

## EFFECT OF MAGNESIUM ON THE HYDRAULIC CONDUCTIVITY OF Na-SMECTITE-SAND MIXTURES<sup>1</sup>

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**Abstract**—Changes in hydraulic conductivity (HC) and clay dispersion of smectite-sand mixtures as a function of exchangeable Na in Na-Ca and Na-Mg systems were measured. The charge density on the smectites had no effect on Na-Ca and Na-Mg equilibrium, and the affinity of the clays for Na was similar in both systems. A decrease in HC at 0.01 M concentration was found to be due to clay swelling. Mg was found to be less effective than Ca in preventing the breakdown of the packets by low concentrations of exchangeable Na, and Na-Mg-smectite swelled more than Na-Ca-smectites.

Na-Mg-clay particles dispersed more readily than Na-Ca-clay particles when the mixtures were leached with distilled water; however, if the electrolyte concentration in the clay-sand mixture was controlled by the leaching solutions, no difference between the Na-Mg- and Na-Ca-clays was noted. Thus, the effect of Mg on clay mixtures leached with distilled water was apparently due to the effect of Mg on the hydrolysis of the clays. Increase in charge density increased the stability of the R<sup>2+</sup> clay packets, and higher concentrations of Na were needed to break the packets. Mg was less effective than Ca in stabilizing the packets, and lower concentrations of Na were needed to break the Mg-packets.

**Key Words**—Charge density, Dispersion, Hydraulic conductivity, Magnesium, Salinity, Smectite, Swelling.

### INTRODUCTION

The permeability of montmorillonitic soils is strongly dependent on the type of exchangeable cation and the salt concentration of the percolating solution. Permeability tends to decrease with increasing exchangeable sodium percentage (ESP) and decreasing salt concentration. Adsorbed Ca stabilizes the soil structure and counteracts the dispersive effect of Na<sup>+</sup> (Quirk and Schofield, 1955). Fewer reports on effect of Mg<sup>2+</sup> on soil permeability have been published, and results seem to be contradictory, possibly due to differences in soils mineralogy and sample preparation procedures. The U.S. Salinity Laboratory Staff (1954) reported that Ca and Mg were similarly beneficial in developing and maintaining soil structure. On the other hand, McNeal *et al.* (1968) showed that mixed Na-Mg soils developed lower hydraulic conductivities (HC) than Na-Ca soils under similar conditions.

In recent works (Chi *et al.*, 1977; Emerson and Chi, 1977; Abder-Rahman and Rowell, 1979) a distinction was made between the direct effect of exchangeable Mg in causing decreases in HC and the inability of Mg in irrigation waters compared with Ca ions to prevent accumulation of exchangeable Na in the soil. In these reports Mg was shown to have a direct effect in illite-dominated, but not in montmorillonite-rich soils. Alperovitch *et al.* (1981) suggested that in calcareous

montmorillonitic soils exchangeable Mg had no direct effect on the HC and clay dispersion. They suggested that in these soils the presence of exchangeable Mg enhanced the dissolution of CaCO<sub>3</sub>, and the electrolyte concentration in soil solution was high enough to prevent clay dispersion and HC losses. Conversely, in non-calcareous, highly weathered soils, if the Na-Mg soils were leached with distilled water (simulating rain water) exchangeable Mg appeared to effect both HC losses and clay dispersion. Alperovitch *et al.* (1981) proposed that Mg-saturated soil clays were chemically more stable and did not release electrolytes into the solution. Thus, they dispersed more easily when they were leached with distilled water.

The effect of clay mineralogy on the response of smectite-sand mixtures to Na and Ca ions and to saline conditions was studied by Alperovitch *et al.* (1985). They found that smectites having low charge density (e.g., Wyoming montmorillonite) swelled and dispersed more than smectites having high charge density (e.g., Polkville and Otay smectites). The charge density on the smectites also determined the chemical stability of the clay. The purpose of the present study was to investigate the effect of Na-Mg mixtures on swelling, dispersion, HC, and the effluent electrical conductivity (EC) of smectite-sand mixtures.

### MATERIALS AND METHODS

#### Materials

Four smectites from Ward's Natural Science Establishment, Rochester, New York, were selected for study. Their

<sup>1</sup> Contribution from the Agricultural Research Organization, The Volcani Center, Bet Dagan, Israel. 2066-E, 1987 series.

Table 1. Sources and properties of the clays used in the study.

Smectite <sup>1</sup>	Cation-exchange capacity (meq/100 g)		Specific surface (m <sup>2</sup> /g)	Octahedral substitution (atom/unit cell)		Tetrahedral substitution (atoms/unit cell)	Charge density (meq/cm <sup>2</sup> × 10 <sup>7</sup> )
	Low (1980)	This study		Mg	Fe		
Upton, Wyoming (API 25)	85	90.7	800	0.65	0.32	0.18	1.13
Belle Fourche, South Dakota (API 27)	85	92.4	776	0.57	0.36	0.20	1.19
Polkville, Mississippi (API 21)	105	103.4	760	0.90	0.29	—	1.36
Otay, California (API 24)	120	122.2	552	1.20	0.11	0.05	2.21

<sup>1</sup> Obtained from Ward's Natural Science Establishment, Rochester, New York; numbers are American Petroleum Institute reference clay numbers.

source, identifying API number, amount of octahedral and tetrahedral substitution, cation-exchange capacity (CEC), and specific surface area (S), as reported by Low (1980), are presented in Table 1. The charge on the four clays is predominantly due to cation substitution in the octahedral layer.

Clay-sand mixtures were prepared by mixing 5 g of dry, powdered (untreated) clay and 95 g of acid-washed quartz sand (0.1–0.6-mm diameter). The clay-sand mixtures were mixed thoroughly and wetted with 10 ml of distilled water. Following 3 hr of equilibration at room temperature, the wetted mixtures were dried at 60°C and cooled in a desiccator. Wetting the clay-sand mixtures bound the clay platelets to the sand grains and prevented segregation of the clay and the sand when the downward packed columns were prepared by packing 100 g of the clay-sand mixture into 5-cm-diameter plastic cylinders to a bulk density of 1.35 g/cm<sup>3</sup>. The mixture length in the column was 3.7 cm. Based on a particle density of 2.65 g/cm<sup>3</sup>, the pore volume of the columns was 36.3 cm<sup>3</sup>. Bottom support for the clay-sand mixtures consisted of a rubber stopper with a hole to accommodate an outflow tube. A circle of 20-mesh bronze screen cut to fit the inside of the cylinder and covered with 1.0-cm layer of sand served as a filter. Dispersed clay particles could be leached freely from the columns.

#### Methods

The saturated HC of the clay-sand mixture in the columns was used as a measure of the effect of the treatment. Each column was initially wetted from the bottom with the 0.5 M Cl<sup>-</sup> solution having an appropriate sodium adsorption ratio (SAR = (Na)/(Ca)<sup>1/2</sup> or SAR = (Na)/(Mg)<sup>1/2</sup>), where the concentrations are in mmole/liter. Saturated HC was determined by leaching the column with the solutions using a constant head device and measuring the drainage rate. Effluent was collected incrementally using a fraction collector. The HCs of the sand-clay mixtures in the columns obtained using 0.5 M solutions (~480 mm/hr) were taken as the "base" HC. Columns were then consecutively leached with 0.05 and 0.01 M Cl<sup>-</sup> solutions of the treatment SAR until steady state flows and effluent

compositions were achieved. The columns were then differentially leached with solutions of the same SAR but with a salt concentration of 0, 1.0, 2.0, or 3.0 mmole Cl<sup>-</sup>/liter. The volume of leachate at a given time interval and clay dispersion was recorded. Each treatment was repeated, and the agreement between replicates was good (coefficient of variability of 10%).

Half-gram samples of clay were equilibrated with 0.5 M solutions of SAR 3, 5, 10, and 20 made of Na-Ca and Na-Mg mixtures. The suspension was centrifuged, the supernatant was decanted, and another solution of the same SAR and same concentration was added. Following three washings with 0.5 M solutions, the clay was washed three times with 0.01 M Cl<sup>-</sup> solutions of the same SAR. Finally, the suspension was centrifuged; the supernatant was analyzed for Na, Ca, and Mg; and the suspension was washed with 60% ethanol/water solutions until free of electrolytes. Exchangeable cations were extracted from the clay with 1.0 M NH<sub>4</sub>OAc solutions and determined spectroscopically.

## RESULTS AND DISCUSSION

### Exchange characteristics

The ESP-SAR relationships for the Na-Ca and Na-Mg mixtures adsorbed on the four clays are given in Table 2. A detailed discussion of the monovalent-divalent equilibrium selectivity coefficients for smectites has been presented elsewhere (Shainberg *et al.*, 1987).

Two conclusions may be derived from the data in Table 2: (1) The charge density on the clay had no effect on the affinity for Na-Ca and Na-Mg mixtures, whereas the charge density on the smectites had a marked effect on the affinity of the clay for K in K-Ca-exchange isotherm (Shainberg *et al.*, 1987). (2) The affinity of the clays for Na is similar in both Na-Ca and Na-Mg mixtures. Close examination of the data

Table 2. Exchangeable sodium percentage of the smectites in equilibrium with Na-Ca and Na-Mg solution.

Smectite <sup>1</sup>	Exchangeable sodium percentage							
	Sodium adsorption ratio							
	3		5		10		20	
	Na/Ca	Na/Mg	Na/Ca	Na/Mg	Na/Ca	Na/Mg	Na/Ca	Na/Mg
Upton	1.9	2.0	5.4	5.8	10.5	10.8	21.6	20.8
Belle Fourche	1.2	1.1	5.1	4.7	9.7	9.6	19.7	20.6
Polkville	—	—	5.0	4.8	12.0	9.6	22.0	21.2
Otay	—	—	4.9	4.6	10.3	9.0	21.2	20.5

<sup>1</sup> See Table 1 for sample descriptions.

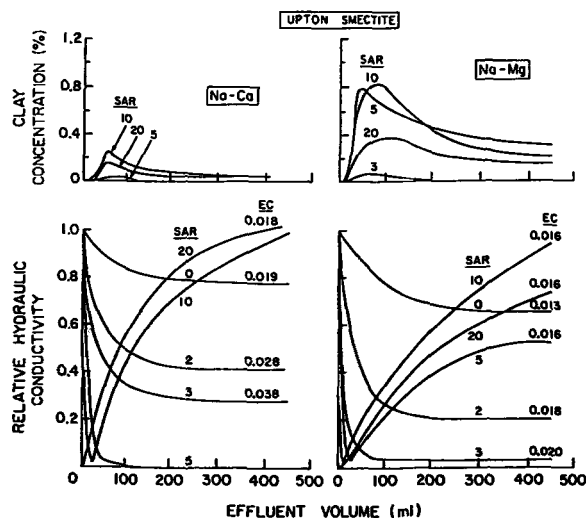


Figure 1. Relative hydraulic conductivity and effluent clay concentration of Na-Ca- and Na-Mg-Wyoming smectite-sand mixtures leached with distilled water. The clay-sand mixtures were equilibrated with Na-Ca and Na-Mg  $\text{Cl}^-$  0.01 M solutions having various sodium adsorption ratios (SAR) prior to the leaching with distilled water. Electrical conductivity (EC) of effluent is given in dS/m units.

in Table 2 suggests a possible trend that with an increase in charge density, the affinity for Mg increases and the ESP in Na-Mg-Otay suspensions is lower than in Na-Ca suspension. The opposite behavior was observed for the Wyoming suspensions, and the ESP for the Na-Mg suspensions was higher than for Na-Ca systems. Because of its high charge density, the Otay clay may behave in a way similar to vermiculite clay, in which the affinity for Mg is very high (Levy and Shainberg, 1972).

#### Hydraulic conductivity

Hydraulic conductivity data are herein expressed as "relative HC." Relative HC is the ratio of treatment HC and the HC of a 0.5 M salt solution. In most of the illustrations, relative HC is presented as a function of the effluent volume for a treatment in which distilled water displaces 0.01 M  $\text{Cl}^-$  solution. In a few of the experiments the 0.01 M  $\text{Cl}^-$  solution was displaced with dilute solutions (1, 2, and 3 mmole/liter). The intercept of all the curves is the relative HC for 0.01 M  $\text{Cl}^-$  solutions of the various treatments.

The relative HC of the Wyoming clay-sand mixtures equilibrated with 0.01 M  $\text{Cl}^-$  Na-Ca and Na-Mg solutions and leached thereafter with distilled water is presented in Figure 1. The electrical conductance (EC) of the effluent after leaching with  $\sim 400$  ml of solution (which corresponds to  $\sim 10$  pore volumes) is also presented in Figure 1. Note that as the ESP of the clay increases, the intercept on the y-axis decreases. The decrease in HC in 0.01 M  $\text{Cl}^-$  solutions is due to clay swelling which reduced pore diameters (Alperovitch *et*

*al.*, 1985). Smectite dispersion was not expected at an electrolyte concentration of 0.01 M, which is well above the flocculation values of the clay at such ESP values (Oster *et al.*, 1980).

The relative HC at 0.01 M concentration as a function of the SAR of the solutions in Na-Ca and Na-Mg mixtures is also presented in Table 3. In Na-Ca mixtures, the change in relative HC between SARs of 0 and 10 was small (30%), compared with that between values of 10 and 20 (a further drop of 65%). Introducing 10% Na into the exchange complex of the Wyoming clay increased the swelling of the clay only slightly. Swelling of the clay increased markedly as the ESP rose above 10%. Similar observations were discussed by Shainberg and Letey (1984). Oster *et al.* (1980) proposed that the size of montmorillonite packets and the osmotically active surface were not significantly affected by  $<10\%$  Na in the exchange complex of Na-Ca montmorillonite. As the percentage of exchangeable Na increased to  $>10$ , breakdown of the packets took place, the osmotically active surface area (i.e., the external surfaces of the packets) increased, and swelling increased.

In Na-Mg mixtures, the sharp drop in relative HC took place between SARs of 3 and 10 (Figure 1 and Table 3). Thus, Mg-packets seem to be less stable than Ca-packets and ESPs of  $>3$  were enough to break the packets. Swelling in Na-Mg-Wyoming montmorillonite was more pronounced than in Na-Ca mixture, and a direct effect of Mg was evident. No difference in swelling (and the resultant hydraulic conductivity) between homoionic Ca and Mg montmorillonite was observed. Thus, the direct effect of Mg was evident only in the presence of sodium in the exchange phase, as was also observed by Rengasamy *et al.* (1986). Adsorbed Mg did not stabilize the clay packets against the dispersive effect of Na, as does adsorbed Ca. If Ca- and Mg-Wyoming montmorillonite in equilibrium with 0.01 M  $\text{Cl}^-$  solutions were leached with distilled water (Figure 1), the relative HC gradually decreased. The relative HC of a Mg-clay-sand mixture dropped to 0.65, whereas the relative HC of Ca-clay-sand mixture dropped to 0.79. The EC of the effluent of Mg-clay-sand and Ca-clay-sand mixtures was 0.013 and 0.019 dS/m, respectively. Release of electrolytes from the clay was mainly by hydrolysis of exchangeable ions. The rate of hydrolysis of Mg-saturated clay is lower than that of Ca-saturated clay (Kreit *et al.*, 1982). The presence of a high concentration of Mg at the clay surface apparently slowed down the release of octahedral Mg from the structure, and therefore the EC of the solution effluent of Na-Mg-clay was lower than that of the Na-Ca-montmorillonite system. Inasmuch as the concentration of electrolytes in the homoionic-clay distilled water leachate was less than the flocculation value of the clay, the clay may have dispersed and the HC dropped. This reduction was more pronounced in

Table 3. Relative hydraulic conductivities (HC) of the four smectites in equilibrium with 0.01 M Cl<sup>-</sup> Na-Ca and Na-Mg solutions and after leaching with distilled water.<sup>1</sup>

Smectite <sup>2</sup>	SAR	Relative HC at 0.01 M		Relative HC at 10 pore volumes		EC at 10 pore volume	
		Ca	Mg	Ca	Mg	Ca	Mg
Upton	0	1.0	1.0	0.77	0.65	0.019	0.013
	2	1.0	0.97	0.41	0.20	0.028	0.018
	3	0.96	0.90	0.28	0.03	0.030	0.020
	5	0.93	0.83	0.0	0.52	—	0.018
	10	0.70	0.26	0.94	0.88	0.018	0.016
	20	0.05	0.02	1.02	0.70	0.018	0.016
Belle Fourche	0	1.0	1.0				
	3	1.0	1.0	0.68	0.50	0.034	0.022
	5	1.0	0.95	0.32	0.14	0.036	0.020
	10	0.78	0.60	0.06	0.71	0.036	0.016
	20	0.02	0.01	0.50	0.76	0.029	0.018
Polkville	5	1.0	1.0	0.83	0.70	0.013	0.013
	10	1.0	0.93	0.45	0.65	0.018	0.018
	20	0.81	0.70	0.68	0.52	0.015	0.015
Otay	5	1.0	1.0				
	10	1.0	0.95	0.50	0.42	0.018	0.010
	20	0.95	0.80	0.34	0.69	0.023	0.012

<sup>1</sup> The electrical conductivity of the water effluent at 10 pore volumes is also presented.

<sup>2</sup> See Table 1 for sample descriptions.

the Mg-clay, because the electrolyte concentration in Mg-clay was lower.

If the 0.01 M Cl<sup>-</sup> Na-Ca solutions having SARs of 10 and 20 were replaced by distilled water, the relative HC of the mixture dropped sharply to <5%, followed by a sharp increase (Figure 1). Also, the concentration of clay in the effluent peaked at about one pore volume before gradually decreasing (Figure 1). Similar HC and clay concentration curves were reported for sandy soils by Frenkel *et al.* (1978) and Pupisky and Shainberg (1979). The large percentage of clay in the effluent indicates that dispersion and long-distance movement of the clay particles had taken place. Deposition of the clay particles in pore spaces led to the sharp drop in the HC values. The subsequent increase in the HC can be explained as follows. As the clay dispersed in the distilled water, the flow changed from flow of solution in a sandy clay matrix, in which the sand particles are covered with a skin of clay, to flow of suspension in a pure sand matrix. Removing the clay skin from the sand particles increased both the pore radii and the HC. With further leaching the increase in pore radii resulted in a relative HC of >1.0 (Figure 1).

If the 0.01 M Cl<sup>-</sup> Na-Ca solution of SAR 5 was replaced by distilled water, the decrease in HC was not followed by an increase in HC. The dispersion of the clay was not intensive enough to change the mechanism of flow from that of a solution in a clay-sand mixture to that of a suspension in sand. The limited dispersion and deposition of the clay particles in the conducting pores led to the decrease in HC. As the ESP of the clay was further reduced to 3 and 2, the decrease in HC was more gradual (Figure 1).

Na-Mg breakthrough curves are quite similar to those of Na-Ca-Wyoming montmorillonite (Figure 1); however, the following differences are noted: (1) The clay concentration in the effluent of Na-Mg systems is much higher than that in Na-Ca systems, indicating that the clay particles in Na-Mg systems are more dispersive and more mobile. (2) Whereas an ESP of 5 was not enough to cause an increase in HC in the Na-Ca system, an intensive clay dispersion and an increase in HC were observed in Na-Mg-clay saturated at this ESP. (3) The steady state HC, at each of the ESP values, is lower in Na-Mg systems than in the corresponding Na-Ca systems. Similarly, the EC of the effluent in Na-Mg systems is lower than that in Na-Ca systems. The higher dispersivity of Na-Mg-clay may be related to the lower electrolyte concentration in the effluent.

#### *Effect of low electrolyte concentration on hydraulic conductivity*

The Na-Mg-Wyoming clay dispersed more than the Na-Ca-Wyoming clays. To separate the direct effect of adsorbed Mg from the electrolyte concentration effect, 0.01 M Cl<sup>-</sup> solutions of SAR 10 and 20 (Na-Ca and Na-Mg systems) were displaced with solutions of the same SAR but having total electrolyte concentrations of 0.001, 0.002, 0.003, and 0.004 M Cl<sup>-</sup>. The HC curves of these experiments are presented in Figure 2. The relative HC of Wyoming Na-Ca-clay-sand mixture in equilibrium with an SAR of 10 in a 0.01 M Cl<sup>-</sup> solution was 0.70 (intercept on y axis, Figure 2). If the 0.01 M solution was displaced with a 0.001 M solution, a HC curve similar to that for distilled water was obtained. The intense dispersion of the clay in the 0.001 M so-

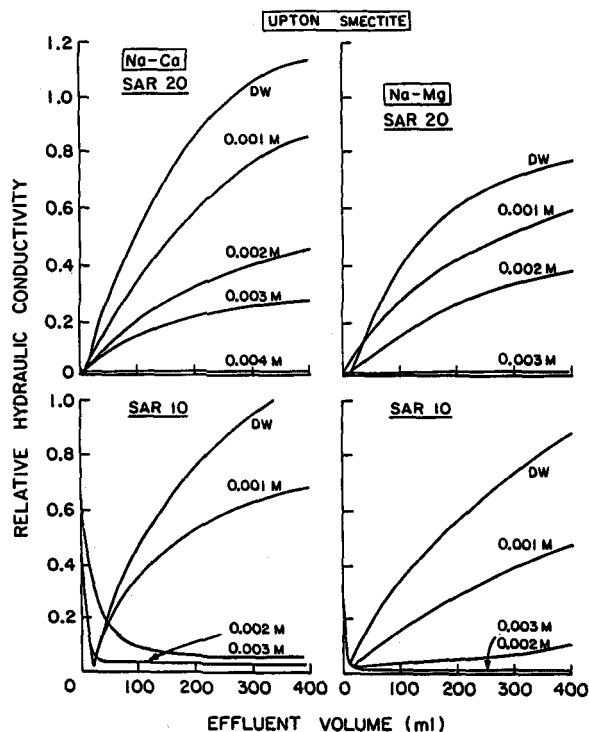


Figure 2. Relative hydraulic conductivity of Na-Ca- and Na-Mg-Wyoming smectite-sand mixtures leached with dilute salt solutions. DW = distilled water; SAR = sodium adsorption ratio.

lution resulted in an increase in HC (Figure 2). Concentrations of  $>0.002$  M were sufficient to prevent the intensive dispersion, and only a decrease in HC was observed. Similar results were obtained for Na-Ca-clay saturated with SAR 20 solutions. As the concentration of electrolytes increased, no clay was observed in the leachate, and the clay-sand mixtures became clogged (Figure 2).

The concentrations at which no increase in HC in Na-Mg systems was observed were similar to those for Na-Ca-clay-sand mixtures. At a concentration of  $0.002$  M the clay particles did not disperse readily nor did the HC of the Wyoming clay-sand mixture in equilibrium with SAR 10 solutions increase. At a concentration of  $0.003$  M, the HC of the Na-Mg SAR 20 system also did not increase. Na-Ca-Wyoming smectite was dispersed even more readily than the Na-Mg system in equilibrium with SAR 20 solutions. This is probably due to the higher swelling of Na-Mg clay than that of Na-Ca clay under similar conditions (Table 3). If the electrolyte concentration in the clay-sand mixture was controlled by the leaching solutions, Na-Mg-clays dispersed no more readily than Na-Ca-clays. Thus, the direct effect of exchangeable Mg in Wyoming montmorillonite leached with distilled water was apparently an effect of Mg on the hydrolysis of the clay.

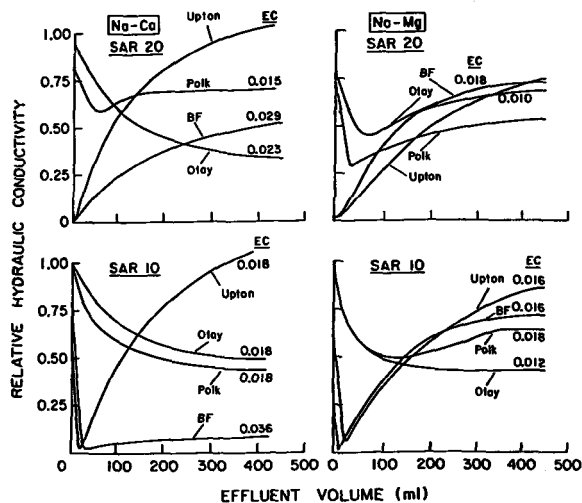


Figure 3. Relative hydraulic conductivity of Na-Ca and Na-Mg of smectite-sand mixtures leached with distilled water. (SAR = sodium adsorption ratio; BF and Polk = smectites from Belle Fourche, South Dakota, and Polkville, Mississippi, respectively).

The specific clay mineralogy affected the HC of the clay-sand mixtures (Figure 3). The effect of clay swelling on the relative HC of the clay-sand mixture equilibrated with  $0.01$  M  $\text{Cl}^-$  solution was evaluated from the drop in the HC. The relative HC of the different smectites was: Wyoming = Belle Fourche  $>$  Polkville  $>$  Otay. The swelling of the Polkville and Otay smectites was not sufficient to change the HC of the mixture saturated with a solution of SAR 10; however, differences between these minerals were evident if the mixtures were equilibrated with  $0.01$  M  $\text{Cl}^-$  SAR 20 solutions. This order of swelling is similar to that reported by Low (1980). The swelling of the smectites appears to be a function of specific surface area (Table 1), surface charge density, and the  $b$ -dimension of the clay (Low, 1980). Both the  $b$ -dimension and the charge density of the clays examined in the present investigation increased with an increase in the ionic substitution in the octahedral layer of clay structure, and both appear to be related to the fraction of the clay that expanded. Smectite clays having larger charge densities appeared to have lower specific surface areas and swelled less, and soils leached with electrolyte solutions should less affect the HC (Tables 1 and Figure 3).

The HC of the various Na-Ca-clay-sand mixtures varied markedly on leaching with distilled water. The montmorillonites from Belle Fourche and Wyoming swelled to about the same degree, but dispersed differently. The Belle Fourche montmorillonite at ESP 10 dispersed less than the Wyoming clay. Thus, the change in the mechanism of flow found for the Wyoming clay at an ESP of 10, was not observed for the Belle Fourche clay. The marked swelling and limited dispersion of

the Belle Fourche clay resulted in a very low relative HC at ESP 10. At ESP 20, an increase in clay dispersion was accompanied by an increase in HC, similar to that found for the Wyoming montmorillonite at ESP 10.

The Otay montmorillonite, having the highest charge density among the smectites examined, swelled and dispersed the least, and the change in the HC curve was minimal. The limited dispersion was insufficient to change the mechanism of flow, and the HC curve decreased gradually to the final observed values. The Polkville clay swelled slightly more than the Otay montmorillonite, and its HC curve was below that of the Otay clay at an ESP of 10. The Polkville clay dispersed slightly more than the Otay clay; thus, at an ESP of 20, its HC curve initially decreased and then increased in a manner similar to that found for the Wyoming and Belle Fourche montmorillonites.

The effect of Mg on the swelling and dispersion of the various smectites is presented in Figure 3 and Table 3. Less swelling was noted for the smectites having higher charge densities. Smectite from Belle Fourche swelled less than Wyoming montmorillonite in both the Na-Ca and Na-Mg forms (Table 3). The differences in swelling between Na-Ca- and Na-Mg-Belle Fourche clay was noted only at ESP > 5.0. Similar behavior has been reported for the Wyoming montmorillonite (Rengasamy *et al.*, 1986) for soil clays. The direct effect of Mg on clay swelling is observed only under sodic conditions.

As the charge density on the smectites increased (Polkville and Otay clays), the swelling of Na-Mg-clay-sand mixtures also decreased. A direct effect of Mg on clay swelling was noted only at ESPs of  $\geq 10$ , and no direct effect of Mg was observed at ESP < 5.0. With an increase in charge density, the packets of divalent cation smectites were apparently more stable, and higher percentages of Na were needed to break the packets. Electrostatic forces of attraction, which are proportional to the charge density (Norrish, 1954), account for the increased stability of the Polkville and Otay smectite packets. For Na-Mg-clays, less Na was necessary to break the packets than for Na-Ca-clays. Thus, a direct effect of Mg on smectite swelling was observed.

If the various smectites in equilibrium with Na-Mg 0.01 M Cl<sup>-</sup> solutions were leached with distilled water, their HC decreased initially and then increased (Figure 3). Whereas the Belle Fourche clay in equilibrium with Na-Ca SAR 10 did not readily disperse (Figure 3), the Na-Mg-Belle Fourche clay with ESP 10 dispersed readily and its HC increased abruptly. The EC of the effluent after leaching with 10 pore volumes of solution is also presented in Figure 3. The Belle Fourche clay with ESP 10 and Mg as the complementary cation released less electrolyte than the corresponding Na-Ca-clay (0.016 dS/m vs. 0.036 dS/m). The higher concentration of electrolytes in the Na-Ca-Belle Fourche clay inhibited the dispersion. The differences between the

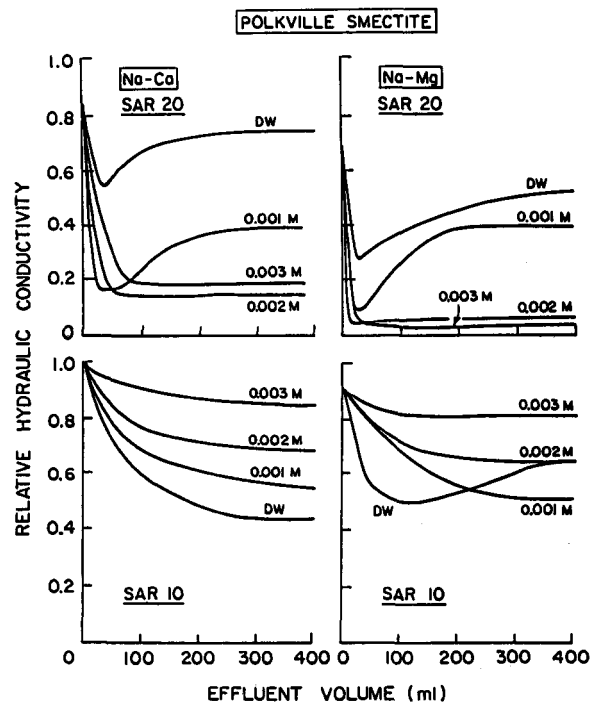


Figure 4. Relative hydraulic conductivity of Na-Ca- and Na-Mg-Polkville smectite-sand mixtures leached with dilute salt solutions. DW = distilled water; SAR = sodium adsorption ratio.

Wyoming and the Belle Fourche clays decreased in Na-Mg systems, and both clays dispersed readily.

The direct effect of Mg was also evident in the Polkville and Otay smectites that were equilibrated with SAR 10 and 20 solutions and leached with distilled water (Figure 3), whereas the Otay clay did not disperse in Na-Ca solutions of ESP 10 and 20 and no increase in HC was observed. The Otay clay dispersed readily in the Na-Mg system with ESP 20, possibly because of the lower ECs in the leachate for Na-Mg mixtures. Conversely, for Polkville smectites, the ECs of both the Na-Ca and Na-Mg effluents were identical; nevertheless the Na-Mg mixtures dispersed more readily (Figure 3).

The mechanism by which Mg affected the HC of the Polkville clay-sand mixture was determined by a study of the effect of a dilute salt solution on its HC (Figure 4). If the columns were leached with dilute salt solutions, and the leaching solution controlled the EC of the interclay solution, the direct effect of Mg disappeared. Thus, the direct effect of Mg on the HC of smectite-sand mixtures leached with distilled water is due to the effect of Mg on the concentration of electrolytes in the interclay solution. If the clay was leached with distilled water most of the electrolytes in the clay solution were derived from the hydrolysis of the clay minerals. Exchangeable magnesium decreased this hy-

drololysis (Kreit *et al.*, 1982) and caused the concentration of electrolytes to be lower than in the presence of exchangeable Ca. Under these conditions clay dispersion was enhanced and typical HC curves of Na-Mg-clay-sand mixtures were obtained.

#### ACKNOWLEDGMENT

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