

# SODICITY: A REASSESSMENT OF THE INFLUENCE OF SODIC/SALINE CONDITIONS ON MINE LAND RECLAMATION<sup>1</sup>

by

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**Abstract:** The impact of SAR on soil physical properties is highly dependent on soil salinity. The electrolyte concentration of the soil system must be taken into account to predict the impact of SAR on the physical state of the soil. In addition, the physical nature of the system must be addressed. Natural soils usually are complex heterogeneous aggregates made up of many clay types, silts and sand, intimately associated with inorganic and organic polymers. Most often soils are not saturated, particularly in semi arid climates. The research, and, thus the guidelines used to regulate reclamation activities at coal mines are based on information collected during the study of saturated, aqueous systems where clay particles were suspended. It is important to evaluate sodic/saline conditions in light of the unsaturated soil conditions most often experienced in mine land reclamation.

Any attempt to set critical SAR values in mine reclamation without simultaneously considering total cation concentration is a misrepresentation. Sodic soils will remain flocculated when salinity is maintained at or above the threshold electrolyte concentration. One exception is when sodic surfaces are impacted with water (rainfall) containing low levels of electrolytes. Spoil materials found in arid and semiarid mining environments are usually not highly weathered, therefore, exposure to weathering readily provides salts to the soil water system. Many of the soluble minerals contain calcium (Ca), thus providing a source for self-remediation. Where levels of Ca, magnesium, (Mg), and sodium (Na) are low in spoil, contributions of Ca and Mg, through weathering, will significantly reduce the SAR. In addition, spoil weathering also provides electrolytes at levels that will keep the spoil flocculated.

Guidelines used for regulating mine land reclamation have not adequately addressed the importance of the sodic/saline interactions. Most guidelines include SAR (ESP), soil texture, and saturated percentage without any evaluation relating to EC or electrolyte concentrations. Guidelines that do not include the SAR/salinity interaction do not provide realistic evaluations of SAR impact on the physical conditions of spoil materials under field conditions. This paper addresses developing standards that reflect the sodicity/salinity relationships for mine land reclamation under realistic environmental conditions.

**Additional Key Words:** hydraulic conductivity, infiltration rate, clay dispersion, sodium adsorption ratio, electrical conductivity, guidelines

## Introduction

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In the past, researchers have used a model evaluating the forces generated between colloidal clay minerals suspended in saturated systems to explain sodic soil behavior. Two major problems are apparent with this model. First, natural soils usually are complex heterogeneous aggregates made up of many clay types, silts and sand, intimately associated with inorganic and organic polymers. These aggregates do not resemble pure clay systems. In addition, the aggregates are not suspended in water. As a result, forces other than those that operate in saturated

systems must be overcome during aggregate slaking and clay dispersion. Therefore, it is important to use a natural soil model that shows how sodicity and salinity impact the physical conditions of soil and/or spoil materials not suspended in aqueous solutions. The model described by Rengasamy and Sumner (1998) will be used to address this important concept. The fact is that aggregate slaking and clay dispersion decrease as the system contains less water.

The impact of sodium adsorption ratio (SAR) on the physical character of a soil is greatly dependent on the salinity of the soil. It is impossible to estimate the impact of low or high SAR values on the physical state of a soil or spoil material without knowing the electrical conductivity (EC) or electrolyte concentration of the system (Shanmuganathan and Oades, 1983). Any attempt to set critical exchangeable sodium percentage (ESP) or SAR values for land management would be arbitrary unless electrolyte levels are taken into consideration simultaneously (Sumner et al., 1998). Research has shown that extremely high SAR values do not cause physical degradation of soil materials if the system also contains high levels of salts. This fact was first shown by research done by Quirk and Schofield (1955). Their work demonstrated that a soil with an ESP of 40 maintained a stable permeability with an electrolyte concentration of about 30 mmol/L (about EC = 2.1 dS/m). McNeal and Coleman (1966) pointed out that typical arid land soils (having clay mineralogy dominated by 2:1 layer silicates with only moderate amounts of montmorillonite) could tolerate ESP values of 15 or greater before serious reductions in hydraulic conductivity occur, if the salt concentration of the percolating solution exceeds 3 mmol/L (0.2 dS/m). Gardner et al. (1959) came to the same conclusion dealing with unsaturated soils. This phenomenon has since been demonstrated on numerous occasions by a number of investigations and is well documented in the literature.

This paper will provide a review of the chemistry of sodic/saline systems with regard to natural soil conditions and the forces involved in the physical structure of soils during the wetting process from dry to near saturation. The primary objective is to review the chemistry of the sodicity/salinity relationships expected in the coal mining areas of New Mexico and to provide support for the modifications of guidelines or standards where appropriate to include both sodicity and salinity into the guideline.

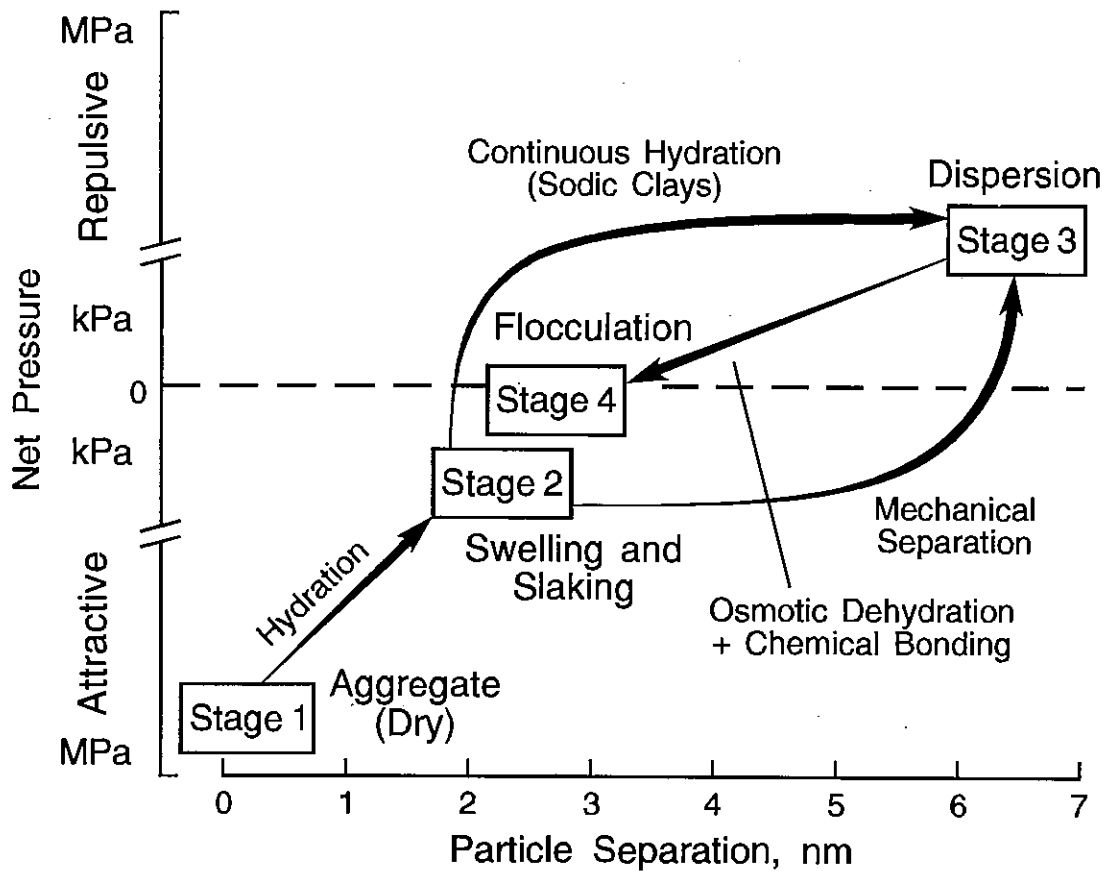
#### **Model for Sodic Soil Behavior**

In the past, soil scientists have used a model involving electrical diffuse double layer theory to explain sodic soil behavior. This explanation was

usually conducted using pure clay minerals in saturated systems. However, in natural systems, complex clay systems are bound together into aggregates with silt and sand particles by inorganic and organic compounds and are usually not suspended in water. The slaking of aggregates and the dispersion of clays requires forces other than those that operate in colloidal clay suspensions. Rengasamy and Sumner (1998) have developed a model that describes the processes that take place during the wetting of a dry soil aggregate. Their model will be presented in this paper as a realistic approach describing the influences of sodicity and salinity on the physical nature of natural soil systems.

The model consists of four (4) stages as shown in Figure 1. Dry soil aggregates are held together by inorganic and organic compounds and associated bonds that produce very strong attractive forces. The forces involved include Lifshitz-van der Waals, ionic bonds, hydrogen, hydrophobic, and hard-soft acid-base reactions. As dry aggregates are wetted, solvation or hydration forces become important. The stability of aggregates, and hence the pore systems, depends upon attractive and repulsive forces resulting from intermolecular and electrostatic interactions between soil solution and soil particles (Rengasamy and Olsson, 1991). When an aggregate is placed in contact with water, the interactive forces lower the potential energy of water molecules; thus releasing energy for structural changes and as heat. Aggregate slaking, clay swelling, and clay dispersion are the major mechanisms that occur during these transformations.

Thus, as an aggregate is hydrated, the initial attractive forces between clay particles decrease. As hydration increases, the distance between particles increases. In general, if the clay particles are saturated with Ca or Mg, additional hydration does not increase the inter-particle distance beyond a few nanometers, resulting in a net force that is attractive and the aggregates are held together by hydrated cations. The swelling resulting from these reactions will occur even with high electrolyte concentrations. Slade and Quirk (1991) found that the change in separation to 1.5 nm is not affected by electrolyte solution (crystalline swelling) and that the separation from 1.5 to 1.9 nm is an osmotic process that includes electrolyte concentrations, charge density, and the location of the charge in the clay minerals. If the clays are saturated by monovalent cations such as Na, the clay particles are separated beyond 7 nm dependent on the ionic strength and the existence of soft-hard acid-base strength and the existence of soft-hard acid-base reactions. This results in clay dispersion shown as



Source: P. Rengasamy and M.E. Sumner, 1998

Figure 1. Stages that take place during the wetting of a dry aggregate.

Stage 3 in Figure 1. Stage 3 can also be reached when a source of mechanical energy is applied to the clay domains that have undergone limited separation. Mechanical energy resulting from raindrop impact and surface water flow can overcome the attractive forces causing the system to separate. Once the system is completely dispersed, the electrostatic repulsive forces as predicted by the electrical double layer theory become important to the physical nature of the system. A dispersed clay system will become flocculated as the difference in the electrical potentials in the inner and outer solutions approach zero and as the clay particles approach each other. The repulsive pressure is balanced by osmotic pressure, and the van der Waals attractive forces become dominant. At this point, the clays become flocculated as identified in Figure 1 as Stage 4 of the model.

Since much of the research regarding sodic/saline conditions has been conducted using saturated aqueous systems, some concern exists for

whether or not these studies apply to unsaturated conditions. Since low water contents result in low repulsion forces, unsaturated systems would be expected to have higher attractive forces as compared to saturated systems. Rengasamy and Sumner (1998) indicated that spontaneous dispersion takes place when sodic clay is impacted with water of very low electrolyte concentration. However, water content below saturation results in limited swelling and incomplete separation of clay particles with the interparticle distance depending upon the water content. Therefore, aggregate slaking and clay dispersion in unsaturated systems would be limited as compared to saturated systems for specific SAR/EC conditions. Russo and Bresler (1977) demonstrated this fact in their study evaluating hydraulic conductivity ( $K$ ) with regard to cationic ratio ( $\text{Na}^+ / (\text{Ca}^{+2})^{1/2}$  ( $R$ ), electrolyte concentrations ( $C$ ), and volumetric water content ( $\theta$ ). This study showed that under specific combinations of these variables the value of the cationic ratio can be estimated for a given hydraulic conductivity ( $K$ ). For example, under saturated conditions with  $C =$

0.02 N (approximate irrigation field soil) it is possible to maintain  $K \geq 0.5$  cm/s as long as  $R \leq 14$ . Under the same conditions (C and K), but in unsaturated soils the corresponding value for R is 20. This study shows that water of poorer quality (higher sodicity) can be applied when unsaturated conditions are maintained during irrigation. These studies demonstrate that the negative effect of high SAR and low solution electrolyte levels decreases in dryer soils.

### **Threshold Electrolyte Concentrations**

The impact of sodicity on the physical properties of soils is dependent on the electrolyte concentration associated with the system. If salt is added to a dispersed clay in a suspension, the increased electrolyte concentration causes the clay particles to stick together forming flocs that settle (Stage 4 of the model discussed in the previous section). The minimum electrolyte concentration required to cause flocculation is referred to as the threshold electrolyte concentration (TEC) or flocculation value (FV). This value is dependent on counter-ion valency and clay type. The TEC values for a sodium-montmorillonite were shown to be about  $12 \text{ mol/m}^3$  NaCl or  $0.86 \text{ dS/m}$  and  $0.25 \text{ mol/m}^3$   $\text{CaCl}_2$  or  $0.02 \text{ dS/m}$  for calcium-montmorillonite (Van Olphen, 1977). Corresponding values for sodium and calcium illites were found to be  $40 \text{ mol/m}^3$  to  $50 \text{ mol/m}^3$  NaCl and  $0.25 \text{ mol/m}^3$ , respectively (Arora and Coleman, 1979). These data show that a sodium montmorillonite can be maintained in a flocculated condition if the salt levels of the same ion (Na) are about  $1 \text{ dS/m}$  and sodium illites will tend to remain flocculated if salt levels with the same ion (Na) are about  $3.6 \text{ dS/m}$ . Sposito (1989) indicated through his discussion of the literature that a fully Na-saturated smectite suspension will flocculate if the electrolyte concentration is  $> 8 \text{ mol/m}^3$  ( $0.6 \text{ dS/m}$ ) and a suspension of Na-illite will do the same if the electrolyte concentration reaches about  $50 \text{ mol/m}^3$  ( $3.6 \text{ dS/m}$ ). The conclusion of this work is that soil salinity counteracts the effect of exchangeable sodium on soil structure. The presence of divalent ions such as Ca would reduce the TEC to lower salt concentrations.

If salinity is maintained at or above the TEC value for a specific material, the data show that the physical condition of the material will be maintained in a flocculated state no matter how high the SAR. The only caveat to this situation is that some materials that have high SAR and EC character can become dispersed at the surface if impacted with water containing low levels of electrolytes from

irrigation or rainfall. Under these conditions the surface materials can become dispersed. In addition, mechanical forces resulting from raindrop impact or the use of farm equipment could cause clay dispersion. If measures are taken to eliminate these potential impacts to the system, the high SAR soil/spoil material will usually be maintained in good physical condition. One method of doing this is to cover such spoils with topdressing material. Topdressing material is good-quality overburden (soil) that is special handled for placement at the surface to cover lower quality spoil materials. This fact was demonstrated during a recent visit to the La Plata Mine. A soil pit had been dug at a reclaimed site that had about 10 inches of topdressing material over spoil material that exceeded the New Mexico Mining and Minerals SAR standards of 16 for clay loam textured materials. The spoil material had SAR values from 11 to 75 in the top 4 ft with EC values ranging from 3.5 to 7.3 dS/m at various depths within the same depth zone. The roots of re-established native vegetation covering the site exhibited no problems growing through this material. In fact, the rooting showed numerous branching and overall good health. The spoil materials to about 4 inches below the topdressing/spoil interface showed evidence of weathering with the development of a very porous, subangular blocky structure. Migration of Na at or near the topdressing/spoil interface was not evident. The elevated SAR values associated with the spoil did not have a detrimental impact on plant growth as compared to adjacent areas with low SAR ( $<16$ ) materials.

### **Impact of Sodicity/Salinity on Hydraulic Conductivity and Infiltration Rate**

Hydraulic conductivity (K) is less sensitive to sodic conditions as compared to infiltration rate (IR). The primary factor responsible is the influence of mechanical energy resulting from the impact of raindrops at the surface. This mechanical energy promotes the disintegration of aggregates and the dispersion of clays resulting in the formation of a structural crust. Crusts are formed as a result of the physical disintegration of aggregates, while compaction is caused by the impact of the water droplets and chemical dispersion of clays near the surface. Smectitic soils are very sensitive to reduced IR even at very low ESP levels ( $\text{ESP} < 3$ ). A very important factor in the degradation of IR is that rainfall contains very low levels of salts. Therefore, rainfall is responsible for leaching electrolytes from the surface, leaving the surface materials more susceptible to dispersion. Hydraulic conductivity (K) is much less susceptible to degradation, except at the surface, mainly because of the reduced impact of mechanical forces and the electrolyte levels that often occur. The mineral phase associated with arid land materials usually readily

weathers providing electrolytes to the system enhancing its ability to maintain structure.

This discussion supports the fact that topdressing placed over sodic materials will alleviate the development of poor physical conditions in the sodic materials. The surface layer of material (topdressing) eliminates the mechanical energy input from raindrop impact and/or surface water flow and the low electrolyte water that would promote aggregate slaking and clay dispersion. Weathering of the surface layer and the underlying sodic materials would result in increased electrolyte levels in solution that would prevent dispersion; and the  $\text{Ca}^{+2}$  present in the solution would tend to self-remediate the sodic condition.

### **Sodicity as it Relates to Reclamation in the Coal Mining Areas of New Mexico**

The previous discussion forms the basis for development of standard criteria that is appropriate for estimating the suitability of spoil materials to be used in the post-mining root-zone. New criteria must be developed to categorize Na-affected soils for management purposes. Such a system should be based upon soil behavior with regard to sodicity, electrolyte concentration, and other factors such as pH, rather than upon arbitrary SAR criteria. These criteria must follow a logical progression from a chemistry that causes the system to be flocculated, to a system that is dispersive under mechanical energy, to a system that is spontaneously dispersive. Sumner et al. (1998) defines these classes as follows: (1) flocculated soils; soils that contain more than the minimum electrolyte concentration required for flocculation of the clay fraction will present few physical problems, but the levels of salts could be excessive and limit productivity by drought stress. Therefore, the salt concentrations must be above the TEC, but must not have a detrimental impact on plant growth. Much of the vegetation growing on reclaimed sites in the arid environment of New Mexico would be expected to grow well in materials that maintain electrolyte concentrations above the TEC. The current maximum threshold limit (MTL) for EC at many mines in northwestern New Mexico is  $> 16 \text{ dS/m}$ , which is much higher than the TEC for any clay material found at many mines in the New Mexico; (2) potentially dispersive soils; Soils that require inputs of mechanical energy (raindrop impact, tillage) to bring about dispersion will experience problems of crusting, reduced porosity, and infiltration rate when disturbed by raindrops or intensive cultivation. However, as discussed in the previous section, the use of topdressing material over

the regraded spoil should eliminate dispersion problems; and (3) dispersive soils; Soils that disperse spontaneously without shaking will have severe problems associated with crusting, reduced porosity, and infiltration rates even when subjected to minimum mechanical stress, e.g. under zero tillage. This class of material can have SAR values from about 6 to very high levels but also is characterized by very low electrolyte concentrations. In other words, a soil with a SAR of 6 can be dispersive if the EC of the material is  $< 0.3 \text{ dS/m}$ . Use of topdressing over the spoil material should eliminate dispersion problems under these conditions.

The soil/spoil materials as discussed and documented previously show that materials characterized by high SAR and high EC values support healthy communities of native vegetation at the La Plata Mine. However, the question of future deterioration comes up as a basis of concern for the development of a guideline that allows high SAR/high EC materials to be treated as suitable plant growth medium. For example, if high SAR/high EC material is impacted by low EC rainwater, EC levels of the spoil material may be reduced to levels below its TEC. As a result, the spoil could disperse and the physical condition of the material may become detrimental to plant growth. However, the topdressing and spoil materials found in arid and semiarid environments usually are not weathered to any great extent, and therefore readily provide salts to the soil water system. The readily soluble minerals found in these topdressing materials are expected to contain elements such as Ca that will provide a self-remediation mechanism to the system through the exchange of Ca for Na on the exchange sites, reducing the sodic condition. In addition, the topdressing materials evaluated at the La Plata mine usually contain from 1% to 5%  $\text{CaCO}_3$ . Although  $\text{CaCO}_3$  is rather insoluble under high pH conditions, it provides a source of Ca for extended periods of time. In addition, as the  $\text{CO}_2$  levels of the soil material increase from about  $10^{-3.5} \text{ atm}$  to about  $10^{-2.5} \text{ atm}$  due to root growth activity and microbial growth, the pH of the system will tend to decrease. As a result, the dissolution of the  $\text{CaCO}_3$  present in the system will increase. The dissolution of the  $\text{CaCO}_3$  will tend to increase the pH of the system through hydrolysis of the carbonate. Therefore, the pH of the materials will be buffered but at a lower pH level. Under these conditions the pH of the system will tend to decrease with the increased  $\text{CO}_2$  levels. As the pH of the material declines an accompanying reduction in negative surface charge will reduce the dispersive nature of the plant growth materials. Therefore, as water moves through the topdressing material, relatively high levels of salts containing beneficial elements such as Ca will move into the spoil materials. The salts will promote the flocculated condition of the spoil material and will tend to remediate

the material through cation exchange processes with the Na. This phenomenon is especially important at the La Plata mine, since some of the spoil materials found are characterized by high SAR values and rather low EC values. In the worst situations i.e. SAR values of 70 and EC values of < 2.0 dS/m, the amount of Na, Ca and Mg found in solution is very low. Even at these high SAR levels, an electrolyte concentration of 2.0 dS/m will likely maintain good physical conditions of the material. In addition, these conditions will result in contributions of Ca and Mg that will significantly reduce the SAR values of the spoil. Placement of topdressing materials at the surface will readily provide electrolytes, including Ca, to the system from the weathering process as discussed previously. This process will reduce the SAR levels to values that will maintain good physical character of the spoil material. X-ray diffraction data generated from core samples collected from the La Plata mine show that feldspars and other readily weatherable minerals exist in the spoil material. The weathering of the spoil material should provide electrolytes that will tend to keep the spoil flocculated and cations such as Ca that will promote the self-remediation of sodic conditions that might exist.

### Conclusions

The impact of SAR on soil physical properties is highly dependent upon soil salinity. Any attempt to set standards for sodic conditions using SAR values must also consider total cation concentration. Sodic soils will remain flocculated when salinity is maintained at or above the threshold electrolyte concentration. Spoil materials found in arid and semiarid environments are usually unweathered, therefore, exposure to weathering readily provides salts to the soil solution maintaining the system in a flocculated condition. In addition, many of the soluble minerals contain Ca, thus providing a source for self-remediation. Where solution levels of Ca, Mg, and Na are low in spoil, contributions of Ca and Mg, through weathering of spoil and topdressing materials, will significantly reduce the SAR.

Guidelines used for regulating mine land reclamation have not adequately addressed the importance of the sodic/saline interactions. Most guidelines include SAR (ESP), soil texture, and saturated percentage without any evaluation relating to EC or electrolyte concentrations. Guidelines must include the SAR/salinity interaction to make realistic evaluations of the impact of Na on the physical conditions of spoil materials under field conditions.

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