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Mineralogy and aggregate stability of soils in the arid region of Southeastern Iran

A. H. Moghimi^{1*}, J. Hamdan¹, J. Shamsuddin¹, A. W. Samsuri¹ and A. Abtahi²

¹Department of Land Resource Management, Faculty of Agriculture, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.

²Department of Soil Science, Faculty of Agriculture, Shiraz University, Shiraz, Iran.

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The stability of arid soils can be affected by their chemical and mineralogical properties. A study was conducted to investigate the influence of soil chemical and mineralogical properties on soil stability indices in the Shamil-Ashkara Catchment area of Iran. Eight soil profiles were dug and all the soils were classified as Entisols and Aridisols. These soils are calcareous in nature with high amounts of basic cations. There was a significant positive correlation between water-stable aggregates (WSA) and organic carbon (OC), exchangeable Ca^{2+} and kaolinite contents with *r*-values of 0.70, 0.45, and 0.62, respectively. Soil pH affects stability indices the most as indicated by the highest significant correlation between pH and water-dispersible clay (WDC) ($r = 0.87$). Among the minerals present, palygorskite significantly influences the WSA ($r = -0.46$) and WDC ($r = 0.68$) the most, while chlorite has the least significant effect. The results indicated that the significant positive factors affecting WDC are in the order of: $\text{pH} > \text{Fe}_2\text{O}_3 > \text{CEC} > \text{palygorskite} > \text{Na}^+ > \text{SAR} > \text{Mg}^{2+}$ and the positive factors affecting WSA are: $\text{OC} > \text{kaolinite} > \text{Ca}^{2+}$, respectively.

Key words: Mineralogical properties, aggregate stability, arid region soils, soil properties.

INTRODUCTION

Soil sustainability and crop production affect stability of soil aggregates, which is an important factor in the formation of soil properties. For sustainable use of soil and preserving soil productivity, minimizing soil degradation and sustainable agriculture, high soil aggregate stability is a necessity (Amezketta, 1999). In the arid regions, the stability of soil aggregates is an important issue to address because problems arise from intensive agricultural practices, land use change, low content organic matter, and high content of sodium in the soil. Arid soils are structurally unstable and disperse easily in water. The dispersed clay subsequently migrating and plugging the conducting soil pores is regarded as the dominant process restricting the water intake of irrigated arid soils (Frenkel et al., 1978). Previous studies have reported some factors affecting aggregate stability as follows: clay minerals (Denef and Six, 2005), clay content (Lloyd et al., 2006), soil organic matter (Bipfubusa et al., 2008), pH (Tayel et al., 2010),

cation exchange capacity (Dimoyiannis, 2011), exchangeable cations (Bronick and Lal, 2005), and Fe_2O_3 (Barthes et al., 2008). Chorom et al. (1994) observed that clay disperse readily with increasing soil pH. Aggregation is formed by flocculation, cementation and the rearrangement of particles (Duiker, 2003). In general, high content of base minerals increased the stability of soils, due to the applied chemical bonding of the aggregates. The stability of soils is affected by the chemical properties and the kinds of clay minerals present (Morgan, 2005). Amezketta (1999) reported the influence of common clay minerals such as smectite, kaolinite and illite on clay dispersivity. Singer (1994) found that smectite is the most dispersive while kaolinite is the least dispersive among clay minerals in soils. Neaman and Singer (1999) concluded that among the clay minerals, palygorskite decreased the stability of the aggregate more than the others did. The palygorskite minerals are fiber type and therefore do not form into aggregates in soils.

Minerals play an important part in aggregate stability of soils (Denef and Six, 2005). Stability of aggregates can be assisted by organic material (OM) (Le Bissonnais et

*Corresponding author. E-mail: moghimiabolhasan@gmail.com.

al., 2006), although Lado et al. (2004) and Dimoyiannis (2011) have not indicated significant correlation between stability aggregates and OM. Several studies indicated a high correlation between OM and aggregation (Le Bissonnais et al., 2006; Barthes et al., 2008). Bronick and Lal (2005) indicated that polyvalent cations, such as Ca^{2+} , Fe^{3+} and Al^{3+} make a bridging with OM and clay particles and increases stability of soil aggregates. Soil aggregate stability is a crucial soil property affecting soil sustainability and crop production in arid regions. Although several studies on the characteristics of arid soils have been reported, there is still insufficient documentation on the structural stability of soils of Southern Iran. This study was conducted to determine factors affecting aggregate stability in arid soils in Southeastern Iran.

MATERIALS AND METHODS

Description of the study area

The study was conducted in the Shamil-Ashkara Catchment area located between latitude $28^{\circ} 8'$ and $28^{\circ} 15'$ North and longitudes $56^{\circ} 5'$ and $56^{\circ} 15'$ East in the province of Hormozgan of Southeastern Iran (Figure 2). The climate is arid with an average annual precipitation and evaporation of about 162 and 4243 mm, respectively. The moisture regimes are aridic and ustic with a hyperthermic temperature regime (Banaei, 1998). The catchment area which is underlain by sedimentary rocks accompanying marine deposits of the tertiary age, are predominantly composed of thick alluvial and colluvial materials, occasionally deposited by the dehshaykh river for the past thousands of years. The river dried most of the time except during heavy downfall. The catchment is currently an important agricultural area cultivated with wheat, maize, potato, watermelon (Moghimi, 2002). Eight soils representing the alluvial fan and the colluvial deposits along the slope area of the catchment were selected. The morphological properties of the soil were described in the field (Soil Survey Staff, 2004) and were classified according to Soil Taxonomy (Soil Survey Staff, 2010). Soil samples were taken from the pedogenic horizons of each representative profile for various laboratory analyses.

Physical and chemical analyses

The field study and samples collection were carried out in the summer season of 2009 (August to September). They were air-dried and sieved with a 2 mm sieve and kept ready for analysis. The removal of CaCO_3 with 2N HCl and organic matter with 30% H_2O_2 was done prior to particle-size distribution which was determined by the pipette method (Gee and Bauder, 1986). Water-stable aggregates (WSA) were measured using 4 g of 1- to 2-mm air-dried soil into the 0.25 mm sieves with a wet-sieving apparatus. The wet-sieving method was adapted from Kemper and Rosenau (1986) and calculated by the following equation:

$$\%WSA = \frac{W - S}{4 - S} \times 100$$

Where W = weight of oven dry aggregates; S = weight of sand particles.

The determination of the water-dispersible clay (WDC) content of the soil was done by shaking the soil with distilled water without any

addition of dispersing agent as outlined in VanReeuwijk (1993). A mixture of 10 g of soil and 400 ml distilled water was shaken and transferred to 1-L sedimentation cylinder and made up to the mark. After that, 20 ml aliquot was withdrawn by means of a pipette and oven-dried at 105°C overnight. The WDC content was calculated using the following equation:

$$\%WDC = [50 \times R/S] \times 100 \times mcf$$

Where R = oven-dry weigh of 20 ml aliquot; S = air-dry sample weigh; Mcf = moisture correction factor.

The organic carbon content was determined by the Walkley and Black procedure (1947), while Fe_2O_3 was estimated by the dithionite-citrate-bicarbonate method (Mehra and Jackson, 1980). The soil pH was determined in a saturated paste by a glass electrode (McLean, 1982). The electrical conductivity (EC) analysis was done in the saturated extract (Salinity Laboratory Staff, 1954). The calcium carbonate equivalent (lime) was measured by acid neutralization (Allison and Moodi, 1965). Cation exchange capacity (CEC) was estimated using sodium acetate (NaOAc) at pH 8.2 (Chapman, 1965). For the determination of calcium and magnesium, the the complexometric titration method was used (Chapman, 1965). Potassium and sodium were determined from ammonium acetate leachate using the flame photometer. The soil solution data (Na^+ , Ca^{2+} , Mg^{2+} given in $\text{cmol}_c\text{kg}^{-1}$) was used to calculate the sodium adsorption ratio (SAR) where $\text{SAR} = \text{Na}^+ / [(\text{Ca}^{2+} + \text{Mg}^{2+}) / 2]^{0.5}$.

Mineralogical analyses

Prior to the mineralogical analysis, chemical cementing agents in the soils were removed and the separation of different size fractions for mineralogical analysis were done according to Kittrick and Hope (1963) and Jackson (1975). To remove organic matter and carbonate, samples were treated with 1 N HCl and 30% H_2O_2 , respectively. Clay samples were saturated with Mg^{2+} and K^+ , using 1 N MgCl_2 and 1 N KCl, respectively. K-saturated clays were heated at 550°C for 2 h and Mg-saturated clays solvated by ethylene glycol. The clay samples were finally examined by X-ray diffraction analysis using a Philips diffractometer with Co K α radiation in order to allow for a more reliable comparison between the relative heights of peaks in the X-ray diffraction data. Estimates of clay minerals were made by directly converting the diffraction peak areas using the method of Klages and Hopper (1982). Selected clay samples were studied under a transmission electron microscope (TEM, LEO 912 AB). The samples were suspended in 100% alcohol and the suspension was dropped on Formvar coated copper grids. The extra liquid was drained with the edge of a filter paper, air dried and tested for their morphology. The soil properties and their relationship with the aggregate stability and water-dispersive clay indices were analyzed using Statistics and Excel softwares. The aim was to assess the relationship between the indices and soil properties.

RESULTS AND DISCUSSION

Soil classification and field observation

Pedons 1, 3, 7 and 4 are soil developed on the piedmont alluvial plains, while pedons 2 and 6 are soils formed on the river alluvial plains. Pedons 5 and 8 are soils sitted on the higher slope area and are formed by the alluvio-colluvial fans. All pedons were deep with a maximum depth of 150 cm and obvious textural changes throughout

Table 1. Summary of classification of the soils.

Profile	USDA Soil Survey Staff (2010)	FAO (2007)
1	Fine loamy, mixed(calcareous), hyperthermic, Calcic Haplosalids	Calcic Solonchaks
2, 6	Coarse loamy, mixed(calcareous), hyperthermic, Aridic Ustorthents	Calcaric Regosols
3, 7	Fine loamy, mixed(calcareous), hyperthermic, Aridic Ustorthents	Calcaric Arenosols
4	Loamy skeletal, mixed(calcareous), hyperthermic, Aridic Ustifluvents	Calcaric Fluvisols
5, 8	Sandy skeletal, mixed(calcareous), hyperthermic, Aridic Ustorthents	Calcaric Regosols

the profile were observed. Since the plain is part of an alluvial and colluvial fan, the deposition of materials from the alluvial and colluvial wash varies from time to time creating different textural layers. This was observed in all soils studied where the soils textural changes were quite extreme, particularly for the silt and sand content. There were also variations in their structures, which is also associated with the amount of sand and silt in the soil. The soils tend to be massive when the silt content is high, otherwise the structure would be single grain when the sand content is high. The rounded nature of these gravels suggests that they were washed and deposited along part of the plain. All soils were weakly developed with only weak profile horizon formation. Under the arid environment with precipitation value of less than 200 mm and higher evaporation of more than 4000 mm, one would surely expect to see slow rate of soil pedological development because of very low rate of P/ET^0 (Khormali and Abtahi, 2003). The eight representative profiles were internationally classified using the criteria of soil taxonomy (USDA, 2010) and their approximate classes in the FAO (2007) world reference base for soil resources. All soils are young and were differentiated by their moisture regime. They were identified as calcic haplosalids, aridic ustorthents and aridic ustifluvents (Table 1).

Physical properties

The soil's physical data are presented in Table 2. None of the soil physical characteristics showed any clear trend with depth. In pedon 1, the clay content distribution was irregular. In pedons 4, 5, 7, and 8, clay increases with depths, while in pedon 2, it increases only until 100 cm. In contrast to the aforementioned observations, pedon 6 exhibited a remarkable decrease in clay content with soil depth. In pedons 3 and 4, the silt content increases towards the surface. The sand size particles are dominant in all pedons except for pedons 1 and 7, but their distribution throughout the profile is very irregular. The results assent with the nature of alluvial and colluvial deposition that varies from time to time. A similar deposition trend was also observed by Khresat and Qudah (2006) on studying the Azraq Basin in Northeastern Jordan.

Chemical properties

The soil chemical data of the representative profiles are presented in Table 3. The soils are alkaline and calcareous in nature containing 19.83 to 61.45% $CaCO_3$ throughout the profiles. All soils have pH values above 7.0 showing that they are alkaline. The average electrical conductivity values are somewhat variable among the soils studied, placing these soils from slightly saline to saline level. In pedons 2, 4, 5 and 8, the soils were noted to be non-saline with EC values ranging from 0.4 to 2.64 dSm^{-1} , while soils in pedons 3, 6 and 7 were slightly saline with EC values ranging from 2.1 to 7 dSm^{-1} . Pedon 1 soil was observed to be saline with EC values ranging from 18.11 to 30.5 dSm^{-1} . The sodium content showed slight variability among the soils studied. In pedons 2, 5 and 8, the amount of sodium was between 0.4 and 6.8 $cmol_c kg^{-1}$ as compared to pedons 1, 3, 4, 6, and 7 containing 1.84 to 20 $cmol_c kg^{-1}$. The soils however, are non-sodic with SAR values ranging from 0.3 to 7.7. The cation exchange capacity indicated a mean variability with values, ranging from 1.7 to 41.4 $cmol_c kg^{-1}$.

In pedons 1, 3, 6 and 7, the CEC was between 19.5 and 41.1 $cmol_c kg^{-1}$ as compared to pedons 2, 4, 5 and 8, with values of 11.7 to 21.5. The organic carbon content was low in all soils, which is common for soils of these regions where the vegetation is strongly influenced by the climatic conditions. The variability of the soil chemical properties again reflect the alluvial and colluvial nature of soil deposition and their rocks origin. According to Navai (1976), the predominant rocks surrounding the study area are limestone and dolomite (Jahrom Formation), limestone and marl (Aghajari Formation), limestone and green marl (Mishan Formation), salt domes (Hormoze Formation) and conglomerate (Bakhtiari Formation). The weathered rock materials from these formations were washed to the catchment areas and these contributed to the variability in the soil physical-chemical properties.

Clay mineralogy

The clay mineralogy of the studied soils is summarized in Table 4. The identification of the minerals through XRD diffractograms (Figure 3) based on d -spacing are as follows: Smectite (14.02 to 15, 3.18 to 3.20 Å),

Table 2. Some physical properties of the representative profiles.

Soil no.	Depth (cm)	Clay Silt Sand			WSA	WDC
		(%)				
1	0-25	34	56	10	1.8	10
	25-85	14	36	50	1.6	9.5
	85-100	32	48	20	1.7	11
	100-150	12	22	66	1.4	7.0
2	0-20	10	40	50	1.1	2.8
	20-50	10	8	82	1.3	2.7
	50-100	12	16	72	1.25	3.0
	100-150	8	2	90	5.5	3.1
3	0-30	18	38	44	3.1	5.2
	30-80	16	37	47	2.2	4.8
	80-150	16	12	72	1.5	4.5
4	0-20	10	16	74	3.7	3.8
	20-70	8	16	76	4.0	3.6
	70-95	14	12	74	3.0	3.4
	95-150	12	4	84	7.0	2.2
5	0-45	18	20	62	5.0	2.1
	45-150	24	20	56	7.2	1.1
6	0-42	16	34	50	3.4	2.8
	42-88	10	12	78	5.5	2.9
	88-150	12	26	62	2.0	2.2
7	0-36	24	42	34	4.3	3.5
	36-86	30	50	20	5.3	3.3
	86-150	26	38	36	3.5	5.3
8	0-30	12	14	74	1.5	3.2
	30-70	10	8	82	1.0	3.1
	70-150	14	14	72	1.2	3.0

WSA=Water-stable aggregate; WDC=water-dispersible clay.

palygorskite (10.4 to 10.6, 6.34 to 6.4, 3.23 and 4.25 to 4.47 Å), chlorite (7.01 to 7.11, 3.53 Å), illite (9.97 to 10.09, 4.98 to 5.02 Å), Kaolinite (7.2 to 7.3, 2.28 Å), and sepiolite (12.10 to 12.11). The presence of smectite was proven by Mg-glycolated sample, which expanded due to treatment with Mg-saturated (Figure 3). It is obvious that smectite, palygorskite, illite, chlorite and kaolinite are the common minerals in the soils of the Shamil-Ashkara catchment. Kaolinite are found in all soils with the exception of pedon 8. The sepiolite exists in pedons 3, 4, 6 and 7.

The dominance of these minerals in the arid regions agrees with the results obtained by Owliaie (2006), and Emadi et al. (2008). Palygorskite and sepiolite are fibrous

clays and are considered to be of authentic origin, inherited from weathered parent materials of the surrounding hills and plateaus (Khormali and Abtahi, 2003). The presence of kaolinite in most soils is probably due to inheritance from the weathering of coarse and fine materials transported from the surrounding upland zones. It may also suggest the occurrence of palygorskite and sepiolite kaolinization which apparently may be due to the effect of organic matter decomposition and to fibrous clay destabilization caused by Mg uptake by plants (Khademi and Arocena, 2008). The study showed that there is a negative correlation between smectite and palygorskite in the soils studied (Table 4). Previous studies have shown that palygorskite can transfer to smectite (Khormali and Abtahi, 2003). Besides, Mark et al. (2005) indicated that palygorskite is converted to smectite by means of dissolution with coetaneous nucleation and epitaxial growth of smectite on the palygorskite.

Soil aggregate indices

The distribution of WSA and WDC is shown in Table 2. The WSA values varied from 1 to 7.2%, while that of WDC was between 1.1 to 11%. In all cases, the distribution of WSA and WDC values in the soils was highly variable and this obviously is related to the deposition of alluvial and colluvial materials. Organic matter content in all soils is very low and probably assist little in soil aggregate cementation. The WSA and WDC values are therefore strongly dependent upon the inherent soil characteristics and their mineralogy (Morgan, 2005).

In pedon 1, the WDC value is the highest, ranging from 5 to 13%. The higher dispersibility of clay fraction in pedon 1 is probably due to the effect of Na (Table 3). The Na⁺ has the highest hydrated size among the monovalent and some divalent cations of soil and therefore, can increase the thick of different double layer around the colloidal particles and improve their dispersibility (Bohn et al., 1985). The result agrees with that obtained by Rengasamy and Olsen (1991).

Relationship between soil properties and aggregate stability

The correlation coefficients of soil properties with the stability indices are shown in Table 5. The clay content has a positive correlation with WDC, but it did not give any significant relationship with WSA. Six et al. (2002) did not find any correlation between clay content and aggregate stability. Even so, clay minerals have a significant correlation with WDC and WSA. A negative and significant relationship was obtained between WSA and palygorskite (Table 5). As observed through the Transmission electron microscopy (TEM) the palygorskite

Table 3. Chemical properties of the representative profiles.

Soil No.	Depth (cm)	pH H ₂ O	O.C (%)	CCE (%)	SAR	EC (Dsm ⁻¹)	cmol.c.kg ⁻¹					Fe _{DCB} (%)
							CEC	K ⁺	Na ⁺	Mg ²⁺	Ca ²⁺	
1	0-25	7.64	0.34	21.37	7.4	29.85	41.4	0.67	20	8.5	6.5	0.05
	25-85	7.11	0.20	24.98	7.0	27.5	26.3	0.22	14	4.5	3.5	0.04
	85-100	7.25	0.23	19.83	6.6	30.5	33.4	0.36	16	7.2	4.3	0.03
	100-150	7.60	0.12	23.70	7.7	18.11	31.3	0.17	15.4	5.2	3.3	0.06
2	0-20	8.36	0.18	27.04	3.6	0.96	21.5	0.23	6.8	4.8	2.5	0.08
	20-50	8.50	0.14	27.55	3.7	0.40	18.2	0.22	5.7	4.6	2.2	0.10
	50-100	8.20	0.13	28.32	1.8	1.20	15.4	0.20	3.4	4.3	2.4	0.09
	100-150	8.23	0.16	24.46	0.7	0.93	11.7	0.17	1.4	1.7	2.3	0.10
3	0-30	7.80	0.37	51.5	3.5	4.28	23.3	0.40	7.7	6.7	2.8	0.08
	30-80	7.70	0.20	57.16	4.6	7.00	34.7	0.25	12.1	10	3.2	0.09
	80-150	7.80	0.17	58.97	4.5	5.48	29.5	0.22	10.8	8	3.7	0.05
4	0-20	7.95	0.33	28.84	2.4	2.64	17.6	0.51	5.2	4.7	5.3	0.10
	20-70	8.16	0.35	28.85	3.0	1.45	16.1	0.18	5.2	1.3	4.6	0.12
	70-95	8.13	0.30	27.29	1.0	1.03	14.4	0.18	1.84	1.5	4.8	0.11
	95-150	8.53	0.43	27.98	1.6	1.21	11.7	0.15	2.6	0.8	4.3	0.15
5	0-45	7.85	0.35	58.20	1.5	1.54	15.1	0.21	2.8	0.6	6.5	0.12
	45-150	8.05	0.38	56.45	0.3	0.37	13.2	0.20	0.4	0.5	6.4	0.13
6	0-42	7.70	0.29	28.24	3.9	5.16	27.5	0.39	9.7	6.6	6.5	0.09
	42-88	8.20	0.33	23.53	2.6	2.10	19.5	0.17	5.7	4.8	5.0	0.11
	88-150	7.75	0.16	25.36	4.8	4.92	25.8	0.23	10.8	5.8	4.5	0.12
7	0-36	7.74	0.37	61.45	2.9	4.55	24.3	0.22	6.9	5.1	6.7	0.10
	36-86	7.75	0.39	60.41	2.1	5.25	26.7	0.24	5.4	6.1	6.4	0.09
	86-150	7.76	0.29	60.67	2.9	4.96	25.8	0.26	7.5	8.9	4.5	0.08
8	0-30	8.20	0.24	31.12	2.2	0.57	16.8	0.36	4	2.6	4.3	0.03
	30-70	8.13	0.25	31.90	2.1	0.80	18.4	0.24	3.8	2.2	4.8	0.04
	70-150	8.24	0.26	28.5	3.3	0.66	17.5	0.18	6	2.7	4.3	0.04

O.C=Organic carbon; SAR=sodium adsorption ratio; CCE=calcium carbonate equals; CEC=cation exchangeable capacity.

minerals are fibrous in nature and therefore do not have the tendency to form aggregates in the soils (Figure 1). According to Neaman and Singer (2004), Mg is released from palygorskite into the soil solution during irrigation. Magnesium as an exchangeable cation, in turn, is known to decrease aggregate stability and to enhance the dispersivity of the soil clay fractions.

In our present study, magnesium has a significant correlation with WSA and WDC, with *r* values of -0.40 and 0.52, respectively (Figure 4). This suggests that exchangeable magnesium are crucial in soil aggregation and stabilization. The findings agreed with those reported by Dontsova and Norton (2002) and Emmanuel (2009). The smectite has a positive significant correlation with

WDC (*r* = 0.40). Smectite disperse readily compared to mica and kaolinite (Singer, 1994; Wakindiki and Ben-Hur, 2002). Kaolinite has a significant correlation with WSA (*r* = 0.63) and WDC (*r* = -0.62). Among the minerals present, kaolinite has the highest negative correlation coefficient with WDC. Smectite has dispersivity effects on soil aggregates due to its high swelling property while kaolinite had a positive effect because of its low swelling capacity (Wakindiki and Ben-Hur, 2002; Morgan, 2005). A similar result was previously obtained by Yilmaz et al. (2005). The illite had a significant correlation with WSA and WDC with *r* values of 0.66 and -0.45, respectively. The result indicated that K⁺ increased the stability of aggregates due to the smaller edge-to-face attraction

Table 4. Summary of clay minerals of the soils.

Soil no.	Depth (cm)	%					
		Chl	Sme	Pal	Ill	Kao	Sep
1	0-25	25	10	38	9	18	-
	25-85	15	6	37	14	28	-
	85-100	18	11	43	7	21	-
	100-150	20	8	36	9	27	-
2	0-20	16	24	18	10	32	-
	20-50	44	18	24	9	5	-
	50-100	36	9	20	8	27	-
	100-150	11	44	23	11	11	-
3	0-30	14	21	31	28	6	-
	30-80	16	18	38	8	8	12
	80-150	9	29	35	18	10	-
4	0-20	25	8	16	32	8	11
	20-70	9	9	9	36	27	10
	70-95	36	9	10	27	9	9
	95-150	36	10	10	27	9	8
5	0-45	18	18	19	36	9	-
	45-150	24	17	21	38	-	-
6	0-42	25	24	8	24	7	12
	42-88	16	24	9	32	8	11
	88-150	27	8	24	24	8	9
7	0-36	24	18	24	18	6	10
	36-86	8	20	32	24	8	8
	86-150	9	26	18	27	9	11
8	0-30	41	28	21	10	-	-
	30-70	40	33	26	16	-	-
	70-150	25	44	25	21	-	-

Pal= Palygorskite; Sme= Smectite; Chl= Chlorite; Ill= Illite; Kao= Kaolinite; Sep=Sepiolite.

forces in comparison to the other clay types because of the irregular and terraced surfaces of the illite particles (Amezketá, 1999). The results are consistent with those findings of Mehmet et al. (2004). The CEC has a positive significant correlation with WDC ($r = 0.74$), while it has a negative significant correlation with WSA ($r = -0.44$). This demonstrates that the amount of stable aggregates decreases as the amount of CEC increases. Since organic matter is low in the soils, the CEC is affected by the expanding minerals (e.g., smectite) (Igwe et al., 1999) and basic exchangeable cations (e.g., Na). The results are compatible with those of Levy (1997). The WDC and total clay content had a positive significant correlation ($r =$

0.64) (Figure 7) and this result agrees well with those presented previously by Brubakar et al. (1992).

The SAR has a significant correlation with WSA and WDC with r values of -0.60 and 0.80, and exchangeable sodium values of -0.40 and 0.52, respectively. This indicates that the sodium adsorption ratio plays a significant role in soil aggregation and stabilization. The increase in the SAR values expand the minerals and the expansion is due to the replacement of calcium and magnesium ions by sodium, resulting in water uptake and consequently the collapse of soil aggregate (Morgan, 2005). The results agreed with those obtained by Garcia et al. (2005). Nevertheless, the Ca^{+2} has a positive correlation with WSA ($r = 0.45$). The Ca^{+2} acts as bonding agents for primary particles. It also forms bridges between clay fraction and OC particles resulting in aggregation (Bronick and Lal, 2005). The pH has a negative significant correlation with WSA ($r = -0.55$) but has a positive significant correlation with WDC ($r = 0.87$). This is indicated by the higher positive correlation ($r = 0.87$) between pH and WDC (Figure 6). The results agreed with the reports by Chorom et al. (1994), and Levy (1997) which stated that clay dispersion increased with increasing pH due to its dependence on the net negative charge. The negative charges, thereby causing the double layer expansion (Mehmet et al., 2004). The electrical conductivity (EC) also has a positive correlation with WDC ($r = 0.84$) but has a negative correlation with WSA ($r = -0.43$) because the cations in the solution were occupied further by Na^{+} and Mg^{2+} .

The study shows that the concentration of Fe_2O_3 in the soils (Table 3) has a significant correlation with WSA and WDC with r values of 0.74 and -0.63, respectively. The results show that iron oxide can increase the stability of aggregates. This is because the Fe oxide acts as a binding agent in the arid and tropical soils (Barthes et al., 2008) and it affects the edge charge and the variable surface charge on clays and minerals (Suarez, 1984). The findings are in agreement with those obtained by Dimoyiannis (2011). Aggregate stability is affected by soil OC by reason of the binding agent of humic materials and other microbial byproduct (Shepherd et al., 2001), and this is shown by the significant positive correlation coefficient between WSA and the organic carbon ($r = 0.70$) (Figure 5). The strong correlation between organic materials and aggregation has been reported by Le Bissonnais (2006) and Barthes et al. (2008).

Conclusion

Structural stability of soils is one of the most important characteristics related to soil degradation in semiarid areas. This study shows that the WDC and WSA are dependent on the physico-chemical properties and the mineralogical composition of the soils. The soils of the study area have weak aggregate stability due to the high

Table 5. Simple linear correlation between aggregate stability indices and some soil properties.

Property	pH	Pal	Kao	Ill	Sme	Na ⁺	Mg ⁺²	Ca ⁺²	CEC	OC	SAR	EC	clay	Fe ₂ O ₃	K ⁺	WDC	WSA	
pH	1.00																	
pal	0.76**	1.00																
Kao	0.27	0.17	1.00															
Ill	-0.32	-0.52**	0.68**	1.00														
Sme	-0.52**	-0.33	0.30	0.03	1.00													
Na ⁺	0.75**	0.76**	-0.30	-0.26	-0.48*	1.00												
Mg ⁺²	0.54**	0.40*	0.20	-0.04	-0.13	0.78**	1.00											
Ca ⁺²	-0.09	-0.09	0.24	0.37	0.03	0.00	-0.04	1.00										
CEC	0.74**	0.87**	-0.16	-0.19	-0.39*	0.95**	0.83**	0.08	1.00									
OC%	-0.15	-0.35	0.49*	0.54**	0.28	-0.18	0.00	0.54**	-0.11	1.00								
SAR	0.70**	0.71**	-0.35	-0.25	-0.53**	0.96**	0.66**	-0.18	0.85**	-0.33	1.00							
EC	0.69**	0.73**	-0.49*	-0.39*	-0.42*	0.70**	0.37	0.00	0.65**	-0.30	0.70**	1.00						
Clay%	0.60**	0.54**	0.09	-0.05	0.00	0.53**	0.56**	0.32	0.70**	0.29	0.35	0.39*	1.00					
Fe ₂ O ₃	0.75**	0.76**	-0.57**	-0.37	-0.59**	0.76**	0.44*	0.05	0.75**	-0.31	0.72**	0.74**	0.43*	1.00				
K ⁺	0.37	0.31	-0.26	-0.12	-0.19	0.50**	0.40*	0.12	0.47*	0.26	0.35	0.16	0.46*	0.35	1.00			
WDC	0.87**	0.68**	-0.63**	-0.45*	0.40*	0.84**	0.52**	-0.07	0.74**	-0.17	0.80**	0.84**	0.64**	-0.63**	0.42*	1.00		
WSA	-0.55**	-0.46*	0.62**	0.66**	-0.20	-0.50**	-0.40*	0.45*	-0.44*	0.70**	-0.60**	-0.43*	0.13	0.74**	0.16	-0.45*	1.00	

*,** Significance at the 95% (P<0.05) and 99% (P<0.01) respectively. WSA= water-stable aggregates (%); WDC= water-dispersible clay (%); SAR=sodium adsorption ratio; CEC=cation exchange capacity (cmol.kg⁻¹); Pal= Palygorskite; Sme= Smectite; Chl= Chlorite; Ill= Illite; Kao= Kaolinite; EC = electrical conductivity (dSm⁻¹); OC = organic carbon (%).

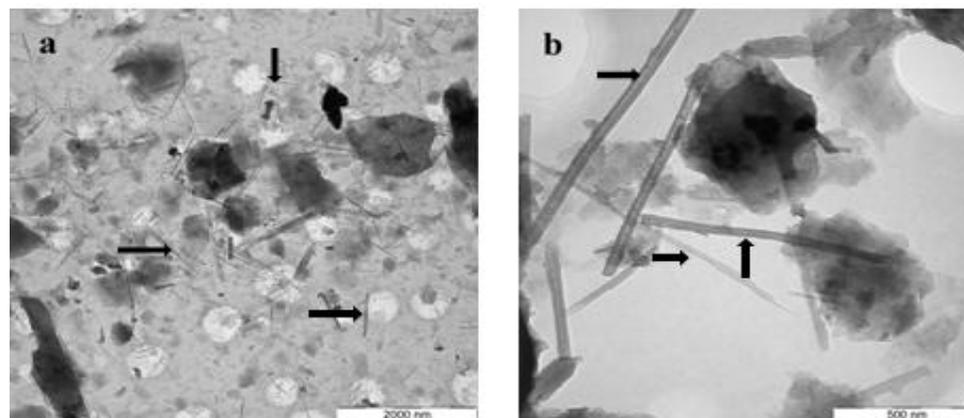


Figure 1. Transmission electron micrographs showing the aggregation of palygorskite in soil aggregates. (a) topsoil of pedon 1, (b) topsoil of pedon 2.

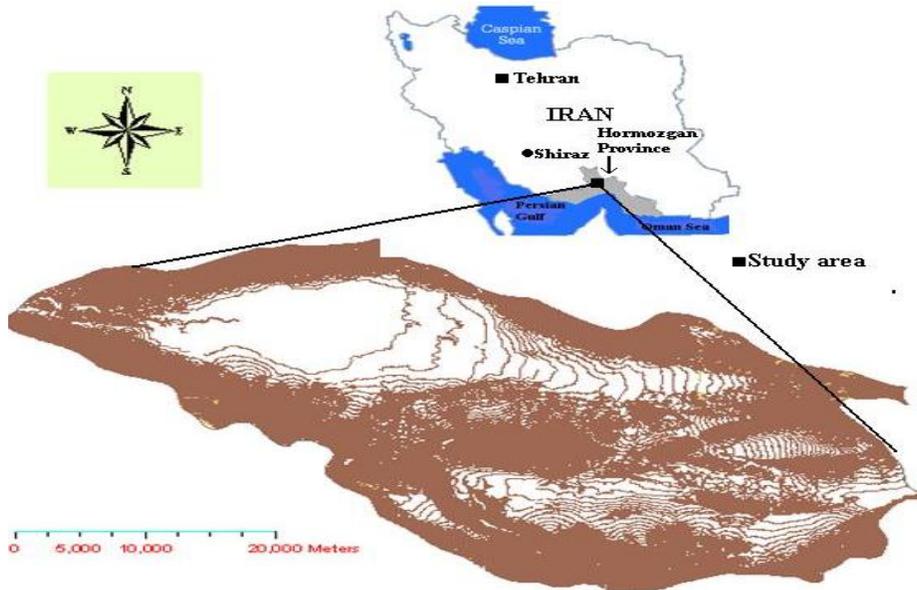


Figure 2. Location of study area.

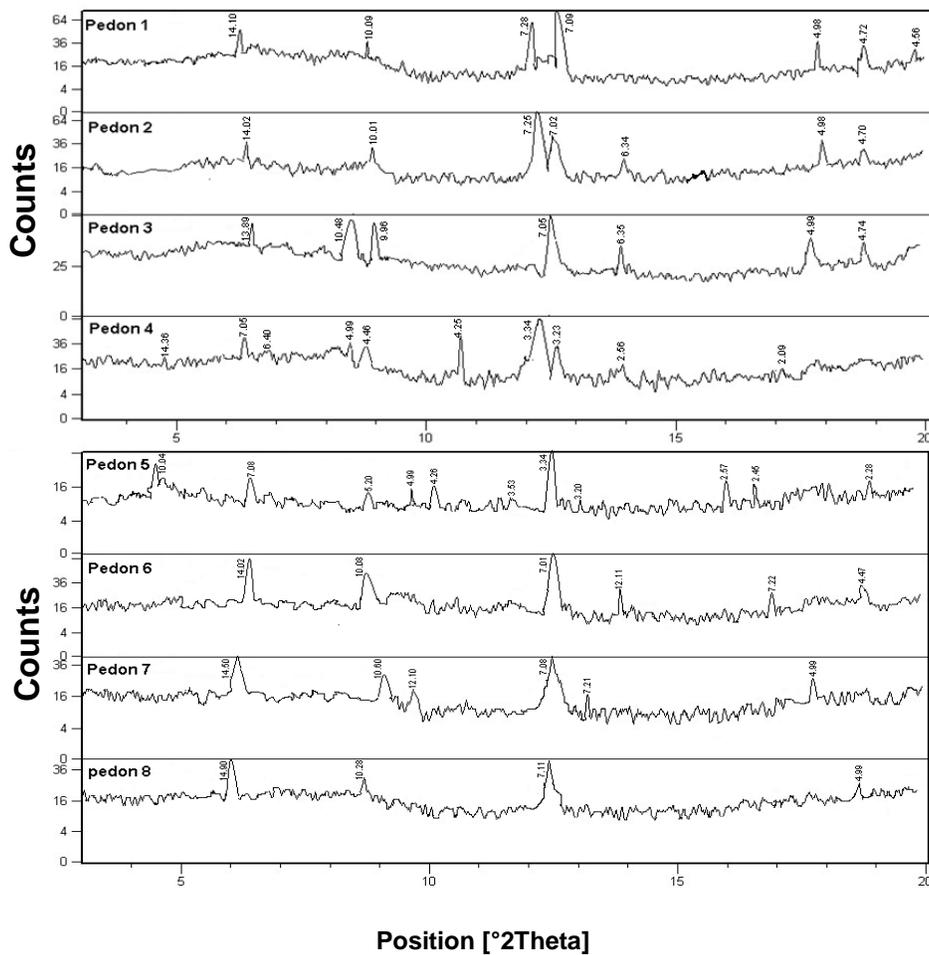


Figure 3. XRD diffractograms of the Mg saturated clay fraction (<2 μm) of the eight studied pedons topsoils (each peak characterized by d-spacing belong to each mineral).

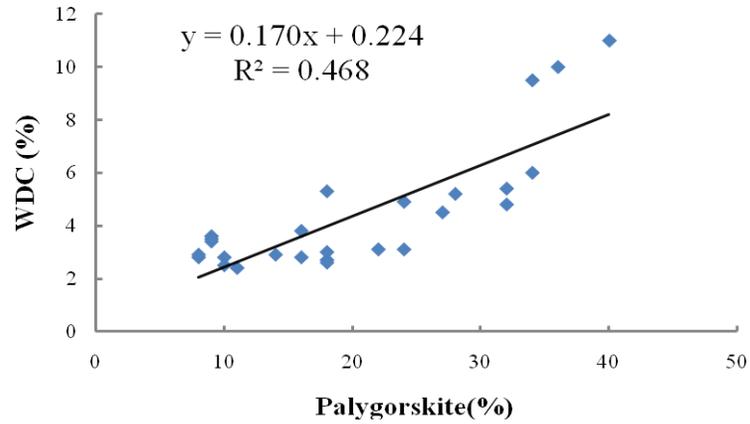


Figure 4. Relationship between water-dispersible clay and Palygorskite.

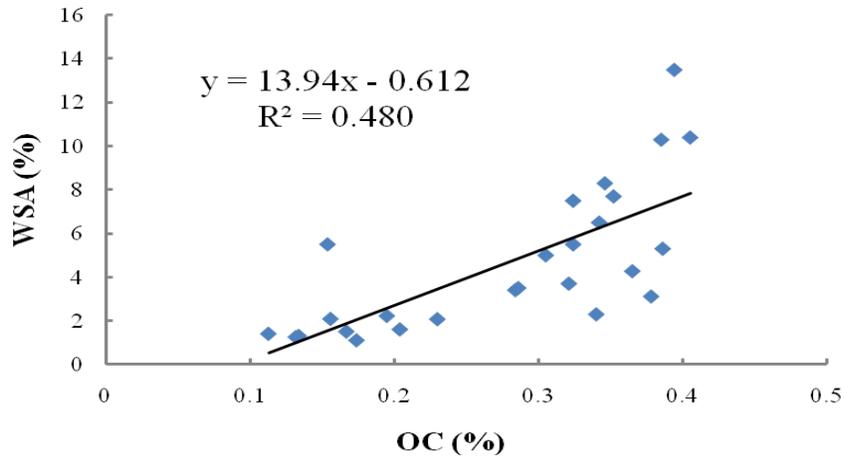


Figure 5. Relationship between water-stable aggregates and organic carbon content.

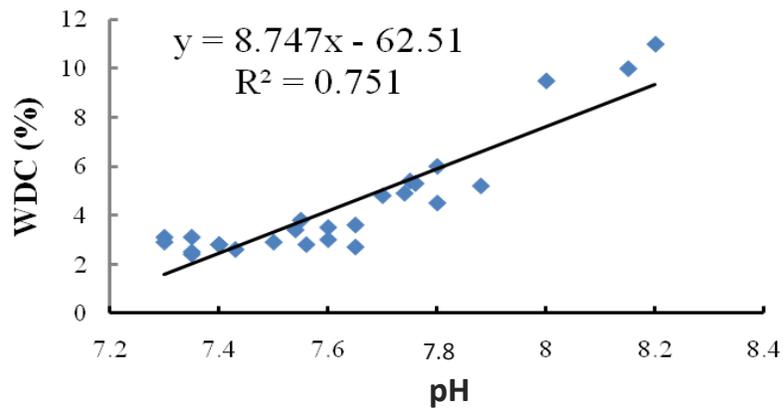


Figure 6. Relationship between water-dispersible clay and pH.

pH, Na, Mg, and 2:1 clay minerals such as palygorskite and smectite. The soils also have low humic substances, iron and aluminium oxides. Organic additions can

considerably improve soil structure and prevent soil degradation.

There is therefore a need to look into the relationship

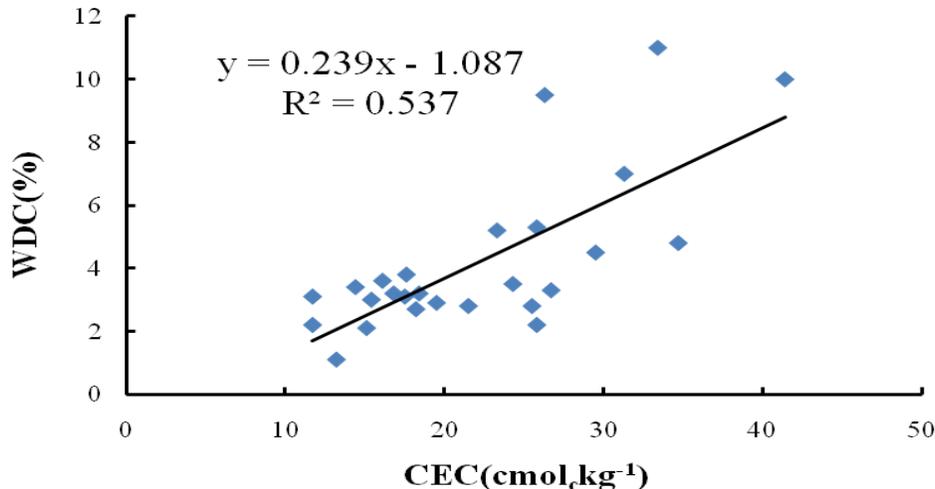


Figure 7. Relationship between water-dispersible clay and cation exchange capacity.

between various soil conditioners and different tillage and their effect on soil aggregate stability. Other than the crop standing residues, animal manures and crop wastes are cheap and easily available to the farmers, and should be considered for soil structure improvement. Studies focusing on deriving models associated with the effect of pH, palygorskite, and sodium on aggregate stability would assist in reducing soil degradation.

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