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**EVALUATION OF THE POTENTIAL USE OF LANGBEINITE ($K_2SO_4 \cdot 2MgSO_4$)
AS A RECLAIMING MATERIAL FOR SODIC AND SALINE SODIC SOILS**

By

HELUF GEBREKIDAN

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In the Graduate College

THE UNIVERSITY OF ARIZONA

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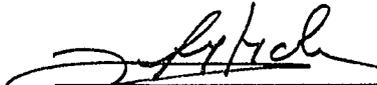
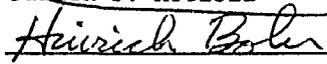
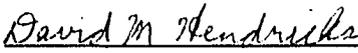
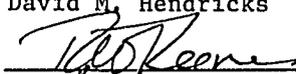
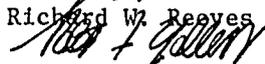
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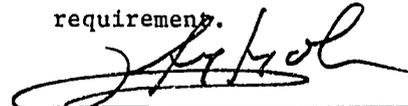
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ABSTRACT

Soil sodicity/salinity and scarcity of water are important constraints of agricultural development in arid lands. Excessive exchangeable sodium of sodic and saline sodic soils cause swelling of clays and dispersion of colloidal particles, and results in poor soil-water-air relationships. Reclaiming sodic and saline sodic soils involves the displacement of exchangeable sodium and its subsequent leaching from the root zone. This further depends upon the choice of chemical or cation to exchange for sodium and the quality and availability of water for leaching.

Therefore, a series of experiments including soil characterization, laboratory batch studies, column leaching studies and greenhouse crop response studies were conducted to evaluate the potential use of langbeinite as a reclaiming material for saline sodic soil. Both the Grabe clay loam and the Guest clay soils met the requirements of a saline sodic soil category. The Grabe clay loam was more strongly saline sodic than the Guest clay soil, and was therefore used in the subsequent studies. In the batch studies involving a 1:1 soil:water extracts, langbeinite proved to be more efficient than gypsum in replacing exchangeable Na especially at higher levels of applied amendments.

In the column studies, the amount of exchangeable Na displaced due to gypsum and langbeinite was the same when high amount (4 pore volumes) of water was used for leaching. However, langbeinite removed considerably higher amounts of sodium than gypsum with the use of lower volumes of leaching water. Accordingly, savings of over 9 acre-inch of irrigation water per acre of reclaimed land can be realized by using langbeinite over gypsum to lower the ESP of the soil to about 10% when both

amendments are applied at a rate of 12 tons/ha. The hydraulic conductivity (HC) of the soil increased significantly due to application of both gypsum and langbeinite and decreased due to leaching with increasing pore volumes of water. Although steady state HC was not attained with the use of gypsum, the HC of the soil treated with gypsum was higher than the langbeinite treated soil after leaching with 4 pore volumes of water.

Similarly, seed germination and dry matter yield of lima bean plants responded to the application of gypsum and langbeinite and leaching both with Safford irrigation water and Tucson tap water. Such responses both to the amendments and volumes of leaching water were of a higher magnitude with langbeinite than with gypsum.

CHAPTER 1

INTRODUCTION

The challenge to agricultural scientists and farmers today is how and where to produce enough food crop to feed the rapidly growing world population. Apparently, substantial improvement in such an agricultural production must come from higher yields on lands already under cultivation and/or from lands now uncultivated and considered marginal. Leading soil scientists and crop science specialists of the world agree that the arid and semiarid lands of the earth have high potential for multiple cropping.

It follows, therefore, that these arid and semiarid regions of the planet offer considerable promise for development as major food producing regions. Many of the inhospitable deserts of such regions require only irrigation water for conversion to viable agricultural lands. This has been demonstrated in Australia, Southwestern United States, Soviet Union, China, Mexico, and throughout the Mediterranean areas (Bresler et al., 1982). Israel may be considered a pioneer in research, development, and efficient utilization of irrigation water resources and arid lands for agricultural purposes.

An edaphological problem commonly encountered with developing arid and semiarid lands is the accumulation of either soluble salts, or exchangeable sodium, or both in the soil in excessive concentrations. These soils are collectively referred as salt affected soils. Based on their chemical properties mainly electrical conductivity of saturation extracts (EC_e), exchangeable sodium percentage (ESP) and pH, salt affected soils are classified as saline, saline sodic (or saline alkali) and sodic (or alkali) soils (U. S. Salinity Laboratory Staff, 1954; Abrol et al., 1975; Bresler et al., 1982).

Saline soils contain excessive amounts of soluble salts ($EC_e > 4\text{mmhos/cm}$) and have ESP values less than 15 and pH less than 8.5. Sodic soils are characterized by excessive contents of exchangeable sodium ($ESP > 15$), EC_e less than 4mmhos/cm and a pH value often greater than 8.5. Saline sodic soils contain excessive concentrations of soluble salts ($EC_e > 4\text{mmhos/cm}$) and high levels of exchangeable sodium ($ESP > 15$) and a pH value seldom greater than 8.5 (U.S. Salinity Laboratory Staff, 1954; Abrol et al., 1975; Abrol et al., 1978; James et al., 1982; Bresler et al., 1982).

Another constraint of agricultural development in arid and semiarid region lands is inadequacy or absence of irrigation water resources. Moreover, most of the irrigation water, particularly the ground water resources available in these areas contain high levels of total dissolved salts (TDS) and high values of sodium adsorption ratios (SAR). The concentrations of soluble salts and exchangeable sodium in saline sodic and sodic soils and irrigation waters are high enough to impose a stress on crop plants and lead to decreased yields, or complete crop failure in severe cases.

Weathering of rocks and primary minerals, residual or fossil salts of former marine or lacustrine environments and the atmosphere are the main sources of soluble salts and exchangeable sodium in salt affected soils and waters (Bresler et al., 1982; Bohn et al., 1985; Stroehlein and Pennington, 1986). From whichever source it comes, the physical and chemical weathering of rocks and minerals is the ultimate source of all soluble salts and sodium in soils. However, the rate of their release and excessive accumulation in situ from this source alone is low compared with their removal by water. Thus, the adverse processes of salinization and alkalization of soils are the results of

redistribution of salts and sodium by the action of surface and ground waters, often as a result of man's activities. Soil physical properties, climate, topography and biological activities other than that of man are additional factors causing soil salinity and sodicity.

It is apparent that salt affected soils occur for the most part in the arid and semiarid regions of the earth. The insufficient annual rainfall to leach down soluble salt constituents from the root zone of the soil favor their development in these regions (U.S. Salinity Laboratory Staff, 1954; Bohn et al., 1985). Geographically, salt affected soils are widely spread throughout the various continents of the world which have a continental or arid climate and where, therefore, evapotranspiration exceeds precipitation either permanently or for some time of the year (Kovda, 1965). Accordingly, they are found in cold (permafrost), temperate, subtropical, and tropical belts, that is, all the way from the subarctic to the equator and far south of it. Gupta and Abrol (1990) estimated that salt affected soils occupy, on a global basis, 952.2 million hectares (ha) of land. These constitute nearly 7% of the total land area or nearly 33% of the potential agricultural land area of the world.

Once developed, sodic and saline sodic soils are agriculturally problematic soils. Physical and chemical properties of sodic soils such as stability of aggregates, soil structure, permeability (hydraulic conductivity and infiltration), aeration, and nutrient solubility and availability to plants are adversely affected by the presence of high levels of exchangeable sodium (Abrol et al., 1975; Abrol et al., 1978; Carter and Webster, 1979; Carpenter et al., 1979; Park and O'Connor, 1980; James et al., 1982; Bresler et al., 1982; Keren and O'Connor, 1982; Sandhu et al., 1982; Stroehlein and Pennington,

1986; Gupta and Abrol, 1988; Bajwa and Josan, 1989; Armstrong and Tanton, 1992; Dubey and Mondal, 1993; Ilyas et al., 1993; Ghassemi et al., 1995). Swelling and dispersion of soil colloidal particles, and their migration resulting in plugging of soil pores, have been suggested as possible mechanisms for the reduced hydraulic conductivity and infiltration rates of sodic soils (McNeal et al., 1966; Shainberg et al., 1971; Frenkel et al., 1978; Pupisky and Shainberg, 1979; Park and O'Connor, 1980; Bohn et al., 1985; Armstrong and Tanton, 1992; Dubey and Mondal, 1993; Ilyas et al., 1993; Ghassemi et al., 1995).

When soluble salts occur in excess in a given soil, as with saline and saline sodic soils, they limit the availability of water to plants by increasing the osmotic potential or reducing the water potential of the soil solution (Stroehlein and Pennington, 1986). Moreover, soluble salts increase the concentration of certain ions that have a characteristic toxic effects on plant metabolism (James et al., 1982; Bohn et al., 1985). These effects, coupled with the problems associated with soil physical properties, require plants in sodic and saline sodic soils to grow in a particularly delicate balance with their environment. As a result, crop production in such soils when grown without reclamation, leaching and proper drainage, is gradually reduced to a level where the land is abandoned for agricultural use.

Accordingly, there are hundreds of millions of ha of land worldwide that are at present not used for agricultural purposes. Many of these lands could be of great value if salinity and sodicity could be controlled or minimized. In USA, salinity and sodicity have significantly reduced the productivity of over one-fourth of the lands under

irrigation and prevented the farming of additional areas of its dry land regions (Ghassemi et al., 1995). An estimated 5 million ha of irrigated lands are known to be salt affected in the USA, mostly in the 17 western states (Bohn et al. 1985). These represent only 27% of the total area of salt affected lands in the whole nation (Ghassemi et al., 1995).

Excessive exchangeable sodium (soil sodicity) alone has limited crop production in nearly 2.5 million ha of lands in the Indo-Gangetic Plains of India (Abrol and Bhumbla, 1979). Over 50% of the lower Rafidian Plain of Iraq (Kadry, 1969) and about 30% of the Peruvian Coastal Zone lands under cultivation (Zavaleta, 1965) are severely affected by salinity and sodicity with large areas going out of cultivation every year. In Ethiopia, about 200 ha of lands of the limited areas of irrigated lands in the Rift Valley System are abandoned for agricultural crop production every year due to sodicity and associated land drainage problems (Heluf, 1987). The total land area affected by salinity and sodicity in Ethiopia is estimated at 11 million ha (Szabolcs, 1989).

Reclamation of sodic and saline sodic soils can be accomplished in many ways, best dictated by local conditions, available resources and time, and the kinds of crops to be grown on the reclaimed soils (Gupta and Abrol, 1990). High crop yield per unit area can still be obtained on these lands with the use of appropriate technologies. However, the cost of production per unit area of land is increased leading to an overall decrease of land productivity. For example, about 70,000 tons of gypsum were used to reclaim saline sodic soils in the State of Arizona during the 1989 season (ACAH-OSC, 1990). With a general tendency of increasing total area of salt affected soils, the use of chemical amendments is expected to grow in Arizona as it is around the world.

The increasing demand for food and raw materials necessitates the reclamation of salt affected soils and the development of a system for their optimal utilization. By doing so economic crop yields can be obtained from such lands already under cultivation, and currently uncultivated marginal lands can be turned to viable agricultural lands. Such a reclamation will provide a unique opportunity not only for increasing total bioproduction but also for alleviating pressure on currently cultivated lands of humid regions. The concern of the series of experiments whose results are reported in this dissertation paper is the reclamation of sodic and/or saline sodic soils using langbeinite ($K_2SO_4 \cdot 2MgSO_4$) as a chemical amendment and compare its efficiency with gypsum ($CaSO_4 \cdot 2H_2O$); the most commonly used chemical amendment.

The sodicity problem of soils is of a more permanent nature and its reclamation is more challenging than the salinity problem because exchangeable sodium usually persists after the soluble salts are removed from the surface soil by leaching. As a result, reclaiming sodic and saline sodic soils requires the displacement of sodium present in the soil exchange site by the application of suitable chemical amendments, and the subsequent removal by leaching of the sodium that has become part of the soil solution. This process largely depends, therefore, on adequate supply of good quality leaching water, provision of adequate surface and subsurface drainage and availability of a suitable chemical amendment to exchange for adsorbed sodium.

Depending upon soil characteristics, mainly alkaline earth carbonate content and pH, the desired rate of displacement and economic considerations, various kinds of chemical amendments have been suggested and used to replace exchangeable sodium.

According to the U.S. Salinity Laboratory Staff (1954) and Gupta and Abrol (1990), the list of chemical amendments that may be used to reclaim saline sodic and sodic soils include soluble Ca-salts ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, CaCl_2), acids or acid formers (elemental sulfur, H_2SO_4 , $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$, CaS_5 , pyrites) and Ca-salts of low solubility including CaCO_3 , $\text{CaMg}(\text{CO}_3)_2$ and byproduct lime from sugar companies. Moreover, considerable research has been underway since the mid 1960s on the use of synthetic polymers as soil conditioners to improve aggregation and soil surface crusting of various kinds of soils, including sodic and saline sodic soils.

In reclaiming sodic soils, adsorbed sodium is the cation of concern that must be displaced from the exchange site and subsequently removed from the soil solution by leaching. Hence, a chemical amendment containing an appropriate source of cation to exchange with sodium must be applied to the soil. Since most of the soil exchange reactions are reversible (or otherwise the replaced sodium will increase the electrolyte concentration of the soil solution causing soil salinity), the exchanged sodium must be leached out from the root zone by applying a sufficient amount of good quality water.

In arid and semiarid regions where soil sodicity is prevalent, water is one of the most limiting resources. Therefore, the chemical carrying the replacing cation needs to be readily soluble in water in order to economize the use of this limiting resource and save enough for irrigation purposes. Moreover, the cation applied to displace adsorbed sodium is required to have a flocculating effect and thereby improve soil structure, surface crusting, hydraulic conductivity, infiltration rate and overall soil physical and chemical conditions.

Among the various chemicals, Ca applied in the form of gypsum has proved to be very good in effecting the displacement of exchangeable sodium and improving soil physical and chemical properties. Traditionally, gypsum is applied broadcast on the soil surface after the soil has been rough tilled and leveled. However, the water solubility of gypsum is very low, only 2.1 to 2.6 g/l (Oster and Frenkel, 1980; Hagstrom, 1986), and therefore requires multiple heavy applications of high quality water in order to dissolve, react with the exchange site and leach the displaced sodium salts from the root zone.

The U.S. Salinity Laboratory Staff (1954) recommends the use of 1.7 tons of gypsum per acre-foot of soil to displace 1 meq. of exchangeable sodium per 100g of soil. Considering the solubility of gypsum in water (about 2.4 g/l), 0.5 acre-foot of water will be required to dissolve 1.7 tons of gypsum (saturated condition). In practice, however, once the gypsum is spread (dry application), an acre-foot of applied water may dissolve as little as 250 lbs (1/8 of a ton) of gypsum (FCH,1988). This is due to varying grain and particle size and varying purities of gypsum materials that are used for reclamation purposes.

Because of its low solubility, gypsum moves only slowly in to the soil. Therefore, it should be mixed to the depth of the soil where replacement of exchangeable sodium is to be effected, which requires further saturating the entire depth of the soil. These factors make the reclamation of sodium affected soils very much water intensive and as well as time and energy consuming.

On the other hand, dissolving 1.7 tons of gypsum per acre-foot of water prior to application is impractical. Applications of 10-15 tons of gypsum per acre of land on

moderately saline sodic and/or sodic soils are not uncommon. Very high amounts (as high as 20 tons) of gypsum (FAO, 1989) or even as high as 30 tons (Abrol and Bhumbra, 1979) per acre of land are required for highly sodic soils and if rapid reclamation is needed. Based on the estimates provided by (FCH, 1988), such large tonnage of gypsum (20-30 tons/acre) requires therefore about 160 to 240 acre-foot of leaching water to reclaim an acre of land.

This thesis presents the results of a series of experiments conducted in an effort to introduce a new chemical amendment known as langbeinite ($K_2SO_4 \cdot 2MgSO_4$) for the reclamation of sodic and saline sodic soils. Langbeinite, also called Sul-Po-Mag by the International Minerals and Chemicals Corporation (IMC) or K-Mag by the Western Ag-Minerals Company, is a mineral (co-crystallized form) of two readily water soluble salts of sulfate: potassium sulfate and magnesium sulfate. Sul-Po-Mag or K-Mag is mined and processed by two USA companies (IMC and Western Ag-Minerals Company) near Carlsbad, New Mexico from the world's largest and purest deposits of langbeinite ore.

Langbeinite is an evaporite mineral and unlike gypsum; it is one of the highly water soluble salts found in the ocean (Hagstrom, 1986; IMC, 1990; western Ag-Minerals Company, 1995). Millions of years ago, part of what is now eastern New Mexico was a large, isolated lake. Langbeinite was one of the last minerals to be deposited as the water evaporated, and is now located 300 to 1,800m below the earth's surface in that area (Hagstrom, 1986). The fertilizer grade of langbeinite typically analyzes 22% K_2O (18.2% K^+), 18.5% MgO (11.1% Mg^{2+}) and 67% SO_4^{2-} (22% S) and is marketed as ideal fertilizer material for maintaining the proper balance between K and

Mg in soils and plants as well as sulfate (Hagstrom, 1986; IMC,1990; Mathews and Joost, 1990; Western Ag-Minerals Company, 1995).

Unlike many other fertilizer sources of magnesium, langbeinite is 100% water soluble. The solubility rate depends on its chemical nature and particle size. Refined and ground into various screen sizes, Sul-Po-Mag goes to work immediately upon application, provided there is enough soil moisture to support crop growth. Yet, its granular form dissolves slowly, so it resists rapid leaching loss from the soil by excessive moisture.

The water solubility of langbeinite is 280 g/l at 21°C (Hagstrom, 1986). Considering the water solubilities of gypsum (2.1 g/l) and langbeinite (280 g/l) reported by Hagstrom (1986), langbeinite is over 130 times more water soluble than gypsum. Hence, langbeinite could easily be applied along with the irrigation water either at low or very high rates for the purpose of reclaiming sodium affected soils. For instance, 1.7 tons of langbeinite can be dissolved in less than 1,500 gallons of water at 21°C. Therefore, one acre-inch (~2,500 gallons) of water could easily dissolve several tons of langbeinite. In theory, this would result in a more efficient exchangeable sodium displacement and leaching with significant water savings as compared to gypsum. Moreover, although conflicting results exist, there is general acceptance that the behavior of Mg in the soil exchange complex is more like Ca than the monovalent cations such as Na and K (Smith et al., 1949; U. S. Salinity Laboratory Staff, 1954; Ahmed et al. 1969; Thellier and Sposito, 1989).

The selectivity coefficient of Mg over Na is usually close but not as high (favorable) as that of Ca over Na ion. The symmetry values (% saturation or selectivity)

of K, Mg and Ca ions over Na in montmorillonite clay are 64, 82 and 88%, respectively (Dixon and Weed, 1989). Thus, both Mg and Ca ions can readily displace exchangeable sodium (Dixon and Weed, 1989; Sposito, 1989). There is, however, only little information available on the fertility and physical properties of Mg saturated soils. Moreover, no research has been conducted to date to evaluate the potential use of langbeinite for reclaiming sodium affected soils. However, in a study conducted to neutralize acid soils in Louisiana, langbeinite was found to be more effective than gypsum in the reduction of subsoil exchangeable Al (Mathews and Joost, 1990).

Potassium which constitutes about 33% of the cation equivalent capacity of langbeinite will also help to displace exchangeable sodium because its selectivity coefficient is higher than that of sodium for most soils. This is particularly true in soils with high levels of swelling and expanding smectite clays (Dixon and Weed, 1989). Therefore, increased levels of K ion in the soil solution should lead to sodium displacement from the exchange sites both by preferred K^+ over Na^+ ion and by mass action. Moreover, K saturated soils have been shown to swell less than Na saturated soils (U. S. Salinity Laboratory Staff, 1954).

Langbeinite has a total of 14.3 cation equivalents per kg, of which 9.5 (66%) are due to the divalent cation (Mg), whereas gypsum has a total of about 11.6 cation equivalents which all comes from Ca ion. Langbeinite crystals are 18% more dense than gypsum crystals, and commercially available langbeinite has a purity of ~95%, whereas the purity of commercial gypsum is often less than 70%. Apart from its potential as a reclaiming material for sodium affected soils, the commercial value of langbeinite is a

high grade readily soluble source of sulfur, potassium and magnesium in a single naturally occurring mineral. Accordingly, langbeinite is an excellent fertilizer to correct S, K and Mg deficiencies of heavily cropped soils in the wet regions of USA (Hagstrom, 1986; IMC, 1990; Western Ag-Minerals Company, 1995). However, the cost of gypsum ranges between \$30 and \$40 per ton, while langbeinite sells for about \$90 per ton.

Considering the above conditions, langbeinite may be economically advantageous over gypsum because significant savings can be realized in its ease of handling and application. To achieve comparable soil reclaiming effects, langbeinite may have significantly lower water use requirements than gypsum. Moreover, langbeinite could be a much faster acting agent in the displacement of sodium from sodium affected soils, thus providing significant time savings. It is thus hypothesized that langbeinite can be used safely and is more efficient and economical than gypsum for reclamation of sodic and saline sodic soils.

To study these, a series of laboratory and greenhouse experiments were conducted with the following specific objectives:

1. To determine and compare the optimum levels of langbeinite and gypsum required to displace exchangeable sodium and lower the ESP of a sodium affected soil to an agriculturally acceptable level.
2. To study the hydraulic conductivity of a saline sodic soil saturated with exchangeable Mg and compare it with one saturated with exchangeable Ca.

3. To measure the amount of water required for saline sodic soil reclamation using langbeinite and gypsum and compare the amendments with regards to their water use efficiencies.
4. To evaluate and compare seed germination, growth and dry matter yield responses of a lima bean crop grown in the greenhouse on a saline sodic soil reclaimed with langbeinite and gypsum.
5. To compare the overall economic advantages of using these amendments on the basis of their effectiveness in Na displacement, improving soil hydraulic conductivity, water use efficiency, ease of handling and application, and crop growth and yield.

CHAPTER 2

REVIEW OF LITERATURE

1. Salt Affected Soils: An Overview

The preceding section has made it apparent that soil salinity and sodicity are common problems in arid and semiarid regions of the earth. Such soils are found in every continent of the world where evapotranspiration exceeds precipitation either permanently or for much of the year (Kovda, 1965). As a result, salts that are already present in or may be introduced into the soil are not leached from the root zone. Owing to low rainfall and the resultant insufficient leaching under arid semiarid conditions, these salts can accumulate in concentrations and types detrimental to plant growth. The chemistry of salt affected soils is well known and adequately treated by a number of soil chemistry texts and other reference materials (eg. U. S. Salinity Laboratory Staff, 1954; Kovda, 1965; Bresler et al., 1982; James et al., 1982; Bohn et al., 1985; Sposito, 1989; Szabolcs, 1989).

Being are common problems of the climatically arid and semiarid regions of the earth, salt affected soils often occur in irrigated lands. In the United States alone, 5 million ha of irrigated lands have been estimated to be salt affected, mostly in the 17 western states (Bohn et al., 1985). According to same, as much as one-third of all irrigated lands in the world may be plagued by salt problems. The dimensions of the problem are truly impressive when salt problems of nonirrigated lands and lands that are currently considered as marginal areas are added to these figures. Recent surveys by Gupta and Abrol (1990) indicated that salt affected soils occupy, on a global basis, an

estimated 952.2 million ha of lands. These constitute about 33% of the potential agricultural lands in the world.

Soluble salts and sodium accumulate in soils from three main natural sources. These include physical and chemical weathering of rocks and the minerals contained in them, atmospheric precipitation, and fossil salts from former marine or lacustrine environments (Bresler et al., 1982; Bohn et al., 1985; Stroehlein and Pennington, 1986). More commonly, however, salts and exchangeable sodium accumulate in soils in high concentrations as a result of man's activities.

Some such activities are inadequate development of irrigation projects, inefficient irrigation systems, use of irrigation waters containing high levels of dissolved salts, lack of proper drainage, capillary rise from mineralized ground waters when water tables have risen due to excessive application of irrigation water without proper drainage, application of amendments and fertilizers, environmental mismanagement such as the clearing of native vegetation, and combinations thereof (Bohn et al., 1985; Stroehlein and Pennington, 1986; Ghassemi et al., 1995). These plus other human-induced salinization and alkalization processes are responsible for the loss of millions of hectares of agricultural and grazing lands, as well as the misuse of scarce water resources.

The U.S. Salinity Laboratory Staff (1954) classified salt affected soils as saline, saline sodic (or saline alkali) and sodic (or alkali) soils based on the amounts of soluble salts and exchangeable sodium they contain. A common definition of a saline soil is one having an E_{Ce} of more than 4 mmhos/cm (U. S. Salinity Laboratory Staff, 1954). However, from practical point of view, E_{Ce} values as low as 2 mmhos/cm may cause

problems for the germination and growth of salt sensitive crops (Stroehlein and Pennington, 1985). Sodic soils have more than 15% of the cation exchange sites occupied by sodium (U. S. Salinity Laboratory Staff, 1954; Abrol et al., 1975; James et al., 1982; Bresler et al., 1982). However, ESP values as low as 7 may cause problems in fine textured soils, especially where water with low electrolytes are used for irrigation purposes (Stroehlein and Pennington, 1986). Saline sodic soils form as a result of the combined processes of salinization and alkalization. Therefore, saline sodic soils contain high concentrations of both soluble salts ($EC_e > 4$ mmhos/cm) and exchangeable sodium ($ESP > 15$).

Once accumulated to high levels, soluble salts and exchangeable sodium of sodic and saline sodic soils interfere with crop production through decreased availability of water to plants, decreased infiltration and permeability, and accumulations of ions toxic to plants. Soluble salts increase the osmotic potential of the soil solution and thereby reduce the availability of water to plants (U. S. Salinity Laboratory Staff, 1954; Bresler et al., 1982; James et al., 1982; Bohn et al., 1985; Stroehlein and Pennington, 1986).

Irrigation waters of high sodium contents tend to produce soils of high exchangeable Na levels. Moreover, soils with high exchangeable sodium may develop from sources other than irrigation water. The presence of sodium ion either in irrigation waters or in soil solutions and/or exchange sites represents a potential hazard to soils and crops for two reasons (Frenkel et al., 1978; Frenkel and Meiri, 1985). One is the high sodium concentration may be toxic to certain plants. The other and more serious reason is related to the destructive effect of exchangeable sodium on the soil structure.

Soluble salts and exchangeable sodium interact with soil structure in opposite ways. Sodium causes swelling and dispersion of soils and therefore reduce hydraulic conductivity and infiltration rates. In contrast, high concentrations of salts, especially those of calcium cause flocculation and increase infiltration rates. These and other effects of soluble salts and exchangeable sodium have been studied in detail (Doneen, 1948; Quirk and Schofield, 1955; Reeve and Bower, 1960; McNeal and Coleman, 1966; Frenkel et al., 1978; Alawi et al., 1980), and will be discussed further in the forthcoming sections. Excessive exchangeable sodium also causes high pH values and, thus, reduce the solubility and availability of most micronutrients to plants.

The deleterious effect of adsorbed sodium on the physical properties of soils is manifested in a low infiltration rate of water, low permeability of the soil to water and gases, and poor structural quality of the media (Frenkel and Meiri, 1985). The degree to which the physical condition of the soil deteriorates in the presence of exchangeable sodium is a function of the amount and type of the clay mineral in the soil and the total electrolyte concentration of the soil solution (Quirk and Schofield, 1955; Frenkel et al., 1978; Shainberg et al., 1981a; Shainberg et al., 1981b; Frenkel and Meiri, 1985).

As a rule soils containing high levels of exchangeable sodium frequently crust badly and swell or disperse, greatly decreasing the hydraulic conductivity or permeability to water (Frenkel et al., 1978; Bohn et al., 1985; Frenkel and Meiri, 1985). Clay particles disperse and plug soil water flow channels. Swelling clay particles into flow channels also slows water flow. Decreased permeability can interfere with the drainage

required for normal salinity control and with the normal water supply and aeration required for plant growth (Bohn et al., 1985).

Irrigation waters and soil solutions of salt affected soil also contain potentially toxic ions (specific ion effects) such as boron, lithium, sodium, and chloride. Sodium and chloride ions are hazardous to fruit and berry crops and to other woody species (Bohn et al., 1985). Direct sensitivity to exchangeable or soluble sodium is more apparent at low salt levels, and therefore is difficult to differentiate from the effects of sodium on soil permeability. For plants that are extremely sensitive to sodium, as little as 5% exchangeable sodium may lead to toxic accumulations of sodium in leaf tissues (Bohn et al., 1985). Deciduous fruits, nuts, citrus and avocado are extremely sensitive (ESP:2-10) and beans are sensitive (ESP:10-20) to sodium even though the physical condition of the soil may be good (Bohn et al., 1985).

Another mechanism for potential salt injury to plants involves nutritional imbalances. For example, high sodium levels could conceivably lead to calcium and magnesium deficiencies, and salts high in magnesium could produce plant calcium deficiencies. The high pH levels of sodic soils may accentuate deficiencies of many of the micronutrients (Bohn et al., 1985).

Therefore, maintenance and improvement of irrigated crop yields of arid and semiarid regions depend on soil and water management techniques which maintain exchangeable sodium and salt levels as low as practical, based on soil properties and quality and quantity of irrigation water available. The basis for reclamation of saline and sodic soils has been known for many decades (Catlin and Vinson, 1925; Kelley, 1937).

Basically leaching with excess water will remove soluble salts, while exchangeable sodium must be displaced by a more beneficial ion such as calcium. As salts are leached away, the soil tends to become less permeable, and if soluble Ca and/or Mg are not present, a sodic soil may result.

2. Colloidal Properties of Na/Ca Soils

Salt affected soils and irrigation waters usually contain a mixture of sodium and calcium ions. The dispersion and other colloidal properties of clays and organic matter is of great importance in determining various soil properties such as hydraulic conductivity. On the other hand, dispersion of soil and organic matter particles depends on the clay mineralogy and proportion of cations in the soil exchange site. Therefore, it is important to consider the behavior of mixed Na/Ca system.

Sodium montmorillonite in dilute suspensions exists as single platelets (Van Olphen, 1977). Calcium montmorillonite exists in packets (tactoids or quasicrystals), each consisting of several clay platelets with a film of water 0.45nm on each external surface (Blackmore and Miller, 1961). Illites, on the other hand, exist in quasicrystals, regardless of the composition of the adsorbed cations (Greene et al., 1978).

Historically it was assumed that ions in heter-ionic clay systems were randomly mixed throughout the exchange complex. However, for mixed Na- and Ca-montmorillonite, Glaeser and Mering (1954) showed that demixing of cations occurred, so that some interlayer spaces are predominantly Na^+ saturated, while in others Ca^{2+} is predominant. They also claimed that complete mixing occurred in the first stages of substituting of Ca^{2+} for Na^+ , with demixing starting at approximately 30% substitution

and essentially complete at 40% substitution. McNeal et al. (1966) and O'Connor and Kemper (1969) showed that swelling and exchange isotherms of extracted soil clays and montmorillonite in mixed NaCl-CaCl₂ solution were affected by the presence of quasicrystals (tactoids) or packets.

Shainberg and Otoh (1968) studied the size and shape of montmorillonite particles saturated with mixtures of Na⁺ and Ca²⁺ ions in salt-free suspension. They found that introducing small amounts of Na⁺ ions into the exchange complex of Ca tactoids was not enough to break down the tactoid. However, introducing Na⁺ ions in amounts over 20% of the soil's cation exchange capacity (CEC) resulted in the breakdown of the tactoids. The platelets became completely separated when 60% of the adsorbed Ca had been replaced by Na. As long as tactoids exist, Ca ions will concentrate on the interlayer surfaces between individual clay platelets, while Na ions on the external surfaces of the tactoids, and, the size will remain unchanged (Shainberg and Otoh, 1968).

While developing a direct method for determining the number of plates per tactoid of expandable clays, Shomer and Mingelgrin (1978) obtained a result that was contradictory to those reported by Shainberg and Otoh (1968), but in agreement with those of Dufey et al. (1976). The findings of Shomer and Mingelgrin (1978) indicated that the average number of plates per tactoid depends on the ESP even at very low amounts of adsorbed sodium. For example, increasing the ESP from 0 to 5% caused a sharp decrease in the size of the Ca tactoid, and the number of plates decreased from 16.1 to 6.6 in suspensions of a Na/Ca bentonite system. This further indicates that a significant dispersion of expandable clay occurs as the ESP is increased from 0 to 5%.

Increasing the amount of sodium above 5% caused a continuous and gradual decrease in the number of plates per tactoid (Shomer and Mingelgrin, 1978).

Frenkel and Shainberg (1980) showed that the hydroxy polymers of Al and Fe affect the structure of the clay particles and prevent tactoid disintegration as long as the pH of the system is less than 9.0. According to same workers, an increase in the pH above this value causes the hydroxy-Al and Fe polymers to dissolve and to form aluminate and ferrate, and complete dispersion of Na-montmorillonite takes place. It is also obvious that the electrolyte concentration in the aqueous clay suspensions as well as other factors affect the dispersion in a given ESP (Shomer and Mingelgrin, 1978).

Soils that contain either very low amounts of exchangeable sodium or very high amounts of soluble salts are usually flocculated. Therefore, it important to consider the flocculation values of Na/Ca systems of minerals common in soils. Flocculation is a process of sticking together colloidal particles in the form of loose, irregular clusters in which the original particles can be recognized, and is usually brought about by adding an electrolyte to a system to compress the diffuse double layer (Frenkel and Meiri, 1985). The flocculation value of an electrolyte is the minimum concentration needed to flocculate a suspension of a soil in some arbitrary time (Van Olphen, 1977; Oster et al., 1980). The flocculation value is influenced by the clay type and the composition of the exchange complex.

The flocculation value for Na- and Ca-montmorillonite are 12 to 15 and 0.25 meq/l of NaCl and CaCl₂, respectively (Van Olphen, 1977) and for Na- and Ca-illite, they are 40 and 0.25 meq/l, respectively (El-Swaify , 1976; Greene et al., 1978). Oster

et al. (1980) found that the flocculation values of montmorillonite and illite clays are very sensitive to a low fraction of Na in the exchange complex. Whereas the flocculation value of both Ca-clays is 0.25 meq/l, the flocculation value of montmorillonite and illite clays with an exchangeable sodium fraction of 0.2 is 7.0 and 18.0 meq/l, respectively.

Van der Waals attraction forces are the main forces responsible for flocculation in Ca-montmorillonite and illite systems. Whereas the edge-to-face attraction plays a dominant role in the gel formation of Na montmorillonite (Oster et al., 1980). The high dispersivity of the clays in the presence of low percentage of exchangeable sodium explains the high sensitivity of soils with low exchangeable Na to leaching with dilute solutions or distilled water. Such a large effect of small amounts of exchangeable sodium in montmorillonite suspensions results from demixing of exchangeable ions, whereby Na^+ is the predominant cation on the external surfaces when ESP is less than 20% (Oster et al., 1980).

3. Hydraulic Conductivity of Sodium Affected Soils

The most severe deleterious effect of sodium ions on the physical properties of field soils, especially when coupled with high smectite clay contents, is the reduction in hydraulic conductivity (HC) of the soil (Ilyas et al., 1993). Increasing amounts of exchangeable sodium promote structural changes of soil matrix by two main mechanisms: clay swelling and soil particle dispersion. Dispersion and swelling of clays within the soil matrix are interrelated phenomena, and both act to reduce the hydraulic conductivity of the soil (Frenkel et al., 1978; Shainberg et al., 1981a; Frenkel and Meiri, 1985).

It can be deduced from the double-layer theory that both swelling and particle dispersion increase as the concentration of salt in the soil decreases and the sodium-to-calcium ratio of the solution increases (Bresler, 1972; Oster et al., 1980). Experimental results (Quirk and Schofield, 1955; McNeal and Coleman, 1966; Felhendler et al., 1974; Frenkel et al., 1978; Pupisky and Shainberg, 1979; Shainberg et al., 1981a) have confirmed that the HC behaves accordingly: higher HC in concentrated solution and at low Na/Ca ratios and lower HC in dilute solutions and at high Na/Ca ratios.

Examination of the soil permeability data in the literature shows that soils with similar texture and cation exchange capacity (CEC) may vary considerably in their susceptibility to the deleterious effects of exchangeable sodium and electrolyte concentration (McNeal and Coleman, 1966; Rhoades and Ingvalson, 1969; Yaron and Shainberg, 1973; Felhendler et al., 1974; Frenkel et al., 1978; Shainberg et al., 1981a). Moreover, differences in opinion can be found in the literature as to whether swelling or dispersion is the major cause of reduced permeability of sodic soils. McNeal (1968), Rowell et al. (1969), and Russo and Bresler (1977) have published equations that relate HC and swelling. On the other hand, several investigators (Rhoades and Ingvalson, 1969; Felhendler et al., 1974; Frenkel et al., 1978; Pupisky and Shainberg, 1979; Shainberg et al., 1981a) have demonstrated clearly that clay dispersion movement and consequent pore blockage were the main causes of reduction in hydraulic conductivities of several soils with an ESP less than 15 when irrigated with distilled water.

Frenkel et al. (1978) presented data which show that plugging of pores by dispersed clay particles is the major cause of reduced hydraulic conductivity in

montmorillonitic, vermiculitic, and kaolinitic soils in the range of exchangeable sodium and electrolyte concentration most commonly encountered in soils irrigated with sodic waters (SAR's of 10 to 20 and salt concentrations of 0 to 10 meq/l). Their results indicate that the exact levels of exchangeable sodium and electrolyte concentration at which hydraulic conductivity is appreciably reduced vary with mineralogy, clay content, and soil bulk density. The sensitivity to excessive exchangeable sodium and low electrolyte concentration increases with increasing clay content and bulk density.

The hydraulic conductivity of relatively coarse textured soils (clay percentages as low as 8) with ESP's of 10 or more is also appreciably reduced by dispersion at sufficiently dilute electrolyte concentrations (Frenkel et al., 1978). With very coarse textured soils (2.9% clay), plugging does not occur because the pore are too large and the water velocity is too fast. The findings of Frenkel et al. (1978) also revealed that the kaolinitic soil was less sensitive than the montmorillonitic soil at low electrolyte concentrations although its HC was reduced markedly, even at ESP of 10, when leached with nearly pure water. However, the effects of ESP, such as would occur during rainfall infiltration, and solution concentration on HC were similar for both montmorillonitic and vermiculitic soils (Frenkel et al., 1978).

The distinction between the two processes: swelling dispersion and movement may be quite important. Swelling is essentially a reversible process, and reduction in permeability may be reversed by adding electrolytes or divalent ions to the system. Dispersion and particle movement are virtually irreversible (Frenkel et al., 1978); thus, reduction in permeability may be permanent in soils where the latter process takes place.

While both swelling and dispersion are related and either one of them can reduce HC under the proper circumstances, it is important to understand the soil conditions favoring either mechanism.

Swelling reduces soil pore sizes and dispersion clogs soil pores (Frenkel et al., 1978; Bohn et al., 1985). If dispersed particles do not lodge, however, their transport can actually result in increased porosity and hydraulic conductivity. The works of Frenkel et al. (1978) and Shainberg et al. (1981a) have tried to answer why soils are sensitive to ESP below 15 and why soils that have the same texture and clay mineralogy respond quite differently to the same sodic conditions.

Swelling is not generally appreciable unless the ESP exceeds about 20 to 25 (Aylmore and Quirk, 1959; McNeal et al., 1966; Quirk, 1968; Shainberg and Caiserman, 1971; Shainberg et al., 1971). However, dispersion can occur at ESP levels as low as 10 to 20 if the electrolyte concentration is less than 10 meq/l (Felhendler et al., 1974) and even as low as 2 to 5 when leached with rain water (Shainberg et al., 1981a).

That dispersion can occur at lower exchangeable sodium levels than swelling may be explained by the effect of exchangeable cation composition on the structural arrangement of the clay particles (Aylmore and Quirk, 1959; Blackmore and Miller, 1961; Shainberg and Otoh, 1968; Quirk, 1968; and Shainberg and Caiserman, 1971). Calcium saturated montmorillonite clay particles commonly consist of packets (tactoids) of four to nine clay platelets arranged parallel to each other at distances of 0.9 nm (Blackmore and Miller, 1961; Frenkel et al., 1978). These structural units tend to maintain their integrity and behave as discrete entities.

Consequently, the swelling of calcium montmorillonite is limited by its reduced effective surface area. With the first addition of sodium, $ESP < 20$, sodium is adsorbed on the external surfaces and edges of the tactoids, while calcium remains in the interlayer positions of the tactoid (Frenkel et al., 1978). A more diffuse electrical double layer then develops around the tactoids, the extent varying with electrolyte concentration, creating repulsive forces between tactoids and an increasing electrophoretic mobility (Shainberg, 1968; Shainberg and Otoh, 1968).

As a result, dispersion between tactoids is enhanced, but little interlayering occurs since tactoid integrity is maintained. With further addition of sodium ($ESP > 20$), exchangeable sodium invades the interlayer position, diffuse double layers develop on the interlayer of each platelet, and the interlayer repulsion and swelling increase along with the deterioration of the tactoid structure (Shainberg and Caiserman, 1971). The tactoids breakdown completely when the ESP reaches about 50% (Frenkel et al., 1978).

In an attempt to answer why soils that have the same mineralogy and texture respond differently to sodic conditions, Shainberg et al. (1981a) and Shainberg et al. (1981b) hypothesized that the major factor causing differences among various sodic soils in their response to sodic conditions was their rate of salt release through mineral weathering. They predicted that sodic soils that contain minerals, such as $CaCO_3$, and mafic ones, which are readily released to the soil solution, will not disperse when leached with distilled water (simulating rainwater) at low or moderate ESP because they have the ability to maintain the soil solution concentration above the flocculation value. The results of their studies clearly supported these hypothesis. According to Frenkel et al.

(1978), clay will be found in the leachate only in a coarse-textured soils. When the soil texture is fine or the bulk density is low, the conducting pore size is small and therefore clay will move only short distances before it clogs the soil pores.

While working with Californian soils that contain minerals of different dissolution properties, Shainberg et al. (1981a) and Shainberg et al. (1981b) proved that the response of soil to exchangeable sodium during leaching with distilled water depends on the concentration of electrolytes that the solid phase of the soil maintains. Their findings revealed that the chemically stable Fallbrook soil was the most sensitive soil to exchangeable sodium effects on clay dispersion and loss in HC in spite of the presence of sesquioxides and kaolinite in its clay fraction. Two other soils which have higher mineral dissolution rates were less affected by exchangeable sodium. Thus clay dispersion, movement, and possible lodgement in conducting pores in the chemically stable soil is caused by low levels of electrolytes even at low levels of exchangeable sodium (Shainberg et al., 1981b).

Differences among soils in their capacity to release salt and to undergo dispersion are probably especially important in affecting crust formation under rainfall conditions. Soils that have moderate ESP levels may maintain reasonable physical properties through most of the profile and yet still be susceptible to dispersion near the surface (Shainberg et al., 1981a, Shainberg et al., 1981b). This is because during a rainstorm, the soil solution electrolyte concentration in the surface layers may drop to very low concentration, and even low ESP levels may enhance disaggregation, reduce the infiltration rate, and promote surface crust formation.

4. Exchangeable Magnesium Effects on Hydraulic Conductivity

Considering the effect of exchangeable Mg on soil physical properties such as hydraulic conductivity is important because this study deals with the use of langbeinite, whose dominant cation is Mg, as a reclaiming material for sodium affected soils. Conflicting results have been published regarding the influence of exchangeable magnesium on soil physical properties such as structural stability and hydraulic conductivity. The U.S. Salinity Laboratory Staff (1954) grouped Ca and Mg together as similar ions beneficial in developing and maintaining soil structure. The theoretical basis for combining the ions in one group is the fact that ion valence is a considerably more sensitive parameter for prediction of ion exchange than ion size.

However, it has often been suspected that Mg can cause the soil structure to deteriorate and lead to the development of Mg solonetz soils. Laboratory studies have also suggested that Mg may be less effective than Ca in maintaining structural stability in some circumstances. For instance, McNeal et al. (1968) and Levy et al. (1988) showed that mixed Na-Mg soils developed lower hydraulic conductivities than Na-Ca soils under similar conditions.

A distinction was also made between the direct effect of exchangeable Mg in decreasing structural stability (or in causing decreases in HC), which has been termed as specific effect, and the ability of Mg in irrigation waters to cause higher exchangeable Na levels to build up in soil (Chi et al., 1977; Emerson and Chi, 1977; Rahman and Rowell, 1979). The latter effect is related to the fact that Na may be more (or less) competitive against Mg than Ca for soil exchange sites (Curtin et al., 1994). The degree

of preference for Na in Mg compared in Ca saturated soil apparently depends on the nature of the exchange complex (Haghnia and Pratt, 1988) and clay mineralogy (Rahman and Rowell, 1979; Rowell and Shainberg, 1979).

In the studies referred to above and others, the findings vary, depending on soil properties and sometimes the results are contradictory. According to Rahman and Rowell (1979), Mg saturated montmorillonite and illite systems adsorbed more Na than their respective Ca saturated systems, with the magnitude of the preference becoming greater as organic matter content increases (Haghnia and Pratt, 1988). Vermiculitic soils behaved differently, in that Na was less competitive with Mg than with Ca (Rahman and Rowell, 1979). Levy and Shainberg (1972) also reported a pronounced Mg preference by vermiculite at equivalent fractions greater than 40% Mg, and the effects of this were seen in the isotherms where greater amounts of Na were adsorbed by the Ca systems.

Working with samples of prairie soils (Haploborolls) from Canada, Curtin et al. (1994) obtained increasing levels of exchangeable Na as the Mg/Ca ratio increased. They found that averaged from all SAR treatments, the Mg-Na systems had between 17 and 37% more exchangeable Na than did the Ca-Na systems. The authors attributed this Mg-induced increase in exchangeable Na to the preference by the soils for Ca over Mg, which makes Na more competitive against Mg than against Ca. Contrary to the findings of Rahman and Rowell (1979) and Curtin et al. (1994), illite systems showed no preference for Ca over Mg (Chi et al., 1977).

The question whether Mg has a specific effect has been a subject of considerable debate in the literature (Smith et al., 1949; Ahmed et al., 1969; Rahman and Rowell,

1979; Rowell and Shainberg, 1979; Alperovitch et al., 1981; Yousaf et al., 1987; Curtin et al., 1994). From a study with California soils, Yousaf et al. (1987) concluded that Mg did not have a specific effect. More clay dispersion when Mg, rather than Ca, was the divalent counter ion was attributed to higher levels of exchangeable Na and lower electrolyte concentrations in the Mg systems.

Smith et al. (1949) studied the physical properties of certain nonproductive soils of northern Arizona which exhibit notably poor structure and permeability to water and which contain an unusually high percentage of exchangeable magnesium. The results particularly with Casa Grande, Mohave and Gila soils showed that the Mg-saturated soils behaved much like the same soils saturated with Ca, and not at all like the Na-saturated soils. They suggest that magnesium ion in the exchange complex is not responsible for the unfavorable physical conditions of these soils.

Ahmed et al. (1969) investigated the effects of adsorbed cations on physical properties of tropical red earth, consisting predominantly of kaolin and iron oxide, and a tropical black earth consisting predominantly of montmorillonite. Their results revealed that percentage stable aggregates and hydraulic conductivity were affected by the four cations in the order: $Ca = Mg > K > Na$ and were also significantly affected by clay type. Combinations of the four cations generally gave intermediate effects with Ca-saturated soils more susceptible to deterioration by K or Na than Mg-saturated soils. From this they concluded that Ca and Mg had similar effects on aggregate stability and hydraulic conductivity of soils, whereas the effect of K is similar to that of Na ion.

From measurements of clay swelling, clay dispersion, and hydraulic conductivity, Rahman and Rowell (1979) concluded that Na-Mg montmorillonite and a montmorillonitic soil behaved identically to their Na-Ca counterparts at the same ESP and electrolyte concentration; that is, there was no specific effect. However, an illitic soil and an illitic-montmorillonitic soil showed evidence of specific effect. In addition, the works of Chi et al. (1977) and Emerson and Chi (1977) also indicated that Mg has a specific effect on the dispersion and hydraulic conductivity in soils dominated by illite but not in montmorillonitic soils. The montmorillonite results were obtained for both a pure montmorillonite clay and for a heavy textured soil with high organic matter content where clay swelling was the dominant process causing structural deterioration. Emerson and Chi (1977) deduced that Mg was about one-tenth as effective as an equivalent amount of exchangeable Na in causing dispersion of illite clay.

In contrast, Thellier and Sposito (1989) reported that dispersion of specimen illite (Silver Hill illite) was independent of whether the divalent cation was Ca or Mg. Moreover, exchangeable Mg appeared to have no specific effect on soil hydraulic conductivity of the A and C horizons of a sodic sandy loam soil dominated by montmorillonite and kaolinite clay minerals leached with solutions with SAR < 20 and electrolyte concentration of 10 meq/l (Rowell and Shainberg, 1979). However, there was evidence of a specific effect of Mg when the soils were subsequently leached with distilled water, that is, under conditions favorable for clay dispersion.

Alperovitch et al. (1981) have also noted differences within a group of Israeli soils in their response to magnesium. They found that exchangeable Mg did not have a

specific effect on hydraulic conductivity and clay dispersion in calcareous soils, but the noncalcareous, chemically stable soils showed evidence of specific effect of exchangeable Mg when the soil is leached with rain (or distilled) water, in spite of the presence of sesquioxide and kaolinite in their clay fractions. The calcareous soils, which have higher mineral dissolution rates, were less affected by exchangeable sodium and did not show the specific effect of Mg on clay dispersion and HC losses, and in these soils Mg could be considered as beneficial ion to soil structure as is Ca. They explained this effect that the presence of exchangeable Mg enhances the dissolution of CaCO_3 in calcareous soils, thus providing electrolyte concentration above the flocculation value and preventing clay dispersion and reduction in soil hydraulic conductivity. Clay dispersion, movement and possible lodgement in conducting pores are caused by low levels of electrolytes even at low levels of exchangeable sodium in the noncalcareous soils (Alperovitch et al., 1981).

Very recently, Curtin et al. (1994) assessed the effect of Mg on structural stability by measuring saturated hydraulic conductivity and found that the Na-Mg soil systems maintained lower saturated hydraulic conductivity than the corresponding Na-Ca system using Mg-Ca-Na solutions with Mg/Ca ratios ranging from 0:1-1:0. Mixed Mg-Ca-Na systems with intermediate Mg/Ca ratios of 1:2 and 2:1 behaved more like the Ca than the Mg system. Clay concentration in leachate from soil columns increased as Mg/Ca ratio increased, suggesting that Mg had a specific effect on clay dispersion. However, Mg appeared to be only 4 to 5% as dispersive as equivalent amount of exchangeable Na (Curtin et al., 1994). Considering the overall small effect of Mg, Curtin et al. (1994) concluded that lumping Mg together with Ca to characterize irrigation water quality is

certainly acceptable for practical purposes, and specific allowance for Mg, as suggested by Rahman and Rowell (1979) is probably not necessary.

5. Surface Crusting and Infiltration

Infiltration is one of the more important processes in irrigated land. Infiltration refers to the entry of water into a soil profile from the soil surface boundary. The rate at which water enters the soil surface is therefore referred to as the infiltration rate (IR). The rate of infiltration relative to the rate of water supply determines how much water will enter the root zone and how much will run off.

In the field, the surface layer of the soil is frequently less permeable than the subsurface horizons, particularly when a surface crust forms (Jury et al., 1991). In this case, if a thin layer of water is ponded on the soil surface, the (steady-state) flux through the soil will be less than the saturated hydraulic conductivity of the lower horizons but greater than the saturated hydraulic conductivity of the surface crust. The infiltration rate of a soil is influenced by such factors as the condition of the soil surface, the chemical and physical status and nature of the profile, and the distribution of water in the profile (U. S. Salinity Laboratory Staff, 1954). More importantly, the infiltration rate of a soil is strongly influenced by the ESP of the soil and by the electrolyte concentration of the applied water (Agassi et al., 1981; Kazman et al., 1983; FAO, 1989). The infiltration rate generally increases with increasing salinity and decreases with either decreasing salinity or increasing SAR.

Infiltration rate (IR) is defined as the volume flux of water flowing into the profile per unit of area of the soil, and it has a dimension of velocity. In general, the soil

infiltration capacity is initially high, particularly when the soil is initially dry, but it tends to decrease monotonically until it asymptotically approaches a constant rate: the steady-state infiltration rate. When the water application rate to the soil surface is less than the soil infiltration capacity, water infiltrates at the rate typical to the application; however, when the application rate exceeds the infiltration capacity, it is the latter that determines the actual IR, and the process becomes a surface controlled process (Hillel, 1980).

Numerous formulations have been proposed in attempts to express the infiltration rate capacity as a function of time or the quantity of water infiltrated into the soil (Hillel, 1980; Jury et al., 1991). Most of the research treating this aspect in the past concentrated on the impact energy of the water drops on the stability of the soil surface structure. However, recently it was found that soil surfaces are especially susceptible to the chemistry (electrolyte concentration and composition) of the applied water. Because of the mechanical action of the falling drops and the relative freedom for particles to move at the soil surface, aggregates at the soil surface are more sensitive to breakdown and dispersion than aggregates within the soil profile, thus causing the formation of a thin, dense layer, which is defined as soil crust (Agassi et al., 1981; Kazman et al., 1983).

Agassi et al. (1981) and Kazman et al. (1983) studied the effect of electrolyte concentration and soil sodicity on crust formation and concluded that crust formation is the result of two complementary mechanisms: physical dispersion caused by drop impact and chemical dispersion, which depends on the ESP of the soil, the electrolyte concentration of the applied water, and the mineralogy of the clay. Chemical dispersion is limited in Ca-soils or when a high electrolyte concentration is present in the applied

water. The intensity of chemical dispersion increases sharply with increases in soil sodicity (at ESP up to 5) when distilled water is applied. When water of intermediate salinity is applied, the rate and extent of soil dispersion increases with increasing soil sodicity. Application of water of high salinity (EC of 5.6 mmhos/cm) diminished strongly the chemical dispersion, and the resulting crust-formed by the physical action of the drops alone-maintained an infiltration rate four times higher than that of the soil exposed to distilled (rain) water of similar mechanical parameters (Agassi et al., 1981).

The studies of Keren and Shainberg (1981), Agassi et al. (1981) and Kazman et al. (1983) compared the effect of ESP on HC and IR for two soils that differ mainly with respect to the existence of CaCO_3 . Infiltration rate decreased in both soils, whereas HC was less sensitive in calcareous soils. Furthermore, IR was affected by an ESP as low as 2, and HC was affected at an ESP of 20 and above for the calcareous soil, or an ESP of 10 in the noncalcareous soil.

The studies by Kazman et al. (1983) revealed that the final infiltration rate of the noncalcareous soil with ESP 1.0 was maintained at 7 mm/hr, but it dropped to 2.3, 0.7, and 0.6 mm/hr for soil samples with ESP values of 2.2, 4.6, and 11.6, respectively. In relative terms, if the final IR of the soil with ESP 1.0 is 100%, the corresponding values for the soils with ESPs 2.3, 4.6, and 11.6 were 32, 10 and 9%, respectively. Similarly for the calcareous soil with ESPs 1.8, 6.4, and 26.0, the infiltration rate dropped to 3.2, 1.2 and 1.0 mm/hr, respectively. They attributed this to the fact that the electrolyte concentration in soil solution at the soil surface is determined solely by the electrolyte

concentration in the applied water (rain water); thus aggregate dispersion takes place at the surface at low levels of exchangeable sodium, even in calcareous soils.

Recently, Keren (1990) observed that exchangeable Mg decreased the infiltration rate in both calcareous and noncalcareous montmorillonitic soils exposed to rain drops having an intermediate kinetic energy. The specific effect of Mg on IR was explained by the presence of Mg ions on the external surfaces of the clay tactoids and the larger hydration shell of the Mg ion compared to Ca. Moreover, Keren (1989) showed that the IR values were always lower for Mg soils than for Ca soils.

The high sensitivity of IR to the ESP of the soil surface and the electrolyte concentration of the applied water raised the possibility of controlling surface crusting and maintaining high IR by application of gypsum. Keren and Shainberg (1981) compared the effect of spreading phosphogypsum (PG) on the soil surface on the IR of two sodic soils. They found that PG was more effective in maintaining the IR of both soils. The beneficial effect of PG appeared to be caused by a rapid dissolution resulting in an increase in electrolyte concentration rather than cation exchange. Phosphogypsum was effective in maintaining IR even in soils having a low ESP (1.0); however, its effect was more pronounced under high ESP values.

The effects of ESP, electrolyte concentration of the applied water, and the addition of gypsum on infiltration were studied under field conditions by Hadas and Frenkel (1982). In this work, the effect of long-term use of saline sodic water could be evaluated by means of changes in soil infiltrability. The effect of exchangeable sodium percentage-electrical conductivity (ESP-EC) relations on the final IR in the field was:

saline sodic water + gypsum > saline sodic water > distilled water + gypsum > distilled water. However, a large range of values within treatments was obtained. The mean final IR of a field irrigated for eight years with saline sodic water (SAR-26) is similar to the final IR measured in rain simulator for the same soil and ESP (Agassi et al., 1981; Keren and Shainberg, 1981).

6. Reclamation of Sodic and Saline Sodic Soils

6.1. Theory and Background of Reclamation

Reclamation of sodic and saline sodic soils require displacement of part or most of the exchangeable sodium through the introduction of divalent cations (usually Ca^{2+}) into the exchange complex and the removal of the displaced Na^+ ions below the root zone by leaching. The most deleterious effect of Na^+ ions on soil reclamation, especially when coupled with clays of high shrink-swell potential such as smectite, is the reduction in hydraulic conductivity of the soil (Ilyas et al., 1993). It is made clear in the preceding sections that higher exchangeable Na percentages increase clay swelling, dispersion of clay, and formation of surface crust; and all act to reduce hydraulic conductivity and infiltration rates.

Theoretically, sodic and saline sodic soils can be reclaimed by providing a source of Ca^{2+} , such as gypsum, to replace Na^+ from the colloid's cation exchange sites, a process that requires the flow of water through the soil. In other words, the success of sodic soil reclamation is critically dependent on maintenance of hydraulic conductivity to ensure transport of Ca^{2+} ions into the soil and to facilitate the removal of sodium that has become part of the soil solution. If the soil profile has limited permeability or if there

is an impermeable layer(s) at shallow depths, little or none of the exchanged Na^+ will be removed and reclamation will not be accomplished (Ilyas et al., 1993).

The least permeable soil layer limits the rate of movement of water through the entire soil profile. If water movement is slow, permeability of the soil must be improved before any chemical amendment can be effective. High electrolyte concentration increases the HC of the soil but also wastes amendment because a smaller proportion of it is exchanged (Doering and Willis, 1975). This effect is amplified as the ESP of the soil being reclaimed is reduced. Therefore, the use of concentrated solution to reclaim sodic soils of high ESP saves time and water, but as the ESP is lowered, the concentrated solution becomes increasingly less efficient.

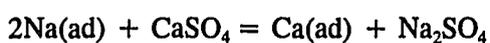
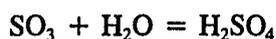
The kind and amount of chemical amendments to use in reclaiming sodic soils vary depending on physical and chemical properties of the soil, time available for reclamation, amount of water available, depth of reclamation required, the kinds of crops to be grown during and after reclamation, final required ESP and hydraulic conductivity, and costs of amendment, water and application. Numerous workers (eg., U. S. Salinity Laboratory Staff, 1954; Bohn et al., 1985; Stroehlein and Pennington, 1986; Gupta and Abrol, 1990) grouped the list of chemical amendments for reclaiming sodic soils into three broad categories: (1) soluble calcium salts (gypsum or $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, CaCl_2 , phospho-gypsum), (2) sparingly soluble calcium salts (calcite: CaCO_3 , $\text{CaMg}(\text{CO}_3)_2$), and (3) acids or acid formers (H_2SO_4 , iron and aluminum sulfates, elemental sulfur, pyrite).

Among the long list of chemical amendments gypsum, calcium chloride, sulfuric acid and elemental sulfur are more frequently used for reclamation purposes. The

common characteristic of all chemical amendments when used under appropriate soil conditions is that they directly or indirectly, through chemical or microbial action, furnish divalent cations (usually Ca^{2+}) to replace exchangeable Na. Acid amendments react immediately with lime, naturally present in sodic soils, to produce soluble Ca. Materials such as sulfur or iron pyrite must first oxidize to sulfuric acid, which in turn produces calcium sulfate, and consequently are less effective than gypsum or sulfuric acid (Gupta and Abrol, 1990).

Sulfuric acid and acid forming amendments are more effective than the neutral salts (gypsum and calcium chloride) in reclaiming calcareous sodic soils (Yahia et al., 1975; Prather et al., 1978; Bohn et al., 1985; Stroehlein and Pennington, 1986). If a drop of acid added to a soil causes effervescence, the lime content is generally sufficient for use of acid-forming amendments. However, there are basic differences in the materials to be considered such as time schedule required, tillage, equipment for application, water supply, and economic considerations.

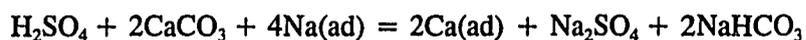
Sulfur must oxidize to sulfuric acid by soil microorganisms before it becomes effective. A lead time of several weeks or even several months can be required for microbial oxidation before leaching is begun (Bohn et al., 1985). The basic reaction sequence is:



where the suffix (ad) signifies the adsorbed or exchange state. The soluble Na_2SO_4 produced is subsequently removed from the soil by leaching with irrigation water.

Unless used as a slurry or specially formulated, the application of fine particle S may be dusty and, under certain conditions, explosive. Since S is insoluble in water, its rate of oxidation is based to a great extent on particle size or the surface area of the material (Stroehlein and Pennington, 1986). Other factors associated with S oxidation are environmental factors which affect the activity of the microorganisms such as available soil moisture, oxygen, nutrients, temperature, and pH. If the soil is extremely sodic and low in soluble salts, an extended incubation time of several months may be necessary before leaching (Stroehlein and Pennington, 1986). This means that the soil must be kept relatively moist for an extended period of time which can significantly increase the labor and water required for reclamation.

Interest on the use of sulfuric acid as an amendment declined until the early 1970's due to increased use of gypsum and the hazardous nature and high costs of H_2SO_4 . Sulfuric acid is generally superior to other amendments for removing Na from calcareous soils. Sulfuric acid reacts immediately in the soil to form colloidal gypsum and increases the soluble salt content which flocculates the soil. Under most efficient conditions, the action of H_2SO_4 in releasing adsorbed Na can be described by the reaction (Stroehlein and Pennington, 1986):



At such high efficiency, one atom of S can exchange four atoms of adsorbed sodium; and

at low efficiency, one atom of S exchanges with two atoms of adsorbed sodium as:



Sulfuric acid is a rapid and efficient amendment reacting immediately with a calcareous soil, but is dangerous, heavy and corrosive when water is present (Stroehlein and Pennington, 1986).

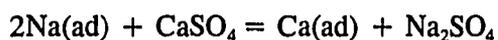
Although CaCl_2 is generally too expensive to compete with other amendments, in some situations it is available as an industrial by-product and therefore inexpensive. Magdoff and Bresler (1973) used a simplified Gapon-type equation to predict the effect of various CaCl_2 concentrations (in the irrigation water) on reclamation of sodic soil. They found that it is preferable to apply it in irrigation water and that the more dilute the solution, the better. Their predictive model showed good agreement with experimental results. However, when water infiltration is the main limiting step for reclamation, it is advisable to use concentrated CaCl_2 solutions (Alperovitch and Shainberg, 1973; Prather et al., 1978). For such conditions, the overall time and water requirement are much less than for gypsum.

Because of its general availability and relatively low cost, gypsum is the most common source of calcium to reclaim sodic soils and of electrolyte to maintain adequate permeability and water infiltration rates. Its use for sodic soil reclamation dates back 100 years (Kelly and Brown, 1934). Fireman and Bodman (1939) and Doneen (1948) reported on the effect of gypsum in increasing infiltration and saturated hydraulic conductivity of sodic soils.

6.2. Gypsum as a Reclaiming Material

Properties of gypsum which affect its effectiveness are solubility, fineness, and purity. Gypsum is weakly soluble and the solubility increases in the presence of other salts. Gypsum should be finely ground for soil application and its purity should be known when calculating quantities to apply or actual cost of the material. Chawla and Abrol (1982) have shown that better results can be achieved if gypsum ground to pass through a 2-mm sieve is used for reclamation. Because of its low solubility in water, Gupta and Abrol (1990) stressed that gypsum use for sodic soil reclamation can only be justified economically by worthwhile yield response, usually over several seasons.

Gypsum is applied broadcast on the soil surface after the soil has been rough tilled and leveled. A light disking will aid mixing with the soil, but thorough mixing with the plow layer is not desirable since the increased infiltration must begin at the soil surface. Burying the gypsum too deeply will not improve infiltration nor aid leaching. The soil surface should be left in a rough condition to achieve maximum infiltration rates (Harris et al., 1965). Leaching and allowing the soil to dry, followed by second leaching, generally removes more salts than one leaching with an equal volume of water. Gypsum reacts with the soil as follows:



The amount of gypsum needed to reclaim a sodic soil which is termed as gypsum requirement (GR) is a function of the depth of the soil to be reclaimed, CEC, and the initial ESP and final ESP being sought (Gupta and Abrol, 1990). Several empirical formulas based on different exchange efficiencies have been used by the U. S. Salinity

Laboratory Staff (1954) in order to set out a method for determining gypsum requirement. Recently Oster and Frenkel (1980) used a numerical simulation of reclamation to estimate the amount of gypsum and water required for reclamation. They assumed that the reaction rates of gypsum dissolution and exchange are sufficiently rapid to maintain soil solution and exchangeable ion compositions in equilibrium with gypsum as the water moves through the soil. They suggested that the gypsum requirement for sodic calcareous soils should be increased by a factor of 1.1 to 1.3, depending on the desired final level of exchangeable sodium.

Moreover, Oster and Frenkel (1980) reported that the water requirement for reclamation with gypsum is less than that traditionally estimated from its solubility in distilled water, 2.6 kg m^{-3} . The amount of gypsum dissolved is a function of the amount of exchangeable Na, that is CEC and ESP. Numerical simulation of representative situations indicate that a reasonably accurate estimate of water requirement can be made assuming a threefold increase in effective solubility, or $7.8 \text{ kg of gypsum per m}^3$ of water (Oster and Frenkel, 1980).

Gypsum added to sodic soils can improve permeability due to both electrolyte concentration and cation exchange effects. The relative significance of the two effects is of great practical interest. In many situations, the required amount of gypsum for reclamation of even shallow depths of soil will be beyond the economic capacity of the farmer. Therefore smaller application can provide immediate benefits from the electrolyte effect and some residual exchange, which can be built up by later application (Loveday, 1976).

The relative significance of the electrolyte effect during sodic soil reclamation was estimated by Shainberg et al. (1982) by comparing the effects of equivalent amounts of gypsum and CaCl_2 applied on the soil surface of three Israeli soils, using distilled water. Whereas the exchange reclamation was similar with both amendments, there was a difference in the effect on the hydraulic conductivity. The slow dissolution of gypsum maintained a higher hydraulic conductivity for a longer time in comparison with CaCl_2 in a chemically stable soil that did not release salt into solution (Shainberg et al., 1982). Conversely, the efficiency of the two amendments was similar for a calcareous soil. The soil, even without gypsum, released enough electrolyte into the soil solution to prevent clay dispersion and HC losses. The ability of gypsum to maintain a moderate concentration of electrolyte in the percolating water is very important in preventing crust formation or soil sealing under rainfall conditions (Keren and Shainberg, 1981).

Equilibrium conditions probably do not apply to the dissolution of surface-applied gypsum. Here, the kinetics of dissolution are limited due to the shallow depth of the gypsum-soil layer and to the high soil water flux rates associated with the initial stages of infiltration. Keren and O'Connor (1982) found that gypsum dissolution rate was very sensitive to the water velocity, tending to increase with increases in the flow rate, but the efficiency of replacing Na (reclamation) decreased. Thus, were it possible to control the water flow velocity, for example, by sprinkler irrigation, a reduced velocity would give an increased contact time between water and gypsum fragments, and therefore greater efficiency of exchange would be achieved.

The preceding information is based on the dissolution rate of mined gypsum. According to Keren and Shainberg (1981), the rate of dissolution of phosphogypsum (PG) can be ten times greater. The concentration derived from PG is about three times greater than that of mined gypsum at application rates less than 5 ton/ha; at high application rates (15 ton/ha), the concentration differed by a factor of two. As a result, the efficiency of the industrial gypsum in maintaining a high infiltration rate in sodic soils was much higher than the mined gypsum (Keren and Shainberg, 1981). They attributed the high efficiency of industrial gypsum in maintaining a high infiltration rate to its high rate of dissolution in water and purity compared to the mined gypsum.

In general a great deal of research has been conducted on the use of gypsum as a chemical amendment for reclaiming sodic and saline sodic soils. As the most commonly used chemical amendment, gypsum was found to improve flocculation and macroporosity (Chartres et al., 1985; Greene et al., 1988), reduce surface crusting (Gal et al., 1984), decrease bulk density (Southard et al., 1988), and increase permeability (Frenkel et al., 1989) of sodic and saline sodic soils. Many of the effects of gypsum, however, including better permeability, are limited to shallow depths (Ilyas et al., 1993), and, generally, it is not a fast acting amendment.

For instance, according to Ilyas et al. (1993) gypsum alone, without a crop or wheat straw, did not affect permeability at any of the soil depths at the end of the first 6 months. After 1 yr, however, gypsum application significantly increased the permeability in the upper 20 cm of the soil. The increase in permeability after 1 yr in the surface 20 cm soil layer of the gypsum application to fallow plots was possibly the result

of two actions, as observed by Greene et al. (1988), Chartres et al. (1985) and Southard et al. (1988). First, the replacement with Ca of some exchangeable Na in the soil may have increased soil aggregation and porosity and reduced surface crusting. Second, some weeds grew in gypsum treated plots; these weeds might have improved the surface soil's physical condition because of their root systems. It is known that gypsum application in poorly structured soils helps crop establishment and increases crop growth (Carter et al., 1986; Bajwa and Josan, 1989). Gypsum is also known to increase the depth of root penetration (Carter and Pearen, 1988).

It is difficult to improve the physical properties of saline sodic soils in a short period of time (Ilyas et al., 1993). Mitchell and Donovan (1991) observed that soils deflocculated by treatments prior to a reduction in their exchangeable Na percentage were not quickly aggregated and better permeability was slow to establish. In the studies conducted by Ilyas et al. (1993), no individual or combined effect of gypsum and crops was highly effective at the end of 6 months. However, after one year, gypsum and crops interacted well and together increased the permeability of the soil under study.

Amendments also can be applied in combination to minimize time and costs and to increase efficiency of water use and reclamation (Prather et al., 1978). It was found that the most efficient amendment was CaCl_2 , followed closely by H_2SO_4 . The least effective amendment was gypsum. However, gypsum combined with sulfuric acid or calcium chloride improved water and time efficiencies as compared with gypsum alone. The cost of mixed amendments is also less than the cost of acid or calcium chloride alone.

The use of synthetic polymers as soil conditioners has been researched since the 1960s. The results obtained from these studies are encouraging and have added to the current knowledge on the field of reclamation and management of sodic and saline sodic soils. Some such results indicated that synthetic polymers can be beneficial in reducing surface sealing and crusting (Mitchell, 1986; Cook and Nelson, 1986; Wallace and Wallace, 1986; Helalia and Letey, 1988b; Ben-Hur et al., 1989). Moreover, application of synthetic polymers can be useful for improving aggregation and reducing clay dispersion (Cook and Nelson, 1986; Terry and Nelson, 1986; Aly and Letey, 1988; Helalia and Letey, 1988a)

Very recently, Zahow and Amrhein (1992) reported that synthetic polymer treatments had a highly significant effect on increasing the saturated hydraulic conductivity of soils with ESP values < 15 , but had no significant effect with ESP values > 15 . The addition of gypsum increased the hydraulic conductivity from 0.0 to 0.063 mm/hr in the soil with an ESP of 32. When polymers were used in conjunction with gypsum, the hydraulic conductivity increased to 0.28 mm/hr (Zahow and Amrhein, 1992). They attributed the improvement in hydraulic conductivity with polymer treatment at low ESP values and in the gypsum treated soil to a reduction in soil slaking and dispersion. At ESP values > 15 , an additional mechanism that may have been controlling the hydraulic conductivity was swelling, and none of the polymers reduced soil swelling (Zahow and Amrhein, 1992).

6.3. Crop Response to Reclamation of Sodium Affected Soils

Sodicity effects on commercial yield (quantity and quality) are of primary importance. Therefore, the ultimate goal of reclamation of sodic and saline sodic soils is to increase total biomass production and quality of products. Crop response to reclamation of sodic and saline sodic soils vary depending on their tolerance to exchangeable sodium and the degree of soil sodicity. The response of crops to reclamation may be due to increased availability of water, improved soil permeability (or hydraulic conductivity), improved aeration, improved nutritional balance, decreased specific ion effects or toxicity.

For instance, bean plants have been shown to be sensitive to high content of sodium ion in the soil exchange site (Wadleigh and Bower, 1950). Specific ions' effects was found when Cl and SO₄ effects were compared with beans (Meiri et al., 1971). Abrol and Bhumbra (1979) found no reduction in rice yield up to an ESP of 55 and only 20% yield reduction at an ESP of 75. Wheat, on the other hand, did not grow at an ESP of more than 55, and a yield reduction of about 40% occurred at an ESP of 45. In general, gypsum application at a rate of 30 ton/ha increased the yields of dhaincha, wheat, rice, lentil and gram by 41.4, 37.9, 22.7, 11.2, and 8.0 qt/ha, respectively, when compared to their respective yields on plots with no gypsum (Abrol and Bhumbra, 1979). The ESP of the soil was originally 62 and was reduced to 24.5 when 30 ton/ha of gypsum was applied.

Several workers (Oster, 1982; Dubey et al., 1987; Bajwa and Josan, 1989; Singh and Bajwa, 1991; Malhi et al., 1992; Dubey and Mondal, 1993) have reported the

beneficial effect of gypsum in reclaiming sodic soils and increasing crop yields. Dubey et al. (1993) compared the reclaiming efficiency of various organic and inorganic amendments using saline water. The application of amendments significantly enhanced the yields of both rice and wheat crops and decreased ESP, irrespective of the quality of irrigation water used and followed the order gypsum + farm yard manure (FYM) > pyrite > pyrite + FYM > gypsum > pyrite > FYM > Control (Dubey et al., 1993). Application of gypsum increased the grain yields of rice from 16.3 to 43.8 g/pot and the yield of wheat from 4.9 to 27.7 g/pot. Gypsum +FYM further increased the grain yields of rice and wheat to 81.2 and 37.2 g/pot, respectively.

Singh and Bajwa (1991) reported that application of increasing levels of gypsum for initial sodic soil reclamation increased the dry matter yield of rice and wheat crops both in the presence and absence of gypsum applied at each irrigation. Moreover, soil properties and crop yields were improved with gypsum applied at each irrigation. Rice plants performed better than wheat without gypsum applied at each irrigation. This was explained both by Abrol and Bhumbla (1979) and Singh and Bajwa (1991) to the greater tolerance of rice to sodicity than wheat.

Bajwa and Josan (1989) also found that application of gypsum decreased pH, SAR, and ESP of the top 0-60 cm soil and hence increased grain yields of both rice and wheat crops. They reported that gypsum, to supply 2.5 and 5.0 meq/l of sodic irrigation water for wheat and rice crops, respectively, was sufficient to maintain high yields. The relatively higher tolerance of wheat to sodicity than rice was contradictory to the findings of Abrol and Bhumbla (1979) and Singh and Bajwa (1991) but was in agreement with the

findings of the U. S. Salinity Laboratory Staff (1954) which rated rice as only moderately tolerant crop and wheat as tolerant to excess exchangeable sodium.

Application of various organic and inorganic amendments improved germination, growth and nodulation of *Trifolium alexandrium* in saline sodic soils (Somani, 1991). Gypsum and pyrites applied at rates to increase neutralization of residual sodium carbonate in water from 0 to 100% increased the yields of maize and wheat crops (Muralidhar and Yadav, 1991). Gypsum was less effective than elemental sulfur (Hussain et al., 1988; Somani, 1991) but slightly more effective than pyrites (Muralidhar and Yadav, 1991) in reclaiming saline sodic soils. Hussain et al. (1988) reported that a combination of gypsum at 50% GR plus FYM was a best amendment for saline sodic soil reclamation and for increasing the yields of rice, barseem and wheat crops.

Carter and Pearen (1988) studied the effect of Ca applied as gypsum to saline sodic soil on the growth and mineral composition of barley seedlings in pot culture experiments. They found that seedlings grown on Ca-amended soil had higher shoot dry weights and increased root penetration compared with seedlings grown on the unamended soil. Plant accumulation of Ca, Mg and K was enhanced and Na accumulation was reduced by Ca treatments. In another but similar study, Carter and Pearen (1989) reported that applications of gypsum at a fraction of the soil GR, and ammonium nitrate (80 kg N/ha) reduced the SAR of a saline sodic soil from 29.0 to approximately 15.0 and 1.7 after 3 and 6 years, respectively. In consequence, the Ca concentration and the ratio of K/Na in the foliage of the bromegrass was increased.

Combined applications of 4 ton gypsum plus 50 kg zinc sulphate/ha on saline sodic soil gave a 256% increase in the yield of wheat compared to the control (Patel et al., 1986). Gypsum incorporated with moldboard plow was more effective in increasing yield than when mixed in the surface soil. Gypsum also increased N, P and K uptake by the crop. Moreover, Keshwa and Singh (1988) reported a significant increase in wheat yield and NP uptake with the application of gypsum at 50% GR followed by pyrites. Kumar (1990) studied the effect of gypsum application on six different forage species grown on a highly sodic soils and found that application of gypsum increased green forage yields of all crops.

A highest gypsum use efficiency was found when gypsum was applied to a sodic soil at the lowest rate (25% GR) because of the shorter time required for its dissolution (Gupta et al., 1988). Gypsum at 50% and 75% GR showed highest efficiency after the 3rd and 4th cropping season, respectively, suggesting that all the applied gypsum was dissolved within 2 years after application. Increasing rates of applied gypsum also increased yields of both rice and wheat crops grown on sodic soils (Sharma and Gupta, 1986; Gupta et al., 1988). Pyrites was almost as effective as gypsum in reducing sodicity and increasing yields of rice and wheat crops (Sharma and Gupta, 1986). Moreover, Swarup (1991) reported that gypsum application decreased the soil pH and ESP and increased the grain and straw yields and Zn, Fe and Mn concentrations of rice plant. When green manure and FYM were applied with gypsum, rice yield increased further.

In pot trials with a wheat/rice/wheat cropping sequence on sodic soils, gypsum increased yield of the third wheat crop only, whereas FYM increased the dry matter

yields of all three crops (Sachdev and Deb, 1990). However, gypsum markedly decreased the pH of the soil, while FYM was less effective in decreasing soil pH. Similarly, Singh and Abrol (1988) observed increasing yield of wheat up to the fourth year after gypsum application to sodic soil suggesting that gypsum solubility is very low. They also noted more improvement of ESP in deeper layers of the soil from the fourth year onward.

Costs of sodic soil reclamation can be reduced when coarse-grade gypsum is used, as the production and transport prices of this gypsum are much lower than that of agricultural-grade gypsum. Realizing this, Elshout and Kamphorst (1990) conducted a laboratory experiment to evaluate the leaching water requirement for five gypsum grades with different particle size distributions. The results indicated that the leaching water requirements do not differ significantly for the mixtures studied, provided that the percolation rates are low. The total time of reclamation increases with increasing particle size. Among the different methods of application tested, the largest efficiency was obtained when an amount equal to the GR was partly mixed with the soil and partly applied to the soil surface (Elshout and Kamphorst, 1990). This makes the process of sodium affected soil reclamation using gypsum much more time and energy consuming.

CHAPTER 3

MATERIALS AND METHODS

1. General Description of Experiments

The objectives of the overall saline sodic soil reclamation project were evaluated by conducting four different series of experiments. Moreover, three of these four series of experiments consisted two sets of experiments: one using gypsum and the other using langbeinite. The first of these series of experiments dealt with the characterization and investigation of the salinity and sodicity related properties of two soil types and irrigation water from Safford Agricultural Research Center of the University of Arizona. The results of this experiment were then used to determine the appropriate type of soil and water to be used in the experiments to follow. Accordingly, the Grabe clay loam soil and the well water used for irrigating the soil were selected and used in the subsequent experiments.

In the second experiment, the ease of displacement of exchangeable sodium by the application of varying rates of gypsum and langbeinite was studied by the use of laboratory batch studies. To this end, two sets of independent trials, that is one using varying rates of gypsum and another using varying rates of langbeinite were carried out side by side. Based on the results of the first experiment, the laboratory batch studies were conducted using the Grabe clay loam soil and the irrigation water of Safford Agricultural Research Center. This experiment investigated the appropriate ranges of gypsum and langbeinite levels that would be advanced to the laboratory column studies.

The third experiment consisted of two sets of laboratory column leaching studies involving gypsum and langbeinite independently as reclaiming materials. Gypsum and langbeinite rates considered in this experiment were selected based on the results of the laboratory batch studies. In addition to varying rates of gypsum and langbeinite, varying volumes of leaching water were also studied in this phase of study. The varying rates of gypsum and varying volumes of leaching water were therefore combined in factorial arrangements. Similarly, the varying rates of langbeinite and varying volumes of leaching water were arranged under factorial experiments. The results of this phase of experiment enabled among other benefits, the selection of promising rates of gypsum and langbeinite and volumes of leaching water to be used as treatments in the next series of experiment.

The last series of experiment investigated the response of a sodium sensitive (indicator) crop to the effects of different rates of applied gypsum and langbeinite and varying volumes of leaching water under greenhouse conditions. In line with the laboratory batch and column studies, the greenhouse crop response experiments considered the use of gypsum and langbeinite independently in two distinct sets of trials. The respective amendment rates and volumes of leaching water under each set of trial were factorially combined.

The rates of gypsum and langbeinite as well as the different volumes of leaching water studied in the greenhouse experiment were selected based on the results of the laboratory column leaching studies. Unlike the other experiments, each set of this phase of experiment was conducted twice. In the first experiment, the irrigation water of Safford Agricultural Research Center was used to leach the soils and irrigate the

greenhouse crop throughout its growth period for both sets of trials. Tucson tap water was used both for leaching and irrigation purposes during the second period for both sets of trials.

2. Experiment I: Soil and Irrigation Water Sampling and Characterization

Composite surface soil samples (0-20 cm) were collected from the Grabe clay loam (field B) and Guest clay (field J) soils of Safford University of Arizona's Agricultural Research Center. The locations in the field of the two soil types are shown on a farm map (Fig. 1). Soil physical analysis data by Post et al. (1977) indicated that the Grabe soil is clay loam in texture with a particle size distribution of 29.5% sand, 37.5% silt and 33.0% clay, whereas the Guest soil is heavy clay (2.8% sand, 36.5% silt, and 60.7% clay) in texture. The carbonates at the soil surface reported as calcium carbonate equivalent of the Grabe clay loam and Guest clay soils are 1.8 and 1.9, respectively. Montmorillonite was the most abundant clay mineral constituent followed by mica and kaolinite in the A horizons of both soil types (Post et al., 1977).

The Grabe clay loam soil was irrigated with well water and the Guest soil with river water when available and with well water at other times. Neither soil was known to be sodic, but according to the Center Manager, these are the most likely sodic soils on the farm. Therefore, it was necessary to evaluate the sodicity and salinity related characteristics of the soils and the water used for irrigating the soils.

In line with this, the composite soil samples collected from both soil types were air dried, ground and passed through a 2mm size sieve. Saturated soil paste extracts were prepared from the soil samples that passed through the 2mm sieve. The saturation

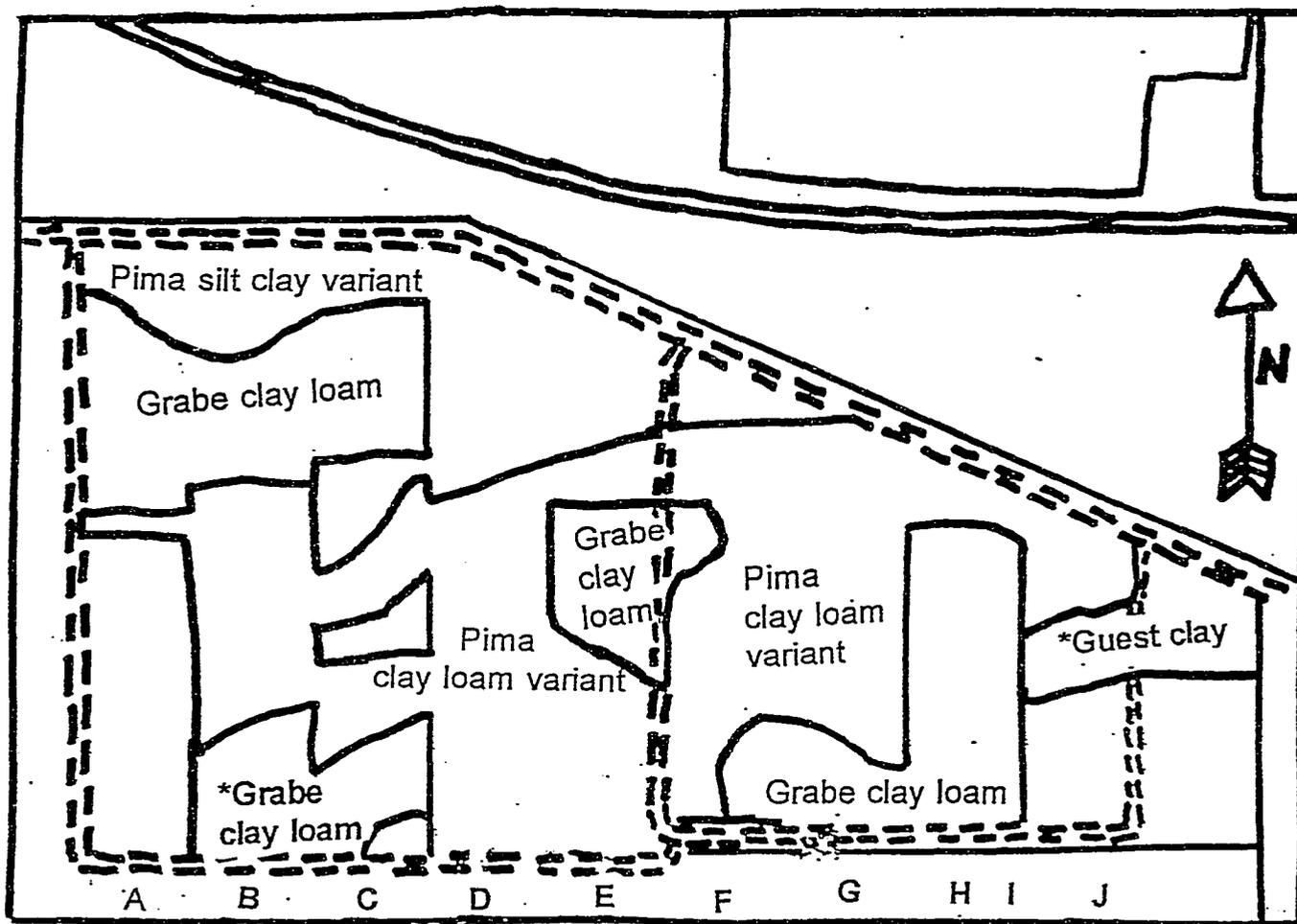


Fig. 1. Soil map and location of the Grabe clay loam and Guest clay soils of Safford Agricultural Research Center of the University of Arizona.

extracts were analyzed for pH, EC, soluble cations (Ca^{2+} , Mg^{2+} , Na^+ and K^+) and anions (Cl^- , SO_4^{2-} , NO_3^- , NO_2^- , and HCO_3^-). Exchangeable cations and cation exchange capacity (CEC) were determined from ammonium acetate/sodium acetate extracts made after a repeated washing of the soil sample with isopropyl alcohol to remove the water soluble constituents of the soil.

Inductively Coupled Plasma (ICP) emission spectroscopy was used to measure the concentrations of the soluble cations in the saturated soil paste extracts. Similarly, the exchangeable cations and CEC in the ammonium acetate/sodium acetate extracts were determined using ICP emission spectroscopy. Anions in the saturation extracts were analyzed using ion chromatography. Exchangeable sodium percentage (ESP) was calculated as a percentage of exchangeable sodium content to CEC when both quantities were expressed in meq/100g soil. Sodium adsorption ratio (SAR) of the soil solution was calculated from the concentrations of soluble Na^+ , Ca^{2+} , and Mg^{2+} as follows:

$$SAR = \frac{Na}{\sqrt{\frac{(Ca+Mg)}{2}}}$$

when all constituent concentrations are expressed in meq/l.

The results of the soil analysis indicated that the Grabe clay loam soil was more appropriate for the overall study. Thus, the well water that is used to irrigate the Grabe clay loam soil was evaluated for its chemical properties related to its quality for irrigation purposes. Chemical constituents of the irrigation water analyzed include pH, EC, cations

(Ca, Mg, Na and K) and anions (Cl, SO₄, NO₃, F and Br). The cations were analyzed using ICP emission spectroscopy, whereas the anions were determined using ion chromatography. SAR for the irrigation water was calculated from the concentrations of Na, Ca and Mg analyzed from same using the formula given above. Adjusted SAR for the irrigation water were calculated from its SAR and pH_c as follows:

$$\text{Adjusted SAR} = \text{SAR} (1 + (8.4 - \text{pH}_c))$$

Concentrations of Ca, Mg, HCO₃ and CO₃ and second dissociation constant of H₂CO₃ (pK₂) and solubility product of CaCO₃ (pK_c) were used to compute pH_c (calculated pH of the irrigation water when equilibrated with CaCO₃) using the formula given below:

$$\text{pH}_c = (\text{pK}_2 - \text{pK}_c) + \text{p}(\text{Ca} + \text{Mg}) + \text{p}(\text{HCO}_3 + \text{CO}_3)$$

The concentrations of the different cations and anions in the equation above were expressed as moles of charge per liter.

Analysis of all constituents in the soils and irrigation water were made in triplicate samples. Therefore, data of chemical properties thereof presented in the results and discussion section are averages of three repeated analysis results.

3. Experiment II. Laboratory Batch Studies

The objective of this phase of experiment was to determine the ease of displacement of exchangeable sodium using varying amounts of langbeinite and gypsum and thereby identify promising range of amendments levels that can be promoted for further studies under simulated field (packed column) conditions. Accordingly, two sets of trials: one involving langbeinite and another involving gypsum as chemical amendments were conducted side by side. In the first set of trial, eleven different rates

of langbeinite corresponding to 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0 g/100g soil were used as treatments. Similarly, in the second set of trial, gypsum at rates same as that of langbeinite were used. These rates correspond to 0, 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 tons of gypsum and/or langbeinite per ha.

A 1:1 soil to water suspensions were prepared by mixing 100g of the Grabe clay loam soil to 100 ml of irrigation water for each rate of gypsum and langbeinite. The predetermined rates of gypsum and langbeinite were weighed and added to each suspension flasks. The suspensions were thoroughly mixed, stirred occasionally and allowed to stand overnight. After 24 hours of soaking, the suspensions were shaken and centrifuged at 1500 revolutions per minute for 15 minutes. The supernatant liquids were filtered and saved for the analysis of sodium displaced as a result of the applications of the chemical amendments.

Concentrations of sodium in the essentially 1:1 soil:water extracts were determined by atomic absorption spectrophotometer using its emission line. The sodium content measured in the control 1:1 soil:water suspensions (no gypsum and/or langbeinite added) represents the soluble sodium in the soil plus the sodium present in the irrigation water. Whereas the sodium measured in the suspensions where either gypsum or langbeinite were added represent the soluble sodium present in the soil, the sodium present in the irrigation water plus the exchangeable sodium displaced due to the application of the respective amounts of the amendments.

Therefore, exchangeable sodium displaced due to gypsum and langbeinite applications were obtained by subtracting the soluble sodium determined in the 1:1

soil:water extracts prepared without gypsum and/or langbeinite from that determined on the extracts treated with the amendments. The exchangeable sodium displaced was then subtracted from the exchangeable sodium of the soil determined prior to reclamation to obtain the amount that remained in the soil after reclamation. The ESP after reclaiming the soil with gypsum and langbeinite was calculated as the percentage of exchangeable Na remained in the exchange complex to the CEC determined in the original soil sample.

To minimize errors of undertaking the overall experiment and analytical procedures, each of the 1:1 soil:water suspensions and the analytical procedures thereafter were made in duplicate samples whose variance can be analyzed using a procedure appropriate for completely randomized design (CRD). The amount of sodium displaced from the exchange site and the ESP that remained in the soil after the applications of the amendments were computed and compared both within treatments of the same amendment and between treatments of the different amendments. Finally, the results of exchangeable sodium displaced and the new ESP were reported as averages of two replicate analysis results. Based on the results of the laboratory batch studies, seven rates of gypsum and seven rates of langbeinite including the control (no gypsum/no langbeinite applied) that appeared promising and representing the optimum ranges of the respective amendment concentrations were promoted for leaching reclamation studies involving packed column conditions in the laboratory.

4. Experiment III. Laboratory Column Leaching Studies

In accordance with the laboratory batch studies, two sets of independent trials: one using seven different rates of gypsum and another one using seven different rates of

langbeinite were conducted in the laboratory under packed column conditions. In addition to the determination of the optimum levels of gypsum and langbeinite required for saline sodic soil reclamation, this phase of experiment was also geared to investigate the amount of leaching water required to effect the dissolution, exchange reaction and leaching of displaced sodium under comparable mass rates of the two distinct types of chemical amendments. Therefore, each of the sets of trials was conducted using four different volumes of leaching water. The different rates of gypsum and langbeinite were combined with the varying volumes of leaching water in factorial arrangements.

Accordingly, each set of trial was conducted as a 7 X 4 factorial arrangement in a completely randomized design with two replications. The treatment combinations for the gypsum and langbeinite column studies are presented in Table 1 and 2, respectively. Data points for the parameters considered were, however, collected for every half a pore volume of applied leaching water and are accordingly presented in the "Results and Discussion" section. The column was 15cm long and 5cm in diameter. Each time the treatment is changed the column was packed to approximately field soil condition with an average soil weight of about 435g per column. In the trials involving gypsum, the predetermined amount of gypsum was weighed and mixed with the soil before packing. This procedure is parallel with the traditional way of applying gypsum to the field soil for reclaiming sodic and saline sodic soils. The packed column was then hung vertically and slowly saturated with the irrigation water from the bottom of the column.

With regards to the langbeinite treatments, each column was packed with an average soil weight same as that with gypsum. The predetermined rates of langbeinite

Table 1. Treatment combinations of the column leaching studies with the application of gypsum.

Gypsum rates (tons/ha)*	<u>Amount of leaching water in pore volume (pv)</u>			
	1pv	2pv	3pv	4pv
G0(0)	G0,1pv	G0,2pv	G0,3pv	G0,4pv
G1(2)	G1,1pv	G1,2pv	G1,3pv	G1,4pv
G2(4)	G2,1pv	G2,2pv	G2,3pv	G2,4pv
G3(6)	G3,1pv	G3,2pv	G3,3pv	G3,4pv
G4(8)	G4,1pv	G4,2pv	G4,3pv	G4,4pv
G5(10)	G5,1pv	G5,2pv	G5,3pv	G5,4pv
G6(12)	G6,1pv	G6,2pv	G6,3pv	G6,4pv

* Figures in parenthesis indicate gypsum rates in tons/ha

were weighed and dissolved in one pore volume of irrigation water and the soil packed column was saturated with the pore volume of solution containing the respective amounts of langbeinite. Each column in both sets of trials was slowly but completely saturated as indicated by water appearing in the tubes on the top end of the column. After the appearance of water in the tubes on the top end of the column, each column was kept for

Table 2. Treatment combinations for the column leaching studies with langbeinite.

Langbeinite rates (tons/ha)*	<u>Amount of leaching water in pore volume (pv)</u>			
	1pv	2pv	3pv	4pv
L0(0)	L0,1PV	L0,2pv	L0,3pv	L0,4pv
L1(2)	L1,1pv	L1,2pv	L1,3pv	L1,4pv
L2(4)	L2,1pv	L2,2pv	L2,3pv	L2,4pv
L3(6)	L3,1pv	L3,2pv	L3,3PV	L3,4pv
L4(8)	L4,1pv	L4,2pv	L4,3pv	L4,4pv
L5(10)	L5,1pv	L5,2pv	L5,3pv	L5,4pv
L6(12)	L6,1pv	L6,2pv	L6,3pv	L6,4pv

* Figures in parenthesis are langbeinite rates in tons/ha

10-12 hours to insure complete saturation and facilitate the exchange reaction. The volume of water that the soil in the column can hold (or the pore volume) were determined from the difference of the weights of the saturated column and the dry soil packed column. The saturated columns were therefore leached by applying the predetermined amounts of pore volumes of water which varied depending on the treatment combinations.

While leaching the soil, the required volumes of leaching water was applied to the column by maintaining a constant hydraulic head. This was done by pumping water from a pool of irrigation water in to a plastic container that was connected to the upper end of the column through a plastic tube at its bottom end and has an outlet at the center to allow the water in excess of the desired head level to drain out in to the pool of irrigation water. Whenever necessary, the head level was changed by keeping records of time and the new head level and labelling the volume of water collected during the specific time.

The water passing through the column (eluent) was collected in plastic tubes using an autosampler programmed by time. This allowed measuring the volume of water that can pass through the soil in the column at a known time interval and known hydraulic head. A direct measurement of EC of the eluent was made by an EC meter whose electrode is connected to the extract outlet tubing. The Meter was programmed to measure the EC of the eluent at an interval of 15 minutes. The measured EC values were then automatically recorded by a computer connected to the EC meter.

Saturated hydraulic conductivity of the soil was calculated after every half a pore volume of water was passed through the column. To calculate the saturated hydraulic conductivity, the flux density (J_w) was first calculated as follows:

$J_w = V/AT$, where J_w (cm/hr) is the flux density, V (cm³) is the volume of extract passed through the column at a given time, A (cm²) is the area of the column and T (hr) is the time taken to collect the extract. Once the flux density is known, the

saturated hydraulic conductivity (k_{sat}) was calculated using Darcy's Law for constant head permeameter as follows:

$K_{sat} = (Jw*L)/H_2-H_1$, where K_{sat} (cm/hr) is saturated hydraulic conductivity, L (cm) is the length of column and H_2-H_1 (cm) is the hydraulic head difference.

The concentration of sodium in the column leachates for each treatment of gypsum and langbeinite was determined by atomic absorption spectrophotometer using the emission line. The sodium displaced due to the application of different rates of chemical amendments was obtained by subtracting the amount of sodium measured in the eluent of the columns where no gypsum and/or no langbeinite was applied (control) from that measured on the eluent treated with different rates of the amendments. Similarly, the sodium remained unexchanged in the exchange site after the reclamation procedure was determined by subtracting the exchangeable sodium displaced due to the applied respective amendment rates and volumes of leaching water from the exchangeable sodium measured in the original soil sample during initial characterization. The new ESP (ESP after reclamation) was then calculated as the percentage of the sodium that remained in the exchange complex to the CEC of the original soil sample.

As each treatment was conducted in duplicates, data of either ESP and/or exchangeable sodium content presented in the text are averages of two observations. Exchangeable sodium content displaced and the resultant ESP values for both sets of trials were statistically analyzed using a procedure appropriate for CRD. Depending on the results of the column studies, the four better performing gypsum rates including the control (no gypsum applied) and three volumes of leaching water were promoted for crop

response evaluation under greenhouse conditions. Moreover, the four better performing rates of langbeinite including the control (no langbeinite applied) along with three volumes of leaching water were promoted for the greenhouse study from the second set of trial. Furthermore, both sets of trials included an additional control treatment where neither any of the chemical amendments nor leaching water was applied.

5. Experiment IV. Greenhouse Crop Response Studies

Based on the results obtained from the laboratory column leaching experiments, two sets of greenhouse crop response studies were conducted side by side at the UA Campus Transgenic greenhouses between February and September 1995. The first set of experiment was carried using four rates of gypsum (0, 4, 8, and 12 tons/ha) and three volumes (1.5, 2.5, and 3.5 pore volumes) of leaching water. In addition a control involving application of neither gypsum nor leaching water was included as a treatment. The varying gypsum rates and volumes of leaching water were therefore combined in a 4x3 factorial arrangement. Including the control, the factorial arrangement of the various treatments of the two factors yielded a total of 13 treatment combinations. Consisting of 13 treatment combinations, this set of experiment was conducted in a CRD with three replications.

The second set of trial was conducted using four rates of langbeinite (0, 4, 8, and 12 tons/ha) and three volumes (1.5, 2.5, and 3.5 pore volumes) of leaching water. Moreover, as with gypsum, a control (without langbeinite and no leaching) treatment was included in the study. In accordance with that of gypsum, this experiment was also conducted in a 4x3 factorial arrangement under a CRD. Including the control, the trial

consisted of a total of 13 treatment combinations. In harmony with that of gypsum, this study was conducted by replicating the treatment combinations three times.

In undertaking the greenhouse crop response studies, 2.5 kg of Grabe clay loam (saline sodic) soil sample collected from Safford Agricultural Research Center was weighed and placed in plastic pots. In the first trial, the respective amounts of gypsum were weighed and thoroughly mixed with the soil before potting. Whereas with langbeinite, the respective rates were weighed and applied to the potted soils along with one pore volume of irrigation water. Accordingly, the soil in the pots receiving gypsum was saturated by applying one pore volume of water. The saturated soils that were treated both with gypsum and langbeinite were then left standing for 24 hours to aid dissolution of the amendments and facilitate the reaction between the constituents of the amendments and the soil exchange site.

After 24 hours, about 100ml of water was added to each pot to bring the soil back to complete saturation state. The predetermined volumes of leaching water was then applied to the soils in each pot immediately after complete saturation. After leaching, the soils in the pots were left to drain and partially dry. The freely drained and partially dried soils were loosened and each pot was planted with six seeds of lima bean crop. The number of lima bean seeds germinated were counted and recorded to determine the effect of the treatment combinations on germination rate of the crop. Following full seedling development stage, the plants in each pot were thinned to three final stands if the germination rate was greater than 50%. No thinning were made on pots with germination rates of 50% or less. The final dry matter yield measurements were made on the three

or less crop stands that were left to grow to maturity.

Each of the two sets of the greenhouse crop response studies were conducted two times. During the first time, the Safford irrigation (well) water was used both for leaching the soils and irrigating the crop throughout its growth stage for both the trials involving gypsum and langbeinite. The second trials with both the amendments were conducted using Tucson tap water both for leaching and irrigation purposes.

A lima bean is a crop very sensitive both to soil salinity and soil sodicity. Therefore, the experiment using Tucson tap water was conducted because the Safford irrigation water was saline (EC: 2 mmhos/cm) and so had potentially masked the effect of the treatments. Moreover, in the second experiment, nitrogen and phosphorus fertilizers at flat rates of 64 kg N/ha and 80 kg P₂O₅/ha were applied. The fertilizers were applied in response to the nitrogen and phosphorus deficiency symptoms observed on the crop during the first experiment.

The first experiment involving both gypsum and langbeinite was conducted between February and May 1995. The second batch of experiments of both the amendments were carried out between June and September 1995. The crops of both the first and second trials of the two sets of experiments reached maturity in about three months after planting. The above ground part of the crops in each pot were then harvested and a total dry matter yield was determined. Finally, the germination rate and the dry matter yield data were subjected to statistical analysis appropriate to CRD. The mean germination percentage and dry matter yield data were compared both within and between treatments.

CHAPTER 4

RESULTS AND DISCUSSION

1. Experiment I. Initial Characterization of Soils and Irrigation Water

As observed in the field and according to the Center Manager, the Grabe clay loam and the Guest clay soils were the most likely sodic soils at the Safford Agricultural Research Center. These soils were therefore evaluated for their chemical properties related to soil salinity and sodicity. Table 3 presents the soluble chemical properties of both the Grabe clay loam and the Guest clay soils. Similarly, the exchangeable chemical properties of both the soils under study are presented in Table 4.

The Grabe clay loam and the Guest clay soils were both moderately alkaline (pH: 8.2-8.3) in reaction. With regards to salinity, the Grabe clay loam met the requirements ($EC_e > 4$ mmhos/cm) of the U. S. Salinity Laboratory Staff (1954) to be classified as a saline soil. Whereas the Guest clay soil with an average EC_e of 3.85 mmhos/cm was slightly below the minimum requirement for a soil to be generally classified as a saline soil based on the traditional classification system mentioned above.

Sodium followed by calcium were the dominant soluble cations in both the Grabe clay loam and Guest clay soils (Table 3). In the Grabe clay loam soil, Cl^- followed by HCO_3^- and NO_3^- in this order were the dominant anions. Whereas in the Guest clay, Cl^- followed by NO_3^- and HCO_3^- in this order were the dominant anions. Soluble sulphate content in the Grabe clay loam soil was relatively higher than in the Guest clay soil. The mean SAR (21.6) of the Grabe clay loam soil was considerably higher than the mean SAR (11.91) of the Guest clay soil (Table 3).

Table 3. Soluble chemical properties of Safford Grabe clay loam and Guest clay soils as measured from saturated soil paste extracts.

Sample No.	pH	ECe, mmhos/cm	Soluble cations				K	SAR	F	Cl	Soluble anions			HCO ₃
			Ca	Mg	Na						NO ₂	NO ₃	SO ₄	
			meq/l	meq/l	meq/l	meq/l				meq/l	meq/l	meq/l		
Grabe clay loam soil														
A	8.2	5.3	11.3	2.0	55.7	0.6	21.6	0.2	24.6	0.4	13.4	7.0	23.2	
B	8.1	5.3	11.4	1.7	55.2	0.5	21.6	0.2	24.3	0.3	13.3	7.0	23.2	
C	8.2	5.3	11.5	1.8	55.7	0.5	21.6	0.3	25.0	0.5	13.6	7.1	23.2	
Mean	8.2	5.3	11.4	1.8	55.5	0.6	21.6	0.2	24.6	0.4	13.4	7.0	23.2	
Guest clay soil														
A	8.2	4.0	10.0	2.2	30.4	0.6	12.3	0.2	22.2	0.5	8.9	4.0	7.3	
B	8.3	3.8	9.5	2.1	30.0	0.6	12.4	0.2	20.2	0.5	8.5	3.9	7.3	
C	8.3	3.8	9.6	2.2	26.7	0.6	11.0	0.2	20.3	0.4	8.4	3.8	7.3	
Mean	8.3	3.9	9.7	2.2	29.0	0.6	11.9	0.2	20.9	0.5	8.6	3.9	7.3	

The order of predominance of the exchangeable cations in the Grabe clay loam and the Guest clay soils was identical. In both soils, exchangeable Ca was the highest and was followed by exchangeable Na, Mg and K (Table 4) in this order. However, the average CEC (66.1 meq/100g soil) of the Guest clay soil was over three times greater than the average CEC (20.86 meq/100g soil) of the Grabe clay loam soil. Although, the exchangeable sodium content of the Guest clay was about twice that of the Grabe clay loam, the ESP (24.94) for the Grabe clay loam was appreciably higher than the ESP (18.15) of the Guest clay soil (Table 4).

According to the criteria established by the U. S. Salinity Laboratory Staff (1954), both the Grabe clay loam and the Guest clay soils met the requirements (ESP > 15) of a sodic soil. However, the Grabe clay loam soil was more strongly sodic than the Guest clay as indicated by its significantly higher ESP values (Table 4). The higher SAR values of the Grabe clay loam than that of the Guest clay (Table 3) is also an evidence of the greater degree of sodicity of the Grabe clay loam compared to the Guest clay soil.

The unusually very high values of exchangeable Ca contents in the Grabe clay loam and particularly in the Guest clay soils may be attributed to the contribution from the Ca that exists as precipitated in the form of calcium carbonate. Calcium carbonate commonly exists in appreciable quantities in sodic and saline sodic soils of arid regions. Moreover, Post et al. (1977) reported an appreciably higher quantities of calcium carbonate in both the Grabe clay loam and Guest clay soils. Although it is insoluble or only slightly soluble in water, calcium carbonate readily dissolves in ammonium acetate solution and is a major source of error in Ca and CEC determinations.

Table 4. Exchangeable chemical properties of Safford Grabe clay loam and Guest clay soils

Sample No.	Exchangeable cations (meq/100g soil)				CEC (meq/100g)	ESP from CEC
	Ca	Mg	Na	K		
Grabe clay loam soil						
A	32.1	3.0	5.3	1.1	20.4	25.9
B	31.0	2.8	5.1	1.4	21.4	24.0
C	32.8	3.0	5.2	1.2	20.9	24.9
Mean	32.0	2.9	5.2	1.2	20.9	24.9
Guest clay soil						
A	53.4	8.6	12.0	3.2	66.5	18.1
B	52.4	8.2	11.7	3.2	75.3	15.5
C	55.0	9.1	12.3	3.5	56.5	21.7
Mean	53.6	8.6	12.0	3.3	66.1	18.2

Therefore, the dissolution of calcium carbonate mineral and the release of Ca during the extraction of the exchangeable cations using ammonium acetate solution was the most likely source of error in the determination of Ca actually adsorbed by the soil exchange site. Similar error could also be encountered with the determination of exchangeable Mg using the same method if the soil contains carbonate minerals of Mg such as dolomite (Determination(CO_3)).

Based on the soluble (Table 3) and exchangeable (Table 4) chemical properties and more specifically the E_{Ce} (> 4 mmhos/cm) and the ESP (> 15%), the Grabe clay loam was classified as a saline sodic soil. Moreover, the Guest clay was classified as sodic and slightly saline soil. The pH of both soils also being less than 8.5 agreed with the generally accepted characteristics of saline sodic soils. However, as indicated by its higher ESP and E_{Ce} values, the Grabe clay loam soil was more strongly saline sodic than the Guest clay soil. As a result, the Grabe clay loam soil was preferred, and hence selected, over the Guest clay to be used as an experimental unit in the overall study involving the evaluation of the potential use of langbeinite, relative to gypsum, as a reclaiming material for sodic and saline sodic soils.

In line with the selection of the Grabe clay loam soil, the chemical properties of the water used to irrigate the soil (well water) which affects its quality for irrigation purposes were evaluated in the laboratory. Table 5 presents the results of the laboratory analysis made on the irrigation or well water. The irrigation water was slightly alkaline (pH 7.8) in reaction. Moreover, the irrigation water contained very high amount (EC: 2.0 mmhos/cm) of dissolved salts that makes its use for irrigation purposes questionable.

Sodium followed by magnesium were the dominant cations and Cl^- followed by SO_4^{2-} were the dominant anions in the ionic composition of the irrigation water (Table 5). The water also contained an appreciable quantity of NO_3^- nitrogen. The high salinity level of the irrigation water explains the salinity of the Grabe clay loam soil. The SAR value (8.7) was also high enough to turn a nonsodic soil in to a sodic soil. In general the practice of continued use of irrigation water with high level of soluble salts and high SAR values without or with minimum periodic leaching are the most common causes of soil salinity and sodicity, respectively (U. S. Salinity Laboratory Staff, 1954; Frenkel et al., 1978; Shainberg et al., 1981a; Bohn et al., 1985; Gupta and Abrol, 1990; Ghassemi et al., 1995).

2. Experiment II. Laboratory Batch Studies

The ease of displacement of exchangeable sodium from a saline sodic soil (the Grabe clay loam soil) in response to the applications of different levels of gypsum and langbeinite as chemical amendments was evaluated in a laboratory batch studies involving 1:1 soil:irrigation water extracts. Table 6 presents the quantities of exchangeable sodium replaced due to the application of different levels of gypsum. Similarly, the quantities of exchangeable sodium replaced due to applied levels of langbeinite are shown in Table 7.

As it can be seen from the data in these Tables, applying gypsum and langbeinite at varying rates released appreciable amounts of exchangeable sodium as a result of the exchange reactions between the cations contained in the chemical amendments and the sodium present in the soil exchange site. However, the amount of exchangeable sodium

Table 5. Some selected chemical composition of safford irrigation (well) water.

pH	EC (mmhos /cm)	SAR	Adj. SAR	Ca	Mg	Na	K	Br mg/l	Cl	NO3	SO4	SO4
7.8	2.0	8.7	12.6	18.4	125.0	433.0	3.0	2.3	406.0	48.4	217.0	217.0

released from the soil exchange site due to gypsum and langbeinite applications when compared at an equal mass based rates of the chemical amendments differed significantly (Tables 6 and 7).

Increased rates of gypsum application after 4 tons/ha of gypsum did not reveal a significant increase in the release of exchangeable sodium (Table 6). However, the quantities of exchangeable sodium displaced from the soil exchange site as a result of langbeinite application increased almost linearly up to the maximum (20 tons/ha) rate of applied langbeinite (Table 7). At the lower rates of applied chemical amendments, gypsum appeared as efficient as langbeinite with regards the displacement of sodium from the soil exchange site. In fact, the mean exchangeable sodium displaced due to addition of gypsum at a rate of 4 tons/ha matched exactly (1.99 meq/100g soil) with the mean exchangeable sodium displaced due to the application of langbeinite at a rate equal to that of gypsum (Tables 6 and 7).

However, at higher rates of applied chemical amendments, langbeinite was far better than gypsum in displacing exchangeable sodium from the soil exchange complex. For example, gypsum applied at the maximum rate (20 tons/ha) displaced 2.12 meq. of exchangeable sodium/100g of soil. Whereas, langbeinite applied at the same maximum rate displaced 4.27 meq. of exchangeable sodium/100g of soil. Thus, the amount of exchangeable sodium displaced from the soil exchange site as a result of langbeinite application at the maximum rate was more than two times the amount displaced due to gypsum application at the same maximum rate.

Table 6. Exchangeable sodium (meq/100g soil) replaced as a result of different rates of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) application under laboratory batch studies.

Applied gypsum (tons/ha)	<u>Replication</u>		Mean*
	A	B	
0	0.00	0.00	0.00c
2	1.24	1.05	1.14b
4	1.87	2.10	1.99a
6	2.20	1.82	2.01a
8	2.10	1.98	2.04a
10	2.10	1.90	2.00a
12	1.78	2.35	2.06a
14	2.25	2.01	2.13a
16	2.04	2.18	2.11a
18	1.94	2.42	2.18a
20	2.05	2.18	2.12a

* Means followed by the same letter are not significantly different at the 0.05 probability level as tested by Duncan's Multiple Range Test.

Table 7. Exchangeable sodium (meq/100g soil) displaced as a result of different rates of langbeinite ($K_2SO_4 \cdot 2MgSO_4$) application under laboratory batch studies.

Applied langbeinite (tons/ha)	Replication		Mean*
	A	B	
0	0.00	0.00	0.00h
2	1.43	1.37	1.40g
4	2.31	1.67	1.99f
6	2.04	2.06	2.05f
8	2.31	2.36	2.34ef
10	2.54	2.60	2.57de
12	2.79	2.57	2.68de
14	3.02	2.88	2.95cd
16	3.02	3.48	3.25bc
18	3.50	3.36	3.43b
20	4.43	4.11	4.27a

* Means followed by the same letter are not significantly different at the 0.05 level as tested by Duncan's Multiple Range Test.

The amount of exchangeable sodium displaced due to the application of 20 tons/ha of langbeinite was statistically different ($P < 0.05$) compared to the amount of same displaced by any other rate of applied langbeinite (Table 7). Whereas the amount of

exchangeable sodium released by applying 20 tons/ha of gypsum was not significantly higher compared to the sodium released by applying 4 tons/ha of gypsum. In general, almost every increment of applied langbeinite displaced a significantly higher amount of exchangeable sodium (Table 7).

Fig. 2 compares the average quantities of exchangeable sodium displaced as a result of reclaiming the Grabe clay loam saline sodic soil using varying levels of applied gypsum and langbeinite. It is evident from the graphs that the efficiency of langbeinite in the removal of exchangeable sodium is nearly the same with that of gypsum when the applied levels of both chemical amendments were 6 tons/ha or lower. However, after this level, langbeinite appeared to be more efficient than gypsum in terms of the amount of sodium removed from the soil exchange sites (Fig.2).

The ESP of the soil studied after its reclamation with gypsum and langbeinite under the laboratory batch studies is presented in Fig. 3. Increasing the rate of applied gypsum from 0 to 20 tons/ha reduced the ESP of the soil from 24.9 to 14.8%. On the other hand, increasing the rate of applied langbeinite from 0 to 20 tons/ha lowered the ESP of the soil from 24.9 to 4.6%. Applying gypsum and langbeinite independently each at a rate of 12 tons/ha reduced the ESP of the soil to 15 and 12%, respectively (Fig. 3).

The increased displacement of exchangeable sodium with increasing rates of langbeinite as compared with that of gypsum is attributed more than any other reasons to the differences in their water solubility. Langbeinite is over 100 times more water soluble than gypsum (Hagstrom, 1986). Thus, since the batch studies were conducted in a 1:1 soil:irrigation water extracts irrespective of the applied levels of the amendments,

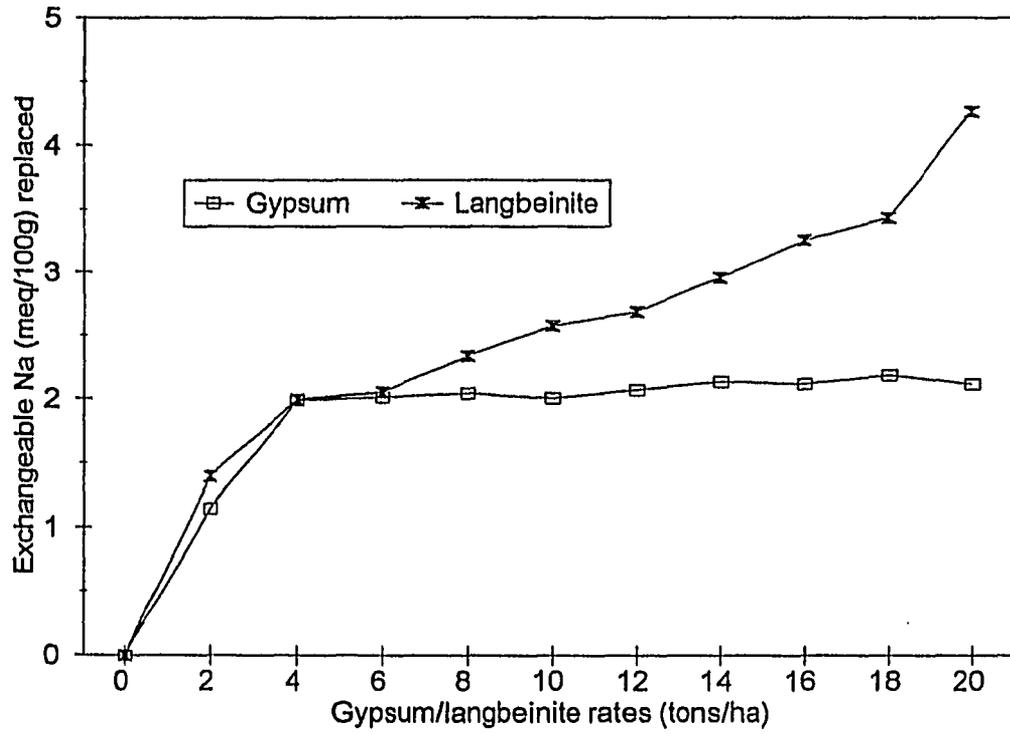


Fig. 2. Exchangeable Na (meq/100g soil) displaced due to gypsum and langbeinite applications under laboratory batch studies.

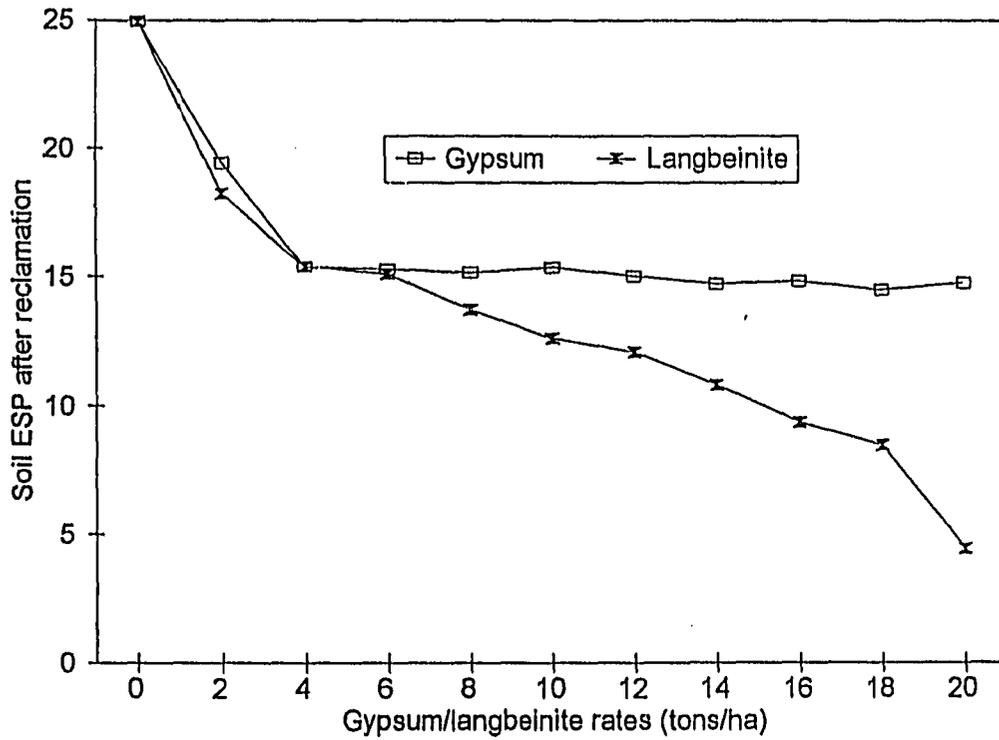


Fig. 3. ESP of the Grabe clay loam soil after its reclamation with different levels of gypsum and langbeinite amendments under laboratory batch studies.

the solubility of the higher rates of gypsum was limited by the amount of available water before that of langbeinite. Hence, increased rates of applied gypsum over 4 tons/ha did not contribute any more dissolved calcium ions available for exchange with adsorbed sodium. Whereas, with langbeinite more dissolved Mg and/or K ions were released with increasing rates of the applied chemical amendment and exchanged with the sodium ion on the soil exchange site.

Among the various treatments considered, seven levels of gypsum (0, 2, 4, 6, 8, 10 and 12 tons/ha) and seven levels of langbeinite (0, 2, 4, 6, 8, 10 and 12 tons/ha) were selected and promoted for further evaluation under laboratory column studies. The selection of these treatments was based on the results of the laboratory batch studies and the amount of exchangeable in the soil required to be displaced to convert the saline sodic soil into a nonsodic soil. Applying langbeinite at a rate of 12 tons/ha converted the saline sodic soil (ESP: 24.9) into a nonsodic soil (ESP: 12.0) under the batch studies. If dissolved in more water, gypsum applied at a similar rate could theoretically lower the ESP of the soil to an agriculturally acceptable level.

3. Experiment III. Laboratory Column Leaching Studies

In addition to the investigation of the ease of displacement of exchangeable sodium using gypsum and langbeinite as chemical amendments, this phase of the trial was also geared to determine the optimum amount of irrigation water required to dissolve the amendments, facilitate the exchange reaction, and leach the sodium salts that become part of the soil solution. Moreover, the effects of gypsum and langbeinite applications on the saturated hydraulic conductivity of the soil were evaluated and compared. Therefore, the

major parameters studied in this phase of the study were the electric conductivity of the eluent, the amount of exchangeable sodium displaced from the soil exchange site due to gypsum and langbeinite application, and the hydraulic conductivity of the soil in the column during and at the end of the reclamation process using both chemical amendments.

3.1. Electrical Conductivity of the Eluents

The EC of the eluent is a measure of the sum total of the salts in the water used for leaching, the soluble salts present in the soil and the sodium salts resulting from the exchange reaction between the applied amendments and the sodium adsorbed in the soil exchange site and thus become part of the soil solution. Therefore, the EC values of the eluent were measured throughout the leaching process using an EC meter whose electrodes are connected to the outlet (drain) tube of the columns. Such EC readings were taken every 15 minutes and were recorded automatically by a computer program.

The electrical conductivity of the columns leached without application of any of the chemical amendments is a measure of the salts in the water used for leaching and the soluble salts present in the soil. Therefore, the EC of the eluents from the columns treated with the chemical amendments in excess of the EC of the columns leached without adding the amendments is a contribution of the sodium salts formed from the reaction of the sodium released from the exchange site and the anions of the amendments. The EC of the eluents varied with type and rate of applied chemical amendments and with the amount of leaching water passed through the column or with the time of leaching. Selected typical EC breakthrough curves for the eluent of the

columns receiving different rates of the chemical amendments are presented in the following series of figures (Figures 4-10).

Fig. 4 presents the EC breakthrough curves for duplicate columns leached with neither langbeinite nor gypsum (L0- or G0-runs). The maximum EC readings for these columns varied from about 4.7 to 6.1 mmhos/cm. Both columns took about 11 hours of leaching to reach the maximum EC readings. After about 20 hrs. of leaching, the EC of the eluent remained constant at an EC of about 2.2 mmhos/cm (Fig. 4), which was approximately the EC of the irrigation water passing through the column.

The breakthrough curves for the EC of the columns which received 2 tons/ha of gypsum (G1-run) and 2 tons/ha of langbeinite (L1-run) are presented in Fig. 5. The maximum EC values recorded for both columns were almost the same (about 8.3 mmhos/cm). However, the peak EC values appeared at different times after the leaching processes were started. With langbeinite application, it took about 4 hrs. of leaching period to attain the maximum EC record. Gypsum required about 7 hrs. of leaching period to attain the maximum EC value (Fig. 5).

Moreover, the background (steady state) EC for the langbeinite treated column was reached at less than 10 hrs. of leaching period. But it required leaching for over 20 hrs. to attain the background EC for the column leached with the application of the same amount of gypsum (Fig. 5). These EC breakthrough curves generally indicated that less time and hence less leaching water is required to reclaim the saline sodic soil with the use of langbeinite than reclaiming it with the same amount of applied gypsum. As

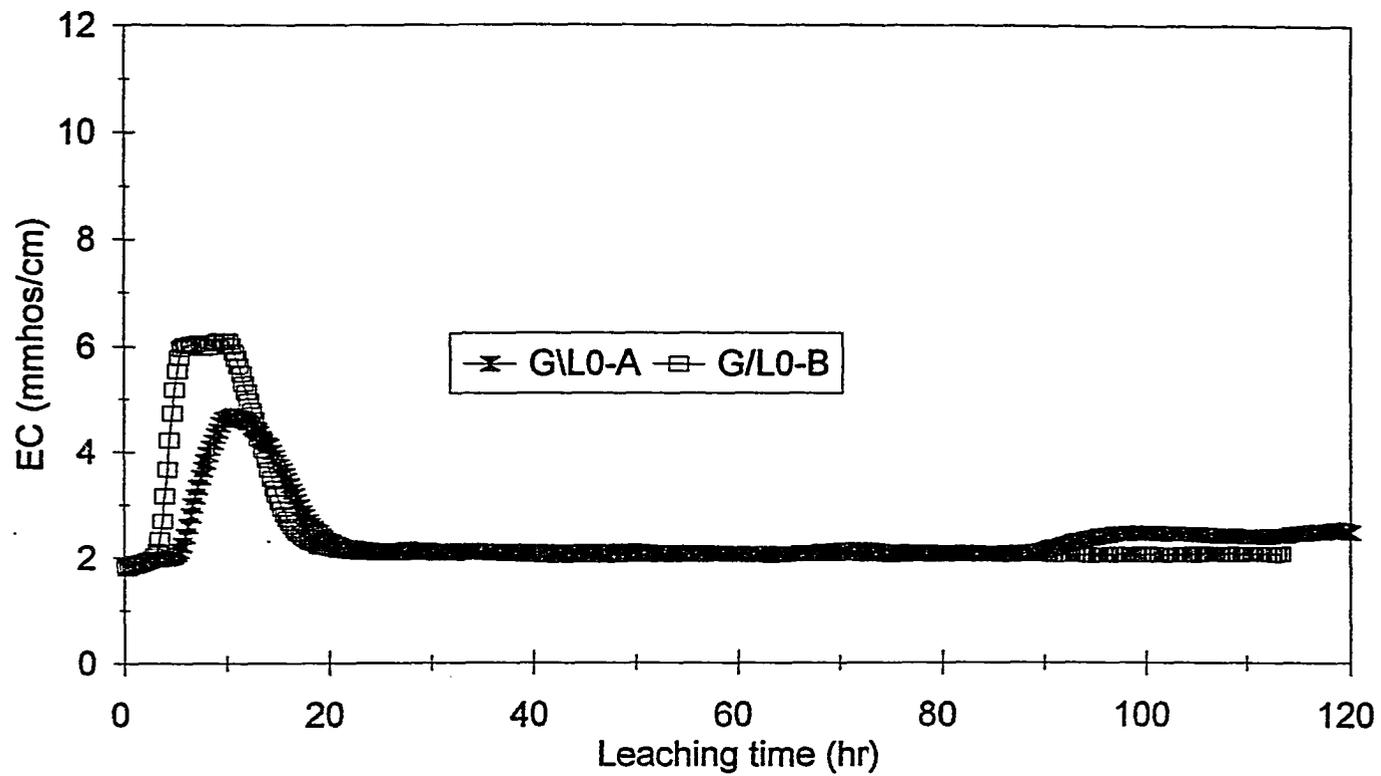


Fig. 4. EC breakthrough curves for the columns leached without the application of either gypsum or langbeinite amendments.

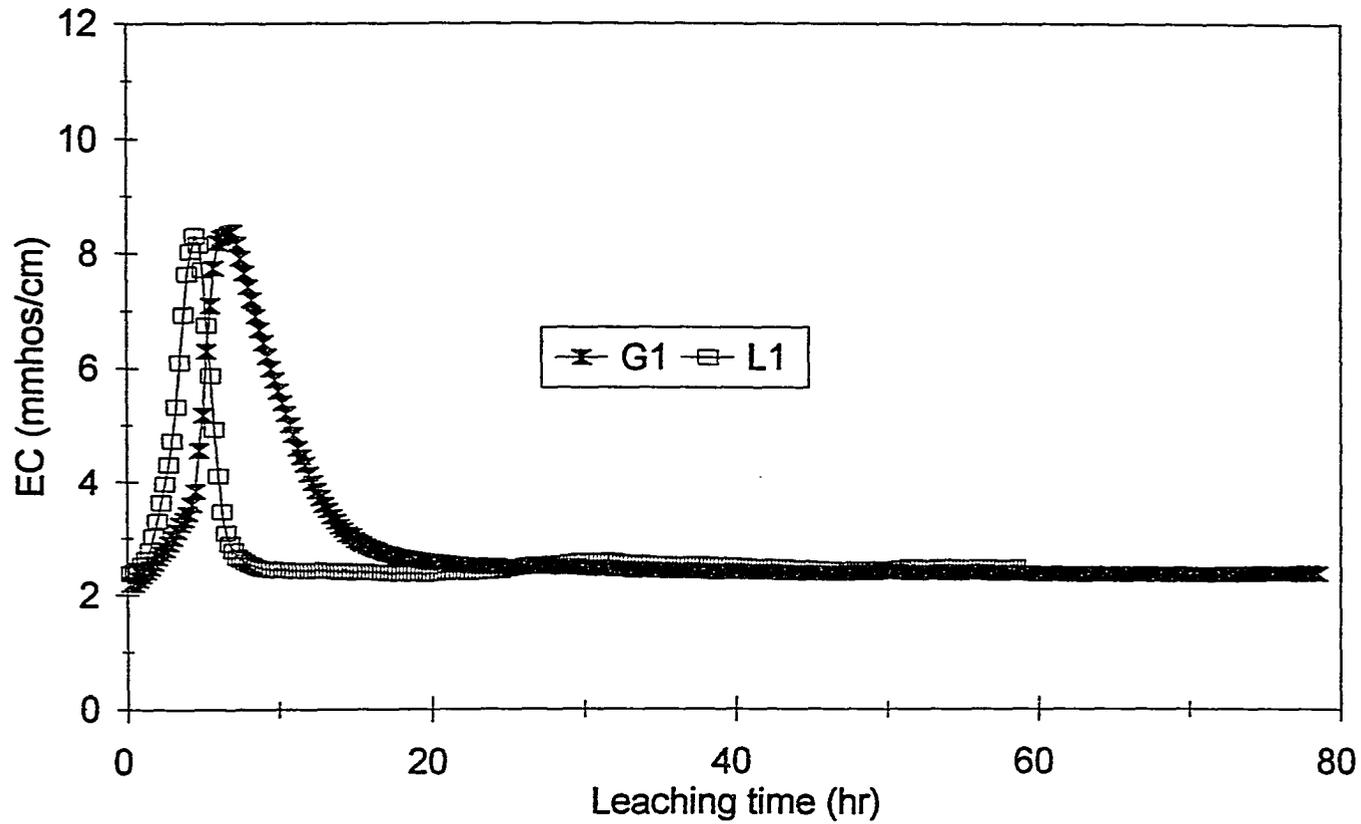


Fig. 5. EC breakthrough curves for the columns leached with the applications of 2 tons/ha of gypsum and 2 tons/ha of langbeinite.

discussed earlier, such a difference in the use of leaching water is attributed to the significantly higher water solubility of langbeinite compared to gypsum.

The EC breakthrough curves for the columns leached with the application of 4 tons/ha of gypsum (G2-run) and 4 tons/ha of langbeinite (L2-run) are given in Fig. 6. The maximum EC for the langbeinite treated column was about 9.1 mmhos/cm, whereas that of the gypsum treated column was about 8.0 mmhos/cm. The gypsum treated column took about 20 hrs. of leaching time to reach the background EC, but the background EC in the langbeinite treated column was reached in about 10 hrs. of leaching period. However, the maximum EC for both the langbeinite and gypsum treated columns were attained at approximately the same time (~5 hrs) after leaching of the columns was started. In these sets, the background EC of the column treated with langbeinite was a little higher than the background EC of the column treated with gypsum (Fig. 6).

Fig. 7 presents the EC readings of the eluents, with time, of the columns leached with the application of 6 tons/ha of gypsum (G3-run) and 6 tons/ha of langbeinite (L3-run). The maximum EC of the column leached with gypsum was 8.6 mmhos/cm and that of the column leached with langbeinite was 10.3 mmhos/cm. It required running the column for about 6 hours in order to obtain the maximum EC reading of the leachates from the column treated with gypsum. However, the maximum EC reading for the leachates of the column treated with the same amount of langbeinite was attained at about 3 hrs. period from the time leaching was started. Moreover, the background (constant) EC reading of the langbeinite treated column was reached at approximately 10 hrs. of

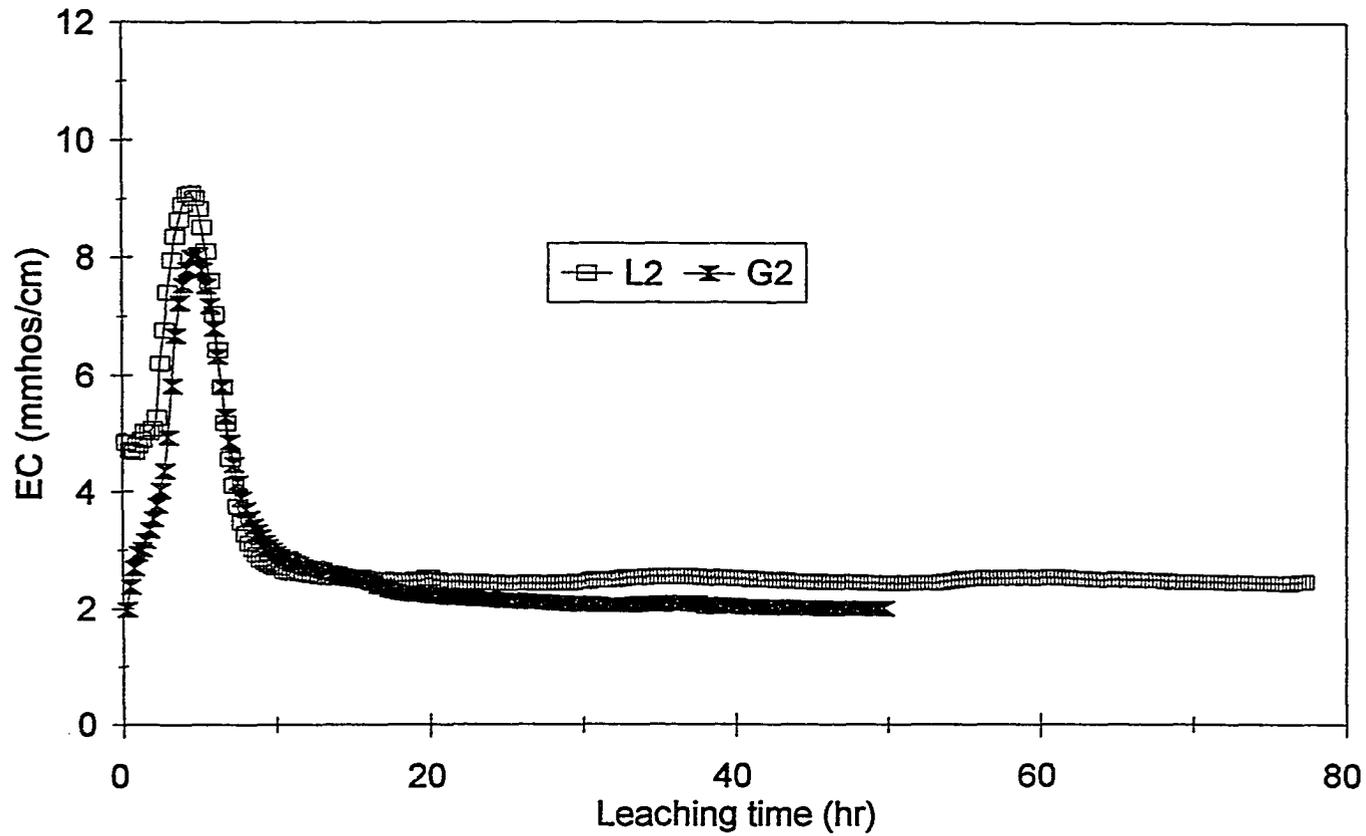


Fig. 6. EC breakthrough curves for the columns leached with the applications of 4 tons/ha of gypsum and 4 tons/ha of langbeinite.

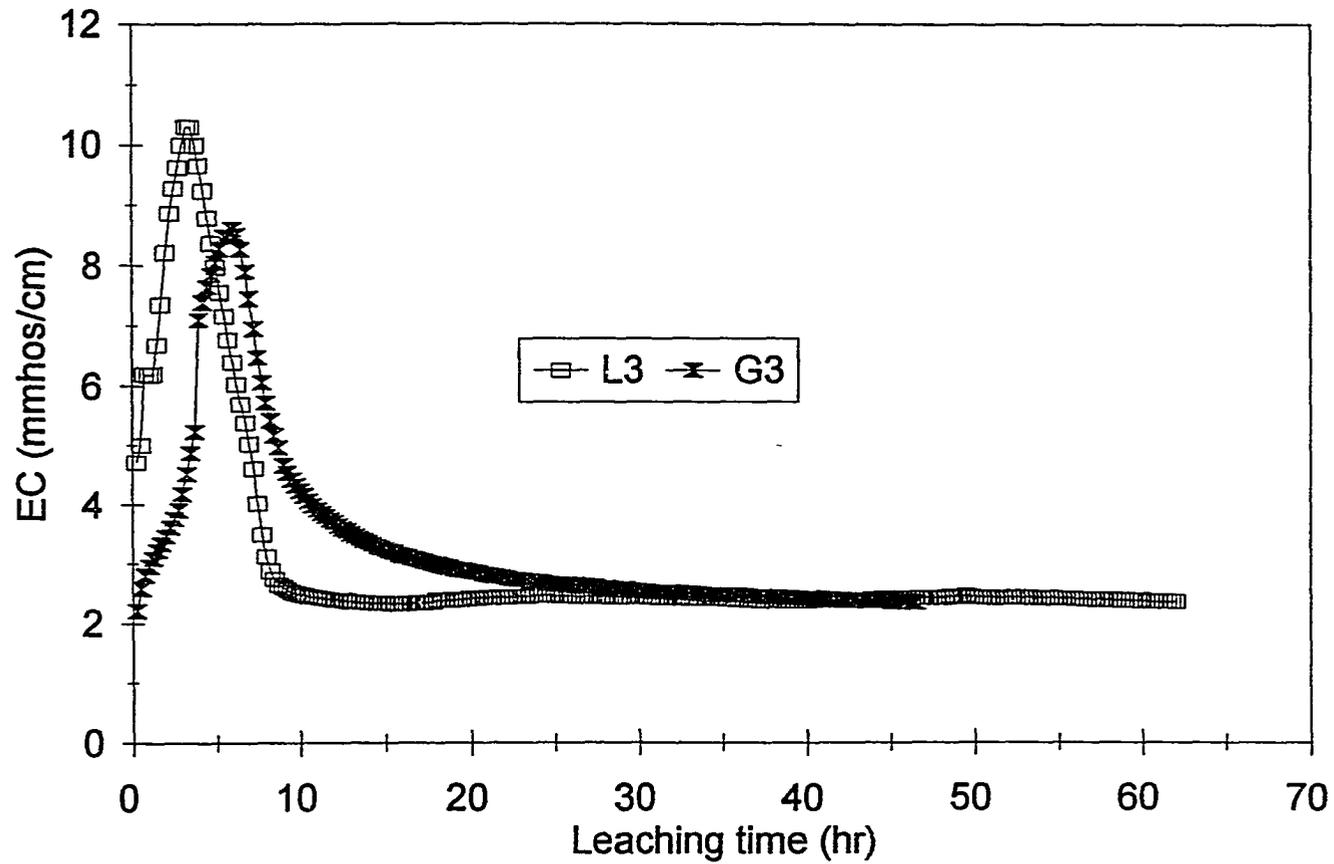


Fig. 7. EC breakthrough curves for the columns leached with the applications of 6 tons/ha of gypsum and 6 tons/ha of langbeinite.

leaching period, whereas the gypsum treated column reached the background EC after 35 hrs of leaching the column with the irrigation water (Fig. 7).

Fig. 8 shows the EC breakthrough curves of the eluents from the columns which received 8 tons/ha of gypsum (G4-run) and 8 tons/ha of langbeinite (L4-run) when plotted against leaching time interval. As it can be seen from the graphs, the maximum EC values of the columns leached with these amounts of applied gypsum and langbeinite were almost the same (~ 9.3 mmhos/cm). Similarly, it took about 5 hrs of leaching period to attain the maximum EC values in both gypsum and langbeinite treated columns. The langbeinite treated column required about 15 hrs of leaching period to attain the constant and/or background EC reading. However, the column leached with the application of gypsum required about 30 hrs of leaching time to obtain a nearly constant EC reading (Fig. 8).

A maximum EC reading of about 10.1 mmhos/cm was recorded for the eluents of the column supplied with langbeinite at a rate of 10 tons/ha (Fig. 9). This maximum EC reading was obtained at exactly 4.5 hrs after the leaching process was started. As with the column supplied with 8 tons/ha of langbeinite, it required approximately 15 hrs of leaching time to reach a stage where the EC of the eluent remains constant. When gypsum is applied at a rate of 10 tons/ha, the highest EC value was about 9.4 mmhos/cm. This maximum EC reading was attained at about 5 hrs after leaching had started. A constant EC reading of the eluents from the column treated with 10 tons/ha of gypsum was obtained after about 20 hrs of leaching period (Fig. 9).

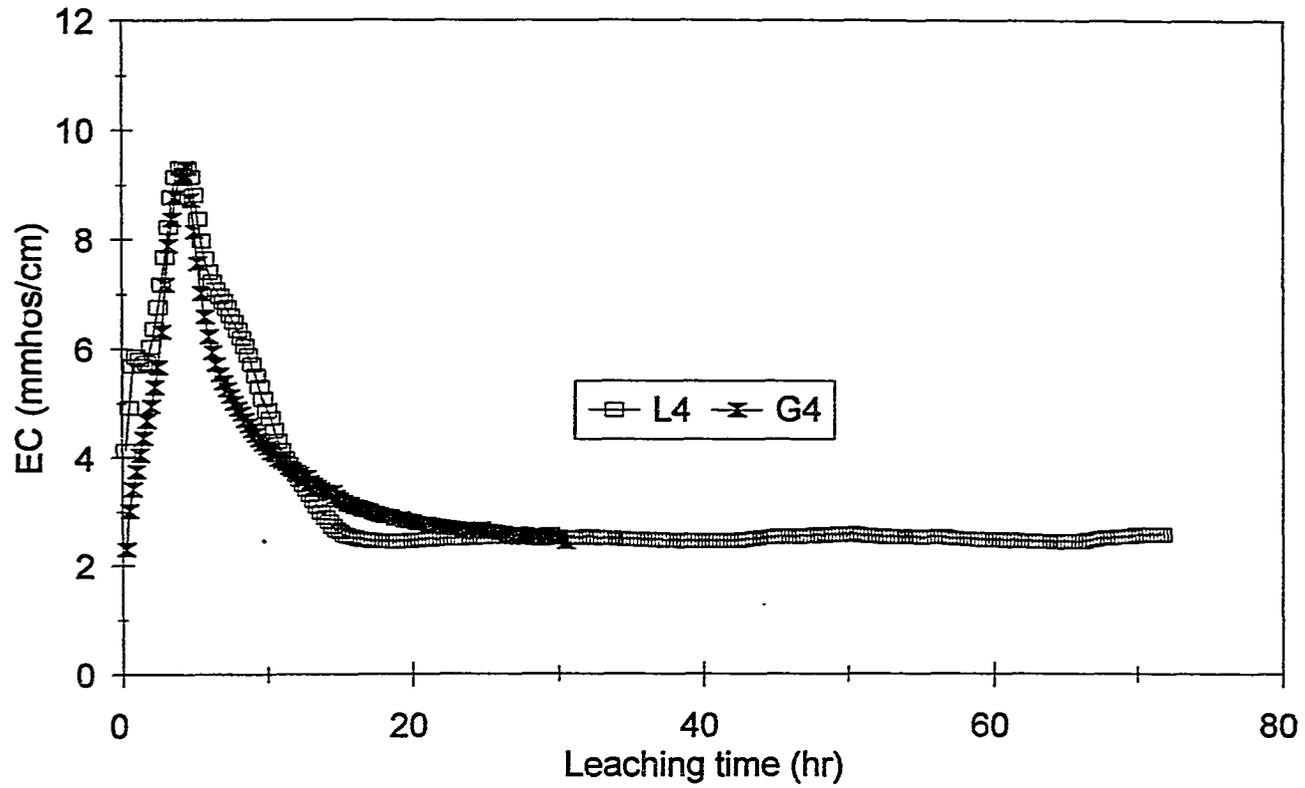


Fig. 8. EC breakthrough curves for the columns leached with the applications of 8 tons/ha of gypsum and 8 tons/ha of langbeinite

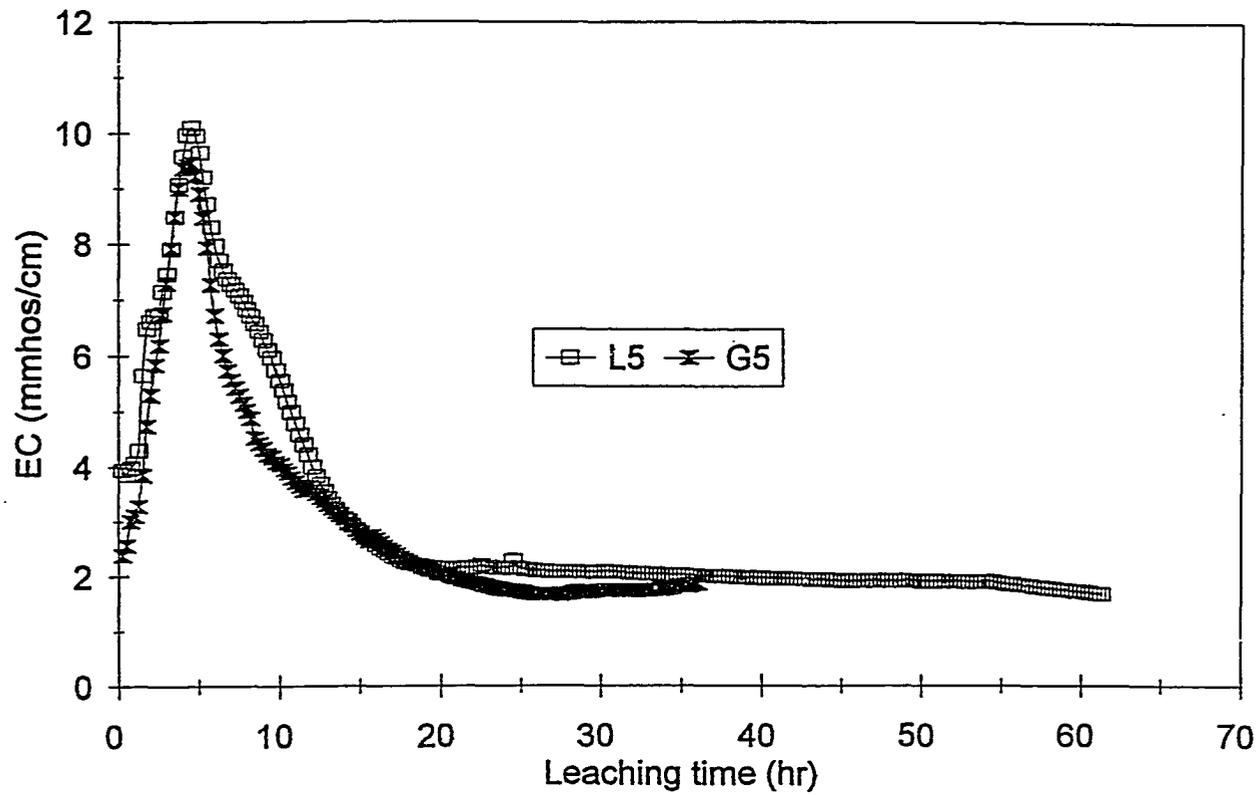


Fig. 9. EC breakthrough curves for the columns leached with the applications of 10 tons/ha of gypsum and 10 tons/ha of langbeinite.

Eluent EC plotted against leaching time interval of the columns treated with 12 tons/ha of gypsum (G6-run) and 12 tons/ha of langbeinite (L6-run) are given in Fig. 10. The background EC of the column involving the use of langbeinite as a chemical amendment was attained after about 16 hrs. of leaching interval. Whereas the background EC of the column treated with gypsum was not attained until all of the four pore volumes of leaching water were passed through the column, that is over 33 hrs of leaching period. Moreover, the maximum eluent EC of the column receiving gypsum (7.7 mmhos/cm) was appreciably lower than the eluent EC of the column treated with langbeinite (9.6 mmhos/cm). However, the maximum EC record for both columns appeared to be obtained at about the same (5 hrs) leaching time interval (Fig. 10).

Although only the EC of the single runs are shown in the text, each of the column considered in this study was run in duplicates. The EC values as plotted against the leaching time interval of the second runs followed the same pattern with their counterpart runs. Therefore, these EC breakthrough curves are not shown in the text.

3.2. Exchangeable Sodium Content and ESP

In accordance with the laboratory batch studies, applying both gypsum and langbeinite as chemical amendments released appreciable quantities of exchangeable sodium from the exchange site of the Grabe clay loam saline sodic soil. Table 8 presents the amounts of exchangeable sodium displaced by applying different levels of gypsum and leaching with varying pore volumes of irrigation water. Similarly, the amount of exchangeable sodium released due to the application of different levels of applied langbeinite and leaching with varying volumes of irrigation water is given in Table 9.

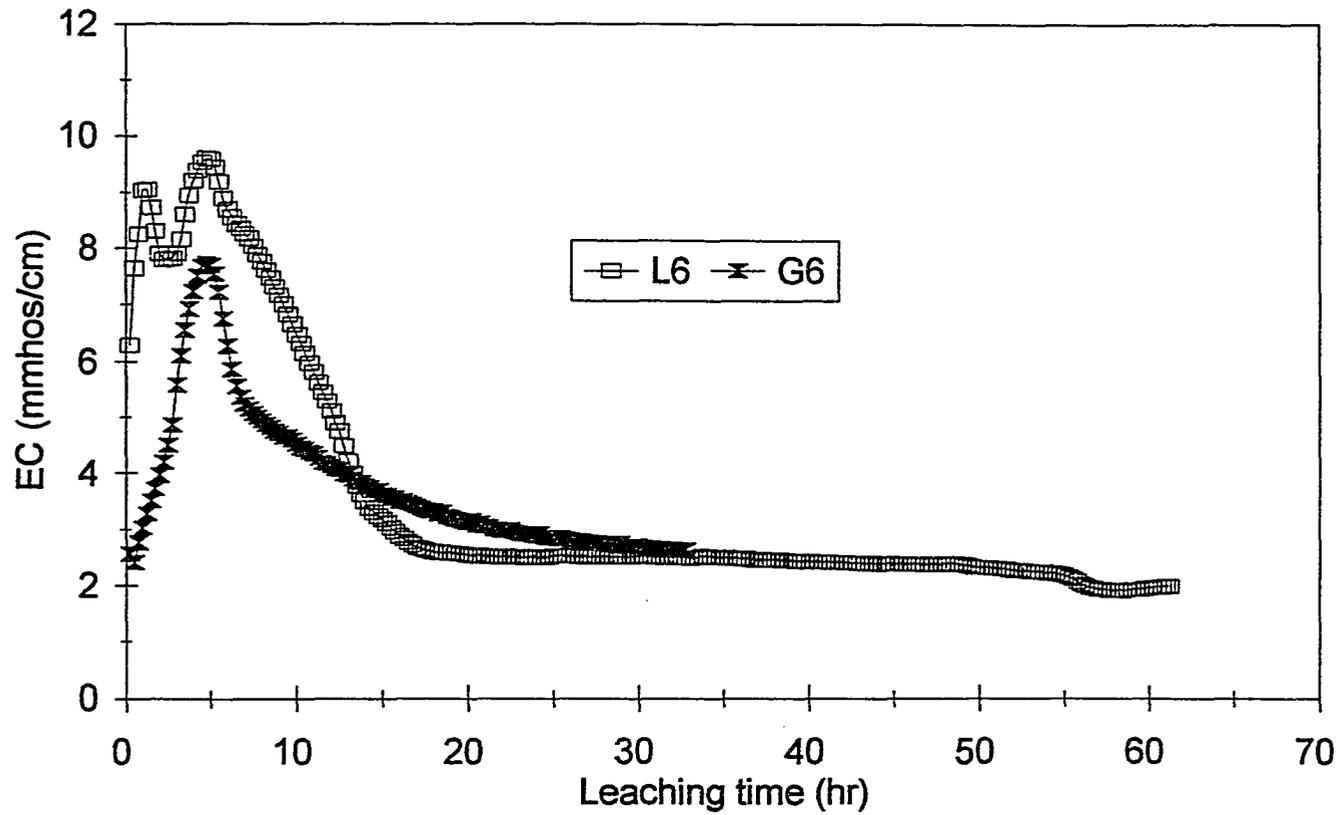


Fig. 10. EC breakthrough curves for the columns leached with the applications of 12 tons/ha of gypsum and 12 tons/ha of langbeinite.

Exchangeable sodium contents displaced due to applications of different levels of both gypsum and langbeinite were significantly different ($P < 0.05$). Likewise the effects of leaching of both the gypsum (Table 8) and langbeinite (Table 9) treated soils with different volumes of irrigation water on the removal of sodium from the soil exchange sites were statistically significant ($P < 0.05$). Moreover, the interaction effects between applied pore volumes of water and levels of gypsum on the one hand, and between pore volumes of water and applied langbeinite rates on the other, were significantly different at the 0.05 probability level.

When leached with the maximum volume (four pore volumes) of irrigation water, the total amount of exchangeable sodium displaced from the soil exchange sites by applying gypsum and langbeinite at an equivalent mass based rates were almost the same except at the lowest rate (2 tons/ha) of the applied chemical amendments. However, applied langbeinite removed significantly higher amounts of exchangeable sodium (Table 9) compared with the same amount of applied gypsum (Table 8) when three or less pore volumes of irrigation water were passed through the columns for leaching purposes.

Accordingly, when langbeinite was used as a chemical amendment, any increment in the volume of leaching water above 2.5 pore volumes did not bring a significant difference ($P < 0.05$) in the amount of exchangeable sodium displaced. However, with gypsum, the average exchangeable sodium displaced by applying four pore volumes of water was significantly higher than the amount displaced by applying three pore volumes of leaching water (Table 8).

Table 8. Mean exchangeable sodium (meq/100g) replaced due to application of gypsum as a chemical amendment and leaching with varying pore volumes of irrigation water ‡†

Applied gypsum (tons/ha)	Applied pore volume								Mean*
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	
2	0.03	0.28	0.49	0.56	0.57	0.58	0.58	0.58	0.46e
4	0.17	0.53	0.85	0.97	1.04	1.07	1.08	1.08	0.85d
6	0.27	0.65	1.19	1.48	1.66	1.77	1.84	1.89	1.34c
8	0.24	0.57	1.22	1.70	1.99	2.17	2.27	2.35	1.56b
10	0.23	0.46	1.08	1.62	1.95	2.17	2.30	2.39	1.53b
12	0.26	0.55	1.25	1.90	2.39	2.71	2.92	3.05	1.88a
Mean**	0.20g	0.51f	1.01e	1.37d	1.60c	1.75b	1.83ab	1.89a	

* Means within a column, followed by the same letter are not significantly different at the 0.05 probability level.

** Means within a row, followed by the same letter are not significantly different at the 0.05 probability level.

‡ Interaction between pore volumes of leaching water and levels of applied gypsum was significant at 0.05 level.

† LSD 0.05 = 0.098 and 0.084 for row and column values, respectively.

Table 9. Mean exchangeable sodium (meq/100g) replaced due to application of langbeinite as a chemical amendment and leaching with varying pore volumes of irrigation water ‡†.

Applied langbeinite (tons/ha)	Applied pore volume								Mean*
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	
2	0.12	0.49	0.78	0.84	0.90	0.96	1.02	1.08	0.77f
4	0.20	0.61	0.98	1.02	1.07	1.12	1.17	1.22	0.92e
6	0.15	0.67	1.49	1.55	1.61	1.67	1.71	1.77	1.33d
8	0.20	0.59	1.76	2.09	2.17	2.23	2.27	2.33	1.71c
10	0.26	0.65	1.83	2.36	2.42	2.44	2.44	2.44	1.86b
12	0.32	0.88	2.26	2.95	3.03	3.06	3.07	3.07	2.33a
Mean**	0.21f	0.65e	1.52d	1.80c	1.87bc	1.91ab	1.95ab	1.99a	

* Means within a column, followed by the same letter are not significantly different at the 0.05 probability level.

** Means within a row, followed by the same letter are not significantly different at the 0.05 probability level.

‡ Interaction between pore volumes of leaching water and levels of langbeinite was significant at 0.05 level.

† LSD 0.05 = 0.077 and 0.066 for row and column values, respectively.

The quantities of exchangeable sodium removed by the different levels of applied gypsum and langbeinite under the influence of varying volumes of leaching water are plotted in Figures 11 and 12, respectively. The increasing rates of release of exchangeable sodium for each level of applied gypsum with increasing pore volume of water upto the maximum amount are clearly indicated in the individual graphs (Fig. 11).

When 12 tons/ha of gypsum was applied as a chemical amendment, the amount of exchangeable sodium displaced increased from 0.26 to 1.90 meq/100g soil as the volume of leaching water increased from 0.5 to 2.0 pore volumes (Table 8 and Fig. 11). This resulted in a decrease in the ESP of the soil from 23.7 to 15.8%. Whereas with the use of the same rate of langbeinite as a chemical amendment, the amount of sodium removed from the soil exchange sites increased from 0.32 to 2.95 meq/100g soil when the volume of leaching water was increased from 0.5 to 2.0 pore volumes (Table 9 and Fig. 12). This implies a reduction in the ESP of the soil from 23.4 (with 0.5 pore volume) to 10.8% (with 2.0 pore volumes). Moreover, each of the remaining levels of applied gypsum and langbeinite closely followed the pattern explained above.

Leaching the soil using two pore volumes of irrigation water increased the amount of exchangeable sodium displaced by applying langbeinite from 0.84 to 2.95 meq/100g soil when the rate of applied langbeinite increased from 2 to 12 tons/ha (Table 9). Similarly, increasing the rate of applied gypsum from 2 to 12 tons/ha increased the amount of exchangeable sodium displaced from 0.56 to 1.90 meq/100g soil when the soil was leached with two pore volumes of irrigation water (Table 8). When langbeinite was applied at a rate of 12 tons/ha, replacement of 96.1% of the total exchangeable sodium

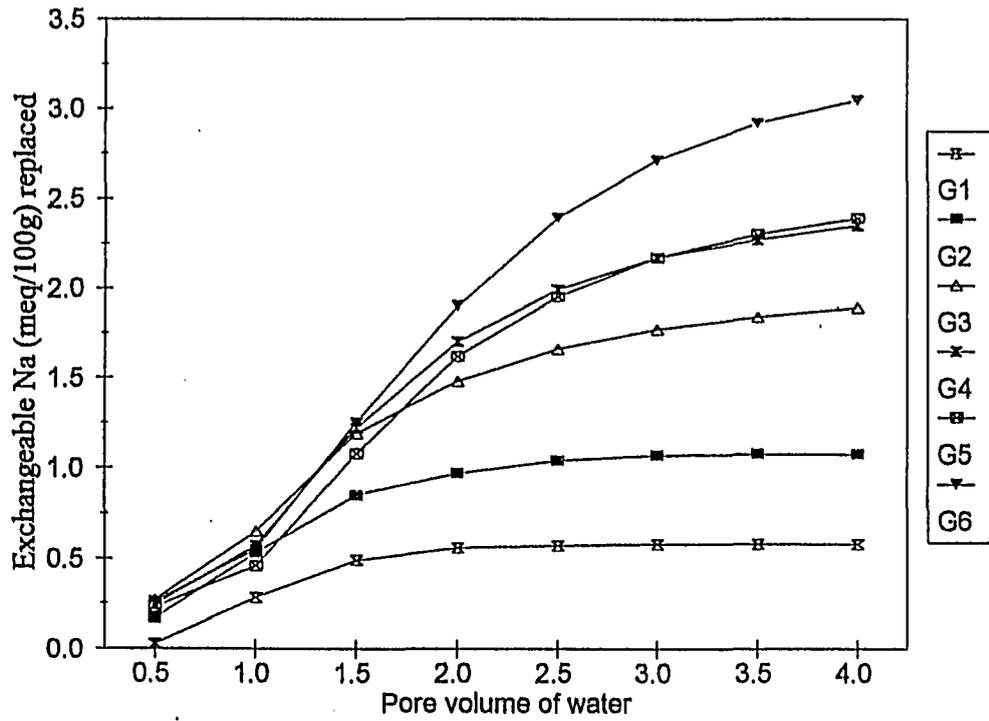


Fig. 11. Effects of gypsum rates and volumes of leaching water on the removal of exchangeable Na from saline sodic soil.

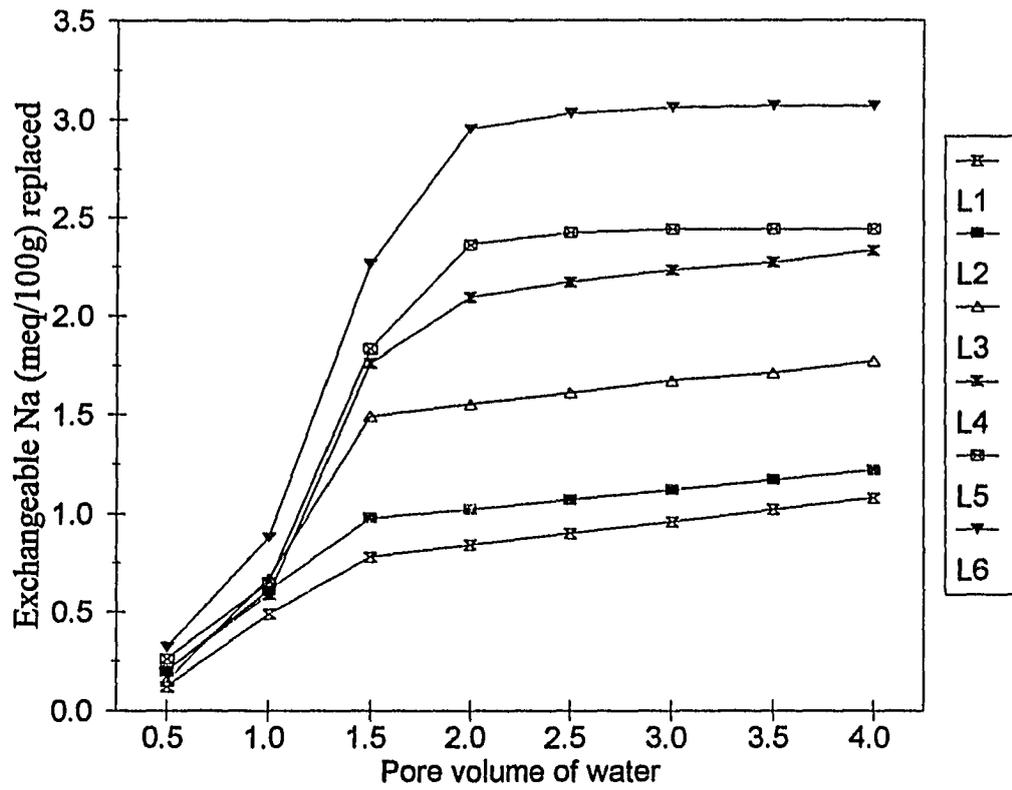


Fig. 12. Effects of langbeinite rates and volumes of leaching water on the removal of exchangeable Na from saline sodic soil.

displaced by leaching the soil with the maximum pore volume of water (4 pore volumes) was achieved by leaching the soil with 2 pore volumes of irrigation water. Whereas when gypsum was applied at the same rate as above, a displacement of only 62.2% of the total sodium displaced by leaching with 4 pore volumes of water was realized when 2 pore volumes of water is used for leaching.

The rate of sodium removal from the exchange sites of langbeinite-treated soil by applying more leaching water after two pore volumes were very small and hence did not bring a significance difference in the ESP of the soil. However, increasing the volume of leaching water after two pore volumes in the gypsum-treated columns increased the release of exchangeable sodium and decreased soil ESP significantly. The increased rates of release of exchangeable sodium for the different rates of applied gypsum with increasing volumes of leaching water can be observed from the graphs of pore volume of water passed through the column plotted against the cumulative amount of replaced exchangeable sodium (Fig. 11). With gypsum, the sodium content displaced did not reach a plateau until four pore volumes of leaching water passed through the columns. However, the sodium removed by applied levels of langbeinite reached a plateau after leaching with about 2 pore volumes of water (Fig. 12).

The total exchangeable sodium replaced due to different levels of applied gypsum and langbeinite each averaged across all added pore volumes of water are shown in Fig. 13. It can be seen from the graphs in this figure that each level of applied langbeinite except at the rate of 6 tons/ha replaced higher content of exchangeable sodium compared to gypsum applied at equivalent rates. Such a higher efficiency of langbeinite than

gypsum over all volumes of leaching water may be attributed to the higher total cation equivalent of langbeinite (14.3 per kg) compared to the total cation equivalent of gypsum (11.6 per kg of gypsum).

Thus, the potassium ion applied in the form of langbeinite had participated in replacing exchangeable cations including exchangeable Na. Moreover, when gypsum is applied to the soil, Ca has to replace most exchangeable cations present in the soil including exchangeable Mg because the selectivity of Ca (88%) ion over Na in montmorillonite clay is higher than the selectivity of Mg (82%) under similar conditions. Therefore, since the Grabe clay loam soil contain an appreciable quantity of exchangeable Mg (2.9 meq/100g soil), this could have reduced the efficiency of gypsum. However, since the selectivity of Mg is lower than Ca, Mg released from the dissolution of langbeinite is not expected to replace an appreciable amount of exchangeable Ca before all exchangeable sodium is depleted.

As a rule the soil exchange site is not homogeneous. It contains various kinds of adsorbed cations. Therefore, a cation added in to the soil has to deal with the heterogeneous nature of the exchange complex. The added cation replaces the exchangeable cations with the lowest selectivity at the initial stage of addition into the soil. Once such cations are depleted, it continues to replace the cations with higher selectivities. This explains the fact that both langbeinite and gypsum replaced very small amounts of exchangeable sodium at initial stages and continue to increase the rate of removal until controlled either by the amount of adsorbed cation or the amount of replacing cation.

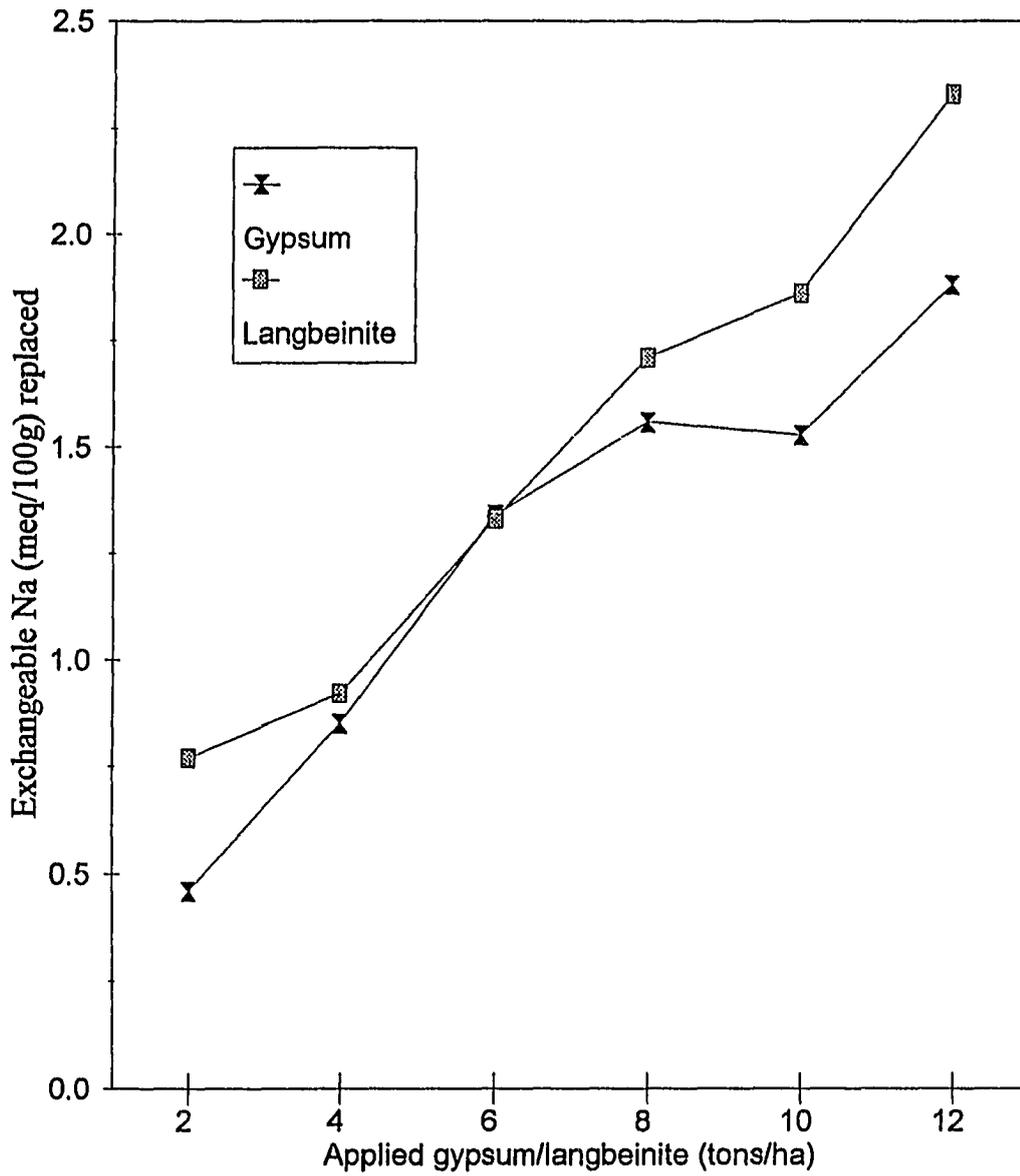


Fig. 13. Effects of gypsum and langbeinite on the removal of exchangeable sodium from saline sodic soil averaged overall applied pore volumes of water.

The effect of applied pore volume of water on the removal of exchangeable sodium from a saline sodic soil using gypsum and langbeinite independently as chemical amendments is presented in Fig. 14. The efficiency of both chemical amendments increased significantly with increasing applied pore volumes of leaching water. However, the rate of release of exchangeable sodium with the use of langbeinite was always higher than with gypsum for every pore volume of water applied for leaching (Fig. 14).

For example, when gypsum is used as a chemical amendment, increasing the pore volume of leaching water from 0.5 to 1.5 increased the rate of exchangeable sodium removal from 0.20 to 1.01 meq/100g soil (Fig. 14 and Table 8). Whereas when langbeinite is used as a chemical amendment, increasing the volume of leaching water from 0.5 to 1.5 pore volumes increased the average amount of exchangeable sodium displaced from 0.21 to 1.52 meq/100g soil (Fig. 14 and Table 9).

At higher pore volumes of leaching water, the rate of increase in the amount of exchangeable sodium displaced was higher with applied gypsum than with langbeinite. This indicates that gypsum is not completely dissolved even with the application of four pore volumes of leaching water. But, langbeinite is nearly completely dissolved with the use of 2.5 pore volumes of leaching water. These differences in the efficiency of gypsum and langbeinite as chemical amendments for the reclamation of saline sodic soil are apparently attributed to the large differences in the water solubility of the minerals.

Figs. 15 and 16 show the breakthrough curves of the removal of exchangeable sodium for the different levels of applied gypsum and langbeinite, respectively. When gypsum is applied, the maximum exchangeable sodium displaced per half a pore volume

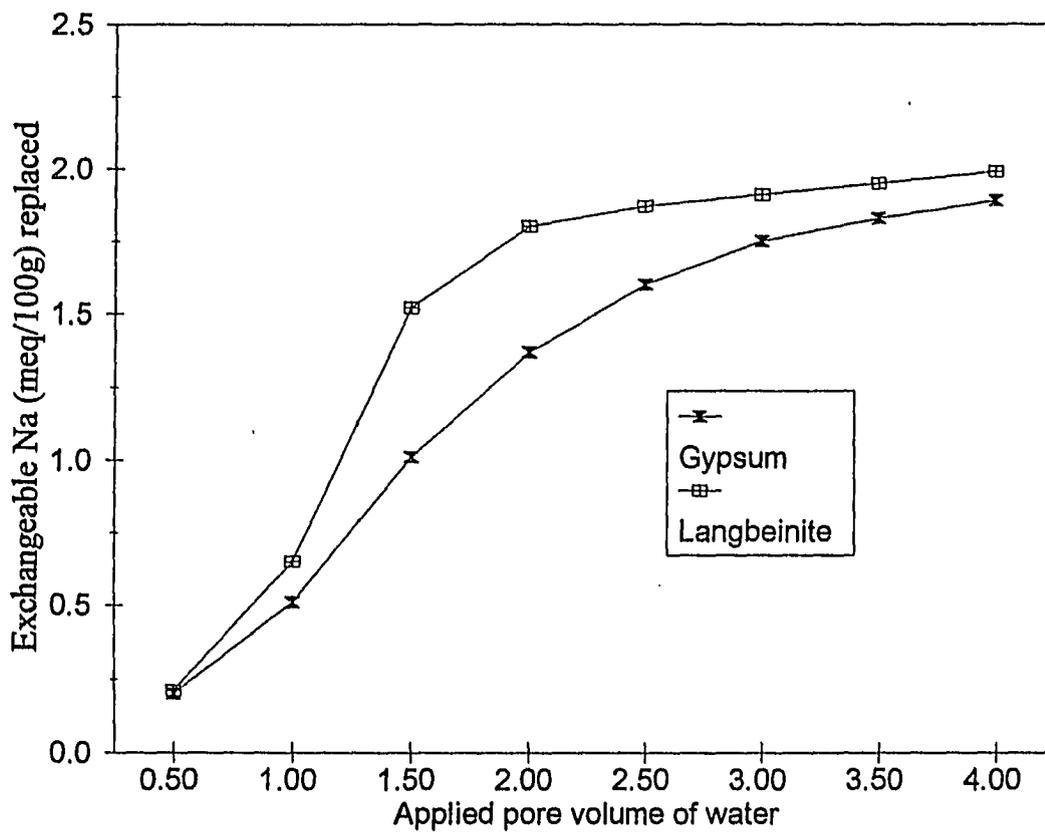


Fig. 14. Effect of applied pore volumes of water on the removal of exchangeable Na from saline sodic soil using gypsum and langbeinite amendments.

of applied leaching water was about 0.69 meq/100g soil for the maximum rate (12 tons/ha or G6-run) of applied gypsum (Fig. 15). Whereas with langbeinite application, the maximum amount of exchangeable sodium displaced per half a pore volume of leaching water was about 1.4 meq/100g soil for the maximum rate (12 tons/ha or L6-run) of applied langbeinite (Fig. 16).

In both cases increasing the rate of applied chemical amendment increased the rate of exchangeable sodium removal. With langbeinite, none of the different levels applied brought an additional release of exchangeable sodium when 2.5 or higher pore volumes of water are used for leaching. With gypsum, however, all applied levels except the lowest rate (2 tons/ha) continued to displace additional exchangeable sodium from the soil exchange sites until the maximum pore volume of water is passed through the column (Fig. 15 and Table 8).

In general, the breakthrough curves of exchangeable Na removal for the gypsum and langbeinite treated columns followed the same pattern with their counterpart EC breakthrough curves given in Figures 4 through 10. It is again evident from these Na breakthrough curves that using langbeinite as a reclaiming material requires much less water and time compared to using gypsum as an amendment. This is simply because langbeinite is much more water soluble than gypsum and compared on a mass basis langbeinite contains higher total cation equivalents in a water soluble form than gypsum.

Group comparison of selected higher but equivalent levels (8, 10 and 12 tons/ha) of applied gypsum and langbeinite are made in Figures 17 through 19 with regards to the exchangeable sodium displaced using different pore volumes of leaching water as percent

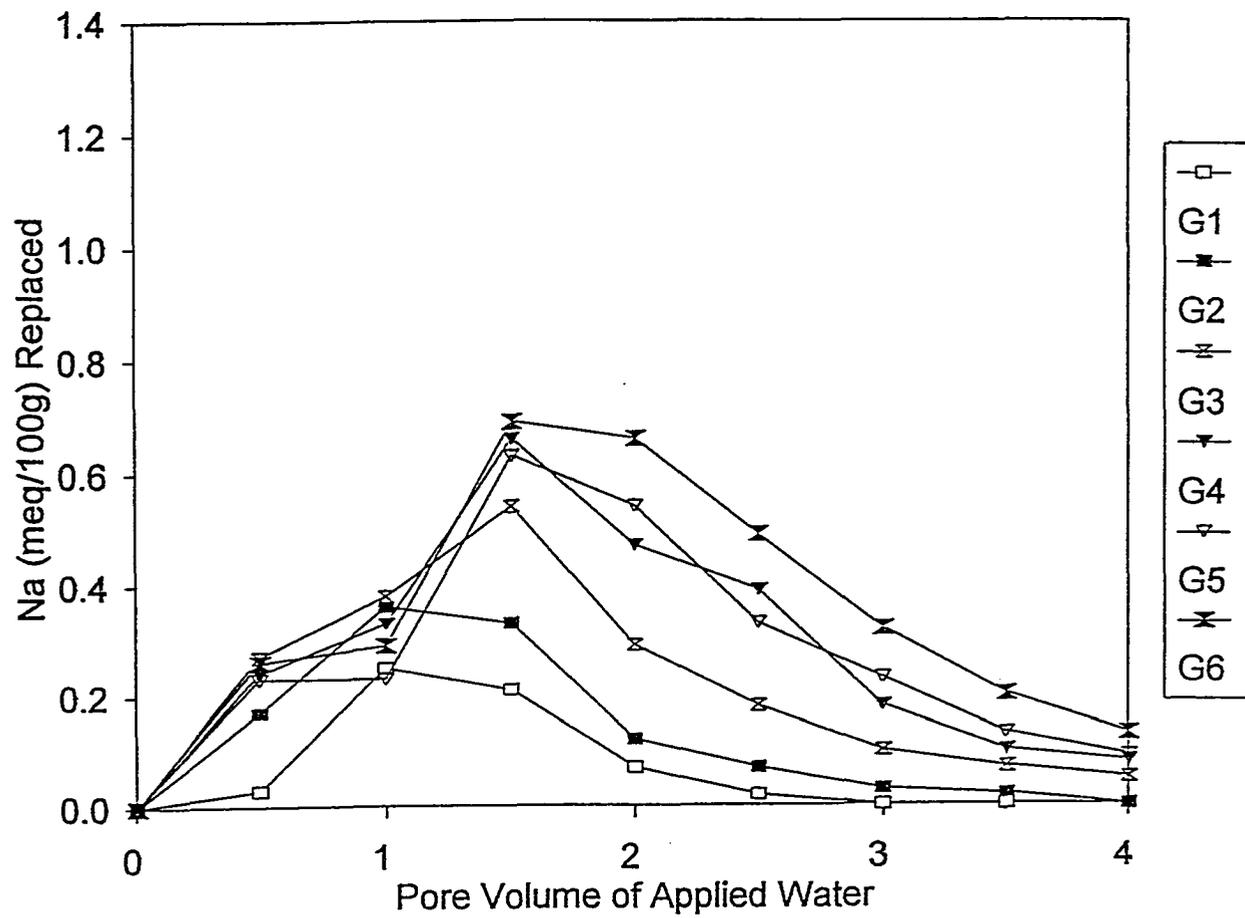


Fig. 15. Breakthrough curves of Na (meq/100g) for the columns leached with the application of different levels of gypsum.

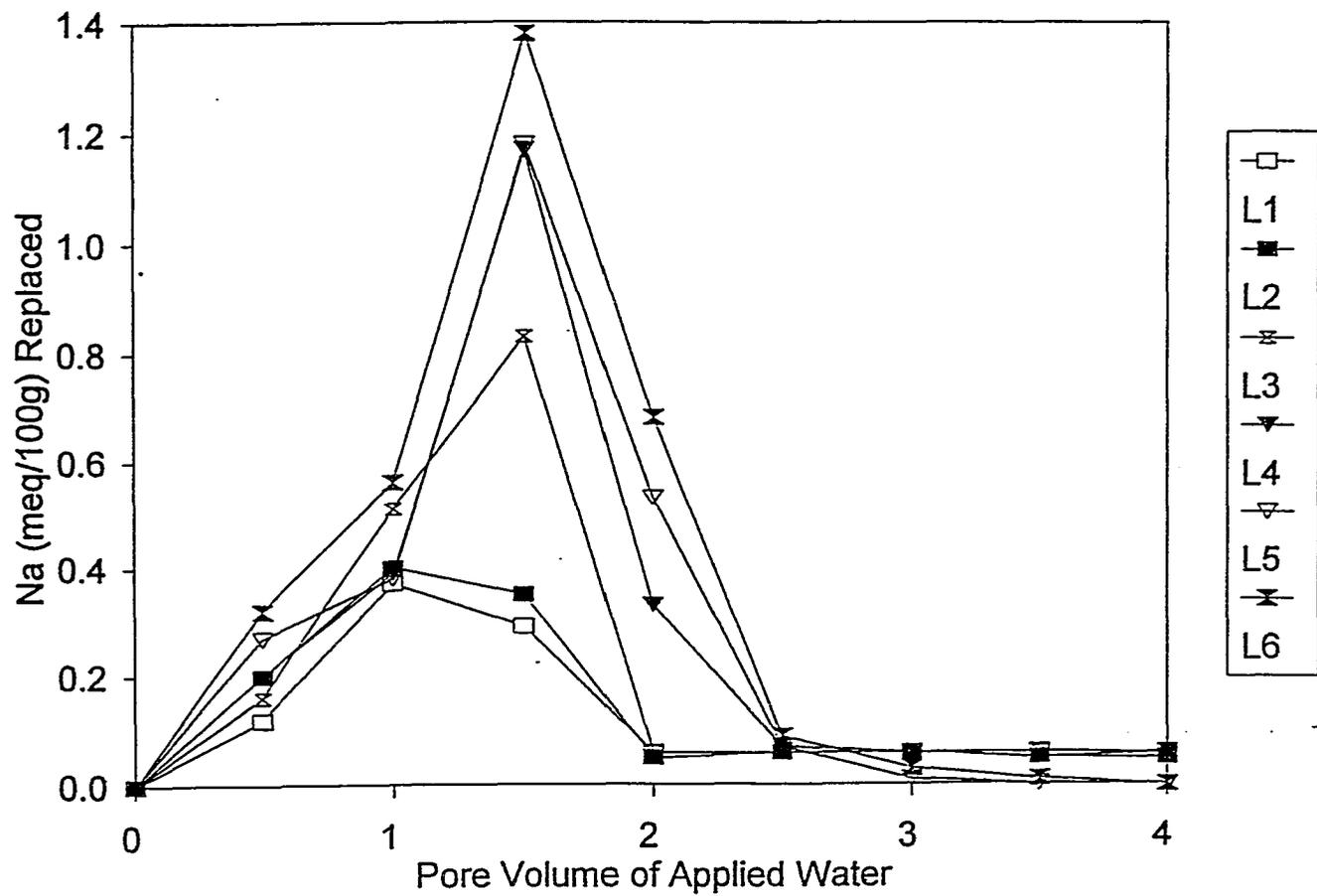


Fig. 16. Breakthrough curves of Na (meq/100g) for the columns leached with the applications of different levels of langbeinite.

of the total exchangeable sodium displaced at the end of leaching. When both of the chemical amendments are applied at a rate of 8 tons/ha (G4- and L4-runs), gypsum and langbeinite replaced 72% and 90%, respectively, of the total sodium exchanged with the use of two pore volumes of leaching water (Fig. 17). When the rate of applied gypsum and langbeinite is increased to 10 tons/ha (G5- and L5-runs), gypsum replaced 67.8% whereas langbeinite replaced 96.7% of the total exchangeable sodium by leaching the columns with 2 pore volumes of water (Fig. 18). Moreover, applying gypsum and langbeinite each at a rate of 12 tons/ha (G6- and L6-runs) resulted in 62 and 96% of the total sodium replacement with gypsum and langbeinite, respectively (Fig. 19). These figures indicated a decreasing efficiency of gypsum with increasing rates of its application and an increasing efficiency of langbeinite with increasing rate of its application when both are compared at a fixed volume of leaching water.

3.3. Hydraulic Conductivity

The most deleterious effect of high levels of exchangeable sodium in soils is the reduction in soil hydraulic conductivity. Therefore, the primary objective of sodic soil reclamation is to reduce the amount of exchangeable sodium to a level where the hydraulic conductivity of the soil is improved. In this study the hydraulic conductivity of the soil was measured for each level of applied gypsum and langbeinite after every half a pore volume of leaching water was passed through the column in order to evaluate the efficiency of the reclaiming materials in improving soil hydraulic conductivity.

Table 10 and Fig. 20 present the average hydraulic conductivity of the soil as influenced by different levels of applied gypsum under varying volumes of leaching

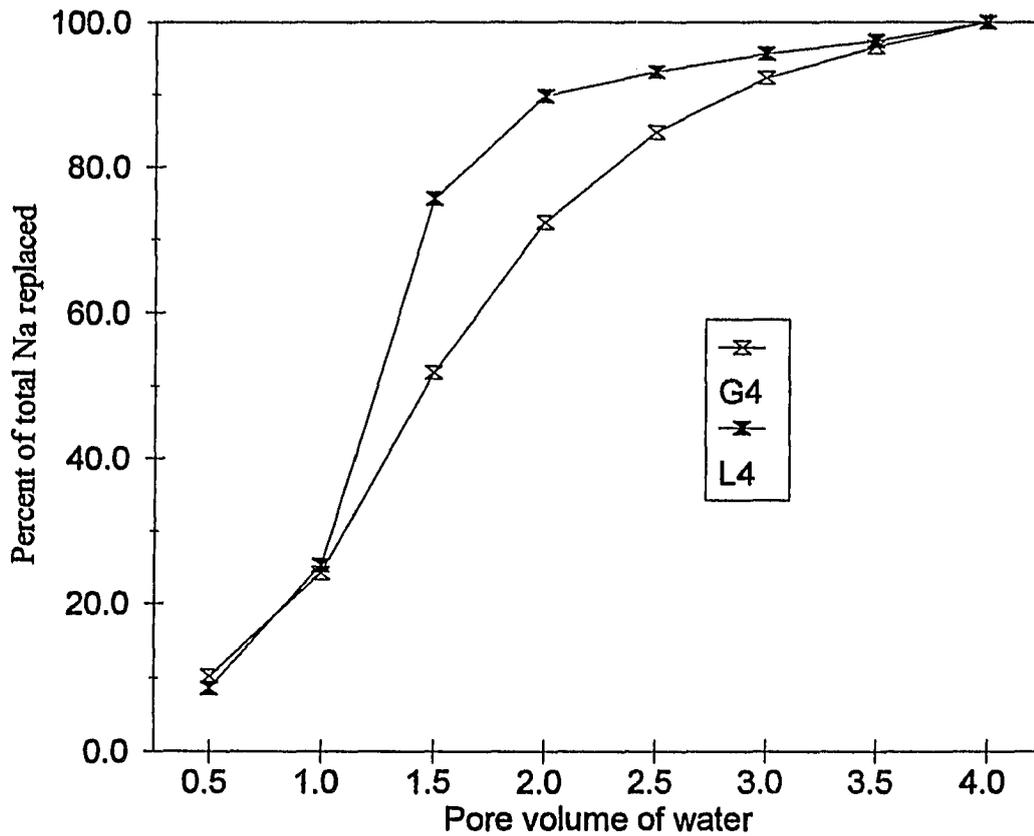


Fig. 17. Percent of total exchangeable Na replaced by different volumes of applied water during reclamation of saline sodic soil with gypsum and langbeinite each applied at a rate of 8 tons/ha.

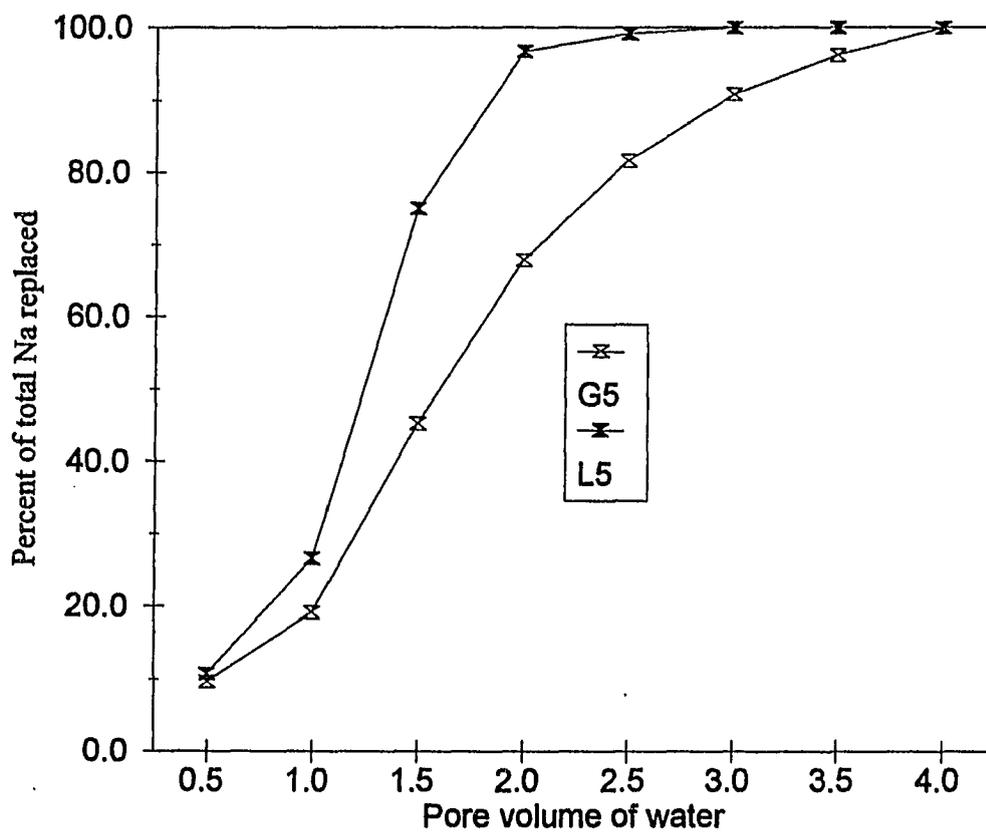


Fig. 18. Percent of total exchangeable Na replaced by different volumes of applied water during reclamation of saline sodic soil with gypsum and langbeinite each applied at a rate of 10 tons/ha.

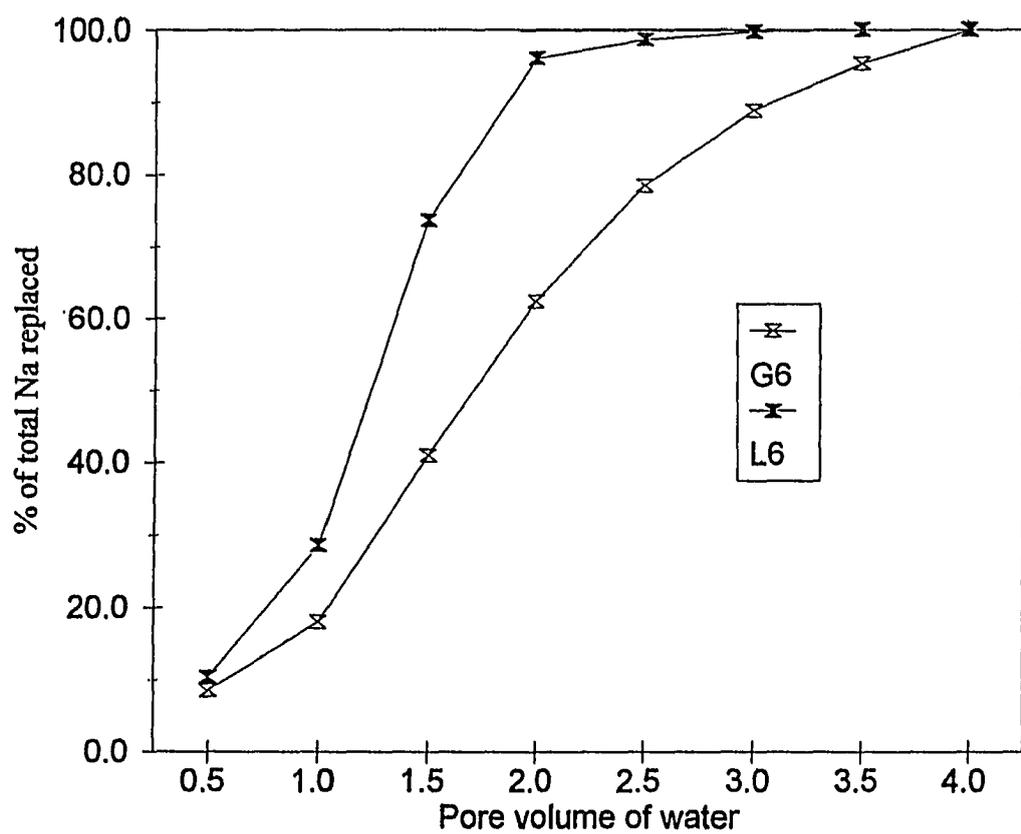


Fig. 19. Percent of total exchangeable Na replaced by different volumes of applied water during reclamation of saline sodic soil with gypsum and langbeinite each applied at a rate of 12 tons/ha.

water. It is evident from the table and figure that increasing levels of applied gypsum increased the hydraulic conductivity of the soil under study. On the other hand, increasing the pore volumes of leaching water decreased the hydraulic conductivity of the soil for each level of applied amendment.

The effect of applied gypsum rates in increasing soil hydraulic conductivity was statistically significant ($P < 0.05$). For example, increasing the rate of applied gypsum from 0 to 10 tons/ha increased soil hydraulic conductivity from 0.82 to 3.37 mm/hr (Table 10). Moreover, the effects of the different pore volumes of leaching water in reducing the hydraulic conductivity of the soil were significantly different ($P < 0.05$) when gypsum was used as a chemical amendment. Increasing the amount of water used for leaching the soil from 0.5 to 4.0 pore volumes decreased the hydraulic conductivity of the soil from 3.63 to 1.26 mm/hr (Table 10). The interaction between the different levels of applied gypsum and the pore volumes of leaching water was not significantly different at the 0.05 probability level.

Fig. 20 clearly indicates that every increment in the rate of applied gypsum increased the hydraulic conductivity of the soil. However, every increment in the pore volume of water applied to leach salts and sodium decreased the hydraulic conductivity of the soil when gypsum was applied as a chemical amendment. Furthermore, the individual graphs (Fig. 20) indicated that a constant hydraulic conductivity is not reached for any of the applied gypsum rates until the four pore volumes of water were passed through the columns. These show that the hydraulic conductivity of the soil will decrease if the soil is leached further with more than four pore volumes of water. It further

Table 10. Mean hydraulic conductivity (mm/hr) as affected by applied gypsum and different volumes of leaching water ‡†.

Applied gypsum (tons/ha)	Applied pore volume								Mean*
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	
0	1.75	1.31	0.94	0.71	0.55	0.47	0.41	0.38	0.82f
2	2.83	2.28	1.63	1.19	0.93	0.72	0.60	0.53	1.34e
4	3.59	2.94	2.24	1.73	1.42	1.15	0.96	0.85	1.86d
6	3.73	3.29	2.75	2.22	1.81	1.51	1.30	1.15	2.22c
8	4.53	4.03	3.60	3.15	2.71	2.31	1.99	1.75	3.01b
10	4.83	4.43	3.90	3.52	3.06	2.71	2.47	2.06	3.37a
12	4.15	3.79	3.44	3.12	2.77	2.53	2.26	2.06	3.01b
Mean**	3.63a	3.15b	2.64c	2.23d	1.90e	1.63f	1.43g	1.26g	

* Means within a column, followed by the same letter are not significantly different at the 0.05 level.

** Means within a row, followed by the same letter are not significantly different at the 0.05 level.

‡ Interaction between volumes of leaching water and levels of gypsum was not significant.

† LSD 0.05 = 0.182 and 0.171 for row and column values, respectively.

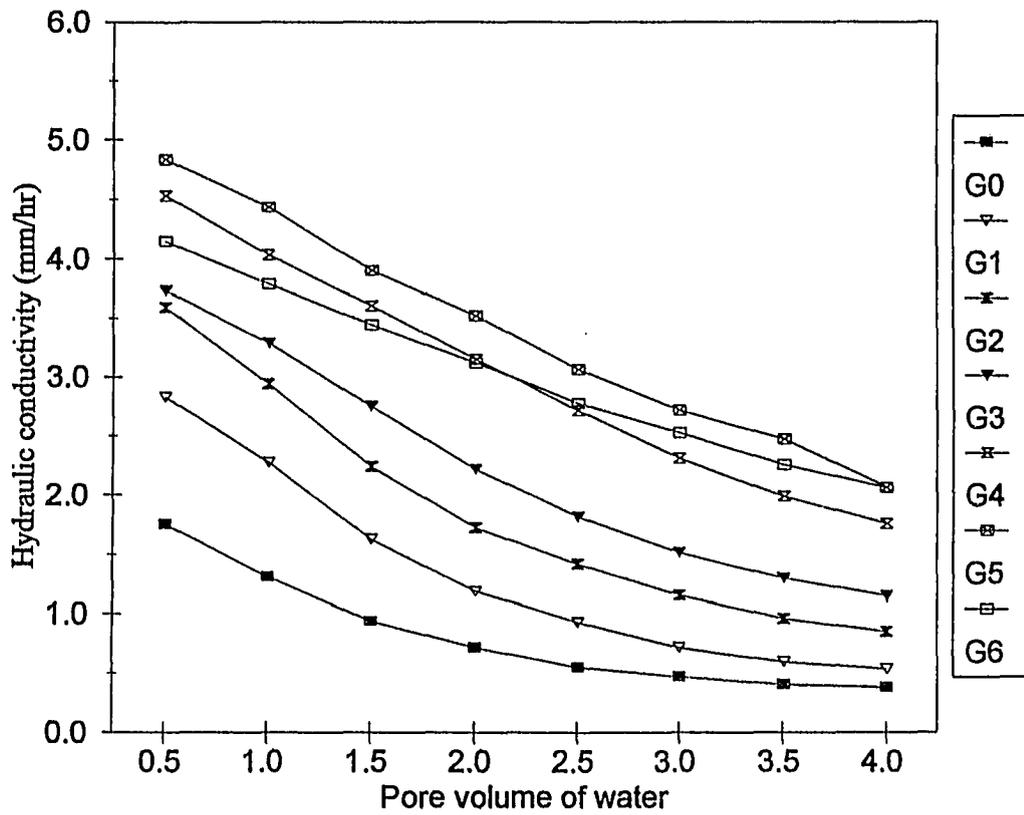


Fig. 20. Effects of applied gypsum levels and volumes of leaching water on soil hydraulic conductivity of Grabe clay loam (saline sodic) soil.

indicates that the electrolyte of the soil solution at the end of leaching with four pore volumes of water is still high enough to maintain a relatively higher soil hydraulic conductivity and require more leaching water to deplete the electrolyte and drop the hydraulic conductivity to a steady state level.

The average soil hydraulic conductivity as affected by different levels of applied langbeinite and different pore volumes of water are given in Table 11 and Fig. 21. As with gypsum, increased levels of applied langbeinite increased the hydraulic conductivity of the soil. Accordingly, the difference in the average hydraulic conductivity of the soil as influenced by different levels of langbeinite was statistically significant ($P < 0.05$). Contrary to the effects of applied langbeinite levels, increasing the pore volumes of leaching water decreased the hydraulic conductivity of the soil (Table 11 and Fig. 21). The effect of increasing pore volume of leaching water in the reduction of soil hydraulic conductivity was significantly different at the 0.05 probability level. Furthermore, unlike with gypsum, the interaction between the pore volumes of leaching water and applied levels of langbeinite was significant.

The rate of increase in soil hydraulic conductivity with increasing levels of langbeinite was smaller than the rate of increase observed with the application of gypsum. With langbeinite, increasing the applied level from 0 to 10 tons/ha increased the hydraulic conductivity from 0.82 to 2.21 mm/hr (Table 11). Whereas gypsum application increased the hydraulic conductivity of the soil from 0.82 to 3.37 mm/hr when the applied gypsum rate increased from 0 to 10 tons/ha.

Moreover, the rate of decrease in soil hydraulic conductivity with increasing pore volumes of water with the use of langbeinite was greater than its rate with the use of gypsum. When langbeinite is used as a reclaiming material, the composite soil hydraulic conductivity across all applied rates decreased from 4.36 mm/hr when 0.5 pore volume of water was applied to 0.63 mm/hr when 4.0 pore volumes of water was used for leaching (Table 11). However, when gypsum is used for reclamation, the average soil hydraulic conductivity across all applied rates decreased from 3.63 to 1.26 mm/hr when the volume of applied leaching water increased from 0.5 to 4.0 pore volumes (Table 10).

As with gypsum (Fig. 20), Fig.21 clearly indicates that increasing levels of langbeinite increased soil hydraulic conductivity, whereas increasing pore volumes of water decreased soil hydraulic conductivity. However, unlike with gypsum, the individual soil hydraulic conductivity graphs (Fig. 21) indicates that the soil has attained its constant (steady state) hydraulic conductivity when leached with about 3.5 pore volumes of water. This means that the hydraulic conductivity of the soil could not be reduced further with more leaching. That is, the electrolyte concentration of the soil solution is equilibrated with the electrolyte of the water used for leaching and no more release of exchangeable sodium can be achieved with further leaching.

The higher soil hydraulic conductivity with langbeinite treated columns than with gypsum when only 0.5 pore volume of leaching water is applied indicates a higher dissolution rate of langbeinite and therefore higher electrolyte in langbeinite than in gypsum treated columns. On the other hand, higher soil hydraulic conductivity with gypsum than with langbeinite at higher rates of applied pore volumes of water indicates

Table 11. Mean hydraulic conductivity (mm/hr) as affected by different levels of applied langbeinite and pore volumes of water ‡†.

Applied langbeinite (tons/ha)	<u>Applied pore volume</u>								Mean*
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	
0	1.75	1.31	0.94	0.71	0.55	0.47	0.41	0.38	0.82c
2	3.49	2.62	1.62	1.14	0.84	0.71	0.61	0.55	1.45b
4	4.26	2.80	1.57	1.08	0.85	0.66	0.57	0.49	1.53b
6	5.53	3.64	2.18	1.58	1.20	0.94	0.76	0.65	2.06a
8	5.22	3.32	1.99	1.40	1.11	0.86	0.75	0.65	1.91a
10	5.45	3.87	2.43	1.71	1.36	1.11	0.90	0.80	2.21a
12	4.82	3.59	2.33	1.70	1.33	1.17	0.99	0.88	2.10a
Mean**	4.36a	3.02b	1.87c	1.33d	1.04de	0.85ef	0.71f	0.63f	

* Means within a column, followed by the same letter are not significantly different at the 0.05 probability level.

** Means within a row, followed by the same letter are not significantly different at the 0.05 probability level.

‡ Interaction between pore volumes of leaching water and levels of langbeinite was significant at 0.05 level.

† LSD 0.05 = 0.302 and 0.282 for row and column values, respectively.

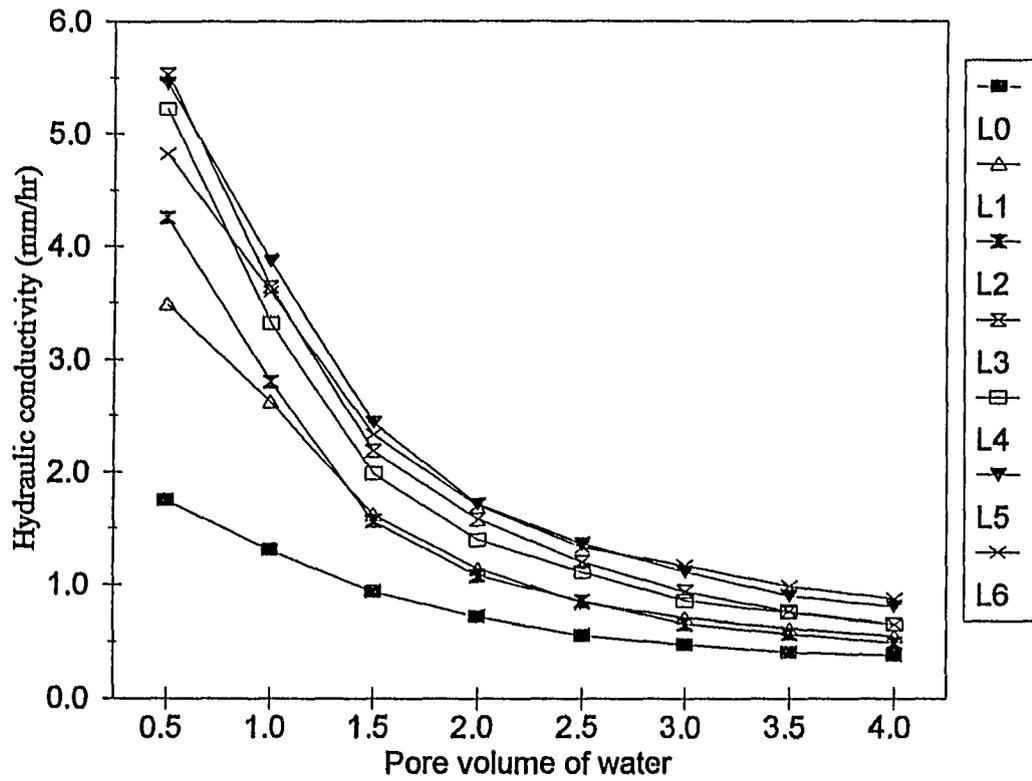


Fig. 21. Effects of applied langbeinite levels and volumes of leaching water on soil hydraulic conductivity of Grabe clay loam (saline sodic) soil.

faster depletion of electrolyte in langbeinite than in gypsum medium. In general, the decrease in soil hydraulic conductivity with increasing pore volumes of applied water in both amendments is attributed to the effect of electrolyte concentration of the soil solution rather than to the effect of exchangeable sodium. Whereas increasing soil hydraulic conductivity with increasing levels of applied amendments in both cases is attributed to the removal of exchangeable sodium.

The effects of applied gypsum and langbeinite on the hydraulic conductivity of the Grabe clay loam saline sodic soil averaged across all pore volumes of water is given in Fig. 22. The graphs clearly indicated that gypsum improved the hydraulic conductivity of the soil greater than langbeinite did when both amendments are applied at rates of 4 tons/ha and higher. Below this rate, the hydraulic conductivity was better improved by langbeinite than by gypsum application. Although the soil hydraulic conductivity with the application of gypsum at all but the 2 tons/ha rate was higher than with langbeinite application, all levels of applied langbeinite had significantly increased the hydraulic conductivity of the soil compared to the control (Table 11 and Figs. 21 and 22). The hydraulic conductivity of the soil without langbeinite application was only 37% of the hydraulic conductivity with the application of 10 tons/ha of langbeinite.

The effects of different pore volumes of leaching water on the hydraulic conductivity of the soil reclaimed using gypsum and langbeinite are shown in Fig. 23. These graphs indicated that the hydraulic conductivity of the soil decreased with increasing volumes of leaching water whether gypsum or langbeinite was used as a chemical amendment. At the lowest volume (0.5 pore volume) of leaching water,

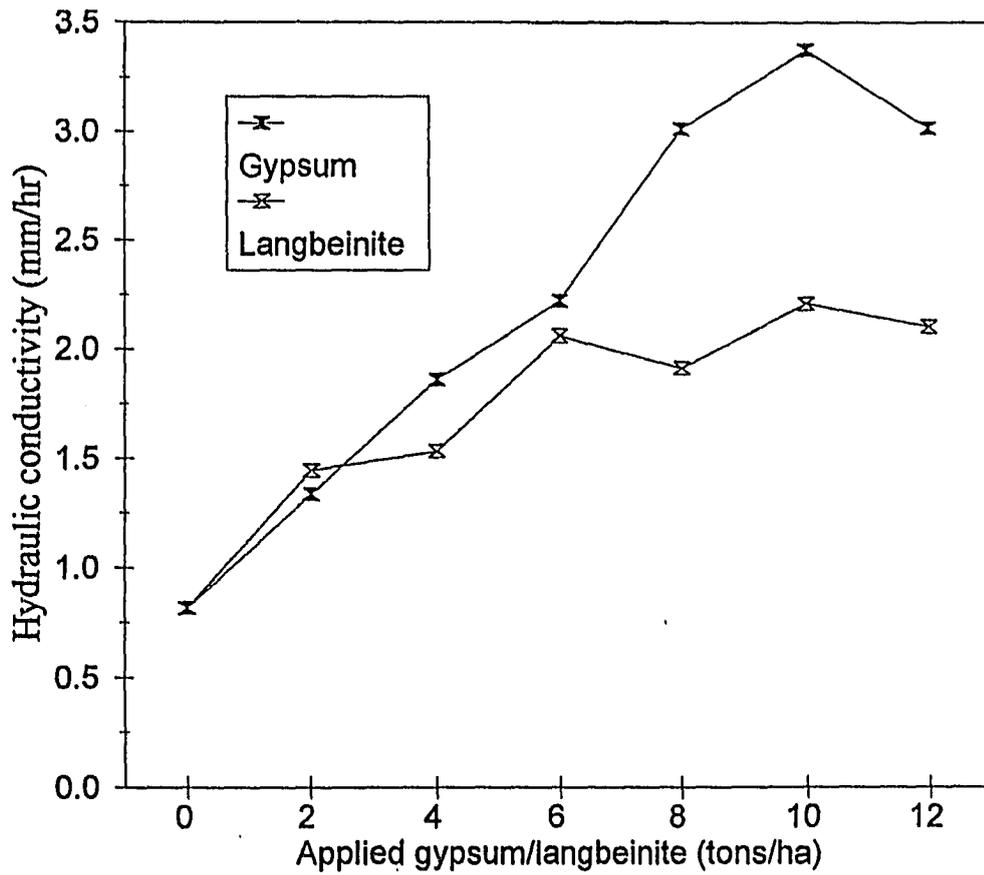


Fig. 22. Effects of gypsum and langbeinite on the hydraulic conductivity of saline sodic soil averaged over all applied pore volumes of water.

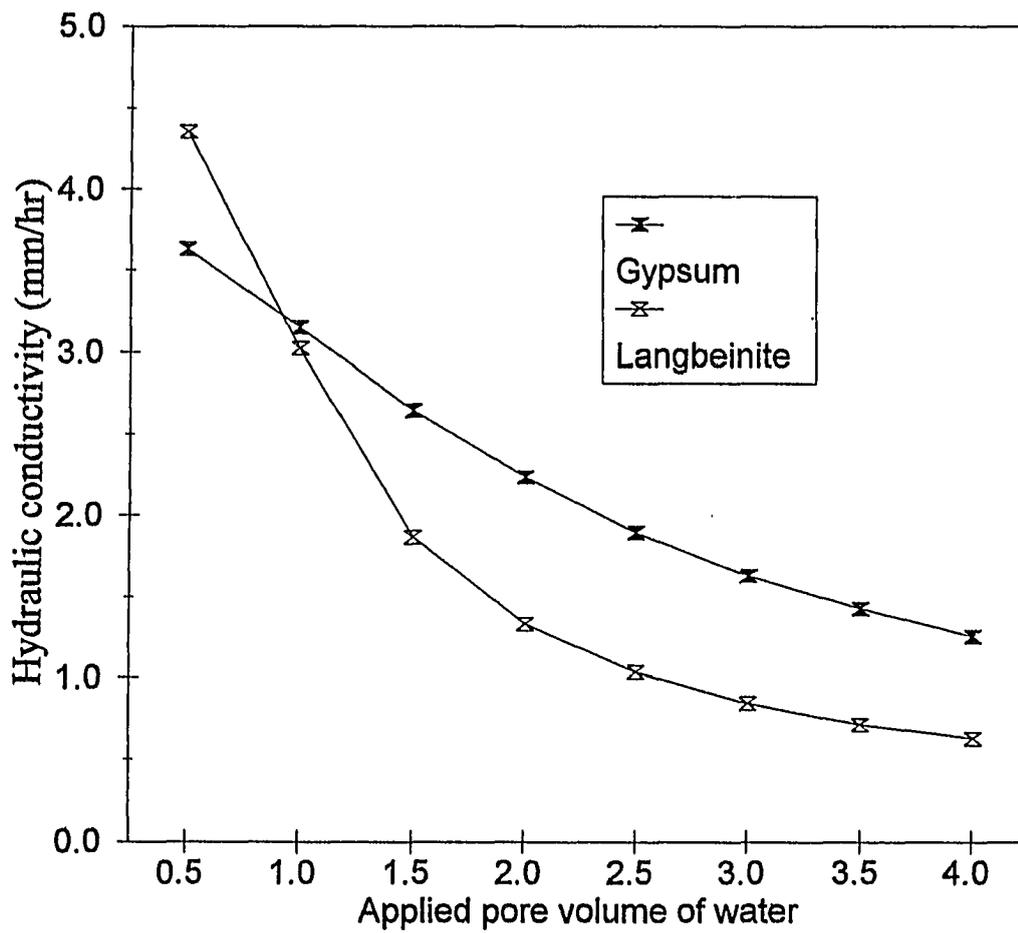


Fig. 23. Effect of applied pore volume of water on the hydraulic conductivity of saline sodic soil reclaimed using gypsum and langbeinite.

langbeinite yielded higher hydraulic conductivity than gypsum. However, at the higher pore volumes of leaching water, gypsum resulted in a relatively higher soil hydraulic conductivity than langbeinite.

It should be noted, however, that each level of applied langbeinite had significantly improved the hydraulic conductivity of the soil compared to the control. Moreover, the soil hydraulic conductivity had almost reached an equilibrium (constant) with the use of langbeinite after about 3.0 pore volumes of leaching water has been applied. This indicates that no more reduction in soil hydraulic conductivity is anticipated if the soil is subject to leaching with more pore volumes of water. However, equilibrium (or steady state) soil hydraulic conductivity is not yet achieved with gypsum at the end of leaching with the maximum volume (4.0 pore volumes) of water. This, on the other hand, indicates that the soil hydraulic conductivity will be further reduced with more leaching. Such a reduction in hydraulic conductivity may result in final hydraulic conductivity that may be equal or even smaller than the final hydraulic conductivity attained by applying langbeinite.

4. Experiment IV. Greenhouse Crop Response Studies

The ultimate goal of reclaiming saline sodic soil is to improve its capacity to produce crops. On the other hand, grain or forage crop production depends on seed germination and total biomass production. Therefore, to evaluate the efficiency of langbeinite as a reclaiming material relative to gypsum, lima bean (sodium sensitive) crop was grown in the greenhouse on a saline sodic soil reclaimed with equivalent but varying levels of applied gypsum and langbeinite and leached with different volumes of water.

As explained in chapter 3, the greenhouse crop response experiment both using gypsum and langbeinite as reclaiming materials was conducted two times. In the first of these trials, Safford irrigation water was used for leaching, whereas in the second trial, the soil was leached with Tucson tap water. In both cases, seed germination rate and dry matter yield of the crop were measured and used to determine the relative effects of the amendments as well as type and amount of leaching water.

4.1. Seed Germination Rate

The germination rates of lima bean as affected by different levels of applied langbeinite and gypsum using Safford irrigation water for leaching are given in Tables 12 and 13, respectively. The effects of both different levels of langbeinite and volumes of leaching water on percent seed germination were significantly different ($P < 0.05$). Seed germination percentage increased from 70.8 to 91.7% when the rate of applied langbeinite increased from 0 to 4 tons/ha. Similarly, the effect of volumes of leaching water on percent seed germination of lima bean crop grown on the langbeinite reclaimed soil was significantly different (Table 12). Leaching the soil with 3.5 pore volumes of irrigation water resulted in germination rate of 90.3% compared to the germination rate of 77.8% obtained with no leaching.

As with langbeinite, the different levels of applied gypsum significantly affected ($P < 0.05$) the rate of germination of lima bean seeds (Table 13). However, when gypsum is used as a reclaiming material, the effect of volumes of applied water on seed germination was not significant. Increasing the rate of applied gypsum from 0 to 12 tons/ha increased the average rate of germination from 70.8 to 86.1%. Similarly, the

average rate of seed germination increased from 77.8% with no leaching to 84.7% when leached with four pore volumes of irrigation water.

The germination data in Tables 12 and 13 indicated that langbeinite resulted in a higher germination rate than gypsum at every equivalent rates of applied amendments. Moreover, the average percent seed germination for each volume of leaching water was higher when langbeinite rather than when gypsum was used as a chemical amendment. However, although the relative efficiency of langbeinite is higher than gypsum, the effects of the chemical amendments and pore volumes of leaching water were not very impressive when compared with the control and as one can expect from the rate of removal of exchangeable sodium in the column studies. This may be attributed to the higher salinity level of the irrigation water and very high sensitivity of the crop both to salinity and sodicity.

Germination rate of lima bean seeds grown on the Grabe clay loam saline sodic soil under the influence of various levels of langbeinite application and leaching with different pore volumes of Tucson tap water is given in Table 14. The effects of both the different levels of langbeinite and pore volumes of leaching water on seed germination percentage were statistically significant ($P < 0.05$). Moreover, the interaction between pore volumes of leaching water and levels of applied langbeinite affected seed germination significantly.

Averaged over all pore volumes of applied water, seed germination rate increased from 44.4 to 79.2% when the rate of applied langbeinite increased from 0 to 12 tons/ha. Similarly, the average rate of seed germination increased from 50.0 to 79.2% when the

Table 12. Seed germination (%) of lima bean crop as affected by langbeinite application and leaching with Safford irrigation water ‡†.

Applied langbeinite (tons/ha)	<u>Applied pore volume of water</u>				Mean*
	0.0	1.5	2.5	3.5	
0	77.8	72.2	66.7	66.7	70.8b
4	77.8	88.9	100.0	100.0	91.7a
8	77.8	94.4	94.4	100.0	91.7a
12	77.8	94.4	94.4	94.4	90.3a
Mean**	77.8b	87.5a	88.9a	90.3a	

* Means within a column, followed by the same letter are not significantly different at the 0.05 probability level as tested by Duncan's Multiple Range Test.

** Means within a row, followed by the same letter are not significantly different at the 0.05 probability level.

‡ Interaction between volumes of leaching water and langbeinite rates was not significant

† LSD 0.05 = 8.25 for both row and column values.

Table 13. Seed germination (%) of lima bean crop as affected by gypsum application and leaching with Safford irrigation water ‡†.

Applied gypsum (tons/ha)	<u>Applied pore volume of water</u>				Mean*
	0.0	1.5	2.5	3.5	
0	77.8	72.2	66.7	66.7	70.8b
4	77.8	77.8	83.3	94.4	83.3a
8	77.8	88.9	83.3	88.9	84.7a
12	77.8	88.9	88.9	88.9	86.1a
Mean**	77.8a	82.0a	80.6a	84.7a	

* Means within a column, followed by the same letter are not significant at the 0.05 level.

** Means within a row, followed by the same letter are not significant at the 0.05 level.

‡ Interaction between leaching water volumes and gypsum rates was not significant.

† LSD 0.05 = 10.96 for both row and column values.

volume of leaching water was increased from 0 to 3.5 pore volumes (Table 14). When the volume of leaching water applied is fixed at 3.5 pore volumes, the rate of seed germination increased from 38.9% on pots with no langbeinite to 94.4% with langbeinite applied at a rate of 8 tons/ha. On the other hand, at a fixed rate of applied langbeinite (8 tons/ha), leaching the soil with 3.5 pore volumes of Tucson tap water increased seed germination rate to 94.4% as compared to 50% obtained with no leaching (Table 14).

Table 15 presents the average percentage of seed germination as affected by gypsum application and leaching with Tucson tap water. In accordance with the use of langbeinite as a chemical amendment, applied levels of gypsum and pore volumes of water as well as their interactions significantly affected ($P < 0.05$) lima bean seed germination rate. However, the magnitude of these effects were not as impressive as with langbeinite (Tables 14 and 15).

For instance, considering the average across all applied pore volumes of water, seed germination rate increased from 44.4 to 65.3% when the rate of applied gypsum increased from 0 to 12 tons/ha. The composite rate of seed germination increased from 50% without leaching to 65.3% on pots leached with 3.5 pore volumes of Tucson tap water (Table 15). Compared at a fixed applied volume (3.5 pore volumes) of water, seed germination rate increased from 38.9% on pots planted without gypsum to 77.8% on pots planted with 12 tons/ha of gypsum. Similarly, when the effects of applied pore volumes of water are compared at a fixed level of applied gypsum (12 tons/ha), the rate of seed germination increased from 50% with no leaching to 77.8% on pots leached with 3.5 pore volumes of water (Table 15).

Table 14. Seed germination (%) of lima bean crop as affected by langbeinite application and leaching with Tucson tap water ‡†.

Applied langbeinite (tons/ha)	Applied pore volume of water				Mean*
	0.0	1.5	2.5	3.5	
0	50.0	44.4	44.4	38.9	44.4b
4	50.0	77.8	88.9	88.9	76.4a
8	50.0	77.8	77.8	94.4	75.0a
12	50.0	77.8	94.4	94.4	79.2a
Mean**	50.0d	69.4b	76.4ab	79.2a	

* Means within a column, followed by the same letter are not significant at the 0.05 level.

** Means within a row, followed by the same letter are not significant at the 0.05 level.

‡ Interaction between volumes of leaching water and langbeinite rates was significant.

† LSD 0.05 = 9.16 for both row and column values.

Table 15. Seed germination (%) of lima bean crop as affected by gypsum application and leaching with Tucson tap water ‡†.

Applied gypsum (tons/ha)	Applied pore volume of water				Mean*
	0.0	1.5	2.5	3.5	
0	50.0	44.4	44.4	38.9	44.4b
4	50.0	61.1	66.7	72.2	62.5a
8	50.0	72.2	72.2	72.2	66.7a
12	50.0	61.1	72.2	77.8	65.3a
Mean**	50.0b	59.7a	63.9a	65.3a	

* Means within a column, followed by the same letter are not significant at the 0.05 level.

** Means within a row, followed by the same letter are not significant at the 0.05 level.

‡ Interaction between leaching water volumes and gypsum rates was significant.

† LSD 0.05 = 7.48 for both row and column values.

Without application of amendments, increasing the volume of leaching water generally decreased the rate of lima bean seed germination (Tables 14 and 15). This may be attributed to the aggravated effect of exchangeable sodium on soil properties with decreasing electrolyte concentration of the soil solution. The effects of both langbeinite and gypsum levels as well as volumes of leaching water became more evident when Tucson tap water rather than Safford irrigation water was used for leaching purposes (compare Tables 12 and 14 and Tables 13 and 15). This condition further indicates that the salinity level of the Safford irrigation water was too high for the crop as to mask the effects of the treatments under consideration.

4.2. Dry Matter Yield

Table 16 presents the dry matter yield of lima bean grown under the influence of different levels of langbeinite application and leaching with Safford irrigation water. Similarly, the dry matter yield data of the crop produced with the application of gypsum and the use of Safford irrigation water for leaching and irrigation purposes are given in Table 17.

The use of both langbeinite and gypsum as chemical amendments significantly affected ($P < 0.05$) the dry matter yield of the crop. Moreover, leaching of both gypsum and langbeinite amended soils with varying pore volumes of Safford irrigation water resulted in a significantly different dry matter yields (Tables 16 and 17). The interaction between langbeinite and pore volumes of leaching water in one hand, and between applied gypsum levels and pore volumes of leaching water in another also affected the dry matter yield significantly. However, the magnitude of the difference in dry matter

yield due to the effects of applied langbeinite was higher than due to gypsum application. Moreover, the effects of varying volumes of leaching water on dry matter yield was higher when langbeinite was used as reclaiming material than when gypsum was used.

For example the mean dry matter yield increased from 3.73 to 5.41 g/pot when applied langbeinite increased from 0 to 12 tons/ha (Table 16). Whereas increasing the levels of applied gypsum from 0 to 12 tons/ha increased the dry matter yield of the crop from 3.73 to 4.63 g/pot (Table 17). Moreover, considering the average dry matter yield across all levels of applied langbeinite, leaching the soil with 3.5 pore volumes of water yielded 5.60 g/pot compared to 3.63 g/pot produced without leaching. But, when gypsum is used as a chemical amendment, leaching with 3.5 pore volumes of water gave 4.74 g/pot while no leaching produced 3.63 g/pot.

Using langbeinite as a reclaiming material, a maximum dry matter yield (6.36 g/pot) of lima bean crop was obtained when the amendment was applied at a rate of 8 tons/ha and the soil was leached with 3.5 pore volumes of irrigation water (Table 16). With the use of gypsum, however, a maximum yield of 5.35 g/pot was obtained with the application of 12 tons/ha of gypsum and leaching the soil with 3.5 pore volumes of Safford irrigation water (Table 17).

The response of the crop to the applications of both gypsum and langbeinite as well as to the volumes of leaching water was higher when Tucson tap water rather than Safford irrigation water was used both for leaching and irrigation purposes. The dry matter yield data of the crop grown on langbeinite and gypsum treated soils are given in

Table 16. Dry matter yield (g/pot) of lima bean as affected by langbeinite application and leaching with Safford irrigation water ‡†.

Applied langbeinite (tons/ha)	<u>Applied pore volume of water</u>				Mean*
	0.0	1.5	2.5	3.5	
0	3.63	3.70	3.87	3.72	3.73c
4	3.63	4.65	5.88	6.12	5.07b
8	3.63	5.92	6.01	6.36	5.48a
12	3.63	5.87	5.95	6.19	5.41a
Mean**	3.63c	5.04b	5.43a	5.60a	

* Means within a column, followed by the same letter are not significant at the 0.05 level.

** Means within a row, followed by the same letter are not significant at the 0.05 level.

‡ Water by lanbeinite interaction was significant.

† LSD 0.05 = 0.18 for both row and column values.

Table 17. Dry matter yield (g/pot) of lima bean as affected by gypsum application and leaching with Safford irrigation water ‡†.

Applied gypsum (tons/ha)	<u>Applied pore volume of water</u>				Mean*
	0.0	1.5	2.5	3.5	
0	3.63	3.70	3.87	3.72	3.73b
4	3.63	4.24	4.51	4.97	4.34a
8	3.63	4.74	4.64	4.90	4.48a
12	3.63	4.69	4.83	5.35	4.63a
Mean**	3.63b	4.34a	4.46a	4.74a	

* Means within a column, followed by the same letter are not significant at the 0.05 level.

** Means within a row, followed by the same letter are not significant at the 0.05 level.

‡ Applied gypsum rates by leaching water interaction was not significant.

† LSD 0.05 = 0.45 for both row and column values.

Tables 18 and 19, respectively. Statistical analysis revealed a significant difference ($P < 0.05$) in the response of the crop both to gypsum and langbeinite treatments and to the pore volumes of applied water both with the application of gypsum and langbeinite. Moreover, the interactions between langbeinite and pore volumes of water and between gypsum and pore volumes of water affected the dry matter yield of the crop significantly.

Using langbeinite as a reclaiming material, the dry matter yield averaged over all pore volumes of applied water increased from 3.63 to 6.59 g/pot when the rate applied increased from 0 to 12 tons/ha (Table 18). Whereas using gypsum for reclamation, the average dry matter yield increased from 3.63 to 4.92 g/pot when the rate of applied gypsum increased from 0 to 12 tons/ha (Table 19). Leaching the langbeinite treated soil with 3.5 pore volumes of water increased the dry matter yield to 6.81 g/pot from 3.84 g/pot that was produced without leaching. However, when gypsum was used as a reclaiming material, the dry matter yield of the crop increased from 3.84 g/pot without leaching to 5.00 g/pot on pots leached with 3.5 pore volumes of Tucson tap water.

In the trial involving langbeinite, a maximum dry matter yield of 8.35 g/pot was obtained by the application of langbeinite at a rate of 12 tons/ha and leaching the soil with 3.5 pore volumes of water. The same rate of applied amendment and pore volumes of leaching water produced the highest dry matter yield in the gypsum reclaimed soil. However, this highest yield was 5.69 g/pot and therefore only 68% of the highest dry matter yield obtained with langbeinite application under comparable conditions.

Table 18. Dry matter yield (g/pot) of lima bean as affected by langbeinite application and leaching with Tucson tap water ‡†.

Applied langbeinite (tons/ha)	Applied pore volume of water				Mean*
	0.0	1.5	2.5	3.5	
0	3.84	3.58	3.38	3.72	3.63c
4	3.84	5.59	6.21	7.78	5.86b
8	3.84	5.86	7.26	7.38	6.09b
12	3.84	6.24	7.91	8.35	6.59a
Mean**	3.84d	5.32c	6.19b	6.81a	

* Means within a column, followed by the same letter are not significant at the 0.05 level.

** Means within a row, followed by the same letter are not significant at the 0.05 level.

‡ Volume of leaching water by langbeinite levels interaction was significant.

† LSD 0.05 = 0.31 for both row and column values.

Table 19. Dry matter yield (g/pot) of lima bean as affected by gypsum application and leaching with Tucson tap water ‡†.

Applied gypsum (tons/ha)	Applied pore volume of water				Mean*
	0.0	1.5	2.5	3.5	
0	3.84	3.58	3.38	3.72	3.63c
4	3.84	4.06	4.15	5.20	4.31b
8	3.84	4.70	5.22	5.38	4.79a
12	3.84	4.71	5.45	5.69	4.92a
Mean**	3.84d	4.26c	4.55b	5.00a	

* Means within a column, followed by the same letter are not significant at the 0.05 level.

** Means within a row, followed by the same letter are not significant at the 0.05 level.

‡ Applied gypsum rates by leaching water interaction was significant.

† LSD 0.05 = 0.26 for both row and column values.

CHAPTER 5

SUMMARY AND CONCLUSIONS

1. Summary

The potential use of langbeinite, relative to gypsum, as a reclaiming material for saline sodic soils was investigated by conducting four series of laboratory and greenhouse experiments. The first experiment characterized the salinity and sodicity related chemical properties of two soil types and an irrigation water from the Safford Agricultural Research Center of the University of Arizona. The results of this experiment enabled the proper identification of a saline sodic soil and water that could be used throughout the rest of the experiments in order to test the hypothesis and meet the general goal of the research work.

The second series of experiment investigated the ease of displacement of exchangeable sodium from the exchange site of a saline sodic (the Grabe clay loam) soil using gypsum and langbeinite as chemical amendments under laboratory batch studies. In the third experiment, the effects of applied gypsum and langbeinite rates as well as volumes of leaching water on the total amount and rate of removal of exchangeable sodium and soil hydraulic conductivity were evaluated by the use of laboratory column leaching studies. The last series of experiment studied the response of exchangeable sodium sensitive crop to the reclamation of saline sodic soil with gypsum and langbeinite and leaching with varying volumes of saline and nonsaline water under greenhouse conditions.

Laboratory chemical analysis were carried on the Grabe clay loam and the Guest clay soils of Safford Agricultural Research Center. Measurement of the ECe and pH revealed that the Grabe clay loam soil met the criteria for its classification as a saline soil based on the traditional system of classification of salt affected soils. Moreover, its ESP and SAR values placed the soil in the sodic soil category of salt affected soils. Characterized by an ECe of greater than 4 mmhos/cm and ESP of higher than 15, the Grabe clay loam soil met the requirements of the generally accepted characteristics of saline sodic soils.

Similarly, the Guest clay soil was classified as a sodic and slightly saline soil. However, as indicated by its higher ESP and ECe values, the Grabe clay loam soil was more strongly saline sodic than the Guest clay soil. As a result, considering the objectives of the overall study, the Grabe clay loam soil was preferred over the Guest clay soil and therefore selected and used as an experimental unit throughout the remaining three series of experiments. Accordingly, the water used to irrigate crops grown on this soil was analyzed for its chemical composition and found to contain high level of soluble salts and sodium to preclude its use for irrigation purposes. The high level of salinity and sodium content (SAR) of the irrigation water is the most probable cause of the relatively high level of salinity and sodicity of the Grabe clay loam than the Guest clay soil which in most cases is irrigated with river water.

The laboratory batch studies was conducted in a 1:1 soil:water extracts. These studies enabled the evaluation of the relative efficiency of langbeinite and gypsum in the displacement of exchangeable sodium under conditions of water limitation for dissolution

of the chemical amendments. Under such a condition, the chemical amendments removed comparable amounts of exchangeable sodium when both were applied at a rate of 6 tons/ha or lower.

However, langbeinite replaced significantly higher amounts of exchangeable sodium than gypsum at all equivalent rates of application above 6 tons/ha. In general, increasing the rate of applied gypsum over 4 tons/ha did not bring a significant increase in the release of exchangeable sodium. This signifies that no additional gypsum was able to dissolve and release Ca ion to exchange with sodium by increasing its rate of application over 4 tons/ha.

Whereas the rate of release of exchangeable sodium due to increasing levels of applied langbeinite upto the maximum (20 tons/ha) was significantly higher from each other, implying that any additional langbeinite rate contributed additional cation that could exchange with sodium. The maximum amount of exchangeable sodium replaced (4.27 meq/100g soil) by langbeinite was realized when the chemical was applied at a rate of 20 tons/ha. This lowered the ESP of the soil under study from 24.9 to 4.5%. While with gypsum the highest rate of release of exchangeable sodium was only 2.18 meq/100g soil at a rate of 18 tons/ha and lowered the ESP of the soil from 24.9 to 14.5%. Such a major difference in the efficiency of the chemical amendments is mainly attributed to the higher water solubility (over 100 times more) of langbeinite than gypsum.

In the laboratory column studies, the effects of application of gypsum and langbeinite and leaching with different pore volumes of irrigation water on the EC breakthrough curves of the eluents, the rate of removal of exchangeable sodium and the

hydraulic conductivity of the soil were studied. The EC breakthrough curves as affected by gypsum and langbeinite varied significantly. In most cases, the peak EC of the eluents from the columns treated with langbeinite was higher than from the columns treated with the same amount of gypsum.

Moreover, it required a much shorter leaching period to attain the peak as well as the steady state (constant) EC when langbeinite rather than gypsum was used as a reclaiming material. In other words, the EC breakthrough curves for the columns leached with the application of gypsum were more spread than with langbeinite application. The characteristics of the EC breakthrough curves generally indicated that reclamation of saline sodic soils can be accomplished in a much less time and using much less water with the use of langbeinite than using gypsum as a chemical amendment. This is further attributed to the significantly higher water solubility of langbeinite than gypsum and probably due to the higher cation equivalent of langbeinite than gypsum when compared per unit mass basis.

The rate of exchangeable sodium removal as indicated by the amount displaced by leaching with specific pore volume of water and its breakthrough curves followed the pattern exhibited by the EC breakthrough curves. At lower rates of applied pore volumes of leaching water, langbeinite proved to be much more efficient than gypsum as a reclaiming material for sodic and saline sodic soils. However, with the use of the maximum volume (4 pore volumes) of leaching water, the amounts of exchangeable sodium displaced by gypsum and langbeinite were almost the same for most equivalent levels of applied amendments.

In general, increasing the rate of applied levels of both gypsum and langbeinite resulted in the displacement of higher amounts of exchangeable sodium. Similarly, increasing the pore volumes of applied water displaced increasing amounts of exchangeable sodium using both gypsum and langbeinite as chemical amendments. However, the rate of increase in the release of exchangeable sodium due to either increased levels of chemical amendments or pore volumes of leaching water was significantly higher when langbeinite rather than gypsum was used as a reclaiming material.

For example, applying langbeinite at a rate of 12 tons/ha and leaching with 2 pore volumes of irrigation water displaced 2.92 meq of exchangeable sodium per 100g of soil. This lowered the ESP of the soil to 10.93%. When gypsum was applied at the same rate as langbeinite, it required leaching with 4 pore volumes of irrigation water to displace 3.05 meq of exchangeable sodium per 100g of soil, and therefore lower the ESP of the soil to 10.31%.

If we consider the final ESP values of the soil given above as the same, we can state that one can save 2 pore volumes of water by using langbeinite over using gypsum when both amendments are applied at equivalent (12 tons/ha) rates to lower the ESP to a specific unit. Assuming the porosity of the soil as 0.38 and soil reclamation to a depth of a foot, the farmer who uses langbeinite as a reclaiming material could save 9.12 acre-inch (0.76 acre-foot) of water per acre of reclaimed land than a farmer who uses the same amount of gypsum as a reclaiming material to lower the soil ESP to the same unit. Comparison of the different levels of applied amendments at a specific volume of applied

water in the ranges between 0.5 to 2.5 pore volumes closely followed the pattern discussed above for the rate of 12 tons/ha of applied gypsum and langbeinite.

The calculated hydraulic conductivity of the soil increased considerably with increasing rates of application of both gypsum and langbeinite. However, leaching the soil with increasing pore volumes of irrigation water decreased the soil's hydraulic conductivity irrespective of the type of reclaiming material used. The rate of decrease in hydraulic conductivity of the soil with increasing pore volume of leaching water was higher in langbeinite treated soil columns than in gypsum treated ones.

As a result, the hydraulic conductivity of the soil after leaching with the maximum volume (4 pore volumes) of water for every level of applied gypsum was greater than the hydraulic conductivity of the soil treated with equivalent rate of langbeinite. It should be noted, however, that the hydraulic conductivity of the soil reclaimed with the different levels of langbeinite had reached a steady state hydraulic conductivity after leaching the soil with about three pore volumes of water. Whereas reclamation with any of the different levels of applied gypsum did not result in an equilibrium or steady state hydraulic conductivity. This indicates that the hydraulic conductivity of the soil reclaimed with gypsum will continue to decrease with further leaching. Such a reduction in hydraulic conductivity with leaching in the gypsum treated columns may result in a final hydraulic conductivity that may be equal or even lower than the final hydraulic conductivity attained by applying langbeinite.

In general, the reduction in soil hydraulic conductivity with increasing pore volumes of leaching water is apparently due to the reduction in the electrolyte

concentration which if high could have counterbalanced the dispersive effect of exchangeable sodium. It follows therefore that higher hydraulic conductivity with gypsum than with langbeinite treated columns until the end of leaching signifies that gypsum, because of its low solubility had maintained high electrolyte concentration for a longer leaching period than langbeinite.

The response of lima bean crop to the reclamation of saline sodic soil using gypsum and langbeinite and leaching both with Safford irrigation water and Tucson tap water was studied in the greenhouse. In both cases, seed germination rate and dry matter yield data were measured and used for interpreting the response.

Seed germination rate increased due to the application of increasing levels of gypsum and langbeinite when the soil was leached either with Safford irrigation water or Tucson tap water. Moreover, increasing the pore volumes of leaching water increased the rates of seed germination of the crop irrespective of the type of reclaiming material used. However, the rate of increase in percent seed germination both due to applied amendments and leaching was much higher on soils reclaimed with langbeinite than with gypsum. The magnitude of the effects of both chemical amendments and volumes of leaching water on seed germination rates were higher when Tucson tap water was used both for leaching and irrigation purposes than leaching and irrigation with Safford irrigation water.

Similarly, the dry matter yield of the crop responded significantly to the different rates of applied gypsum and langbeinite and leaching both with Safford irrigation and Tucson tap waters. In accordance with the rate of seed germination, the dry matter yield

due to increasing levels of chemical amendments and pore volumes of leaching water was higher with langbeinite than with gypsum for every comparable treatment conditions. Moreover, the dry matter yield response both to the applied chemical amendments and leaching was greater when Tucson tap water rather than Safford irrigation water was used for leaching and irrigation purposes.

2. Conclusions

The series of laboratory and greenhouse experiments enabled to test the hypothesis and evaluate the specific objectives of the study successfully. In general, the following conclusions can be drawn from the results of the overall experiment:

1. The Grabe clay loam soil of Safford Agricultural Center was classified as a saline sodic soil according to the traditional system of classification of salt affected soils. The Guest clay was classified as sodic and slightly saline soil.
2. Langbeinite proved to be superior over gypsum as a reclaiming material for saline sodic soils both in the batch and the column leaching studies.
3. Langbeinite required significantly less irrigation water than gypsum to displace and leach the same amount of exchangeable sodium from the soil columns.
4. Applying both gypsum and langbeinite improved the saturated hydraulic conductivity of the soil significantly, but gypsum improved it more than langbeinite.

5. The saturated HC decreased with increasing volumes of leaching water because of decreasing electrolyte concentration in the soil solution with more leaching. The rate of decrease was faster with langbeinite than with gypsum.
6. Seed germination and dry matter yield of lima bean in greenhouse conditions responded significantly to saline sodic soil reclamation both with gypsum and langbeinite as well as leaching. However, langbeinite improved germination and yield considerably more than gypsum.
7. The choice of the amendments is subject to local conditions such as the availability and cost of irrigation water resource, availability and cost of amendments, cost of application and handling of amendments and urgency of implementing the reclamation.
8. Further studies designed to evaluate the relative efficiencies of the amendments with regards to response of crops of economic importance under field conditions are recommended.

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