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Role of Calcium Carbonate and Palygorskite in Enriching Exchangeable Magnesium to Impair Drainage of Vertisols of Semi-Arid Western India

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Abstract–*Shrink-swell soils (Vertisols and their intergrades) as one of the major soils support high crop production in Maharashtra, Madhya Pradesh, Andhra Pradesh and northern Karnataka. Vertisols occur extensively in the states of Maharashtra, occupying 36% of the total area. Under rain-fed conditions, the yield of deep-rooted crops on Vertisols depends primarily on the amount of rainwater stored at depth in the soil profile and the extent to which this soil water is released during crop growth. Both the retention and release of soil water are governed by the nature and content of clay minerals, and also by the nature of the exchangeable cations such as sodium and magnesium. The hydraulic conductivity and clay dispersion of swell shrink soils as a function of exchangeable sodium and magnesium are two important soil properties that need to be understood in view of their concurrent pedogenic processes like clay illuviation, calcium carbonate formation and enrichment of exchangeable sodium and magnesium in the subsoils. Therefore, the present study was undertaken with thirteenVertisols of semi-arid tropical (SAT) western Maharashtra. Results of this study indicate the formation of pedogenic calcium carbonate (PC) triggers the chemical reaction for the concomitant enrichment of exchangeable sodium(ESP) and exchangeable magnesium percentage (EMP) in the subsoils and development of Sodic Haplusterts (ESP > 5) witha low value of sHC (<10 mmhr^{-1}). It was interesting to note similar low values of sHC in Typic Haplusterts endowed with palygorskite mineral. Results indicate that when the impairment of sHC in Sodic Haplusterts is primarily due to increase in ESP and EMP, the enrichment of EMP caused by the presence of palygorskite in Typic Haplusterts is equally capable of impairing the drainage (in terms of hydraulic properties) of Vertisols. This is the opposite effect from that of saturation with Ca^{2+} ions, which leads to blocking of small pores in the soil. This suggests that Mg^{2+} ions are less efficient than Ca^{2+} ions in flocculating soil colloids and also in creating strong plasma separation although the United States Salinity Research Laboratory grouped Ca^{2+} and Mg^{2+} together as both the ions improve soil structure. This fact assumes a great importance in the use and management of palygorskite endowed Vertisols especially when they are still classed as Typic Haplusterts, suggesting no sign of natural soil degradation in them.*

Key words : SAT Vertisols, Maharashtra, Exchangeable sodium percentage, Exchangeable magnesium percentage, Saturated hydraulic conductivity, Natural soil degradation, Palygorskite

Vertisols and their intergrades as one of the major soils support agriculture in India. These are important soils in terms of high crop production in Maharashtra, Madhya Pradesh, Andhra Pradesh and northern Karnataka. Vertisols occur extensively in the state of Maharashtra, occupying 36% of the total area (Bhattacharyya *et al.*, 2013). Majority of these soils occurs in the lower piedmont plains or valleys and in micro-depressions, and are developed in the alluvium of weathered Deccan basalt (Pal and Deshpande 1987). These soils are used for many purposes, including the production of cotton, soybean and sorghum. Vertisols are often difficult

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to cultivate, particularly for small farmers using handheld or animal drawn implements. Subsoil porosity and aeration are generally poor and roots of annual crops do not penetrate deeply. The drainage or hydraulic conductivity of smectitic soils is strongly dependent on the type of exchangeable cation in soils and the salt concentration of percolating solution. Saturated hydraulic conductivity (sHC) tends to decrease with increasing exchangeable sodium percentage and decreasing salt concentration. Adsorbed Ca^{2+} stabilizes the soil structure and counteracts the dispersive effect of Na^+. U.S. Salinity Laboratory Staff (Richards, 1954) reported that Ca^{2+} and Mg^{2+} were similarly beneficial in developing and maintaining soil structure. Alperovitch *et al.* (1981) suggested that in calcareous montmorillonitic soils, exchangeable Mg had no direct effect on the HC and clay dispersion in presence of Ca. Conversely in non-calcareous, highly weathered soils, if the Na-Mg soils are leached with distilled water, exchangeable Mg appeared to affect both HC losses and clay dispersion. Earlier studies on chemical degradation of Vertisols (Kadu *et al*., 1993; Balpande *et al.*, 1996; Pal *et al*., 2006) indicated that in soils even with ESP <5, the sHC showed a decline with pedon depth. However, despite an increase in exchangeable magnesium percentage (EMP) with depth in general, no significant correlation was obtained between sHC and EMP, possibly because of limited data. The gradual enrichment of EMP with depth, however, did not always reflect in a sharp increase of water dispersible clay (WDC) in calcareous and non-sodic Typic and Aridic Haplusterts (ESP <<5) (Balpande *et al.,* 1996; Pal *et al*., 2006). But a sharp increase in both EMP and WDC in calcareous and sodic (ESP> 5 < 15) Vertisols (Sodic and Calcic Haplusterts) was observed (Pal *et al*., 2006). It was thus safely assumed that the decline in drainage in terms of hydraulic properties of Vertisolsis also get affected by the presence of Mg on soil's exchange sites, suggesting that saturation of Vertisols not only with Na^+ ions but also with Mg^{2+} ions leads to dispersion of clay in a certain extent. The dispersed clay particles block the micro- and macro-pores of soil systems causing reduced HC in the subsoil.Considerable research effort has been expended on an attempt to understand the role of adsorbed Na ion on soil physical properties but the effect of Mg ions is less known particularly in soils high activity clays. It is now well understood that the formation of pedogenic calcium carbonate (PC) and clay illuviation are the two concurrent contemporary pedogenic processes in SAT Vertisols of the Holocene period (Pal *et al*., 2009, 2012). Due to these pedogenic processes, the precipitation of $CaCO_3$ as PC enhances the pH and also the relative abundance of not only Na^+ but also Mg^{2+} ions in soil exchange and in solution (Pal *et al.,* 2012). Enrichment of EMP is also caused by the reported presence of Mg-rich palygorskite mineral in Vertisols of Maharashtra (Zade, 2007; Hillier and Pharande, 2008; Kolhe, 2011). Under rain-fed conditions, the yield of deep-rooted crops on Vertisols enriched either with EMP or ESP and EMP together would depend primarily on the amount of rain water stored at depth in the soil profile and the extent to which this soil water is released between the rains during crop growth. In view of this predicament, there is an urgent need to understand the mechanism on the enrichment of EMP and ESP amidst the formation of PC and the release of Mg ions from palygorskite. The present study, with 13 Vertisols (including Typic and Sodic Vertisols with and without palygorskite mineral) of Marathwada region, Maharashtra (Table 1) was undertaken to pinpoint the respective role of PC and palygorskite in developing EMP enriched subsoils and its influence in declining the drainage of semi-arid tropical (SAT) Vertisols.

Materials and Methods

Thirteen SAT Vertisols were selected in the districts of Buldhana, Parbhani, Latur, Osmanabad, Beed, Jalna and Aurangabad of Maharashtra state (Table 1). These Vertisols are developed in the alluvium of the Deccan basalt. Pedons 1,2,4,7,8,9,12 and 13 were keyed out as Typic at the subgroup level, where as pedons 3,5,6,10 and 11 qualified for Sodic. All Vertisols excepting the pedons 5 and 7 contain Ca-zeolites as confirmed by the XRD method (Jackson, 1979) and micro-morphological soil thin section studies (Zade, 2007).

The characteristics of each pedon and its individual horizons were described following the procedure of the Soil Survey Manual (Soil Survey Division Staff, 1993). Both sphenoids and slickensides observed in the field confirm the presence of slickensided B horizons (Bss)(Soil Survey Staff, 1999). Particle size distribution was determined by the international pipette method after the removal of organic matter, $CaCO_3$and free Fe oxides.Sand (2000-50 µm), silt (50-2 µm) and clay fractions (<2 µm and <0.2 µm)were separated using the size segregation procedure of Jackson (1979).

The $CaCO_{3,}$pH, exchangeable Na and K were determined on total fine earth (<2mm) by standard methods (Richards, 1954). Exchangeable calcium and magnesium were determined from <2 mm sieved samples by leaching with 1N NaCl solution (Piper, 1950) and titrating the leachate against saturated EDTA solution as per the method of Richards (1954). The saturated hydraulic conductivity (sHC) was determined by constant head method as described by Richards (1954). The water dispersible clay (WDC) was determined by taking 10g of soil and then shaking on an end to end shaker for 8 hours. Suspension aliquots were drawn by following the international pipette method (Richards, 1954; Balpande, 1993). For identification of clay minerals, the silt and clay fractions were subjected to X-ray examinations of the parallel oriented samples saturated with Ca and K, using a Philips diffractometer with Ni filtered CuKα radiation at a scanning speed of $2^o 2\theta$/min. Glycolation and different thermal pre-treatments as required were given to distinguish and confirm the type of mineral present (Jackson, 1979). For identification of palygorskite mineral by XRD method, water dispersible clays and silts were used because clays prepared by removing the cementing agents of soils (organic matter, $CaCO_3$ and free Fe_2O_3) did not show the presence of this mineral as this mineral often gets destroyed by such pretreatments (Sombroek, 1981). Limited XRD data on the presence of palygorskite in Vertisols do not however yield sharp peak of palygorskite of 1.05 nm. Instead, a broad and moderate peak around 1.05 nm is generally observed (Pal *et al.*, 2003a; Kolhe *et al.*, 2011). In the present study, after a careful examinationa very small and broad peak around 1.05nm was observed in absence of mica (Figs 2 and 3) and the same was considered to be due to the presence of palygorskite, which was supported by exchangeable Mg enrichment down the pedon depth in poorly drained Typic Haplusterts (pedon 9, Table 2). Undisturbed soil blocks (8cm long, 6cm wide and 5cm thick) were collected from soil horizons, and thin sections were prepared by the methods of Jongerius and Heintzberger (1975). They were described according to the nomenclature of Bullock *et al.* (1985).

Results

Morphological Properties

The studied Vertisols are deep to very deep (100 to more than 150 cm). The cracks were 2 to 10 cm wide at the surface and extended upto a depth of 20 to 60 cm. The pressure faces were observed in all the profiles. Slickensides were tilted to an angle of 45-60 degree from horizontal. The peds broke into small subangular blocky to angular blocky peds. The soils were very dark gray to dark yellowish brown (10YR 3/1.5 to 10YR 4/4). The surface horizon of all the soils generally had subangular blocky structure and slightly hard to hard (dry) and friable to

Table 1. *General properties of the Vertisols selected from different districts and their mean annual rainfall (MAR) and temperature (MAT)*

Pedon No.	Soil Series (Soil Taxonomy) (District)	Parent Material	Latitude	Longitude	MAR[1] (mm)	MAT[1] (^{o}C)	Topography	Special features
1	Chandaj (Very fine, smectitic, isohyperthermic, Typic Haplusterts) (Parbhani)	Basaltic alluvium with zeolites	19^{o}32’42" N	76^{o}42’20" E	957	26.9	Plateau	3-5 cm cracks up to 10-15cm.
2	Satgaon (Very fine, smectitic, isohyperthermic, Typic Haplusterts) (Buldhana)	Basaltic alluvium with zeolites	20^{o}23’53" N	76^{o}13’45" E	899	25.7	Valley	No cracks observed at the time of sampling
3	Kalegaon (Fine, smectitic, isohyperthermic, Sodic Haplusterts) (Jalna)[2]	Basaltic alluvium with zeolites	19^{o}49’15" N	75^{o}59’57" E	840	27.2	Subdued plateau	3-5 cm cracks up to 10-15cm
4	Adgaon (Very fine, smectitic, isohyperthermic, Typic Haplusterts) (Jalna)	Basaltic alluvium with zeolites	20^{o}27’32" N	75^{o}49’20" E	840	27.2	Undulating landscape valley	1-2 cm cracks up to 40 cm and beyond
5	Khasgaon (Very fine, smectitic, isohyperthermic, Sodic Haplusterts) (Osmanabad) [2]	Basaltic alluvium	18^{o}14’59" N	75^{o}29’31" E	809	25.8	Subdued plateau	No cracks observed at the time of sampling
6	NaliWadgaon (Fine, smectitic, isohyperthermic, Sodic Haplusterts) (Osmanabad)[2]	Basaltic alluvium with zeolites	18^{o}35’58" N	75^{o}30’29" E	809	25.8	Watershed basin of interhill	3-4 cm cracks up to 40cm
7	Gategaon (Very fine, smectitic, isohyperthermic, Typic Haplusterts) (Latur)	Basaltic alluvium	18^{o}24’26" N	76^{o}24’37" E	802	26.7	Subdued plateau and beyond	3-5 cm cracks on surface up to 60 cm
8	Sawargaon Deoni (Very fine, smectitic, isohyperthermic, Typic Haplusterts) (Latur)	Basaltic alluvium with zeolites	18^{o}17’20" N	77^{o}06’43" E	802	26.7	Subdued plateau	2-3 cm cracks extend up to 30-40cm
9	Kajal Hipperga (Very fine, smectitic, isohyperthermic, Typic Haplusterts) (Latur)	Basaltic alluvium with zeolites	18^{o}40’14" N	76^{o}53’10" E	802	26.7	Subdued plateau	3-5 cm cracks up to 30-45
10	Bhalgaon (Fine, smectitic, isohyperthermic, Sodic Haplusterts) (Aurangabad) [2]	Basaltic alluvium with zeolites	19^{o}49’38" N	75^{o}28’42" E	792	26.05	Subdued plateau	3-4cm cracks up to 40-45cm in the adjoining field.
11	Babhulgaon (Fine, smectitic, isohyperthermic, Sodic Haplusterts) (Aurangabad) [2]	Basaltic alluvium with zeolites	20^{o}02’40" N	74^{o}58’03" E	792	26.05	Undulating land interhill valley	4-5cm up to 50-60 cm and beyond.
12	Patrud (Fine, smectitic, isohyperthermic, Typic Haplusterts) (Beed)	Basaltic alluvium with zeolites	19^{o}04’15" N	76^{o}12’10" E	685	26.15	Subdued plateau	3-5 cm cracks up to 40 cm
13	Raurgaon (Very fine, smectitic, isohyperthermic, Typic Haplusterts) (Beed)	Basaltic alluvium with zeolites	18^{o}45’43" N	75^{o}42’20" E	685	26.15	Subdued plateau	3-5 cm cracks up to 45 -50cm.

[1] www.indiastat.com; [2] As per criteria of sodic shrink-swell soils advocated by Balpande *et al.* (1996)

moderately friable (moist) consistency (Zade, 2007)). Calcium carbonate was observed throughout the depth of all soils. In pedons 1, 5, 7, 8, 9, the effervescence (with 10% HCl) was slight whereas in pedons 2, 3, 4, 6, 10, 11, 12 and 13, it was strong to violent, which is attributed to the presence of diffuse powdery form of $CaCO_3$.

Physical and Chemical Properties

The soils contain 30-80 per cent clay and 18 to 60 per cent of this is the fine clay (<0.2 µm). Based on mean weighted average, pedons 1, 2, 4, 5, 7, 8, 9, and 13 are classed of clay as very fine and the remaining pedons as fine (Soil Survey Staff, 2014). The clay content gradually increased with depth and in some pedons decreased in the Bss3 and C horizons. The fine clay fractions (<0.2 µm) of all soils contain dominant proportions (>80%) of fairly well crystallized smectite with very minor amounts of kaolin. The expansion of smectite beyond 1.4 nm with glycolation of the K-saturated and heated (300^{o}C) sample, indicated that the smectite possesses low charge (Fig 1). Fine clay smectite in these soils is a low charge di-octahedral smectite and is nearer to montmorillonite in the montmorillonite-nontronite series (Zade, 2007).

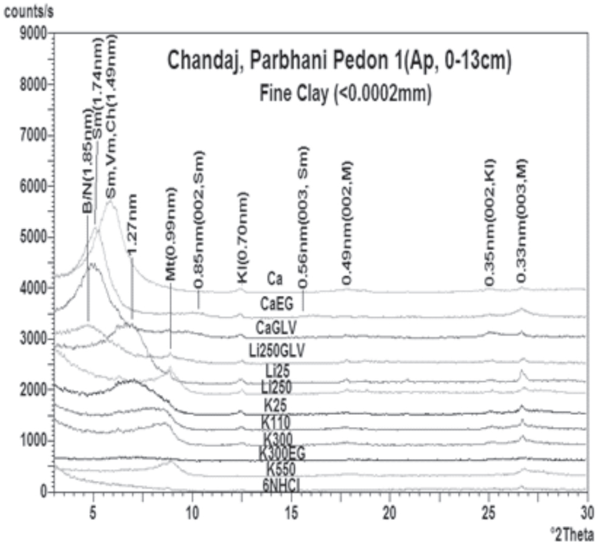

Fig. 1. *Representative XRD patterns of the fine clay fractions of Chandaj, Parbhani. Ca = Ca-saturated, CaEG = Ca-saturated plus glycol vapour, CaGLV = Ca-saturated plus glycerol vapour, Li250GLV=Li-saturated and heated to 250^{o}C(16hrs.) plus glycerol vapour , Li25 = Li-saturated at 25^{o}C, Li250 = Li-saturated and heated to 250^{o}C, K25/110/300/550^{o}C = K-saturated and heated to 25^{o}C, 110^{o}C, 300^{o}C and 550^{o}C, K300EG= K-saturated plus ethylene glycolvapour and heated at 300^{o}C, 6NHCl = HCl treated clay, B/N = beidellite/nontronite, Sm= smectite, Vm=vermiculite, Ch=Chlorite, Mt = Montmorillonite, Kl=kaolin.*

The sHC of soils varied from 0.01 to 5.5 cm hr^{-1}. In Typic Haplusterts (Pedons 1, 2, 4, 7, 8, 9, 12 and 13), the sHC varied from 0.7 to 5.5 cm hr^{-1} and the decrease with depth is gradual but in Sodic Haplusterts (Pedons 3, 6, 10 and 11)it decreased rapidly with depth with a least value of <1 cm hr^{-1} (Table 2). The water dispersible clay (WDC) varied from 4.2 to 40.4 per cent and in non-sodic soils (Typic Haplusterts) it showed a gradual increase whereas in sodic soils (Sodic Haplusterts), it rapidly increased with depth (Table 2). A significant positive correlation was observed between the WDC and the ESP (r= 0.397 at 1% level, Table 3). The non-sodic soils are neutral to mildly alkaline and sodic soils are highly alkaline in reaction and the pH increases with depth in both the non-sodic and sodic soils.

Calcium was the dominant exchangeable cation followed by Mg^{2+}, Na^{+} and K^{+} except some Sodic Haplusterts (Pedons 6, 10 11and 13) where Mg^{2+} is the dominant cation. In general exchangeable calcium decreases and exchangeable Na^{+} and Mg^{2+} increases with depth. The ESP varied from <1 to 37. The ESP value of the surface soil is <5, whereas in subsurface it was >5 in Sodic Haplusterts (Pedons 3, 5, 6, 10 and 11). In Typic Haplusterts (Pedons 1, 2, 4, 7, 8, 9, 12 and 13), the ESP value is less than 5 in both surface and subsurface horizons. It was observed that the decrease in Ca/Mg ratio and Ca/(Mg+Na) ratio (Table 2) appears to be related to development of subsoil sodicity in Sodic Haplusterts (Pedons, 3, 5, 6, 10 and 11).

Table 2. *Sodicity related physical and chemical properties of soils*

Depth (cm)	Exch. Ca/Mg	ECP^1	EMP^2	ESP^3	WDC	Exch. Ca/(Mg+Na)	sHC cm/ hr^5	% $CaCO_3$/ (HCO_3/Ca)
Pedon 1 : Chandaj (Parbhani) - Very fine, smectitic, isohyperthermic, Typic Haplusterts								
0-13	4.8	79.7	16.6	0.8	17.6	4.6	3.0	6.7/(0.5)
13-28	5.8	83.1	14.4	0.5	20.7	5.6	4.9	6.3/(1.5)
28-45	5.2	81.9	15.8	0.5	26.9	5	5.6	6.5/(1.5)
45-75	4.5	80.2	17.9	0.4	28.2	4.4	4.2	6.8 /(0.7)
75-108	3.7	76.8	20.8	0.6	21.4	3.6	4.2	6.7/(0.7)
Pedon 2 : Satgaon (Buldhana) - Very fine, smectitic, isohyperthermic, Typic Haplusterts								
0-6	3.1	73.3	23.3	1.3	22.9	3	1.5	6.0/(0.7)
19-Jun	2.9	72.6	25	1.2	20.1	2.8	2.4	7.8/ (0.6)
19-35	2.9	72.9	25.1	1.6	21.1	2.7	4.0	9.5/ (1.1)
35-51	2.2	67.3	30.6	1.7	22.3	2.1	5.0	14.8/(0.6)
51-118	1.5	57.7	39.3	1.6	18.4	1.4	3.4	16.7/(0.7)
118-130+	1.3	53	42	3.7	20.9	1.2	0.9	24.9/ (1.1)
Pedon 3 : Kalegaon (Jalna) - Fine, smectitic, isohyperthermic, Sodic Haplusterts								
0-14	2	64.6	31.9	1.4	18.5	1.9	1.0	15.0/(0.3)
14-36	1.6	57.1	36.5	4.8	19.4	1.4	1.2	14.2/(0.4)
36-57	1.3	51.5	39.2	7.9	20.2	1.1	0.4	14.4/(0.9)
57-87	0.8	37.1	47.9	12.5	29.5	0.6	0.03	15.5/(0.9)
87-114	0.7	33.6	47.1	17.9	27.3	0.5	0.03	17.0/(1.1)
114-130+	0.8	37.9	44.1	17.7	20.3	0.6	0.1	24.4/(0.4)
Pedon 4 : Adgaon (Jalna) - Very fine, smectitic, isohyperthermic, Typic Haplusterts								
0-12	2.9	70.8	24.4	1	17.4	2.8	1.7	13.2/(0.6)
Dec-33	1.9	63.4	33.4	1.1	16.5	1.8	3.2	11.7/(0.6)
33-49	1.4	56.5	40.4	1.6	12.3	1.3	3.3	14.6/(0.6)
49-82	0.9	46.3	51	1.9	11.4	0.9	4.1	20.5/(0.6)
82-105	1.1	50.4	45.9	2.5	10.1	1	2.4	21.0/(1.5)
105-129+	1.1	51.2	45.3	2.4	12.5	1.1	2.5	24.5/(1.5)
Pedon 5 : Khasgaon (Osmanabad)- Very fine, smectitic, isohyperthermic, Sodic Haplusterts								
0-14	2	63.9	31.9	3.2	11.3	1.8	0.8	8.6/(1.2)
14-30	1.8	60.7	33.5	4.5	13.4	1.6	1.0	9.8/(1.2)
30-53	2.6	67.7	25.6	6.1	14.5	2.1	1.2	10.1/(0.7)
53-77	2.9	68.5	27.4	7.2	16.0	2.2	1.6	9.9/(0.6)
77-102	2.3	63.9	27.6	7.6	15.0	1.8	1.9	11.4(/0.1)
102-150	1.5	55.9	36.5	5.9	8.5	1.3	0.9	15.5/(0.9)
Pedon 6 : NaliWadgaon (Osmanabad) - Fine, smectitic, isohyperthermic, Sodic Haplusterts								
0-13	1.4	55.7	39.9	3	9.0	1.3	1.2	12.7/(0.1)
13-33	1	48.5	46.5	4.1	9.7	1	1.1	13.5/(0.3)
33-53	0.8	40.7	52.8	5.7	10.0	0.7	0.9	13.6/(0.4)
53-82	0.5	31.4	62.8	4.6	10.3	0.5	0.8	13.8/(0.9)
82-99	0.5	33.2	60.9	5.2	10.2	0.5	0.5	13.5/(0.6)
99-150	0.6	34.1	60	4.7	5.2	0.5	0.4	18.9/(0.3)
Pedon 7 : Gategaon (Latur) - Very fine, smectitic, isohyperthermic, Typic Haplusterts								
0-14	4.4	79.8	18	0.7	23.7	4.3	4.7	1.9/(0.6)
14-34	4.5	80.1	17.7	0.7	23.4	4.4	4.1	3.6/(0.4)
34-55	4.2	78.3	18.5	1.8	25.0	3.8	5.4	4.6/(0.4)
55-84	3.7	70.7	20.8	1.4	27.0	3.5	5.5	4.6/(0.4)
84-120	2.9	72.9	24.8	1	26.0	2.8	4.7	4.4/(0.9)
120-150+	3.1	74.3	24.4	0.6	22.3	3	5.5	7.9/(0.4)

Table 2. *Contined ...*

Depth (cm)	Exch. Ca/Mg	ECP[1]	EMP[2]	ESP[3]	WDC	Exch. Ca/(Mg+Na)	sHC cm/ hr[5]	% $CaCO_3$/ (HCO_3/Ca)
Pedon 8 : Deoni (Latur)- Very fine, smectitic, isohyperthermic, Typic Haplusterts								
0-14	1.8	62.9	34.8	0.5	22.5.	1.8	0.6	0.9/(0.7)
14-30	1.9	63.9	33.5	0.7	20.7	1.9	0.2	2.2/(0.7)
30-54	1.9	63.9	34.1	0.7	15.0	1.8	0.4	0.9/(1.0)
54-90	2	65.9	32.6	0.5	20.7	2	0.4	1.6/(1.0)
Pedon 9 : Kajal Hipperga (Latur) - Very fine, smectitic, isohyperthermic, Typic Haplusterts								
0-10	4.9	80.8	16.3	0.5	20.7	4.8	0.6	4.7/0.9
Oct-34	4.1	78.5	19.3	0.3	22.4	4	0.9	4.1/(1.5)
34-66	3.7	77.3	20.6	0.5	22.6	3.7	0.7	5.6/(1.5)
66-89	2.7	71.4	26	0.5	20.4	2.7	0.7	5.8/(0.9)
89-112	3.8	77.2	20.4	0.5	16.0	3.7	0.9	6.9/(1.8)
112-131	5.1	79.5	15.7	3.2	12.6	4.2	—	—
Pedon 10 : Bhalgaon (Aurangabad) - Fine, smectitic, isohyperthermic, Sodic Haplusterts								
0-12	1.4	47.7	34.7	12.9	18.7	1	0.2	12.3/(0.9)
Dec-33	0.9	38.5	42.9	14.8	20.4	0.7	0.01	13.5/(0.8)
33-62	0.8	32.9	40.9	22.6	28.4	0.5	0.08	14.2/(0.9)
62-88	0.8	31.3	39.2	25.4	35.4	0.5	008	14.7/(0.7)
88-123	0.6	24.4	43.7	29.1	40.4	0.3	0.01	—
123-150	0.5	19.7	40.3	37.3	38.4	0.3	0.01	12.8/(2.9)
Pedon 11 : Babhulgaon (Aurangabad) - Fine, smectitic, isohyperthermic, Sodic Haplusterts								
0-15	1.1	47.8	44.6	2.4	4.2	1	0.5	17.3/(1.5)
15-34	0.8	41	49.2	4	6.3	0.8	0.5	18.5/(1.1)
34-72	0.5	27.5	57.9	11.1	10.3	0.4	0.1	17.0/(2.3)
72-97	0.4	21.5	60.1	15.8	12.1	0.3	0.1	17.2/(1.5)
97-130	0.3	22.3	65.4	9.7	17.7	0.3	0.1	20.1/(2.3)
130-160	0.4	22.1	63	12.5	19.8	0.3	0.1	20.2/(2.3)
Pedon 12 : Patrud (Beed) - Fine, smectitic, isohyperthermic, Typic Haplusterts								
0-13	4.6	78.8	17.2	1.1	15.1	4.3	0.7	12.7/(0.4)
13-36	3.2	74.6	23.1	0.7	13.9	3.1	1.4	13.9/(0.4)
36-61	2.9	72.3	25.3	0.3	15.0	2.8	4.4	13.3/(0.1)
61-104	2.1	65.3	31.2	0.9	17.0	2	2.7	12.6/(0.2)
104-140	1.5	59.7	38.7	0.2	17.4	1.5	4.2	13.9/(0.1)
140-160	1.8	61.1	34.9	0.9	16.7.	1.7	3.4	11.8/(1.1)
Pedon 13 : Raurgaon (Beed) - Very fine, smectitic, isohyperthermic, Typic Haplusterts								
0-14	3.1	73.3	23.8	0.5	20.9	3	3.1	11.8/(1.1)
14-28	2.1	65.7	31.8	0.9	24.7	2	2.9	12.2/(1.5)
28-43	1.8	61.9	35.1	1.5	27.4	1.7	1.9	10.2/(1.5)
43-85	1.1	50.5	46.3	1.8	29.2	1.1	1.0	9.9/(2.3)
85-130	0.6	37.9	59.1	1.4	29.0	0.6	0.8	11.8/(2.1)
130-150	0.5	32.6	63	2.8	26.0	0.5	0.6	1.02/(2.0)

[1] ECP = Exchangeable calcium percentage, [2]EMP = Exchangeable magnesium percentage, [3]ESP = Exchangeable sodium percentage, [4] WDC = Water dispersible clay, [5]sHC = Saturated hydraulic conductivity

Discussions

Majority of Vertisols under study indicates that the soils have considerable amount of WDC which increases with depth (Table 2). Following the increase in clays with depth, other properties like WDC, EMP, ESP and $CaCO_3$ (Table 2) also show an increase with depth whereas exch. Ca/

Mg shows a decrease. The depth distribution of these properties point out a fact that dispersion and subsequent movement of clays have been possible in alkaline chemical environment caused by the precipitation of $CaCO_3$ at pH ≥ 8.4 (Pal *et al.,* 2003b) in semi-arid climatic conditions (Balpande *et al.,* 1996; Vaidya and Pal, 2002). Vertisols under study are mildly to strongly alkaline and are calcareous as they belong to Typic/ Sodic Haplusterts (Table 1). The absence or lesser amount of carbonate and dominance of bicarbonate in the saturation extract (Table 2) suggests that during the high evaporative demands for soil water, maintenance of a proper Ca/Mg ratio in the soil solution becomes difficult because Ca^{2+} ions get precipitated as $CaCO_3$ (Table 2). This chemical reaction causes a relative increase in EMP and ESP of soils (Table 2). This is evident from a significant positive correlation between ESP and EMP (r = 0.391 at 1% level) and also through a significant negative correlation between sHC and EMP (r = -0.483 at 1% level, Table 3). This indicates that high amount of magnesium in soils can also cause poor physical properties. Mg^{2+} ions behave more like a Na^{+} ion in impairing hydraulic properties of cracking clay soils (Balpande *et al*., 1996). This is the opposite effect from that of saturation with Ca^{2+} ions, which leads to blocking of small pores in the soil. In other words Mg^{2+} ions are less efficient than Ca^{2+} ions in flocculating soil colloids (Rengasamy *et al.,* 1986), although the United States Salinity Research Laboratory (Richards, 1954) grouped Ca^{2+} and Mg^{2+} together with an assumption that both the ions improve soil structure. Srivastava *et al*. (2002) indicates that the formation of pedogenic $CaCO_3$ (PC) is the prime chemical reaction responsible for increasing pH, the decrease in Ca/Mg and Ca/ (Mg+Na) ratios (Table 2) of exchange site with depth and in the development of subsoil sodicity.

The EMP ranged from 14 to 65 percent. In general, $CaCO_3$ content in Typic and Sodic Haplusterts (without palygorskite) increases with depth and its increase is sharper in Sodic Haplusterts than in Typic Haplusterts (Table 2). Thus the increase of EMP in general with depth is more of an effect of depletion Ca ions as $CaCO_3$ (Pal *et al*., 2000) than by illuviation of Mg-fine clay. It is however reported that

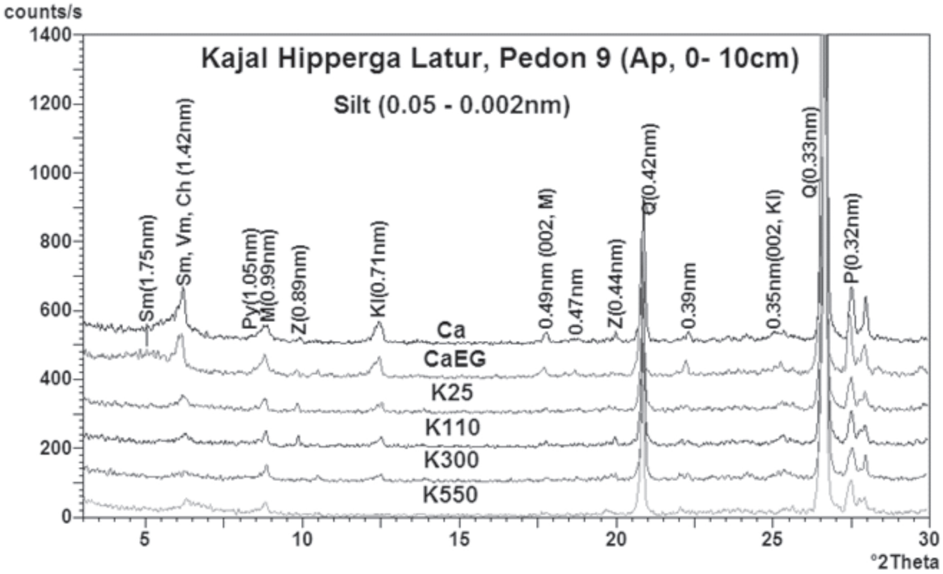

Fig. 2. *Representative XRD patterns of the silt fraction of Kajal Hipperga, Latur. Ca=Ca saturated, CaEG=Ca saturated plus glycol vapour, K25/110/300/550°C=K saturated and heated to 25°C, 110°C, 300°C and 550°C, 6NHCl= HCl treated silt, Sm=Smectite, Vm=Vermiculite, Ch=Chlorite, Py=Palygorskite, M=Mica, Kl=Kaolin, Q=Quartz,*

palygorskite particles are observed to move preferentially over smectite in the soil profile, and eventually clogs soil pores (Neaman and Singer, 2004). In palygorskite containing Typic Haplusterts (Pedons 8 and 9, Table 2), depth distribution of both exchangeable Ca/Mg showed however, a moderate decrease because of the enrichment of Ca ions provided by the Ca-zeolites, but a considerable increase in EMP with depth was observed (Table 2). However, in other Vertisols containing palygorskite (Pedons 3,6, and 10) showed a sharp decrease in Ca/Mg ratio and also a sharp increase in EMP. The depth distribution of Ca/Mg suggests that the precipitation of $CaCO_3$ as PC enhances the relative abundance of Na^+ and Mg^{2+} ions in soil exchange sites and in turn causes dispersion of fine clay smectites and the dispersed clay smectite translocated. The gradual increase in WDC with depth (Table 2) and a significant positive correlation between WDC and ESP (r = 0.397 at 1% level) support this fact. This process results in increase in EMP, ESP and $CaCO_3$ with depth (Table 2) and adversely affects the hydraulic properties of these soils. The impairment of hydraulic properties of soils is evident from significant correlations between sHC and ESP (r = -0.474), sHC and EMP (r=-0.483), $CaCO_3$ and ESP (r = 0.344), $CaCO_3$ and EMP (r= 0.598).

It is worth mentioning that, hydraulic properties of pedons 8 and 9 (Typic Haplusterts) are impaired (sHC < 10 $mmhr^{-1}$) even with very low amount of sodium on the exchange complex (ESP<<5; Table 2) and also in the presence zeolites. Mineralogical studies indicate the presence of silt and clay size palygorskite mineral with smectite, kaolinite, zeolite in pedons 8 and 9 (Figs. 2 and 3). However, the characteristic peak of palygorskite at 1.05 nm is weak, short and broad possibly because of its low content. A recent report on the presence of palygorskite in red Vertisols (Typic Haplusterts) by Kolhe *et al*. (2011) indicated its parental legacy to the red boles, sandwiched between two Deccan basalt flows. Such red Vertisols formed very close to red boles site (< than 500m) and gray Vertisols in basaltic alluvium (Pal *et al.*, 2003a), contain silt and clay size moderately sharp and broad

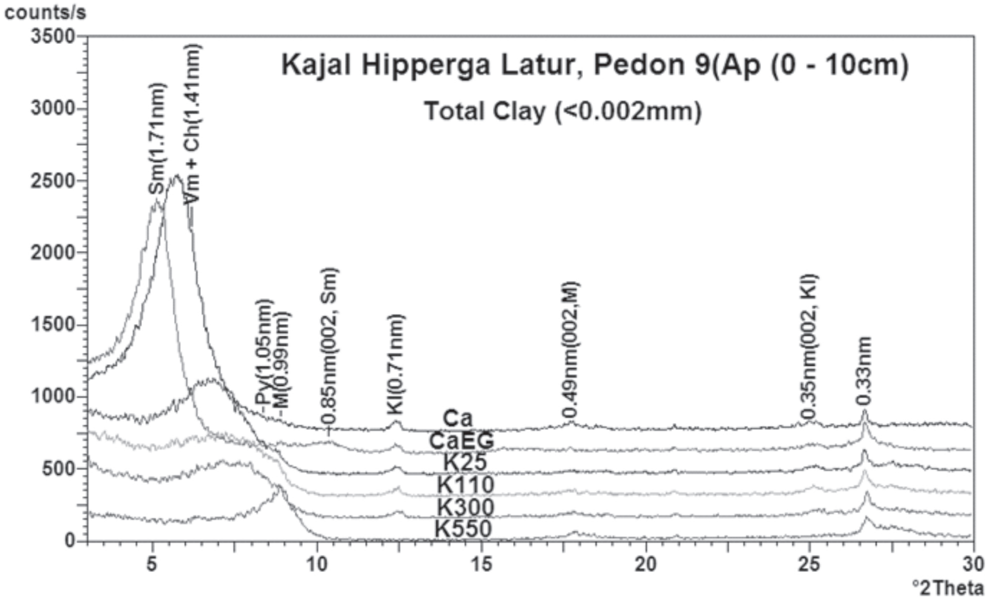

Fig. 3. *Representative XRD patterns of the total clay fraction of KajalHipperga, Latur. Ca=Ca saturated, CaEG=Ca saturated plus glycol vapour, K25/110/300/550°C=K saturated and heated to 25°C, 110°C, 300°C and 550°C, Sm=Smectite, Vm=Vermiculite, Ch=Chlorite, Py=Palygorskite, M=Mica, Kl=Kaolin.*

palygorskite at 1.05 nm. Palygorskite is the most magnesium-rich among the common clay minerals (Weaver and Pollard, 1973; Singer, 2002). Neaman *et al.* (1999) examined the influence of clay mineralogy on disaggregation in some palygorskite, smectite, kaolinite containing soils of the Jordan and Betshe'an Valleys in Israel. Palygorskite was observed to be the most strongly disaggregated mineral among the phyllosilicates that appear in the soil clay fraction. However, pedons 8 and 9 have ESP << 5 and Ca/Mg ratio $\geq$2, indicating the dominance of Ca^{2+} ion on the exchange complex. Although the naturally occurring zeolites in these soils favoured an increase in exchangeable Ca/ Mg ratio, the sHC is still <1 cm hr^{-1} probably because of the much better rate of release of Mg ions from palygorskite than that of Ca ions from Ca- zeolites during the movement of water in soils. Ca-zeolites release << 1 meqL^{-1} in distilled water (Pal *et al.,* 2006). Palygorskite has the strongest disaggregation potential and the highest ability to migrate in the soil among common phyllosilicates such as smectite and kaolinite. Neaman *et al.* (1999) indicated that palygorskite fibres did not associate into aggregates in soils and suspensions, even when saturated with Ca^{2+} ions. Palygorskite particles are thus likely to move preferentially over smectite and kaolinite downward in the soil profile and eventually clog soil pores (Neaman and Singer, 2004). Due to release of Mg^{+2} ions from palygorskite, the EMP often showed a higher value than ECP in Vertisols especially with ESP > 5 (Kolhe *et al*. 2011). The results of present study indicate that the adverse physical condition of Vertisols in terms of

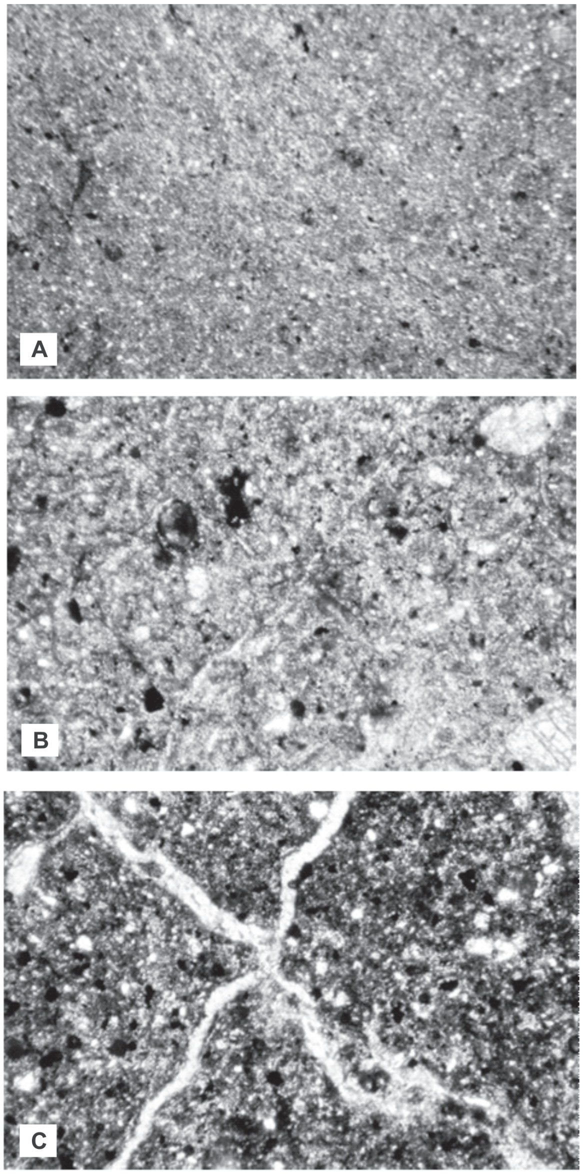

Fig. 4. *Representative photograph of plasmic fabric in cross polarized light: (a) partly unistrial and partly mosaic speckled b-fabric (Typic Haplusterts-Pedon 8, 28-36cm), (b) stipple-speckled b-fabric (Sodic Haplusterts-Pedon 3, 110-118cm),(c)crystallitic b-fabric (Sodic Haplusterts -Pedon 5, 66 –74cm).*

Table 3. Correlation coefficient between soils attributes

No.	Parameter Y	Parameter X	"r" value
	Based on 13 Pedons (75 samples)		
1	WDC^4	ESP	r = 0.397*
2	ESP	EMP	r = 0.391 *
3	sHC^1	EMP^2	r = - 0.483*
4	sHC	ESP^3	r = -0.474*
5	CaCO$_3^5$	ESP	r = 0.344*
6	CaCO$_3$	EMP	r = 0.598*

*Correlation is significant at the 1% level.

[1] Saturated hydraulic conductivity

[2] Exchangeable magnesium percentage

[3] Exchangeable sodium percentage

[4] Water dispersible clay

[5] Calcium carbonate

impairment of sHC (< 10 mm hr^{-1}) is not only due to formation of PC and concomitant development of sodicity but also due to the presence of Mg-bearing palygorskite. SAT Vertisols under study indicated that there was absence of strong plasma separation and orientation in the zone of slickenside development. The plasmic fabric of these SAT Vertisols was predominantly of granostriated, unistrial, reticulated and crystallitic in nature (Fig. 4), which indicate a weak shrink-swell of smectites that could not create the strong plasma separation with parallel striated plasmic fabrics, due to less amount of soil water that are generally made available through easy entry of rains. Despite a high degree of clay activity and shrink–swell process as manifested by high co-efficient of linear extensibility (COLE >> 0.10, Zade, 2007), soils showed weak plasma separation due to less amount of soil water for shrink-swell activity because of reduced sHC, caused by the enrichment of both ESP and EMP in Sodic Haplusterts, and EMP in Typic Haplusterts. Similar observations for Sodic Haplusterts were also made by other researchers (Kalbande *et al*., 1992; Pal *et al*., 2001, 2006, 2009, 2012; Vaidya and Pal, 2002). It is interesting to note that the weak plasma separation is also caused by the presence of palygorskite even though the soils are classified as Typic Haplusterts. This interaction causes drainage problems when such soils are irrigated, presenting a predicament for crop production. In view of their poor drainage conditions and loss of productivity, non-sodic Vertisols (Typic Haplusterts) with palygorskite must be considered naturally degraded soils. Similar soils may be found elsewhere in the world; thus, a new initiative to classify them is warranted (Pal *et al*., 2012).

Conclusion

The results of the present study indicate the contemporary pedogenic processes in SAT Vertisols like the concurrent formation of pedogenic calcium carbonate and the concomitant development of sodicity are primarily responsible for the enrichment of exchangeable magnesium in the subsoils. Exchangeable Mg also causes sufficient dispersion of clay particles and blocking the macro- and micro-pores, resulting in reduced hydraulic properties in clayey and smectitic shrink-swell soils. The hydraulic properties are further impaired with the rise of exchangeable sodium level. Similar dismal hydraulic properties are also caused when SAT Vertisols contain palygorskite mineral in their silt and clay fractions. While the remedial measures to make sodic soils caused by the formation of PC and ESP are available, palygorskite containing ill-drained SAT Vertisols with high EMP need immediate research attention for their proper classification following the US Soil Taxonomy to make them resilient.

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