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The Effects of Four Organic Soil Conditioners on Aggregate Stability, Pore Size Distribution, and Respiration Activity in a Sandy Loam Soil

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Abstract: In coarse-textured soils, low water and nutrient holding capacity due to the high number of macropores limits crop growth. To minimize these limitations the application of various soil conditioners (SCs) has been extensively used in recent decades. The objective of this study was to investigate the influences of anionic polyacrylamide (PAM), cattle manure (M), vermicompost (VC), and biological sludge (BS) as organic SCs on mean weight diameter (MWD) of aggregates, water aggregate stability (WAS), pore size distribution (PRSD), and respiration activity (RA) of a sandy loam soil. PAM (0.25 and 0.5 g kg^{-1} of air-dried soil), M (12.5 and 25 g kg^{-1} of air-dried soil), VC (2.5 and 5 g kg^{-1} of air-dried soil), and BS (1.7 and 3.4 g kg^{-1} of air-dried soil) were mixed with soil and uniformly packed into large and small pots, and then incubated in a greenhouse with FC moisture content of 0.7-0.8 and temperature of 22 ± 4 °C for 6 months. Large pots were used for soil sampling in order to measure MWD, WAS, and PRSD at 7, 30, 60, 120, and 180 days. Respiration activity was measured at the same times in small pots. All SCs, irrespective of their concentrations, significantly ($P \leq 0.05$) increased RA. Manure (25 g kg^{-1}) significantly ($P \leq 0.05$) decreased the number of macropores (> 75 µm) and increased the number of micropores (< 30 µm). Both PAM rates significantly ($P \leq 0.05$) increased MWD, WAS, and the number of mesopores (30-75 µm); the increase in the number of mesopores was accompanied by a decrease in the number of macropores. BS (3.4 g kg^{-1}) significantly ($P \leq 0.05$) decreased the number of mesopores by increasing the number of micropores. Consequently, application of M (25 g kg^{-1}), PAM (0.25 and 0.5 g kg^{-1}), and BS (3.4 g kg^{-1}) each improved the water holding capacity of the sandy loam soil by modifying PRSD.

Key Words: Soil conditioner, mean weight diameter, pore size distribution, soil respiration, water aggregate stability

Abbreviations: SC: soil conditioner; PAM: polyacrylamide; M: manure; VC: vermicompost; BS: biological sludge; MWD: mean weight diameter; WAS: water aggregate stability; PRSD: pore size distribution; RA: respiration activity

Introduction

Aggregate stability, defined as the resistance of soil aggregates to failure when subjected to disruptive forces, provides an integral measure of the strength of intra-aggregate bonds. Sandy loam soils, of the coarse-textured class, often are poorly structured. Water applied as irrigation to these soils, or rainfall, causes aggregate breakdown and undesirable physical conditions because of their weakly bonded aggregates, (Schjonning et al., 1994; Nadler et al., 1996; Imbufe et al., 2005). It leads to seal formation, decreased infiltration, and increased runoff (Sadegian et al., 2006). Other problems of coarse-textured soils are low water and nutrient holding capacity because they contain more macropores (Sen and Bhadoria, 1987; Tester, 1990; Al-Darby, 1996; Nyamangara et al., 2001). In order to eliminate or reduce these limitations researchers have proposed various methods for conditioning or strengthening these soils by the application

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of different natural or synthetic soil conditioners (SCs). Pagliai et al. (1981) showed that application of sewage sludge and compost at the rate of 150 t ha^{-1} on a sandy loam soil significantly ($P \leq 0.05$) increased aggregate stability (wet sieving) by 1-2 mm and total porosity by increasing the number of pores (500-50 and 50-30 µm) and decreasing the number of pores larger than 500 µm. Nyamangara et al. (2001) reported that addition of 37.5 t ha^{-1} of cattle manure on a sandy soil significantly ($P \leq 0.05$) increased water aggregate stability (WAS) by 2-10 mm and water retention capacity at suctions of 5-200 kPa. Sadegian et al. (2006) showed that application of polyacrylamide (PAM), pumice, and straw as SCs on the 0 to 5-cm layer of a sandy loam soil significantly ($P \leq 0.01$) decreased surface sealing by decreasing bulk density and increasing microporosity. Conditioning effects of organic materials, in terms of increasing water holding capacity, modifying bulk density, and PRSD, are more pronounced for coarse-textured soils than for medium and fine-textured soils (Nelson and Kladivko, 1979; Metzger and Yaron, 1987; Bauer and Black, 1992). According to Tester (1990), addition of 268 t ha^{-1} $year^{-1}$ of sewage-sludge compost to a loamy sand soil for 4 years significantly decreased the cone index and bulk density, increased the specific surface area of the soil, and increased the moisture holding capacity of the surface layer. Shaviv and Sinai (2004) reported that spraying LIMA polymer on a silty loam soil at the concentration of 5 g l^{-1} increased aggregate stability of the soil near subsurface drip irrigation tubes and reduced soil clogging. According to Al-Darby (1996), addition of a gel-forming SC (Jalma) to a sandy soil increased the percentage of micropores (5-30 µm) from 10.0 to 17.86 and decreased the diameter of the largest pore from 250 to 120 µm. Bryan (1992) showed that application of anionic PAM at the concentration of 0.5 g kg^{-1} of air-dried soil on several medium- and fine-textured soils significantly ($P \leq 0.05$) increased WAS, saturated hydraulic conductivity, and available water. According to Matyn et al. (1990), use of oil mulch (bituminous) as an evaporation inhibitor on a sandy soil decreased the evaporation rate by 45% under field conditions. Levy and Miller (1999) indicated that application of anionic PAM with a molecular weight of 10^7 Da on a sandy loam soil significantly ($P \leq 0.05$) increased mean weight diameter (MWD) of aggregates (wet sieving), as compared with the control.

Soil PRSD is also important with regard to determining the habitable pore-space for microbes and their activities, i.e. interaction, predation, and competition (Paul and Clark, 1996). According to a limited number of studies, there is a strong correlation between microbial activity and some soil physical properties, such as porosity and penetration resistance (Marinari et al., 2000; Ozturk et al., 2005).

Despite the literature just cited, the effects of natural and synthetic SCs on PRSD (according to the recent classification of SSSA, 1997) have not been thoroughly investigated. Incubation effects of synthetic SCs (gels and polymers) on aggregate stability, PRSD, and respiration activity (RA) of soil still need further investigation. The objectives of the present study were to investigate the effects of natural manure, vermicompost, biological sludge, and synthetic PAM on aggregate stability (MWD and WAS), PRSD (SSSA, 1997), and RA in a sandy loam soil, as well as to assess the temporal variability of their effects.

Materials and Methods

Soil samples were collected from the 0-30-cm layer of a bare farm located at the Karkaj Research Station of Tabriz University, Iran (lat 38°5 N, long 46°17 E, and 1360 m above mean sea level). Soil of the experimental site was classified as loamy, mixed, mesic, and typic calcixerept (Jafarzadeh et al., 1993). The samples, after arriving at the greenhouse, were air-dried and passed through a 4.76-mm sieve. Appropriate soil properties were determined (Table 1) according to procedures described by Klute (1986) and Page (1985). The SCs applied were as follows: anionic PAM with a molecular weight of 18×10^6 g mol^{-1} (supplied by the Polymer Research Center of Iran), biological sludge (BS) produced from sewage purification by the Tabriz Petrochemical Company, cattle manure (M), and vermicompost (VC) prepared from the activity of added *Eisenia foetida* earthworms to cattle manure at the Organic Fertilizer Company Plant of Tabriz municipality. Several properties of the SCs were also measured (Table 1) according to the procedures described by Page (1985). Large pots (50 cm diameter, 25 cm height) were used for measuring aggregate stability and PRSD, and small pots (15 cm diameter, 25 cm height) were used for measuring RA and solute transport parameters (not reported in the present paper). Three SCs, after air-drying and passing through a 2-mm sieve, as BS at rates of 1.7 and 3.4 g kg^{-1}, VC at

Table 1. Some physical and chemical properties of the studied soil and soil conditioners (SCs).

Property	Soil	Manure	Vermicompost	Biological sludge
pH_e	8.1	7.7	8	8.1
EC_e (dS m^{-1})	1.87	15	14.65	11.41
OC (g kg^{-1})	6.2	348	165	266
Total N (g kg^{-1})	-	4	20	74
CCE (g kg^{-1})	210	-	-	-
10 kPa w. c (% w/w)	17.41	-	106.7	109.2
1500 kPa w. c (% w/w)	9.72	-	-	-
AWC (% w/w)	7.69			
Sand (%)	69.44			
Silt (%)	20.9			
Clay (%)	9.66			

rates of 2.5 and 5 g kg^{-1}, and M at rates of 12.5 and 25 g kg^{-1} of air-dried soil were hand mixed with the prepared soil with an FC moisture content of 0.75. The BS rates were chosen according to Kasraei (2004) and the M and VC rates according to the economic consideration of local farmers. Anionic PAM at rates equivalent to 0.25 and 0.5 g kg^{-1} of air-dried soil, as indicated by Bryan (1992), was dissolved in the volume of water needed to raise the initial soil moisture content of a pre-weighed soil to 0.75 FC, and was then uniformly added to the soil. Pots (large and small) were packed with the treated soils layer by layer to achieve a uniform packing, as much as possible; the realized bulk density was 1.48 g cm^{-3}. In order to facilitate fast, free drainage from the pots, the bottoms of the pots were drilled and then placed on a 10-cm thick soil bed. Perforations were made for direct contact between the soil in the pots and the soil bed. The samples were incubated in a greenhouse at moisture and temperature conditions of 0.7-0.8 FC and 22 ± 4 °C (optimal conditions for activity of aerobic microbes), respectively, for 6 months. Tensiometers were installed in the pots at a depth of 10-15 cm in order to maintain soil moisture content in the range of 0.7-0.8 FC, with timely irrigation of the pots. Pots were irrigated when suction shown by the tensiometers exceeded 30 cb, equivalent to 0.7 FC. The amount of water added by irrigation was sufficient to raise the moisture content to 0.8 FC.

To measure aggregate stability, samples were taken from the 10-15-cm layer of the large pots. It was supposed that this layer would have the least variation in moisture and temperature (Paul and Clark, 1996). Water aggregate stability was measured by a modified Yoder wet sieving machine (Yoder, 1936). Sieves had a pore size of 2, 1, 0.5, 0.25, and 0.106 mm. Soil samples taken from each pot were air-dried, 50-g sub-samples were gently transferred to the top most sieve of a sieve set, and sieving was then performed. Vertical sieving oscillation was 37 mm at 30 rpm for 5 min. The fractions remaining on the sieves were oven-dried at 105 °C for 24 h, weighed, and corrected for the sand fraction equal to or greater than the corresponding sieve pore size to obtain the true proportion of the soil aggregates. Mean size of the aggregates retained by each sieve was computed according to the diameters of the adjacent sieves and MWD of the soil samples was computed according to the Van Bavel equation (1950).

Water aggregate stability (WAS) for the 1-2-mm aggregates was measured and computed according to Kemper and Rosenau (1986).

In order to determine PRSD from experimental soil moisture characteristic curves, undisturbed samples taken by steel rings (5.6 cm diameter and 4.0 cm height) from the 10-15-cm layer of the large pots were prepared. The hanging water column technique (Gardner, 1986) was used to measure water content at 0-, 10-, 20-, 30-, 40-, 60-, 80-, and 100-cm suctions. The percentage of pores in each size class, according to SSSA (1997) classification [macropores (> 75 µm), mesopores (30-75 µm), and micropores (< 30 µm)], was computed from the capillary rise equation (Danielson and Sutherland, 1986) using the prepared soil moisture curves.

In order to assess the rate of microbial activity in the pots during the incubation period, the CO_2-release procedure, as an indicator of soil RA, was employed (Isermeyer, 1995). Briefly, a 50-ml plastic container with 25 ml of NaOH (0.1 N) was placed at the top of each small pot and immediately made airtight. After 3 h, the entire contents of each container were transferred to an Erlenmeyer flask by washing twice with 10 ml of distilled water and titrated with HCl (0.1 N). These procedures were also repeated for a sterile soil (blank). The soil respiration rate was calculated as follows:

$$\text{mg of } CO_2 \text{ pot}^{-1}\, 3h^{-1} = (B - V)\, N\, E \tag{1}$$

where B and V are the volume of HCl used for the blank and soil samples (ml), respectively, N is the normality of HCl, and E (= 22) is the gram-equivalent of released CO_2.

All the measurements (MWD, WAS, PRSD and RA) were obtained 7, 30, 60, 120, and 180 days after the start of incubation in order to evaluate the effects of time on the measured structure stability criteria and biological activity.

The experiments were conducted with a factorial with randomized complete block design, in 3 replicates. The 2 factors were 9 SC application rates and 5 incubation times. In order to obtain normal or nearly normal distribution of the data, some were SQRT-transformed before analyzing with ANOVA. Statistical analysis of the data and comparison of the means by Duncan's multiple range test ($P \le 0.05$) was carried out using MSTAT (1988), and figures were drawn with EXCEL software.

Results

Some physical and chemical properties of the examined soil and applied SCs are shown as means in Table 1. Apparently, the soil had low available water capacity (AWC) because it had a high sand fraction. In this soil a surface seal is expected after irrigation and/or rainfall because its organic matter and clay content are very low. High pH and calcium carbonate equivalent (CCE) of the soil may decrease uptake of some nutrient elements, such as P and Fe, by plants and trees.

Table 2 briefly depicts the analysis of variance of the measured characters. The main effects of SC (kind and rates) were significant ($P \le 0.01$) for all characters. Comparison of their means using Duncan's multiple range test ($P \le 0.05$) are shown in Figures 1, 2, 5, and 6. The main effects of incubation time were also significant ($P \le 0.01$) for all characters, except MWD. Comparison of mean respiration rates, PRSD, and WAS using Duncan's multiple range test ($P \le 0.05$) is shown in Figures 3, 4, and 7. Interaction effects of SC rates and incubation times were also significant ($P \le 0.01$) for MWD and WAS. Comparison of their means using Duncan's multiple range test ($P \le 0.05$) is shown in Figure 8 (A and B).

Discussion

Effect of SC on the Respiration Rate and PRSD

Figure 1 shows that all of the SCs (at both rates), except VC1 (2.5 g of vermicompost kg^{-1} of air-dried soil), significantly ($P \le 0.05$) increased the respiration rate, as compared with the control. Probably, VC at the rate of 2.5 g kg^{-1} was not adequate to raise the respiration rate significantly. Among the 4 SCs, M2 (25 g of manure kg^{-1} of air-dried soil), due to having the highest organic carbon content (Table 1), produced the highest respiration rate (Marinari et al., 2000). Ferreras et al. (2006) reported that application of 10 Mg ha^{-1} of vermicompost from household solid waste and chicken manure to a silt loam soil significantly ($P \le 0.05$) increased microbial respiration by increasing soil organic carbon (SOC), as compared to the control. According to Figure 1, although PAM is a

Table 2. Analysis of variance (mean square) of the measured parameters.

Source	Df	Respiration rate	MWD	WAS	Macropores (> 75 µm)	Mesopores (75-30 µm)	Micropores (< 30 µm)
SC	8	1.84**	0.946**	59.101**	0.398**	0.458**	41.056**
IT	4	27.24**	0.006ns	4.138**	3.455**	2.779**	296.909**
SC × IT	32	0.365ns	0.015**	0.437**	0.089ns	0.034ns	6.861ns
Error	88	0.382	0.007	0.168	0.122	0.034	14.411

SC: soil conditioner; IT: incubation time. **Significant at P   0.01. nsNot significant.

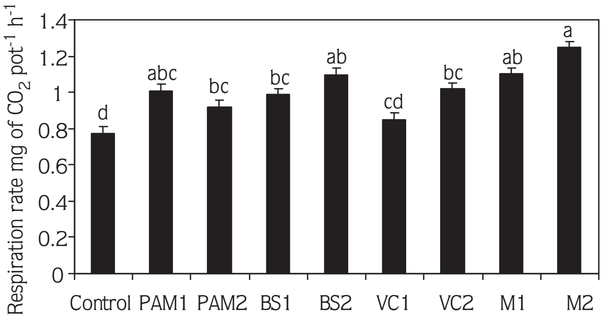

Figure 1. Effects on the mean rate of soil respiration of the SCs at the 2 applied rates. PAM1, PAM2: 0.25 and 0.5 g of polyacrylamide; BS1, BS2: 1.7 and 3.4 g of biological sludge; VC1, VC2: 2.5 and 5 g of vermicompost; M1, M2: 12.5 and 25 g of manure (all rates are kg^{-1} of air-dried soil). Values with common letters are not significantly different at P ≤ 0.05 (Duncan's multiple range test).

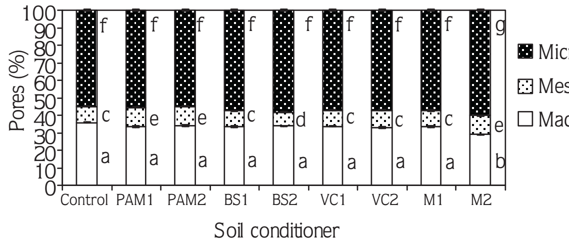

Figure 2. The effect of the SCs at the 2 applied rates on mean PRSD. PAM1, PAM2: 0.25 and 0.5 g of polyacrylamide; BS1, BS2: 1.7 and 3.4 g of biological sludge; VC1, VC2: 2.5 and 5 g of vermicompost; M1, M2: 12.5 and 25 g of manure (all rates are kg^{-1} of air-dried soil). Macropores: > 75 μm; mesopores: 75-30 μm; micropores: < 30 μm. Common letters indicate no significant difference at P ≤ 0.05 (Duncan's multiple range test).

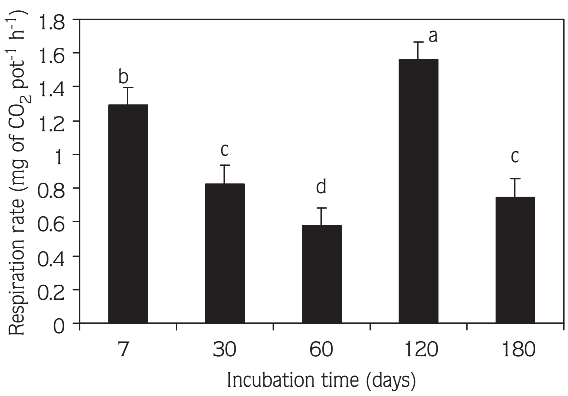

Figure 3. The effect of incubation time on mean soil respiration rate. Common letters indicate no significant difference at P ≤ 0.05 (Duncan's multiple range test).

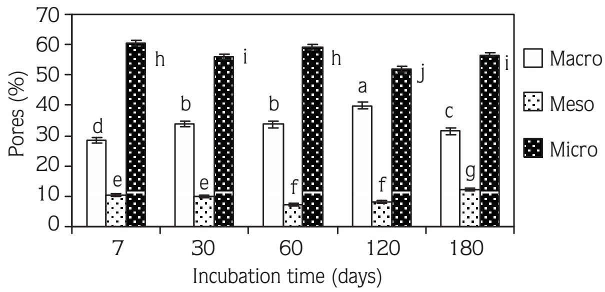

Figure 4. The effect of incubation time on mean PRSD. Macropores: > 75 μm; mesopores: 75-30 μm; micropores: < 30 μm. Common letters indicate no significant difference at P ≤ 0.05 (Duncan's multiple range test).

xenobiotic polymer and its carbon chain is resistant to microbial breakdown, it may have stimulated the growth of the native microorganism population and thus significantly increased RA. Grula et al. (1994) reported that anionic PAM applied to several species of *Pseudomonas* isolated from soil and to sulfate-reducing bacteria stimulated their growth because it provided them with nitrogen (as ammonia). Additionally, Kay-Shoemake et al. (1998) showed that the number of heterotrophic bacterial was significantly elevated in PAM-treated soil in the plot planted with potatoes because it increased the concentration of NO_3^- and NH_3, as compared to the control. They concluded that although soil bacteria utilized PAM as the sole source of N, the monomeric constituents of PAM, acrylamide and acrylic acid, both supported their growth as the sole source of C. Similar findings have been reported by Caesar-Tonthat et al. (2008).

Figure 2 shows that M2 treatment significantly (P ≤ 0.05) decreased the percentage of macropores and significantly (P ≤ 0.05) increased the percentage of micropores, as compared to the control. This finding is important in terms of increasing water and nutrient holding capacity and decreasing the loss of nutrient elements or pollutants, especially nitrate, via deep percolation and preferential flow in coarse-textured soils (Nyamangara et al., 2001; Warrick, 2002). Both levels of

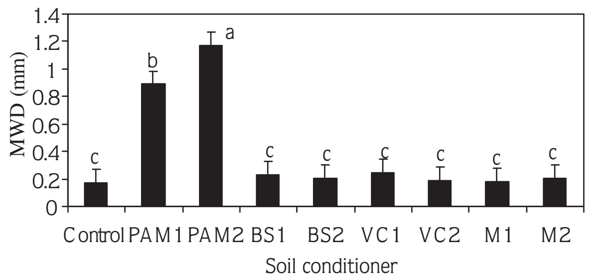

Figure 5. The effect of the SCs at the 2 applied rates on mean MWD. PAM1, PAM2: 0.25 and 0.5 g of polyacrylamide; BS1, BS2: 1.7 and 3.4 g of biological sludge; VC1, VC2: 2.5 and 5 g of vermicompost; M1, M2: 12.5 and 25 g of manure (all rates are kg^{-1} of air-dried soil). Common letters indicate no significant difference at P ≤ 0.05 (Duncan's multiple range test).

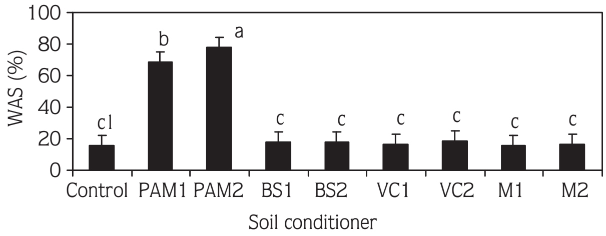

Figure 6. The effect of the SCs at the 2 applied rates on mean WAS. PAM1, PAM2: 0.25 and 0.5 g of polyacrylamide; BS1, BS2: 1.7 and 3.4 g of biological sludge; VC1, VC2: 2.5 and 5 g of vermicompost; M1, M2: 12.5 and 25 g of manure (all rates are kg^{-1} of air-dried soil). Common letters indicate no significant difference at P ≤ 0.05 (Duncan's multiple range test).

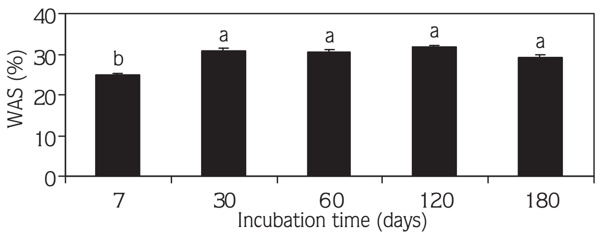

Figure 7. The effect of incubation time on mean WAS. Common letters indicate no significant difference at P ≤ 0.05 (Duncan's multiple range test).

anionic PAM significantly (P ≤ 0.05) increased the percentage of mesopores, as compared with the control, by decreasing macropores. It appears that PAM modified PRSD by increasing soil respiration (Figure 1) and aggregation (Figures 5 and 6), and consequently improved soil water and solute holding capacity. BS2 treatment (3.4 g of biological sludge kg^{-1} of air-dried soil) significantly (P ≤ 0.05) decreased the percentage of mesopores (75-30 μm), as compared to the control, by increasing the number of micropores. Other SCs (BS1, VC1, VC2, and M1) slightly decreased the macropore percentage, as compared to the control, but the decreases were not significant, probably because of inadequate rates of application or the coarse-textured nature of the examined soil.

Effect of Incubation Time on the Respiration Rate and PRSD

Figure 3 shows that 7 days after the onset of incubation RA was significantly (P ≤ 0.05) higher than at 30, 60, and 180 days, probably due to the high availability of organic carbon, which consequently increased the population and activity of soil microorganisms. RA 30 and 60 days after the start of incubation significantly decreased, as compared to 7 days, because of a decrease in the amount of substrate for heterotrophic microorganisms. The reason that RA temporarily increased at 120 days is that soil bacteria activity increased via consumption of cellular materials in dead microbes (Paul and Clark, 1996). Another possible reason is that RA significantly increased due to good aeration conditions at 120 days of incubation because the percentage of macropores (> 75 μm) significantly (P ≤ 0.05) increased at that time (Figure 4). Creation of good aeration conditions and the consequent availability of O_2 is an important factor in microbial aerobic decomposition (Paul and Clark, 1996; Warrick, 2002). There is a strong correlation between RA and the percentage of macropores in soil. For example, Pagliai and Nobili (1993) showed that soil enzymatic activity was generally related to the size of the soil microbial population and that it was positively influenced by the number of pores, ranging from 30 to 200 μm. Finally, RA decreased to basic soil respiration at 180 days of incubation because of the decrease in available organic carbon and macropores (Figure 4).

Effect of SC and Incubation Time on Aggregate Stability

Due to both the sandy texture and low organic matter content (Table 1) of the examined soil (control), MWD and WAS (Figures 5 and 6) were very low. Granulation and porosity of soil crumbs can be easily destroyed by

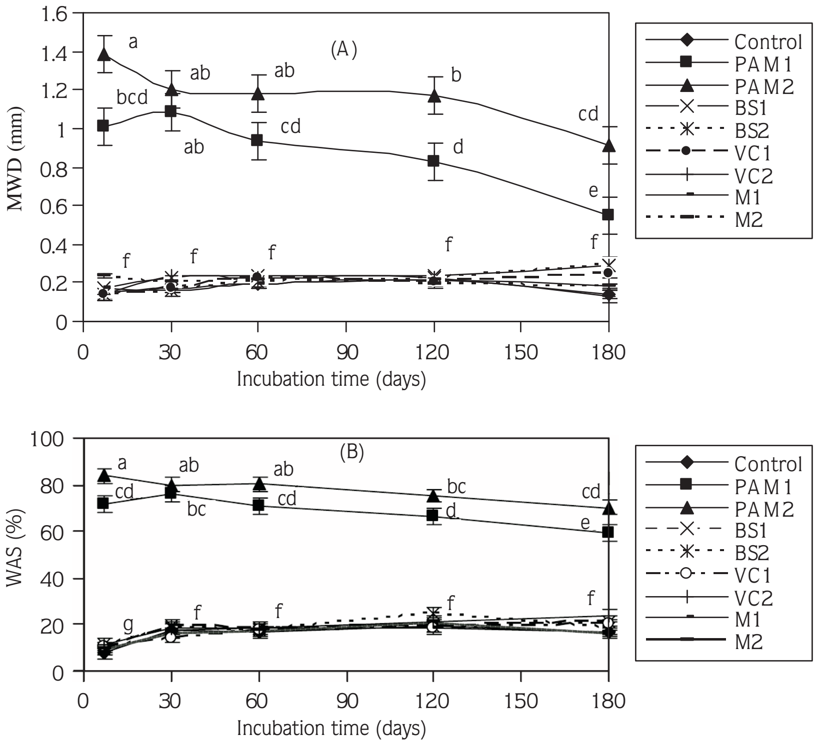

Figure 8. Interaction effects of the SCs at the 2 applied rates and incubation times on mean MWD (A) and WAS (B). PAM1, PAM2: 0.25 and 0.5 g of polyacrylamide; BS1, BS2: 1.7 and 3.4 g of biological sludge; VC1, VC2: 2.5 and 5 g of vermicompost; M1, M2: 12.5 and 25 g of manure (all rates are kg^{-1} of air-dried soil). Common letters in a column and row indicate no significant difference at $P \leq 0.05$ (Duncan's multiple range test).

water impact, due to the difficulty encountered by low organic compounds in binding together the large particles of sand. This condition was apparently further aggravated by the rapid decomposition of organic matter in our coarse-textured soil. Similar findings have been reported by Pagliai et al. (1981) and Sadegian et al. (2006).

Figures 5 and 6 show that PAM1 and PAM2 treatments (0.25 and 0.5 g of polyacrylamide kg^{-1} of air-dried soil, respectively) significantly ($P \leq 0.05$) increased MWD and WAS, as compared to the control, and is in agreement with the findings of several researchers, such as Bryan (1992), Levy and Miller (1999), and Nadler et al. (1996). Figure 7 shows that after 7 days of incubation WAS was significantly ($P \leq 0.05$) lower than at other incubation times, probably because of insufficient decomposition of SCs and release of binding compounds to enhance aggregation.

Interaction effects of SC and incubation time on MWD and WAS (Figure 8A and B) show that PAM1 and PAM2 treatments were able to keep these structural indices significantly ($P \leq 0.05$) high at all incubation times, indicating that this synthetic polymer was resistant to microbial breakdown and leaching. A recent study by Entry et al. (2008) showed that PAM degraded in soil at the rate of 9.8% $year^{-1}$ as a result of physical, chemical, biological, and photochemical processes. Evidently, the level of PAM by both generating stable aggregates (Figures 5 and 6) and inhibiting the surface seal was able to maintain saturated hydraulic conductivity (K_s) [not reported in this paper] at the optimal level, as compared to the control, during the 6 months of the study. Levy et al. (1992) showed that PAM, by cementing aggregates together, increased their resistance to water erosion and also significantly ($P \leq 0.05$) increased the final infiltration rate of both grumusol and loess soils. Other SCs (M, VC, and BS), probably because of their low application rates and/or the coarse-textured nature of the experimental soil (Table 1), rapidly decomposed and were not able to raise MWD or WAS, as compared to the control (Figures 5 and 6). The findings reported by Pagliai et al. (1981) also indicate that application of 50 t ha^{-1} of manure, sewage sludge, and compost on a sandy loam soil during 2 successive years did not significantly affect aggregate stability of 1-2-mm granules at different incubation times because of the coarse-textured nature of the examined soil.

Conclusion

In the present study application of 25 g kg^{-1} of cattle manure on sandy loam soil significantly ($P \leq 0.05$) increased the number of micropores and decreased the number of macropores, as compared with the control. It can therefore be used at that rate for increasing the water holding capacity of the examined soil. Application of PAM (0.25 and 0.5 g kg^{-1}) on this soil significantly ($P \leq 0.05$) improved the soil structure (MWD and WAS) and consequently prevented surface sealing for 6 months, as compared with the control. Although extensive use of PAM at field scale is currently limited by its high cost, even at relatively low rates, as applied in the current study, it might be recommended that application of PAM (0.25 g kg^{-1}) to soil adjacent to the root in row crops or even trees grown in greenhouses would drastically reduce the cost. To investigate in greater detail the effects of the applied SCs on the examined soil, field experiments must be carried out with other application rates and with combinations of SCs to determine if further improvements in soil structure and physical conditions occur.

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