SALT MIGRATION IN HIGHWAY FILLS

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ABSTRACT

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This investigation was intended to provide information useful in describing and predicting the salt migration between a highway fill and its foundation. This migration being due to the difference in their salt content.

For this purpose salted and unsalted soil were put in contact. In time, salt migrated from the salted portion to the unsalted portion.

Two systems, a closed system and an open system, were prepared. For the closed system, the combination of salt and soil was put in contact, wrapped and then coated with wax. In the closed system the dominant factor for salt movement was osmotic pressure. In the open system, one end of the system was exposed to air, causing evaporation and movement of water. In this system water also carried salt molecules. The salt used for this experimentation was commercial sodium chloride.

Experimental data indicated there is a relationship between time, temperature, salt concentration, water content, properties of the soil, the system, and salt migration. These relationships were analyzed and the fundamental laws for salt migration were introduced.

Migration was also analyzed mathematically to help better understand the relative importance of the factors in combination.

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By

Manouchehr Farnoush

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CHAPTER I

INTRODUCTION

The amount of salt content of soil has a great influence on the fabric and structure of the soil. Variation of salt content could alter the fabric and structure of the soil causing the change in properties of soil including strength and bearing capacity. At the time of the formation of a new structure and fabric, i.e., in highway fills, the alteration affects the property of the soil intensly.

Sometimes soil is stabilized by chemicals, but losing a stabilizer causes unfavorable conditions.

When a body of the soil exists in situ for thousand of years, its properties, especially its salt content will have attained almost a balanced condition with the surrounding materials. Variations with respect to age or origin are often so small that they can be ignored.

When the soil is displaced from its origin and is placed in a new location to facilitate a highway, the condition of the surrounding material is changed. The properties of the displaced soil also change.

The newly placed fill soil starts to change and attains a new balance condition with its surroundings gradually attaining ultimate properties. The altering of the properties sometimes occurs rapidly and sometimes slowly. The ultimate properties of the soil under the new environment may not be the same as its properties in situ. It may also differ from the surrounding soils. Therefore a mass of soil is taken from a place with certain properties, altering its properties and placed in a new environment with varied conditions.

The salt content of the soil environment affects the properties of the fill soil either by migrating into it, if the salt content of the new environment is higher than the fill or else by causing the fill soil salt to migrate. This means ionic change of the soil mass, effecting its fabric and structure.

Under these circumstances, one should not expect the soil to have the same strength characteristics as it had previously.

Thus salt migration becomes of great importance for highway fills. In this category, the rate of the migration and the amount of the migrated salt is quite important. If the minimum requirement of salt content occurs prior to the formation of a required fabric, the properties of soil could be quite different.

In this investigation salt migration has been investigated, and the effect of different factors on the quantity of the migrated salt has been analyzed.

CHAPTER II

LITERATURE REVIEW

2-1. General Considerations.

Up to this time, there has been nothing published concerning salt migration in soils.

The main idea for investigating salt migration into the soil body, by salt-self-movement, comes to mind by studying the well known principle of osmotic pressure.

> When an aqueous solution of a solute is separated from pure water by a semipermeable membrane, i.e., a membrane that permits the passage of water but not of dissolved solute, the water always tends to pass through the membrane into the solution, diluting it. The phenomenon called Osmosis, and the pressure causing this action is called Osmotic Pressure. It was first reported by Abbe' Nollet (1748) (12,[1] p. 199).

The apparatus for determining osmotic pressure is a very simple one. A vessel consists of two parts which are separated by a membrane. One part is filled with pure water and the other with a determined solution. Water tends to pass through the membrane into the determined solution and dilute it. In order to resist this osmotic

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[1] Numberals in parentheses refer to corresponding items in Appendix I--References.

action, pressure is applied to the solution to keep it unaltered. This applied pressure is equal to the osmotic pressure.

Since the purpose of the first investigators was only to determine the osmotic pressure, an attempt was made to determine a suitable semipermeable membrane, i.e., a membrane that permits the passage of water but not of dissolved solute.

However, within the soil body no semipermeable membrane ever exists, because every soil body is assumed an absolutely permeable membrane.

If we employ a permeable instead of an impermeable membrane the water will pass through the membrane into the solution, and the dissolved solute will also pass in reverse.

The action of passing water through the membrane into the solution has been investigated partially by various investigators. Some of the neglected problems in this area have attempted to be resolved in this investigation.

The prime purpose of the investigation for this thesis, was not studying the resembled water passing through the membrane but the second phenomenon which is the passing of the dissolved solute into the water.

For engineering applications the passage of the disolved solute into water is of prime importance. An alteration in the structure and fabric of the soil body (11 and 15), the loss of stabilizers by long term duration, etc. may result from this phenomenon.

2-2. Computing Osmotic Pressure.

The accepted equation for computing osmotic pressure in dilute solutions is Van't Hoff's equation (12, p. 202)

$$\pi V = in'RT \tag{2-1}$$

Where:

i is the Van't Hoff's factor for electrolytes.

π is osmotic pressure, Atmosphere.

n' is the number of moles of solute contained in V liters of solution.

$R = 0.0827$

$T = 273.2 + C°$

Better results may be obtained when the concentration is expressed in moles per 1000 grams of solvent, i.e., molality rather than moles per liter of solution. This idea was suggested by Morse later (12).

2-3. Relation of Osmotic Pressure to Vapor Pressure.

For high concentrated solutions, Van't Hoff's equation becomes somewhat invalid. For these kind of solutions thermodynamic equations give better results. Relation is given by (12, equation 30)

$$\pi = \frac{RT}{V} \ln \frac{P_o}{P} \tag{2-3}$$

Where,

π is the osmotic pressure.

R is the gas constant.

T is the absolute temperature.

v is the volume of one mole of solvent.

P_o is the vapor pressure of pure solvent at temperature T.

P is the vapor pressure of solvent above the solution whose osmotic pressure is π.

For solutions of electrolytes, the osmotic pressure obtained by equation (2-1) should be multiplied by Van't Hoff's factor for the electrolyte, i.

2-4. Force Fields between Soil Particles and Exchangeable Ions.

> . . . the face of clay minerals have a net residual negative charge due to dissociation of hydroxyls (kaolin) and isomorphic substitution in the crystal lattice (illite, montmorillonite); the edges of the clay minerals may be either positively charged (adsorption of hydrogen ions in acid solutions) or negatively charged (dissociation of hydroxyl at the edge of the octahedral sheet in alkaline solutions). This charge is balanced by the attraction of exchangeable cations (and anions) from the surrounding water, which orient themselves in a pattern around the charged particles while at the same time altering the orientation of the water molecular that also surround the soil particles. The force fields that develop between the charged soil particles, the surrounding water, and the associated ions have a controlling influence on soil properties which--and this is important from a practical standpoint--can be varied within wide limits by changing such factors as the type of ions and their concentration, the temperature, and the nature and amount of pore fluid. For these reasons, and because the effects of each of the

> factors involved are difficult to isolate experimentally, a theory relating these factors and the resultant force fields would be of great utility. Such a theory was developed independently by Gouy (1910) and Chapman (1913) and is generally known as the Gouy-Chapman theory" (8, p. 98).

Agreeable to Gouy-Chapman theory, and a derivation patterned by Low (9), the electric potential ϕ, could be found by solution the following equation (8, equation (2-6) and 9, equation (4))

$$\frac{d^2\phi}{dx^2} = - \frac{4\pi\varepsilon}{D} \Sigma Z_i n_o \exp \frac{-Z_i \varepsilon\phi}{kT} \qquad (2\text{-}3)$$

Where,

x = distance from the surface of soil particle.

D = dielectric constant.

ε = electric charge.

Z = ionic valence.

n = concentration of the salt particles.

k = gas constant.

T = 273.2° + C°.

The above mentioned potential has a retarding effect on the movement of the cations, pulling them to the surface of the negatively charged soil particles. Thus in fine grained and/or very fine grained soils, it opposes and retards salt movement.

2-5. Relations between Salt Concentration and Properties of Soil.

According to Mitchell (10, p. 20):

> Although dilute suspensions bear little resemblance to clay soils in terms of physical properties, it is not unreasonable to suppose that some of the interparticle force mechanisms and principles of aggregation and dispersion are the same as in more concentrated clay-water systems.
>
> . . . The great influence of electrolyte concentration in the system is noted, with an increase in electrolyte content leading to a decrease in setting time for thixotropic gel.
>
> . . . The possibility therefore exists that thixotropy depends to some extent on initial structure (as floculated or dispersed) as well as initial water content. The decrease in thixotropic effect at high strains is to be expected, since shearing tends to remold the soil.

Since flocculation and dispersion depends on the ionic properties of pore water during formation (15, p. 50), the effect of concentration appears obvious (14). The following statement emphasizes the preceding explanation.

> The effect of increased electrolyte concentration is a more effective screen. However, it can be applied to dilute electrolytes too (16, p. 25).

The above statement refers to ion exchange phenomena.

Taylor (16, p. 27) under the title "Ion Exchange Phenomena" related to the soil explains:

> The presense of large amount of monovalent ion (more than 15-20% of the total)--and particularly of sodium ion should always be regarded as a danger signal. The danger is particularly acute in such cases if the soil is being maintained in a flocculated

> condition by the presense of excess occluded salt. As long as this remains, little change may take place, but if the salt is removed by percolating rain water or by irrigation with salt free water, the soil will deflocculate with a marked deterioration in strength and structure, changing from a material with a yield point (in the sense that it shows a limiting stress below which no continuous flow takes place) to a viscous slurry which will flow under stress conditions where the flocculated material is stable.

From the above explanation, the effect of the salt concentration on the strength properties of the soil is obvious. In the experimentations for this thesis, however, in addition to the effect of the percolation of the rain water and irrigation with salt free water, there was also the effect of the salt-self movement. In this investigation the effect of the percolating water was also investigated extensively.

Following the previous statement of Taylor (16, p. 27):

> This process (deflocculation by loss of salt content) can easily be reproduced under controlled conditions in the laboratory, and the critical electrolyte concentration at which deflocculation occurs in a given sample can be found with some precision shown in the work of Emerson and Quirk, T. P. In soils where the monovalent ions are less than 10% of the total ions present, which is almost always the case in soils which have not been flooded with saline water, the flocculating efficiency of the divalent cations is such that these soils are stable unless the salt concentration of the percolating solution is less than about N/100. This is rather less than the salt concentration present in the field, where the soil is not subjected to the disruptive tendencies produced by drying, sieving and rewetting. This condition therefore represents a stable situation.

Rosenquist (14, p. 37) on the effect of salt concentration indicates:

> By leaching experiments, it has been shown that the electrical charge of the mineral grains may have an important increase during leaching due to dissociation of the adsorbed cations from the clay minerals. Correspondingly, the negative charge of the mineral may increase when certain anions are adsorbed as for instance a carbonate ion from soda ash or other anions as phosphates and silicates. Salts of such anions are used as dispersents in most soil laboratories. The effect is due to an increase in the repulsive forces between the highly negative charged minerals because of the anions adsorbed. This will change the mechanical properties of a clay water mixture at a given water content. We have shown that the liquid limit of a Norwegian illite clay may decrease from 42 to 29 when small amounts of $Na_4 P_2 O_7$ are added. With addition of such salts, we may influence the shear strength at a given water content in a manner similar to that of leaching out the normal salt content; we may simulate the formation of quick clays.

The same phenomena will occur if there is a natural salt migration resultant of a difference between the salt content of a fill and its foundation soil.

CHAPTER III

EXPERIMENTAL PROGRAM

3-1. Soils Employed.

Soils employed in this investigation are referred to by numbers one through four.

Soil number one was a sandy loam; 16% clay, 17% silt, and 67% sand; liquid limit 17; plastic limit 12; "A_2" horizon, material of local origin.

Soil number two was sand, retained on No. 200 sieve and passing a No. 40 sieve. The sand was subjected to dry sieve analysis with 1% colloids by hydrometer analysis. It was from Ingham County, Michigan.

Soil number three was clay; 41% clay; 28% silt; and 31% sand; liquid limit 34; plastic limit 17; shrinkage limit 16. It contained 27% colloids accounted for in the clay fraction. The soil was a heavy sticky clay, "A_2" horizon, from Ingham County, Michigan.

Soil number four was silty loam; 14% clay; 66% silt; and 20% sand; frost susceptable material; "B" horizon. The upper grain size limit was 0.25 millimeter. It was from Ingham County, Michigan.

The grain size distribution of all four samples was determined by standard hydrometer analysis (1, pp. 191-202).

Corresponding grain size distribution curves are shown in Fig. 1. Appendix II.

3-2. Properties of the Soils Utilized. Upper Grain Size Limitation of the Soils Subjected to Test.

There should be a relationship between the grain size of the soil and the size of the specimen. While the largest grain size for standard compaction test is 4.76 millimeter, i.e., passed from sieve number 4, the largest grain size for determining Atterberg limits is 0.42 millimeter, i.e., passed from sieve number 40. The size of the specimen also has a limitation based on the amount of the soil available.

The water content of the specimens was chosen with respect to their Atterberg limits, and the upper grain size for determination of Atterberg limits was a number 40 sieve (0.42 millimeter opening) (7, p. 24).

The Atterberg limits obtained on soils passing a number 40 sieve is not the same as for soils passing a number 200 sieve. Soils passing the number 40 sieve in comparison with soils passing the number 200 sieve, consist of some large grains which occupy a portion of the voids which should be filled by water and should be accounted for as part of their moisture content. If there are appreciable amounts of larger grains within the soil, soil passing the number 40 sieve would be called sandy soil where as soil passing number 200 sieve may be silt or clay with different Atterberg limits. Thus the upper limit of grain size for all prepared specimens was chosen as 0.42 millimeter, and all soils used for preparation of the samples passed a number 40 sieve.

3-3. Preparing Soil Paste.

Air dried soil was weighed with 0.01 lb. accuracy. The amount of required moisture was added to the soil on the scale. For soils treated with salt, salt was dissolved in added water, required for moisture content of the paste. It appeared that this procedure resulted in a uniform distribution of salt into the soil paste. Prepared soil paste, or moist soil, was stored for a few days. Storage was accomplished to assure uniform distribution of salt and/or water. Concurrent to molding the soils in place, moisture samples were taken from all prepared soils.

For a few initial samples different representative samples were employed for determination of moisture content and/or salt content. Later, the same sample employed for determination of moisture content was also utilized for determination of salt content.

3-4. Aluminum Mold for Soil Samples.

The mold was made from aluminum with a U-shape cross section. The molds had the inside dimension of

6" x 3/4" x 7/8". Soils were placed in these molds to be given a uniform shape and for purpose of storage.

Three inch lengths of the molds were always filled with unsalted soil and the remainder with salted soil. The separation of the two soils, i.e., salted soil and unsalted soil, was indicated on the exterior of the aluminum molds. The number of the sample and the salted and unsalted sides was indicated on the molds.

3-5. Placement of Soils in the Mold.

Soils were either weighed on aluminum foil (for initial samples) or Saran Wrap. The soil was then placed in the aluminum mold, in three uniform layers and compacted. Special attention was taken to insure the soil distribution was as uniform as possible. Subsequent measurement of moisture in different segments of the soil bar indicated that the distribution was not completely uniform. However, it did not significantly affect the results, since the data indicated that salt movement is based on the over all moisture content and salt content of the samples.

Some soils were compacted into the aluminum mold and then weighed. Since the weight of the aluminum mold and Saran Wrap and/or aluminum foil was known, the amount of soil used could be calculated. This method of filling aluminum molds was employed especially for saturated sands or soils with moisture content exceeding the plastic limit.

For soils with moisture content less than shrinkage limit, the soil was first weighed and then placed in the aluminum mold and compacted.

An attempt was made to prepare samples as uniformly as possible. Therefore the weight of the soils of the unsalted portions would normally be equal to the weight of the soil of the salted portions. Since the salted portions had extra weight which was the weight of the salt added, the extra weight was always considered for the salted portions.

During the first stages of sample preparation the aluminum molds containing the samples were wrapped in aluminum foil, prior to the coating of the samples with wax. Since the composition of aluminum foil was not the same as the aluminum molds, in the presence of an electrolyte, during storage of the samples corrosion appeared on the aluminum molds and aluminum foil.

The direction of the corrosion was perpendicular to the direction of the salt migration, except for the two ends of the molds. So its effect on salt migration should be negligible.

In order to eliminate the corrosion effect Saran Wrap was employed in place of aluminum foil at the next stage. Saran Wrap is a dielectric material. Although salt affected this synthetic material too, the effect was much less than the aluminum foil.

For the samples in which aluminum foil was used, soils were placed directly into the aluminum molds and then wrapped into the aluminum foil. For the samples in which Saran Wrap was used, the Saran was used to inter-line the aluminum mold and after the soils were placed in the molds, the Saran Wrap was folded over the soil forming a sheath of Saran around the sample. With this procedure, soils were not in contact with any form of metal.

3-6. Coating Wrapped Samples with Wax.

After wrapping the aluminum mold with Saran Wrap or aluminum foil, it was dipped into melted wax. Since it was possible that the heat of the melted wax could affected salt migration, so the wax was almost melting and then the wrapped sample was dipped into the wax quickly and removed immediately for cooling. This action was repeated until an appreciable amount of wax coated the wrapped soil samples. For some samples stored for extended periods, there was some moisture loss, therefore average moisture contents were considered during the curing period.

The coated samples were stored under refrigeration at -15° C., open atmosphere at 24° C., and in an oven at 44° C.

3-7. Segmentation.

After removing the samples from the oven, freezer, or atmospheric storage, the Saran Wrap on the top of the mold was cut in two lines longitudinally and the top portion of the cover was removed. Then the covering of the sample sides was turned out to make easy segmentation. The soil bar in the aluminum mold was measured longitudinally by means of a scale, and marked at each inch. The soil was then cut by means of a spatula, and removed to sample tins. Special care was given to the segmenting of dried cohesionless materials. Normally segments of cohesionless materials were separated by paper dividers. The paper dividers extended between the segments and was placed by the edge of a spatula. The segmented sample were removed part by part into the sample tins. The process was done with care to prevent the mixing of alien segments.

For removing the segments from the aluminum mold special processes were required. First the unsalted portion was removed segment by segment, then the salted portion was removed. In this manner, there were no inaccuracies in the amount of salt in any segment resulting from the mixture of segments. Since the order of the removal was the opposite way of the salt migration, it occasionally opposed the migration slightly.

Immediately after placing the soil segment into the tin, the lid of the tin was placed firmly. All tins with segments from the same mold were weighed and placed in the oven for drying.

The summation of the weights of segments should not necessarily be equal to the weight of the soil bar originally placed in the aluminum mold, because during segmentation some particles were discarded which broke from the segments. This frequently occurred with cohesionless soils.

Normally each closed sample was removed in 6 one-inch segments. However, there were samples which had an open extreme and were exposed to weather. Since the extreme part of these samples had a great amount of salt, thin sections of these extremes were taken separately. Preparing samples from exposed extremes was done prior to the opening and segmenting of the entire sample.

Sometimes, in case of cohesionless soils, the soil was poured out of the unsalted open end. Obviously, that portion was not affected by migration. That part was collected separately and called "unsalted extreme-poured out." Experience indicated that in the case of pouring out, due to the loosening of the adjacent section and opening and exposing the sample to the air, the adjacent section to the portion of soil poured out was not influenced enough by salt migration. The maximum concentration of salt content will go deeper in the sample, rather than being at the open end.

To prevent the pouring of the soil out of the molds for open systems, the exposed extremes were compacted by hand to provide stable conditions. The compacting of the open ends was done after coating the samples. However, this procedure resulted in an increase of moisture content at the compacted ends. It was especially noted in sample number 6 of soil number 3, clay (Table A-6, Appendix II). Salt migraion was not affected significantly by this kind of moisture variations, because it is based on the over all conditions of the samples, rather than any local differences.

3-8. Silver Nitrate Solution.

Measuring the amount of sodium chloride in soil was done by silver nitrate. According to the formula:

$$AgNO_3 + NaCl \longrightarrow AgCl \downarrow + NaNO_3$$

In this measurement, potassium chromate or sodium chromate is an indicator (19, p. 110).

$$2AgNO_3 + K_2CrO_4 \longrightarrow Ag_2CrO_4 \downarrow + 2KNO_3$$

By adding silver nitrate solution from a burette drop by drop into a sodium chloride and potassium chromate solution, silver nitrate reacts with sodium chloride and the silver chloride settles out. As long as there is a sign of sodium chloride, silver nitrate reacts with it and not with potassium chromate. Immediately after finishing sodium chloride, a permanent reddish brown color which is silver chromate, the indicator, remains even after mixing the solution. At this time the milliliters of silver nitrate solution should be recorded.

According to the above formula, 2.90 grams of silver nitrate reacts with one gram of sodium chloride, thus if we prepare a solution of 29 grams of silver nitrate in one liter of solution, then utilizing every milliliter of this solution indicates 1/100 gram of sodium chloride.

Such a solution was prepared and utilized.

3-9. Salt Content and Water Content of the Soil Segments.

After twenty-four hours of oven drying at 110° C., the moisture tins were removed from the oven and cooled at room temperature (7, p. 10). They were reweighed and the moisture loss calculated.

Salt measurements for all segments of the soil bar of a given aluminum mold were carried out simultaneously. Six or seven 200 milliliter volumetric bottles with a set of glasses in front of them were arranged. All of them washed with water and rinsed with small amount of distilled water prior to the test. The moisture tins were shaken to some extent in order to rub off any part of soil which might have adhered to the tin. Soil, then, was poured into the glass, 100 milliliter of distilled water was measured by means of a volumetric bottle and poured into the tin over the glass in order to wash the tin and contents into the glass. If there was a small amount of salt adhering to the tin, it would then be washed into the glass. The tin was placed in front of the glass for identification of the number of the sample. This procedure was done for all of the sets.

The suspension in the glass was stirred vigorously and then was allowed to settle.

If there was no salt in the fine grained soils, settlement of soil particles would occur very slowly. In order to assist the settlement of the fine soil particles, the addition of a small amount of potassium chromate was necessary.

Lyotropic series is as follows:

$$\text{Li: Na: K: NH}_4\text{: Rb: CS}$$

$$\text{Mg: Ca: Sr: Ba}$$

This indicates increasingly strong adsorbtion to the surface of soil particles from left to right (16, p. 26). According to this series, potassium chromate by its K-Cation would free the Na-Cation of sodium chloride from the surface of the soil particles into the solution.

After settling the soil particles, though not necessarily colloids, the water on the top of the settled soil particles was carefully removed into a 200 milliliter volumetric bottle. Filtering was not needed. Since the small amounts of soil would not effect the results and color.

After rinsing the water from the top of the settled soil particles, 100 milliliter of water was poured into the glass. The suspension was again stirred vigorously with a glass rod and let settle. The water on the top of the settled soil particles was again poured into the 200 milliliter volumetric bottle.

The water in the 200 milliliter volumetric bottle should contain all of the salt of the sample. This was demonstrated by sampling a third wash of the sample with no apparent salt remaining. Therefore two washings of the samples was accepted as standard.

The 200 milliliter flask was then shaken vigorously to insure a uniform mixture. One hundred milliliters of the solution measured and poured into a glass container under the burette. The burette was filled up with $Ag\ NO_3$ solution. The amount of salt content was then measured by means of the silver nitrate solution added.

Repetition of the test was carried out on the remainder of the salt solution for checks.

CHAPTER IV

RESULTS

4-1. General Considerations.

The migration of salts into sandy soils provide basic investigations for salt migration, because in sandy soil, the factor affecting salt molecules is the osmotic pressure. Whereas in fine-grained and very fine-grained soils, the electric charge of soil particles, the effect of salt on the electric charge and double layer, also affect migration. There are other factors that affect salt migration in fine-grained soils, and the effect of these factors, such as permeability, capillary action and the effect of electric charge of soil particle it self, should be discussed concerning the salt migration characteristics of fine-grained and very fine-grained soils.

With the above explanation, the effect of some of the factors on salt migration may be explained by data obtained from one type of soils much better than from others. For this reason the results are classified under two titles, namely, (a) salt migration in sands, and (b) salt migration in fine-grained and very fine-grained soils. Obviously title (b) will not be repeating title (a) but under title (b) the effect of the other factors which have not been described under title (a) will be described. A comparison of salt migration in coarse, fine, and very fine-grained soils will be considered.

A brief consideration of salt migration in partly frozen soils will be considered under a separate title.

A. Salt Migration in Sands.

4-2. Review of Formulas and Comparison with Actual Results.

As an example in samples 4 to 6 of soil number 2 (sand), Tables A-1 and A-2 Appendix II, there was 30% salt concentration ratio, i.e., per cent of salt over water, in one side of the samples and 0% in the other side. According to Van't Hoff's equation for osmotic pressure (12, p. 202).

$$\pi V = in'RT$$

Assuming the least amount for $i = 1$, one can write.

$$\pi = \frac{30/58.5}{100/1000} \times 0.0827\ (273.2 + 24)$$

$$\pi = 126 \text{ Atmosphere pressure}$$

One hundred twenty-six atmospheres of pressure is such a tremendous pressure that it should disintegrate the sample and absorb all pore water of the unsalted portion.

However, the amount of osmotic pressure calculated, is the least amount, because we know (12, equation 30) that for high concentrations, it is better to use the following equation:

$$\pi = \frac{RT}{V} \ln \frac{Po}{P}$$

By this equation relatively more realistic osmotic pressures are determined between two sides of the sample, which is much greater than the above mentioned 126 atmosphere.

Experience indicates, under such extremes of pressure, even water does not move from the unsalted portion to the salted portion, appreciably. In some instances water moves from salted portion to the unsalted portion, i.e. in partially frozen soil.

Since osmotic pressure is due to the attractive forces between salt in solution and pure water, in the case of fixed water in soil, the salt is forced to move. Salt moves slowly from the salted portion to the unsalted portion.

According to the above explanation, one should add a proposition to the Abbe' Nollet's report (12, p. 199), which has not been considered at this point. Under the osmotic pressure water itself resists movement, regardless of the effects of the soil particles, i.e., even if two sides of the basic osmotic pressure apparatus is separated by a zero resisted membrane. In other words if salted and unsalted water is placed in contact with each other directly, there still will not be any immediate appearance of mixing pure water and salted water.

However, at least water should move from the salted portion to the unsalted portion, very slowly, but closed samples did not show an appreciable amount of water movement, or difference in water content with respect to the great amount of osmotic pressure.

Closed samples also indicated the movement of water occurred during the first few days and then remained constant for the entire curing period. Changes in water content, there after, occurred only through evaporation.

On the other hand, salt moves gradually and approaches its final position, which is the almost uniform distribution of salt into the entire sample, i.e., salted and unsalted portions combined.

Therefore, there were some forces which restricted the movement of water, where as they did not affect salt movement. Some of these restricting factors are as follows:

a. Hysteresis in capillarity with different size of pores (21, p. 130).

According to Croney and Coleman (3, p. 76):

> There is a marked hystersis between the curves corresponding to the wetting and drying conditions. This hystersis probably arises in materials of this type from the degree of control which the smaller pores escert on the suction at which the larger pores release their moisture as the suction is increased.

> Thus water is retained in large pores at suctions much greater than those at which the same pores will refill during the wetting process.

b. Variation of capillary potential resultant of release and increase of water concentration. Different experimental equations indicate the relationship between capillary potential and the water content. According to Gardner (5).

$$\psi = \frac{C}{\rho} + b$$

Where, ψ is the capillary potential, ρ is the density of water (amount of water per unit volume of soil), C and b are arbitrary constant.

c. The electric charge of the surface of the particles, for fine-grained and very fine-grained soils. However, this electric charge also affects the salt molecules.

4-3. Effect of Salt Concentration Ratio (Ratio of Salt Content to Water Content) on Salt Movement.

Experimental data (Tables A-1 and A-2, Appendix II) show that the movement of salt is based on the over all salt concentration ratio in different parts of soil body, rather than the condition of the "in contact" parts.

It was supposed that salt should move the direction of, higher osmotic pressure to the lower osmotic pressure. Since the value of salt concentration ratio is proportional to the amount of osmotic pressure, direction of salt movement should be from higher salt concentration ratio to the lower salt concentration ratio. For example for sample No. 18 (Tables A-1 and A-2, Appendix II) Table 4-1 is extracted.

Table 4-1.--Salt Concentration Ratio for Sample No. 18.

	Unsalted Portion			Salted Portion		
Segments	A	B	C	D	E	F
Salt Content %	1.34	1.37	1.41	1.50	1.64	1.68
Water Content %	8.75	9.10	8.95	9.80	10.50	10.15
$\frac{\text{Salt Content}}{\text{Water Content}}$	1.53 ↖	1.50 ↙	1.58 ↖	1.53 ↙	1.56 ↙	1.66

Table 4-1 shows that under the over all osmotic pressure of the system, salt moves from segment D, with lower osmotic pressure, to the segment C, with higher osmotic pressure. Also it moves from segment B to segment A, with segment A having higher osmotic pressure than segment B.

It will be demonstrated later that the salt movement in fine-grained soils also emphasized the above relationship.

4-4. Effect of Moisture Content on Salt Movement.

In order to study the effect of moisture content on salt movement in two comparison samples, the ratio of salt content and moisture content should remain constant, i.e., if we had the moisture content of one sample twice that of the other, the salt content should also be made twice.

Neglecting higher ionization in dilute solutions, osmotic pressure will remain constant comparing the following properties of samples No. 3, 18 and 27 (Tables A-1 and A-2, Appendix II) illustrates the effect of moisture content on salt movement. This comparison is made in Table 4-2.

Table 4-2.--Summary of Original Properties of Samples 3, 18, 27 Extracted from Tables A-1 and A-2, Appendix II.

Sample No.	3	18	27
Place Stored	Oven 44°	Oven 44°	Oven 44°
Original Salt Content of Salted Side (in %)	1.40	2.83	1.34
Original Water Content (in %)	4.28	9.42	9.76
Original Ratio of Salt/Water (in %) (Proportional to Osmotic Pressure)	0.33	0.3	0.14

Since osmotic pressure for sample No. 3 and No. 18 were almost the same, ratios between the salt content of various segments of these two samples should be comparable. The ratios are as indicated in Table 4-3.

Table 4-3.--Ratio Between Salt Contents of Samples 18 and 3.

	Unsalted Portion			Salted Portion		
Segments	A	B	C	D	E	F
Ratios*	3.72	2.92	2.35	2.08	1.96	1.80

$$* \frac{\text{Salt content of the segment of sample No. 18}}{\text{Salt content of the corresponding segment of sample No. 3}}$$

Table 4-3 indicates that the relation of moisture content and salt movement is not linear.

It should be noted that moisture content affects salt movement for varied reasons. At any cross section perpendicular to the direction of the movement of the salt, by increasing moisture content, the area of water in this cross section increases, causing the larger range for salt movement.

Also at low moisture contents, water only makes a film around particles, with contact moisture (18, p. 118) at the place of their contact. In such conditions, salt molecules have to travel around any particles in the film moisture until to arrive at the contact point of two particles, in order to cross from the surface of one particle to the other, in the direction of their destination. Where as if the soil is saturated with water, the path of the travel of the salt molecules will be relatively straight line. In the saturated state, the travel distance for salt molecules will be much shorter than for soil with low moisture content. Also the effect of the electric charge of the surface of the particles will be higher for lower moisture content.

The results obtained on the effect of moisture content on salt movement from comparison of the samples 3 and 18 are emphasized by comparison salt movement in samples No. 27 and No. 3 (Table 4-2). It is shown that osmotic pressure for sample No. 27 is approximately one-half of that for sample No. 3. Therefore, the salt movement of sample No. 27 should be much less than that for sample No. 3. The results obtained from data, Table 4-4, refute this conclusion.

The ratios of salt content for various segments of the sample No. 27, compared to the salt content of the corresponding segment of sample No. 3, are shown in Table 4-4.

The same results are evident for samples cured out of the oven, Appendix II.

Table 4-4.--Ratio Between Salt Contents of Samples No. 27 and No. 3.

	Unsalted Portion			Salted Portion		
Segments	A	B	C	D	E	F
Ratios*	2.05	1.88	1.37	1.12	1.00	0.93

$$^{*}\frac{\text{Salt content of the segment of sample No. 27}}{\text{Salt content of the corresponding segment of sample No. 3}}$$

4-5. Effect of Temperature on Salt Movement.

At high temperatures salt moves rapidly. Mathematical analysis, Chapter V, demonstrates that the effective temperature is the absolute temperature.

Although experimental data emphasizes temperature effect, it also indicates that moisture content influences the effect of temperature change on salt movement. Samples No. 3 and No. 6 (Table A-1, and A-2 Appendix II) initially had a salt content of 1.40% and a moisture content 4.28%. The ratio of salt content of various segments of sample No. 3, stored in oven 44° C, over sample No. 6 stored out of oven, are shown in Table 4-5.

Samples No. 15 and No. 18 initially had a salt content of 2.83% and moisture content 9.21%. The ratio of salt content of various segments of sample No. 18 stored in oven 44° C, over sample No. 15 stored out of oven are shown in Table 4-6.

Table 4-5.--Ratios Between Salt Content of Sample No. 3 over No. 6.

	Unsalted Portion			Salted Portion		
Segments	A	B	C	D	E	F
Ratios	9.61	1.44	0.96	0.74	0.72	0.75

Table 4-6.--Ratios Between Salt Content of the Segments of Sample No. 18 over No. 15.

Segments	A	B	C	D	E	F
Ratios	1.2	1.12	1.12	1.08	1.14	1.13

Comparing the results of two Tables, i.e., Table 4-5 and Table 4-6 indicate that Table 4-6 has relatively uniform ratios, i.e., the effect of temperature on salt movement at high moisture content is small, where as for low moisture contents, it is relatively large.

The effect of soil properties and time on salt movement and salt movement in partially frozen soils will be discussed later.

B. Salt Migration in Fine and Very Fine Soils

4-6. Comparison of Salt Migration in Fine and Very Fine Soils with Sand.

For salt migration, fine and very fine soils are distinguished from coarse soils by their relatively high capillary force, low permeability, and for very fine soils, surface activity of soil particles.

The difference between salt movement in fine and very fine soils and that in coarse grain soils, which have been described previously, are summarized in the three following categories, referenced to experimental data, Tables A-3 through A-6 Appendix II, and related figures.

a. Salt movement in fine grained soils is much slower than in coarse grain soils in closed systems.

b. In open systems, the amount of salt moving toward the open end in fine and very fine grained soils is much more than in coarse grained soils.

c. In fine grain soils, the amount of the salt content in previously salted and unsalted portions did not become equal even after a long period of curing time, which is apparently resultant of surface activity. However, the difference after a long curing period is very small.

There is a steep slope on the salt content curve (Fig. A-6), at the point of contact, for fine soils which does not exist on the curves for coarse grain soils.

There are similarities of salt movement in all types of soils, which are as follows:

a. In fine grain soils, the salt moves slowly, regardless of the "in contact" condition of osmotic pressure, but under the influence of the over all condition of the entire sample.

b. The effect of temperature in fine and very fine soils is the same as for coarse grain soils.

c. The effect of the water in fine and very fine soils is almost the same as for coarse grain soils.

4-7. The Effect of Curing Time on Salt Movement, in Closed Systems.

When we are considering closed systems, the movement is influenced by osmotic pressure only. Where as, in open systems additional movement of salt, also, becomes on effect, i.e., water moves and it appears a carrier for salt, so the salt moves also. The real amount of salt movement will be the combined effects of the carrying the salt molecules by water and the direct movement of the salt molecules due to osmotic pressure, in open systems. Salt movement in open systems are described separately.

Prepared samples from soil No. 1 (sandy loam) were cured for a relatively long period of time, i.e., 231 days maximum, and 16 samples with varied moisture contents tested at different time intervals. The entire description of the effect of time on salt movement is based on testing these samples, which are tabulated in Table A-3 and A-4, in Appendix II. The results are as follows:

a. With extended curing, moisture content curves are more uniform than before, especially the relatively large difference of water contents between in contact parts of the salted and unsalted portions, i.e., segments C and D release the relatively higher difference of the amount of water. This could be explained as resultant of the change in the fabric of the soil in the sample.

b. Curves for the salt content become relatively irregular in long curing periods. This could result either from irregular moisture loss, or the concentration of salts in very fine-particle concentrations due to irregular distribution of very fine particles in samples.

Also there was indicated some leakage of salt and erosion on the aluminum foil wrap, which could affect irregularities of salt distribution for a long curing period.

c. Although samples decrease their accuracy during extended curing periods, the results are sufficient to obtain an indicated trend.

d. Irregularity of salt distribution in samples which are oven cured at 44° C, is more pronounced than in samples air cured. Samples in the oven cure had more erosion in aluminum molds than the air cured samples. It could be reasoned that the irregularity was partly resultant of electrochemical action between salt, the aluminum foil, and aluminum mold.

e. The difference of moisture content between unsalted soil and the soil treated with salt, when they are in contact, was not as much as commonly believed (21), provided other conditions for both portions were the same.

f. The difference in moisture content between salted and unsalted portions occurs during the first few days of controlled curing and then this difference remains almost unchanged, or becomes more uniform. However, when the salt content of the two portions becomes approximately equal, the moisture content does not approach uniformity for the entire sample.

g. Although there was a tendency toward uniform distribution of salt in the salted and unsalted portions of the soils in contact, after curing 231 days the salt content of the originally salted portion was still slightly higher than the unsalted portion.

h. For samples oven cured at 44° C and air cured at 24° C, there was a pronounced difference in the amount of displaced salt. The difference lost its validity as curing time increased. In other words the difference for the first few days was more pronounced.

i. Salt distribution curve (Fig. A-6) for sample No. 1, cured for 207 days, indicates that the high loss of water did not cause irregularity in salt distribution, as long as the loss of water was uniform. The large difference of salt content distribution of sample No. 5 (Fig. A-6) which had lost its moisture, almost entirely, can be explained as experimental failure in coating.

4-8. The pH Distribution in the Aluminum Foil Wrapped Samples.

Erosion was noted on some of the aluminum molds, indicating there could be a difference of pH distribution in soil. Sample No. 9 which had more erosion, was tested. Almost the entire sample had a pH of 7.75, where as the salted extreme side, in contact with aluminum wrap had a pH of 4.75. The deepest eroded place was found at the point of pH 4.75 on the aluminum mold. It should be noted that the soil itself and the salted soil both had the pH of approximately 7, prior to placement in the aluminum mold. At the eroded point, there was a white spongy material which did not dissolve in 5N of HCl, concentrated sodium hydroxide, nor methylene chloride. It was assumed to be aluminum hydroxide.

Since the quality of the components of the aluminum foil was not the same as the aluminum mold, in the presence of an electrolyte as salt, the combined sample worked as a pile or battery and caused erosion on the mold and on some parts of aluminum foil.

Since the direction of this reaction was perpendicular to the direction of the salt movement, it resulted in no determent to the salt movement. However it reduced the total amount of salt content. This reduction was not appreciable.

Saran Wrap was used instead of aluminum foil for later experiments. Although salted soil affected Saran Wrap too, its effect was very slight.

4-9. Open Systems.

The term open system in salt migration indicates samples, which have one end exposed to the air. This exposed end can be either the salted or the unsalted.

In an open system, water always is driven to the open end by capillarity and dissipates from it by evaporation.

In the soil body, salt is dissolved in water, by moving water, free salt also moves more or less at the same rate toward the open end. Evaporation leaves salt crystals distributed over the open end of the soil sample. For this reason, an extra sample was always taken from the exposed extreme, thus the open samples are divided in seven parts, instead of the normal six.

Salt itself moves, independent of the movement of the water. Therefore the resultant movement of salt would be under the combined effect of both, i.e., the independent movement of salt, and the movement of salt by water.

There are many examples in the field which resemble the samples prepared for an open system. For example a bituminus surface based on a stabilized subbase resembles a sample which has the unsalted end open with respect to the open surface of the surrounded soil. Therefore, the results obtained from open systems were applicable to the above mentioned examples.

Three kinds of soils which have been tested as open systems are soil number 3 (clay) presented at Tables A-5 and A-6 Appendix II and related figures, soil number 4 (silty loam) presented at Tables A-7 and A-8 Appendix II and related figures, and soil number 5 (sand) presented at Tables A-1 and A-2 Appendix II and related figures. The tables and figures are presented in the Appendix II.

Studying the salt migration of open systems on samples prepared from silty material has more significance than the others, since silt does not have any appreciable surface activity and also has an appreciable degree of capillarity as compared to sand. It is an intermediate for different types of soils and the conclusions are applicable to other soils.

Samples No. 13 and 14 prepared from silty soil (soil No. 4), Tables A-7 and A-8 Appendix II and related figures were exactly the same, except that the salted end and unsalted end of them respectively was exposed to the air. The original salt content for salted portion was 2.39%, where as the salt content of the exposed extreme, after curing, for samples No. 13 and 14 was up to 47.5% and 10.88%, respectively.

The following have been derived from the data sheets of soil No. 4 (silty soil) comparing samples 13, 14 and 15 in Appendix II. The last one is the same as 13 and 14, but it is a closed system, where as samples 13 and 14 are open systems.

a. The greater the distance between the exposed extreme and the salt source, the less the salt content in the exposed extreme.

In addition to the effect of distance there is another factor which should be considered. The samples which had the salted end open and those which had the unsalted end open, did not follow the same drying curve (2, p. 37).

b. The greater the distance between the exposed end and the salt source, the less the loss of the salt content in the salt source.

Comparing salt distribution curves for samples 1, 2, 3, 4, 5, 6, 17, 18 prepared from soil No. 3, Tables A-5 and A-6 in Appendix II indicate the following:

a. The effect of high temperatures on open systems was much greater than on the closed systems. Probably explanation could be found from Baver's statement (2, p. 40): "Puri, Crowther, and Keen have observed at low humidities that the relative vapor pressure of soils increases greatly with a rise in temperature from 20° C to 40° C."

b. The amount of displaced salt depends on the moisture content. The higher the moisture content the greater the salt movement. Even for original moisture contents as low as 9% the displaced salt could not reach to the unsalted exposed end for sample No. 6 prepared from soil No. 3, Table A-5 and A-6 in Appendix II.

Samples 14 and 15, prepared from soil No. 4 (silty soil), Tables A-7 and A-8 and related figures in Appendix II, resembles to the field constructions and it will be discussed in the conclusion.

C. Frost Action, Partly Frozen Soils, and Salt Migration in Partly Frozen Soils

4-10. Initial Conditions, Comparison with Corresponding Unfrozen Soils.

Some of the samples which were prepared for investigating the salt migration were stored in a freezer at -15° C. Since at this temperature free water and 12.5% salted water will freeze. Twenty-five per cent salted water, and absorbed unsalted water does not freeze at this temperature. Thus the term partly frozen samples and partly frozen soils have been used for explaining samples stored at -15° C.

The resultant data was tabulated in Tables A-9 and A-10 and are presented in related curves, in Appendix II.

It should be restated that there was no difference between the frozen samples and the samples stored out of the freezer except for the temperature and the results were comparable.

According to Beskow (6, p. 53) soil No. 2 (sand) is definitely a non-frost heave material, where as soil No. 4 (silty loam) is suseptible to frost heaving.

Looking at the moisture content curves of sample No. 7 of soil No. 5 (sand), Tables A-9 and A-10 Appendix II, shows that the moisture content had increased greatly in the unsalted portion, as compared to the water content of salted portion. According to the corresponding unfrozen samples, the moisture content in both portions, i.e., salted portion and unsalted portion, should be approximately equal, or the moisture content in the salted portion should be slightly more than the unsalted portion, especially for a silty soil. Therefore the frozen soil opposed the above mentioned principle and the moisture content in some soil segments of unsalted material exceeded the original moisture content. There was an appreciable amount of salt concentration in the unsalted portion, obviously carried by water. Therefore water had moved from the salted portion to the unsalted portion, opposing the normal phenomenon. This indicates a reduction of moisture potential in the unsalted frozen portion, and we therefore should accept the fact that in the soil body, iced crystals act as soil particles rather than free moisture.

If one puts salted and unsalted soil in contact with each other at varied temperatures above the freezing point, water moves from the unsalted portion to the salted portion, due to the osmotic pressure, providing other properties of both portions are the same.

However, there is a temperature, below zero degrees centigrade at which unsalted water in the soil freezes, where as salted soil remains unfrozen.

Water crystalizes in a manner that does not have the character of moisture but it resembles the soil particles. The moisture potential in the unsalted frozen soil reduces, approaching zero causing the reverse movement of water, i.e., from salted portion to the unsalted portion. When the salty water passes through the first portion of unsalted frozen soil, part of the salty water penetrates into the ice crystals. The other portion of salty water continues movement through the voids. The translated salty water then penetrates the next portion partially thawing the ice crystals and making the soil salty.

Experimental data on samples 7, 8, 10, 11 and 12 prepared from soil No. 2 (sand) and sample No. 22 prepared from soil No. 4 (silty soil), Tables A-9 and A-10 Appendix II, show passing salty water through the frozen soils dilutes the salt solution in the salty medium in two ways:

1. Reduces salt content.
2. Increases water content.

In other words, where ever the moisture content is maximum, the salt content is relatively low.

Data also indicates a relationship between isothermal salt concentration and frost penetration (Tables A-9 and A-10 Appendix II).

CHAPTER V

MATHEMATICAL ANALYSIS

5-1. Derivation of the Equation.

a. Let us choose a thin soil rod which has a cross sectional area ds, with insulated longitudinal surface. Take an element in this soil bar of length dx Figure 1.

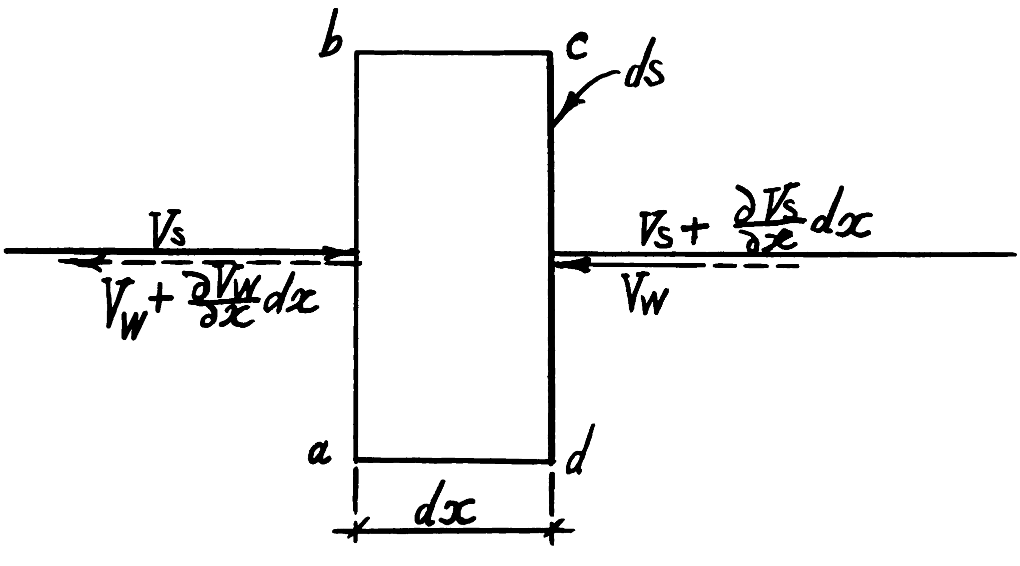

Fig. 1. Illustration for Salt Migration.

A preliminary condition of one dimensional salt movement is assumed, $\overline{bc}$ and $\overline{ad}$ are completely insulated from water and salt. Later consideration will be taken for three dimensional movements.

b. Let n be the weight of salt existent in one gram of soil. Then $\frac{dn}{dt}$ represents the variation of salt content "n" in the element for the unit of the time "t." If the variation is due to the entrance or the depletion of salt, we add subscription "i" or "o" respectively. Hence, there is no difference between the quality of $\frac{\partial n}{\partial t}$, $\frac{\partial n_i}{\partial t}$, or $\frac{\partial n_o}{\partial t}$.

c. Salt moves into the soil body from the more concentrated portion to the less concentrated portion, under the osmotic pressure, under normal conditions. Let "V_s" be the grams of salt passing through one square centimeter during the unit time. If we assume "V_s" is the velocity of salt concentration over the face $\overline{ab}$ of the element, at the time "t," then the velocity of salt concentration or salt diffusion over the face $\overline{cd}$ at that time would be

$$V_s + \frac{\partial V_s}{\partial x} dx .$$

If "$(V_s + \frac{\partial V_s}{\partial x} dx) - V_s$" is positive, the element is depleting its salt content, continually. If it is negative or the velocity of the salt concentration is greater than the velocity of diffusion, then more salt concentrates in the element.

From the above discussion, we can write:

$$\frac{\partial n_i}{\partial t} = \frac{V_s \cdot ds}{ds \cdot dx \cdot D_{bs}} \qquad (5\text{-}1\text{-}a)$$

$$\frac{\partial n_o}{\partial t} = \frac{(V_s + \frac{\partial V_s}{\partial x} dx) \cdot ds}{ds \cdot dx \cdot D_{bs}} \qquad (5\text{-}1\text{-}b)$$

Where "D_{bs}" is the unit weight of soil at the time. If there is no swelling due to water content (assuming it is negligible) and/or salt content, then "D_{bs}" would be the Bulk Density of the Soil.

d. In addition to the movement of salt, water also moves through the element. Water may move in the direction of "V_s" or in opposing direction. Assume the velocity of the water is "V_w," i.e, the weight of water passes through one square centimeter in a unit time. This water also carries salt in solution.

e. The amount of water passing from one face of the element, for example face $\overline{cd}$, in the opposite direction of "V_s," during the time "dt" would be $ds \cdot V_w$. If we assume the amount of salt in one gram of water is c_1 (weight of salt/weight of water is dimensionless ratio), then this water returns $c_1 \cdot ds \cdot V_w$ gram of salt again in the element, at the time dt. From the other side of the element, by assuming the weight of salt per every gram of water "c_2," the amount of salt taken out by water would be

$$c_2 \cdot ds \cdot (V_w + \frac{\partial V_w}{\partial x} dx)$$

Thus the result is:

$$\frac{\partial n_i}{\partial t} = \frac{V_s \cdot ds}{ds \cdot dx \cdot D_{bs}} + \frac{c_2 \cdot ds \cdot (V_w + \frac{\partial V_w}{\partial x} dx)}{ds \cdot dx \cdot D_{bs}} \qquad (5\text{-}2)$$

$$\frac{\partial n_o}{\partial t} = \frac{(V_s + \frac{\partial V_s}{\partial x} dx) ds}{ds \cdot dx \cdot D_{bs}} + \frac{c_1 \cdot ds \cdot V_w}{ds \cdot dx \cdot D_{bs}} \tag{5-2}$$

f. "c" is the weight of salt in one gram of water

or

$$c_1 = \frac{n}{\rho}$$

$$c_2 = \frac{n + \frac{\partial n}{\partial x} dx}{\rho} \tag{5-3}$$

Where ρ is the weight of water per gram of soil, substituting these amounts into the equations (2) yields:

$$\frac{\partial n_i}{\partial t} = \frac{V_s \cdot ds}{ds \cdot dx \cdot D_{bs}} + \frac{\frac{n + \frac{\partial n}{\partial x} dx}{\rho} ds (V_w + \frac{\partial V_w}{\partial x} dx)}{ds \cdot dx \cdot D_{bs}} \tag{5-4-a}$$

$$\frac{\partial n_o}{\partial t} = \frac{V_s + \frac{\partial V_s}{\partial x} dx) ds}{ds \cdot dx \cdot D_{bs}} + \frac{\frac{n}{\rho} ds \cdot V_w}{ds \cdot dx \cdot D_{bs}} \tag{5-4-b}$$

In the above formula, "V_w" would be positive if it is in the direction of "V_s," otherwise it has the negative sign. In the Figure 1, it assumes negative sign. In all cases, a sign exists for the V_w quantity.

It has been assumed that $\frac{\partial \rho}{\partial x} dx = 0$. According to data obtained (Tables A-1 through A-10), this is evident for coarse-grain soils, but not necessarily for fine soils. However, this assumption is only for simplification of the equations. Investigators for movement of water have neglected $\frac{\partial \rho}{\partial x}$ dx (5, p. 216). Whereas, there, water was the prime consideration.

> If, however, minor factors may be temporarily ignored and the major ones divided into a small number of groups, it may thus be possible to construct in the imagination an ideal problem which in reality may differ only slightly from the actual case, but the solution of which may lie within our power.

Here the negligence of $\frac{\partial \rho}{\partial x}$ dx term is more reliable, since all samples were prepared with a uniform water content for both sides of the soil bar, i.e., salted portion and unsalted portion. Also experimental data show a very small $\frac{\partial \rho}{\partial x}$ dx.

Subtracting equation (5-4-b) from (5-4-a) will yield:

$$\frac{\partial n}{\partial t} = \frac{1}{D_{bs}} \frac{\partial V_s}{\partial x} + \frac{n}{\rho D_{bs}} \frac{\partial V_w}{\partial x} + \frac{V_w}{\rho D_{bs}} \frac{\partial n}{x} +$$

$$+ \frac{1}{D_{bs}\rho} \frac{\partial n}{\partial x} \frac{\partial V_w}{\partial x} dx$$

Since $\frac{1}{D_{bs}\rho} \frac{\partial n}{\partial x} \frac{\partial V_w}{\partial x}$ dx is very small compared to the other terms, we may neglect it and the salt diffusion equation, resulting would be:

$$D_{bs} \frac{\partial n}{\partial t} = \frac{\partial V_s}{\partial x} + \frac{n}{\rho} \frac{\partial V_w}{\partial x} + \frac{V_w}{\rho} \frac{\partial n}{\partial x} \qquad (5\text{-}5)$$

Equation (5) may be written mathematically as follows:

$$D_{bs} \frac{\partial n}{\partial t} = \nabla (V_s + \frac{n}{\rho} V_w) \qquad (5\text{-}6)$$

It may be shown that equation (6) is a common form of the equation (5), when the terms $d\rho = \frac{\partial \rho}{\partial t} dt + \frac{\partial \rho}{\partial x} dx$ or $d\rho = \frac{\partial \rho}{\partial t} dt$ are utilized as implied previously.

Equation (6) also implies the three dimensional face of the salt movement, as suggested and indicated.

However, for data of this investigation consideration of the one dimensional face gives satisfactory results.

In equations (5) and (6):

n = Salt density, $\frac{\text{weight of salt}}{\text{weight of soil}}$ which is equal to $\frac{1}{100}$ salt content used in drawing data curves.

ρ = Water density, $\frac{\text{weight of water}}{\text{weight of soil}}$ which is equal to $\frac{1}{100}$ moisture content used in drawing data curves.

V_s = Velocity of salt concentration, $\frac{\text{weight of salt}}{\text{centimeter}^2 \cdot \text{time}}$ i.e., weight of salt passes through one square centimeter of soil during the unit time. A reliable unit of time, in terms of salt movement in soil, is a day.

V_w = Velocity of moisture movement, $\frac{\text{weight of water}}{\text{square centimeter} \cdot \text{time}}$ i.e., weight of water passes through one square centimeter in soil during the unit time.

D_{bs} = Unit weight of soil, on oven dried basis during the time t.

D_{bs} in equation (5) is resultant of the consideration of weight rather than volume. Normally the measure of salt is a ratio of salt weight to soil weight rather than soil volume.

The term $\frac{\partial V_s}{\partial x}$ implies, that salt concentration is not due to the velocity of salt movement, but it is due to the variation of the velocity over a given distance.

The term $\frac{n}{\rho} \frac{\partial V_w}{\partial x}$ implies that the concentration of salt per gram of water, i.e., $\frac{n}{\rho}$ is a dominant factor, only when there is a variation in the velocity of water per a given distance. Otherwise $\frac{n}{\rho}$ will not effect the concentration.

The term $\frac{V_w}{\rho} \cdot \frac{\partial n}{\partial x}$ implies that the velocity of water effects the salt concentration, only when there is a variation in the salt density over a given distance. Otherwise the velocity of water has no effect on salt concentration. Salt dilution results in less movement of salt, even for higher velocities. However, water density effects V_w and the result of duration and velocity will be diminishing water density in some parts of the equation.

5-2. Boundary Conditions and the Solution of Equation (5).

The equation is resolved for closed systems only. Experimental data indicates, in this case V_w is negligible in the laboratory prepared samples. There is not appreciable moisture potential between two portions of the soil bar, i.e., salted portion and unsalted portion. Rational of this phenomen was covered under the title, Salt Migration in Sands, previously. The small variation of moisture between the two portions of the soil sample existed for the first few days only and for the rest of the curing period the moisture was uniform. Therefore, for closed systems, it will not be unreliable if we assume $V_w = 0$.

The ratios of cross section of soil bar with respect to its length is relatively small. Also the face of contact between salted and unsalted portions is a plane surface. Therefore, the salt movement is considered uniform over any given cross section at any instant time. From the above explanation a one dimensional equation may be employed for this case.

Salt movement is assumed resultant of osmotic pressure only, and the deterrent effect of surface activity on a large portion of the salt molecules is negligible, then the condition will be simplified without loss of reliance.

For osmotic pressure the Van't Hoff equation is used (12, p. 202) which is:

$$\pi V = in'RT$$

Where π is Osmotic pressure--Atm.

n' is the number of moles of solute contained in V liters of solution.

R = 0.0827 and T = 273.2 + C°

i = Van't Hoff factor for electrolytes (12, p. 210) or

$$\pi = \frac{in'RT}{V}$$

Converting units to the units previously employed in this thesis:

$$\pi = \frac{D\ \text{water}\ x\ 1000}{58.5}\ \frac{i \cdot RnT}{\rho} \tag{5-7}$$

By assuming the same relationship of Darcy's law exists between velocity of salt movement and the osmotic pressure

$$V_s = k'\ \frac{\partial \pi}{\partial x} \tag{5-8}$$

Replacing $\frac{\partial \pi}{\partial x}$ from equation (7) into equation (8) results

$$V_s = k'\ \frac{1000 \cdot D_{\text{water}} \cdot i \cdot R}{58.5}\ \frac{T}{\rho}\ \frac{\partial n}{\partial x}$$

$$V_s = k''\ \frac{T}{\rho}\ \frac{\partial n}{\partial x} \tag{5-9}$$

Where $k'' = k' \frac{1000 \text{ D water} \cdot i \cdot R}{58.5}$

Replacing $\frac{\partial V_s}{\partial x}$ from equation (9) into equation

$$\frac{\partial n}{\partial t} = \frac{1}{D_{bs}} \cdot \frac{\partial V_s}{\partial x}$$

results

$$\frac{\partial n}{\partial t} = \frac{k'' \cdot T}{D_{bs}\rho} \frac{\partial^2 n}{\partial x^2} \tag{5-10}$$

This is a heat equation. We are looking for the solution n = n (x,t). Since n (x,t) normally would have continuous second partial derivatives with respect to x. So it could not be applied over the entire length of the soil bar, i.e., salted and unsalted side alike, as demonstrated in the experimental data. Therefore, it is applied to the salted portion and unsalted portion separately. First applying it to the salted side:

In equation (10), assuming $\frac{k''T}{D_{bs}\rho} = a^2$ then:

$$\frac{\partial n}{\partial t} = a^2 \frac{\partial^2 n}{\partial x^2}$$

or

$$\frac{\partial^2 n}{\partial x^2} = \frac{1}{a^2} \frac{\partial n}{\partial t} \tag{5-11}$$

The salted portion has two boundaries, i.e., the contact surface with the unsalted portion and the other end. In order to reduce two sets of boundary conditions to a single set of boundary condition, we assume the salted portion extreme is open and is in contact with the salted portion of a similar soil bar. The unsalted portion extreme is also open and is in contact with the unsalted part of a similar soil bar, and this assumed combination is extended to infinity for both portions,Figure 2.

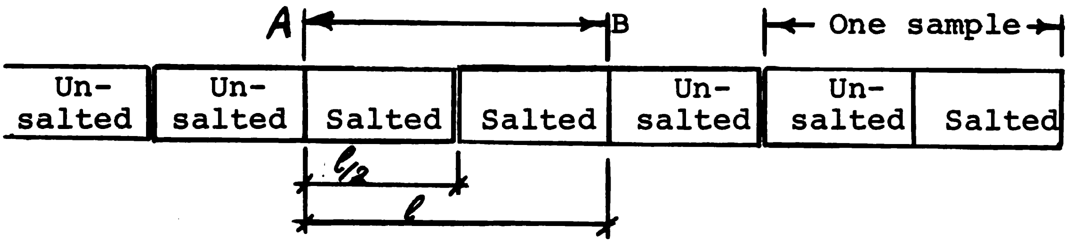

Fig. 2. Combination of Samples.

The result of such an infinite media would be exactly the same as one soil bar only. In other words, there is no difference between the migration of salt in one individual soil bar and the explained combination in Figure 2. We can apply the formula to the part AB Figure 2 where the boundary condition for both ends is the same but the length is l instead of l/2 and the condition of the salted end extreme occurs at the mid point of $\overline{AB}$.

Experimental data indicates that the rate of salt concentration and the rate of the diffusion of salt content, especially for coarse-grain soils is approximately the same and that the electrical charge of the double layer does not have a large deterrent effect on the movement of free salt. There are some highly attracted salt molecules which are affected by the surface activity, but the number of these molecules is small proportionally to the total, and the effect reduces, as the distance from the particle surface increases, exponentially (9, p. 83 and 8, p. 99).

The above explanation indicates the rate of salt concentration and diffusion, for points of equal distance from the contact plane, is approximately the same, or

$$n\ (x_1,t) + n_2\ (x_2,t) = n_1 \qquad (5\text{-}11\text{-}a)$$

Provided $|x_1|=|x_2|$

Where n (x,t) is the salt density of the salted part at any x and any t Figure 3, n_1 is the original salt density of salted portion prior to migration. This equation is correct only when all salt molecules are free to migration.

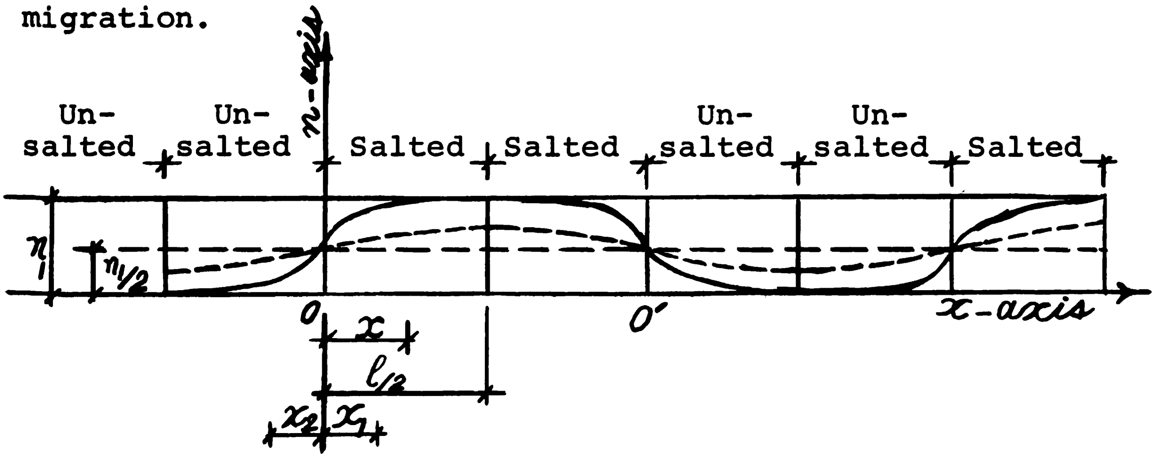

Fig. 3. Schematic Diagram of Salt Migration.

An immediate conclusion of the above explanation is that the amount of salt density at the contact plane is $\frac{n_1}{2}$, at all times. This conclusion is essential for boundary conditions of the mathematical analysis. From the above discussion the schematic diagram for salt density at any time t will be as shown in Figure 3. This condition is more evident when compared to Figure 2.

For salted portion $\overline{AB}$ Figures 2 and 3 the boundary conditions are:

$$n\ (0,t) = n\ (\ell,t) = \frac{n_1}{2} \qquad (5\text{-}12)$$

and initial condition is

$$n\ (x,0) = n_1 \qquad (5\text{-}13)$$

Where n_1 is the original salt density of salted portion. These conditions require further simplification (4, p. 437). $n\ (x,\infty)$ is approximately equal to $\frac{n_1}{2}$. Hence we indicate $\frac{n_1}{2}$, basic salt density and apply the solution for the remainder of the densification, in reverse. The x-axis has been translated up to the $n_{1/2}$, Figure 3. The term $n_b\ (x,t)$ may be introduced by the following equation:

$$n_b\ (x,t) = n\ (x,t) - n\ (x,\infty) = n\ (x,t) - \frac{n_1}{2} \qquad (5\text{-}14)$$

For n_b (x,t) which also satisfies equation (11) the boundary condition will be:

$$n_b\ (0,t) = n_b\ (\ell,t) = \frac{n_1}{2} - \frac{n_2}{2} = 0 \qquad (5\text{-}15)$$

and initial condition is:

$$n_b\ (x,0) = n_1 - \frac{n_1}{2} = \frac{n_1}{2} \qquad (5\text{-}16)$$

and equation (11) becomes:

$$\frac{\partial^2 n_b}{\partial x^2} = \frac{1}{a^2}\frac{\partial n_b}{\partial t} \qquad (5\text{-}17)$$

The technique of separation of variables in equation (17) with respect to the boundary condition (15) and (16) yields the solution (20, p. 297)

$$n_b\ (x,t) = \sum_{m=1}^{\infty} A_m \operatorname{Sin} \frac{\pi m x}{\ell}\, e^{\frac{-a^2\pi^2 n^2}{\ell^2} t}$$

$$(m=1,2,\ldots.)$$

Where

$$A_m = \frac{2}{\ell} \int_0^{\ell} \frac{n_1}{2} \operatorname{Sin} \frac{\pi m x}{\ell}\, dx = \frac{n_1}{\pi m}\,[1-(-1)^m]$$

$$m = (1,2,\ldots.)$$

Resolving equation (14) will result as follows

$$\boxed{\begin{array}{l} n(x,t) = \frac{n_1}{2} + \sum_{m=1}^{\infty} \frac{n_1}{\pi m} [1-(-1)^m] \operatorname{Sin} \frac{\pi m x}{\ell} e^{-\frac{a^2\pi^2 m^2}{\ell^2} t} \qquad (5\text{-}18) \\ \\ m = (1,2,\ldots.) \end{array}}$$

Equation (18) is the primary equation of diffusion in the salted portion at any x and any time t.

Equation for salt concentration in unsalted portion may be readily derived from (18) and (11-2) which results

$$\boxed{\begin{array}{l} n_2(x,t) = \frac{n_1}{2} - \sum_{m=1}^{\infty} \frac{n_1}{\pi m} [1-(-1)^m] \operatorname{Sin} \frac{\pi m x}{\ell} e^{-\frac{a^2\pi^2 m^2}{\ell^2} t} \qquad (5\text{-}19) \\ \\ m = (1,2,\ldots.) \end{array}}$$

Providing the origin of the coordinates is point o' of Figure 3 instead of o.

5-3. Discussion of Equation (18).

At the time t = 0 equation (18) becomes

$$n(x,0) = \frac{n_1}{2} + \sum_{m=1}^{\infty} \frac{n_1}{\pi m} [1-(-1)^m] \operatorname{Sin} \frac{\pi m x}{\ell} \qquad (5\text{-}20)$$

$$m = 1,2,3,\ldots$$

Since the Fourier Sine Series (4, p. 286) of one is as follows:

$$1 = \sum_{m=1}^{\infty} \frac{2}{m\pi} [1-(-1)^m] \text{ Sin } \frac{\pi m x}{\ell} \qquad (5\text{-}21)$$

By multiplying both sides of equation (21) by $\frac{n_1}{2}$ the result is:

$$\frac{n_1}{2} = \sum_{m=1}^{\infty} \frac{n_1}{m\pi} [1-(-1)^m] \text{ Sin } \frac{\pi m x}{\ell}$$

Therefore equation (2) becomes:

$$n\ (x,0) = \frac{n_1}{2} + \frac{n_1}{2} = n_1 \qquad (5\text{-}22)$$

Equation (24) is valid for every x, except for points of discontinuity which are $x = 0$ and $x = \ell$. At points $x = 0$ and $x = \ell$, Sin $\frac{\pi m x}{\ell}$ becomes equal to zero and the equation yields the average of amounts at the point of discontinuity which is:

$$\frac{n_1 + 0}{2} = \frac{n_1}{2}$$

This equation varifies the initial assumption for boundary conditions, equation (12)

In equation (18)

$$a^2 = \frac{kT}{D_{bs}\rho}$$

Where

$$K = \frac{1000\ C \cdot R \cdot D\ \text{water}}{58.5}$$

Calculating any one of these factors, i.e., ρ, i, D_{bs}, etc., requires various assumptions, which might deviate from reliance, thus it is more appropraite to calculate "a^2" directly from equation (18). For $x = \frac{\ell}{2}$, equation (18) becomes:

$$n(\tfrac{\ell}{2},t) = \frac{n_1}{2} \sum_{m=1}^{\infty} \frac{n_1}{m} [1-(-1)^m] \operatorname{Sin} \frac{m\pi}{2} e^{-\frac{a^2\pi^2m^2}{\ell^2} t} \qquad (5\text{-}23)$$

$$m = (1,2,3,\ldots.)$$

For m = (1,2,3,....) the amount of Sin $\frac{m\pi}{2}$ becomes (1,0,-1,0,1,0,-1,...) respectively. Also $[1-(-1)^m]$ becomes (2,0,2,0,2,...) respectively.

Therefore equation (23) becomes

$$n(\tfrac{\ell}{2},t) = \frac{n_1}{2} + \frac{2n_1}{\pi} \sum_{m=0}^{\infty} \frac{(-1)^{m+1} \left[e^{-\frac{a^2\pi^2}{\ell^2} t}\right]^{2m+1}}{2m+1}$$

or:

$$\frac{n}{n_1} = \frac{1}{2} + \frac{2}{\pi} \sum_{m=0}^{\infty} \frac{(-1)^{m+1} e^{-(2m+1)\left(\frac{a^2\pi^2}{\ell^2}\right) t}}{2m+1} \qquad (5\text{-}24)$$

Equations (18) and (24) result in a practical procedure for estimating salt movement. A standard procedure is desired. If the length of the sample and the time may be standardized, equation (24) may be standardized for computerized program with varying a^2. The results may be tabulated $\frac{n}{n_1}$ opposing a^2.

Thus for any sample the amount of $\frac{n}{n_1}$ is a known quantity and a^2 is a determinable value; equation (18) may be solved for the field movement of salts and stabilizers.

For a primary calculation for sample No. 3 of soil No. 2 (sand), the amount of a^2, within the first approximation, is calculated

$$a^2 = 1.2$$

In the field, for the same conditions, the amount of salt loss, due to the direct movement would be implied by:

$$n(x,t) = 0.67 + \sum_{m=1}^{\infty} \frac{1.24}{\pi m} \operatorname{Sin} \frac{\pi m x}{\ell} e^{-\frac{1.2\pi^2 m^2}{\ell^2} t}$$

$$m = (1,2,3,....)$$

Many of the field problems are similar to the samples with one side approaching infinity, i.e., a long sample where the effect of salt movement at the salted extreme would be expected to be zero. Many conditions of field application are similar to open systems, or a combination of both.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6-1. Salt Movement in Water.

Under the effect of osmotic pressure, salt moves in the water media, but water itself resists movement, regardless of the effect of the soil particles. The amount of resistance of the water to the movement is relatively large. The relationship should resemble the well known electricity equation

$$V = R \cdot i$$

Where V is the potential, R is the resistance, and i is the current strength.

In other words, water movement and salt movement are gradual actions, even if two sides of the basic osmotic pressure apparatus is separated by a zero resistant membrane, i.e., salted water and unsalted water in direct contact.

Therefore, for engineering problems, one may not employ total osmotic pressure in equations, but has to add a presumed resistance. One can call it internal resistance of the solution; which depends solely on the salt and water, disregarding the effect of soil particles. Since this internal resistance is not resolved, osmotic pressure from the engineering standpoint is still not a resolved question, as commonly believed (21).

6-2. Movement of Water from Unsalted Soil to the Salted Soil, under the Effect of Osmotic Pressure.

In the preceding paragraph reference is made to in the opposing of the high osmotic pressure, there is a large internal resistance. However, according to existing literature (21), water should move from the unsalted portion to the salted portion very slowly. Closed systems do not show an appreciable amount of water movement and difference in water content of two portions with respect to the high osmotic pressure, namely greater than 126 atmosphere.

Closed systems also show that the movement of water occurs during the first few days and then remains constant for the entire curing time. Any change in water content, thereafter, occurs resultant of evaporation.

6-3. Movement of Salt from Salted Soil to the Unsalted Soil.

Salt moves gradually from the salted soil to the unsalted soil to approach the final equilibrium, which is approximately uniform distribution of salt in the entire sample. For this salt movement, there is not required water percolation, or leaching, as commonly accepted. However, water percolation and leaching themselves affect this movement of salt.

The result of salt migration will be losing some part of soluble stabilizers or changing the fabric and structure of the soil thus affecting strength characteristic of the soil.

Salt moves under the influence of the overall osmotic pressure of an area regardless of the salt content of the in-contact soils. Thus, due to the overall osmotic pressure of an area, the salt moves through the lesser salt content soils toward higher salt content portions.

There is no boundary condition for salt movement and osmotic pressure in the field, and salt moves under the effect of the osmotic pressure of the entire area. The limit is normally infinite and the salt content of every point is under the effect of every other point.

Moisture content affects salt movement in closed systems, or the greater the moisture content, the more the salt movement.

The relationship between moisture content and salt movement is not proportional.

The effect of moisture content on salt movement, at low salt contents is evidenced. The effect of the moisture content on salt movement in open systems, i.e., one end exposed to the atmosphere, will be partly resultant to the water percolation by evaporation.

The higher the temperature, the more the salt movement.

Since the effect of higher temperature on low moisture content is more pronounced, in arid areas, high temperatures have much more effect on salt movement, or stabilizer movement, than in the humid areas.

Sometimes mixtures of stabilizers and soils are required in laboratories. These mixtures are stored for a period of time, to get a uniform mixture. Soils with lower moisture contents are more sensitive by temperature variations.

6-4. Bituminus Surface Courses Over Materials Stabilized by Soluble Stabilizers in Design of Stabilized Wearing Course.

Regarding data for open systems, it can be noted that the effect of insulation over a soluble stabilizer such as calcium chloride or sodium chloride would be simply the extreme reduction of stabilizer over a given period resultant of repetitious variation cycles of moisture content. For this reason an insulated surface course such as bituminus material over any kind of soluble stabilizers is questionable.

6-5. Stabilizing-in-Place, Reflection of Salinity.

From the data obtained, it can be seen that there is a tendency for the movement of salt toward the surfaces subjected to evaporation. Salt sometimes may not reach those surfaces subjected to evaporation but spreads in the soil body approaching the open surface. If there is any indication of saline soil in the foundation of the fill, or if we spread such a soil under the soil body, during future years, it will come up and will remain in the soil body with concentration at the surface. In other words, salinity reflects on the surface.

Conversly, stabilizing could be accomplished by covering the surface of the soil by stabilizer and then covering it by an insulated material which could be either permanent or removable. Within a few years, the salt will migrate into the foundation soil stabilizing it and migrating toward the surrounding open surfaces.

6-6. Partially Frozen Soils.

In the soil body crystaline water does not influence the moisture potential, or frozen water in the soil body has a similar effect of soil particles rather than acting as free moisture.

If there is a source of unfrozen salted soil in contact with frozen soil, the salted water will move into the frozen soil due to the reduction of moisture potential in frozen soil. Since the volume of frozen soil normally exceeds the volume of unfrozen soil, when the salt water migrates into it, it soon becomes over saturated. During thawing periods the soil is affected by the migrated water, and becomes unstable with a probability of damaging the pavement.

Regarding the preceding explanation, one should never allow salt melted water of snow, in contact with the frozen road bed. There is always a possiblity of over saturating the road bed and gradual damage to pavement. If one has to melt snow and ice on the roads by salt, the salty water should be diverted into insulated water ways and disposed of away from the road bed.

RECOMMENDATIONS FOR FURTHER RESEARCH

Further research is needed in several areas related to the salt migration. Several specific problems are briefly described below.

1. Today's world of engineering needs more investigation on osmotic pressure, especially on the velocity of salt movement and water movement due to the osmotic pressure.

2. The effect of varied salts on the salt migration; the effect of a combination of several salts should also be investigated.

3. The system which has been investigated was salted soil in contact with unsalted soil. However, there are other systems which resembles the field conditions that should be investigated. Among them are salted soil and water system, unsalted soil and salted water system and other intermediate systems.

4. Obtaining field data from the movement of salt and stabilizers from the existing roads is desirable.

APPENDICES

APPENDIX I

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APPENDIX II

Table A-1.--Salt Concentration in Sand Samples.

Sample Number	Initial Moisture Content (in %)	Initial Salt Content of Salted Portion (in %)	Average Total Weight of Material in the Mold (in Grams)	Curing Time (in Days)	Curing Temperature (in C°)	Open End
1	4.28	1.405	103	14	44°	Salted
2	4.28	1.405	103	14	44°	Unsalted
3	4.28	1.405	103	14	44°	None
4	4.28	1.405	103	14	24°	Salted
5	4.28	1.405	103	14	24°	Unsalted
6	4.28	1.405	103	14	24°	None
13	9.42	2.83	110	16	24°	Salted
14	9.42	2.83	110	16	24°	Unsalted
15	9.42	2.83	110	16	24°	None
16	9.42	2.83	110	16	44°	Salted
17	9.42	2.83	110	16	44°	Unsalted
18	9.42	2.83	110	16	44°	None
22	9.76	1.34	110	17	24°	Salted
23	9.76	1.34	110	17	24°	Unsalted
24	9.76	1.34	110	17	24°	None
25	9.76	1.34	110	17	44°	Salted
26	9.76	1.34	110	17	44°	Unsalted
27	9.76	1.34	110	17	44°	None

Table A-1.--Continued.

Salt Content of Segments, in %

Unsalted Portion				Salted Portion			
Unsalted Extreme	Part A	Part B	Part C	Part D	Part E	Part F	Salted Extreme
. .	0.	0.	0.	0.275	0.992	2.370	7.84
0.	0.	0.708	1.280	1.135	0.890	0.638	. .
. .	0.375	0.470	0.602	0.724	0.841	0.920	. .
. .	0.	0.	0.	0.207	0.893	1.955	7.81
0.	0.182	0.580	1.281	1.190	0.950	0.600	. .
. .	0.039	0.327	0.629	0.981	1.162	1.230	. .
. .	0.083	0.118	0.172	0.292	0.452	0.862	12.620
8.30	1.350	0.971	0.841	9.904	0.496	0.550	. .
. .	1.098	1.221	1.260	1.390	1.442	1.485	. .
. .	0.	0.061	0.133	0.234	0.355	0.643	17.10
17.38	1.650	1.065	0.855	0.891	0.732	0.502	. .
. .	1.342	1.372	1.415	1.50	1.642	1.685	. .
. .	0.	0.044	0.069	0.151	0.307	0.307	8.15
3.65	0.657	0.612	0.508	0.468	0.381	0.319	. .
. .	0.568	0.635	0.662	0.704	0.791	0.863	. .
. .	0.	0.	0.	0.	0.057	0.326	19.50
6.25	0.888	0.655	0.523	0.435	0.331	0.285	. .
. .	0.765	0.808	0.818	0.810	0.841	0.860	. .

Table A-2.--Moisture Content in Sand Samples. Initial Conditions of the Samples are Tabulated in Table A-1. Moisture Content of Segments is in Per Cent.

Sample	Unsalted Portion			Salted Portion		
Number	Part A	Part B	Part C	Part D	Part E	Part F
3	3.81	3.89	3.87	3.91	4.07	3.92
6	3.94	3.77	3.87	4.36	4.27	4.16
15	8.51	9.12	9.18	9.85	9.35	9.50
18	8.75	9.10	8.95	9.80	10.50	10.15
24	9.80	9.90	9.93	8.36	8.98	9.15
27	9.90	10.50	10.08	9.56	9.88	10.00

Table A-3.--Salt Concentration in Sandy Loam (Soil Number One).

Sample Number	Initial Moisture Content (in %)	Initial Salt Content of Salted Portion (in %)	Average Total Weight of Material in the Mold (in Grams)	Curing Time (in Days)	Curing Temperature (in C°)	Open End
1	10.80	2.30	121.5	207	44°[1]	None
2	10.80	2.30	121.5	14	24°	None
3	10.80	2.30	121.5	29	24°	None
4	10.80	2.30	121.5	90	44°	None
5	10.80	2.30	121.5	177	44°	None
6	10.80	2.30	121.5	90	24°	None
7	10.80	2.30	121.5	177	24°	None
8	10.80	2.30	121.5	207	24°	None
10	14.90	2.35	126.5	177	44°	None
11	14.90	2.35	126.5	29	24°	None
12	14.90	2.35	126.5	177	24°	None
13	14.90	2.35	126.5	231	24°	None
14	20.40	2.04	138.0	231	24°	None
15	20.40	2.04	138.0	35	24°	None
16	20.40	2.04	138.0	177	24°	None

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[1] All of these samples were cured out of oven for 36 days. Only after that time some of them were put in oven (44°) as it is written.

Table A-3.--Continued.

Salt Content of Segments in Per Cent					
Unsalted Portion			Salted Portion		
Part A	Part B	Part C	Part D	Part E	Part F
1.327	1.350	1.448	1.542	1.530	1.662
0.	0.243	0.751	1.395	1.660	1.958
0.366	0.685	1.090	1.598	1.92	2.08
1.102	1.121	1.130	1.250	1.267	1.382
0.675	0.660	0.808	0.874	1.245	3.480
1.117	1.130	1.220	1.350	1.445	1.475
1.490	1.440	1.670	1.730	1.710	1.730
1.315	1.352	1.360	1.507	1.515	1.455
1.560	1.520	1.460	1.660	1.870	1.580
0.433	0.725	1.005	1.535	1.860	1.980
1.226	1.220	1.183	1.395	1.475	1.540
1.545	1.600	1.620	1.710	1.700	1.780
1.500	1.360	1.510	1.460	1.390	1.590
0.467	0.624	0.847	1.240	1.430	1.740
1.281	1.208	1.330	1.315	1.340	1.622

Table A-4.--Moisture Content in the Sandy Loam (Soil Number One) Samples. Initial Conditions of the Samples are Tabulated in Table A-3. Moisture Content of Segments is in Per Cent.

Sample	Unsalted Portion			Salted Portion		
Number	Part A	Part B	Part C	Part D	Part E	Part F
1	7.32	7.40	7.40	7.50	7.52	7.65
2	10.25	10.35	10.14	10.88	10.58	10.61
3	10.22	10.18	10.10	10.85	10.80	10.76
4	9.21	9.37	9.35	9.85	10.08	10.02
5	. .	. .	. .	. .	. .	. .
6	9.55	9.67	9.78	10.45	10.30	10.20
7	9.10	9.45	9.31	10.18	9.88	9.80
8	9.34	9.31	9.40	10.15	10.22	10.15
10	11.68	11.70	11.58	12.10	12.30	12.42
11	14.00	13.98	13.70	15.18	14.70	14.55
12	13.03	13.00	12.98	14.18	14.00	14.30
13	13.10	13.00	12.90	14.35	14.30	14.25
14	18.60	18.20	18.00	18.00	17.40	18.00
15	19.40	18.80	17.62	18.55	18.21	18.68
16	18.82	17.80	18.02	18.42	18.55	17.75

Table A-5.--Salt Concentration in the Clay (Soil Number Three).

Sample Number	Initial Moisture Content (in %)	Initial Salt Content of Salted Portion (In %)	Average Total Weight of Material in the Mold (in Grams)	Curing Time (in Days)	Curing Temperature (in C°)	Open End
1	20.50	2.55	140	23	44°	Salted
2	20.50	2.55	140	23	44°	Unsalted
3	20.50	2.55	140	23	44°	None
4	20.50	2.55	140	23	24°	None
5	9.12	2.29	105	23	44°	Salted
6	9.12	2.29	105	23	44°	Unsalted
17	9.12	2.29	105	23	44°	None
18	9.12	2.29	105	23	24°	None

Table A-5.--Continued.

Salt Content of Segments, (in %)							
Unsalted Portion				Salted Portion			
Unsalted Extreme	Part A	Part B	Part C	Part D	Part E	Part F	Salted Extreme
. .	0.	0.	0.073	0.188	0.446	2.730	35.800
4.920	3.170	1.110	0.940	0.807	0.892	0.800	. .
. .	0.618	0.865	1.262	1.662	2.00	2.160	. .
. .	0.414	0.648	1.210	1.765	2.160	2.480	. .
. .	0.	0.	0.474	1.042	2.270	2.860	3.500
0.	0.	0.163	1.568	2.310	1.980	1.900	. .
. .	0.186	0.830	1.175	1.920	1.962	2.120	. .
. .	0.	0.338	0.975	1.700	2.300	2.420	. .

Table A-6.--Moisture Content in the Clay (Soil Number Three) Samples. Initial Conditions of the Samples are Tabulated in Table A-5. Moisture Content of Segments is in Per Cent.

	Unsalted Portion				Salted Portion			
Sample Number	Unsalted Extreme	Part A	Part B	Part C	Part D	Part E	Part F	Salted Extreme
1	. .	7.95	7.82	7.60	6.75	6.00	5.12	4.04
2	2.76	3.78	4.45	5.12	5.70	6.00	6.05	. .
3	. .	19.92	20.00	19.95	20.80	20.70	20.60	. .
4	. .	20.00	19.99	19.99	20.80	20.60	20.60	. .
5	. .	3.02	2.95	2.80	2.52	2.02	1.29	0.32
6	0.98	2.52	0.96	1.99	2.52	3.20	3.76	. .
17	. .	6.31	6.42	7.78	8.89	8.82	8.80	. .
18	. .	8.50	8.48	8.58	9.45	9.26	9.15	. .

Table A-7.--Salt Concentration in the Silty Loam (Soil Number 4) Samples.

Sample Number	Initial Moisture Content (in %)	Initial Salt Content of Salted Portion (in %)	Average Total Weight of Material in the Mold (in Grams)	Curing Time (in Days)	Curing Temperature (in C°)	Open End
13	19.80	2.39	152	24	44°	Salted
14	19.80	2.39	152	24	44°	Unsalted
15	19.80	2.39	152	24	44°	None
25	9.30	2.52	128	24	44°	Salted
26	9.30	2.52	128	24	44°	Unsalted
27	9.30	2.52	128	21	24°	None
29	9.30	2.52	128	21	44°	None

Table A-7.--Continued.

Salt Content of Segments (in %)							
Unsalted Portion				Salted Portion			
Unsalted Extreme	Part A	Part B	Part C	Part D	Part E	Part F	Salted Extreme
. .	0.062	0.161	0.161	0.304	0.670	1.620	47.50
10.880	4.300	0.670	0.545	0.457	0.386	0.37	. .
. .	0.908	0.980	1.185	1.540	1.725	1.840	. .
. .	0.	0.	0.	0.	0.077	3.53	32.50
1.080	3.060	1.860	1.140	0.925	0.805	0.810	. .
. .	0.300	0.594	1.100	1.610	2.050	2.350	. .
. .	0.710	1.010	1.375	1.600	1.900	1.900	. .

Table A-8.--Moisture Content in the Silty Loam (Soil Number 4) Samples. Initial Conditions of the Samples are Tabulated in Table A-7. Moisture Content of Segments is in Per Cent.

	Unsalted Portion				Salted Portion			
Sample Number	Unsalted Extreme	Part A	Part B	Part C	Part D	Part E	Part F	Salted Extreme
13	. .	6.25	6.25	6.25	6.30	6.48	6.12	4.5
14	0.17	1.10	0.78	1.22	1.49	1.63	1.75	. .
15	. .	18.00	17.90	18.20	18.50	17.80	18.25	. .
25	. .	1.23	1.10	0.94	0.74	0.62	0.74	0.20
26	0.90	0.93	0.71	0.97	1.36	1.90	1.90	. .
27	. .	8.40	8.50	8.30	8.80	9.00	9.00	. .
29	. .	8.45	8.62	8.50	9.37	9.20	9.00	. .

Table A-9.--Salt Concentration in the Partly Frozen Soil Samples.

Sample Number	Initial Moisture Content (in %)	Initial Salt Content of Salted Portion (in %)	Average Total Weight of Material in the Mold (in Grams)	Curing Time (in Days)	Curing Temperature (in C°)	Open End	Soil Type
22	19.80	2.39	152	27	-15°	Salted	Silty Loam
7	4.28	1.405	103	49	-15°	Salted	Sand
8	4.28	1.405	103	49	-15°	Unsalted	Sand
10	9.42	2.83	110	49	-15°	Salted	Sand
11	9.42	2.83	110	49	-15°	Unsalted	Sand
12	9.42	2.83	110	49	-15°	None	Sand

Table A-9.--Continued.

Salt Content of Segments (in %)							
Unsalted Portion				Salted Portion			
Unsalted Extreme	Part A	Part B	Part C	Part D	Part E	Part F	Salted Extreme
. .	0.045	0.300	1.050	2.250	2.440	2.720	4.640
. .	0.370	0.426	0.624	1.050	1.100	1.020	14.15
0.300	0.480	0.376	0.660	1.080	1.300	1.520	. .
. .	0.640	0.590	0.750	1.940	2.870	3.140	16.44
2.160	0.868	0.521	0.518	1.480	2.200	2.300	. .
. .	0.550	0.545	0.650	1.390	2.34	2.75	. .

Table A-10.--Moisture Content in the Partly Frozen Soil Samples. Initial Conditions of the Samples are Tabulated in Table A-9. Moisture Content of Segments is in Per Cent.

	Unsalted Portion				Salted Portion			
Sample Number	Unsalted Extreme	Part A	Part B	Part C	Part D	Part E	Part F	Salted Extreme
22	. .	19.40	20.30	21.60	17.10	17.30	16.82	13.20
7	. .	4.68	4.85	4.50	2.47	2.30	2.17	. .
8	2.00	3.95	4.70	4.20	2.70	2.68	2.72	. .
10	. .	7.40	8.61	9.20	9.15	9.05	8.90	8.30
11	4.93	6.46	7.25	7.80	7.15	6.95	7.04	. .
12	. .	7.12	8.08	9.00	8.99	8.50	8.35	. .

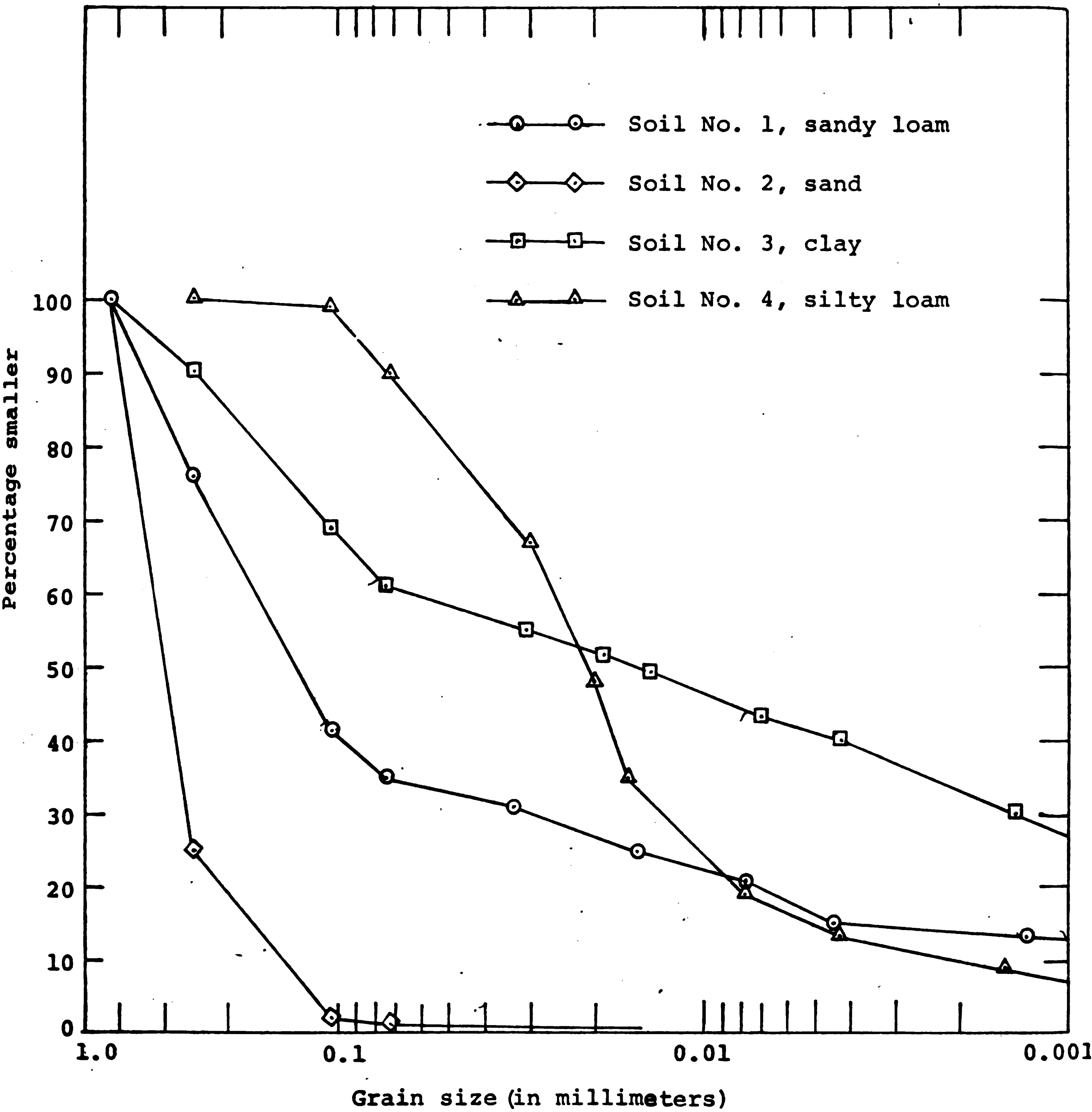

Fig. A-1. Grain Size Curves for Soil Samples.

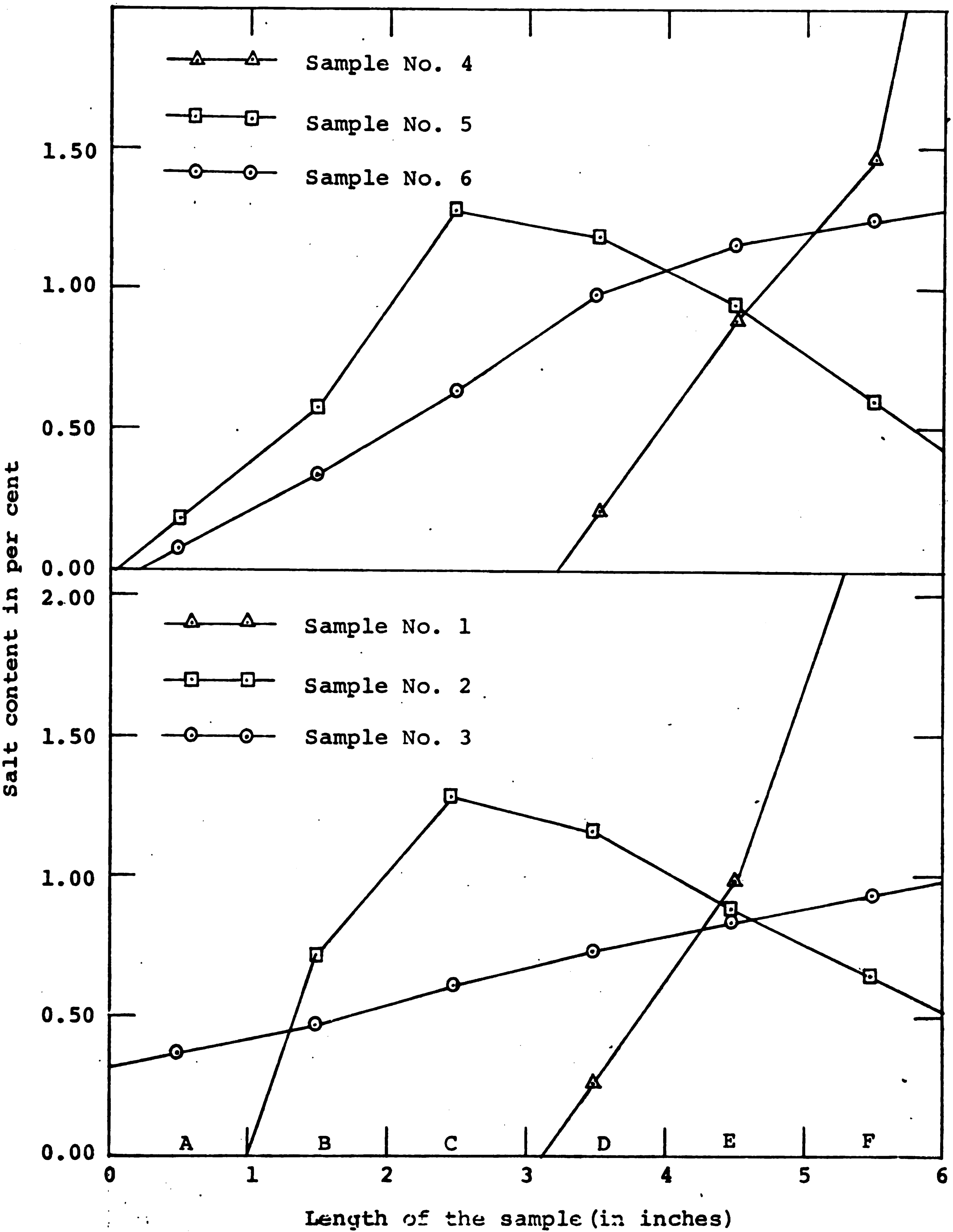

Fig. A-2. Salt Migration in Sand Samples 1, 2, 3, 4, 5, and 6 from Table A-1.

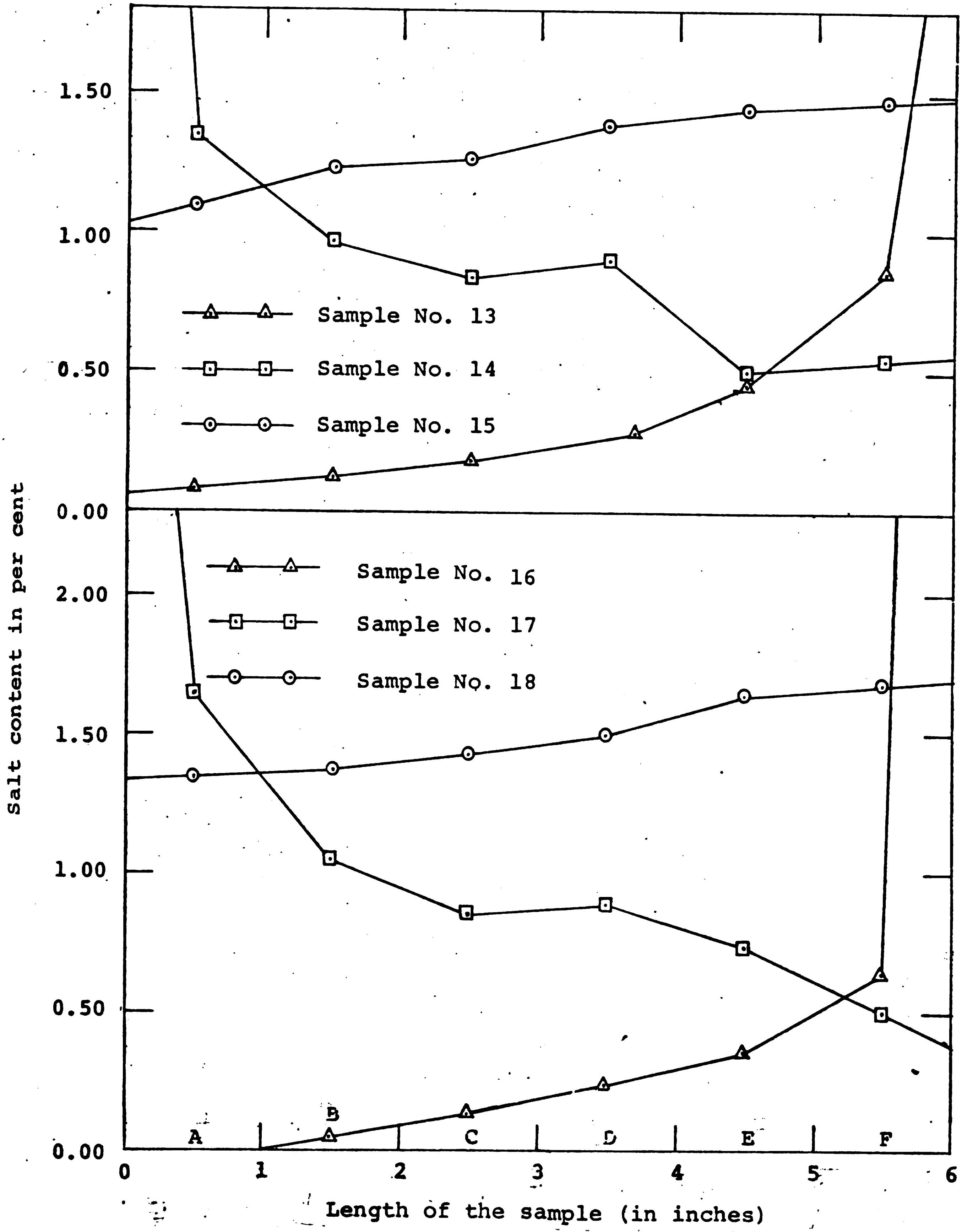

Fig. A-3. Salt Migration in Sand Samples 13, 14, 15, 16, 17, and 18 from Table A-1.

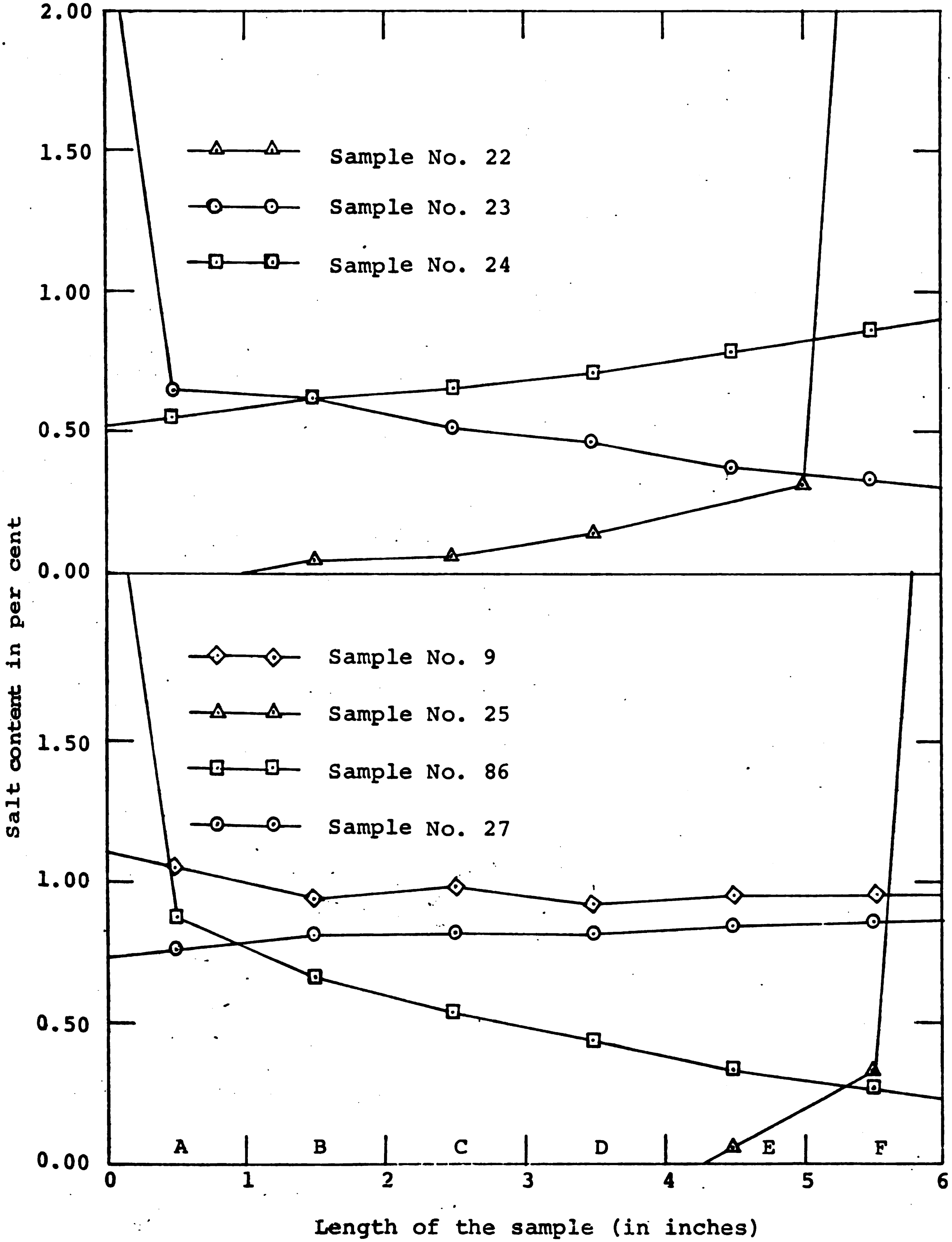

Fig. A-4. Salt Migration in Sand Samples 9, 22, 23, 24, 25, 26, and 27 from Table A-1.

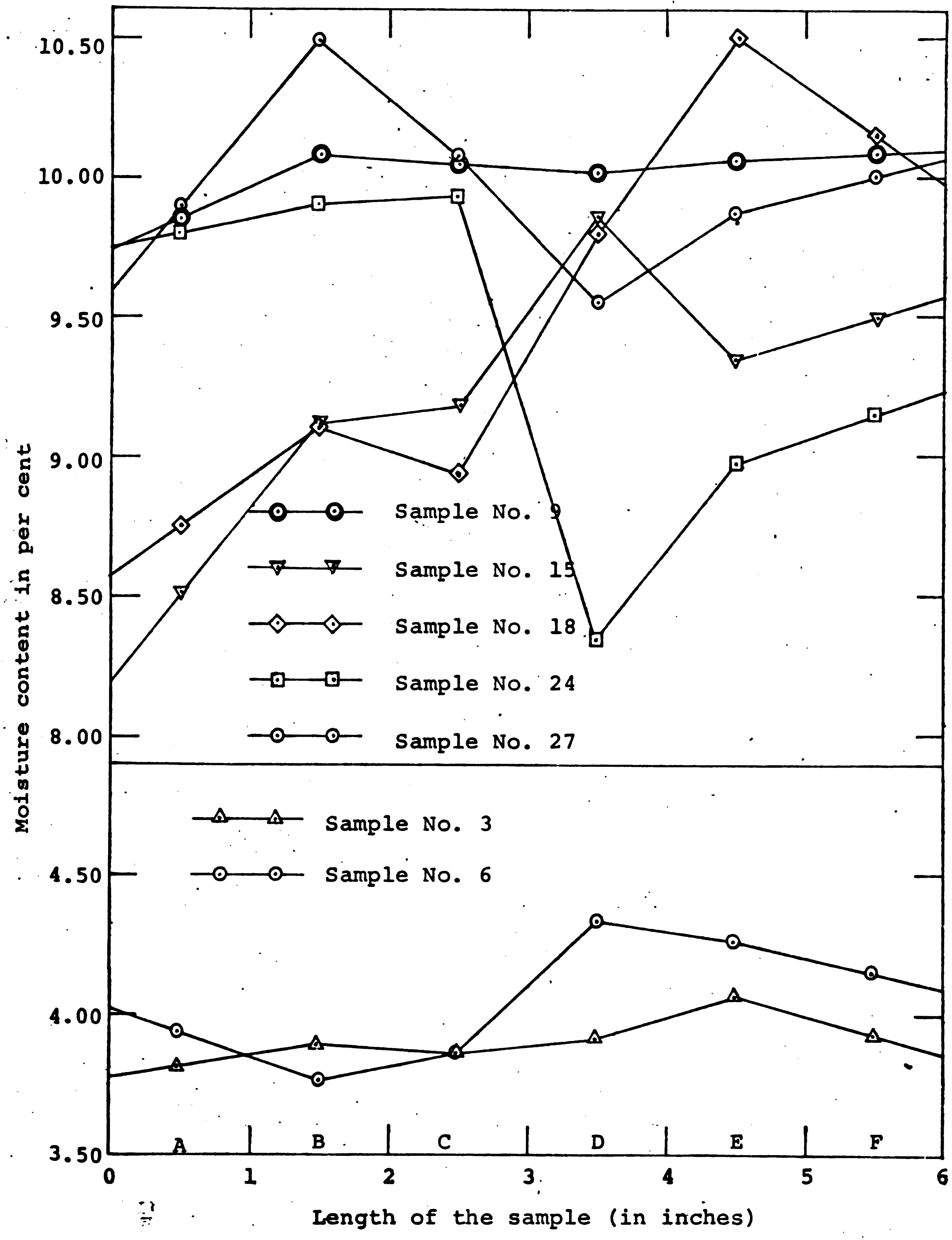

Fig. A-5. Moisture Content in Sand Samples 3, 6, 9, 15, 18, 24, and 27 from Table A-2.

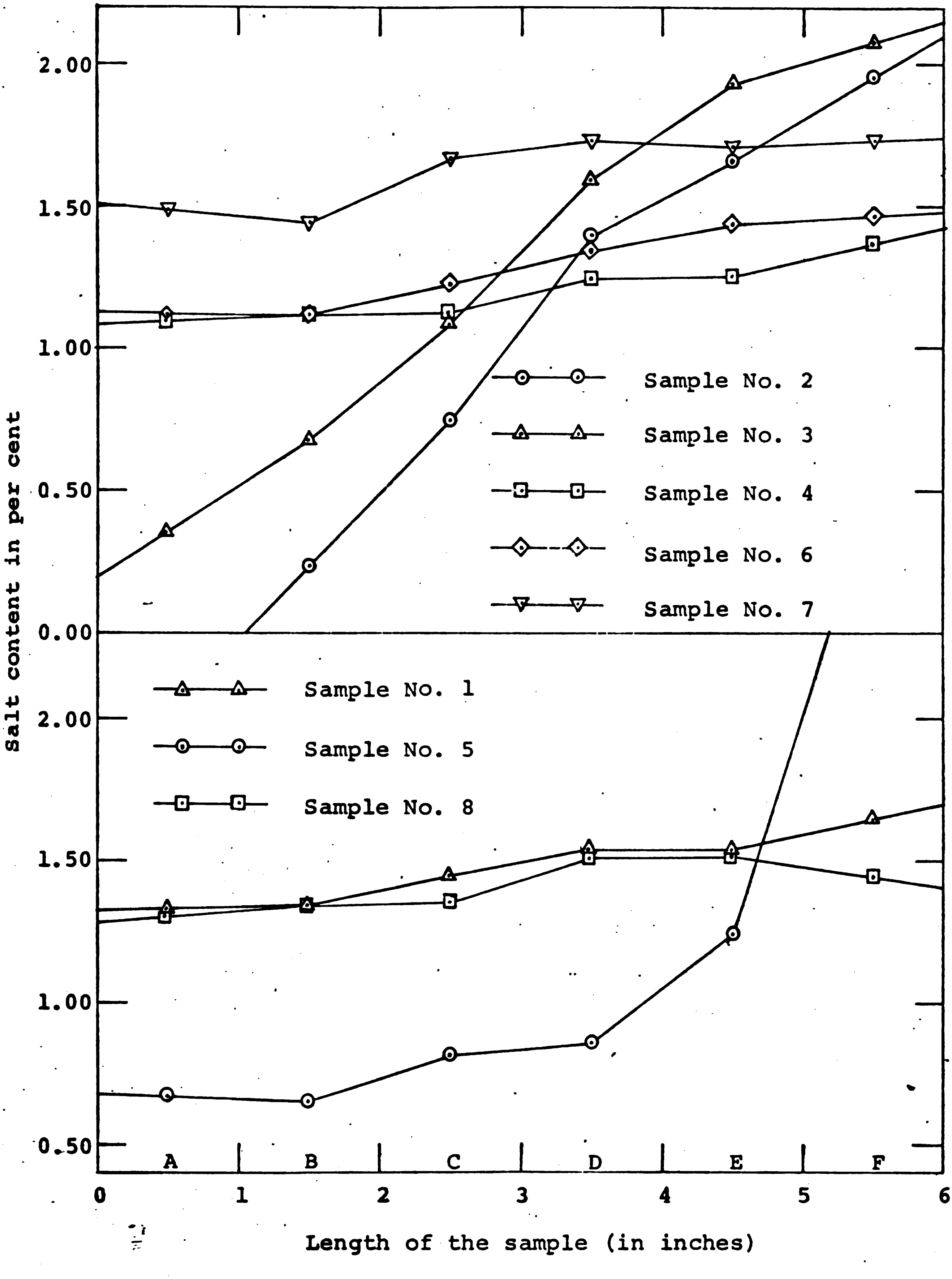

Fig. A-6. Salt Migration in Sandy Loam (Soil Number One) Samples 1, 2, 3, 4, 5, 6, 7, and 8 from Table A-3.

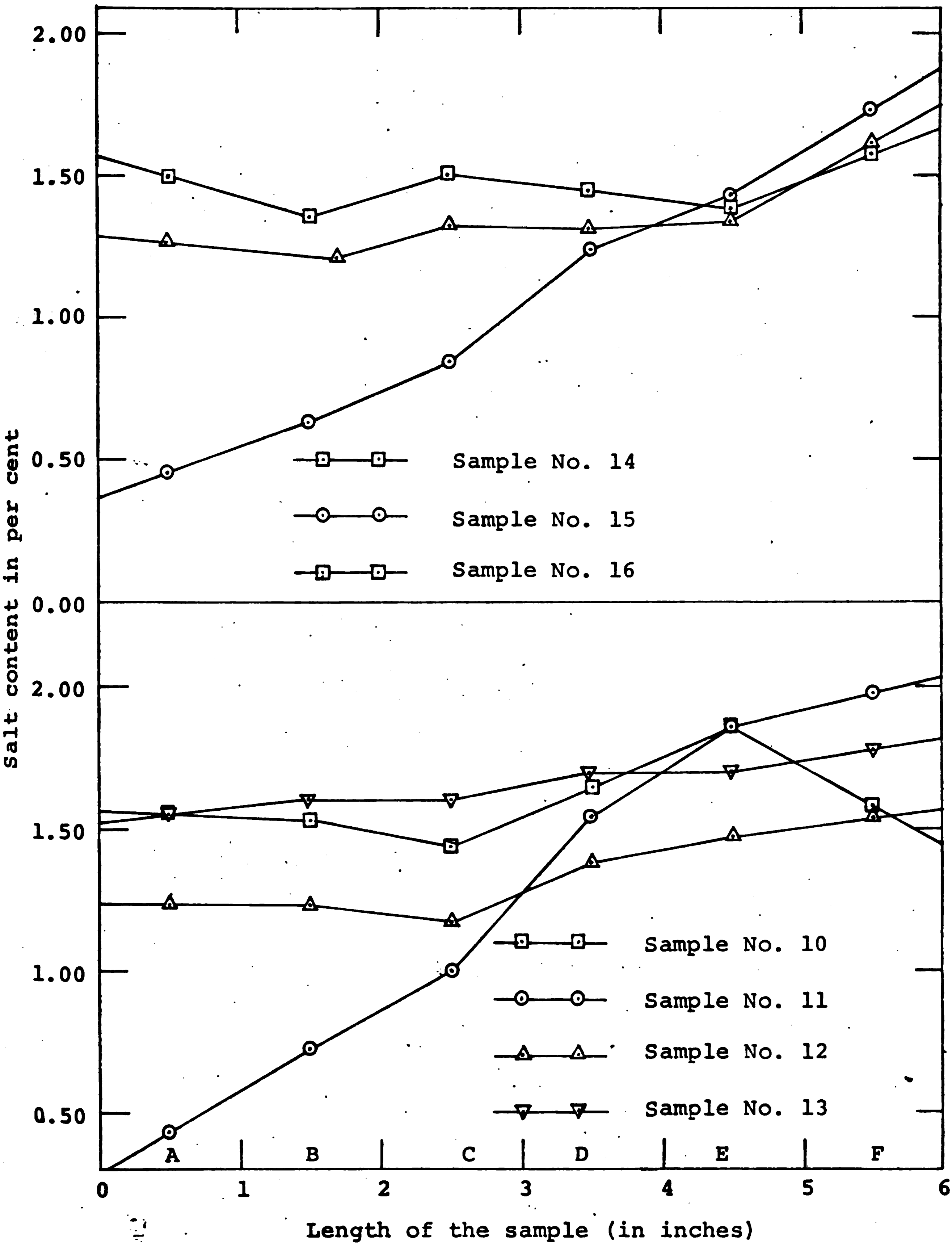

Fig. A-7. Salt Migration in Sandy Loam (Soil Number One) Samples 10, 11, 12, 13, 14, 15, and 16 from Table A-3.

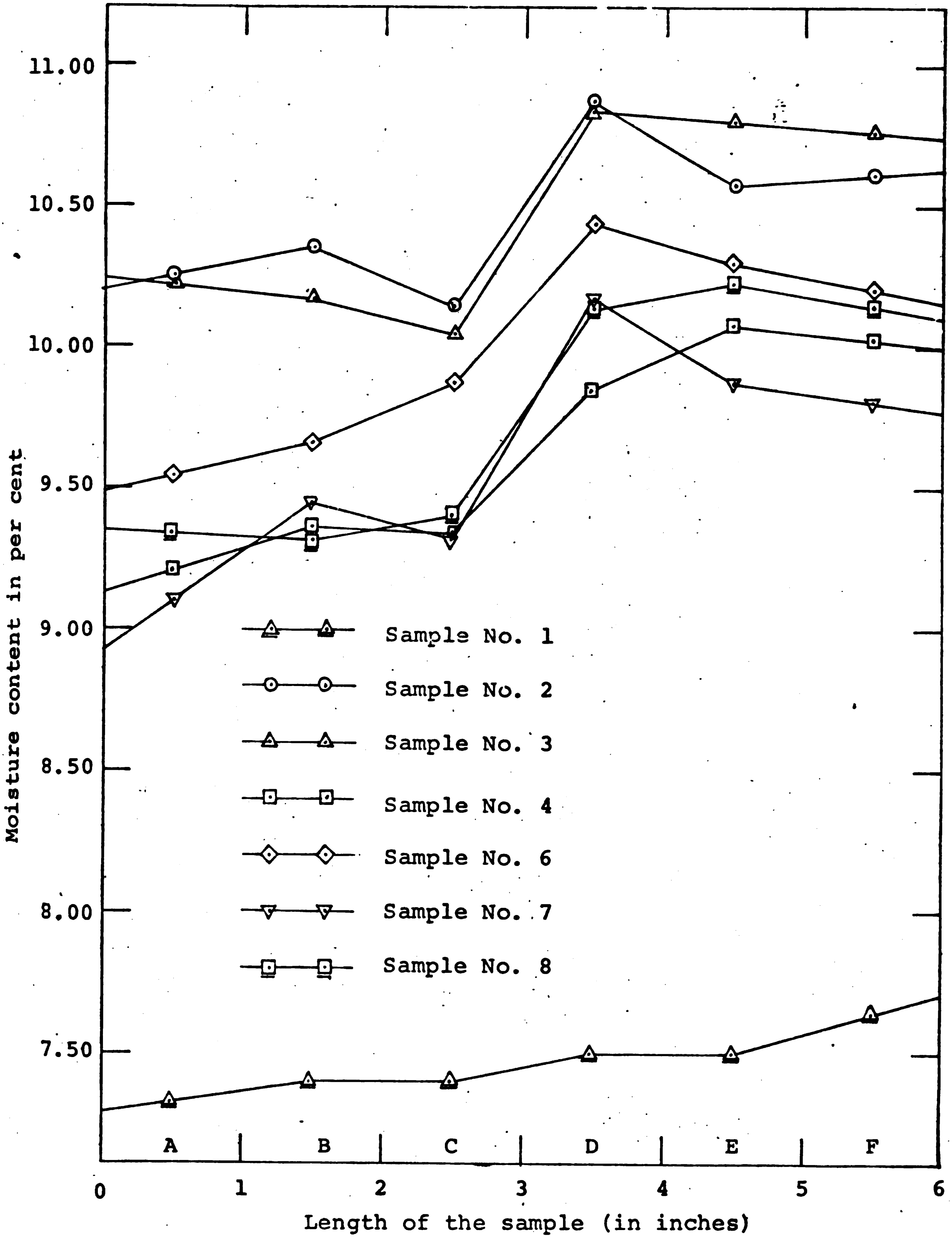

Fig. A-8. Moisture Content in Sandy Loam (Soil Number One) Samples 1, 2, 3, 4, 6, 7, and 8 from Table A-4.

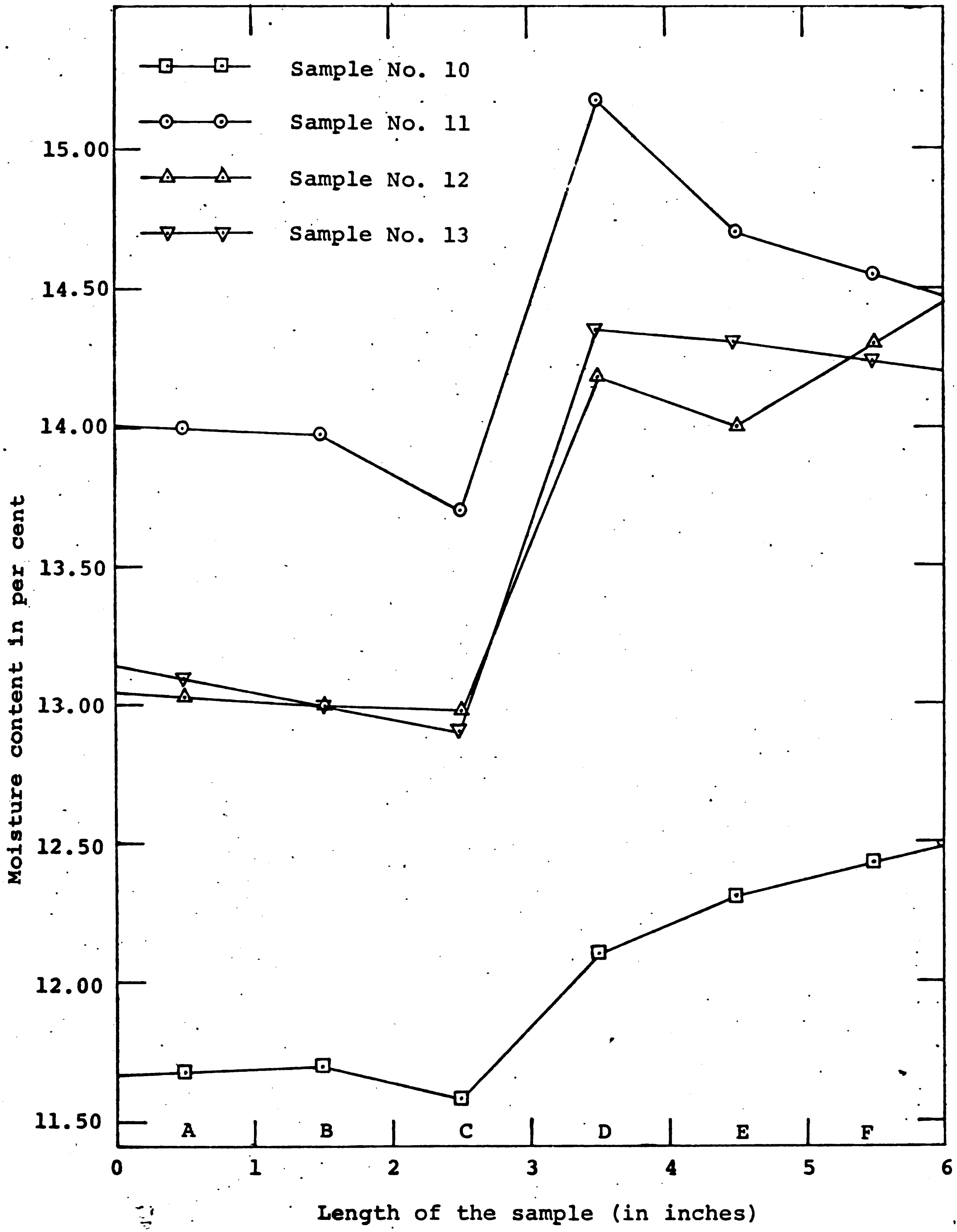

Fig. A-9. Moisture Content in Sandy Loam (Soil Number One) Samples 10, 11, 12, and 13 from Table A-4.

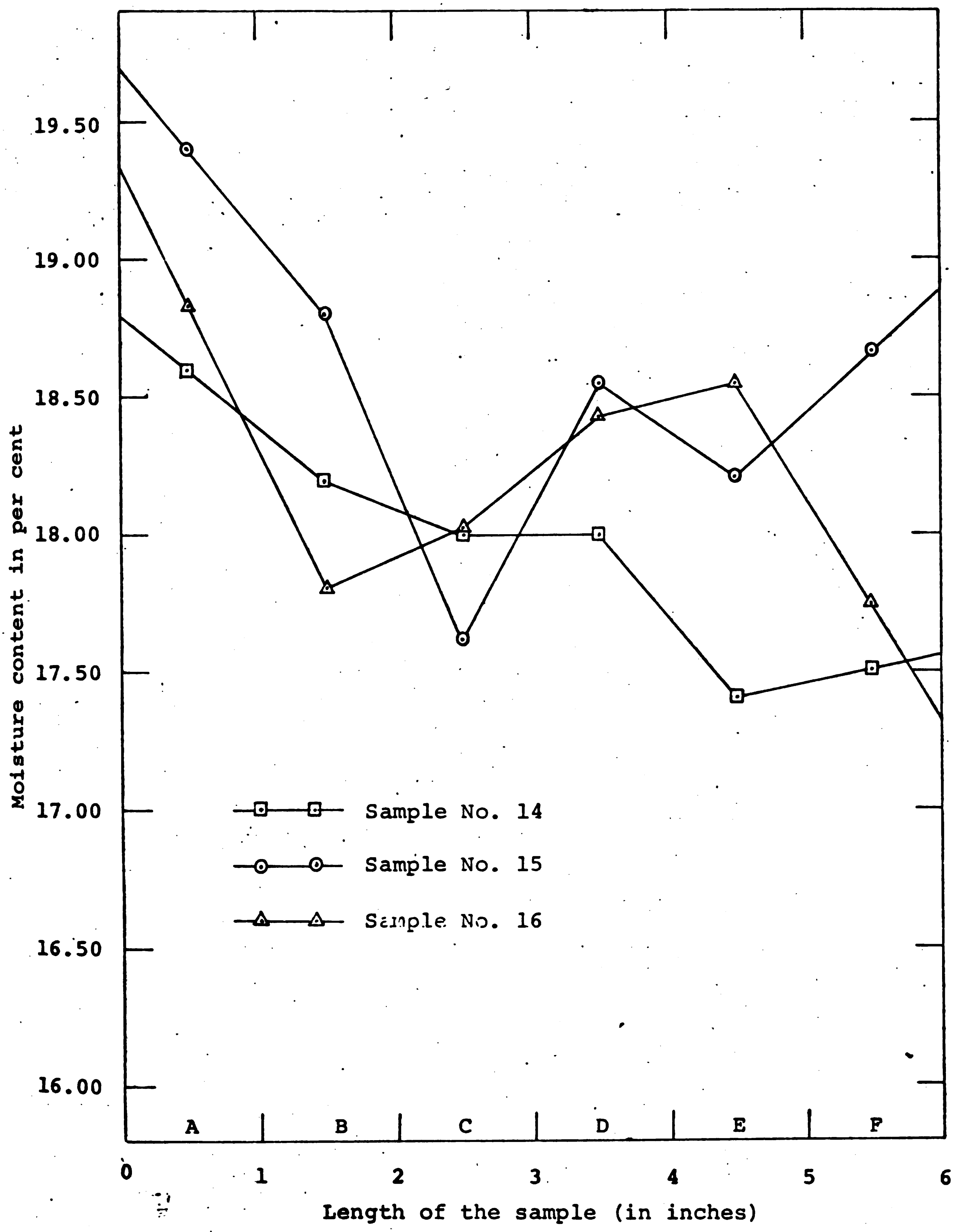

Fig. A-10. Moisture Content in Sandy Loam (Soil Number One) Samples 14, 15, and 16 from Table A-4.

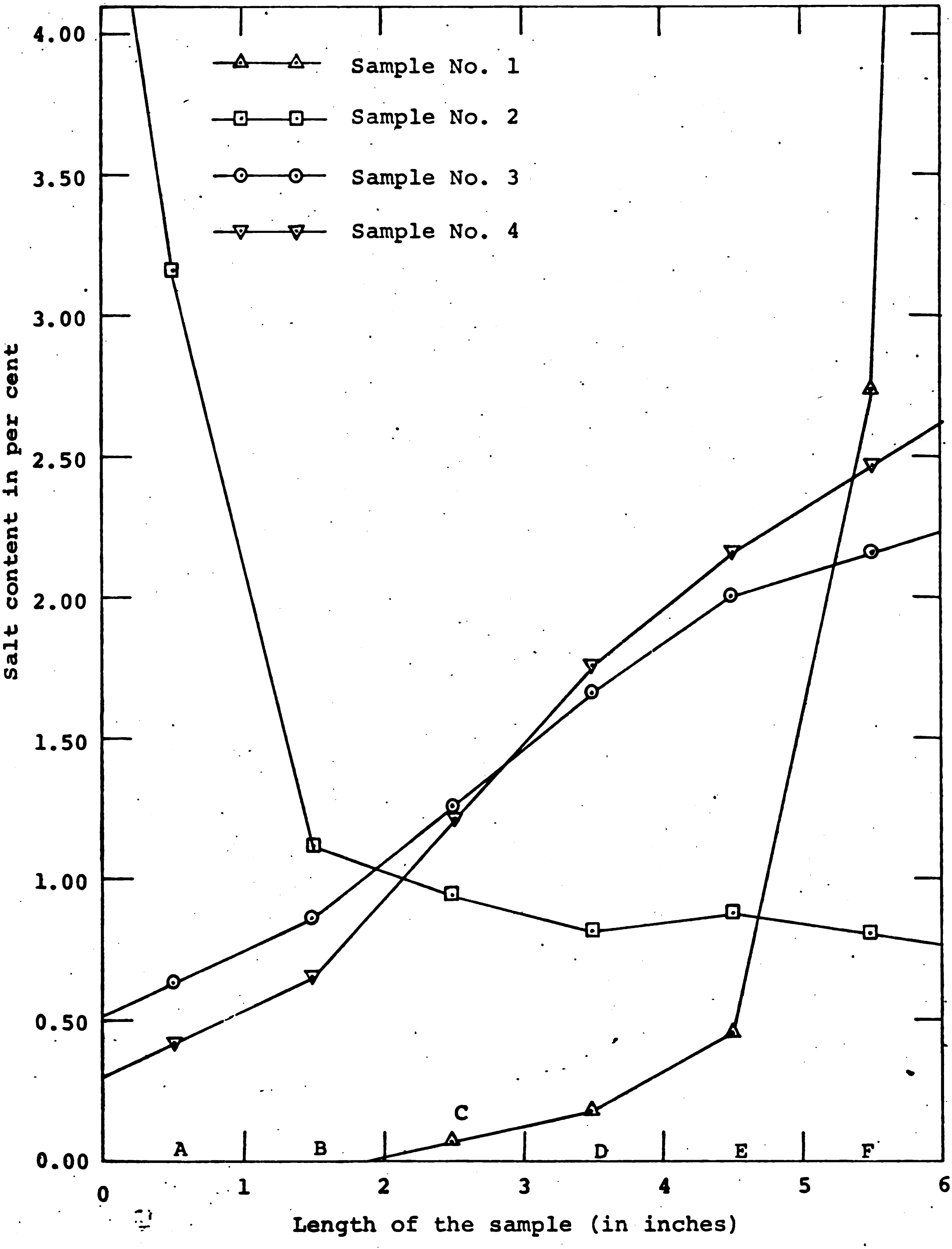

Fig. A-11. Salt Migration in Clay (Soil Number Three) Samples 1, 2, 3, and 4 from Table A-5.

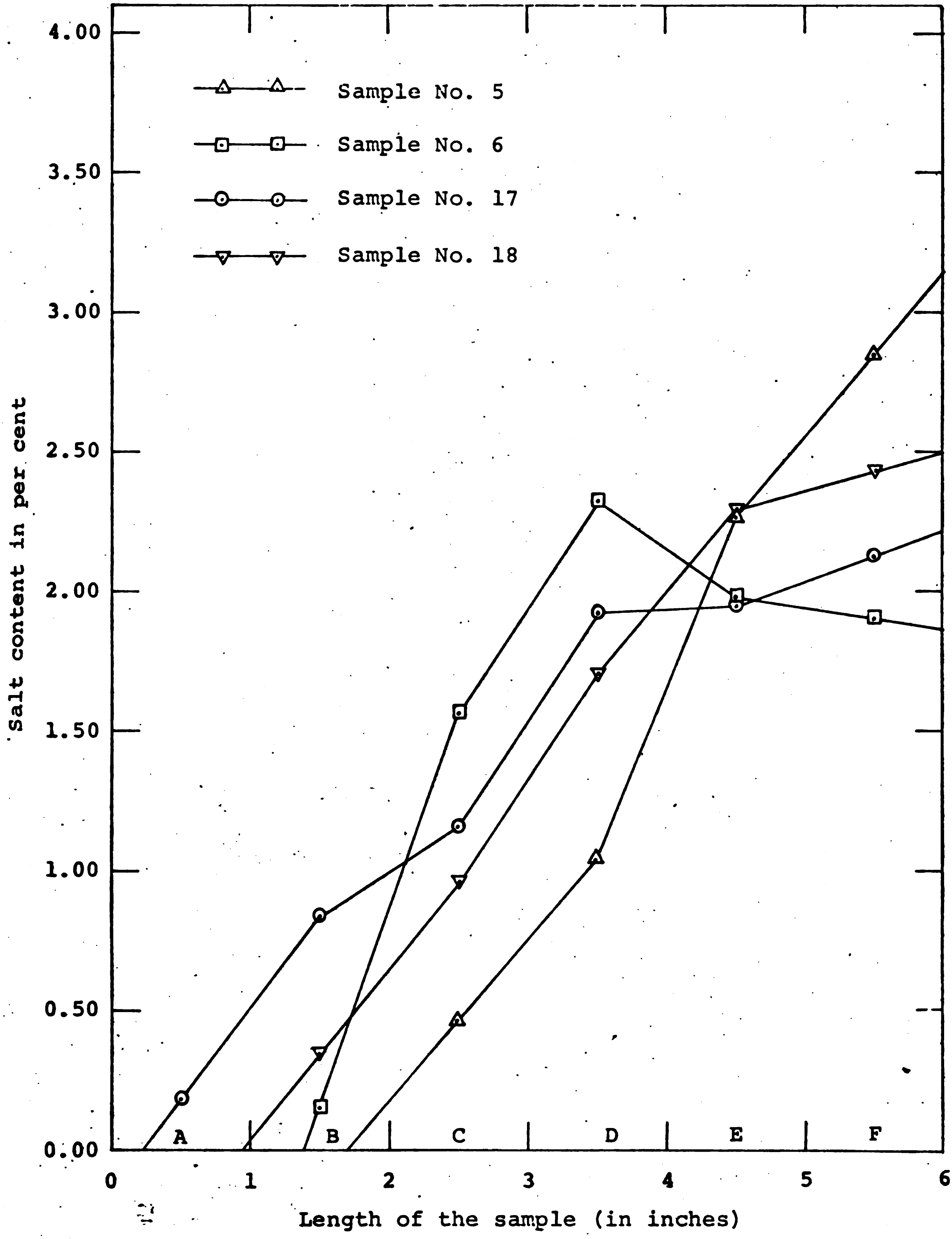

Fig. A-12. Salt Migration in Clay (Soil Number Three) Samples 5, 6, 17, and 18 from Table A-5.

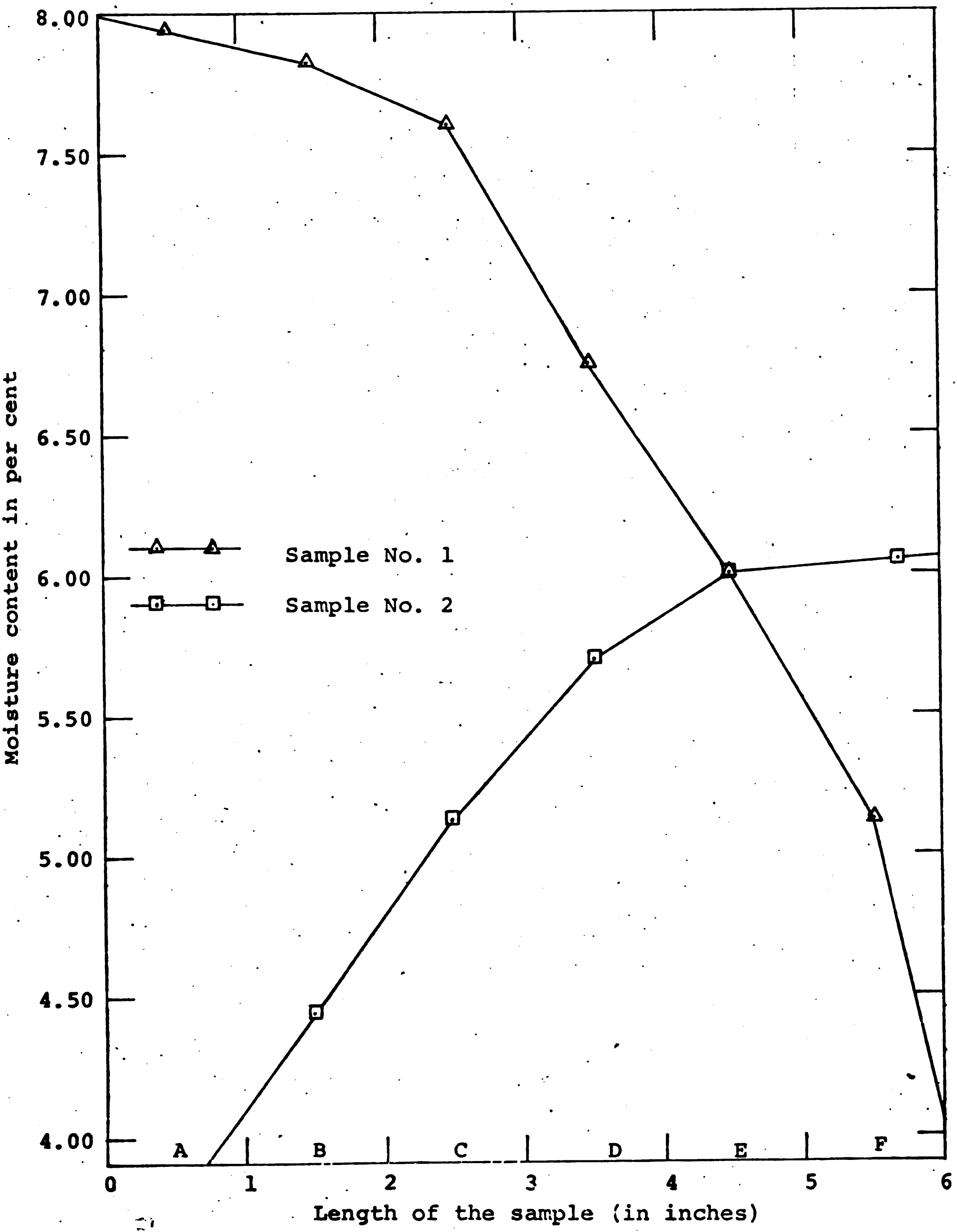

Fig. A-13. Moisture content in Clay (Soil Number Three) Samples 1 and 2 from Table A-6.

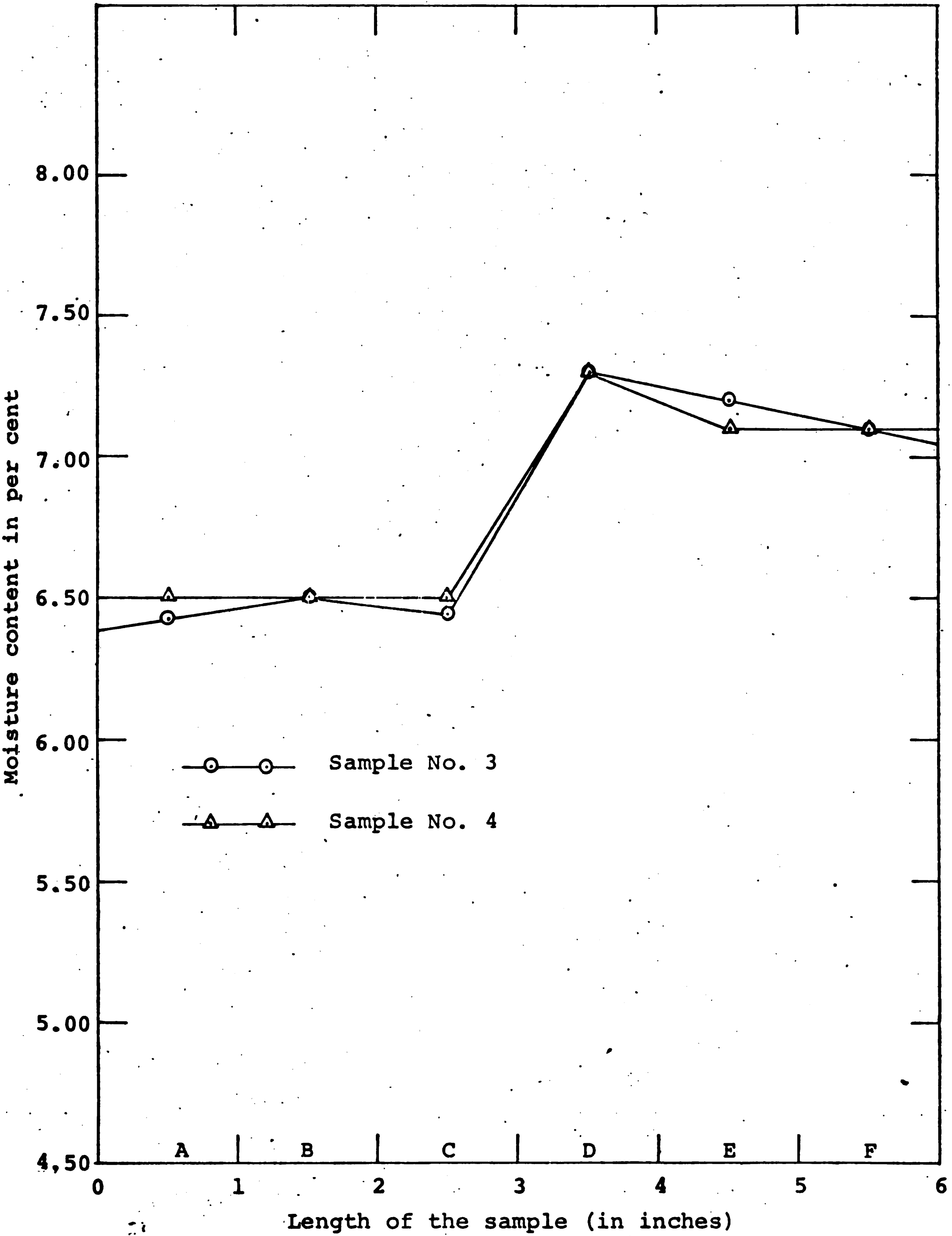

Fig. A-14. Moisture Content in Clay (Soil Number Three) Samples 3 and 4 from Table 6.

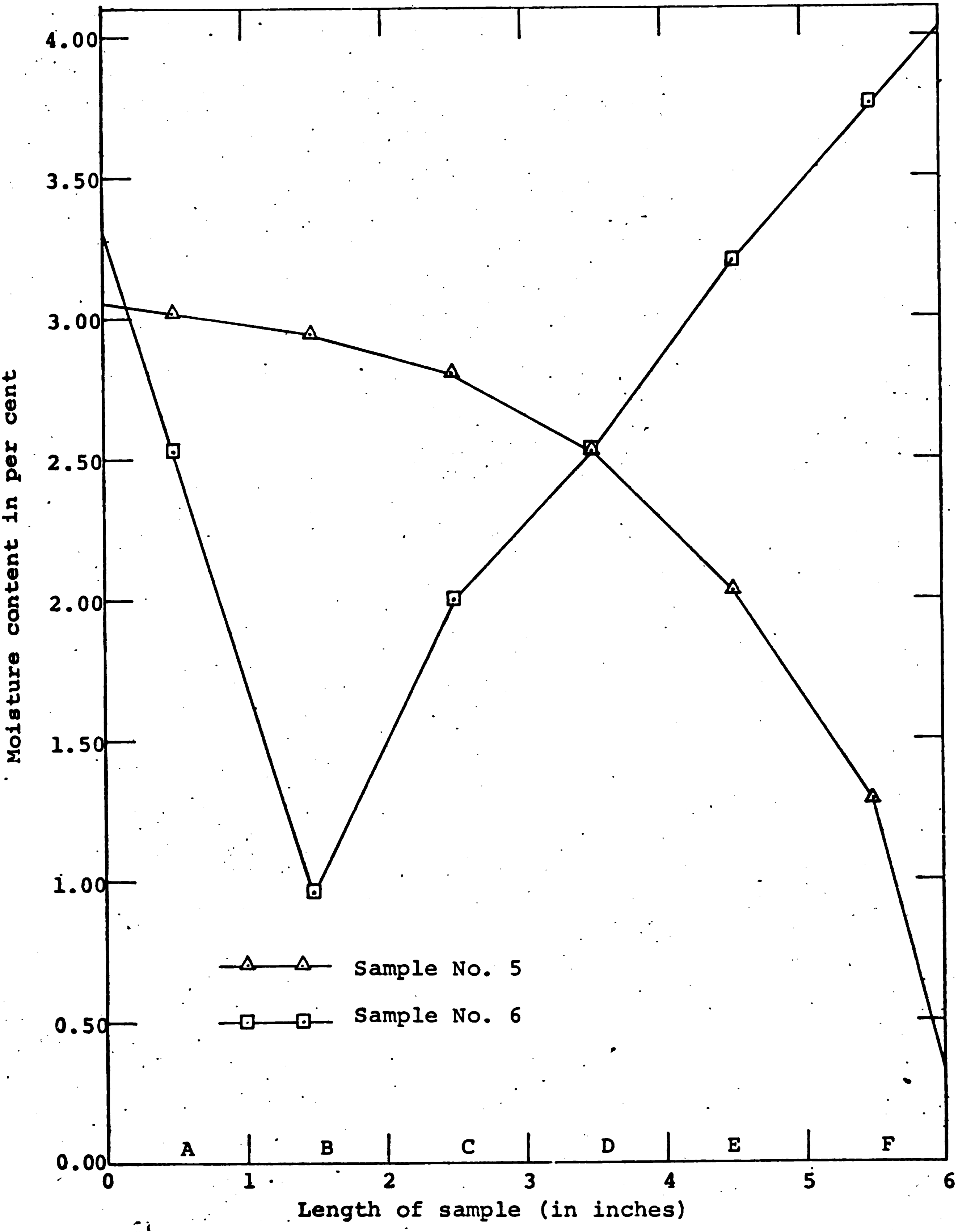

Fig. A-15. Moisture Content in Clay (Soil Number Three) Samples 5 and 6 from Table A-6.

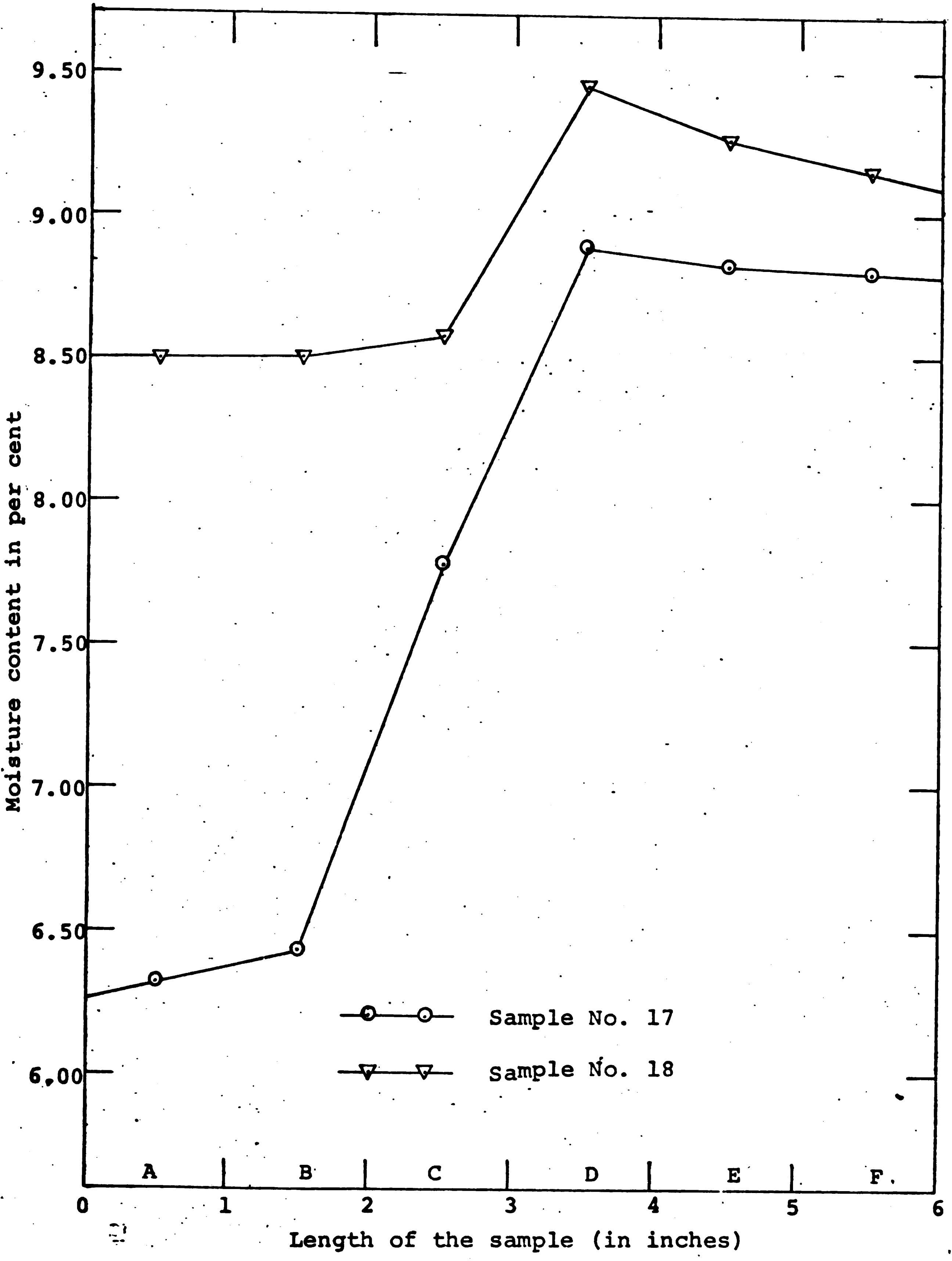

Fig. A-16. Moisture Content in Clay (Soil Number Three) Samples 17 and 18 from Table A-6.

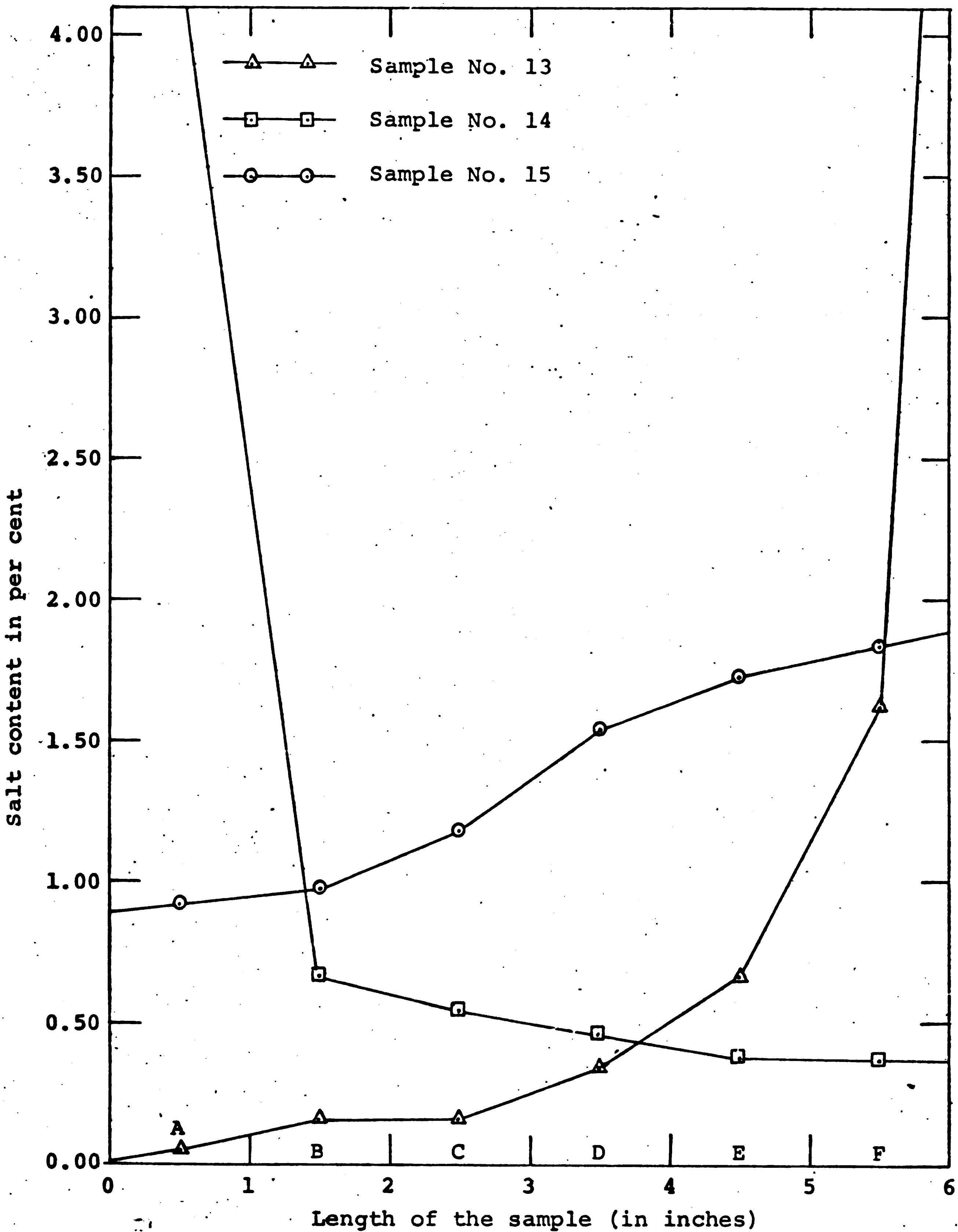

Fig. A-17. Salt Migration in Silty Loam (Soil Number Four) Samples 13, 14, and 15 from Table A-7.

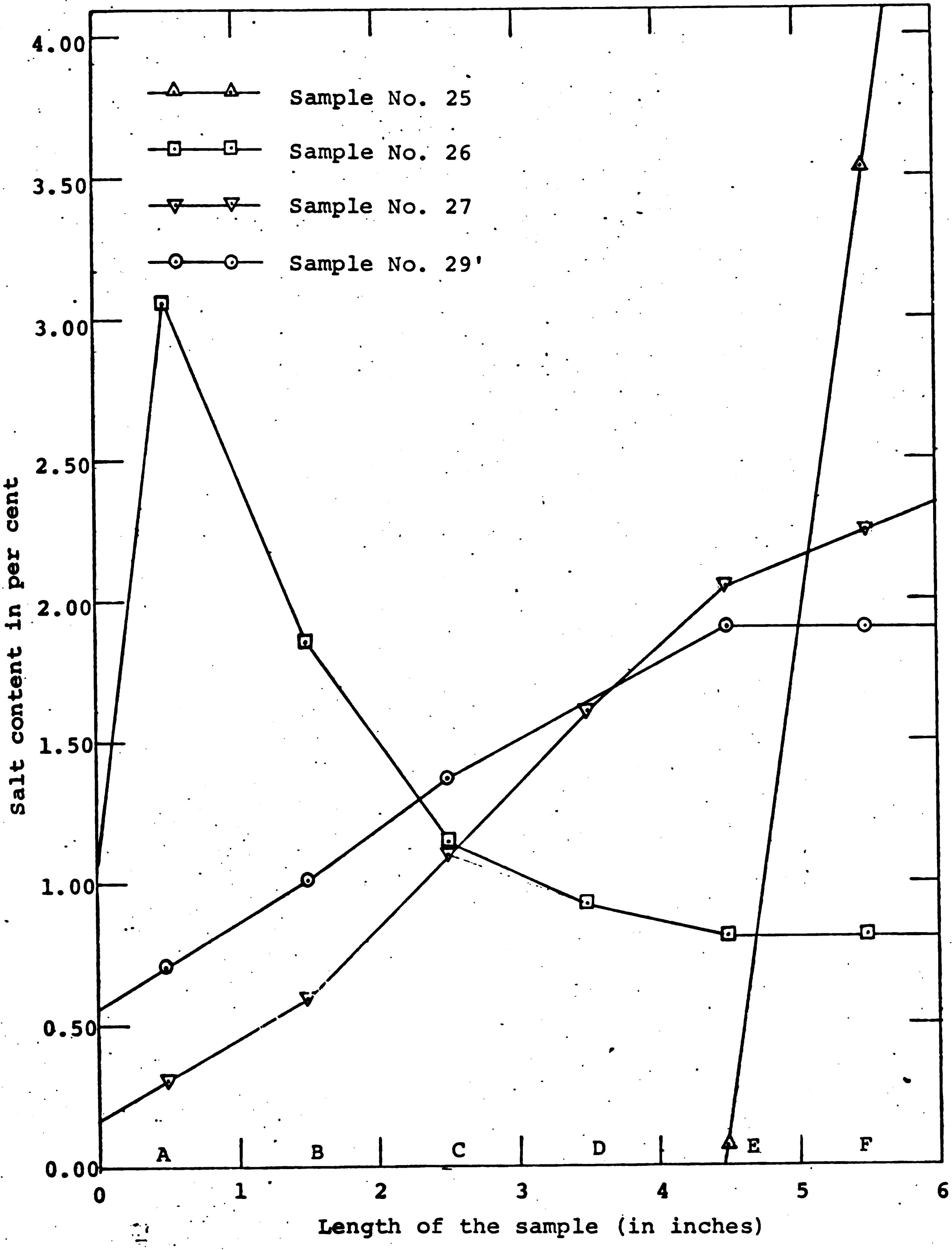

Fig. A-18. Salt Migration in Sand Samples 25, 26, 27 and 29' from Table A-7.

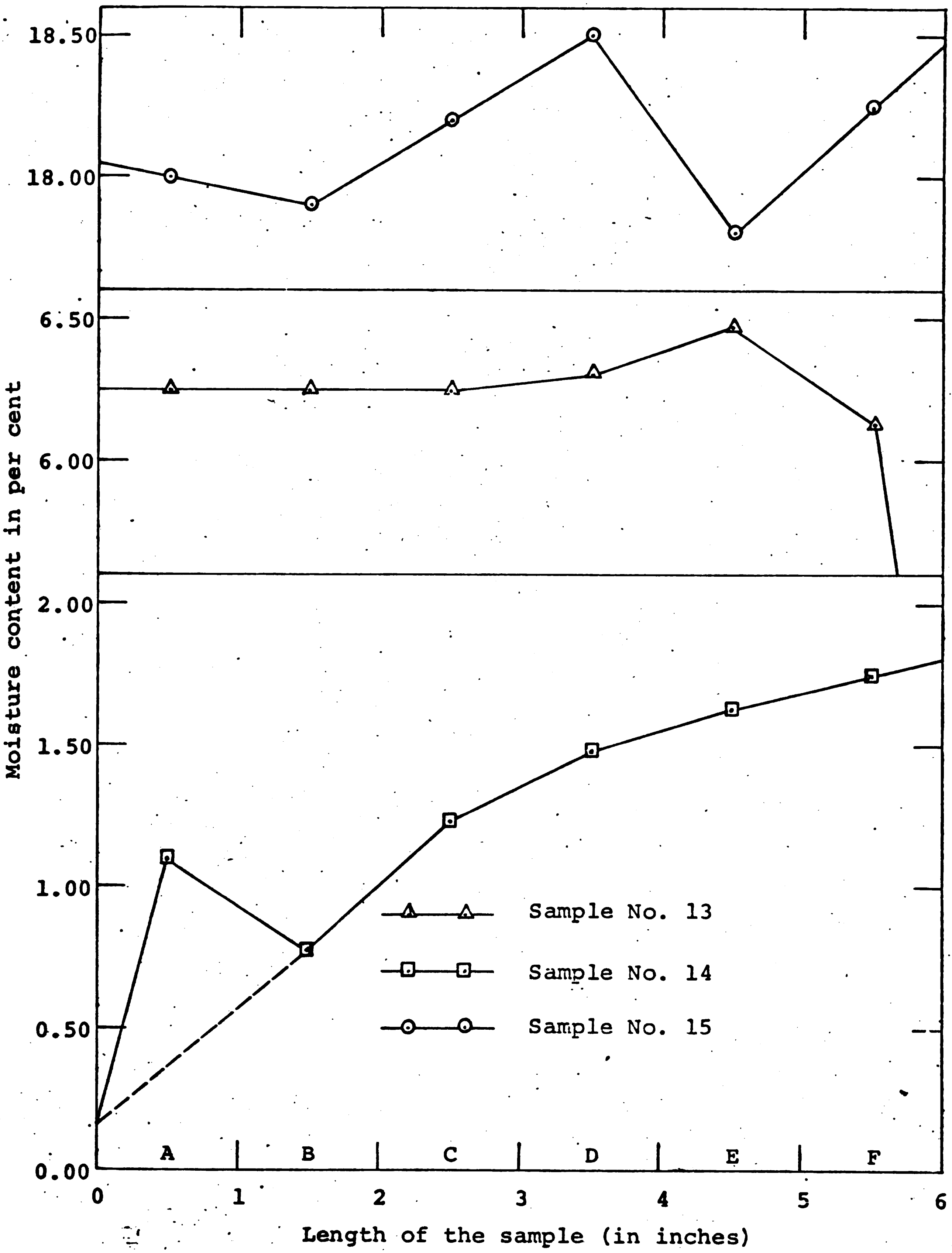

Fig. A-19. Moisture Content in Silty Loam (Soil Number Four) Samples 13, 14, and 15 from Table A-7.

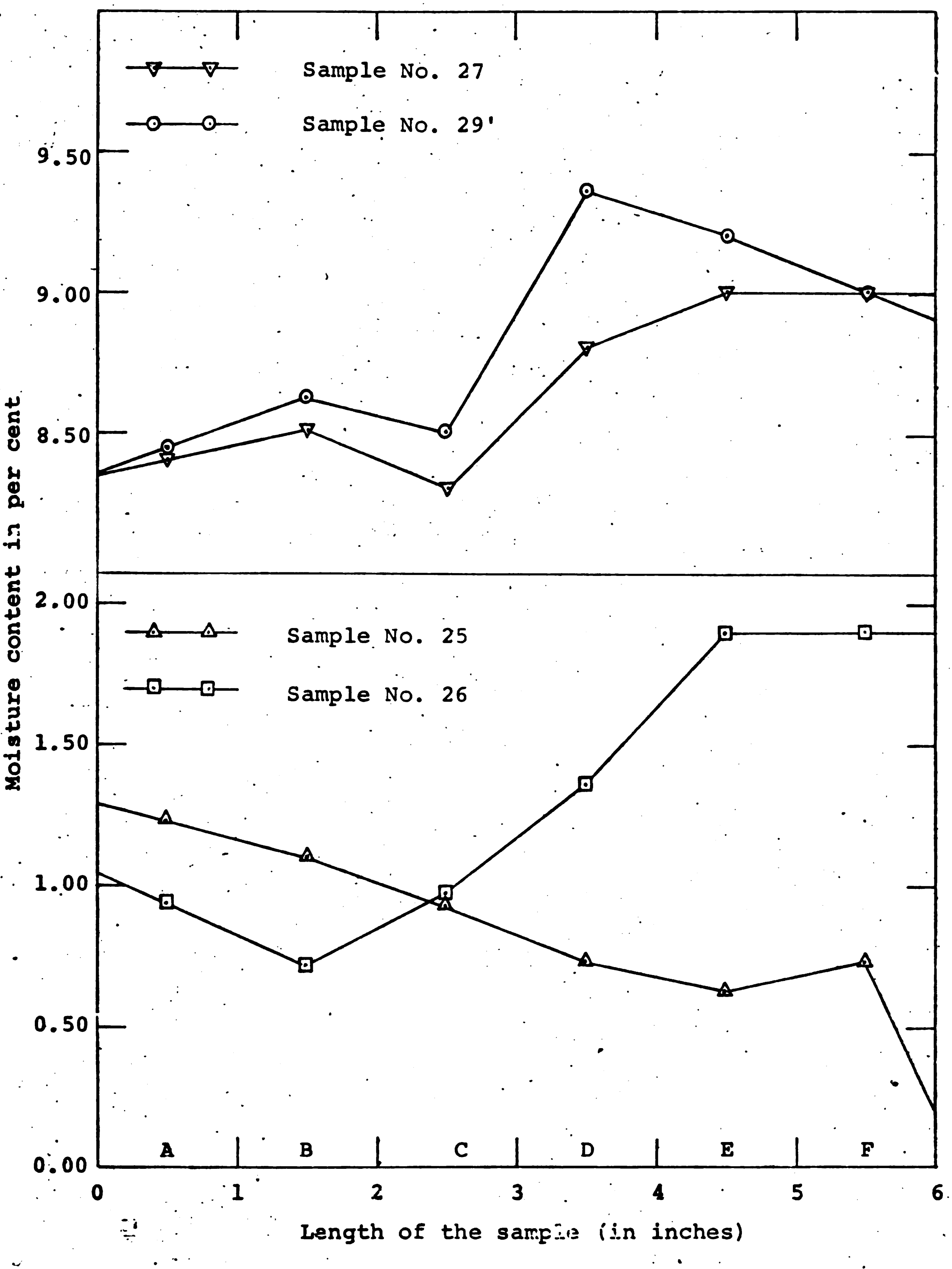

Fig. A-20. Moisture Content in Silty Loam (Soil Number Four) Samples 25, 26, 27, and 29' from Table A-8.

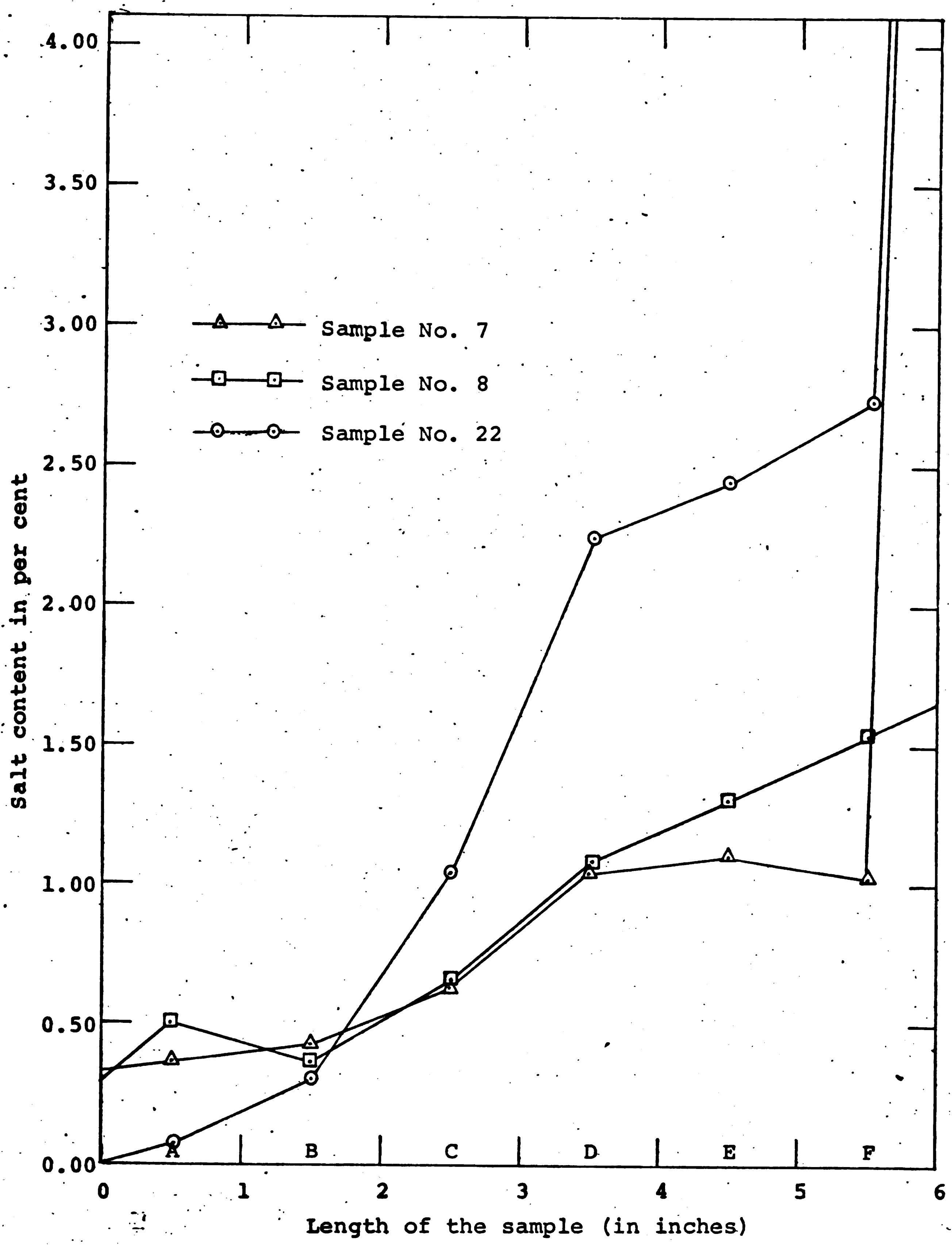

Figure A-21. Salt Migration in Partly Frozen Soils, Silty Loam (Soil Number Four) Sample 22 and Sand (Soil Number Two) Samples 7 and 8 from Table A-9.

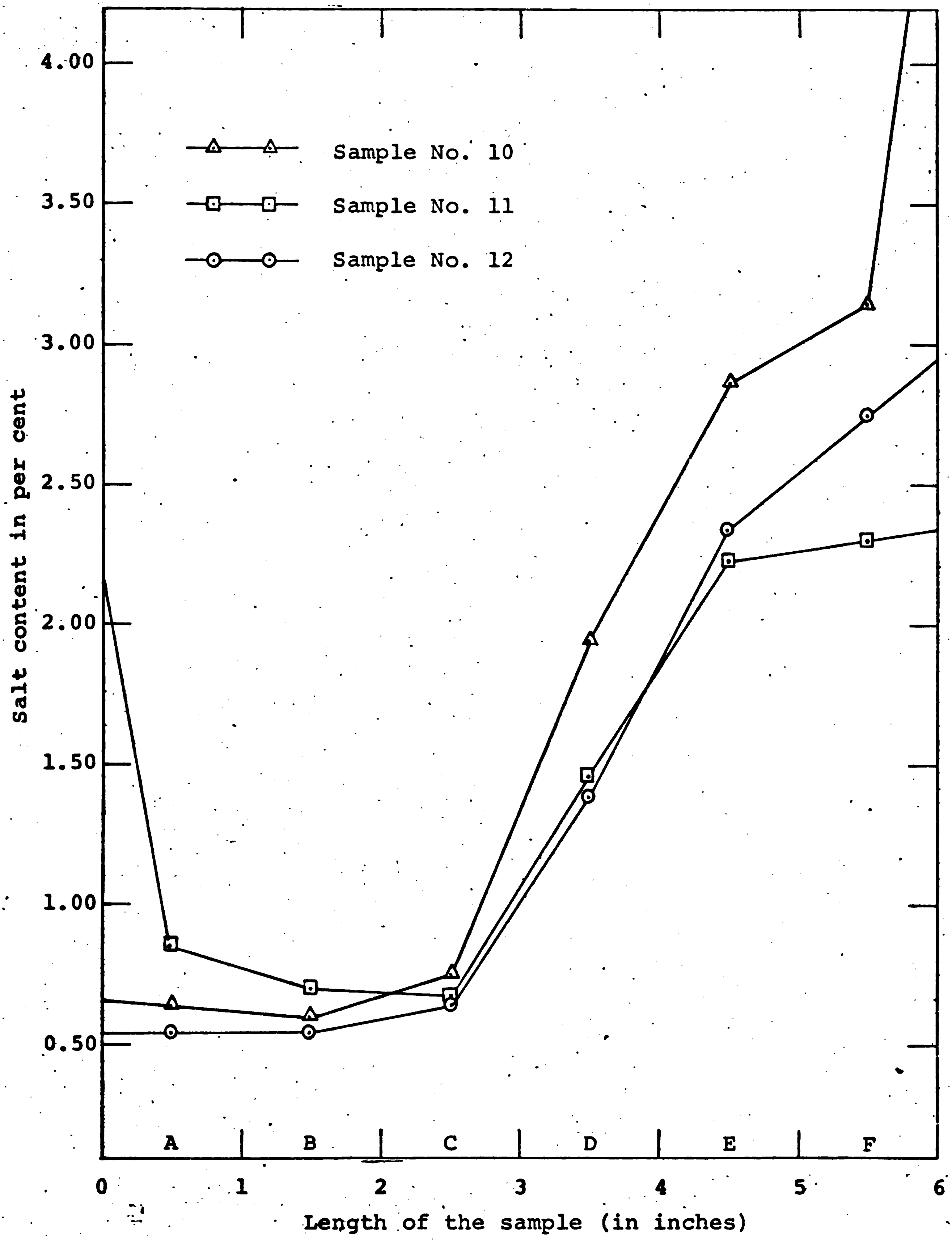

Fig. A-22. Salt Migration in Partly Frozen Sand Samples 10, 11, and 12 from Table A-9.

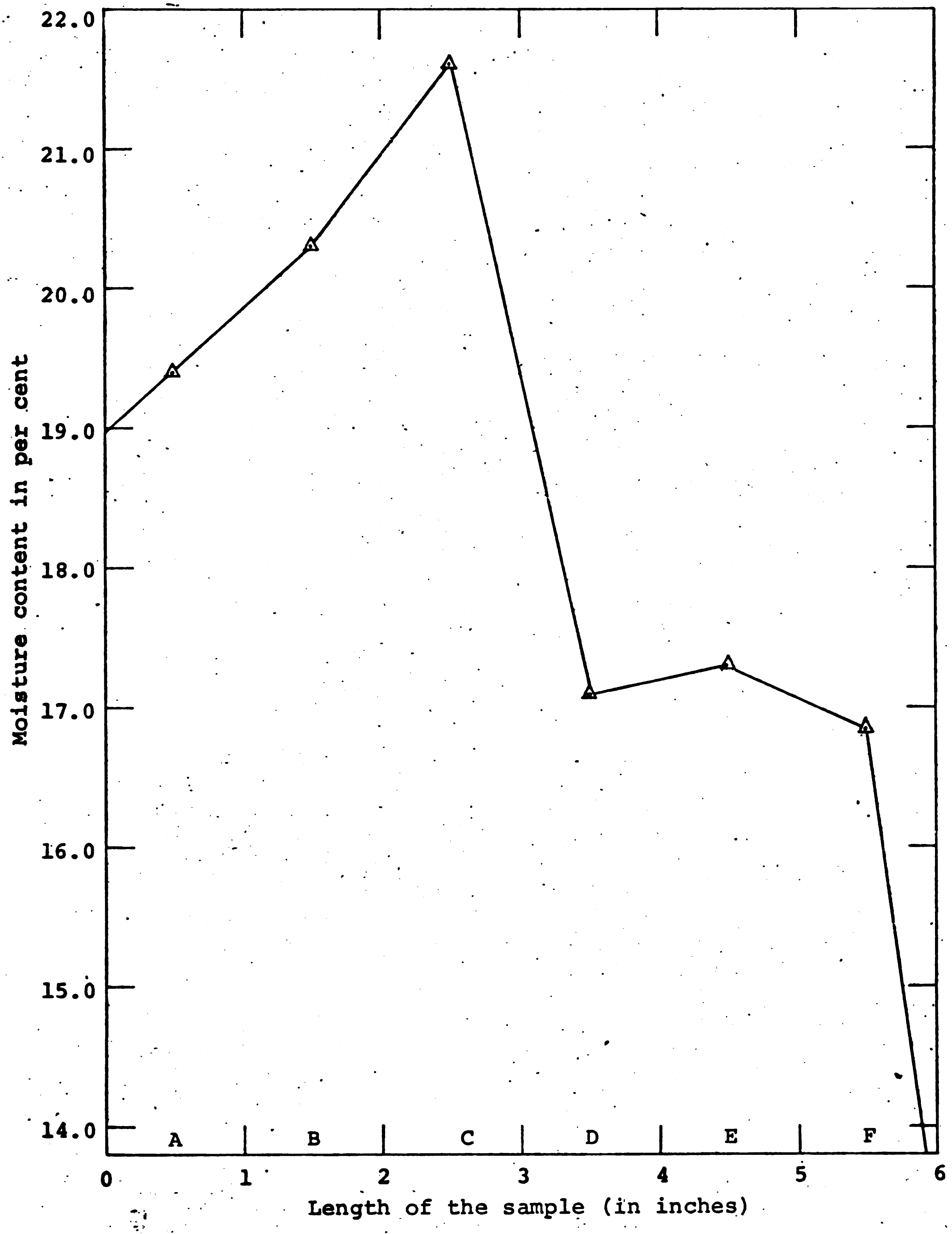

Figure A-23. Moisture Content in Partly Frozen Silty Loam Sample from Table A-10.

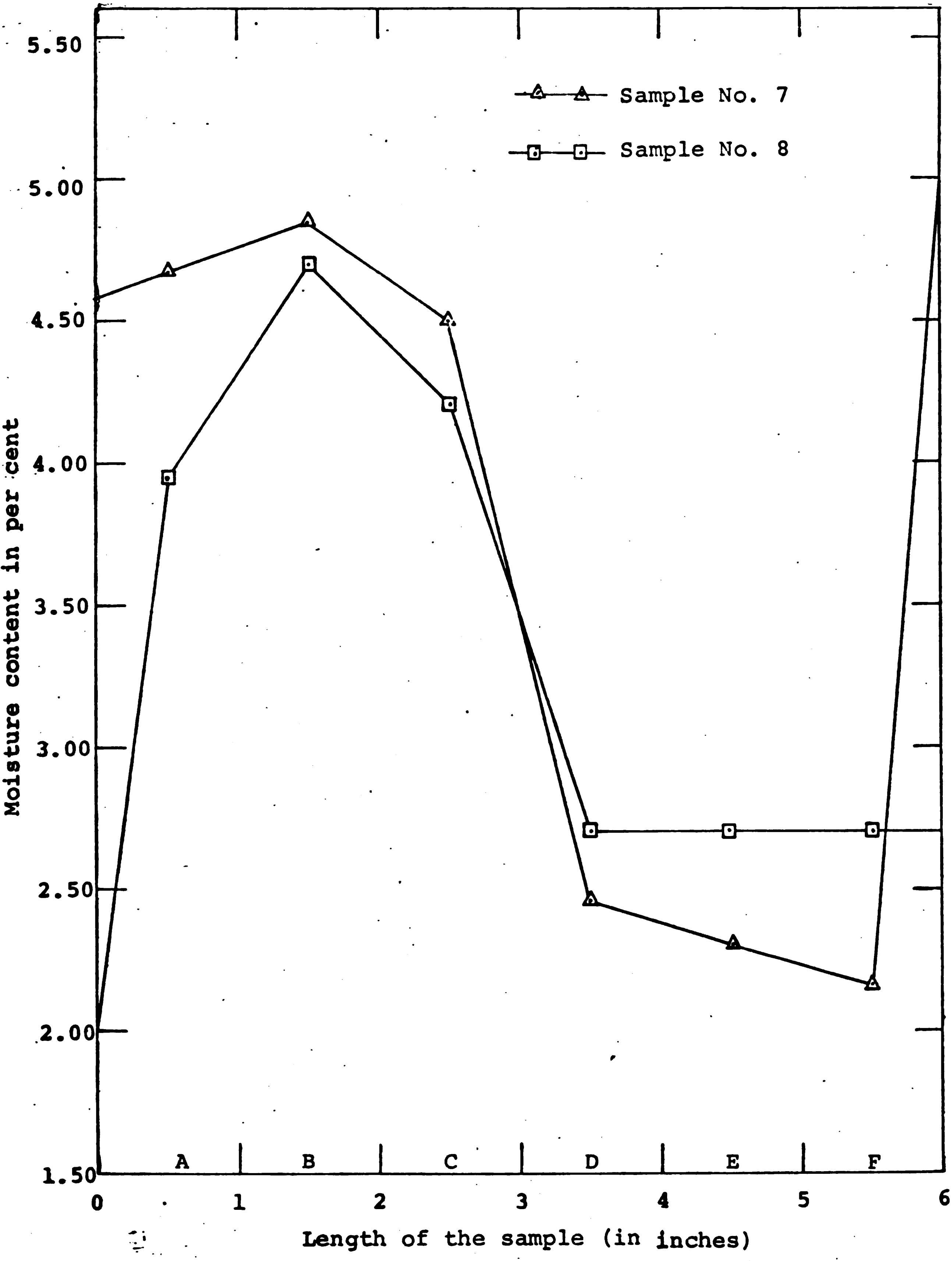

Fig. A-24. Moisture Content in Partly Frozen Sand Samples 7 and 8 from Table A-10.

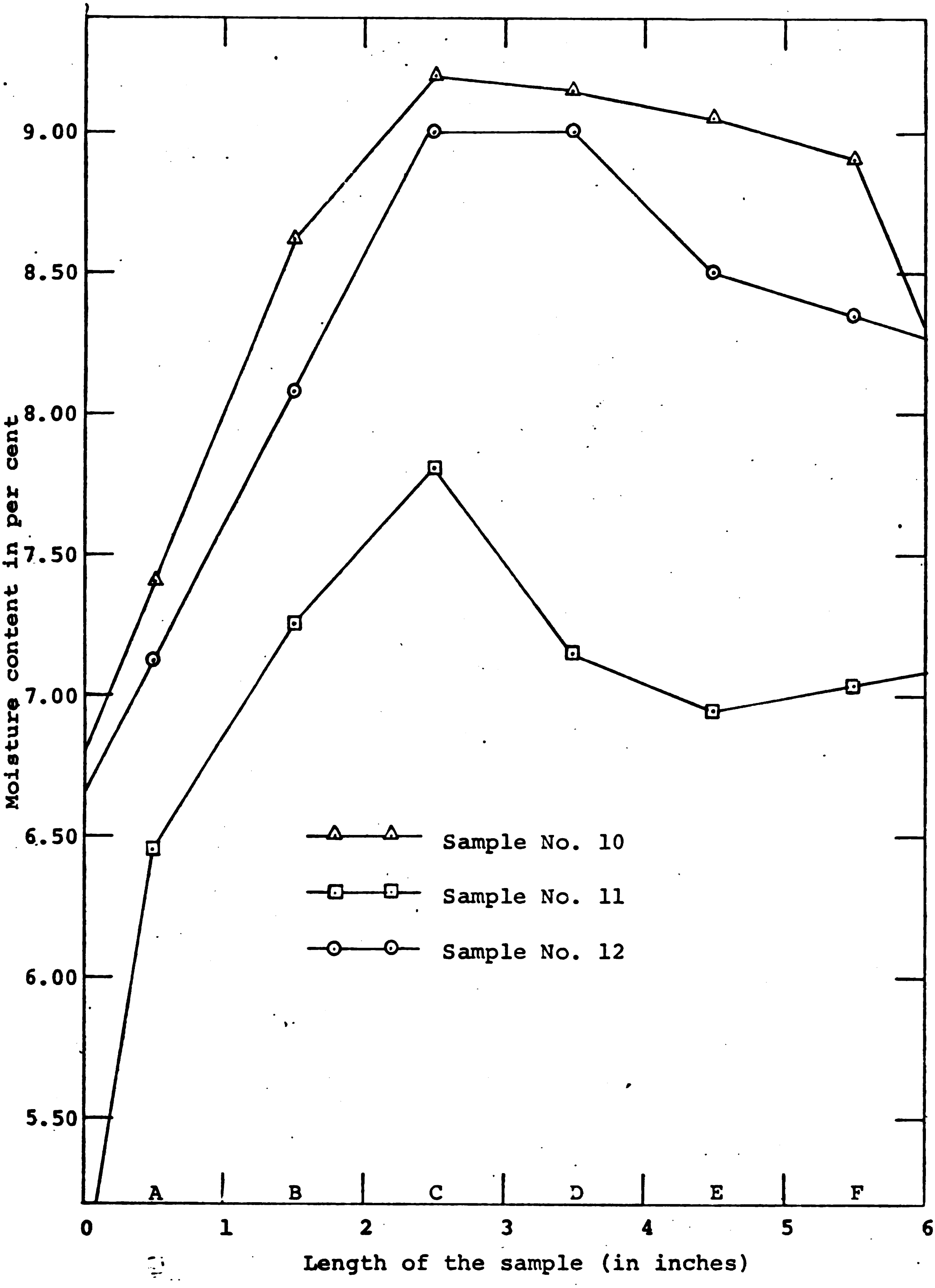

Fig. A-25. Moisture Content in Partly Frozen Sand Samples 10, 11, and 12 from Table A-10.