POLISH JOURNAL OF SOIL SCIENCE
VOL. LII/2 2019 PL ISSN 0079-2985

DOI: 10.17951/pjss/2019.52.2.277

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COFFEE GROUNDS AS A SOIL CONDITIONER: EFFECTS ON PHYSICAL AND MECHANICAL PROPERTIES – II. EFFECTS ON MECHANICAL PROPERTIES

Received: 20.03.2019
Accepted: 07.11.2019

Abstract. Applying coffee grounds (CG) to sandy, calcareous, and clayey soils resulted in notable effects on soil expansion, cracking, cohesion, internal friction, initial stress and resistance to penetration. In sand, expansion upon saturation was greater after wetting-and-drying cycles. Highest increases were 15.71%, 16.14% and 31.86% for sandy, calcareous and clayey soils, respectively. Effect of CG on cracking was negligible in sand and very slight (<1.0%) in the calcareous soil but marked in clay (14.18% at 10% CG). In sand, cohesion (*c*) increased significantly with CG up to the 10% content. Cohesion increased by 2.5-folds and 4.5-folds at 5% and 10% CG, respectively. The presence of fine CG grains among larger sand particles, boosted microbial activities, and the resulting cementing and binding effects resulted in increased cohesion. For calcareous soil, cohesion rose from 0.04 $kg \cdot cm^{-2}$ to 0.13 $kg \cdot cm^{-2}$ as CG increased from 0% to 15%. In clay, maximum cohesion (0.20 $kg \cdot cm^{-2}$) was associated with the 10% CG and was highest of all soils. In sand, the angle of internal friction (φ) decreased notably as CG increased from 5% to 10% but there was no consistent pattern in any of the soils. An increase in initial stress (p_i) was observed between 0% and 10% CG in sand and between 0% and 15% in calcareous soil while clay showed no particular trend. Patterns of p_i were, thus, consistent with those of cohesion for all soils. Resistance to penetration increased substantially with CG in sand. The effect in calcareous and clayey soils took an opposite trend to that of sand and resistance was generally higher in calcareous soil. Overall

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effects of CG on resistance were desirable in all soils as far as agriculture (seedling emergence, crop growth, irrigation, etc.) is concerned.

Keywords: coffee grounds, mechanical properties, soil amendments, soil conditioners

INTRODUCTION

The benefits of applying organic additives to soil have long been known (Hillel 1982, Marshall and Holmes 1988). Organic matter (OM) provides numerous physical, biological and chemical reactions in the soil and has a major role in the soil complex system in the formation of soil aggregates (Emerson 1959, Harris *et al*. 1966). The role played by microorganisms in improving aggregate formation was reported (Alexander 1977) as a function of the nutrient status of the soil substrate, among other factors. Aggregates formation and stability and soil structure improve with a number of factors (Emerson 1959, Harris *et al*. 1966, Kemper and Koch 1966), such as clay content, OM, free iron and aluminum oxides, calcium carbonates, and markedly decrease with soil exchangeable sodium content. Soil aggregation is favorable for better structure, water flow, soil water retention, and aeration. Thus, applying OM can improve many soils, sandy or clayey.

Recycling agricultural waste such as straws, stalks, rice husks, etc. provides sources of OM for increasing crop productivity. El-Torky and Bedaiwy (1998) used rice husk as a partial substitute of the expensive traditional medium components for producing high quality greenhouse and nursery crops. The same approach was used with other crops (Sharma *et al*. 1988, El-Torky and El-Shennawy 1995, Cerff *et al*. 1985, Sawan *et al*. 1986). Physical and mechanical characteristics of the soil are drastically affected by OM content (Henderson and Perry 1955, Tisdall and Oades 1982, Rolston *et al*. 1988, Sumner 2000). Favorable effects of OM and compost on sandy soils involve enhancing aggregate formation and water-stability, and boosting the water holding capacity. Soil condition of loamy and clayey soils also can be improved by organic substances through providing good aeration, better water infiltration and drainage. Physical and mechanical properties that are affected by organic materials include water holding capacity, water flow, evaporation, bulk density, structure and aggregate stability, swelling (expansion), cracking, soil consistency (plastic and liquid limits), cohesion, internal friction, resistance to penetration (strength), crusting, among several others.

In recent years, coffee grounds (CG) have been gaining attention as a potential organic amendment. Every year, hundreds of thousands of tons of used CG are discarded from households and restaurants. Many home owners and gardeners now use CG as an amendment for lawns and yards, realizing that they provide nitrogen, phosphorus, potassium, magnesium, and copper to the soil and the plants, besides improving the physical and mechanical properties of the soil. General observations and basic research in the U.S. (e.g. *Sunset*, 2009) indicated that an application of CG up to 35% by volume will improve soil structure. Pennsylvania State Cooperative Extension (2007) suggested that CG represent an excellent source of soil nutrition when mixed with other materials, acting as a green material with a carbon-nitrogen (C-N) ratio of approximately 20-1, which makes also an excellent addition to compost. According to the data of Pennsylvania State Cooperative Extension (2007), as well as of Feather (2008) and Soil and Plant Laboratory Inc. Bellevue, WA (*Sunset*, 2009), CG are rich in nitrogen (1.45%–2.28%) and have considerable concentrations of phosphorous (0.06%–0.30%), potassium (0.12%–0.60%), calcium (0.039%) and magnesium (0.045%).

The work presented in this article is a part of a study directed at examining the effects of CG on some of the basic physical and mechanical properties that could influence soil condition and productivity. The effects of applying CG to the soil on physical properties were discussed in the previous paper (Bedaiwy *et al*. 2018). In this article, effects of applying CG to three soils, sandy, calcareous and clayey soils on the soils' basic mechanical characteristics are presented. Examined mechanical properties include swelling (linear expansion), cracking, soil cohesion, internal friction, initial stress, and soil resistance to penetration (soil strength).

MATERIALS AND METHODS

Soils: Three typical Egyptian soils known to have different physical, hydro-physical, mechanical and fertility properties were tested in this work: 1) sandy soil from the desert west of the Delta (Bustan area); 2) calcareous soil (sandy clay loam texture) from south east of Alexandria (North Tahrir area); and 3) clayey soil from the center of the Delta (Kafr El-Zayat area). Soil samples were dried and processed according to standard methodologies. Soil was passed through a no. 4 (4.75 mm) sieve.

Coffee grounds (CG): CG were obtained through arrangements with major chain coffee shops (Starbucks Coffee® and Costa Coffee® chains) in Alexandria, Egypt.

Soil treatments: CG were applied to soils at rates of 5%, 10%, and 15% by volume, in addition to a control. Experiments were done in two to three replications.

Wetting-and-drying cycles (WDC): Two sets of measurements were made: One shortly (approximately one week) after CG were applied, and another after approximately seven months of wetting-and-drying cycles. For the before-WDC treatments, treated soils were wetted to field capacity one time then allowed to dry in open air before measurements were made.

Chemical analysis: Chemical analysis of the test soils was performed according to Page (1982), total calcium carbonate content, $CaCO_3$%, by volumetric calcimeter method, soil organic matter, OM according to Black (1965).

Physical and mechanical properties: Treated soils were packed into tin pots, 20 cm in diameter and 20 cm high. For soil expansion and cracking experiments, cylinders, 5.6 in diameter and 7 cm high, were used. Packing was performed such that each soil type maintained as closely as possible the same dry bulk density (γ_d). Pertinent physical characteristics of the test soil and coffee grounds were done based on standard methods (Klute 1986). Mechanical properties addressed in this work include: soil swelling (linear expansion), cracking, soil cohesion, coefficient and angle of internal friction, initial stress, soil strength (resistance to penetration).

I. Swelling (linear expansion)

Swelling was determined by measuring the linear expansion upon saturation. Before each of the two determinations (before and after WDC) samples were allowed to saturate by capillarity and the maximum expansion was recorded. Linear expansion was calculated as the relative change (%) in soil column length. That is:

$$\varepsilon = (\Delta L/L) \times 100 \qquad (1)$$

Where: ε is relative linear expansion (%), ΔL is the increase in soil column height, and L is the original soil column height.

II. Cracking

Cracking was determined by calculating the area of cracks at the surface of soil samples. Determinations were made after WDC. The area of cracks was related to the total area, and cracking was expressed as percentage. Measuring the area of cracks was performed using the AutoCAD software (2012).

III. Shear tests – soil cohesion, internal friction angle (φ) and coefficient (tan φ), and initial stress (p_i)

Direct shear tests were used to determine soil cohesion, angle and coefficient of internal friction, and initial stress of the soils. Tests were performed on soil samples taken from the tin pots after WDC. Standard mechanical shear test apparatus was used. Soil samples were saturated and placed in the water-filled shear box for every test. Readings were taken on the proving ring against three successive loads in each test. Shear stress (τ) was determined and graphical plots were constructed between normal stresses ($\sigma_{n\ eff}$) and shear stresses. Soil cohesion (c), internal friction angle (φ) and coefficient ($\tan\varphi$), and initial stress (p_i) were determined graphically from $\sigma_{n\ eff}$-τ graphs.

IV. Soil strength (resistance to external forces or resistance to penetration)

Soil strength was determined using a spring penetrometer (SoilTest® unconfined strength spring penetrometer model ci 700). Resistance (measured as pressure $kg\cdot cm^{-2}$) was determined throughout the experiment and was related to water content. Average of five penetrations was taken for every reading.

RESULTS AND DISCUSSION

Basic physical and chemical properties of the three test soils are presented in Table 1. Physical and chemical properties of CG are shown in Tables 2a and 2b, respectively.

Table 1. Some pertinent properties of experimental soils

Soil		Sand	Calcareous	Clay
Particle-size analysis	Sand, %	96.12	56.53	32.90
	Silt, %	2.25	14.27	22.06
	Clay, %	1.63	29.19	45.04
Soil texture designation		Sand	Sandy clay loam	Clay
Dry density, γ_d, Mg/m^{-3}		1.83	1.16	1.21
Saturated hydraulic conductivity, K_s, cm/min		0.814	0.044	0.005
EC, dS/m^{-1}		5.08	2.67	3.81
pH		7.68	8.22	7.56
Sodium adsorption ratio, SAR		5.3	4.3	2.5

Table 2a. Some pertinent physical properties of the coffee grounds

Air-dry moisture content, $\theta_{air\text{-}dry}$, %	Saturation percent, θ_{sat}, %	Mean weight diameter MWD, mm	Geometric mean diameter, GMD, mm	Unit weight, $\gamma_{air\text{-}dry}$, Mg/m^{-3} (Range measured) min.	max
7.15	≈175–250	0.519	0.996	0.41	0.77

Table 2b. Basic pertinent chemical properties of the used coffee grounds

EC (dS/m^{-1})	Cations, % pH	Ca^{++}	Mg^{++}	Na^{+}	N, %	P, %	K, %	Fe, ppm	Zn, ppm	Mn, ppm	Cu, ppm	OM, %
3.19	5.91	1.0	0.2	0.1	2.24	0.15	0.47	70.6	11.9	24.5	22.2	78.4

I. Linear expansion (swelling)

Linear expansion was determined as an indicative of the change in the ability of soil to absorb water and swell. Before WDC, applying CG to the three soils resulted in marked increase in the size of soil samples upon saturation (Fig. 1). While soil type had the main role in the expansion process, the rate of CG applied also has an obvious effect. Over tested range of CG, linear expansion pattern for sand followed a polynomial function ($r^2 = 0.999$) of the form $y = ax^2 + bx + c$, while calcareous and clayey soils fitted exponential functions of the form $y = ae^{bx}$, where y is the relative rate of linear expansion, and x is CG rate, with $r^2 = 0.90$ and 0.99 for the calcareous and clayey soils, respectively. As seen in Fig. 1, while sand showed 0% expansion in its normal (untreated) conditions, its response to CG was high. CG is an organic matter with a high surface area. Hence, this high response of sand indicates that the water holding capacity of sand improved significantly with CG, which is obviously a favorable effect from an agricultural viewpoint.

At the end of WDC, different soils maintained the same trends as before WDC (Fig. 1). In sand, relative linear expansion markedly increased from 0% to 15.71% as CG rate increased from 0% to 15%. Water holding capacity and the formation of soil aggregates are both expected to improve as a result of the presence of the organic CG. This is an advantageous effect in sand. Moreover, as the soil expands, its apparent density (both wet and dry densities) decreases, which means – broadly speaking – a more open soil system. Plant roots benefit from such environment, where flow of water and air are adequate.

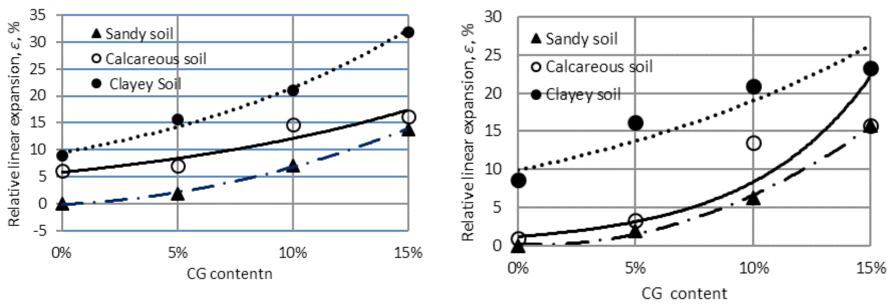


Fig. 1. Rate of linear expansion (ε) in the tested soils in response to different rates of CG before WDC (left) and after WDC (right)

Apparently, the soil benefited more of the CG application at the 15% rate after WDC (an increase of 15.71% in linear expansion in comparison with 13.86% before WDC). Microorganisms' activities were quite notable with time as the soil underwent WDC (Bedaiwy *et al.* 2018). Microbial activities were enhanced by the application of the organic CG, and this boosted the process of aggregate formation over the extended interval of the WDC.

Trend in the case of the calcareous soil at the end of WDC was essentially similar to that seen before wetting and drying. The clayey soil showed very marked response to the application of CG. Expansion was substantial – ranging from 16.19% at 5% to 23.33% at 15% CG rate. Corresponding values determined prior to WDC were 15.71% to 31.8%. The response at the 15% was noticeable. Before WDC, the expansion associated with 15% CG rate was higher than after WDC. This is consistent with results obtained previously (Bedaiwy *et al*. 2018). During the processes of successive cycles of wetting and drying, some of the applied CG are washed out with drainage water. Results reiterate the suggestion that the optimum application rate of CG for clays lies – most likely – between 10% and 15%.

II. Soil cracking

Soil cracking is an important mechanical characteristic. Cracks provide large paths that supply greater depths of soil profile with air and water, particularly in heavy, fine textured soils. Cracking usually takes place in clayey soils, mainly soils rich in readily-expanding clay minerals such as montmorillonite. When these soils are wet, they become extremely cohesive and massive and their conductance to water and their drainage capability become very poor. Air flow also decreases. This happens mainly due to swelling caused by water absorption within mineral lattices. Adequate drainage and air flow are necessary for proper plant root functions and good plant growth. As the soil dries out, it shrinks once again and soil matrix starts to split apart and crack. This means that cracking happens in the types of soil where it is needed most. In this work, cracking was examined after seven months of WDC. Cracking was measured as a percentage of the total soil surface area. Expectedly, cracking in sand was negligible even under the highest rate of applied CG (Fig. 2). Apparently, the very high frictional characteristic of sand stays dominant and prevents cracking even at high CG rates. Sandy soils are generally highly frictional, low-to-non-cohesive soils. Cohesion and internal friction characteristics of the experimental soils are discussed in the following section.

The calcareous soil showed very slight cracking (Fig. 2). At 0% and 5% CG, cracking was negligible. At higher rates (10% and 15%) some minor cracking was seen, and the developing cracks were very thin. Cracking percentages were < 1% for both 10% and 15% CG contents. The calcareous soil used in this work had a medium texture (sandy clay loam, Table 1), which means that it has a significant content of fine particles (silt- and clay-size fractions). These fine particles are expected to have cohesive characteristics that are manifested in some swelling and cracking. This is boosted by added CG which contains significant amount of fine particles.

Highest cracking was seen in clay (Fig. 2). Clayey soil showed substantial cracking under all CG rates. Cracking percentages determined for the clayey soil were as high as 14.18% (at 10% CG) as shown in Table 3. Apparently, the improvement in soil aggregation induced by CG boosted the cracking process. Again, the clayey soil responded favorably up to the rate of 10% then the trend was reversed. This was explained before as due to the loss of some of the free CG with drainage water out of the soil system. Moreover, at this high rate of CG, it is quite likely that some of the excess CG could have resulted in some changes in the pore space sizes and geometry, especially with the extremely high water holding capacity of CG and the resulting swelling. Additionally, and as a result of the high water-holding capacity, fine particles of CG could still retain significant amounts of water even when the soil is air-dry past a wetting cycle. This high moisture would be reflected in the relative reduction in the susceptibility of the soil to cracking. Cracking percentage associated with the 15% CG rate was < that associated with the 10% rate (Table 3), but was still > that of the untreated soil. Examples of cracking cases for the three soils are shown in the photos in Fig. 2.

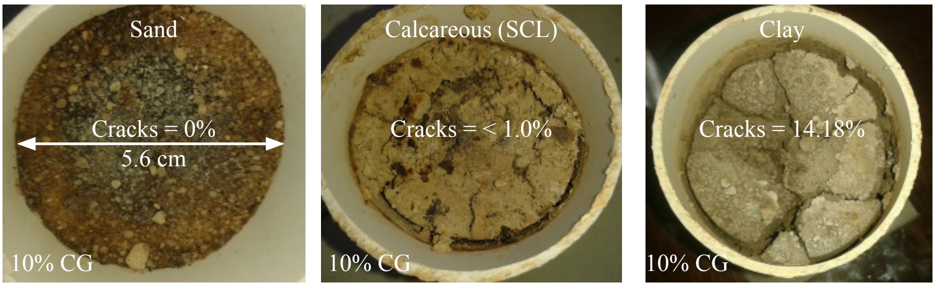


Fig. 2. Examples of cracking cases for the three soils (at 10% CG as an example)

Table 3. Effect of coffee ground application rate on soil cracking in sandy, calcareous (SCL) and clayey soils

CG application rate %, vol.	Cracks, percent of surface area		
	Sand	Calcareous (SCL)	Clay
0	0	0	6.16
5	0	0	7.74
10	0	<1.0	14.18
15	0	<1.0	7.57

III. Soil cohesion (c), angle and coefficient of internal friction (φ and tan φ), and initial stress (p_i)

Soil cohesion (c), internal friction angle (φ), internal friction coefficient (tan φ), and initial stress (p_i), are important soil mechanical properties. They define many of the properties that influence soil condition, and, thus, they have crucial impacts in agriculture and civil engineering. In agriculture, these properties determine how suitable the soil is as a medium for plant growth. Also, they determine how well the soil can be managed for different agronomic activities and practices as well as irrigation and drainage.

In this work, the three parameters (c, φ and p_i) were determined through direct shear tests. Soil shear strength indicates the resistance to deformation by continuous shear displacement of soil particles or *en masse* upon the action of a tangential (shear) stress. The shear strength of a soil is made up (Jumikis 1967) of: 1) the structural resistance to displacement of a soil because of the interlocking of the soil particles, 2) the frictional resistance to translocation between the individual soil particles at their contact points, and 3) cohesion (adhesion) between the surfaces of the soil particles.

Shear strength (τ), as represented by the τ-line on the graph in Fig. 3 is given analytically by the following straight-line equation, known as Coulomb's shear strength equation:

$$\tau = \sigma_{n\,eff} \tan \varphi + c \text{ (kg/cm}^2\text{)} \tag{2}$$

Where: the intercept c is the cohesion of the soil; the slope of the τ-line, tan φ, is termed the coefficient of internal friction of the soil; φ – angle of internal friction of the soil, and $\sigma_{n\,eff}$ – effective normal stress on the rupture plane.

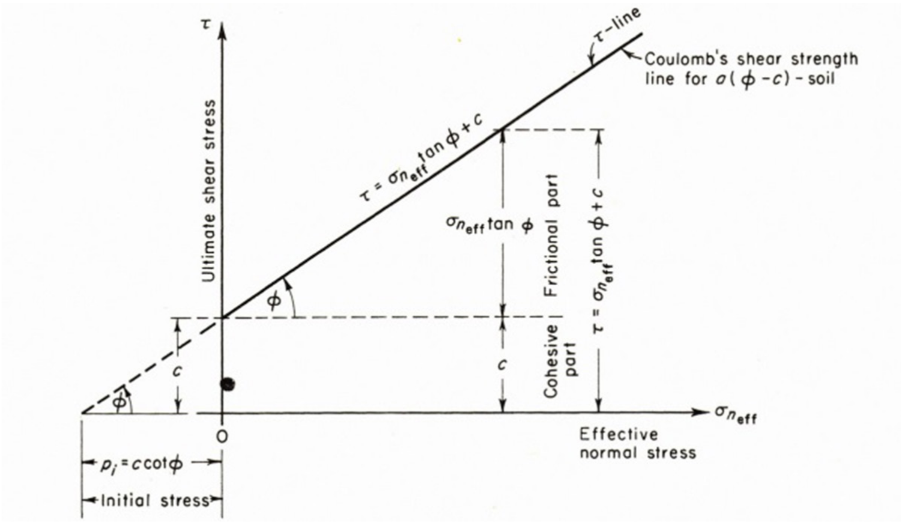


Fig. 3. Graphical representation of shear strength factors

Equation (2) shows that the shear strength τ of a frictional-cohesive soil varies as a straight line function of the applied effective, normal stress $\sigma_{n\,eff}$. The shear test is performed under an inundated condition to exclude from test results the effect of apparent cohesion (cohesion induced by capillary forces). Shear test (Fig. 3) produces shear stress-normal stress (τ-$\sigma_{n\ eff}$) graphs. The above parameters are determined from the graphs: The slope of the τ-$\sigma_{n\ eff}$ straight line is the tangent of the angle of internal friction or tan φ; the cutoff made by that line on the ordinate is the cohesion (c); and the cutoff made by the same line on the abscissa is the initial stress (p_i).

a. Soil cohesion, c

Table 4 displays the determined values of cohesion for different soils. In sand, soil cohesion (c) increased significantly with CG content up to the 10% rate. Cohesion increased by 2.5-folds and 4.5-folds as CG increased from 0% to 5% and 10%, respectively. The presence of fine CG grains among larger sand particles provides conditions of bonding of the latter, resulting in increased cohesion. Cohesion may thus be looked at as an indicative of the degree of aggregation of the sandy soil. After a long interval of WDC, bonding and aggregate formation increased and hence c increased. High cohesion here reflects also the degree of interlocking between soil particles. A major factor playing in aggregate formation is increased microbial activities during WDC interval, and the resulting binding effects.

At 15% CG, soil cohesion decreased. As discussed before, apparently, there is an optimum CG content where soil benefits most. This was suggested to be in the vicinity of 10%, or somewhere between 10% and 15%. Beyond this content, some excess or "free" CG is leached off out of the soil, and some of that excess CG remains in the soil but functions unfavorably due to its high retained moisture. Excessive moisture in CG weakens the binding process. As seen in Table 4, at 15% CG, sand has a substantially high water content of 19.35%, compared with 12.02% in untreated soil.

For calcareous soil, there was a clear response of cohesion to the content of CG. Cohesion rose progressively from 0.04 kg·cm^{-2} to 0.13 kg·cm^{-2} as CG increased from 0% to 15% (Table 4). Comparing with sand, although both soils had the same initial value of cohesion (0.04 kg·cm^{-2}), the response in sand was sharper over the 5% and 10% CG rates. Cohesion in sand increased markedly to 0.18 kg·cm^{-2} at 10% CG, exceeding the highest cohesion attained by the calcareous soil, which apparently indicates that, due to the nature of the sandy soil (being mainly frictional) it has high inclination to gain cohesion from CG and to benefit more readily from its application.

The effect of the applied rates of CG on cohesion of the clayey soil is presented in Table 4. Initial cohesion of the untreated soil was much greater than that of both the sandy and calcareous soils. Clayey soils are usually characterized by having the highest cohesion among all soils. The maximum cohesion attained under different CG rates is that associated with the 10% rate (0.20 kg·cm^{-2}), which is greater than the highest cohesion attained by both the sandy and calcareous soils. As with the sandy soil, the maximum cohesion in the clayey soil was associated with the 10% CG content. The reasons mentioned in previous discussions with regards to the 15% CG content appear to apply here as well. The excessive application of CG appears to result in a significant amount of “free” CG. This results in the loss of some of the applied CG in WDC, reiterating that for the clayey soil the optimum rate of coffee grounds lies in the area of 10% or somewhere between 10% and 15%. General trends of change in soil cohesion in response to CG are summed-up in Fig. 4.

b. Angle and coefficient of internal friction, φ and tan φ

The definition of the angle of internal friction (Swiss Standard SN 670 010b) is derived from the Mohr-Coulomb failure criterion and it is used to describe the friction shear resistance of soils together with the normal effective stress. In the stress plane of τ-$\sigma_{n\,eff}$, the soil friction angle is the angle of inclination with respect to the horizontal axis of the Mohr-Coulomb shear resistance line (Fig. 3). Internal friction (the resistance of a soil mass to sliding) is inversely related to the amount of moisture in the soil and thus greater in sands and gravel than clays. In this work, the angle of internal friction was obtained from the graphs generated from direct shear tests. Results are shown in Table 4. The response of internal friction of sand did not follow a clear pattern as the content of CG increased from 0% to 15%. However, an observation can be made comparing φ at the two low CG contents with φ at the two high contents. At 0% and 5% CG, φ did not change significantly (only by 1.5°, Table 4); similarly, between 10% and 15% CG, φ changed also very slightly (only by 1.1°). On the other hand, a marked decrease in φ (4.7°), and accordingly a decrease in the coefficient of internal friction, tan φ, were seen as CG content increased from 5% to 10%. This result supports the observation that the rate of 10% appears to represent some significant CG content. In this case, as φ of sand decreases, c is expected to increase. Increasing cohesion in sand is a favorable effect in agriculture as it provides better conditions for aggregate formation and structure development, and makes the soil easier to manage and more suitable for growing crops. The implications with regard to water holding and water flow in irrigation and drainage are also obvious.

In the calcareous soil, also no solid pattern could be detected. However, some decrease in φ did take place upon applying CG. As discussed in the previous section, cohesion of the calcareous soil showed a positive response (steady increase) to CG (Fig. 4). Although such trend is not seen with φ, a general conclusion can still be made that the calcareous soil did respond favorably to CG, based on increased cohesion.

No trend of change in φ was seen in the case of the clayey soil. Clays consist mainly of very fine, low friction particles and have very little sand content, and hence a substantially smaller internal friction angle in comparison with sandy and calcareous soils. Initial ϕ in clay was 8.8º (Table 4) compared with 30.7º and 22.1º for the sandy and calcareous soils, respectively. Internal friction remained lower than that of the other two soils for all CG contents. General trends of change in the angle of internal friction with CG for the three soils are presented in Fig. 5.

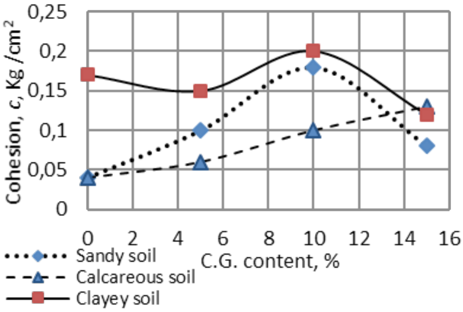


Fig. 4. Change in soil cohesion (c) in response to application rates of coffee grounds (CG) for the three soils

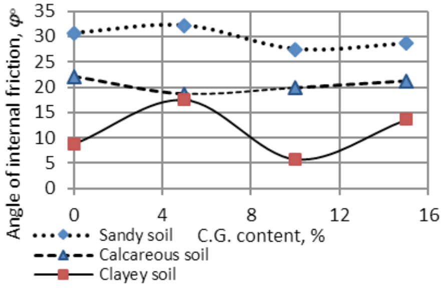


Fig. 5. Change in the angle of internal friction (φ) in response to application rates of coffee grounds (CG) for the three soils

c. Initial stress, p_i

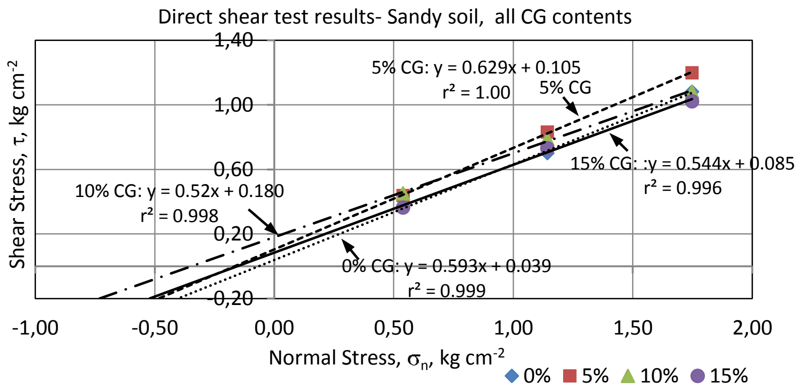
Initial stress (p_i) is the negative pressure brought about by capillary stresses (stresses induced by surface tension) in a cohesive soil. Initial stress is determined graphically from the $\sigma_{n\ eff}$-τ plots. It is represented by the cutoff, made on the normal-stress, $\sigma_{n\ eff}$ axis (the abscissa) by the τ-line (Fig. 3). Mathematically, the initial stress (p_i), is thus calculated as:

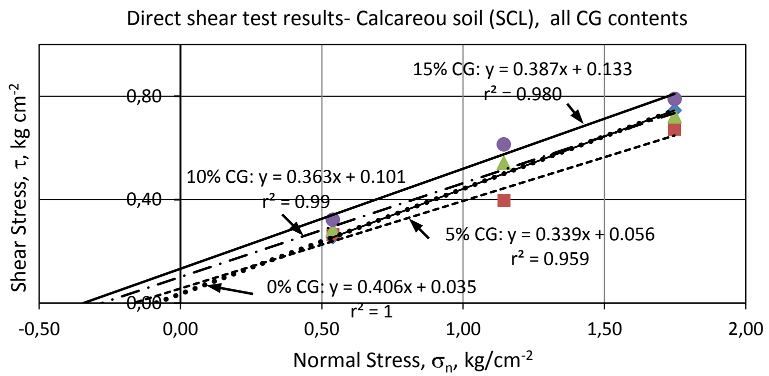
$$p_i = c \cot \varphi \tag{3}$$

As can be inferred from the graphs and from equation (3), the value of the initial stress (p_i) depends on both the cohesion and the angle of internal friction. For a given value of soil cohesion (c), the initial stress increases as the angle of internal friction decreases and *vice-versa*. Also, for a given angle of internal friction (φ), the initial stress increases as cohesion increases. Determined values of initial stress of the three soils is shown in Table 4. Trends of the initial stress matched those of cohesion, particularly in sandy and calcareous soils. In sand, an increase in p_i was observed with CG between 0% and 10%, then a relative decrease at 15%. In the calcareous soil, a solid trend of increase was seen between 0% and 15%, exactly as was the case with soil cohesion in that soil. In clay, where there was no obvious trend of soil cohesion, there is also no trend in the initial stress. Shear graphs obtained for different soils, showing trends and relative magnitudes of c, φ, and p_i can be seen in Fig. 6.

Table 4. Soil cohesion (c), angle of internal friction (φ), coefficient of internal friction (tan φ), and initial stress (p_i), in tested soils as affected by the application rate of coffee grounds (CG). There are also the densities (γ_{wet} and γ_{dry}) and water contents determined during shear test

Soil	CG rate, %	γ_{wet}	γ_{dry}	Water content, %	Cohesion, c kg/cm^2	φ, degree	Coefficient of internal friction, tan φ	Initial stress, p_i = C cot φ
Sand	0	2.080	1.857	12.02	0.04	30.7	0.593	0.067
	5	2.120	1.820	16.46	0.10	32.2	0.629	0.159
	10	2.080	1.781	16.8	0.18	27.5	0.520	0.346
	15	1.940	1.625	19.35	0.08	28.6	0.545	0.147
Calcareous (SCL)	0	1.800	1.354	32.92	0.04	22.1	0.406	0.099
	5	1.840	1.288	42.83	0.06	18.7	0.338	0.177
	10	1.660	1.157	43.42	0.10	19.9	0.362	0.276
	15	1.720	1.163	47.87	0.13	21.2	0.388	0.335
Clay	0	1.790	1.292	38.55	0.17	8.8	0.155	1.099
	5	1.700	1.148	48.05	0.15	17.5	0.315	0.476
	10	1.720	1.168	47.28	0.20	5.8	0.102	1.970
	15	1.660	1.107	49.97	0.12	13.6	0.242	0.496





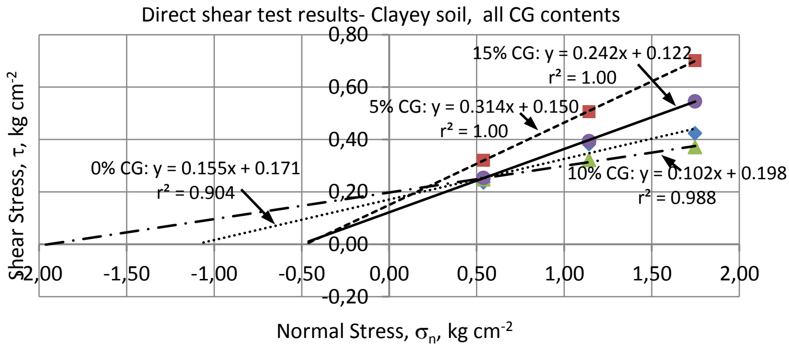


Fig. 6. Shear stress results of test soils under different coffee grounds (CG) treatments. The cutoff made by the τ-line on the ordinate is soil cohesion (c); the slope of the line ($\tan \varphi$) is the coefficient of internal friction, and the cutoff on the negative side of the abscissa made by the τ-line is the initial stress (p_i)

IV. Soil resistance to penetration (soil strength)

Soil surface strength is often determined by its resistance to penetration with a metal probe or a penetrometer. Several types and designs of penetrometers are used for this purpose (Callebaut *et al*. 1985, Rolston *et al*. 1991, Bedaiwy and Rolston 1993). Other devices are also used to measure soil surface strength (e.g. a rupture, shear penetration machine [Upadhyaya *et al*. 1995]).

Soil resistance to penetration is an indicative of the condition of the surface layer of the soil and could even reflect the condition of deeper soil layers, depending on the type of penetrometer and test used. Soil surface may be subjected to external factors (e.g. compaction) or internal factors (particle rearrangement, close-packing, sealing and crusting) that result in detrimental effects on the soil with regard to plant growth and irrigation. Specifically, surface crusts and densified layers were proven to: 1) slow water infiltration into the soil, and hence, 2) increase chances of water runoff and erosion, and 3) hinder or prevent seedling emergence. Sealing of the soil surface or the formation of surface densified layers take place through a process of particle rearrangement that leads to close-packing and hard interlocking of soil particles (Bedaiwy and Rolston 1993). Surface seal can turn into a hard, dense crust with extremely low permeability and high strength. Sealing, crusting and densification usually occur in medium-to-fine-textured soils and not in sand. Adding organic matter to soils that are susceptible to sealing or crusting is a good preventive practice. Results of resistance to penetration of the different soils at different CG rates are presented in Fig. 7.

Since resistance in the sandy soil is very low under normal conditions, it was expected to increase upon adding CG. This was the case. At 0% CG, resistance was extremely low (< 0.3 kg·cm^{-2}) for water contents ranging from < 1.0%

to about 13% (weight basis), and the resistance did not take a falling trend with water content as in sand with added CG. It rather took a hyperbolic shape close to that of a typical "moisture content dry density curve" or "compaction curve" (Proctor 1933) (Fig. 7). As moisture of initially dry sand increases gradually, a stage is reached when the air content of the soil attains a minimum volume, thus, making the dry density a maximum. The water content corresponding to this maximum dry density is called the "optimum moisture content" (≈ 4% to 6% in this case, Fig. 7). This maximum density was apparently reflected in maximum soil resistance. As the rates of CG increased, the resistance to penetration increased substantially and was highest at the rate of 15%. This effect in sandy soil is quite favorable. The low resistance in sand under normal conditions is a direct result of the abundance of large pores and the low cohesion. As CG are added, soil starts to form aggregates with smaller pores within, which improves water holding capacity, and soil cohesion increases. This represents a better environment for growing plants.

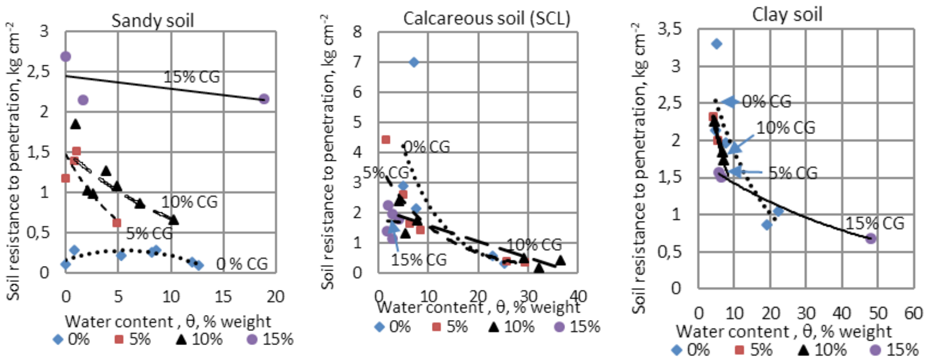


Fig. 7. Soil surface strength – measured as resistance to penetration – as a function of soil water content in sandy, calcareous and clay soils at different rates of coffee grounds

Note: resistance value of 7.0 kg·cm^{-2} (in calcareous soil) is an extrapolated estimate where resistance exceeded maximum penetrometer limit of 5.5 kg·cm^{-2}.

In the case of the calcareous soil (Fig. 7), two principal observations can be made. First, the effect of applying CG to the soil took an opposite trend to that of the sandy soil. As CG increased, the resistance to penetration decreased for all treatments. Second, the magnitudes of resistance were greater than those in sand. The resistance in the clayey soil took essentially the same pattern as in the calcareous soil, where resistance decreased as CG increased. The entire range was, however, somewhat lower in clay than in the calcareous soil, but was greater than in sand. Clay results are shown in Fig. 7 (data points are few due to technical difficulties). The fact that resistance values encountered in the case of the calcareous soil are generally greater than those seen in clayey soil is understandable. Calcareous soils are rich in lime (calcium carbonate, $CaCO_3$) which exists either in pure granules or as cementing material to other soil particles and peds. This results in high resistance, particularly if the soil is compacted.

It can be concluded here that CG did indeed improve the resistance of sand (by increasing it) and of both the calcareous and the clayey soils (by decreasing it). Both effects are desirable as far as agriculture (seedling emergence, crop growth, irrigation, etc.) are concerned.

CONCLUSIONS

Coffee grounds improved a number of mechanical properties of soil. Expansion upon saturation increased with CG (clay > calcareous soil > sand). Cracking increased markedly only in clay. Cohesion increased with CG up to the 10% content in sand and clay and the 15% content in calcareous soil. Angle of internal friction and coefficient of internal friction decreased in sand as CG increased from 5% to 10%. No pattern was detected in calcareous or clayey soils. Initial stress increased in sand, between 0% and 10%, and in calcareous soil between 0% and 15% CG, with no trend in clay. Resistance to penetration increased substantially in sand with increased CG, while decreased in calcareous and clay soils, which are favorable effects from agricultural viewpoint.

ACKNOWLEDGEMENTS

The authors wish to thank the managers at Starbucks Coffee and Costa Coffee chains of Alexandria (Egypt), for supplying the coffee grounds used in this research work. Their contribution was quite helpful.

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