Dielectric Studies Of Saline Soils At Microwave Frequency

Kamlesh Kumari
Department of Physics Raj Rishi Government P.G. College **Alwar** (Rajasthan)-301001

Abstract

Dielectric constant (ε') and dielectric loss (ε'') of artificially salinized and moistened soil samples are determined at a single microwave frequency 9.78 GHz and at a single temperature 35.0 ^{0}C using a wave guide cell method. Further, the values of ε' and ε'' of saline and moist soil samples are obtained theoretically with Wang-Schmugge model at 35.0 ^{0}C with the incorporation of salinity effect. The present study reveals that soil salinity has a little influence on ε' unless the soil is sufficiently moist while ε'' of soil increases significantly as the salinity increases.

Key words: Saline soils, dielectric constant, microwave emissivity, microwave remote sensing, radar backscattering coefficient and soil moisture content.

1. Introduction

The increasing percentage concentration of salts in agricultural soil is a crucial environmental hazard and may be one of the causes for the decline and disappearance of a civilization[1]. Worldwide, presence of salt in soil is one of the principal causes of its degradation. Ghassemi[2] estimated that nearly 20.0% of all irrigated land and approximately 7.0% soils of all over the world are salt-affected and these proportions tend to increase in spite of considerable efforts dedicated to land reclamation.

Soil salinity is the most crucial agronomic and ecological problems affecting the soil of Alwar, semi-arid regions of eastern Rajasthan. Large-scale application of fertilizers and improper irrigation techniques results in the salinization of large tracts of arable land. Salts introduced through irrigation, infiltrate deep inside the soil. Due to transportation of underground water by capillary movement, consequently evaporates at the surface salts accumulate in the upper soil profile. It is imperative the careful monitoring of the status of soil salinity and its dynamics to curb degradation trends and secure sustainable land use.

The effect of soil moisture on dielectric properties of soil has been widely investigated and variety of models is devised. But a little work has reported regarding the influence of salts on dielectric properties of soils. Compared to soil moisture studies, research on soil salinity and its effect on the dielectric constant is far less complete. Soil salinity and its dielectric properties are a complex multiple-factor-driven subject, a field that only a few papers have touched on. However, the concentration of salts in water affects its dielectric properties in a well-known manner. Salts may affect, ε' which is related to the polarization of medium that governs the velocity of propagation of microwaves through the material and ε'' which is related to the conductivity of the medium and represents the microwave attenuation by energy absorption (ohmic losses).

2. Dielectric properties and microwave remote sensing of saline soil

2.1 Dielectric properties of saline soil

According to Schmugge[1] effect of salinity is somewhat little on ε' of soil while salinity produces a large increase in ε'' particularly at low microwave frequencies. The ε'' of saline soil increases due to it's enhance ionic conductivity. Lasne *et al*[2] studied that high soil salinity may significantly influence the electrical conductivity and imaginary part of the dielectric permittivity and these are interrelated each other. Microwave response study of Sreenivas *et al*[3] concluded that the ε' is independent but ε'' is strongly dependent of salinity and further emphasised that the ε' is strongly related with SMC only.

Yun Shao *et al*[4] studied the dielectric properties of artificially moistened and salinized soil (with sodium chloride solution) and natural soil samples taken from a Salt Lake in northern China over a frequency range 1.0–18.0 GHz and observed that both the soil moisture and salinity affected the ε' and ε''. The influence of soil salinity on ε' was relatively small and could even be negative in comparison to impact of soil moisture while ε'' shows a much higher respective correlation with soil salinity.

Mironov *et al*[5] observed that if soil is salinized with sodium chloride, the complex dielectric constant of bound water in saline soil depends on salinity concentration. Mohamed *et al*[6] reported that, the effect of salinity on the imaginary part depends on wetness and texture of soil and significant only at higher level of SMC. The important dielectric mixing models to determine ε' and ε'' of moist soil, W S Model[7] and Dobson Model[8] utilize the ε'

and ε'' of pure water as input parameters which can be determined by Debye theory[9]. Ulaby *et al*[10] suggested a modification in Debye equations for saline water and determined ε' and ε'' of saline soils.

Lasne *et al*[11] reported that to characterize the dielectric properties of the soil and saline water mixture the W S Model[7] modified according to Stogryn[12] provide a better description. Further, Lasne *et al*[11] reported that salinity has a little influence on ε' except for soil with high moisture content ($m_v > 0.2$) for which ε' decreases with increasing salinity. For small salinity values, the increasing moisture content appears to be the main factor in ε' variations. On the contrary, the imaginary part ε'' is strongly affected by both salinity and moisture of the soil. The strong effect of salinity on the imaginary part particularly at higher levels of SMC is observed. Recently the simulation study of Wu and Wang[13] and experimental results of Meena and Behari[14] confirm that real part of dielectric constant decreases with soil salinity content while the imaginary part increases.

3. Materials and method

The soil from superficial horizon of local profile of Alwar region with textural composition sand=79.0%, silt=14.6% and clay=6.4% has been selected for preparation of samples. Texture of soil is determined using sieving and sedimentation methods. Firstly salt free soil is obtained by leaching of salts from the soil through repeatedly flushing with conductivity water until the residual d.c. conductivity of soil extract remains negligible. Salt free soil was oven dried for twenty-four hours at 110 ^{0}C and divided in eight different Groups namely A,B,C,D,E,F,G and H respectively.

The eight different solutions of NaCl soluble in conductivity water with different concentrations in part per million (ppm) corresponding to 0 ppm, 5000 ppm, 10000 ppm, 15000 ppm, 20000 ppm, 25000 ppm, 30000 ppm and 35000 ppm are prepared. Then each NaCl solution is mixed with dry soil such that each soil group (A to H) possess eight different desired level of saline water concentrations (0.0%, 2.0%, 4.0%, 6.0%, 8.0%, 10.0%, 12.0%, and 14.0%).

Total sixty four samples of saline soil at different levels of salinity (0 ppm to 35000 ppm) and moistness (0.0%, to 14.0%) are prepared. The saline water properly mixed with salt free soil and these artificially salinized and moistened soil samples are kept in air tight plastic container for uniform mixing and to avoid any evaporation from soil. Time of setting was twenty-four hours for homogeneous distribution of saline water within the entire volume of soil.

3.1 Determination of Dielectric Constant

3.1.1 Experimental

The real and imaginary part of dielectric constant (ε' and ε'') artificially salinized and moistened soil samples prepared in the laboratory as a function of salinity and water content are evaluated. The ε' and ε'' of artificially salinized and moistened soil samples are determined at a single microwave frequency 9.78 GHz and at a single temperature 35.0 ^{0}C using the wave guide cell method developed by Yadav and Gandhi[15]. The ε' and ε'' of the soil samples are measured using shift in minima of the standing wave pattern inside the slotted section of a X-band rectangular wave guide excited in TE_{10} mode.

3.1.2 Theoretical

The values of real and imaginary part of dielectric constant (ε' and ε'') of saline soil samples are theoretically determined at 35.0 ^{0}C by W-S model[7] model with the incorporation of salinity effect as performed by Ulaby *et al*[10]. Wang and Schmugge[7] presented a set of equations which accounts for soil texture, bulk and particle density for real and imaginary parts of dielectric constant of a soil-water mixture (ε) are given as:

$$\varepsilon = W_c.\varepsilon_x + (P - W_c).\varepsilon_a + (1-P)\varepsilon_{rock} \qquad W_c \le W_{ct} \tag{1}$$

$$\varepsilon_x = \varepsilon_i + (\varepsilon_w - \varepsilon_i).\left(\frac{W_c}{W_{ct}}\right).\gamma \tag{2}$$

$$\varepsilon = W_{ct}.\varepsilon_x + (W_c - W_{ct}).\varepsilon_w + (P - W_c).\varepsilon_a + (1-P)\varepsilon_{rock} \qquad W_c > W_{ct} \tag{3}$$

$$\varepsilon_x = \varepsilon_i + (\varepsilon_w - \varepsilon_i).\gamma \tag{4}$$

Where W_c is the volumetric water content [m^3 m^{-3}] of the soil, P the porosity of the dry soil (total volume occupied by pores per unit volume of soil), γ is an empirical parameter and W_{ct} is the transition moisture [m^3 m^{-3}]. ε_a ε_w , ε_{rock} and ε_i are the dielectric constants of air, pure water, rock and ice respectively. ε_x stands for the dielectric constant of the initially absorbed water.

Both γ and W_{ct} can be determined by particle size distribution through wilting point of soil[6]

The complex dielectric constants for ice (ε_i), solid rock (ε_r) and air (ε_a) are 3.2+j0.1, 5.5+*j*0.2 and 1+*j*0, respectively. The real and imaginary parts of dielectric constant of pure water ($\varepsilon_w^{'}$ and $\varepsilon_w^{''}$) can be given by the well known Debye equations[9].

For saline water Ulaby *et al*[10] (1986) used a slightly different version of Debye equations[9] incorporating the term effective ionic conductivity $\sigma(T,S)$ of saline water and given by equation (5) and (6).

$$\varepsilon_{sw}^{'} = \varepsilon_{sw\infty} + \frac{(\varepsilon_{sw0} - \varepsilon_{sw\infty})}{1+(2\pi f \tau_{sw})^2} \tag{5}$$

$$\varepsilon_{sw}^{''} = \frac{2\pi f \tau_{sw}(\varepsilon_{sw0} - \varepsilon_{sw\infty})}{1+(2\pi f \tau_{sw})^2} + \frac{\sigma(T,S)}{2\pi\varepsilon_0 f} \tag{6}$$

$\varepsilon_{sw}^{'}$ and $\varepsilon_{sw}^{''}$ are the real and imaginary part of dielectric constant of saline water. ε_{sw0} and $\varepsilon_{sw\infty}$ are the static and high frequency limit of the dielectric constant of saline water. f is the observation frequency in Hertz and τ_{sw} is the relaxation time of saline water. $\sigma(T,S)$ is the ionic conductivity of the aqueous saline solution and ε_0 is the permittivity of free space. Stogryn[12] pointed out that $\varepsilon_{sw\infty}$ is independent of salinity and has the value equal to high frequency limit of the dielectric constant of pure water ($\varepsilon_{sw\infty} = \varepsilon_{w\infty} = 4.9$).

Here, the three variables of equation (5) and (6), static dielectric constant (ε_{sw0}), relaxation time (τ_{sw}) and ionic conductivity $\sigma(T,S)$ of the aqueous saline solutions are strong functions of salinity and temperature as given by Stogryn[12].

The dependence of ε_{sw0} on salinity (S_{sw}) and temperature (T ^{0}C) is given by equation (7).

$$\varepsilon_{sw0}(T,S_{sw}) = \varepsilon_{sw0}(T,0).a(T,S_{sw}) \tag{7}$$

Where, $\varepsilon_{sw0}(T,0)$ is the dielectric constant of pure water and $a(T,S_{sw})$ is salinity and temperature dependent function.

Klein and swift[16] generated the expressions (8) and (9) for $\varepsilon_{sw0}(T,0)$ and $a(T,S_{sw})$ from the experimental data measured by Ho and Hall[17].

$$\varepsilon_{sw0}(T,0) = (87.134 - 1.949\times10^{-1}\times \mathrm{T} - 1.276\times10^{-2}\times \mathrm{T}^2 + 2.491\times10^{-4}\times \mathrm{T}^3) \tag{8}$$

$$a(T,S_{sw}) = (1+1.613\times10^{-5}\times \mathrm{T}\times S_{sw} - 3.656\times10^{-3}\times \mathrm{S_{sw}} + 3.210\times10^{-5}\times \mathrm{S_{sw}^2} - 4.232\times10^{-7}\times \mathrm{S_{sw}^3}) \qquad (9)$$

The relaxation time of saline water is given by equation (10).

$$\tau_{sw0}(T,S_{sw}) = \tau_{sw0}(T,0).b(T,S_{sw}) \qquad (10)$$

Where, $\tau_{sw0}(T,0)$ is the relaxation time of pure water and $b(T,S_{sw})$ is salinity and temperature dependent function.

Stogryn[12] and Klein and swift[17] generated the expressions (11) and (12) for $\tau_{sw0}(T,0)$ and $b(T,S_{sw})$.

$$2\pi\tau_{SW}(T,0) = (1.1109\times10^{-10} - 3.824\times10^{-12}\times \mathrm{T} + 6.938\times10^{-14}\times \mathrm{T}^2 - 5.096\times10^{-16}\times \mathrm{T}^3) \qquad (11)$$

$$b(T,S_{sw}) = (1.0 + 2.282\times10^{-5}\times \mathrm{T}\times \mathrm{S_{sw}} - 7.638\times10^{-4}\times \mathrm{S_{sw}} - 7.760\times10^{-6}\times \mathrm{S_{sw}^2} + 1.105\times10^{-8}\times \mathrm{S_{sw}^3} \qquad (12)$$

Temperature and salinity dependence of ionic conductivity of the aqueous saline solution for sea water is derived by Weyl[32] (1964) and later modified by Stogryn[16] (1971) as given by equation (13).

$$\sigma_i(T,S_{sw}) = \sigma_i(25,S_{sw})e^{-\phi} \qquad (13)$$

Where, $\sigma_i(25,S_{sw})$ is the ionic conductivity of sea water at 25 ^{0}C which is given by equation (14).

$$\sigma_i(25,S_{sw}) = (0.18252 - 1.4619\times10^{-3}\,S_{sw} + 2.093\times10^{-5}\,\mathrm{S_{sw}^2} - 1.282\times10^{-7}\,\mathrm{S_{sw}^3})\mathrm{e}^{-\phi} \qquad (14)$$

The function ϕ depends upon S_{sw} and Δ expressed by following equation (15).

$$\phi = \Delta[\,2.033\times10^{-2} + 1.266\times10^{-4}\,\Delta + 2.464\times10^{-6}\,\Delta^2 - \mathrm{S_{sw}}(1.849\times10^{-5} - 2.551\times10^{-7}\,\Delta + 2.551\times10^{-8}\,\Delta^2)] \qquad (15)$$

Where $\Delta = 25 - T$,

Ulaby *et al*[10] pointed out that above expressions are valid for the salinity range of water $0 \le \mathrm{S_{sw}} \le 40{,}000$ ppm

Using the above equations (7) to (15) the three variables ε_{sw0}, τ_{sw} and $\sigma(T,S)$ are determined at the temperature 35 ^{0}C and at the salinity values varying from 0 ppm to 35000 ppm. The real and imaginary parts of complex permittivity of saline water are determined at 9.78 GHz by modified Debye equations (5) and (6) as used by Ulaby *et al*[10]. Further, using real and imaginary part of complex permittivity of saline water along with other required parameters described above in Wang-Schmugge model[7] the real and imaginary parts of complex permittivity of saline soil are calculated.

4. Results and Discussion

Variations of ε' and ε'' of soil with respect to salinity of NaCl (0-35000 ppm) at different levels of SMC (0.0% to 14.0%) determined, experimentally and W S model are shown in figures-1,2 and 3,4 respectively.

(i) It is evident from the figures:1 and 3 that real part of dielectric constant (ε') increases with increasing percentage concentration of SMC. Initially ε' increases slowly when water is added to dry soil but at a certain moistness around SMC=10% addition of more water in soil causes the increases of ε' rapidly. Molecules of water possess permanent electric dipole moment because polarization. The high dielectric constant of water depends on the molecule's ability to align its dipole moment along an applied field. Hindrance to the molecule's alignment (adsorption, freezing, tight binding to a soil particle, etc.) reduces the dielectric constant of water. Since the initial water quantity added to dry soil is tightly bound to the surface of the particles, it will cause only a small increase of the soil dielectric constant. This water is referred to as bound water. As more water is added, above a transition limit of moisture, the soil dielectric constant will rapidly increase because the additional molecules are far from the soil particle surface and free to align. Water in this phase is referred to as free water. Dielectric constant of free water is higher than that of bound water. The imaginary part of dielectric constant value is slightly increases with increases in SMC.

(ii) It is evident from the figures: 2 and 4 that imaginary part of dielectric constant (ε'') increases with increasing percentage concentration of SMC. Due to increases in the SMC, conduction loss, polarization loss, rotational inertia are increases. Hence, there is increasing lag between the forcing field and orientation of dipole. Resulting more power absorption in the soil and causing enhancement in the dielectric losses.

In addition of more water with soil more and more polar molecules are available to interact with microwaves, dielectric constant of moist soil is proportional to the number of water dipoles per unit volume, so that real and imaginary part of dielectric constant of soil increases as the SMC of soil increases.

(iii) An inspection of figures-1 and 2 reveals that soil salinity has a little influence on ε' unless the soil is sufficiently moist. The negative correlation is observed between ε' and salinity of the wet soils. Dielectric constant of soil is primarily controlled by SMC and according to Stogryn[16] dielectric constant of water decreases as its salinity increases. Hence, the increasing salinity of mixing water produces slightly decreasing trend in wet soils.

(iv) There is no effect of salinity on dielectric constant is observed for dry soil but for wet soils the effect of salinity increases as moistness increases. The influence of salt on dielectric properties of soil is related to its solubility in free water. At low levels of moistness only bound water phase of SMC dominates and salts are not properly dissolved to interact with bound water, resulting into a weak effect of salinity on real part of dielectric constant. At higher levels of SMC salts are easily dissolved into water and interact with soil particles.

(v) An examination of figures-3 reveals that the imaginary part (ε'') is strongly affected by both salinity and moisture of soil samples. ε'' of soil increases as the salinity increases. At the higher magnitudes of humidity the stronger effect of salinity on the dielectric loss factor is observed. In case of dry soils effect of salinity on the imaginary part is negligible. The effect of salinity on ε'' can be explained on behalf of the conductivity of soil. Increase in soil moisture content leads to a greater amount of salts dissolved in the free water component. Large number of positive and negative ions is available and thus, increase in ionic conductivity of soils is observed. These free ions or charges interact with oscillating electric field of microwaves and enhance the conduction losses. Hence, ε'' is proportional to the salinity or conductivity of soils.

(vi) An examination of in figures-4 reveals that the W S Model calculated values of ε'' soil at different levels of SMC are weakly dependent on salinity of NaCl. The experimentally determined values of ε'' are higher than that of predicted values by model calculations. This can be explained as the W S Model is a semi-empirical model derived from specific data sets and is mostly valid only for certain soils and emphasize on certain parameters (particle size and moisture content) in the soil. Soil is a complex mixture and its dielectric properties are characterized by a large number of parameters so that the experimental values may differ to the values derived by the W S Model.

5. Conclusions

The negative correlation is observed between real part of dielectric constant and salinity of the wet soils. The imaginary part of dielectric constant is strongly affected by both salinity and moisture of soil samples. Dielectric study of salt affected soils is very important regarding mapping, monitoring and management of salt effected soils. Because of the differential behaviour of the real and imaginary parts of the complex permittivity, microwave remote sensing appear to be efficient in detecting soil salinity (the real part is independent and imaginary part is highly sensitive to variations in salinity). This allows separating saline soils from non-saline soil.

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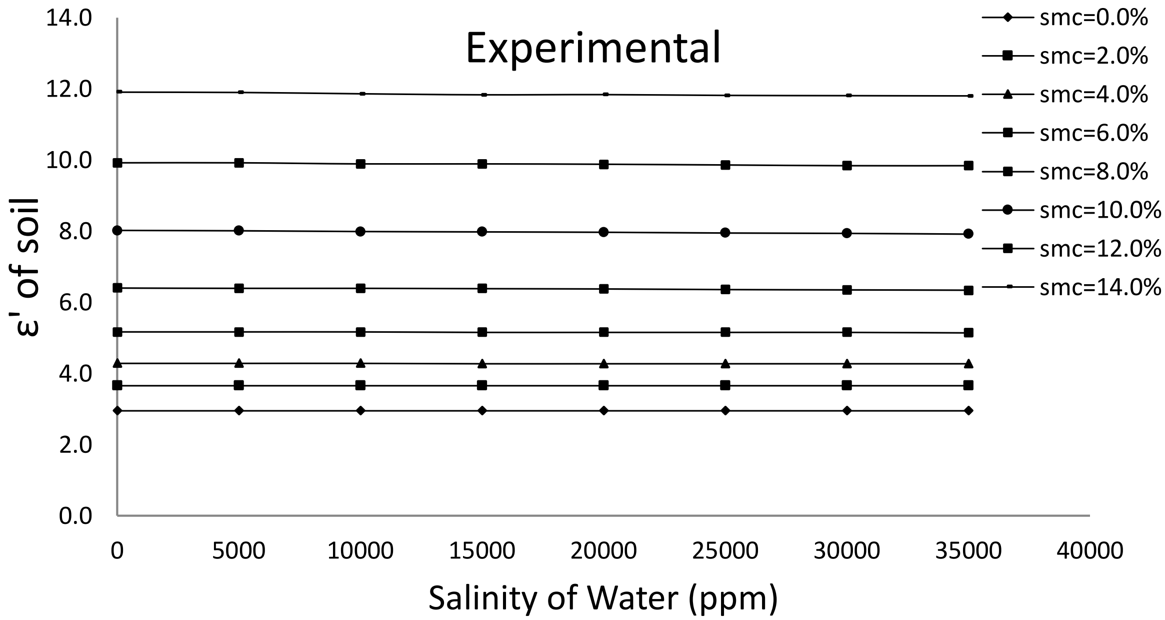

Fig-1: Variations of experimental values of ε' of soil w.r.t salinity of NaCl at different levels of SMC

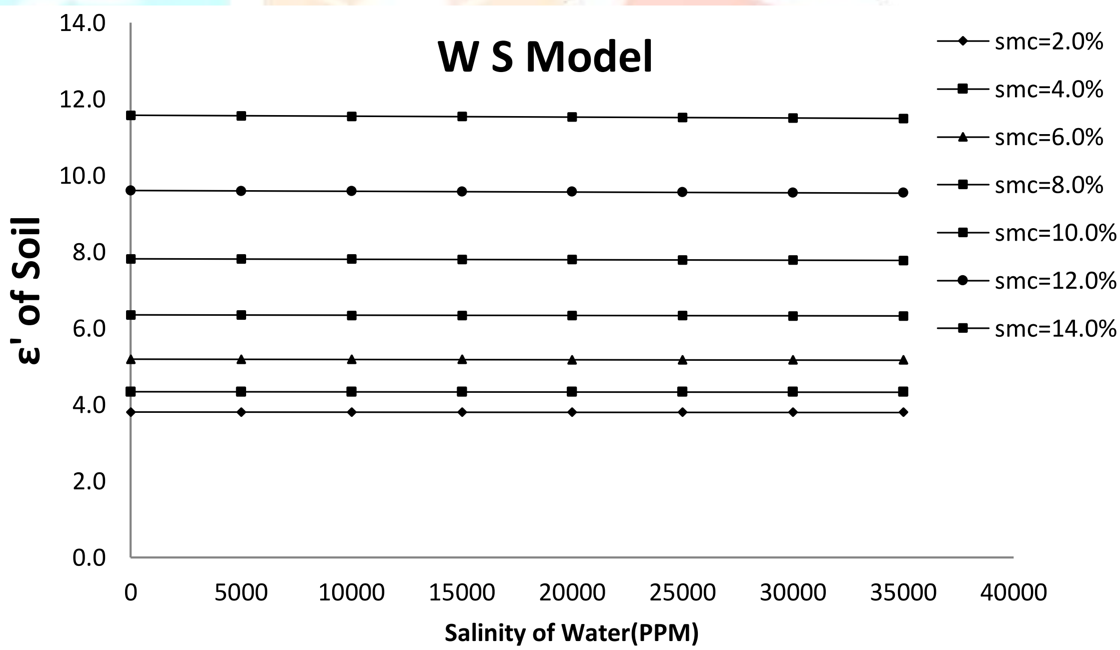

Fig-2: Variations of W S Model calculated values of ε' of soil w.r.t salinity of NaCl at different levels of SMC.

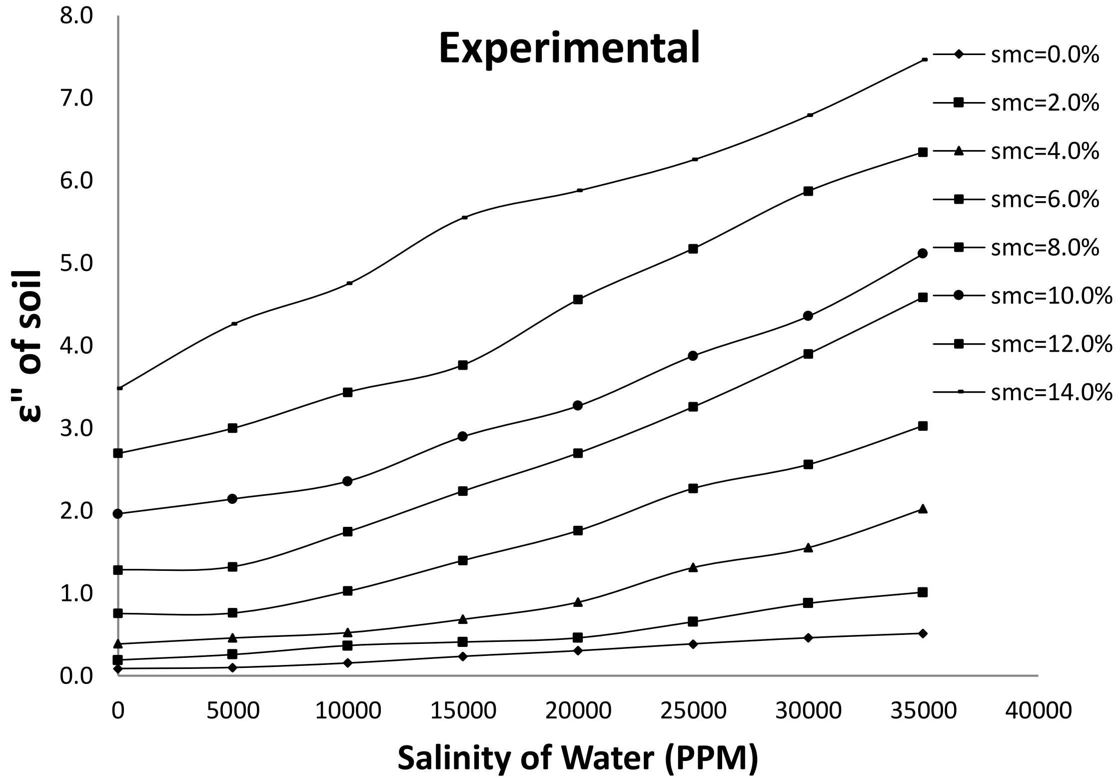

Fig-3: Variations of experimental values of ε'' of soil w.r.t salinity of NaCl at different levels of SMC

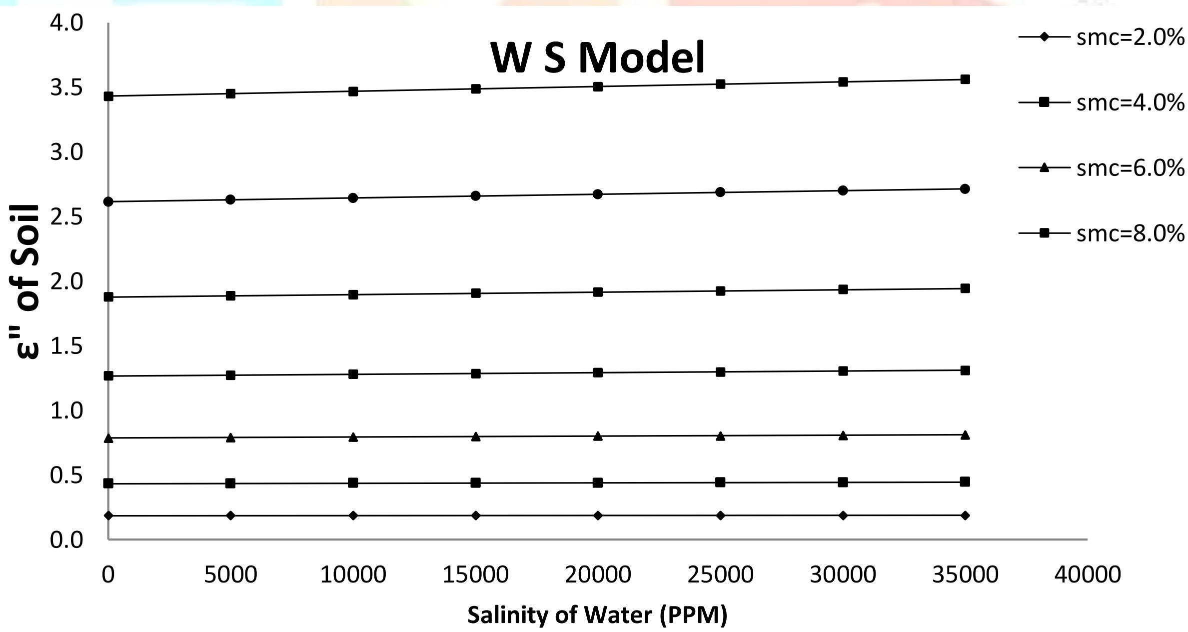

Fig-4: Variations of W S Model calculated values of ε'' of soil w.r.t salinity of NaCl at different levels of SMC