ON THE DIELECTRIC CONSTANTS OF MINERALS

(The Determinations of Dielectric Constants of Minerals and Rocks²⁵⁾ and their Applications to the Mineralogical and Geological²³⁾ Studies, Part 1)

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Preface

The dielectric constants of minerals have been determined by numerous investigators to whom L. Boltzman,²⁾ L. Graetz,³⁾ L. Fomm, W. M. Thornton,²⁷⁾ J. Curie,³⁾ Th. Liebisch,¹³⁾ H. Rubens, W. Schmidt,¹⁹⁾ J. Takubo²²⁾ are included. W. Schmidt has determined the dielectric constants of various minerals using the immersion method and their values have been hitherto under the most utilization. According to the Maxwell's⁷⁾ theory, the dielectric constants of non-metallic crystals such as sulfur and diamond which are constructed from a single element are related to the refractive indices by the simple formula as $n^2 = \epsilon$. But common ionic crystal exhibits some of the three kinds of polarizations⁶⁾ under the electromagnetic vibration with appropriate frequencies. The maximum dielectric loss owing to the electronic polarization arises on the frequency of visible or infra-violet ray, and that owing to the atomic polarization arises on the infra-red frequency.

In addition to these polarizations, the dipolar substances have orientational polarization due to the orientational displacement of dipole. In the case of common ionic crystals,²⁴⁾ therefore they should show higher dielectric constants than those obtained by squaring the refractive indices owing to other polarizations beside the electronic one and do not satisfy the Maxwell's formula. Notwithstand-

ing of this fact, the dielectric constants generally show analogous changes to those of refractive indices. Therefore, the mineralogical studies which have been carried on by the determinations of the refractive indices should be made more effectively by the determinations of the dielectric constants. From the above reasons, the writers dare say that the study of dielectric constant shall be developed to the important researching method of mineralogy in near future.

Measuring methods of dielectric constants

For the measurements of dielectric constants, two following methods were adopted.

*Measurement by ultra short wave-length.*²²⁾ The Barkhausen and Kurz¹⁾ vibration of ultra short wave length such as 101.43 cm. was excited by using a vacuum tube US 6B made by the Japan Wireless

Fig. 1. Apparatus of Lecher's system by ultra short wave.

G: Galvanometer S: Scale B: Metal Bridge T: Telescope
 V: Vacuum Thermo-couple C: Condenser (a, b)
 V_g : Volt-meter of Grid V_a : Volt-meter of Anode
 I_f : Ampere-meter of Filament.

Telephony Company and it was resonated with the Lecher's system connected to a condenser. The exact syntonization may be ascertained from the deflection of galvanometer which was connected to a vacuum thermo-couple inserted to Lecher's system. The whole apparatus is indicated in Fig. 1.

The condenser was connected with the parallel lying Lecher wires. Thus a circuit was made, consisting of the Lecher wires, metal bridge and the condenser. The circuit was resonated with the radiated electromagnetic wave by means of sliding the metal bridge and the position of it was read on the scale at just time when the maximum syntonization was ascertained by the deflection of galvanometer. As the standard solution, we used the acetone, benzene and several mixed solutions of them. The scale reading was obtained with the condenser containing suitable amount of a standard solution. After the same procedure was repeated respectively with each standard solution, the curve representing the relation between the scale readings and the dielectric constants of the standard solutions was made. In this way, the operations were undertaken with the condenser containing both the standard solution and the mineral specimen and another curve was made from the thus obtained scale readings. The dielectric constant of the mineral under consideration was determined, corresponding to that of a cross point of these two curves.

The condenser (b) was used for the polished plate and (a), for the powder sample of the mineral.

Measurement by moderate wave length such as 500 kc.¹⁷⁾ The measuring apparatus is shown in Fig. 2.

The standard frequency wave excited by the emitter (O) is syntonized by means of (L) and (L_c). The immersion method was applied as in the case of (A). The condenser (C_x) containing standard solution and mineral may be syntonized by changing the capacity of standard condenser (C_s). The dielectric constant of mineral corresponds with that of the intersection of two curves, of

Fig. 2. Measuring apparatus for 500 kc. frequency.

- O: Standard oscillator C: Resonance condenser
 L_o: Oscillation coil C_s: Standard condenser
 L: Resonance coil C_x: Condenser with Sample
 L_c: Regeneration coil V: Autodyne coherer.

which one curve relates to the dielectric constants of standard solutions and readings of capacities of standard condenser (C_s), and other relates to those obtained by using condenser (C_x) containing a mineral immersed in the standard solution. The cell constant of (C_x) condenser was determined with distilled pure acetone made by Merk Company accepting its dielectric constant as 19.54 at 18°C. The dielectric constants of mixed standard solutions of acetone and benzene in various proportions were measured by using the determined cell constant. These results are shown in the following Table.

Table 1

Acetone %	ϵ		Acetone %	ϵ	
	1	2		1	2
0	2.28	2.25	35.0	7.14	7.62
9.8	3.52	3.49	40.0	8.01	8.23
15.0	4.31	4.23	45.0	8.79	9.09
20.0	5.05	4.98	49.5	9.81	9.90
25.0	5.88	5.78	60.0	11.48	11.87
31.0	6.64	6.73	69.4	—	13.85

ϵ 1: D. C. determined with 500 kc. in frequency

ϵ 2: D. C. determined with 76 cm. in wave length by W. Schmidt⁽²⁰⁾.

Experimental results

The dielectric constants of various kinds of minerals. With the above mentioned methods, the dielectric constants of various kinds of minerals were determined. The results are summarized as follows.

Table 2

Mineral	locality	ϵ (1)	ϵ (2)	ϵ (3)
Garnet	Wada-toge, Nagano Pref.	11.58	12.71	
Zincblende	Ani-mine, Akita Pref.	7.90	7.60	
	Chichibu-mine, Saitama Pref.	7.90		
	Nakatatsu-mine, Fukui Pref.	12.13		
	Zoplin, Misoro, U. S. A.	7.90		
	Claustal, Harz.	7.88		
Fluorite	Akenobe-mine, Hyogo Pref.	6.26		
	Aokawa, Wakayama Pref.		$\begin{cases} 6.28 \\ 6.21 \end{cases}$	6.69
	Ikuno-mine, Hyogo Pref.	6.28		
	Gonberg, Schweiz.	6.26		
	Durham, England.	$\begin{cases} 6.33 \\ 6.26 \end{cases}$		
	Freiberg, Sachsen	$\begin{cases} 6.63 \\ 6.58 \end{cases}$		
Opal	Bodai, Ishikawa Pref.	7.18	18 10	
	Hōsaka, Fukushima Pref.	7.43	22 30	
Agate	unknown	7.43	44 40	
Rock Salt	Huetra von Sal	$\begin{cases} 5.55 \\ 5.55 \\ 5.56 \end{cases}$		
	Stassfurt, Sachsen	5.40		
Hyalite	Tateyama, Toyama Pref.	$\begin{cases} 4.12 \\ 4.22 \end{cases}$	4 51	
Chalcedony	Tateyama, Toyama Pref.	5.48		
Analcime	Seiser Alp. Tirol	$\begin{cases} 5.88 \\ 5.87 \end{cases}$		
Leucite	Albanergebirge, Italy	$\begin{cases} 7.08 \\ 7.13 \\ 7.18 \end{cases}$		
Calcite	Kamioka-mine, Toyama Pref.	$\perp c$ 8.60	$\perp c$ 8.15	8.35
		//c 7.88	//c 7.41	
	Taio-mine, Fukuoka Pref.	$\perp c$ 8.49		

Table 2 — *Continued*

Tourmaline	Cumberland	//c	7.87	6.68	
		⊥c	8.53		
		//c	7.87		
		⊥c	8.50		
		//c	7.82		
	Ishikawa-yama, Fuku-shima Pref.	⊥c	6.83		
		//c	5.43		
	Ashiya-mine, Yamana-shi Pref.	⊥c	6.82		⊥c 6.82
					//c 5.60
	Ceylon	⊥c	6.68		
//c		5.43			
⊥c		6.82			
//c		5.61			
Dolomite	Binnental, Schweiz.	⊥c	7.50		
		//c	6.15		
		⊥c	7.56		
		//c	6.07		
Beryl	Mursinka, Uralgebirge	⊥c	6.18		
		//c	5.67		
		⊥c	6.17		
		//c	5.67		
		⊥c	6.18		
		//c	5.67		
					⊥c 6.59
					//c —
					⊥c 11.14
					//c 10.27
Apatite	Madagascar Ashio-mine, Tochigi Pref.	⊥c	9.47		
		//c	7.62		
		⊥c	10.20		
		//c	7.62		
		⊥c	9.48		
Kamioka-mine, Gifu Pref.	//c	7.43			
	⊥c	4.10			
	//c	4.22			
Quartz	Naegi-cho, Gifu Pref.				
	Mt. Hira, Shiga Pref.				⊥c —
			//c 4.52		

Table 2 — *Continued*

Diaspore	Mt. Kinpo, Yamanashi Pref.	⊥ c	4.13		
		// c	4.28		
	Cumberland	⊥ c	4.09		
		// c	4.48		
		⊥ c	4.08		
		// c	4.32		
	Mitsuishi-mine, Oka-yama Pref.	⊥ a	7.70		
		⊥ b	8.38		
		⊥ c	7.27		
		⊥ a	7.71		
		⊥ b	8.37		
		⊥ c	7.30		
Sulphur	Perticara, Rimini, Italy	⊥ a	3.44		
		⊥ b	3.66		
		⊥ c	4.30		
		⊥ a	3.43		
		⊥ b	3.61		
		⊥ c	4.24		
Topaz	Naegi-cho, Gifu Pref.	⊥ a	6.31	⊥ a	6.66
		⊥ b	6.44	⊥ b	6.58
		⊥ c	6.28	⊥ c	6.48
		⊥ a	6.34	6.61	
		⊥ b	6.42		
		⊥ c	6.29		
Aragonite	Bilin, Böhmen	⊥ a	9.58		
		⊥ b	7.28		
		⊥ c	6.26		
	Matsushiro-mine, Shi-mane Pref.			⊥ a	9.31
				⊥ b	7.19
				⊥ c	6.59
Baryte	Kamioka-mine, Gifu Pref.	⊥ a	7.70		
		⊥ a	7.80		
	Shodo-mine, Korea Trintington, England	⊥ a	7.80	⊥ a	7.85
		⊥ b	12.33	⊥ b	12.00
		⊥ c	7.85	⊥ c	7.82

Table 2—*Continued*

Celestin	Girgemt, Sizilien	$\perp a$	7.58		
		$\perp b$	—		
		$\perp c$	8.25		
		$\perp a$	7.61		
		$\perp b$	—		
		$\perp c$	8.27		
Damburite	Toroku, Miyazaki Pref.			$\perp a$	6.35
				$\perp b$	6.34
				$\perp c$	6.58
				$\perp a$	—
				$\perp b$	6.34
				$\perp c$	6.77
Gypsum	Hanaoka-mine, Akita Pref.	$\perp b$	4.98		
				$\perp b$	5.00
Vivianite	Ashio-mine, Tochigi Pref.	$\perp b$	6.07		
				$\perp b$	6.34
Epidote	Zalzbachtal, Tirol	εI	7.69		
		εII	10.11		
		εIII	15.39		
Moonstone	Binzan, Korea	//(100)	5.71		
		//(010)	5.96		
		//(001)	5.71		
		//(100)	5.77		
		//(010)	6.01		
		//(001)	5.76		
Allanite	Sandaiko, Manchuria			19.40	10.40
				19.40	10.90 (800°C)
				29.10	
	Mt. Suisho, Fukushima Pref.			25.90	14.10
				16.10	14.10 (800°C)
				12.50	12.50
	Morimoto, Kyoto Pref.				14.30 (800°C)
				14.80	17.10
					11.20 (800°C)
	Tatsurido, Korea			15.63	14.00

Table 2—*Continued*

			14.90 (800°C)
Tscheffkinites	Kawabe, Kyoto Pref.	25.30	
Yttrianite	Iisaka, Fukushima Pref.		11.30
			11.20 (800°C)
Gadolinite	Arendal, Norway	11.00	11.50
			10.20 (800°C)
	Hittero, Norway		10.30
			9.70 (800°C)
Ampangabeite	Madagascar	22.80	22.50
			24.20 (800°C)
Orangite	Norway		13.20
			13.00 (800°C)
Blomstrandite	Hittero, Norway		16.60
			22.90 (800°C)
Lessingite	Heiko, Korea	17.60	
Monazite	Tetsuzan, Korea	11.90	
Yttriotitanite	Arendal, Norway		19.00
			20.90 (800°C)
Ellsworthite	Ontario, Canada		17.60
			40.00 (800°C)
Kobeite	Kawabe, Kyoto Pref.		19.50
			27.20 (800°C)
Tantalite	Marblo Bar		26.40
	Greenbushes		26.70
	Brazil		28.10
Columbite	Ginkoku, Korea		36.70
			43.30 (800°C)
	Tanyo, Korea		23.70
			22.80 (800°C)
	Ishikawayama, Fukushima Pref.		45.80
Samarskite	North Calorina, U. S. A.	28.90	30.60
			56.00 (800°C)
	Mitchel Co., North Calorina	36.20	
		31.80	33.50
		35.50	32.80 (800°C)
	Daiboshin, Manchuria	25.80	24.40

Table 2 — *Continued*

Fergusonite	Arendal, Norway			31.40 (800°C)
				24.70
				30.20 (800°C)
	Kawabe, Fukushima Pref.		25.80	28.10
	Daiboshin, Manchuria		21.80	n. d. (800°C)
				19.80
Euxenite	Oro, Kyoto Pref.		22.40	19.20 (800°C)
				21.30
	Hakata, Ehime Pref.		29.10	18.40 (800°C)
				22.10
	Sandaiko, Manchuria		25.20	18.60 (800°C)
				23.60
	Brevig, Norway		24.80	29.90 (800°C)
				23.70
	North Carolina, U. S. A.			22.30
				26.20 (800°C)
				25.30
				32.70 (800°C)

In the above Table, $\epsilon(1)$ and $\epsilon(2)$ show the dielectric constants determined respectively with the wave having 101.43 cm. in length and 500 kc. wave using a thin plate of the mineral, and $\epsilon(3)$ those of the powder specimens pulverized into 80–100 mesh with 500 kc. wave. The dielectric constants of massive specimens having no defined crystal faces or of fine grained specimens which can not be polished into thin plates were measured with pulverized powders. $\perp a$, $\perp b$ and $\perp c$ stand for the thin plates perpendicular to crystal axes a , b and c , $//a$, $//b$ and $//c$ the parallel sections to each axis and $//(100)$, $//(010)$ and $//(001)$ the parallel sections to the crystal faces (100), (010), (001). On the metamict minerals, measurements were made either with the original and crystallized specimens which were preheated at 800°C.. These values of the latter are distinguished from those of former by denoting 800°C.. According to the above described results, no remarkable difference can be recognized between the two dielectric constants which were measured with

ultra short wave 101.43 cm. and intermediate frequency wave 500 kc.. But on the dielectric constants measured by 500 kc. wave, the hydrated amorphous or cryptocrystalline minerals such as opal, agate show, however, more significant high dielectric constants than that of non-hydrated quartz. This phenomena²⁶⁾ should be ascribed to the orientational polarization of dipole substances. The minerals having the complicated chemical composition such as allanite, tantalite, columbite, samarskite, fergusonite, euxenite and etc. show remarkably higher dielectric constants than those of common silicate minerals and the values of same species are different according to their localities. These facts should be ascribed to the discrepancies of minute chemical compositions according to their localities or to the additions of some dipole substances. The dielectric constants of the preheated metamict minerals differ from those of non-heated metamict minerals; some increase their values and others decrease.

Fig. 3. Relationship between dielectric constant and An-content of plagioclase.

Table 3

Comp.	(1) Albite ⁹⁾	(2) Albite	(3) Albite	(4) Albite	(5) Albite	(6) Albite	(7) Albite	(8) Albite	(9) Oligoclase	(10) Oligo- class ³⁰⁾
SiO ₂	66.84	68.20	65.79	66.41	67.20	66.28	67.00	67.10	61.75	62.80
Al ₂ O ₃	19.62	19.28	21.03	20.81	19.93	20.90	20.60	20.22	23.89	23.23
Fe ₂ O ₃	0.57	0.35	0.37	—	0.49	0.10	0.34	0.24	0.15	0.18
CaO	0.59	0.18	1.08	0.90	0.40	1.17	0.26	0.36	0.98	4.64
MgO	—	0.06	0.04	0.03	—	—	0.03	—	0.04	—
Na ₂ O	11.53	11.55	10.93	9.88	11.32	10.48	10.83	11.39	8.70	8.51
K ₂ O	0.10	0.34	0.32	1.32	0.08	0.48	0.42	0.33	0.25	0.81
H ₂ O ⁺	0.73	0.30	0.21	0.29	0.53	—	0.26	0.36	0.19	—
H ₂ O ⁻	0.04	0.03	0.09	0.03	0.08	—	0.05	0.05	0.04	—
Total	100.02	100.29	99.86	99.67	100.03	99.36	99.79	100.05	99.99	100.17
ε	5.57	5.45	5.58	5.53	5.55	5.64	5.55	5.40	Ab ₇₆ An ₂₄	Ab ₇₇ An ₂₃
Comp.	(11) Andesine	(12) Andesine	(13) Andesine 515)	(14) Labra- dorite ³⁰⁾	(15) Labra- dorite	(16) Anorthite	(17) Anorthite	(18) Anorthite	(19) Anorthite	(20) Anorthite 3200)
SiO ₂	58.60	59.03	56.39	53.87	54.94	43.79	42.70	43.20	44.18	44.77
Al ₂ O ₃	26.29	26.05	28.76	29.87	28.24	35.79	36.78	36.43	35.18	36.42
Fe ₂ O ₃	0.24	—	1.00	1.33	0.12	0.43	0.31	0.43	1.03	0.08
CaO	6.80	7.51	8.96	11.05	10.92	18.68	19.44	18.91	18.30	18.98
MgO	0.02	—	—	—	0.12	0.33	0.52	tr	0.10	0.10
Na ₂ O	7.00	6.60	6.30	4.60	4.98	0.42	0.23	0.23	0.71	0.40
K ₂ O	0.18	0.75	0.75	0.02	0.68	0.03	0.03	0.03	0.03	0.02
H ₂ O ⁺	0.41	—	—	0.21	—	0.59	0.61	0.61	0.85	—
H ₂ O ⁻	0.06	—	—	0.12	—	0.06	0.08	0.08	0.08	—
Total	99.60	99.94	101.72	101.07	100.40	100.13	100.28	99.92	100.46	100.78
ε	Ab ₈₅ An ₁₅	Ab ₆₁ An ₃₉	Ab ₅₆ An ₄₄	Ab ₄₃ An ₅₇	Ab ₄₅ An ₅₅	Ab ₄ An ₉₆	Ab ₂ An ₉₈	Ab ₂ An ₉₈	Ab ₇ An ₉₃	Ab ₄ An ₉₆
	6.20	6.31	6.47	6.62	6.51	7.05	7.23	7.15	7.05	7.22

Dielectric constants of rock forming minerals. The chemical compositions and dielectric constants of common rock forming minerals such as plagioclase-, pyroxene-, amphibole-group minerals were determined. The dielectric constants of these minerals were measured with pulverized powders.

Plagioclase-group. The chemical compositions and dielectric constants are shown in Table 3 and An %- ϵ diagram is shown in Fig. 3.

The relationship between the dielectric constants and An-contents

Table 4—1

Comp.	(1)	(2)	(3)	(4)	(5)	(6)	(7)
SiO ₂	57.25	47.89	52.82	44.77	50.58	39.39	49.59
Al ₂ O ₃	2.65	—	18.02	7.67	4.24	11.29	1.14
Fe ₂ O ₃	3.73	10.01	3.08	4.07	4.36	12.99	—
FeO	4.21	2.89	4.74	4.18	—	4.12	23.76
CaO	2.02	0.82	3.69	24.35	22.69	29.46	22.13
MgO	29.25	35.08	17.70	14.81	17.23	3.76	1.64
K ₂ O	TiO ₂ 0.10	—	—	—	—	—	MnO 1.48
Na ₂ O	—	—	—	—	0.44	—	0.45
H ₂ O ⁻)	—	—	—	—	—	—	—
H ₂ O ⁺)	0.35	4.01	0.34	0.15	—	0.41	—
Total	99.56	100.70	100.39	100.00	99.54	101.42	100.19

Comp.	(8)	(9)	(10)	(11)	(12)	(13)
SiO ₂	50.07	53.56	50.18	51.00	63.25	51.77
Al ₂ O ₃	—	0.26	2.80	12.41	27.65	6.71
Fe ₂ O ₃	—	2.75	—	2.27	0.53	—
FeO	24.04	8.69	12.50	8.05	0.42	1.27
CaO	21.41	30.16	17.79	14.49	0.83	37.92
MgO	3.25	1.70	13.54	6.32	—	—
K ₂ O	—	—	—	0.23	—	—
Na ₂ O	—	2.64	—	5.12	1.35	—
H ₂ O ⁻)	—	—	—	—	5.81	—
H ₂ O ⁺)	0.33	—	1.02	—	0.23	1.03
Total	99.10	99.76	97.83	99.89	100.07	98.70

Table 4—2

Nominated Mineral	R ₁ SiO ₃			Main-composition	ε	Extinction Angle	Locality
	MgSiO ₃	CaSiO ₃	FeSiO ₃				
(1) Enstatite	90.0	4.5	5.5	(Mg, Fe, Ca) SiO ₃	5.66	0°00'	Norwegen
(2) Enstatite	94.1	1.6	4.3	(Mg, Fe, Ca) SiO ₃	6.15	10°30'	Arifuku
(3) Bronzite	76.9	11.5	11.6	(Mg, Fe, Ca) SiO ₃	7.50	13°10'	Steinmark
(4) Diopside	42.7	50.4	6.9	(Ca, Mg, Fe) SiO ₃	7.64	38°40'	Schweiz
(5) Diopside	51.2	48.8	0.0	(Mg, Ca) SiO ₃	7.90	41°50'	Kamisano ¹⁰⁾
(6) Hedenbergite	8.5	77.7	13.8	(Ca, Fe, Mg) SiO ₃	9.22	56°40'	Nordmarken
(7) Hedenbergite	5.3	50.0	44.7	{ (Ca, Fe, Mg) SiO ₃ ⁸⁵ { (NaAl (SiO ₃) ₂ ¹	9.17	55°30'	Obira
(8) Hedenbergite	9.6	45.8	44.6	(Ca, Fe, Mg) SiO ₃	9.25	55°00'	Kamioka
(9) Augite	6.0	76.9	17.1	{ (Ca, Fe, Mg) SiO ₃ ¹ { NaAl (SiO ₃) ₂ ¹⁶	9.16	66°00'	Yoneyama ¹¹⁾
(10) Augite	38.9	40.9	20.2	{ (Ca, Mg, Fe) SiO ₃ ³⁰ { (Mg, Fe) (Al, Fe) ₂ SiO ₆ ... ¹	8.89	66°50'	Nishigatake ¹⁸⁾¹²⁾
(11) Aegirine	29.7	49.0	21.3	{ (Ca, Mg, Fe) SiO ₃ ⁹ { NaAl (SiO ₃) ₂ ² { (Mg, Fe) (Al, Fe) ₂ SiO ₃ ... ¹	9.05	67°00'	Norwegen
(12) Spodumen				LiAl (SiO ₃) ₂	8.45	30°30'	Sterling
(13) Wollastonite				CaSiO ₃	7.80	0°00'	

of plagioclases can be shown by the following formula, $\epsilon = 5.473 (\pm 0.016) + 0.00241 (\pm 0.00010) \text{An} - 0.000070 (\pm 0.000010) \text{An}^2$. Where An denotes the contents of anorthite by percentage. From this experimental formula, the An contents may be easily calculated by measuring the dielectric constant without chemical analysis or microscopic determination.

Pyroxene-group^{(4), (31), (4), (21), (15)}. The chemical compositions and dielectric constants of pyroxene-group minerals are indicated in Table 4-1 and Table 4-2.

The molecular percentage of MgSiO_3 and ϵ are related in Fig. 4.

Fig. 4. ϵ - MgSiO_3 content diagram of pyroxene.

The increase of molecular percentage of MgSiO_3 proportionally decreases the dielectric constants of minerals. The dielectric constants of pyroxenes which contain MgSiO_3 less than 17% are above 9, MgSiO_3 17-44% show 9-8, MgSiO_3 44-72% 8-7, MgSiO_3 72-100% lower than 7. The CaSiO_3 and FeSiO_3 components present almost no different influence upon the dielectric constant of pyroxene. Accepting the facts that the dielectric constant of pyroxene is

remarkably effected by the MgSiO_3 component and have no different influence by CaSiO_3 or FeSiO_3 , the three components and ϵ of pyroxene-group minerals are related as the following diagram.

Fig. 5. Diagram showing the relation of three components (MgSiO_3 , CaSiO_3 , FeSiO_3) and ϵ .

Fig. 6. Relationship between dielectric constant and extinction angle of pyroxene.

Wollastonite differs in the crystal structure from other pyroxene minerals and shows lower dielectric constant notwithstanding its negligible small amount of MgSiO_3 component. On the alkali-bearing pyroxene, the dielectric constant of jadate is lower than that of spodumen and that of aegirine is relatively high. As is shown in Fig. 6 showing the relation between the extinction angles and dielectric constants, the increase of extinction angle shows a tendency to increase the dielectric constants.

Amphibole-group^{(28), (29)}. The amphibole-group minerals generally contain more $\text{R}_2^{\text{III}}\text{O}_3$, $\text{R}_2^{\text{I}}\text{O}$ and H_2O components comparing with the pyroxene-group minerals. Accordingly, these components should be accounted for the dielectric constants of amphiboles. From the analytical results, the molecular ratio $\text{R}_2^{\text{I}}\text{O}:\text{R}_2^{\text{II}}\text{O}:\text{R}_2^{\text{III}}\text{O}_3:\text{H}_2\text{O}$ and $\text{MgSiO}_3:\text{CaSiO}_3:\text{FeSiO}_3$ were calculated and these values as well as the dielectric constants and extinction angles of these minerals are shown in Table 5.

Table 5

Nominated-Mineral	$\text{R}_2^{\text{I}}\text{O}$	$\text{R}_2^{\text{II}}\text{O}$	$\text{R}_2^{\text{III}}\text{O}_3$	H_2O	$\text{R}_2^{\text{II}}\text{SiO}_3$			ϵ	Ext. Angle
					MgSiO_3	CaSiO_3	FeSiO_3		
1 Actinolite		82.42	4.45	13.13	63.68	27.19	9.13	6.23	15°30'
2 Actinolite		89.85	2.58	7.57	60.31	25.26	14.43	6.60	17°30'
3 Tremolite		68.61	20.23	11.16	6.85	85.38	7.77	8.65	27°40'
4 Tremolite		82.19	17.30	0.51	29.46	69.20	1.34	6.80	—
5 Tremolite		84.05	11.76	4.19	75.64	24.36		5.95	16°50'
6 Hornblende		63.24	19.16	17.60	32.64	32.40	34.96	8.90	40°30'
7 Hornblende	3.93	83.15	4.58	8.34	59.64	24.71	15.65	7.15	19°50'
8 Hornblende		62.83	22.80	14.37	39.39	41.89	18.72	7.11	24°10'
9 Hornblende		70.08	14.01	15.91	33.97	33.32	32.71	7.90	25°20'
10 Hornblende	5.36	66.53	25.68	2.43	58.44	38.27	3.29	8.45	25°20'
11 Hornblende		64.01	20.10	15.89	50.07	37.27	12.66	10.40	37°40'
12 Hornblende		70.49	20.08	9.43	52.56	35.83	11.61	8.55	28°50'
13 Hornblende		65.25	17.01	17.74	5.53	30.69	63.78	7.85	—
14 Riebeckite	24.34	53.26	19.74	2.66	16.94	0.00	83.06	7.23	63°00'

The dielectric constants of amphibole minerals change their values according to the ratio of MgO , $(\text{Ca}, \text{Fe}) \text{O}$, $(\text{Fe}, \text{Al})_2 \text{O}_3$, Na_2O and H_2O contents. Of these components, H_2O is almost always contained and Na_2O is negligible excepting some special minerals, so that the ratio $\text{MgO} : (\text{Ca}, \text{Fe}) \text{O} : (\text{Al}, \text{Fe})_2 \text{O}_3$ of each minerals were calculated in the next Table.

Table 6

Nominated Mineral	$(\text{Al}, \text{Fe})_2 \text{O}_3$	$(\text{Fe}, \text{Ca}) \text{O}$	MgO	Locality
1 Actinolite	5.19	39.85	48.36	Daishōji
2 Actinolite	7.55	21.81	45.89	Mähren
3 Tremolite	23.33	58.78	3.09	Nagahara
4 Tremolite	34.25	29.34	36.41	Tessin
5 Tremolite	12.48	27.07	60.45	Anto, China
6 Hornblende	41.25	44.93	13.81	Mushiana
7 Hornblende	10.25	45.84	43.91	Norwegen
8 Hornblende	44.79	38.09	17.12	Fukuoka ³³⁾
9 Hornblende	36.39	48.00	15.59	Schweisberg
10 Hornblende	49.98	25.14	24.88	Böhmen
11 Hornblende	44.39	33.24	22.37	Taihoku
12 Hornblende	45.37	30.90	23.73	Nitatōge
13 Hornblende	36.99	60.86	2.15	Norwegen
14 Riebeckite	53.76	40.65	5.59	Portuga

The dielectric constants of amphibole minerals are so effected by their high contents of $\text{R}_2\text{III}\text{O}_3$ as is shown in Table 5, that there is no regular relationship between the $\text{R}^{\text{II}}\text{O}$ components and ϵ excluding the $\text{R}_2\text{III}\text{O}_3$ components. From Table 6 these three components are related to the dielectric constants as diagrammatically shown in Fig. 7.

It is noticeable that three kinds of mineral groups are distinguished among the amphibole minerals; two groups are plotted on the broken lines and the other is not belonged to these group. The minerals of the first group which contain relatively small amounts of R_2O_3 and over than 80% of $\text{R}^{\text{II}}\text{O}$ consisted with 24-27% CaO are

shown by a general formula $\text{H}_2\text{O} \cdot 2\text{CaO} \cdot 5(\text{Mg}, \text{Fe})\text{O} \cdot 8\text{SiO}_2$ corresponding to the tremolite-actinolite series in amphibole-group. The dielectric constants of these minerals increase proportionately with the decrease of MgO or increase of FeO . On the contrary, the minerals of the second group contain 30-40% of CaO and larger amount of $\text{R}_2\text{III}\text{O}_3$ component than those of the first group, so that the effects of $\text{R}_2\text{III}\text{O}_3$ component upon dielectric constant must be considered. As in the Fig. 7, the minerals of the second group also show a regular relationship between the dielectric constants and three components by considering the $\text{R}_2\text{III}\text{O}_3$ component. Generally, the $\text{R}_2\text{III}\text{O}_3$ components enlarge the dielectric constant more than the $(\text{Ca}, \text{Fe})\text{O}$ components in $\text{R}_2\text{II}\text{O}$ do. Other minerals which do not belong to these two groups are alkali-bearing amphibole or significantly weathered minerals which show no characteristic properties of amphibole. The alkali-bearing amphiboles have relatively low dielectric constants. Therefore the direct relation between

Fig. 7. Diagram showing the relation of three components MgO , $(\text{Ca}, \text{Fe})\text{O}$, $(\text{Fe}, \text{Al})_2\text{O}_3$ and ϵ .

MgO-contents and dielectric constants was not recognized on the amphibole minerals. On the other hand, the amphibole minerals have more regular relations than pyroxene minerals considering the extinction angles and dielectric constants as shown in Fig. 8. The higher the dielectric constant is, the larger the extinction angle is.

Fig. 8. Relationship between dielectric constant and extinction angle of amphibole.

Résumé

(1) The dielectric phenomena of minerals are derived from the atomic and electronic polarizations and with some minerals orientational polarizations arise on an adequate magnetic frequency wave. No remarkable difference can be recognized between the two dielectric constants which were measured with ultra short wave having the wave length 101.43 cm. and with intermediate wave having 500 kc. with the exceptions of hydrated minerals such as opal and agate.

(2) A relationship between the dielectric constants and An contents of plagioclases can be shown by the experimental formula, $\epsilon = 5.473 (\pm 0.016) + 0.00241 (\pm 0.00010) \text{ An} - 0.000070 (\pm 0.000010) \text{ An}^2$. From this formula, the An contents of plagioclase may be obtained by determining the dielectric constant.

(3) The component of MgSiO_3 is so related to the dielectric constant of pyroxene mineral as the decrease of its contents inverse proportionally increase the constant. The CaSiO_3 and FeSiO_3 components show almost no different influence on the dielectric constants.

(4) The tremolite-actinolite series which contain relatively small amount of $\text{R}_2^{\text{III}}\text{O}_3$ and CaO component, increase their dielectric constants according to the increase of FeO or decrease of MgO component as like the pyroxene minerals. On the other hand, some varieties of amphiboles, containing a large amount of $\text{R}_2^{\text{III}}\text{O}_3$ components, show no regular relationship between the dielectric constants and merely $\text{R}^{\text{II}}\text{O}$ components, while a regularity between the components MgO, (Ca, Fe) O, (Al, Fe) $_2\text{O}_3$ and dielectric constants was found.

(5) The extinction angles are also intimately related to the dielectric constants of these minerals. The increase of extinction angle is followed by its high dielectric constant.

(6) The dielectric constants of minerals change their values according to the chemical constitutions and crystal structures. So it was an important problem to solve the close relations between the chemical compositions and dielectric constants of isomorphous minerals.

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