Reinforcing Spent Coffee Grounds for Geotechnical Applications

Jair de Jesus Arrieta Baldovino, Ronaldo Luis dos Santos Izzo, and Carlos Millan-Paramo

Abstract— **Recent studies demonstrated the use of spent coffee grounds (CG) in geotechnical engineering applications. These studies focusing on chemical stabilization of CG using by-products and traditional binders as cement and lime. However, reinforcing CG with synthetic fibers has not been reported in the current literature. Thus, this paper demonstrates the efficiency of reinforcing CG using polypropylene fibers in 0.5% by weight. Compaction tests reveal that CG alone does not achieve good compaction properties (i.e., high maximum dry density and high optimum moisture content). Given this, a silty soil was added by weight (i.e., 25%, 50%, and 75%) to stabilize granulometrically the CG grains before reinforcing them with the fibers. The results showed an increase of unconfined compressive strength (q_u or UCS) of CG-silt-fibers compacted blends in 80% comparing to CG-silt blends. Further, Maximum Dry Density (MDD) of CG increase from 4.16 kN/m^3 to 10.38 kN/m^3 by the addition of 75% silty soil. For the potential use of fiber-reinforced CG in geotechnical earthworks, it is recommended to use at least 50% silty soil to improve the compaction and mechanical properties of blends.**

Index Terms— **Spent coffee grounds, reuse, stabilization, reinforcing.**

I. Introduction

SPENT coffee grounds (CG) is an agro-industrial residue prevenient from coffee consumption. Large quantities of CG are generated by coffee industry every year and the final deposited generally in landfills. CG is composed of cellulose, lignin, and hemicellulose. Mineral composition of spent coffee grounds covers iron, aluminum, copper, manganese, potassium, and cobalt, mainly [1]. In addition, CG has a crystalline and amorphous region in its structure from cellulose and hemicellulose molecules, respectively.

Due to chemical and functional properties of CG, extraction oil, produce biodiesel and combust from CG is a suitable procedure [2]. Another industrial process denotes sugar extraction from CG [3], supercritical fluid extraction to oil production [4], CG bio-refinery resulting in final products have low economic value [5], CG biopolymer, carotenoid, biosorbent, antioxidant, biocomposite and management using circular economy and policy considerations [6], and oil extracted from CG for fatty acid methyl ester manufacturing [7]. Thus, residues of coffee can be used as a renewable energy source and avoid destinations in landfills.

Recently, CG has been used in ground improvement based on geopolymers. Due chemical composition of CG and its reaction with amorphous composites based on calcium and silica in an alkaline environment, CG can be stabilized. [8] characterized CG samples using traditional geotechnical tests (i.e., granulometry, Atterberg limits, specific gravity, consolidation and triaxial) and leaching analysis. Results reveal a green use of CG as non-structural fill material in road embankments for low traffic loads. In addition, CG does not represent an environmental/leaching problem in its application as filler material. Due to poor mechanical resistance of CG, [9] combined CG with Fly ash (FA) as a geopolymer precursor active with Na_2SiO_3-NaOH composts. By replacing 30% FA into CG at 50/50 Na_2SiO_3-NaOH index, geopolymerization occurred after 7-d cure. Strong geopolymers are obtained at 50°C and CG-FA stabilized compacted blends are suitable for embankment structural fill material in road embankments. [10] introducing slag as a geopolymer precursor in CG-FA blends active with Na_2SiO_3 and NaOH. In this research, the authors obtained good q_u values of combined raw materials to use them in road construction projects. Because low dry unit weight and high water content of CG blends when standard Proctor is employed, [11] improved the compaction properties of CG by the addition of recycled glass, FA and slag. Dry unit weight increases from 10 kN/m^3 to 15 kN/m^3 by addition of 50% recycled glass and 30%FA. 70% Na_2SiO_3 and 30% NaOH was used to optimally induce geopolymerization, and 10.86 MPa was reached using a temperature of 50°C at 7-d cure. Studies carried out by [12] analyzed the influence of addition bagasse ash/slag to provide the strength of CG. The authors evaluated q_u and microstructural evolution of blends and confirm the improvement compaction properties for replacing CG by bagasse ash/slag and the increase of q_u for the long-term due to alkaline activation of precursors with sodium hydroxide and cure temperature of 50°C. Other opportunities to promote geopolymers based on CG is by adding of rice husk ash [13], ground granulated blast-furnace slag, Portland cement (PC) and hydrated lime [14]. Cement and lime addition are insufficient to meet subgrade requirements of CG, and CG stabilized with FA/Slag with replacing values of 10%–50% by weight met the requirement for subgrade. On the other hand, mixes stabilized CG by using geopolymers precursors was evaluated in pavement layers

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for CG-Slag-FA mixes [15], CG-recycled glass mixes [16] by carried out resilient modulus and deformation tests. Finally, [17] evaluated the environmental and economic viability of CG-FA-slag compacted blends and concluded the suitable used of recycled materials as CG and by-products as FA and slag in ground improvement to reduce cement production and CO_2 emissions.

Although some studies have been conducted to stabilize coffee grounds based in geopolymers, there is none with fiber reinforcement. Thus, this paper advance on reinforcing spent coffee grounds using polypropylene fibers. In addition, to improve the compaction properties of CG, a granulometric stabilization can be made employing silty soil.

II. Materials and Methodology

The materials and methods employed in the present study are explained below

A. Materials

CG was collected in the cafeteria of the Technological University of Paraná, in Curitiba-Brazil. CG was placed in an oven for drying, for approximately 5 days at a constant temperature of 50°C to avoid burning the organic matter and modifying its content. Then, approximately 30 kg of CG were homogenized to carry out characterization tests (i.e., granulometric curve, specific gravity, and chemical composition), in triplicate. Figure 1 shows the grain size distribution of CG sample.

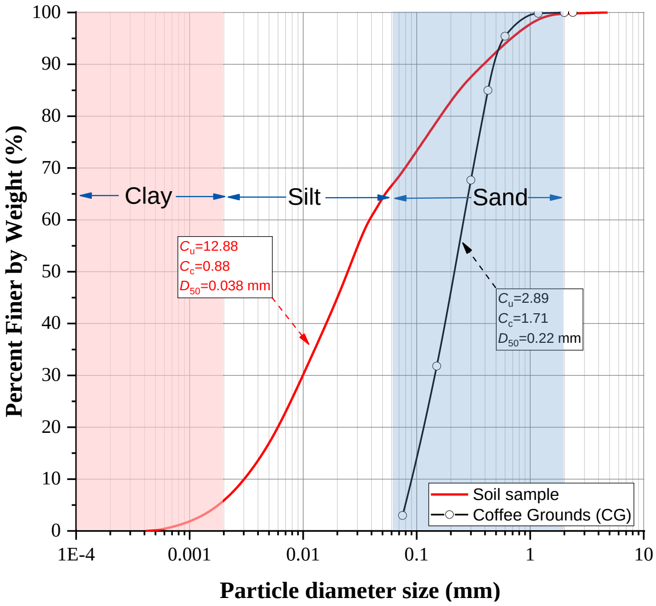

Fig. 1. The grain size distribution of CG and soil sample.

Figure 2 shows the grains of CG sample separated conforming sieve apertures. CG is composed by 5% coarse sand (0.6 mm<diameter<2mm), 50% medium sand (0.2 mm<diameter<0.6mm) and 45% fine sand (0.06 mm<diameter<0.2mm). The diameters corresponding to passing 10% (i.e., effective size), 30%, 60% and 90% were calculated as D10=0.09 mm, D30=0.2mm, D60=0.26mm, and D90=0.5mm. The coefficient of curvature and uniformity were measured as 1.71 and 2.89 respectively, and mean particle diameter (D50) was calculated as 0.22 mm. Thus, CG is geotechnically classified as a sandy material. The specific gravity of CG is 1.33 and Atterberg limits were carried out and were concluded CG was a non-plastic material. X-Ray analysis was conducted, and cellulose, lignin, and hemicellulose were detected. In addition, 81% LOI was calculated for CG.

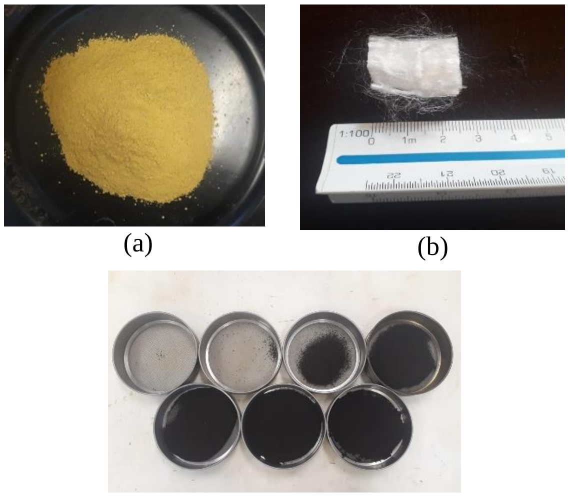

Fig. 2. Raw materials. (a) Silty soil sample (b) Monofilament polypropylene fibers, and (c) Grains of coffee grounds separated conforming sieve apertures.

Silty soil was collected from Metropolitan Region of Curitiba-Brazil. Figure 1 shows the granulometric curve of the soil samples. The soil is classified as MH in concordance to USCS System [18]. Table I presents the physical properties of soil samples. In addition, soil is composed by SiO_2 (48.78%), Al_2O_3 (44.51%), Fe_2O_3 (0.61%), K_2O (0.84%), TiO_2 (0.92%) and SO_3 (4.12%) with a LOI of 0.22% by weight. Finally, the predominant color in the soil is yellow as can be seen in Figure 2a.

TABLE I
Properties of the Soil Sample

Properties	Value	Standard
Liquid limit, %	50.82	
Plastic limit, %	35.96	[19]
Plastic index (PI), %	14.86	
Coarse sand (0.6 mm<diameter<2 mm), %	5	
Medium sand (0.2 mm<diameter<0.6 mm), %	12	
Fine sand (0.06 mm<diameter<0.2 mm), %	18	
Silt (0.002 mm <diameter<0.06 mm), %	60	[20]
Clay (diameter < 0.002 mm), %	5	
Effective size (D_{10}), mm	0.003	
Mean particle diameter (D_{50}), mm	0.038	
Uniformity coefficient (C_u)	12.88	–
Coefficient of curvature (C_c)	0.88	–
Specific gravity of soil	2.62	[21]
Activity of clay, A [A=PI/(%< 0.002 mm)]	2.97	[22]
Color	Yellow	–
Classification (USCS)	MH	[18]
q_u-natural state, kPa	104.58	[23]
q_t-natural state, kPa	16.62	[24]
q_t/q_u index-natural state	0.16	–
ϕ- Natural state, (°)	26	[25]
Cohesion- natural state, kPa	23	
OMC (from Standard effort), %	26	
MDD (from Standard effort), kN/m^3	13.7	
OMC (from Intermediate effort), %	20.50	[26]
MDD (from Intermediate effort), kN/m^3	15.43	
OMC (from Modify effort), %	14.50	
MDD (from Modify effort), kN/m^3	16.75	

Monofilament Polypropylene (pp) fibers (F) were used in this study. Fibers were obtained by a local manufacturer. The specific gravity of fibers is 0.91 and the length is 24 mm. The diameter of pp fibers is 18 µm, specific surface area of 244 m^2/kg, linear strain at failure of 80%, tensile strength of 300 MPa, and Young Modulus of 3GPa. The fibers were previously separated with air to mix with CG and soil. A pp fiber sample can be seen in detail in Figure 2b.

B. Methods

To study compaction properties of CG, soil and CG-soil mixes, three percentages of soil was added by weight into CG: 0%, 25%, 50%, 75%, and 100%. Compaction tests were carried out in concordance to Brazilian standard NBR 7182 [26]. Results of compaction properties for soil, coffee grounds, and CG-Soil blends are shown in Table 2.

Test samples having a height and diameter of 100 and 50 mm, respectively, were molded for the unconfined compressive tests in triplicate. For preparing unconfined compressive specimens, the CG and silty soil were dried and divided into uniformly distributed portions. A quantity of dry soil was added to achieve five different addition contents (0%, 25%, 50%, 75%, and 100%). The mixture of the CG with soil was prepared to be as homogeneous as possible. Subsequently, a percentage of water was added to achieve the OMC (optimum moisture content) depending on blend composition. For the compacted specimens, the required mass of CG+soil was mixed with an amount of distilled water to prepare an initial water content show in Table II. The blend was mixed by hand until all raw materials were fully dispersed. A number of dry fibers were also added to achieve the contents of 0.5%, equally in reference to the dry mass of soil plus CG (when convenient, for reinforced specimens). Separated fibers were added by layer after CG-soil-water homogenization to avoid the flotation of them and try to assure perfect homogenization. The samples for molding the test specimens were statically compacted in three layers (the top of each layer was slightly scarified) in a stainless-steel mold. The specimens were extruded from its molds by using a hydraulic device. To ensure the dry unit weight of molding (i.e., MDD), the mold volume and weight of the wet mixture necessary for each test specimen were calculated. The time used to prepare, mix, and compact the specimens were always less than 12 min. The test specimens were weighed on a 0.01 g precision scale, and the dimensions were measured using a caliper with a 0.01 mm error. The extracted test specimens were wrapped in a transparent plastic film to maintain the moisture content. Finally, the test specimens were stored in a humidity chamber for the curing process for one day to homogenization, at a mean temperature of 23±2 °C and relative humidity above 95%. Finally, the maximum errors were considered when conducting an unconfined compressive strength for the samples: sample dimensions had a diameter of ±0.5 mm and height of ±1 mm, molding dry unit weight (γ_d) of ±1%, and water content (ω) of ±0.5% [27]. Figure 3 shows the characteristics of samples containing soil, CG and fibers during sample preparation, before and after compressive tests.

To perform unconfined compressive tests, an automatic press was used with a ring calibrated for an axial load with a capacity of 10 kN. The tests were conducted using an automated system at a speed of 1.00 mm per minute to measure the applied force at a resolution of 2.50 Newtons and a deformation sensitivity of 0.01 mm. The procedures for the unconfined compressive tests are shown in the American standard ASTM 2166 [28].

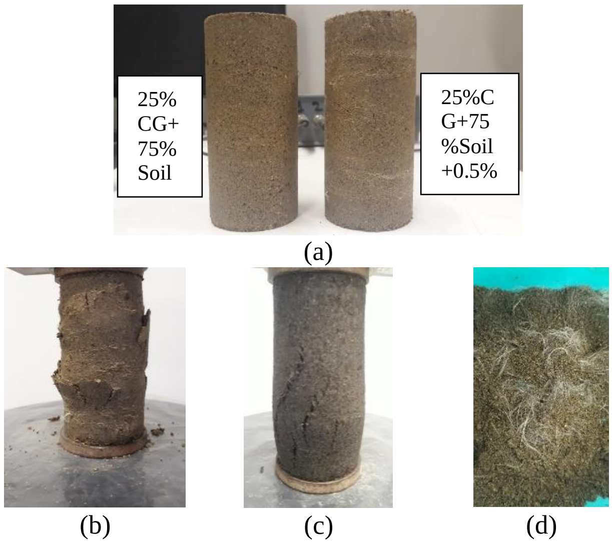

Fig. 3. Specimens of compacted blends. (a) Example of samples compacted blends using 25%CG, 75% soil and 0.5% F (in reference to CG plus soil). (b) Typical failure of CG-Soil-F samples. (c) Typical failure of CG-Soil samples (d) Visual of CG-Soil-F mix design.

III. Results and Discussions

A. Compaction properties of CG-soil blends

During the CG compaction tests, three zones were verified in the curve as shown in Figure 4. The first zone is a dusting zone comprises of 80% moisture. In this zone, CG grounds presents superficial low moisture. Because of dynamic compaction produced by the socket and low density of CG, the fine and medium particles fly. Therefore, compacting coffee grains in this area is not recommended. The second zone is a stable zone. CG in the stable zone has medium and medium-high moisture content and the dusting effect disappears when the grains are compacted. The particles are better accommodated within the mold volume, with which more solid lumps are formed in the compacted mass. Finally, after 140% moisture, CG fails to retain the water for which this leaching. In the zone of leaching, at least 10% of the water added to compact is leached carrying with its fine particles of coffee.

Figure 5 presents the compaction curves of soil samples, coffee grounds, and coffee grounds-soil blends. Soil shows an MDD=13.7 kN/m^3 and OMC=26% employing the standard Proctor effort. CG is a lightweight material with specific gravity equal to 1.33. Fig. 4 presents a compaction curve of waste CG with low MDD=4.16 kN/m^3 and high OMC=123%. To improve these compaction properties, the soil was added to CG. Fig. 5 presents an increase in MDD and a decrease in OMC of CG by adding soil in three quantities: 25%, 50%, and 75%. The higher increase in MDD is when 75% of soil is mixed. This occurs due large porosity of compacted CG, by addition of silty soil, reduces the voids and improved the mix structure. Therefore, decreases the quantity of water to reach the MDD of CG-Soil. [14] stabilized CG with FA and slag obtaining MDD=7.2 kN/m^3 and OMC=55% when FA=50% was used. These results are like compaction properties of 50%CG-50%Soil in the present study. On the other hand, when 40% of slag was used by authors, similar compaction properties were reached too. Thus, granulometric stabilization of CG is possible when dense and fine materials are employed. In addition, Figure 6 presents the influence of CG on compaction properties of mixes. MDD and OMC of compacted blends are controlled by Equation (1) and (2), respectively, depending on CG. MDD and OMC of whatever CG-Soil composition can be calculated using Equation (1) and (2).

$$\mathrm{MDD} = 13.72e^{-0.012\times CG} \quad (1)$$

$$\mathrm{OMC} = 26.22e^{0.0154\times CG} \quad (2)$$

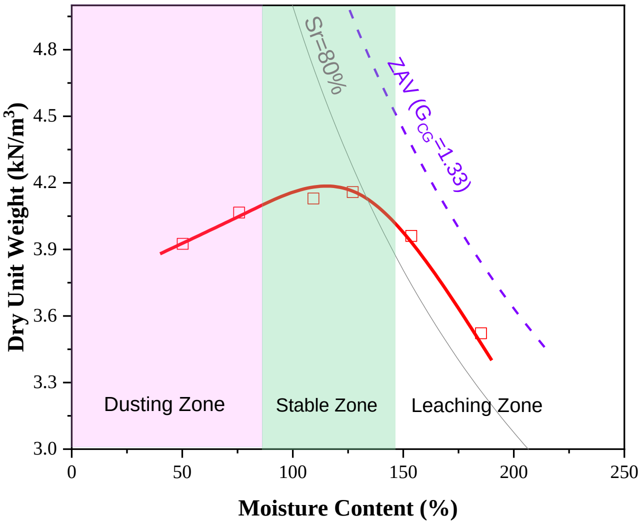

Fig. 4. Compaction curve of coffee grounds.

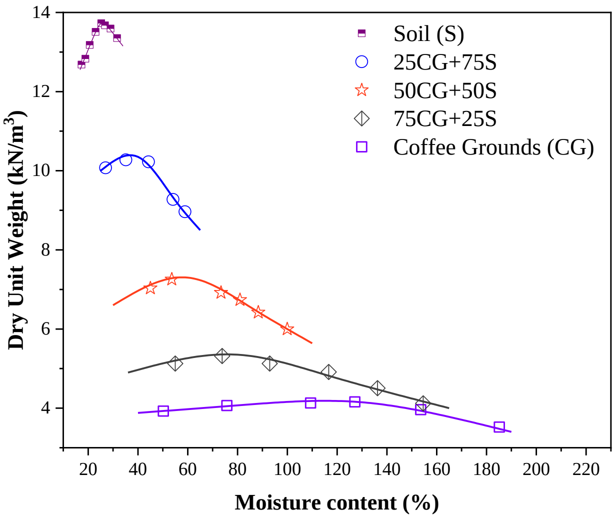

Fig. 5. Compaction curves of soil sample, soil-coffee grounds blends and coffee grounds.

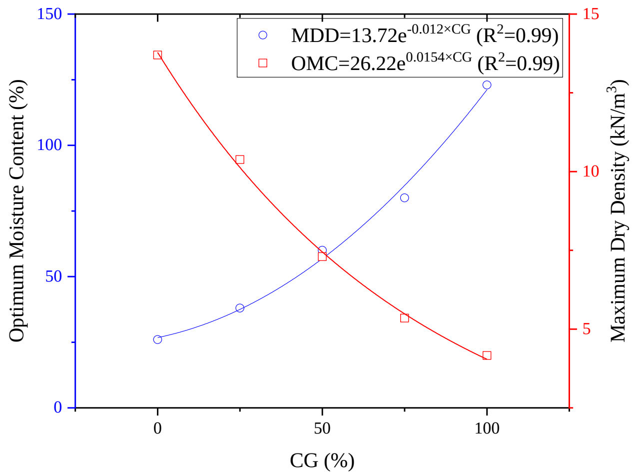

Fig. 6. Influence of CG on MDD and OMC of blends.

TABLE II
RESULTS OF COMPACTION PROPERTIES FOR SOIL, COFFEE GROUNDS, AND CG-SOIL BLENDS

Composition	Maximum Dry Density (MDD), kN/m^3	Optimum Moisture Content (OMC), %
Soil (S)	13.7	26
Coffee Grounds (CG)	4.16	123
75CG+25S	5.35	80
50CG+50S	7.3	60
25CG+75S	10.38	38

B. Unconfined compressive strength of non-reinforced and reinforced blends

Figure 7 presents the results of UCS of CG-silty soil blends considering the addition of soil by weight in three percentages: 75%, 50%, and 25%. An average of three specimens was plotted in q_u-axial strain plane. The UCS of blends increases when silty soil was an increase. Because the addition of soil improves the compaction properties of CG, mechanical resistance was improving too. UCS increase from 11.2 kPa for CG to 55 kPa for 25%CG-75%S (i.e., increase of 400%). Figure 8 shows the influence of fiber addition on CG-Soil blends. Comparing Figure 7 and 8, fiber improves UCS in 1005% observing CG and 25%CG-75%S-0.5%F blends. Thus, 75% of soil addition reinforced with 0.5% F was the better option to stabilize the CG in concordance to the experimental program.

Figure 9 summarizes the effects of CG on UCS for non-reinforced and reinforced compacted blends. It´s obvious that there is a turning point at 50%CG where the resistance increases at a higher ratio compared to the resistance of the mixtures with the addition of CG<50%. Consequently, 50% is the minimum percentage appropriate to improve CG. In general, comparing the CG-silt and CG-silt-F blends, in average, q_u increase in 80% by fiber addition.

Kua et al. [14] add cement and lime into CG. The authors calculated UCS of 60-80 kPa by cement/lime addition. Results in the present study reached higher UCS values than theirs (UCS=219.7 kPa was obtained here). UCS results for 25%CG-75%S-0.5%F is also like CG-Slag-Rice Husk Ash mixes cured in 7 days studied by [13]. By [8], CG can be employed as a material for the non-structural embankment. Improving UCS values CG with silty soil and fibers can be used in structural embankment but considering low traffic load, in rural and non-industrial areas, for example.

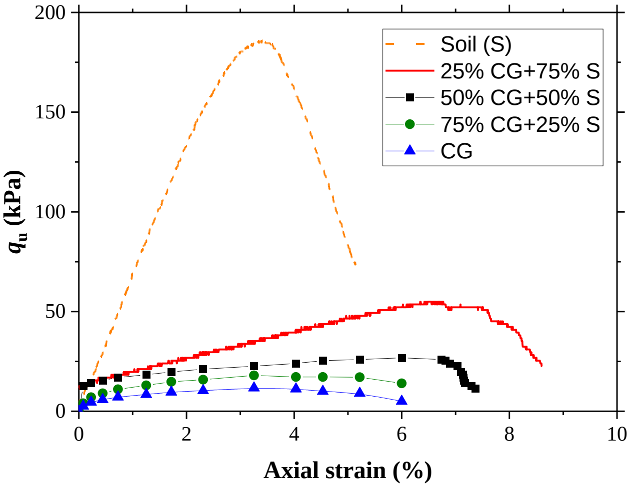

Fig. 7. Compaction curve of coffee grounds.

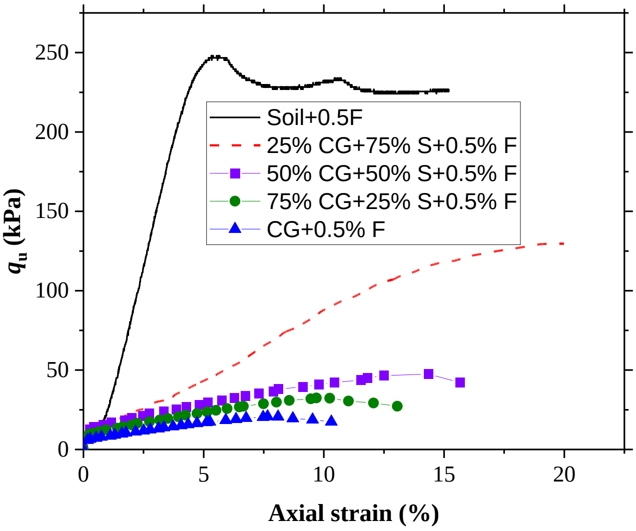

Fig. 8. Compaction curves of soil sample, soil-coffee grounds blends and coffee grounds.

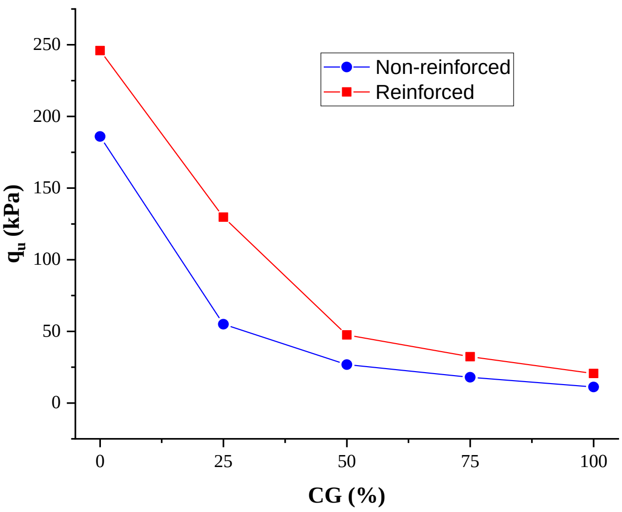

Fig. 9. Influence of CG on MDD and OMC of blends.

IV. Conclusion

In concordance to the experimental program and results, the following conclusions can be addressed:

– Silty soil addition improves compaction properties and unconfined compressive strength of CG.

– Reinforced CG with pp fiber improves the mechanical resistance of CG-soil blends by 80%.

– To stabilize the CG is necessary to add at less 50% soil to reach good compaction (i.e., high MDD and low OMC) and compressive properties.

– CG is a suitable material to use in geotechnical earthworks (i.e., non-structural and structural embankment for low traffic loads) because presents good physical-mechanical properties when are stabilized/reinforced with dense materials and fibers.

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