. Senkayi. 1989. Silica in soils: Quartz and disordered silica polymorphs. 913–974. *In* J.B. Dixon and S.B. Weed (ed.) Minerals in soil environments. SSSA Book Series No. 5. SSSA, Madison, WI.
- Ficai, C. 1959. Caracteristiques des matieres argileuses etablies en mesurant les constants et les pertes dielectriques dans le domaine de frequence compris entre 30 kHz et 3 MHz. *Bull. Soc. Fr. Ceram.* 42:7–16.
- Fontanella, J., C. Andeen, and D. Schuele. 1974. Low-frequency dielectric constants of  $\alpha$ -quartz, sapphire,  $MgF_2$ , and  $MgO$ . *J. Appl. Phys.* 45:2852–2854.
- Friedman, S.P. 1998. A saturation degree-dependent composite spheres model for describing the effective dielectric constant of unsaturated porous media. *Water Resour. Res.* 34:2949–2961.
- Heydweiller, A. 1920. Dichte, dielektricitatskonstante und refraction fester salze. *Z. Physik.* 3:308–317.
- Huang, P.M. 1989. Feldspars, Olivines, Pyroxenes, and Amphiboles. p. 975–1050. *In* J.B. Dixon and S.B. Weed (ed.) Minerals in soil environments. SSSA Book Series No. 5. SSSA, Madison, WI.
- Huisman, J.A., C. Sperl, W. Bouten, and J.M. Verstraten. 2001. Soil water content measurements at different scales: Accuracy of time domain reflectometry and ground-penetrating radar. *J. Hydrol. (Amsterdam)* 245:48–58.
- Jones, S.B., and S.P. Friedman. 2000. Particle shape effects on the effective permittivity of anisotropic or isotropic media consisting of aligned or randomly oriented ellipsoidal particles. *Water Resour. Res.* 36:2821–2833.
- Keller, G.V. 1989. Section V electrical properties. p. 376–378. *In* R.S. Carmichael (ed.) CRC practical handbook of physical properties of rocks and minerals. CRC Press, Boca Raton, FL.
- Lowndess, R.P., and D.H. Martin. 1969. Dielectric dispersion and structures of ionic lattices. *Proc. R. Soc. London A* 308:473–496.
- McClune, W.F. 1980. Mineral powder diffraction file data book. JCPDS, Swarthmore, PA.
- Nelson, S.O. 1992. Estimation of permittivities of solids from measurements of pulverized or granular materials. p. 231–271. *In* A. Priou (ed.) Dielectric properties of heterogeneous materials PIER 6. Progress in Electromagnetics Research. Elsevier, Amsterdam.
- Nelson, S.O., D.P. Lindroth, and R.L. Blake. 1989. Dielectric properties of selected minerals at 1–22 GHz. *Geophysics.* 54:1344–1349.
- Olhoeft, G.R. 1981. Electrical properties of rocks. p. 298–329. *In* S.Y. Touloukian and C.Y. Ho (ed.) Physical properties of rocks and minerals. McGraw-Hill, New York.
- Robinson, D.A., J.P. Bell, and C.H. Batchelor. 1995. Influence of iron and titanium on water content determination by TDR. *Proc. Of the Symposium, Time Domain Reflectometry, Applications in Soil Science.* S.P. Rep. No. 11. Research Centre Foulum, Denmark.
- Robinson, D.A., and S.P. Friedman. 2002a. Particle shape characterization using angle of repose measurements for predicting the effective permittivity and electrical conductivity of saturated granular media. *Water Resour. Res.* 38, 11, 1236, doi:10.1029/2001WR-000746.
- Robinson, D.A., and S.P. Friedman. 2002b. The effective permittivity of dense packing of glass beads, quartz sand and their mixtures immersed in different dielectric backgrounds. *J. Non-Cryst. Solids.* 305:261–267.
- Robinson, D.A., and S.P. Friedman. 2003. A method for measuring the solid particle permittivity or electrical conductivity of rocks, sediments, and granular materials. *J. Geophys. Res.* Vol. 108. NO. B2:2076 10.1029/2001JB000691.
- Robinson, D.A., S.B. Jones, J.M. Wraith, D. Or, and S.P. Friedman. 2003. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. *Vadose Zone J.* 2:444–475.
- Robinson, D.A. 2004. Measurement of the solid dielectric permittivity of clay minerals and granular samples using a time domain reflectometry immersion method. *Vadose Zone J.* 3:705–713.
- Schmidt, W. 1902. Bestimmung der dielektricitatskonstanten von krystallen mit elektrischen wellen. *Ann. Physik* 9:919–937.
- Sen, P.N., C. Scala, and M.H. Cohen. 1981. A self-similar model for sedimentary rocks with application to the dielectric constant of fused glass beads. *Geophysics* 46:781–795.
- Shannon, R.D., 1993. Dielectric polarizabilities of ions in oxides and fluorides. *J. Appl. Phys.* 73:348–366.
- Shannon, R.D., M.A. Subramanian, S. Hosoya, and G.R. Rossman. 1991a. Dielectric constants of tephroite, fayalite and olivine and the oxide additivity rule. *Phys. Chem. Miner.* 18:1–6.
- Shannon, R.D., R.A. Oswald, T.H. Allik, J.P.M. Damen, D. Mateika, B.A. Wechsler, and G.R. Ossman. 1991b. Dielectric constants of  $YVO_4$ , Fe-, Ge-, and V-containing garnets, the polarizabilities of  $Fe_2O_3$ ,  $GeO_2$ , and  $V_2O_5$ , and the oxide additivity rule. *J. Solid State Chem.* 95: 313–318.
- Shannon, R.D., M.A. Subramanian, A.N. Mariano, T.E. Gier, and G.R. Rossman. 1992. Dielectric constants of diasporite and B-, Be-, and P-containing minerals, the polarizabilities of  $B_2O_3$  and  $P_2O_5$ , and the oxide additivity rule. *Am. Mineral.* 77:101–106.
- Shannon, R.D., and G.R. Rossman. 1992. Dielectric constants of silicate garnets and the oxide additivity rule. *Am. Mineral.* 77:94–100.
- Sherman, G.D. 1952. The  $TiO_2$  content of Hawaiian soils and its significance. *Soil Sci. Soc. Am. Proc.* 16: 15–18.
- Subramanian, M.A., R.D. Shannon, B.H.T. Chai, M.M. Abraham, and M.C. Wintersgill. 1989. Dielectric constants of BeO, MgO, and CaO using the two-terminal method. *Phys. Chem. Miner.* 16:741–746.
- Topp, G.C., et al. 2002. Water content. p. 417–545. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Series No. 5. SSSA, Madison, WI.
- Weast, R.C. 1984. Handbook of Physics and Chemistry. CRC Press, Boca Raton, FL.
- Young, K.F., and H.P.R. Frederikse. 1973. Compilation of the static dielectric constant of inorganic solids. *J. Phys. Chem. Ref. Data* 2:313–409.