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Paresh H. Shah[1] *and D. N. Singh*[2]

Generalized Archie's Law for Estimation of Soil Electrical Conductivity

ABSTRACT: Archie's law, which is an empirical relationship between the electrical conductivity of rocks and their porosity, has been used widely for saturated rocks, while Archie's second law has been developed for unsaturated rocks. Both of these laws assume that the rock matrix is non-conducting and the conduction takes place through the pore-solution only. However, not many efforts have been made by the researchers to check suitability and applicability of Archie's law to the saturated or unsaturated states of the soils. Hence, a generalized Archie's law for soils, by incorporating their physical properties, volumetric moisture content, and bulk and pore-solution conductivities, was attempted in this study utilizing the data available in the literature. Further, to demonstrate the validity of this law, four soils with entirely different properties were used. These soils were characterized by conducting conventional laboratory tests, and their bulk and pore-solution conductivities were determined with the help of an impedance analyzer and a pressure membrane extractor.

KEYWORDS: soil, bulk conductivity, pore-solution conductivity, volumetric moisture, Archie's law

Nomenclature

θ	volumetric moisture content of the soil
θ_b	bound volumetric moisture content of the soil
θ_{sat}	volumetric moisture content of the saturated soil
ϕ	reduced volumetric moisture content
ϕ_{sat}	reduced saturated volumetric moisture content
α	exponent used in the logarithmic mixing model
γ_b	bulk unit weight of the soil
γ_d	dry unit weight of the soil
γ_w	unit weight of water
η	porosity
σ	bulk electrical conductivity
σ_p	conductivity of the soil particles
σ_w	conductivity of the pore-solution
σ_s	surface conductivity
a,b,A	empirical constants
AEV	air entry value
B	cementation factor
c	fitting parameter used in the generalized Archie's law
CEC	cation exchange capacity

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[1] Research Scholar, Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai-400 076 p2paresh@civil.iitb.ac.in, and Member, ASTM International.
[2] Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai-400 076 dns@civil.iitb.ac.in, and Member, ASTM International.

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d cementation factor
CL clay content (in %)
F formation factor
FN fine (<75 μm) content (in %)
G_s specific gravity of the soil
GR gravel content (in %)
k exponent used in the modified Archie's law
L/S liquid to solid ratio
m fitting parameter used in the generalized Archie's law
LL liquid limit (in %)
PI plasticity index (in %)
PL plastic limit (in %)
R^2 regression coefficient
R_0 bulk resistance
s exponent used in the modified Archie's law
S degree of saturation
SN sand content (in %)
SL shrinkage limit (in %)
SSA specific surface area
t empirical constant
T transmission coefficient
w gravimetric moisture content (in %)
w_{sp} moisture content of the saturated soil paste (in %)
X empirical constant
Z' real part of the complex impedance
Z'' imaginary part of the complex impedance

Introduction

The electrical conductivity of soils has been used for its non-destructive characterization, determination of the moisture content [1,2], salinity [3,4], porosity [5], degree of saturation [6], degree of compaction [7], liquefaction potential [8,9], consolidation [10], and permeability [5,6,11] characteristics. These studies demonstrate that the soil electrical conductivity includes contributions of the particle conductivity σ_p, the pore-solution conductivity σ_w, and the surface conductivity σ_s [12]. In addition to this, for predicting bulk electrical conductivity σ of the porous media, several mixing models have been developed and proposed by the researchers [1, 13–17]. Table 1 presents a brief summary of these models.

Most of the models presented in Table 1 assume a saturated porous media, consisting of two conducting phases: a liquid phase and a porous matrix phase. However, many of these models are valid for well-defined simple geometric distributions of the solid and fluid phases (e.g., parallel and series model). The logarithmic mixing rule yields more general solution by combining both parallel and series additions of the conducting phases (α = 1 for parallel addition, –1 for series addition, and $-1<\alpha<1$ for the mixed case). Using the effective medium theory, one of the earliest attempts was made by Maxwell, who determined electrical conductivity of a heterogeneous media consisting of spherical particles immersed in a dilute suspension [15]. This model was later extended to the ellipsoidal particles in dilute solution [18].

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In addition to this, a general effective media (GEM) theory, which combines both percolation and effective media theories, has also been proposed [16]. However, these models are valid for a particular geometry and represent a single-degree of connectivity of the conducting phases.

TABLE 1—*Various mixing models used for electrical conductivity of the porous medium.*

Name	Equation
Parallel Model [1]	$\sigma = (1-\eta).\sigma_p+\eta.\sigma_w$
Series Model [13]	$\frac{1}{\sigma} = \frac{(1-\eta)}{\sigma_p} + \frac{\eta}{\sigma_w}$
Logarithmic Model [16]	$\sigma^\alpha = (1-\eta).\sigma_p{}^\alpha + \eta.\sigma_w{}^\alpha$
General Effective Medium Model [16]	$\frac{(1-\eta)(\sigma_p{}^{1/t} - \sigma^{1/t})}{\sigma_p{}^{1/t} + X\sigma^{1/t}} + \frac{\eta(\sigma_w{}^{1/t} - \sigma^{1/t})}{\sigma_w{}^{1/t} + X\sigma^{1/t}} = 0$
Maxwell Model [15]	$\frac{\sigma}{\sigma_w} = \frac{2\sigma_w + \sigma_p - 2(1-\eta)(\sigma_w - \sigma_p)}{2\sigma_w - \sigma_p + (1-\eta)(\sigma_w - \sigma_p)}$
Archie's Law [17]	$\sigma = c\sigma_w.\eta^B$
Modified Archie's Law [14]	$\sigma = \sigma_p.(1-\eta)^k + \sigma_w.\eta^s$ where $k = \log(1-\eta^s)/\log(1-\eta)$

However, the model that has been found to be quite useful for most of the soils is represented by Eq 1 [1,2].

$$\sigma = \sigma_w \cdot \theta \cdot T + \sigma_s \tag{1}$$

where σ is the bulk soil electrical conductivity, σ_w is the pore-solution conductivity, σ_s is the surface conductivity, θ is the volumetric moisture content, and T is the transmission coefficient that can be expressed as:

$$T = a \cdot \theta + b \tag{2}$$

where a and b are empirical constants.

Another model that has been used for predicting electrical conductivity of the saturated and unsaturated soils is represented by Eq 3 [19]. This model assumes that the tortuosity factor that affects the soil electrical conductivity is identical to that usually defined for predicting the soil hydraulic conductivity.

$$\sigma = \sigma_w \cdot \frac{\phi^{\eta+2}}{\phi_{sat}} \tag{3}$$

where $\phi = (\theta - \theta_b)$, $\phi_{sat} = (\theta_{sat} - \theta_b)$, and θ_b is the bound volumetric moisture content.

Gunzel [20] has modified the model proposed by Sen et al. [21] for determining σ and has proposed the following relationship:

$$\sigma = \theta^d \cdot [\sigma_w + \sigma_w \cdot \frac{0.193 \cdot d \cdot \gamma_b \cdot CEC}{(1000 \cdot \sigma_w + 0.7) \cdot \theta}] \tag{4}$$

where γ_b is the bulk unit weight of the soil (in kN/m^3), CEC is the cation exchange capacity of the soil (in meq/100 g), σ and σ_w are in S/m, and d is the cementation factor that can be obtained from Eq 5.

$$d = 1.67 + 0.1953 \cdot CEC^{0.5} \tag{5}$$

A critical comparison of the above-mentioned conductivity models, for soils, reveals that Eq 1 incorporates σ_s, which is independent of θ. However, considering the fact that σ_s of the soil is

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mainly attributed to the increased cation concentration in the double layer, which is dependent on several parameters such as moisture content, pore-fluid chemistry, pH, etc., it must be dependent on θ and σ_w (i.e., $\sigma_s = f\{\theta, \sigma_w\}$) [22]. Nadler and Frenkel [23] have reported that for low salinity of the pore-solution (i.e., σ_w<0.4 S/m), σ_s is not a constant and depends on σ_w. As surface conduction is not entirely due to the ionic conductance at the solid surface and also includes the ionic conduction of the solution bridging two adjacent particles, σ_w will also affect the surface conduction [23]. In addition to this, it has been opined by researchers [19] that Eq 3 can be applied only to coarse-grained soils. Further, it has been assumed by these researchers that the ionic mobility, very close to the solid surface, gets considerably diminished as compared to the mobility at the central part of the pores. Hence, to account for the reduced mobility of ions in the double layer, ϕ has been used in Eq 3. The model depicted by Eq 4 incorporates basic properties of the soil such as *CEC* and its compaction state (i.e., γ_b and θ). It must be noted that *CEC* is an important parameter, which represents overall characteristics (i.e., physical, chemical, and mineralogical) of the soil and on which σ_s depends strongly. Also, in order to use Eqs 1, 3, and 4, determination of σ_w by extracting the pore-solution from the in situ soil samples corresponding to the field moisture content is essential. However, such samples are difficult to obtain and are cost and time intensive [24]. Hence, saturated soil pastes or soil-water mixtures with different liquid to solid ratio *L*/*S* are being used by researchers [19,25–27].

Archie [17] has proposed a simple relationship between the bulk conductivity σ, the pore solution conductivity σ_w, and the porosity η, for brine-saturated rocks:

$$\sigma = c \cdot \sigma_w \cdot \eta^B \tag{6}$$

where *c* is the fitting parameter, and *B* is the cementation factor, which is related to the tortuosity and interconnectivity of the pore network. These parameters help in incorporating the influence of tortuosity and interconnectivity of pores and make Archie's law more versatile in nature.

For unsaturated porous media, Eq 6 can be expressed as:

$$\sigma = c \cdot \sigma_w \cdot \eta^B \cdot S^m \tag{7}$$

or

$$\sigma = c \cdot \sigma_w \cdot \eta^{B-m} \cdot \theta^m \tag{8}$$

where *S* is the degree of saturation and *m* is the fitting parameter.

However, it has been reported in the literature [28] that $m \approx B$, and hence the influence of η is insignificant. Moreover, experimentally obtained σ of the soil and its θ can be related easily in the form of Eq 9, which has been referred as the generalized Archie's law in this paper.

$$\sigma = c \cdot \sigma_w \cdot \theta^m \tag{9a}$$

or

$$\sigma / \sigma_w = 1/F = c \cdot \theta^m \tag{9b}$$

where *F* is the formation factor, and *c* and *m* are parameters that primarily depend on the particle size characteristics of the soil.

Since Archie's law (Eq 6) does not account for the electrical conductivity of the solid material matrix, many researchers [21,29–31] have suggested modification of Archie's law by including the surface conductivity σ_s. The authors of this paper hold the opinion that effect of σ_s will be included in *c* and *m* automatically, and hence it should not be considered separately. This is also in line with the fact that σ_s is not constant and will depend on θ and σ_w, as explained earlier.

Since not many efforts have been made by earlier researchers to correlate σ of the unsaturated soils with σ_w and θ, efforts were made to validate Eq 9 by using the data of 26 soils

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(i.e., physical properties, σ, σ_w, and θ), which are available in literature [27,32–38]. In addition to this, four soils with entirely different physical and mineralogical characteristics, and which were characterized to determine their σ and σ_w, corresponding to different compaction states, were also used in this study. An impedance analyzer (IA) and a pressure membrane extractor (PME) were employed to achieve this. Further, an attempt was made to generalize Eq 9 by correlating parameters *c* and *m* to physical properties of the soil.

Experimental Investigations

Soil Properties

Three locally available soils, silty soil (ST), black cotton soil (BC), marine clay (MC), and commercially available white clay WC were used in this study. Specific gravity *G*s, particle size characteristics and Atterberg limits of these soils were obtained following the guidelines provided by the ASTM [39–42], mineralogical composition of these soils was obtained using the X-ray diffraction technique [43]. Physical and mineralogical characteristics of these soils along with their classification [44] are listed in Table 2.

TABLE 2—*Physical and mineralogical properties of the soils used in the study.*

Property	Soil Sample			
	ST	BC	WC	MC
G_s	2.80	2.65	2.63	2.78
Particle Size Distribution				
Sand Content (%)				
Coarse (4.75–2.0 mm)	21	1	…	12
Medium (2.0–0.425 mm)	22	10	…	3
Fine (0.425–0.075 mm)	5	9	…	9
Silt (0.075–0.002 mm) content (%)	34	27	46	44
Clay (<0.002 mm) content (%)	18	53	54	32
Consistency Limits (%)				
LL	44	73	54	61
PL	29	31	28	37
PI	15	42	26	24
SL	23	14	25	18
Soil Classification	ML	CH	CH	MH
SSA (m^2/g)	25.86	37.8	15.95	27.74
CEC (meq./100 g)	57.52	36.88	9.8	53.5
Minerals present	Montmorillonite, Albite, Anorthite	Quartz, Mullite	Kaolinite, Illite	Quartz, Illite, Anorthite

CH: Inorganic clay of high plasticity; MH: Inorganic silt of high plasticity; ML: Inorganic silt of low plasticity.

Determination of Electrical Conductivity of Pore-Solution

Sample Preparation—The soil was mixed thoroughly with different amounts of distilled water to achieve: a) the saturated soil paste and b) different dilution ratios (*L/S* = 1, 2, and 5). The saturated soil paste was prepared by mixing the dry soil and distilled water in a glass container. These samples were stored in airtight glass containers for 24 h in the humidity and temperature-controlled room.

Pore-Solution Extraction—A pressure membrane extractor (PME) manufactured by Eijkelkemp, Netherlands, as depicted in Fig. 1, was used for extraction of the pore-solution. A

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cellulose acetate membrane, with its properties listed in Table 3, was used as the filter. The permeability of the membrane was determined by measuring the amount of extracted water under an applied pressure of 5 kg/cm^2 for certain duration. Porosity of the membrane was calculated with the help of moisture content of the saturated membrane. The membrane was placed over a nylon filter cloth, which rests on the base plate, as depicted in Fig. 1. The membrane and the filter cloth were soaked in distilled water for 48 h before mounting them in the PME. Twelve PVC rings, which are open on both ends and are of 42 mm internal diameter and 10 mm height, were used for containing the soil sample. The matured soil pastes and samples were poured/packed in these rings, which were placed on the membrane. The PME is closed properly, and air pressure of 5 kg/cm^2 is applied. The pore-solution that comes out of the soil sample gets collected in the sampling bottle, as depicted in Fig. 1.

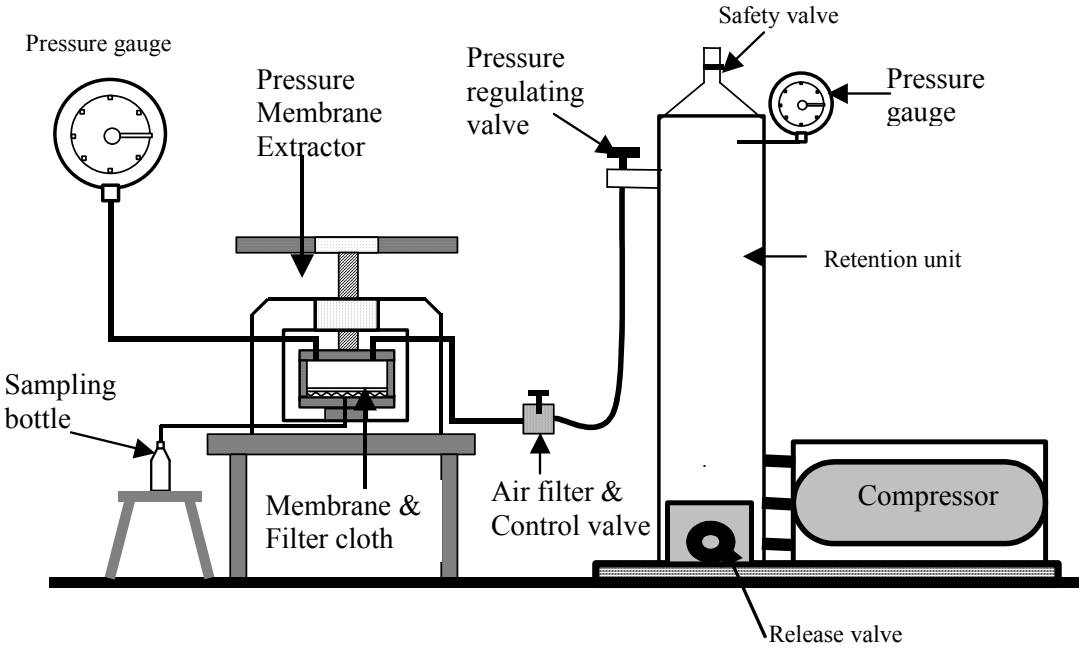

FIG. 1—*The pressure membrane extractor (PME) assembly.*

TABLE 3—*Properties of the cellulose acetate membrane.*

Thickness (μm)	Max. Pore size* (μm)	*AEV** (kg/cm^2)	Permeability (m/s)	η
57.5	2.8	>100	1.16×10^{-11}	0.6

*Data supplied by the manufacturer.

Measurement of the Pore-Solution Conductivity—The pore-solution conductivity σ_w was determined by measuring the impedance of the pore-solution with the help of Agilent LCR meter 4284A and a liquid test fixture (16452A), as discussed in the "Results and Discussions" section of this paper. The LCR meter works in frequency range of 20 Hz to 1 MHz. Two-electrode method of the impedance measurement was preferred over the Four-electrode method to avoid various problems and uncertainties associated with the latter in terms of proper quantification of the cross-section area of the electrodes, path length of the current and disturbance caused to the sample [45]. It must also be noted that the impedance response of a material, over a frequency

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range, helps in eliminating electrode polarization effect [46]. In addition to this, to eliminate electrical interferences caused due to the length of the leads, built-in algorithm in LCR meter was used, and the correction factors recommended by ASTM D 150 [47] were employed. Also, to avoid unwanted impedances due to the sample cell and the connecting leads, open and short circuit corrections were applied before conducting experiments [46].

Determination of Electrical Conductivity of the Soil Sample

The bulk electrical conductivity σ for these four soils, corresponding to different compaction states (dry density γ_d and gravimetric moisture contents w), was determined by using the methodology presented in the following. Details and designation of the samples used for this purpose are presented in Table 4. Wet samples were prepared by mixing the dry soil with the required amount of distilled water and storing them for 24 h to achieve proper maturation. A rectangular Perspex box of size 150 × 150 × 30 mm along with two stainless steel electrodes of size 150 × 150 mm was used for measuring the impedance of the soil sample, with the help of a LCR meter and following the methodology presented in the literature [46]. Compaction of the soil sample was achieved in three equal layers with the help of a wooden rammer, which weighs 250 g, by imparting 25 blows to each layer. The volume of the sample was computed, and its bulk unit weight γ_b was determined. Three stainless steel pats were filled with approximately 25 g of the wet soil and were used for determining w, as per the guidelines presented in the literature [48]. Equations 10 and 11 were used for determining the dry unit weight γ_d and θ of these samples, as listed in Table 4.

$$\gamma_d = \frac{\gamma_b}{1 + w} \tag{10}$$

$$\theta = w \cdot (\gamma_d / \gamma_w) \tag{11}$$

where γ_w is the unit weight of water.

In addition to the wet soil samples, slurries of these soils with different L/S (5, 10, and 100) were also used in the study.

Results and Discussions

From the measured impedance values for the pore-solutions and the soil samples, Nyquist impedance plots were developed following the guidelines presented in the literature [46]. For the sake of brevity, only the results for Sample ST8 and pore-solution sample of the soil WC (L/S =1) are depicted in Fig. 2. σ_w and σ were obtained from the corresponding values of the bulk resistance R_0, which is equal to real part of the complex impedance Z' for the minimum value of imaginary part of the complex impedance Z''. Using this methodology, the σ values for the soil samples were computed and are listed in Table 4.

The variation of σ_w with L/S for the extracts of the saturated soil pastes and slurries is depicted in Fig. 3. It can be noted that σ_w decreases as L/S increases. The variation of σ for the four soils with w was also developed. For the sake of brevity, only the results of soil WC are being reported in Fig. 4. It can be noted from the figure that with increase in w, initially, σ increases very rapidly and attains a maximum value, which occurs at the moisture content corresponding to the saturated soil paste, w_{sp}. Beyond this point, σ decreases with further increase in w. This can be attributed to the dilution of the sample. Hence, σ_w, which is used in Eq

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9, has been considered to be equal to the electrical conductivity of the saturated soil paste extract corresponding to the maximum value of σ_w in Fig. 3. This is in accordance with the standard method employed for obtaining the soil salinity [23,25,27]. The values of σ_w for the soils used in this study are listed in Table 5.

TABLE 4—*Details of the soil samples used in the study.*

Sample	w (%)	γ_d (kN/m^3)	θ	σ (S/m)
ST1	0	14.2	0	2.9E-08
ST2	9.0	13.3	0.12	5.1E-03
ST3	10.8	14.9	0.16	1.9E-02
ST4	17.0	13.7	0.23	3.8E-02
ST5	16.0	16.4	0.26	5.2E-02
ST6	17.0	16.2	0.27	5.9E-02
ST7	18.4	16.6	0.30	5.9E-02
ST8	19.9	16.2	0.32	5.5E-02
ST9	20.7	16.6	0.34	8.5E-02
ST10	29.7	16.3	0.48	1.0E-01
ST11	37.3	13.7	0.51	1.2E-01
BC1	0	13.9	0	6.5E-05
BC2	10.3	12.3	0.12	8.4E-04
BC3	14.1	11.5	0.16	9.5E-03
BC4	15.8	12.5	0.19	1.7E-02
BC5	21.5	10.8	0.23	2.1E-02
BC6	21.5	12.8	0.27	6.5E-02
BC7	25.6	12.7	0.32	1.1E-01
BC8	30.1	11.5	0.34	6.9E-02
BC9	40.5	12.1	0.49	1.2E-01
BC10	52.6	11.7	0.61	2.3E-01
WC1	0	8.8	0	2.1E-07
WC2	1.5	6.7	0.01	3.9E-05
WC3	5.5	9.0	0.05	2.5E-03
WC4	10.5	9.1	0.09	5.0E-03
WC5	11.3	9.0	0.10	5.3E-03
WC6	16.0	11.1	0.17	7.8E-03
WC7	18.6	11.6	0.21	1.7E-02
WC8	19.9	11.4	0.22	1.5E-02
WC9	23.7	13.7	0.32	2.8E-02
WC10	29.7	15.0	0.44	5.1E-02
WC11	33.2	13.5	0.44	7.4E-02
WC12	33.7	14.2	0.47	7.3E-02
WC13	40.7	12.4	0.50	7.4E-02
MC1	0	12.2	0	3.3E-07
MC2	5.8	13.6	0.07	4.2E-03
MC3	11.9	11.6	0.13	5.9E-03
MC4	11.2	12.8	0.14	2.8E-02
MC5	17.6	11.1	0.19	6.5E-02
MC6	16.2	13.2	0.21	2.5E-01
MC7	22.1	11.1	0.24	1.5E-01
MC8	21.1	13.5	0.28	5.1E-01
MC9	26.4	12.1	0.31	4.2E-01
MC10	26.6	14.4	0.38	1.9E+00
MC11	38.8	13.3	0.51	4.2E+00
MC12	47.0	12.8	0.60	5.2E+00

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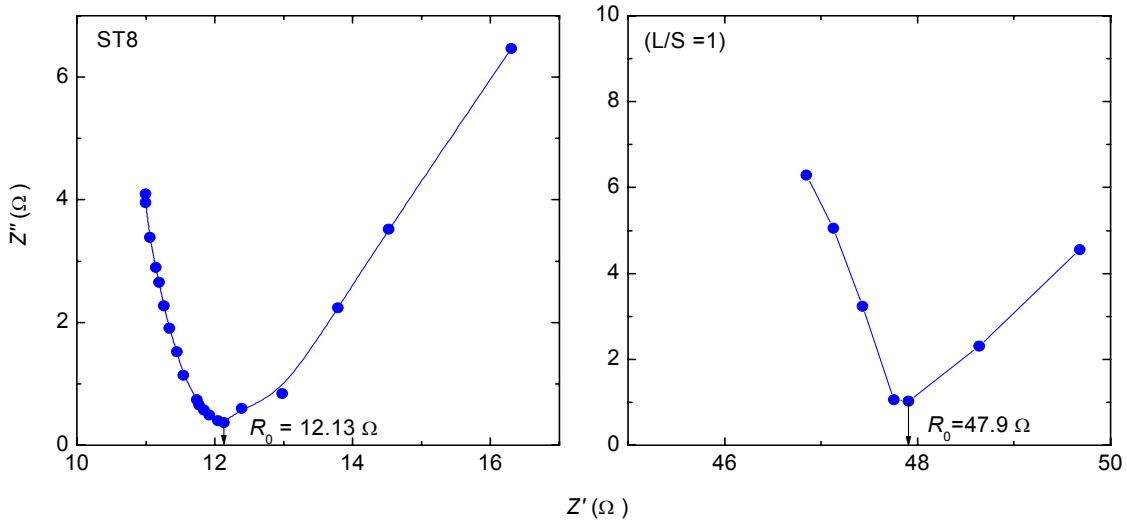

FIG. 2—*Nyquist plots for the Sample ST8 and the pore-solution of the Soil WC.*

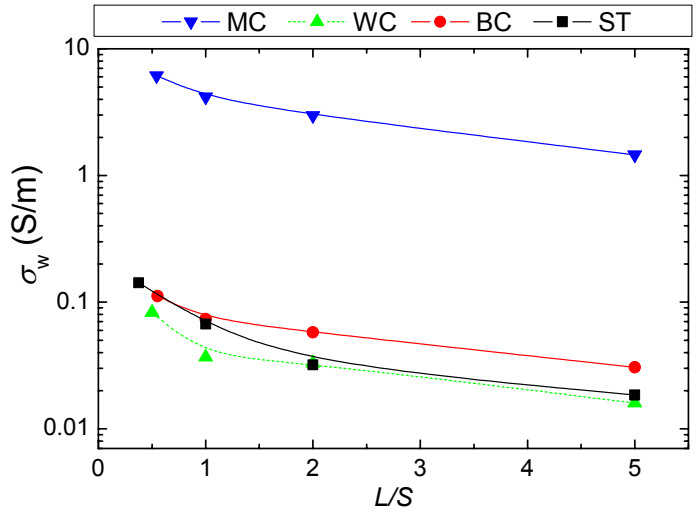

FIG. 3—*Variation of* σ_w *with L/S ratio for different soils.*

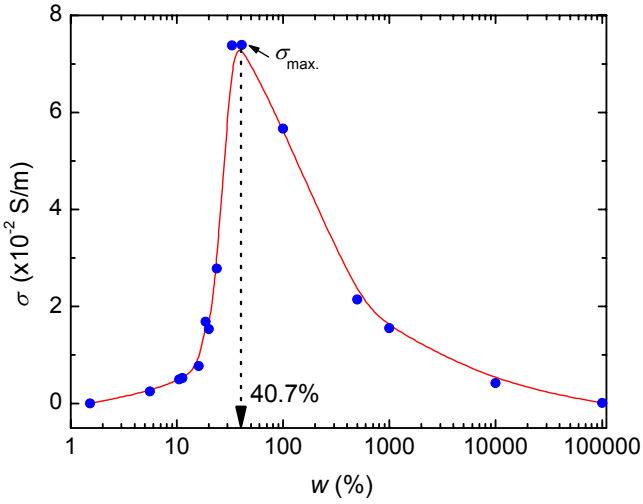

FIG. 4—*Variation of* σ *with w for the Soil WC.*

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TABLE 5—*Properties of the soils used in the study.*

Soil	G_s	*LL* (%)	*PI* (%)	*GR* (%)	*SN* (%)	*FN* (%)	*CL* (%)	*CEC* (meq./100g)	σ_w (S/m)	Ref.
A	2.75	27	15	2	22	76	28	22	0.020	
B	2.80	67	46	0	6	94	53	39	0.248	
C	2.69	61	35	9	38	53	40	11	0.137	
D	2.80	24	11	3	35	62	20	23	0.036	
E	2.70	49	26	0	6	94	40	23	0.024	
F	2.80	70	38	0	6	94	65	8	0.016	
G	2.78	37	20	0	19	81	25	27	0.406	
H	2.68	29	16	0	48	52	16	8	0.198	[32]
K	2.68	58	15	0	36	64	23	5	0.346	
L	2.67	23	5	0	46	54	7	25	0.057	
M	2.90	53	41	0	12	88	36	31	0.076	
NL	…	…	…	…	…	…	30.5*	23	0.16–1.6	[27]
ML	…	…	…	…	…	…	11*	11	0.19–1.1	
GK	…	…	…	0	20	80	10	…	0.26	
FR	…	…	…	0	11	89	63	…	0.08	[33]
MN	…	…	…	0	3	97	40	…	0.32	
HM1	…	…	…	…	82.8	17.2	1.2	…	0.122	
HM2	…	…	…	…	81.8	18.2	3.1	…	0.125	[34]
HM3	…	…	…	…	68	32	4.8	…	0.150	
HM4	…	…	…	…	57	43	8.7	…	0.128	
RN	…	…	…	…	37.3	62.7	28.4	…	0.3-2.19	[35]
PR	…	…	…	…	…	…	0	…	0.043-0.48	[36]
ND1	…	…	…	…	64.4	35.6	11.7	13.1	0.15-0.59	[37]
ND2	…	…	…	…	…	…	6.0	…	…	
ND3	…	…	…	…	…	…	12.0	…	…	[38]
ND4	…	…	…	…	…	…	17.4	…	…	
ST	2.8	44	15	0	48	52	18	57.52	0.142	
BC	2.65	73	42	0	20	80	53	36.88	0.112	Present
WC	2.63	54	26	0	0	100	54	9.8	0.083	study
MC	2.78	61	24	0	24	76	32	53.5	6.145	

… = not reported.
* = obtained from Fig. 5.

Twenty-six soils for which physical properties, *CEC*, σ, and σ_w (or *F*) are available in the literature [27,32–38] were selected in this study, and their details are presented in Table 5. However, as for Nibley silt loam (NL) and Mesa Sandy loam (ML), particle size fractions are not reported by the authors [27], their clay fraction *CL* has been obtained based on the reported *CEC* values. To achieve this, data of 33 soils reported in the literature [49] were used, and a relationship between *CEC* and *CL*, as depicted in Fig. 5, was developed. It has been reported by the authors [27] that approximately 60 tests were conducted on NL and ML soils, corresponding to different moisture contents and KCl contents, using the four-electrode method [50,51]. Abu-Hassanein [32] has used eleven soils, compacted at different moisture contents in three different compaction states (i.e., reduced Proctor, standard Proctor, and modified Proctor), for determining their electrical conductivity using four-electrode method. Hilhorst [33] has used three soils, Groesbeek (GK), Ferrasol (FR), and Munnikenlad (MN) for the same purpose. Conductivity measurements, with the help of time domain reflectrometry (TDR) and frequency-domain (FD) sensors were conducted on these three soils, corresponding to different moisture contents. Soils HM1 to HM4 [34], RN [35], PR [36], and ND1 to ND4 [37,38] have also been used in this study.

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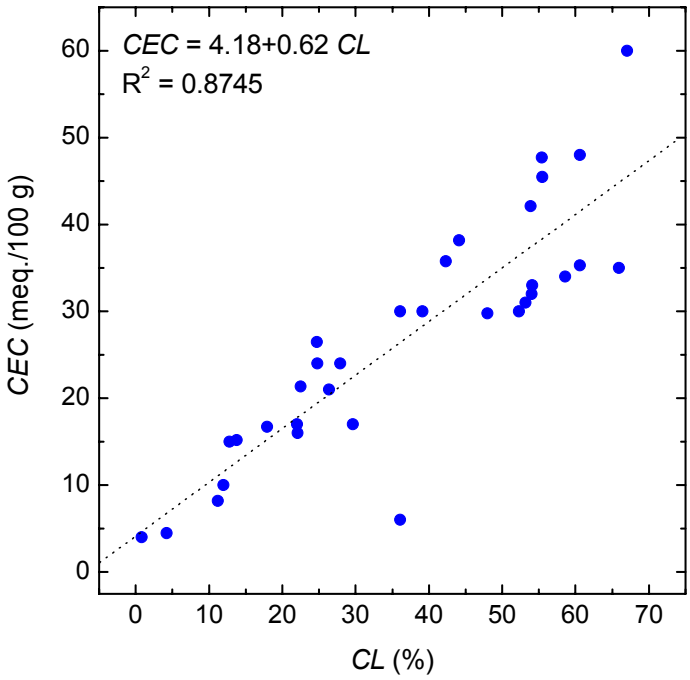

FIG. 5—*Variation of CEC with* CL *for different soils [49].*

Variation of $1/F$ with θ, for each of these 26 soils, from the literature, and the four soils used in this study, was developed, and some typical trends are depicted in Fig. 6. From these fits c, m, and regression coefficient R^2 were obtained, and their values are listed in Table 6. It is observed that c and m vary from 0.33–15.85 and 0.74–3.92, respectively. For most of the soils, R^2 is found to be very close to unity. Incidentally, the value of m has been reported to vary from 1.5–2.0 for sand, and to increase with decreasing sphericity of the particles (i.e., 1.3 for glass spheres, 1.8 for kaolinite, and >3 for sodium montmorillonite) [52–54]. In another study, c and m for marine clays are reported to be varying from 0.95–1.25 and 1.36–3.5, respectively [5]. It has been reported that $c>1$ implies that the soil matrix phase is conductive, which is mainly attributed to the clay content CL of the soil [53]. On the contrary, for rocks and sands, c is reported to be ≈ 1 by some researchers [5,17].

As m mainly depends on the tortuosity, while c indicates soil matrix phase conductivity, both of these parameters should depend on the plasticity index PI, fine content FN, and clay content CL of the soil. With this in view, attempts were made to correlate c and m with PI, FN, and CL, respectively, for these 26 soils. However, the trends obtained when c and m are plotted against CL as depicted in Fig. 7 were found to be quite well-defined as compared to the trends obtained by plotting them against PI and FN. Incidentally, this is in accordance with the fact that (only) CL has been reported to be the main parameter that affects the electrical conductivity [55–59]. Low values of R^2 for the trends depicted in Fig. 7 can be attributed to the uncertainty associated with determination and reporting of parameters CL, σ, and σ_w by previous researchers. The trends depicted in Fig. 7 can be expressed as:

$$\text{For } CL \geq 5\ \%: \quad c = 0.6 \cdot CL^{0.55} \tag{12a}$$

$$m = 0.92 \cdot CL^{0.2} \tag{12b}$$

$$\text{for } CL < 5\ \%: \quad c = 1.45 \tag{12c}$$

$$m = 1.25 \tag{12d}$$

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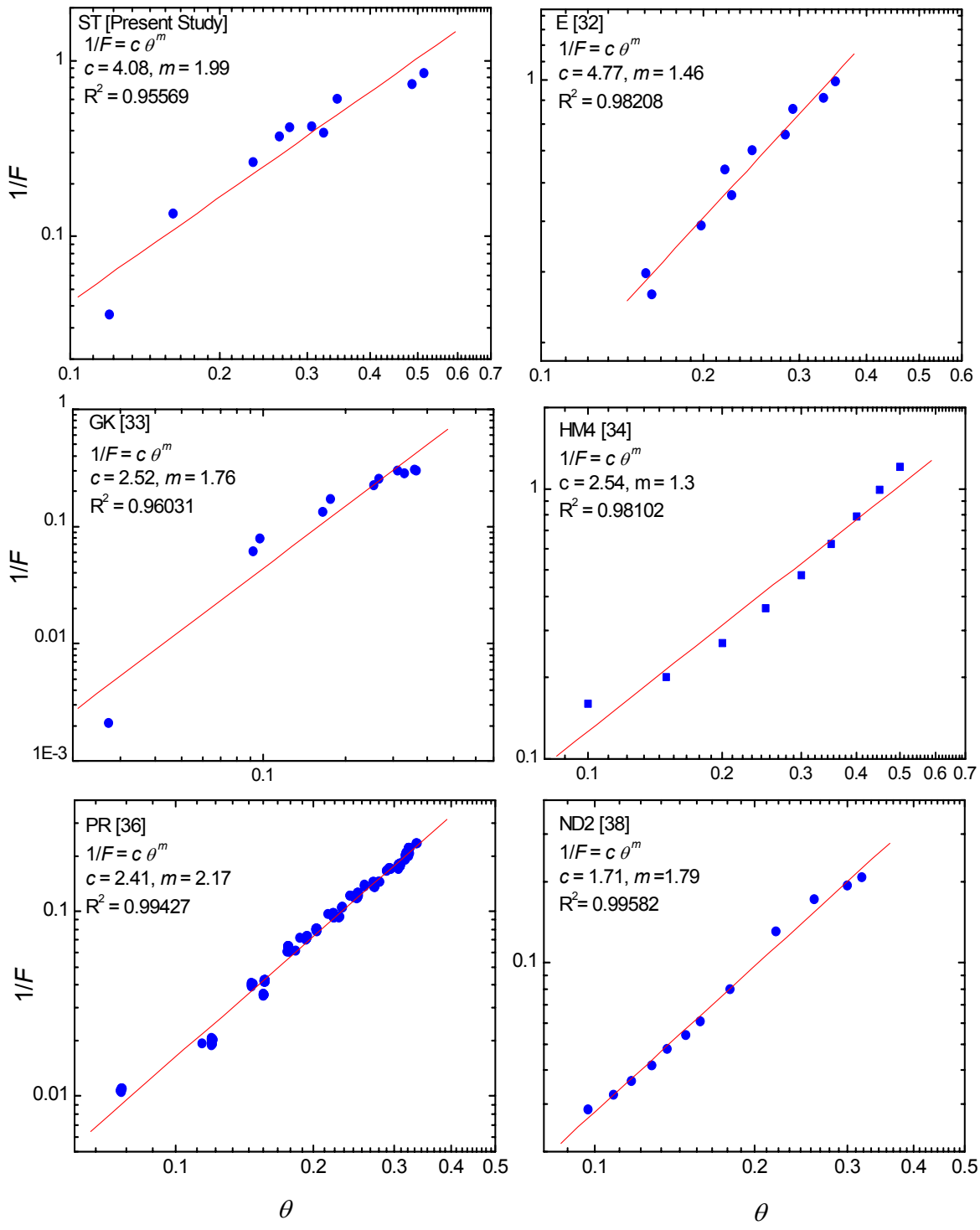

FIG. 6—*Variation of 1/*F *with* θ *for different soils.*

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TABLE 6—*Fitting parameters for the generalized Archie's law.*

Soil	*c*	*m*	R^2
A	6.84	1.53	0.93647
B	7.89	1.89	0.92439
C	0.33	1.25	0.92979
D	7.03	1.45	0.98483
E	4.77	1.46	0.98208
F	5.79	1.97	0.96788
G	2.45	0.74	0.8996
H	2.06	0.77	0.82218
K	2.2	1.03	0.97939
L	3.07	0.94	0.98989
M	5.86	1.41	0.9389
NL	4.96	2.45	0.90088
ML	4.39	1.6	0.95759
GK	2.52	1.76	0.96031
FR	2.12	2.35	0.95175
MN	6.47	2.69	0.94775
HM1	1.04	1.16	0.98589
HM2	0.48	0.91	0.99975
HM3	0.70	1.03	0.98513
HM4	2.54	1.3	0.98102
RN	6.9	3.17	0.96537
PR	2.41	2.17	0.99427
ND1	4.66	2.24	0.98589
ND2	1.71	1.79	0.99582
ND3	2.03	2.05	0.99888
ND4	1.53	2.03	0.99332
ST	4.08	1.99	0.95569
BC	15.85	3.11	0.92571
WC	3.19	1.81	0.98735
MC	8.2	3.92	0.97204

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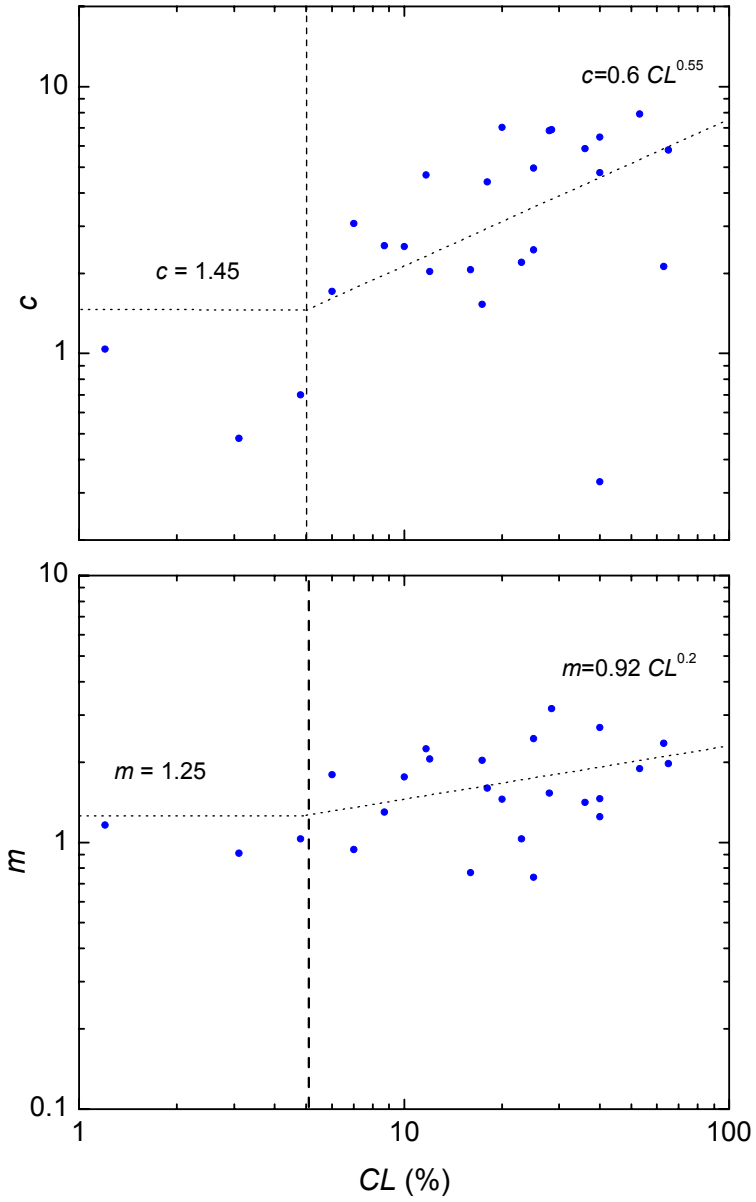

FIG. 7—*Variation of parameters c and m with CL.*

To check the validity of Eq 12, *c* and *m* were computed, as described above, for soils ST, BC, WC, MC, AK1, AK2, AK3, and AK4. Details of Soils AK1–AK4 are presented in Table 7 [56]. Using Eq 9, $1/F$ for these eight soils was computed, designated as $1/F_{\text{Eq. 9}}$ and compared with the $1/F$ obtained from the experimental data, designated as $1/F_{\text{Exp.,}}$ as depicted in Fig. 8*a*. It can be noted from the figure that there is a very small variation of ≈4 % in the expected trend (shown as dotted line) and the trend exhibited by the combined data (shown as solid line). This demonstrates the utility of Eqs 9 and 12 for estimating electrical conductivity of the soil, however, a large database of well-characterized soils is essential to increase the confidence level in using these equations for practical applications. It must be noted that the generalized Archie's law (Eq 9) would also be quite useful for predicting σ of a soil or for determining σ_w of the soil knowing its moisture content.

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TABLE 7—*Details of the soils used for validation of the generalized Archie's law.*

Soil	*CL* (%)	σ_w (S/m)
AK1	15	0.854
AK2	63	0.284
AK3	31	0.274
AK4	38	0.133

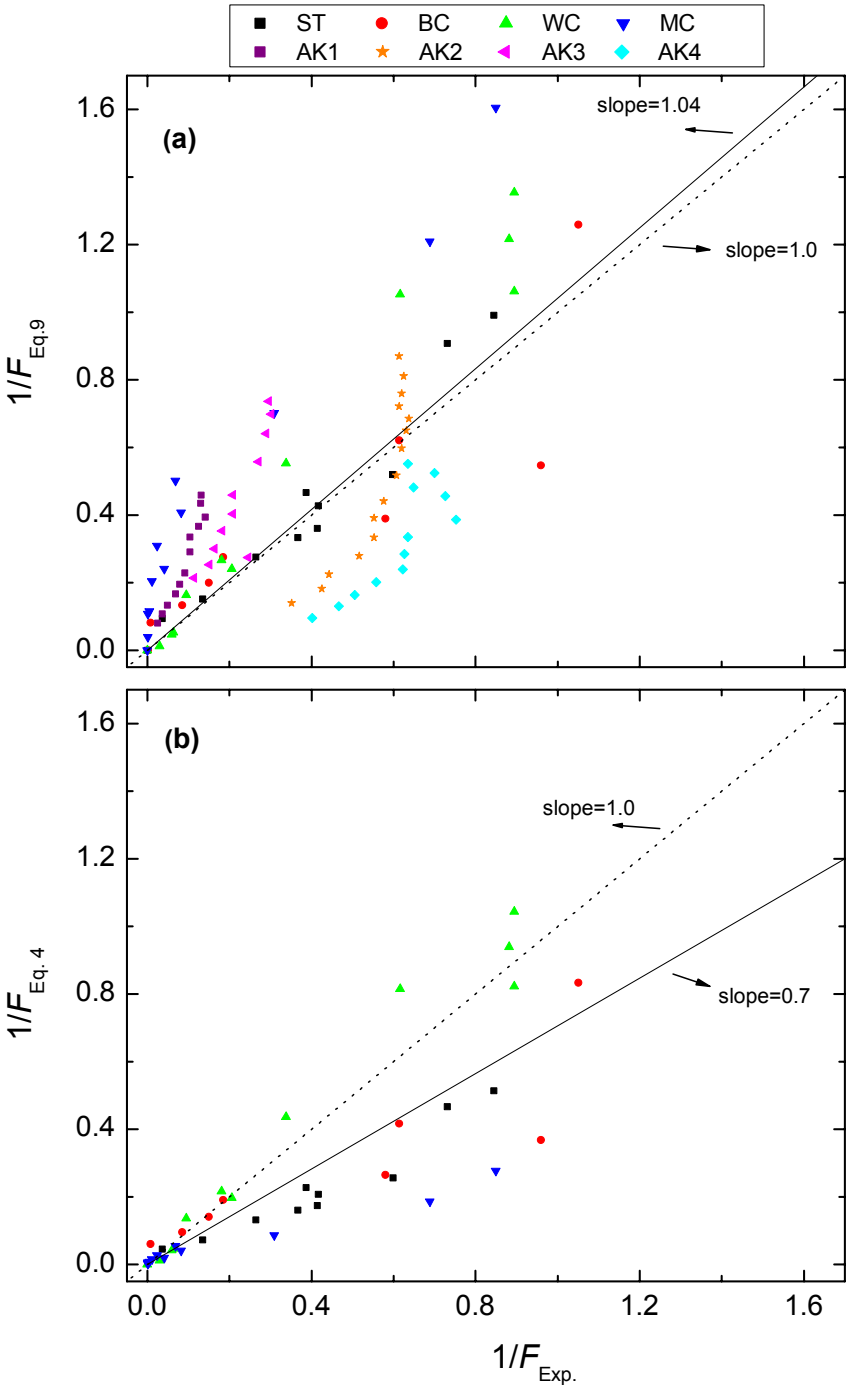

FIG. 8—*Comparison of the computed and experimental values of 1/*F *for different soils.*

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Further, experimental results of soils ST, BC, WC, and MC were fitted to the model proposed by Rhoades et al. [1], which is represented by Eqs 1 and 2, and parameters a, b, and σ_s were obtained, and the same are listed in Table 8. It can be noted from the data presented in the table that for these soils, though R^2 is very close to unity, some values of σ_s are negative. Similar results are reported in the literature [34] as well, wherein the conductivity data for the nine soils has been analyzed. However, it must be noted that negative σ_s is invalid, and hence the model proposed by Rhode et al. [1] cannot be considered as the most appropriate model. In such a situation, authors recommend application of the generalized Archie's law (Eq 9), which has been validated as depicted in Fig. 8*a*.

TABLE 8—*Parameters obtained from Eqs 1 and 2 for different soils.*

Soil	a	b	σ_s (S/m)	R^2
ST	4.46	0.58	–0.009	0.93238
BC	1.04	1.2	–0.005	0.95686
WC	3.77	–0.071	0.001	0.97032
MC	3.68	–0.76	0.467	0.97875

Further, the model proposed by Gunzel [20], which is represented by Eq 4, has also been used to predict σ values for soils ST, BC, WC, and MC. As depicted in Fig. 8*b*, when $1/F_{\text{Eq. 4}}$ is plotted against $1/F_{\text{Exp.}}$, a very large deviation (≈30 %) between the expected trend (shown as dotted line) and the trend exhibited by the combined data (shown as solid line) can be observed. However, an excellent matching between the computed and experimental results can be noticed for $1/F<0.4$. This indicates that Gunzel's model can be used for predicting σ of the soil, with known *CEC* value, particularly for lower values of θ.

Further, the effect of particle conductivity σ_p on σ, which is important for dry soils (i.e., $\theta = 0$), can also be incorporated in the generalized Archie's law by modifying Eq 9, as depicted in the following:

$$\sigma = c \cdot \sigma_w \cdot \theta^m + \sigma_p \tag{13}$$

However, it must be noted that for most of the soils, σ_p is so small that it can be ignored.

Conclusions

The study brings out a generalized Archie's law, which can be used for saturated as well as unsaturated states of all types of soils. Validity of this law has been demonstrated by conducting experimental investigations on four soils with entirely different characteristics, and using their particle-size characteristics, bulk conductivity, and pore-solution conductivity. Based on the analysis of data available in literature, parameters used in the generalized Archie's law have been correlated with the clay fraction of the soil. Superiority of the proposed generalized Archie's law over the models proposed by Rhoades et al. [1] and Gunzel [20] has also been demonstrated.

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