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Comparison of thermal properties of three texturally different soils under two compaction levels

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A laboratory experiment was conducted with tree texturally different soils (Red loamy sand, Black clay soil and Alluvial sandy loam) in PVC columns maintaining at two bulk density levels to compare the thermal properties as influenced by texture, compaction and mineralogical composition of soils. Difference in peak soil temperature (ST) between surface and 20 cm soil layer reduced by 50% or more with increase in compaction level. Monitoring of ST at hourly interval on different days after saturation showed the highest magnitudes of ST at all depths throughout the day in black clay soil and the lowest in alluvial sandy loam soils. Magnitude of volumetric heat capacity (C_V) was in the order: Black clay soil (2.25-2.65 × 10^6Jm^{-3}K^{-1}) >alluvial sandy loam soil (1.85-2.27 × 10^6 Jm^{-3}K^{-1})>red loamy sand soil (1.79-2.22 × 10^6 Jm^{-3}K^{-1}). Magnitude of thermal diffusivity (D) was in the order: black clay soil (1.73-5.33m^{2}sec^{-1}x 10^{-6}) >alluvial sandy loam soil (1.04-3.39 m^{2}s^{-1} × 10^{-6})>red loamy sand soil (0.84-2.36 m^{2}s^{-1} × 10^{-6}). The range of thermal conductivity (K) for was highest for black soil followed by alluvial sandy loam and red loamy sand soil. Thermal properties were the highest for black clay soil followed by alluvial sandy loam soil and were the lowest in red loamy sand soil. In all soil types, C_v and K were higher in compacted soil as compare to loose soil. Hence, downward heat flux was more in compacted soil. The black color of the clay soil might have exerted added effects on the increase in the temperature because of more heat absorption whereas the moderating effect of higher moisture on ST was not prominent. Whereas in lighter colour alluvial soil due to moderating effect of soil water on ST would lead to the reduction evaporational losses and improvement in water use efficiency of crop.

Key words: Soil temperature, thermal conductivity, compaction, soil texture, damping depth.

INTRODUCTION

Soil thermal properties are required in many areas of engineering, agronomy, and soil science, and in recent years considerable effort has gone into developing techniques to determine these properties. Seed germination, seedling emergence, and subsequent stand establishment are influenced by the microclimate. Thermal properties of soils play an important role in influencing microclimate (Ghuman and Lal, 1985). The thermal properties of a soil depend on several factors. These factors can be arranged into two broad groups: those which are inherent to the soil itself, and those which can be managed or controlled, at least to a certain extent, by human management. Those factors or properties that are inherent to the soil itself include the texture and mineralogical composition of the soil (Wierenga et al., 1969). The thermal conductivity of the soil media is highly affected by texture, mineralogical composition and organic matter content that are inherent to the porous media, and by more variable factors including water content, temperature, and porosity, as well as by gas,

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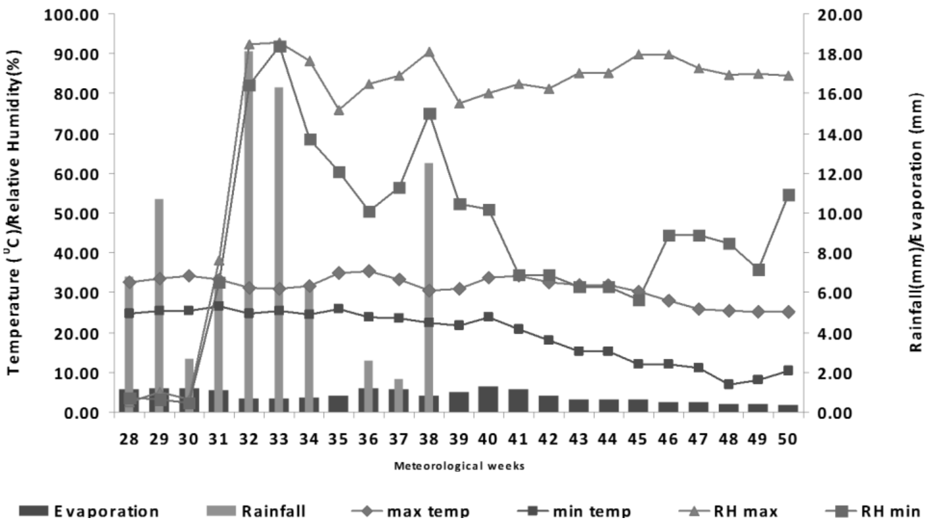

Figure 1. Weekly meteorological data during the study period.

pressure and water vapour content (Steiner and Komle 1991; Tarnawski and Leong, 2000; Ochsner et al., 2001; Abu-Hamdeh, 2003; Evett et al., 2012). The ground surface gets heated more during the day by intense solar radiation than the layers beneath, resulting in temperature gradient between the surface and subsoil on the one hand and surface and air layers near the ground on the other. Within the soil this causes heat flow downward as a thermal wave, the amplitude of which changes with depth. Estimation of heat flux from the soil temperature data can provide an understanding of the gain or loss of heat by the soil from the atmosphere (Chacko and Renuka, 2002). Factors influencing a soil's thermal conductivity that can be managed externally include water content and soil compaction (Yadav and Saxena, 1973, Abu-Hamdeh, 2003). Water content plays a major role in a soil's thermal conductivity. Water content is also the most difficult to manage. The way a soil is managed will play an important part in determining its thermal conductivity (Aggarwal et al., 2009; Maity and Aggarwal, 2012). Any practice or process, which tends to cause soil compaction will increase bulk density and decrease porosity of a soil. This in turn will have a significant effect on thermal conductivity.

However, very limited literature has been found on comparative study of thermal properties of soils with different minerological composition and texture. Hence, an attempt was to study the thermal behavior of red sandy loam (kaolinite as dominant mineral), black clay loam (smectite as dominant mineral) and alluvial sandy loam soil (illite as dominant mineral). At different compaction levels such information about thermal properties is required for modeling energy, water and nutrient movement in soils. Besides, soil thermal properties also control microclimate which influences seed germination, seedling emergence, root growth and crop establishment.

MATERIALS AND METHODS

A laboratory experiment was conducted at advance soil physical laboratory of Indian Agricultural Research Institute, New Delhi, India to compare different thermal properties of soils with different texture and mineralogical composition in PVC columns of 11 cm diameter and 30 cm length. Three different types of soil namely Red loamy sand (Ustic Paleustalfs), Black clay soil (Typic Haplustert) and Alluvial sandy loam (Typic Haplustept) were collected from sub-centre of All India Soil and Land Use Survey, Hyderabad, Andra Pradesh, India (17°18’42” N, 78°23’24” E); main research farm of National Bureau of Soil Survey and Land Use Planning, Nagpur, Maharashtra (21°9’10” N, 79°1’32” E) India and main block, 4C of research farm of Indian Agricultural Research Institute, New Delhi, India (28°22’48” N, 77°12’0” E), respectively. Two compaction levels were fixed, that is, loose condition (1.25 Mg m^{-3} BD for red and alluvial soil and 1.2 Mg m^{-3} for black soil) and compacted condition (1.6 mg m^{-3} for red and alluvial soil and 1.4 Mg m^{-3} for black soil) to compare the effect of compaction and soil water contents on the soil thermal properties of soils. Three replications were used and total number of columns was 18. The columns were saturated and were kept in the field before taking the observations.

The maximum temperature during the study period varied between 31.84 and 25.26°C and minimum temperature varied between 15.27 and 6.86°C (Figure 1). No rainfall occurred during the study period. The range of maximum relative humidity varied from 85 to 90% and the minimum relative humidity was from 30 to 55%. The value of bright sunshine hours (BSS) range was from 0.69 to 6.76. Daily evaporation rate varied between 1.80 and 3.23 mm day^{-1}. The data on mineralogical compositions of soil and other characteristics were collected from records of the respective research farm (Table 1).

The top 15 cm of soils collected from the field was air-dried and ground to pass through 2 mm sieve. Before filling the soils, PVC columns were closed at the bottom end by putting cotton cloth bags. Air dry soils were filled in columns in 3 to 4 cm thick layers and was then compacted by applying appropriate blows of hammer (5 kg mass and diameter slightly less than the diameter of the columns) to get the desired BD levels. For obtaining 100% saturation levels, soil columns were wetted by applying 5 cm of water at regular interval on the surface daily for 3 to 4 days till adequate amount of leachate at the bottom was collected.

Soil temperature from each treatment at 0, 5, 10, 15 and 20 cm were recorded at hourly interval from 10 AM to 7 PM by using digital

Table 1. Collection sites and properties of Alluvial, Red and Black soil.

Properties		Alluvial soil	Red soil	Black soil
Collection site		**MB 4C, IARI, New Delhi**	**Research farm ,Sub-centre of AIS and LUS, Hyderabad (AP)**	**Research farm, NBSSLUP, Nagpur (MAH.)**
Temperature (°C)		15-40	25-42.5	20-42.5
Rainfall (cm)		100-150	50-100	60-140
Clay (%)	Smectite	< 50	Negligible	50-80
	Illite	<30	20-30	<20
	Kaolinite	<20	40-60	<10
Texture		Sandy loam	sandy	Clayey
CEC cmolc kg^{-1}		30	<20	30-50
Organic carbon		<0.5	<0.7	0.5-1.1
Depth (cm)		150	25-40	30-150

Table 2. Soil water content of different soils under two BD levels.

Soil types	BD (Mg m^{-3})	SWC (%)					
		2 DAS		6 DAS		12 DAS	
		0-10	10-20	0-10	10-20	0-10	10-20
Alluvial soil	1.25	22.64	22.73	14.85	16.79	9.64	11.78
	1.6	16.99	17.43	15.32	16.75	8.76	11.73
Red soil	1.25	21.77	22.58	13.92	13.32	8.65	9.27
	1.6	14.31	17.42	10.11	11.40	9.54	10.12
Black soil	1.2	33.01	36.15	23.29	30.91	21.89	22.12
	1.4	30.12	29.33	26.04	27.32	24.70	25.33

thermometer. The soil temperature was recorded at saturation, second day after saturation (2 DAS), 6 days after saturation (6 DAS) and 12 days after saturation (12 DAS). Soil moisture content was determined gravimetrically. Volumetric heat capacity (C_v) (de Vries, 1975), thermal diffusivity (D) (Jackson and Kirkham, 1958), thermal conductivity (K) (Jackson and Kirkham, 1958), soil heat flux (G) due to conduction under steady state (Kirkham and Power, 1972) and damping depth (D_{damp}) (Kirkham and Power, 1972) were computed.

RESULTS AND DISCUSSION

Table 2 showed the average moisture contents of alluvial sandy loam, red loamy sand and black clay soils under two bulk density levels. At 2 days after saturation (2 DAS) 0-10 and 10-20 cm layers of alluvial soil with BD of 1.25 mg m^{-3} contained higher SWC (w/w) (22.64 and 22.73%) than alluvial soil with BD of 1.6 mg m^{-3} (16.99 and 17.43%). Similarly, 0-10 and 10 to 20 cm layers of Red with BD of 1.25 mg m^{-3} contained higher SWC (w/w) (21.77 and 22.58%) than red soil with BD of 1.6 mg m^{-3} (14.31 and 17.42%). Whereas, for 0-10 and 10-20 cm layers of black soil, the reduction in SWC with increase in BD were relatively less (33.01 and 36.15% for BD 1.2 Mg m^{-3} and 30.12 and 29.33% for BD of 1.4 mg m^{-3}). Irrespective of BD levels, the average moisture content was highest in black soil, followed by alluvial soil and was lowest in red soil. It was mainly because black soil was fine, alluvial soil was medium and red soil was coarse in texture while black soil had maximum amount of smectite clay minerals. The effect of texture on the thermal conductivity was clearly demonstrated in previous laboratory experiments indicating that the addition of only a few percent of wax cement to organic granular materials (Seiferlin et al., 2003) or organic matter to mineral soil samples (Rovdan and Usowicz, 2002) causes significant change in the thermal conductivity. In general, the thermal conductivities of wet porous particle packed beds increase with increasing temperature in contrast to the behaviour of dry beds (Blumberg and Schlunder, 1995; Bussing and Bart, 1997). Results also revealed that compacted soil contained less moisture throughout the depth as compare to the loose soil. With passage of time, the magnitude of SWC decreased but the trend among the various soil types and compaction levels remained same.

Results of experiment revealed that throughout the study period, in all soil types the difference in peak ST between 0 and 20 cm soil layer reduced by 50% or more with increase in compaction level (Tables 3 and 4).

Table 3. Arrival of peak temperature at surface and 20 cm soil depth for red, black and alluvial soil (2 DAS)

Soil types	BD (Mg m^{-3})	Depth (cm)	Second day after saturation (2 DAS)			
			Time (h)			
			13:00	14:00	15:00	16:00
Red soil	1.25	0	29.1	29.4	29.1	25.5
		20	21.3	20.8	21.1	21.3
	1.6	0	30.1	31.6	29.5	25.7
		20	29.2	29.4	30.2	29.1
Black soil	1.2	0	30.3	31.7	30.1	25.7
		20	24.3	25.4	26.1	25.5
	1.4	0	29.9	33.2	32.3	26.8
		20	32.2	31.9	32.8	32
Alluvial soil	1.25	0	31.4	29.5	29.2	27.7
		20	22.3	23.0	23.1	23.4
	1.6	0	25.8	26.5	28.9	24.8
		20	23	23.9	24.4	24.2

Table 4. Arrival of peak temperature at surface and 20 cm soil depth for red, black and alluvial soil (6 DAS).

Soil types	BD (Mg m^{-3})	Depth (cm)	Sixth day after saturation (6 DAS)			
			Time (h)			
			13:00	14:00	15:00	16:00
Red soil	1.25	0	23.1	25.5	23.4	24.1
		20	17.9	20.8	21.3	21.8
	1.6	0	24	25.4	24.2	23.6
		20	18.7	23.9	24	22.6
Black soil	1.2	0	24.1	26.2	25	24.1
		20	19.2	22.5	23.2	23.6
	1.4	0	24.3	26.5	25	25
		20	19.8	24.8	24.3	24.6
Alluvial soil	1.25	0	25	23.9	22.5	24.3
		20	18.9	20.5	20.9	21.4
	1.6	0	24.6	23.5	22.3	22.1
		20	19.5	22	22.1	22.2

However, the average temperature gradients were in the order red soil (0.275°C cm^{-1}) > alluvial soil (0.223°C cm^{-1}) > black soil (0.183°C cm^{-1}). Monitoring of ST at hourly interval just after saturation and second day after saturation (2DAS) of the columns showed highest magnitudes of ST at all depths all throughout the day in black soil followed by red and lowest in alluvial soils (Figures 2 to 5). At 2 DAS in comparison to maximum air temperature (26.6°C), average ST at 14:00 h was 3-5, 5-6.6 and 2.3-4°C higher in red, black and alluvial soils, respectively. In all soil types, average temperature of the soil profile again increased with increase in compaction level. At 12 DAS, again the black soil showed higher ST at all depths as compared to red and alluvial soils (Figure 6 and 7).

Volume fraction of red, black and alluvial soil for 0-20 cm of depth (Table 5) at 2 and 6 DAS showed that mineral fractions in loose soil were less as compare to compact soil. For loose soils, mineral fraction of red, black and alluvial soils were 0.47, 0.45 and 0.47,

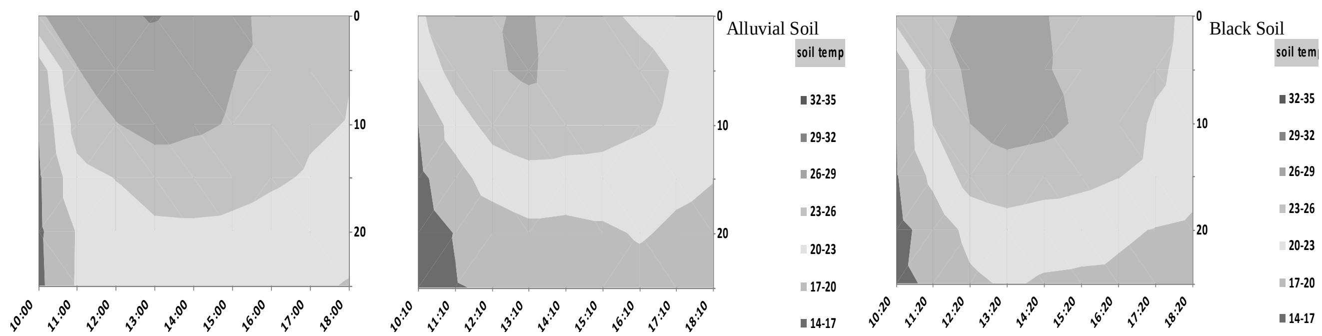

Figure 2. Hourly variation of soil temperature of different soils at saturation at loose condition.

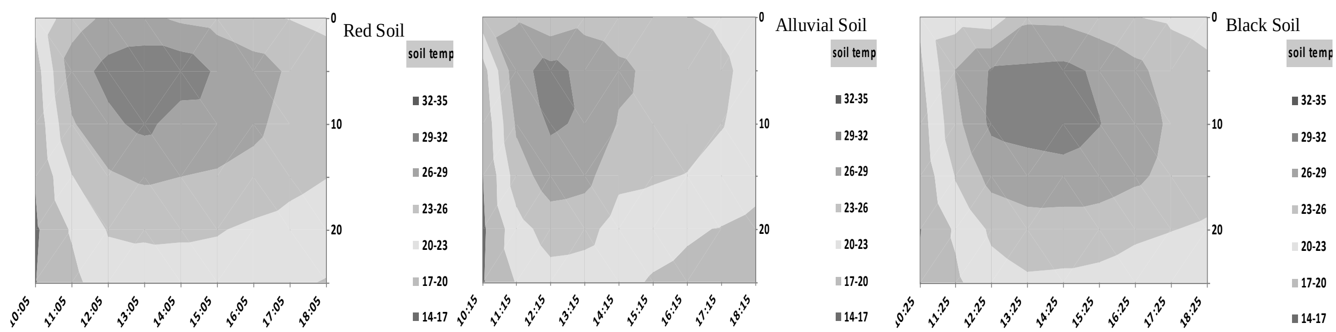

Figure 3. Hourly variation of soil temperature of different soils at saturation at compacted condition.

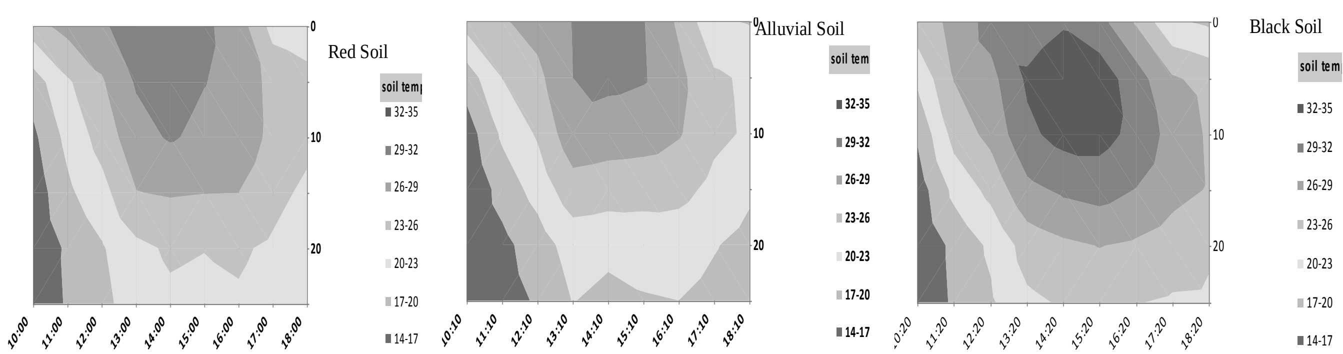

Figure 4. Hourly variation of soil temperature of different soils at 2DAS at loose condition.

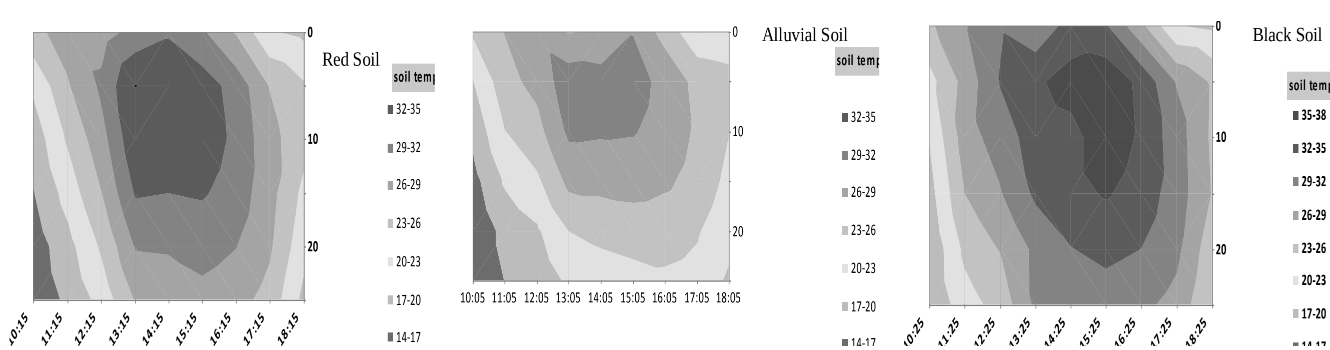

Figure 5. Hourly variation of soil temperature of different soils at 2DAS at compacted condition.

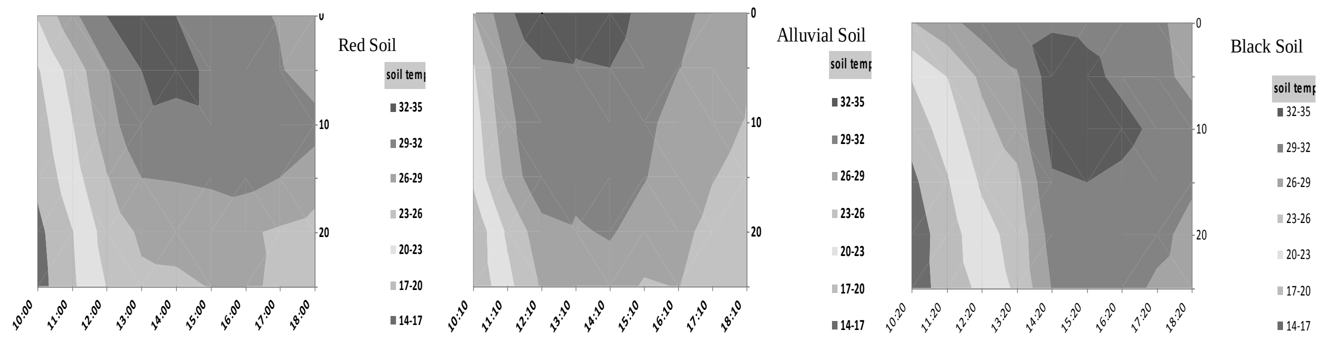

Figure 6. Hourly variation of soil temperature of different soils at 12 DAS at loose condition.

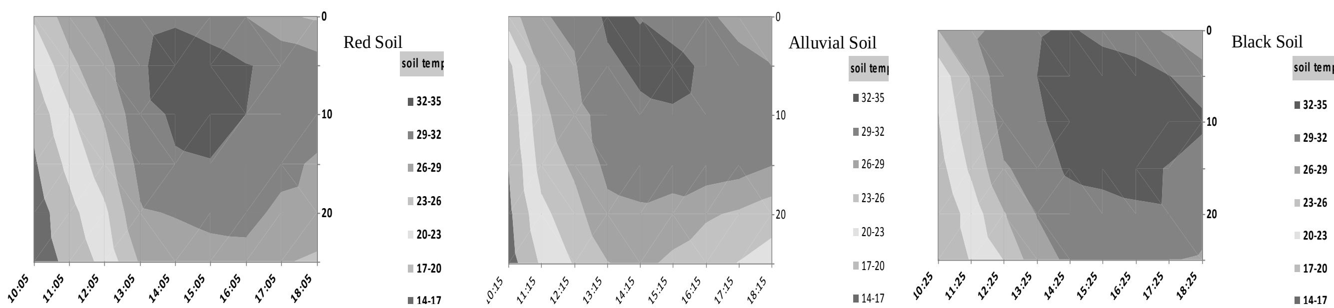

Figure 7. Hourly variation of soil temperature of different soils at 12 DAS at compacted condition.

Table 5. Volumetric compositions of 0-20 cm of Red, Black and Alluvial Soils

Soils	BD (Mg m^{-3})	f_w (2 DAS)	f_w (6DAS)	f_0	f_n
Red	1.25	0.269	0.197	0.009	0.472
	1.6	0.235	0.168	0.008	0.604
Black	1.2	0.407	0.311	0.013	0.453
	1.4	0.348	0.324	0.009	0.528
Alluvial	1.25	0.295	0.212	0.008	0.472
	1.6	0.248	0.185	0.007	0.604

respectively whereas for compacted soils, mineral fraction of red, black and alluvial soils were 0.60, 0.53 and 0.60, respectively. For all three soils under different BD levels, the volume fractions of organic matter were negligible. At 2DAS, volumetric water content (f_w) of loose red, black and alluvial soils were 0.0.269, 0.407 and 0.295, respectively, whereas at 6 DAS, f_w were 0.197, 0.311 and 0.212 for red, black and alluvial soils. Similarly for compacted soils, at 2DAS, f_w for red, black and alluvial soils were 0.235, 0.348 and 0.248, respectively, whereas at 6 DAS, f_w were 0.168, 0.324 and 0.185 for red, black and alluvial soils. Results thus clearly indicated that f_w was higher in black soil as compared to alluvial and red soils at both DAS and compaction levels.

Volume fractions of porous media are significantly influenced by cementation or compaction and associated increase in density (Lipiec and Hatano, 2003). Cementation can be a very effective process to increase the thermal conductivity and thermal inertia of porous media, like soil (Usowicz et al., 1996; Guerif et al., 2001), dust and regolith (Seiferlin et al., 2003). This increase is ascribed to mostly greater contact between the primary particles. The effect of soil density on thermal conductivity was more pronounced at high (field capacity or greater) than at medium soil water contents (Horn, 1994; Usowicz et al., 1996). It was earlier shown that aggregated soil, compared to disturbed soil, is characterized by greater heat flow irrespective of bulk

Table 6. Thermal properties of red, black, and alluvial soil.

Soil types	BD (Mgm^{-3})	Cv($10^6 \times Jm^{-3}K^{-1}$)		D ($m^2s^{-1} \times 10^{-6}$)		K($wm^{-1}K^{-1}$)		Damping depth (cm)	
		2 DAS	6 DAS	2 DAS	6 DAS	2 DAS	6 DAS	2 DAS	6 DAS
Red	1.25	2.10	1.79	2.36	1.32	4.94	2.36	25.47	19.05
	1.6	2.21	1.93	1.73	0.84	3.82	1.62	21.81	15.19
Black	1.2	2.65	2.25	5.30	1.73	14.02	3.88	38.17	21.81
	1.4	2.54	2.44	3.39	2.35	8.61	5.73	30.53	25.42
Alluvial	1.25	2.20	1.85	3.39	1.53	7.46	2.83	30.53	20.51
	1.6	2.27	2.00	2.35	1.04	5.32	2.08	25.42	16.91

Table 7. Heat flux (due to conduction) of red, black and alluvial soils at loose condition.

Soil	Depth (cm)	Time (h)								
		10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Red soil	0	24.4	25.7	27.1	29.1	29.4	29.1	25.5	20.6	19.8
	20	13.7	16.2	18.6	21.3	21.2	21.1	21.3	20.2	19.1
Heat flux (watt m^{-2})		-2.64	-2.35	-2.10	-1.93	-2.03	-1.98	-1.04	-0.10	-0.17
Alluvial soil	0	24.7	27.1	28.3	31.4	29.5	29.5	27.7	22	20.8
	20	14.7	17.5	19.7	22.3	23.4	23.1	23.4	22.5	20.3
Heat flux (watt m^{-2})		-3.73	-3.58	-3.21	-3.39	-2.28	-2.39	-1.60	0.19	-0.19
Black soil	0	24.9	26.5	30.4	30.3	31.7	30.1	25.7	20.5	19.6
	20	14.3	17.8	20.5	24.3	25.4	26.1	25.5	24.5	23.4
Heat flux (watt m^{-2})		-7.43	-6.10	-6.94	-4.21	-4.42	-2.80	-0.14	2.80	2.66

density (Turk et al., 1991). Computation of thermal properties of red, black and alluvial soils (Table 6) showed that on both 2 and 6 DAS, in all three soil types, most of the times, magnitudes of C_V were lower for loose than for compacted soils. Although f_w was found to be lower in compacted soil but because of the increase in mineral fraction, $\mathbf{C}_V$ became higher in compacted in comparison to loose soil. Among soil types, the magnitude of C_V was in the order: black soil (2.25-2.65 x $10^6 Jm^{-3}K^{-1}$) >alluvial soil (1.85-2.27× 10^6 $Jm^{-3}K^{-1}$)>red soil (1.79-2.22×10^6 $Jm^{-3}K^{-1}$).

In general, diffusivity (D) decreased with passage of time because of decrease in SWC. Again, in all soil types, on both 2 and 6 DAS, the computed thermal diffusivity was found to be higher in loose soil as compared to compacted soil. It could be mainly because of higher moisture content in the former. Similar to C_V, magnitude of D followed the same order: black soil (1.73-5.33 m^2s^{-1}× 10^{-6}) >alluvial soil (1.04-3.39 m^2s^{-1} × 10^{-6})>red soil (0.84-2.36 m^2s^{-1} × 10^{-6}). The computed K values followed same trends as D and C_V. The range of K for red, black and alluvial soils were 1.62-4.94, 3.88-14.02 and 2.08-7.46 $wm^{-1}K^{-1}$, respectively. The computed range of damping depth was 15-25 cm for red soil, 21-38 cm for black soil and 17- 31 cm for the alluvial soil. Heat flux in the soil profile was calculated for all the three soils at both loose and compacted soil on 2 DAS (Tables 7 and 8). The result revealed that heat flux was observed maximum in black, followed by red soil and least in alluvial soil. The negative values of heat flux during daytime implied the downward movement of heat and the positive values of heat flux during the late hours of the day implied the upward movement of heat.

Combining the results of variation in ST and variation in soil thermal properties, it is evident that higher magnitude of ST in red soil as compared to alluvial soil is due to lower SWC and lower C_V of red soil which resulted in more increase in temperature for the same supply of heat on the surface. The other reason for higher temperatures in red soil is mainly because of color effect, that is, the red color absorbs more heat than light brown color of the alluvial soils. Black soil, which had highest SWC lead to highest magnitude of C_V, had also shown highest increase in temperature. This is probably due to more absorption of heat by black soil surface as compared to the red and the alluvial soils. Here, the effect of the black color has more dominating effect on increase in the temperature because of more heat absorption whereas the moderating effect of higher moisture on ST was not prominent. Another reason for variation in soil

Table 8. Heat flux (due to conduction) of red, black and alluvial soils at compact condition

Soil	Depth (cm)	Time (h)								
		10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Red soil	0	25.1	27.4	27.7	30.1	31.6	29.5	25.7	20.4	19.3
	20	15.4	19	23.4	29.2	29.4	30.2	29.1	26.5	21
Heat flux (watt m^{-2})		-3.11	-1.60	-0.82	-0.17	-0.42	0.13	0.65	1.17	0.32
Alluvial soil	0	23.5	26.1	27.7	25.8	26.5	28.9	24.8	20.9	20.1
	20	14.5	18	19.6	23	23.9	24.4	24.2	23.3	21.1
Heat flux (watt m^{-2})		-2.39	-2.15	-2.15	-0.74	-0.69	-1.20	-0.16	0.64	0.27
Black soil	0	25.5	28.8	31.7	29.9	33.2	32.3	26.8	20.2	19.4
	20	17.5	23.7	26.2	32.2	31.9	32.8	32	29.8	24.2
Heat flux (watt m^{-2})		-3.44	-2.20	-2.37	0.99	-0.56	0.22	2.24	4.13	2.07

temperature and thermal properties may be due to different mineralogical composition of soil and different organic matter content.

Particle size distribution is frequently used to estimate mineralogical composition, mainly quartz and other minerals that have dominating effect on the thermal conductivity. This estimation is justifiable since most sand fractions consist of quartz, but different forms of quartz can be characterized by different thermal conductivities (Usowicza et al., 2006). Therefore, measurements of mineralogical composition of porous media could improve the accuracy of soil thermal property measurement.

Conclusions

Thermal properties vary with soil texture, water content, mineralogical composition, and organic matter content. As revealed from our study, thermal properties were highest for black soil followed by alluvial soil and lowest for red soil. The effect of the black color as determined by mineralogical composition has more dominating effect on increase in the temperature because of more heat absorption whereas the moderating effect of higher moisture on ST was not prominent. These thermal properties affect the diurnal variation of temperature of the soil profile, which affect various soil physical and chemical processes such as evaporation from soil surface, rate of soil N mineralization, nitrification, oxidation of soil carbon etc which may influence crop production. Hence in depth study is needed for determining the effect of different clay and mineral fractions in modifying the soil temperature and thermal properties.

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