EXPERIMENTAL VERIFICATION OF THE THEORY
OF DESALINIZATION OF SALINE SOIL

—The Fundamental Study on the Desalinization of Saline Soil(2)—

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Abstract In Part 1. of this series, the theory was developed to describe the desalinization process from the adsorption-desorption isotherm, diffusional and hydrodynamic point of view. In the present paper, experimental verification is carried out and the results are discussed in relation to the theory.

The saline soil, subjected to this experiment, was taken from the polder reclaimed land from the sea. The experiment was conducted in a specially designed Soil Electrode Box made of wood, in such a way that the desalinization process was not allowed to be disrupted.

The theory was verified by the following steps.
1. The Theoretical Diffusion Curve obtained from the theory was compared and contrasted with the Observed Diffusion Curve.
2. The theoretical amount of the leached salt derived from the theory was checked with the empirical results.
3. The calculated data of leached salt, obtained from the theory with respect to mean flow velocity were tested with the experimental results.
4. By the Match-Point Coordinate Method, the soil constants such as \(\alpha\) & \(\beta\) were determined from the Diffusion Curves.

I. INTRODUCTION

The theory of the desalinization was expounded in Part 1. The theory necessitated that the verification should be conducted without disrupting the continuous process of desalinization. Therefore, a specially designed experimental model was used. The symbols used below have identical meanings to those used in Part 1, and are therefore not defined explicitly.

II. METHODS AND MATERIALS

1. The principle of electrical conductivity method

For the verification of the theory, it was essential to establish simultaneously, the correlation between the apparent electrical conductivity \( (EC_a) \) of the soil body and the soil salinity, without disturbing the diffusion and desalinization process, under certain given conditions. Therefore, Soils Electrode Box Method has been devised to meet the requirements.

Most soil minerals are insulators and conduction, therefore, occurs through the interstitial water which contains, in the saline soils, appreciable amounts of dissolved electrolytes. In addition, soils may conduct current via the exchangeable cations that reside on the surface of charged soil minerals, which are electrically mobile to various extent. The conductivity of a saline soil should depend primarily on the conductivity of the interstitial electrolyte solution, on the effective soil porosity and on the degree of water saturation. Therefore, for a given soil type, it would be possible to correlate the apparent soil conductivity \( (EC_a) \) with soil salinity, especially if such measurements are made at a constant water content. From the hydraulic point of view, unsaturated soil creates an extremely wide range of microscopic pore velocities associated with nearly emptied pores. In addition...
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2. The experimental apparatus

A wooden box of having an internal length and breadth of 27.1 cm and 27.0 cm, respectively and a depth of 19.8 cm, was readied for this experiment. Six current electrodes of polished copper are set at 3 cm apart from the surface downward across the box, as shown in the Fig. 1.

Fig. 1 Cross sectional view of the soil electrode box.

Internal Length= 27.1 cm
Breadth= 27.0 cm
to this, there are changing cross-sectional areas between displacing and displaced fluids. Hence, even at the same fluxes, the values of the molecular diffusion coefficient calculated could be different.

3. Materials

The saline soil used in this study was obtained from the halogenetic polder land of Kojima Bay, Okayama Prefecture. According to the sedimentation, the texture of these polder soils ranges from fine sand to clay. Composite soil sampling was done from the grayey layer at a depth of 30 cm to 90 cm. The Table 1 and 2 showed some of the soil characteristics.

The clay types of the soil had been verified by the Differential Thermal Analysis. The Differential Thermal Curve for the mixture of Illite and Montmorillonite was illustrated in the Fig. 2. It was also supported by the finding of Yoneda.

About 7.5 Kilogram of this soil (dry weight basis) was mixed homogeneously with deionised water with occasional stirring. It was kept at constant water content (Saturation) under polyethylene paper cover for two days. This was done to stabilize the soil-water system and to eliminate the variable water contents as a factor affecting conductivity reading. The narrower the distribution of pore size the more nearly homogeneous in the microscopic sense is the soil.

4. The experiment and measurements

The saline soil and constant water content was put in the Soil Electrode Box with uniform spreading and moderate compaction. Care was taken to remove the air bubbles. The total soil depth was 16.4 cm in the box. The average bulk density of the soil in the box was 0.528 mg/cm³ and the water content 134.5% (dry weight basis). The soils between the electrodes from the surface to the bottom were designated as soil cells A, B, C, D & E, respectively. Almost equal volume of fresh deionized water was ponded on the surface of the soil by an inlet and discharged after an interval, by another outlet tubes attached to the upper part of the box.

Table 1

<table>
<thead>
<tr>
<th>Coarse Sand (2.00~0.20) mm</th>
<th>Fine Sand % (0.20~0.02) mm</th>
<th>Silt % (0.02~0.002) mm</th>
<th>Clay % (&lt;0.002) mm</th>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>22.25</td>
<td>50.25</td>
<td>27.50</td>
<td>Silty Clay</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>pH Moisture</th>
<th>ECse $\mu$S/cm</th>
<th>% Cl Content</th>
<th>Permeability Const. at 20°C cm/sec</th>
<th>Clay type</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>143.7</td>
<td>0.80</td>
<td>2.07x10^-4</td>
<td>Ilite Mont. Mixture</td>
</tr>
</tbody>
</table>

Fig. 2 Differential Thermal Curves for Mixture of Illite and Montmorillonite.
at different levels. Please refer to it for **Fig. 1.**

The stagnant water zone on the surface of the soil had acted as sink to the ionic diffusion. The conductivity metre provided the source of low frequency alternating current (60 C/sec.) to the current electrodes embedded in the soil. According to Harold, at the peak electrical conductance, sodium was in greater quantity and calcium in less quantity. Therefore, during the experiment, peak apparent electrical conductivity (ECa) was taken into consideration. Temperature measurement of the soil and the apparent electrical conductivities of the different soil cells of the soil body were taken after each discharge of the ponded water at an interval. The soil surface was again ponded with fresh deionized water by the inlet tube from a tank. The discharged water was analysed for sodium chloride content by the determination of chloride, according to the Silver Nitrate Titration Method. Its conductivity was also taken. At the beginning, the determinations were carried out with an interval of a day. But, with the progress of the experiment, the sodium chloride content reduced to very imperceptible quantity in a single day discharge. Therefore, on the later dates, the readings were taken once a week. Thus, following the routine, the experiment was carried out for a total length of 154 days. At the end of the experiment, the whole soil body was cut into slices of soil layers in between the electrodes. Each slice of soil was divided into two parts-the middle part around each electrode with 5cm. width and the side parts, as drawn in the **Fig. 4.**

The middle part was extracted through buchner funnel with vacuum pump. The soil extraction was analysed for sodium chloride content. The last readings for the apparent electrical conductivities (ECa) were taken as the corresponding to the salt concentrations of the soil extractions of the middle parts of the slices. The electrical conductivity of the soil extractions (ECs) were also taken. The apparent electrical conductivity (ECa) of the soil was noted till the average initial ECa reading of 2.575x10^5 μS/cm was changed into three different order of ECa. Such as, the last reading of Cell-A: 2.795x10^6, Cell-B: 6.230x10^4, Cell-C: 9.150x10^4, Cell-D: 1.165x10^6 and Cell-E: 1.180x10^5 μS/cm, respectively.

**5. Correction of the readings**

The current leaving the electrodes was partially restricted by the boundary conditions of the apparatus, the surface area of electrodes as well as the soil resistance. Therefore, all the ECa readings were corrected by the Form Factor. Accordingly, the Form Factor (F) had been defined here as the mean value of the conductivities as affected by the boundary conditions of the apparatus and the changed surface area of the electrodes. Thus: $F = \frac{1}{2} (a' + d)$ where, $a' = \text{Ratio of conductivities of soil cell- C and other soil cells.}$ $d = \frac{C_a}{b}$, where, $C_a = \text{Conductivity (ECwa)}$ of central cell with unrusted electrodes. $b = \text{Conductivity (ECwb) of all cells with rusted electrodes.}$ Unrusted and polished electrodes have become a little bit rusted after the long run of the experiment. This change had been taken into account by the factor ‘d’.

As shown in the **Table 2.**, ‘a’ was determined by filling in the Soil Electrode Box with fresh tap water only and having unrusted electrodes conductivities (ECwa) of all the Soil Cells were taken. The Soil cell-C, being centrally located, was considered to be least affected by the boundary conditions of the box. So, its conductivity was taken as constant factor, on the basis of which, other cell conductivity ratios $a'$ were derived. ECwb were also determined similarly, but with rusted electrodes. Hence, $d$ was defined by the ratio $\frac{C_a}{b}$.

Therefore, Form Factor ‘F’ is the mean value of the two ratios, $a'$ and $d$. The apparent conductivities (ECa) during the experiment were corrected.
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Table 2 Form Factor Data.

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<tbody>
<tr>
<td>$EC_{ac}$ with unrusted electrode &amp; tap water, '$a'$</td>
<td>$2.385 \times 10^3$</td>
<td>$4.310 \times 10^3$</td>
<td>$4.455 \times 10^3$</td>
<td>$4.670 \times 10^3$</td>
<td>$4.200 \times 10^3$</td>
<td>$17^\circ C$</td>
</tr>
<tr>
<td>Ratio of C and other cells, '$a'$</td>
<td>1.66</td>
<td>1.03</td>
<td>1</td>
<td>0.95</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>$EC_{ac}$ with rusted electrodes and tap water '$b'$</td>
<td>$2.300 \times 10^3$</td>
<td>$4.115 \times 10^3$</td>
<td>$4.015 \times 10^3$</td>
<td>$4.115 \times 10^3$</td>
<td>$3.860 \times 10^3$</td>
<td>$14^\circ C$</td>
</tr>
<tr>
<td>$d = \frac{C_a}{b}$</td>
<td>1.93</td>
<td>1.08</td>
<td>1.10</td>
<td>1.08</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>$F = \frac{1}{2}(a'+b)$</td>
<td>1.89</td>
<td>1.05</td>
<td>1.05</td>
<td>1.01</td>
<td>1.10</td>
<td></td>
</tr>
</tbody>
</table>

by multiplying them with '$F$'.

6. Calibration curve

The last apparent conductivities ($EC_a$) of the soil cells, were taken as corresponding to the salt concentrations of the same soil cells extraction. The readings ($EC_a$) were corrected with form factor. They were plotted against salt concentrations to give a straight line on the logarithmic paper. This relationship had been taken as the Calibration Curve. Against it, all the $EC_a$ readings had been interpolated to give the corresponding salt concentrations during the experiment. Calibration Curve was illustrated in the Fig. 4.

III. RESULTS AND DISCUSSIONS

By the aforementioned observations, empirical relations were established for verification of the theory in the following ways:

1. By comparing the calculated values of $\frac{C_t - C_o}{C_o}$ obtained from the equation (20) in Part I, with those observed, when $V=0$.

The boundary conditions of the experiment were, $V=0$ and at the $x=\pm l$, $\partial c/\partial x=0$.

The solution of the equation under these boundary conditions was given in the equation (20) of Part I of this series. Taking $\beta=0.0$ and putting $\alpha =1.0$, the values of $C_t/C_o$ were obtained analytically from this equation. These had been plotted in the Fig. 5.

On the other hand, by the above mentioned experiment, the observed salinity data at a given time $t$ and depth $x$ were obtained and plotted in the Fig. 6, with $C_t/C_o$ against $x/\sqrt{t}$. By the match-point CO-ordinates method, when the observed data curve, Fig. 6, was super-imposed on the type curve, Fig. 5, with the $x$-axis coinciding and on sliding the Fig. 6 to the right or left side; both the curves were coincided on a point-where $x/\sqrt{t}=1.0$ in Fig. 5 corresponded 25 in Fig. 6. Therefore, $\sqrt{\alpha}=1.25$, Hence $\alpha=1.56$.

The general shape of the curve predicted by the theory was in fair agreement with the empirically established course of the desalinization process, as may be seen by comparing the Fig.5 and Fig.6. This fact had justified and proved the validity of the theory expressed in the equation (20) in the Part I of the series.

2. By comparing the calculated amount of le-
ached salt from the following equation (25) with those observed, when $V=0$.

According to the definition of the diffusion process, the amount of the leached salt per unit area by this mechanism was expressed by following equation.

Taking the salt concentration gradient at the soil surface,

$$q = \left[ \frac{\partial C_t}{\partial x} \right]_{x=0} \cdot P_r \cdot \alpha$$  \hspace{1cm} (25)

where, $q =$ quantity of leached salt.

$C_o =$ initial soil salinity as determined experimentally and was 0.80%.

$C_t =$ concentration in the pore solution at a time $t$.

$P_r =$ effective porosity of the soil, which had been assumed to be 40%.

$\alpha =$ diffusion constant.

$x =$ distance from the surface.

$\frac{\partial C_t}{\partial x}$ was obtained from the equation (19)' of Part I of this series. Since the effective porosity could not be measured, it had been assumed to be 40% on the basis of the porosity of 80%. The calculated data from the above mentioned equation (25) were plotted and compared with the experimental results in the Fig. 7.

The agreement between both the values was good and consistence. The assumption of 40% effective porosity based on 80% porosity could be considered as quite rational proportion from experiences. Gardner and Brooks$^1$ in a similar case, has estimated a value of 0.44 for $f$ (fraction of soil volume filled with water) from the amount of water which had entered into the soil while leaching. The 'f' and 'P_r' could be considered quite nearer to each other. Therefore, the degree of the agreement for the verification of the theory was very high.

With the help of this theory, the information on the salt concentration change could be obtained to predict the amount of leaching necessary to reduce the salinity to a given value at a given depth in the soil. And, because the total flux of water moving through field soils is generally small owing to the unsaturated conditions coupled with relatively small gradients and low capillary conductivity values, the role played by diffusion in transporting dissolved solutes must be included in the theory of moist-soil system. Primarily, to magnify the effect of diffusion, the above mentioned experiment was conducted at zero velocity.

3. By comparing the calculated amount of leached salt from the following equation (26) with those observed, when $V=0$.

Separate leaching experiments were conducted with the same kind of soil using Glass Cylinder Apparatus and the amount of leached salts were determined at a mean velocity. The theoretical data of the total salt leached per day under the experimental condition were calculated from the following equation:

$$q = \left[ \frac{\partial C_t}{\partial x} \right]_{x=L} \cdot P_r \cdot \alpha + V_o C_t $$  \hspace{1cm} (26)

where, $V_o, C_t =$ mean velocity of the flow having salt
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![Fig. 8 A plot of leached salt from the Saline Soil Column in the Glass Cylinder. The solid line represents the theoretical curve.](image)

concentration. The other factors are having the same magnitudes as that of the equation (25).

The calculated data and the observed data were plotted in the Fig. 8. Both of the figures had good and consistent agreement in their tendencies and values.

The results on the $\beta$-desorption constant were not evident to be produced in this case of soil. It was thought that, with the cleaning irrigation alone, the salts could be leached gradually up to a level. Any further release of ions or leaching of salts would be very imperceptible or negligible due to higher potential energy requirement. It was also thought that the polder soil of sea origin, as it was used here, had been less impregnated with adsorbed salt than that of the geological origin.

IV. CONCLUSION

The experiment and the verification of the theory of desalination in saline soil with the cleaning irrigation was presented here. The experiment was conducted in a newly designed Soil Electrode Box made of wood.

The desalinization theory was verified and proved by the following ways.

1. The calculated values of $\frac{C_t}{C_0}$ against $x/\sqrt{t}$ obtained from the theory agreed consistently with the observed data. The diffusion coefficient in this system was found to be 1.56.

2. The calculated values of the amount of leached salt from the equation agreed in tendency and values with the experimental values.

3. The theoretical values of the leached salt in case of mean flow velocity coincided fairly well with the observed data.

4. The Soil Constants, such as $\alpha$ and $\beta$ could be determined from the diffusion curves as derived from the equation of the fundamental theory.

APPENDIX

Key to Main Symbols used.

- $EC_a$ apparent soil conductivity.
- $EC_{SE}$ electrical conductivity of the Soil Extractions.
- $EC_{wa}$ or 'a' electrical conductivity with unrusted electrode and tap water.
- $a'$ ratio between the conductivities of soil cell-C and each of the other cells.
- $FC_{wb}$ or 'b' electrical conductivity with rusted electrode and tap water.
- $d$ ratio between the 'a' of the soil cell-C and 'b'.
- $F'$ form factor.
- $C_0$ initial soil salinity.

REFERENCES

8) Richards, L. A.: Editor. Diagnosis and Improvement of Saline and Alkali Soils, USDA. Handbook No. 60 (U. S. Salinity Laboratory Staff, 1954).

[Received January 6, 1972]