Research Article

Syed Husnain Ali Shah*, Mohammad Arif, Qasim ur Rehman, and Fawaz Manzoor

Utilization of dolerite waste powder for improving geotechnical parameters of compacted clay soil

https://doi.org/10.1515/geo-2020-0323
received August 24, 2021; accepted November 28, 2021

Abstract: This study explores how dolerite cutting waste could be utilized for improving the quality of compacted clay soils. Different proportions of dolerite waste powder with varying grain sizes were used as admixtures and their impact on clay soil properties investigated. Ten samples were prepared by mixing clay soil with different proportions of dolerite waste powder having grain sizes of 0.210, 0.297, and 0.420 mm. The resulting samples were subjected to Proctor compaction, and their maximum dry density and optimum moisture content were measured. Next, all the compacted samples were subjected to geotechnical testing, including the determination of Atterberg limits, California bearing ratio (CBR), unconfined compressive strength, and specific gravity (Gs). The values of compaction parameters, Atterberg limits, and Gs were utilized for finding the porosity, void ratio, saturation potential, liquidity index (LI), and consistency index (CI). The results demonstrate that the addition of dolerite powder produces a substantial improvement in the plasticity index, compaction parameters, CBR, unconfined compressive strength, Gs, porosity, void ratio, degree of saturation, LI, and CI. The foremost reason for this improvement is the presence of denser and less water-adoring minerals in the added dolerite relative to pristine clay soil. Furthermore, the observed positive impact on the soils' geotechnical comportment is comparatively higher with coarser than finer dolerite because of the decrease in surface area that causes a reduction in the moisture content and porosity but an increase in the density of soil.

Keywords: weight–volume relationships, void ratio, degree of saturation, clay improvement

1 Introduction

Clay soil characteristically contains a high proportion of clay particles and therefore displays high plasticity, low strength, and cohesive behavior [1]. The degree of plasticity, strength, and cohesion of clay all depend strongly on its mineralogy. The strength and volume of such soils undergo change because of fluctuation in their moisture content [2]. Circulation of water along fissures and cracks in the soil promotes the process of softening leading to a reduction in both shear strength and bearing capacity [3]. The high susceptibility of these soils to settlement under loading may cause considerable damage to the structures constructed over them. Owing to their cyclic swelling–shrinking behavior, expansive clay soil commonly causes severe damage to foundations. The extent of soil swelling and shrinkage depends on both the amount and type of clay present and environmental conditions, including climate [4,5]. Overcoming such an undesirable behavior of clay is one of the major problems and a challenging task faced by geotechnical engineers [6,7]. Such situations are particularly likely to arise during the construction of roads and highways as sites for these developmental projects undergo reduction unceasingly [6,7].

In order to modify the swelling–shrinkage properties of clay soil, extensive investigation has been carried out in the recent decades [8]. The major aim of clay soil stabilization, that is, to improve their geotechnical behavior, has been to normalize volume change and plasticity or workability characteristics, while significantly improving the strength properties [9–11]. In addition, the process may help in resolving problems pertaining to filtration and drainage systems [12,13], and improving permeability

*** Corresponding author: Syed Husnain Ali Shah,** Department of Earth and Environmental Sciences, Hazara University, Mansehra, Pakistan, e-mail: shas.husnain@gmail.com, syedhusnain@hu.edu.pk, tel: +92-3005647476
Mohammad Arif: Department of Geology, University of Peshawar, Peshawar, Pakistan
Qasim ur Rehman, Fawaz Manzoor: Department of Earth Sciences, University of Haripur, Haripur, Pakistan
ORCID: Syed Husnain Ali Shah 0000-0003-1527-5712

and enhancing the soil resistance to weathering and traffic usage, so that the requirements for specific engineering projects can be met [14]. Such a positive modification can be brought about by different options, such as removing water through draining (dewatering methods), compaction, reinforcement, and addition of materials.

Stabilization of clay soil through the addition of industrial stone and other wastes is becoming increasingly common [15–18]. Such wastes contain toxic elements that may pose serious threats to the environment by polluting both surface water and ground water. Fortunately, the extent of the expected environmental degradation can be reduced by properly utilizing these wastes [19–22]. This study utilizes dolerite waste material and aims at analyzing its impact on geotechnical properties of compacted clays. Dolerite waste was used as powder with varying grain sizes so that the role of varying the particle size in clay stabilization could be properly assessed. Besides, the present study includes determination of the liquidity index (LI), consistency index (CI), void ratio (e), porosity (n), and degree of saturation (S) of compacted clay employing weight–volume relationships. An adequate understanding of all these physical characteristics of soils is vital for appropriate foundation designing. Unfortunately, however, studies performed so far on soil stabilization have generally lacked a proper evaluation of these parameters. This work provides a methodology for determining the abovementioned properties of compacted and stabilized clay soil by utilizing the values of compaction parameters, specific gravity (Gs), and Atterberg limits.

2 Materials and methods

The materials used in the study include clay soil and dolerite rock. The dolerite rock samples were collected from a quarry site near Oghi, District Mansehra, Pakistan, whereas the sample of clay was collected from District Haripur, Pakistan (Figure 1). The collected dolerite samples were of irregular shape, truly considered as waste material as it cannot be used for dimensional, decorative, or building stone purposes. Different analyses were performed to obtain the petrographic details (mineralogical composition and texture) of the dolerite and geotechnical parameters of both the rock and soil samples. X-ray diffraction (XRD), sieve analyses, and hydrometer analysis were conducted on the soil sample, whereas the dolerite was investigated for obtaining its petrographic features and determining its unconfined compressive strength (UCS), water absorption, and Gs.

The XRD investigation of the soil sample was performed with a Bruker D8-Advance X-ray diffractometer employing the following conditions: chamber of high temperature up to 900°C with an X-ray generator KRISTALLOFLEX K 760–80 F having power supply of 3,000 W, voltage of 20–60 kV, current of 5–80 mA, and a copper anode. The XRD results revealed that the soil sample was made up of quartz, feldspar, calcite, albite, dickite, and montmorillonites. The sieve and hydrometer analyses were conducted in accordance with the standards contained in ASTM C136 [23] and ASTM 7928 [24]. Three thin sections were prepared for petrographic study of the dolerite in the Mineralogical Laboratory of Peshawar University, Pakistan. The thin sections were examined under a Fein Optic R40POL transmitted and reflected light polarizing microscope. The water absorption, Gs, and UCS of the dolerite samples were determined according to ASTM D6473 [25] and ASTM D7012 [26], respectively.

The dolerite was crushed and ground. The resulting powder was then passed through sieve numbers 40 (0.420 mm), 50 (0.297 mm), and 70 (0.210 mm) to extract samples with three different grain sizes, that is, 0.420, 0.297, and 0.210 mm. Ten samples were prepared by mixing the collected clay soil with different proportions of dolerite waste powder having different grain sizes (Table 1). All ten mixed samples were compacted using Proctor compaction, and the values of their maximum dry density (MDD) and optimum moisture content (OMC) were recorded. The geotechnical parameters, namely Atterberg limits, California bearing ratio (CBR), UCS, and Gs, of all the compacted samples were also measured. The acquired data from Atterberg limit and Gs tests were utilized for computing the porosity (n), void ratio (e), saturation (S), LI, and CI.

The compaction parameters, that is, OMC and MDD, of the clay were determined using the standard Proctor compaction procedure according to ASTM D698 [27]. The soil Atterberg limits, which include the liquid limit (LL), plastic limit (PL), and plasticity index (PI), were determined following ASTM D4318 [28]. The CBR, UCS, and Gs of the samples were determined following the standards provided in ASTM D1883 [29], ASTM D2166-06 [30], and ASTM D854-14 [31], respectively.

The values of LI and CI were determined by following the equations used by Vardanega and Haigh's [32] and Oliveira et al's [33] respectively in their studies.

$$\mathrm{LI} = w - \mathrm{PL}/\mathrm{PI} \times 100, \tag{1}$$

$$\mathrm{CI} = \mathrm{LL} - w/\mathrm{PI} \times 100, \tag{2}$$

where w is the moisture content.

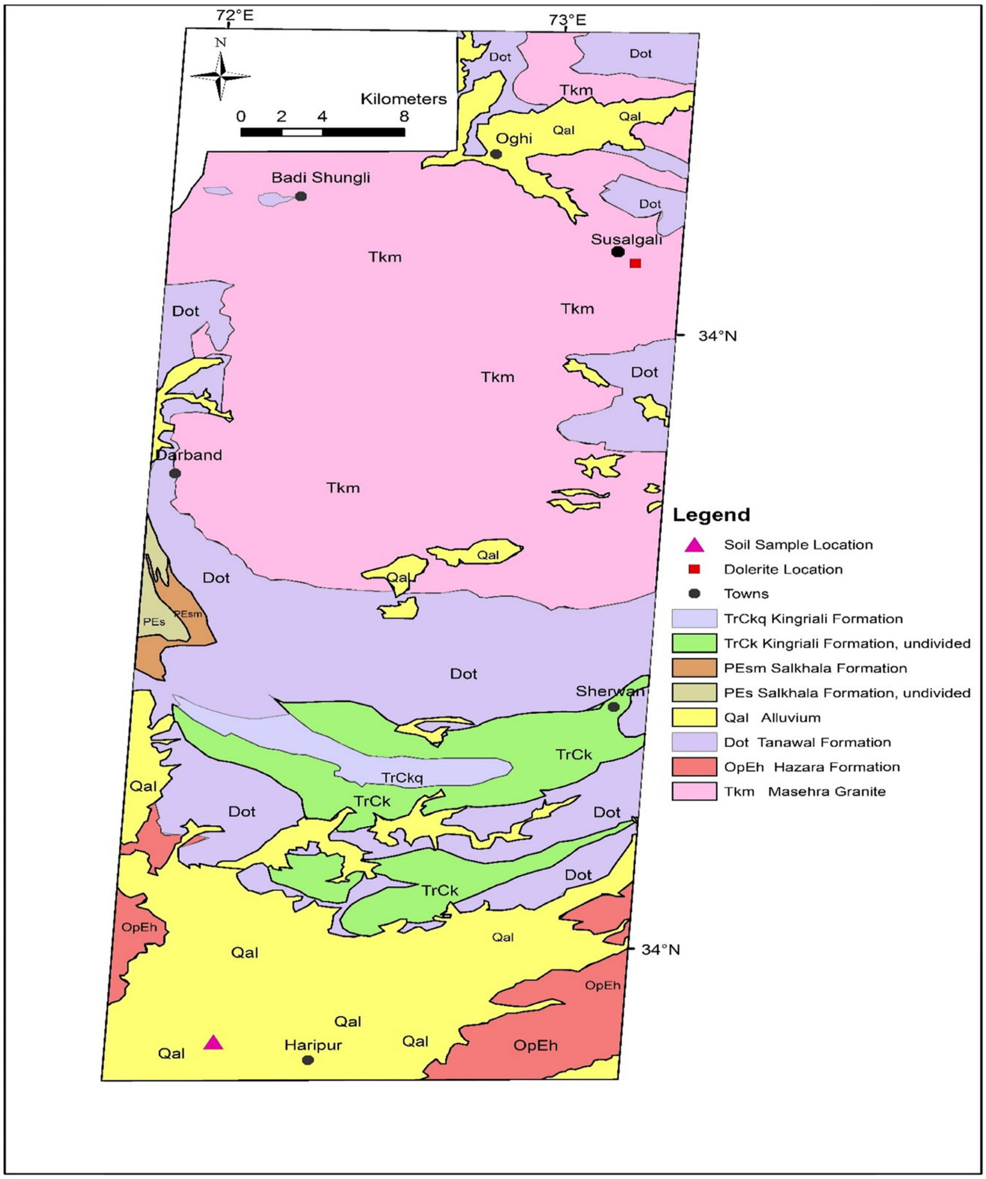


Figure 1: Geological map showing the location of the investigated dolerite and soil samples.

Table 1: Composition of the investigated samples

Sample no.	Dolerite Powder (%)	Clay Soil (%)
1	0	100
2	10 (0.210 mm)	90
3	10 (0.297 mm)	90
4	10 (0.420 mm)	90
5	20 (0.210 mm)	80
6	20 (0.297 mm)	80
7	20 (0.420 mm)	80
8	30 (0.210 mm)	70
9	30 (0.297 mm)	70
10	30 (0.420 mm)	70

The values of OMC instead of moisture content were used as samples of compacted stabilized soil rather than natural soil were used in this investigation.

The three-phase relationships described by Budhi [34] and Arora [35] were used to determine the values of porosity, void ratio, and saturation for samples of the original and the various treated (dolerite waste powder-stabilized) soil samples. Although commonly utilized for investigating natural soils, three-phase relationships are rarely used in calculating properties of stabilized soils. The values obtained from the Proctor compaction test (Table 2) were used in the three-phase relationships for determining the abovementioned parameters.

Table 2: Proctor compaction and Gs data used in the three-phase relationships for determining porosity, void ratio, degree of saturation, LI, and CI

Samples	Wet soil weight (g)	Dry soil weight (g)	Max dry density (kN/m^3)	Optimum moisture content (%)	Gs	Volume of mold (cm^3)
Pure soil	1,836	1,560	16.77	17.7	2.55	911.83
Soil + 10 dolerite powder (0.210 mm)	1,849	1,590	17.11	16.3	2.60	911.83
Soil + 10 dolerite powder (0.297 mm)	1,850	1,602	17.21	15.5	2.61	911.83
Soil + 10 dolerite powder (0.420 mm)	1,874	1,630	17.51	15.0	2.63	911.83
Soil + 20 dolerite powder (0.210 mm)	1,871	1,655	17.80	13.1	2.66	911.83
Soil + 20 dolerite powder (0.297 mm)	1,888	1,680	18.10	12.4	2.68	911.83
Soil + 20 dolerite powder (0.420 mm)	1,925	1,725	18.50	11.6	2.70	911.83
Soil + 30 dolerite powder (0.210 mm)	1,936	1,760	18.91	10.0	2.74	911.83
Soil + 30 dolerite powder (0.297 mm)	1,940	1,780	19.13	8.99	2.77	911.83
Soil + 30 dolerite powder (0.420 mm)	1,971	1,825	19.61	8.01	2.81	911.83

The following formula was used to determine the void ratios:

$$e = \frac{V_v}{V_s},$$

where e is the void ratio and V_v and V_s represent the volumes of voids and solids, respectively.

For V_s determination, we used the derived weight and volume relationship as follows:

$$V_s = \gamma_s / r_w \cdot \mathrm{Gs},$$

where V_s and γ_s represent the volume and weight (i.e., the weight of soil without water) of solids, respectively; r_w is the unit weight of water (standard value 0.99), and Gs refers to specific gravity.

The value of the weight of solids obtained from the Proctor compaction test was used, that is, weight of the dry soil used in the determination of MDD (Table 2), whereas the value of Gs was determined through laboratory test.

For the determination of V_v, we used the formula $V_T + V_s = V_v$, where V_T is the total volume of soil; V_s is the volume of solids; and V_v is the volume of voids.

The total volume (V_T), which was obtained by performing the Proctor compaction test (Table 2), is the volume of the standard Proctor mold.

Porosity of the samples was determined from the following equation:

$$n = \frac{V_v}{V_T},$$

where n = porosity, V_v = volume of voids, and V_T = total volume of the soil.

Porosity can also be determined by using the values of n and e as follows:

$$n = \frac{e}{1 + e}.$$

The following weight–volume relationship was used for determining the degree of saturation:

$$S = \frac{V_w}{V_v} = \frac{w\mathrm{Gs}}{e} \quad \text{or} \quad \mathrm{Se} = w\mathrm{Gs},$$

where S refers to the degree of saturation; w is the moisture content (here replaced with OMC); Gs is the specific gravity; and e is the void ratio.

3 Results

The soil sample was made up of both clay and nonclay minerals. Dickite and montmorillonites are the major clay

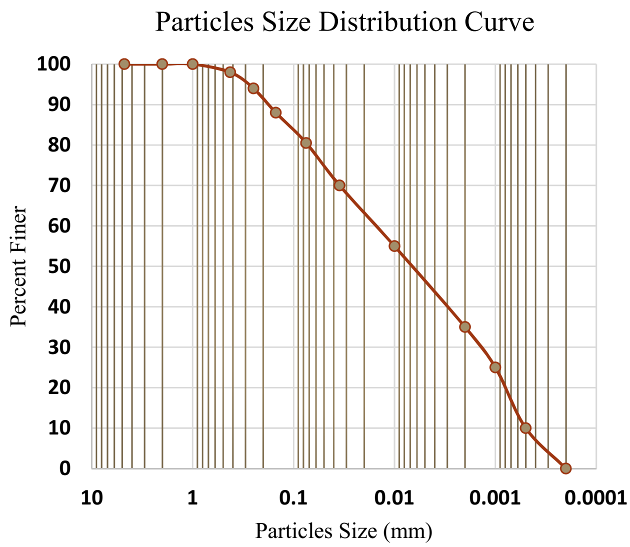


Figure 2: Grain size distribution of the investigated soil sample.

Table 3: Geotechnical properties of dolerite

Water absorption (%)	0.69
Gs	3.12
UCS (MPa)	225.87

minerals, whereas quartz, feldspar, albite, and calcite represent the nonclay constituents of the soil. As shown in Figure 2, 80% of the soil sample consists of material finer than 200 mesh. Petrographic data indicate that the dolerite samples contain plagioclase (49–51%), clinopyroxene (40–43%), and opaque minerals (7–9%) (Figure 3). The geotechnical parameters of dolerite are given in Table 3.

Data on the Atterberg limits, which include LL, PL, and PI, are shown in Figure 4. The addition of dolerite powder obviously reduced the values of both LL and PI.

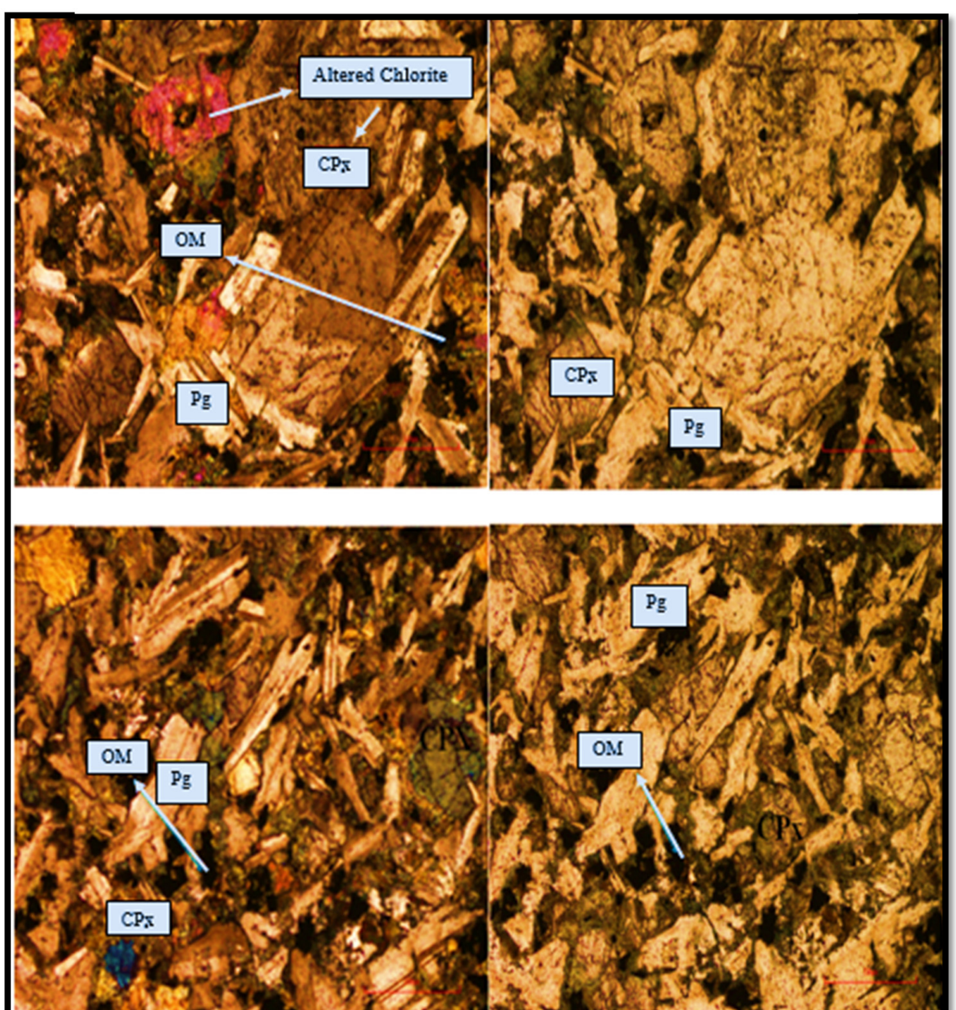


Figure 3: Petrographic results of the dolerite sample used for stabilization (OM = opaque mineral, Pg = plagioclase, CPx = clinopyroxene).

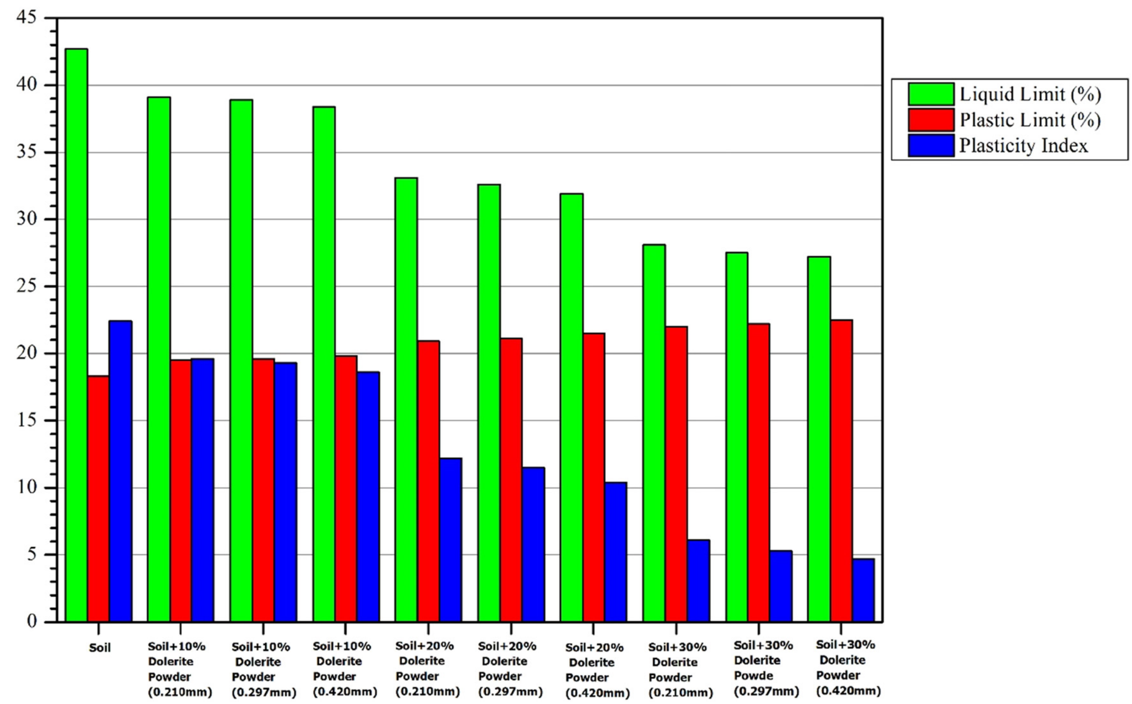


Figure 4: Variation in the Atterberg limits of the original (untreated) and variously treated soil samples.

Besides, the treatment caused augmentation, though very little, in the values of PL. Although the addition of dolerite powder of any size improved the Atterberg limits, the impact of the coarse-grained powder varieties was relatively greater than that of the finer ones. The values of the Atterberg limits are used also for characterizing the investigated clay soil by using the American Association of State Highway and Transportation Officials soil classification system (Figure 5).

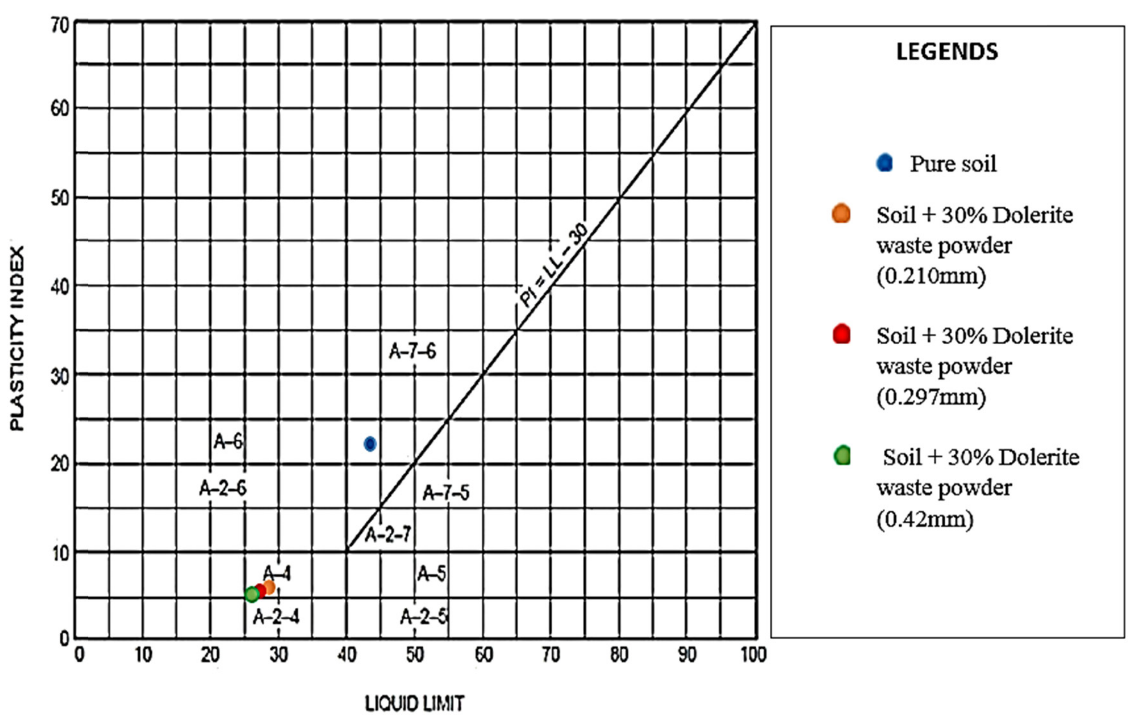
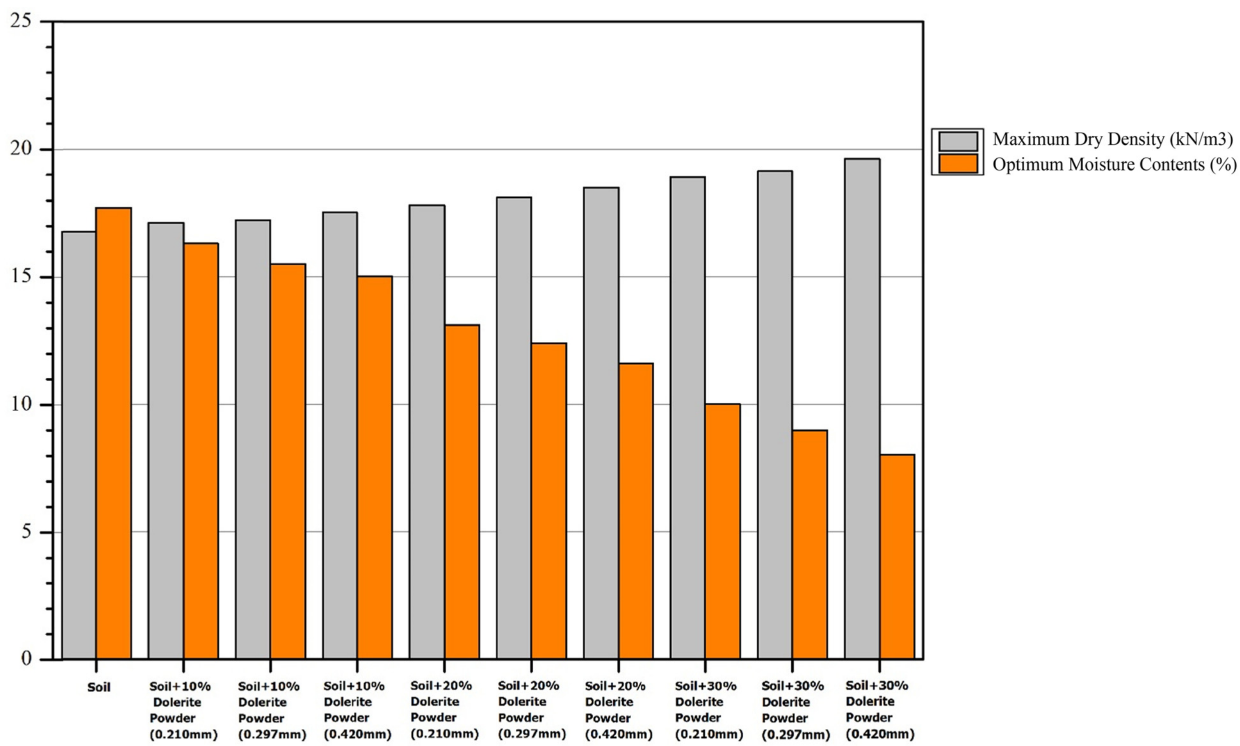
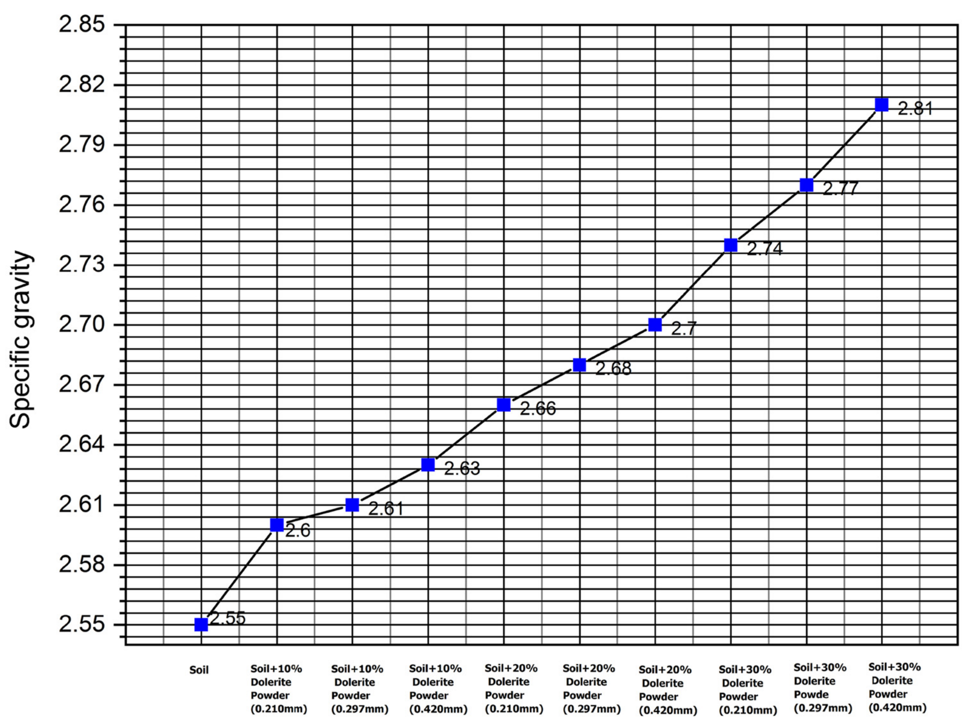


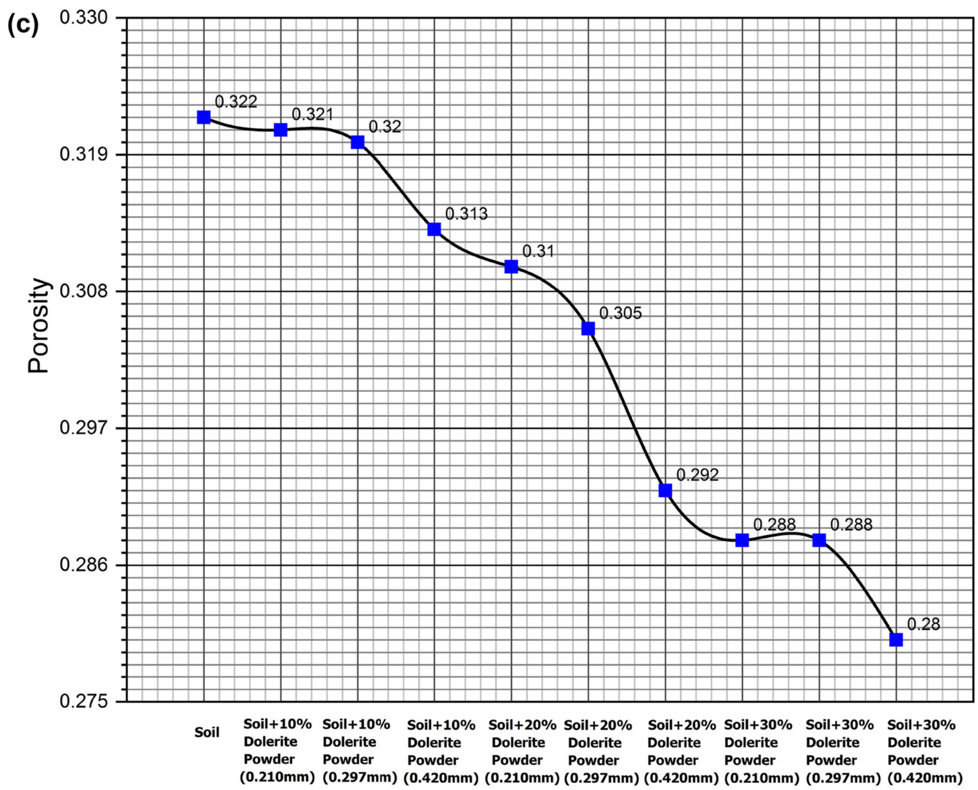
Figure 5: Geotechnical characterization of the untreated and variously treated soil samples.

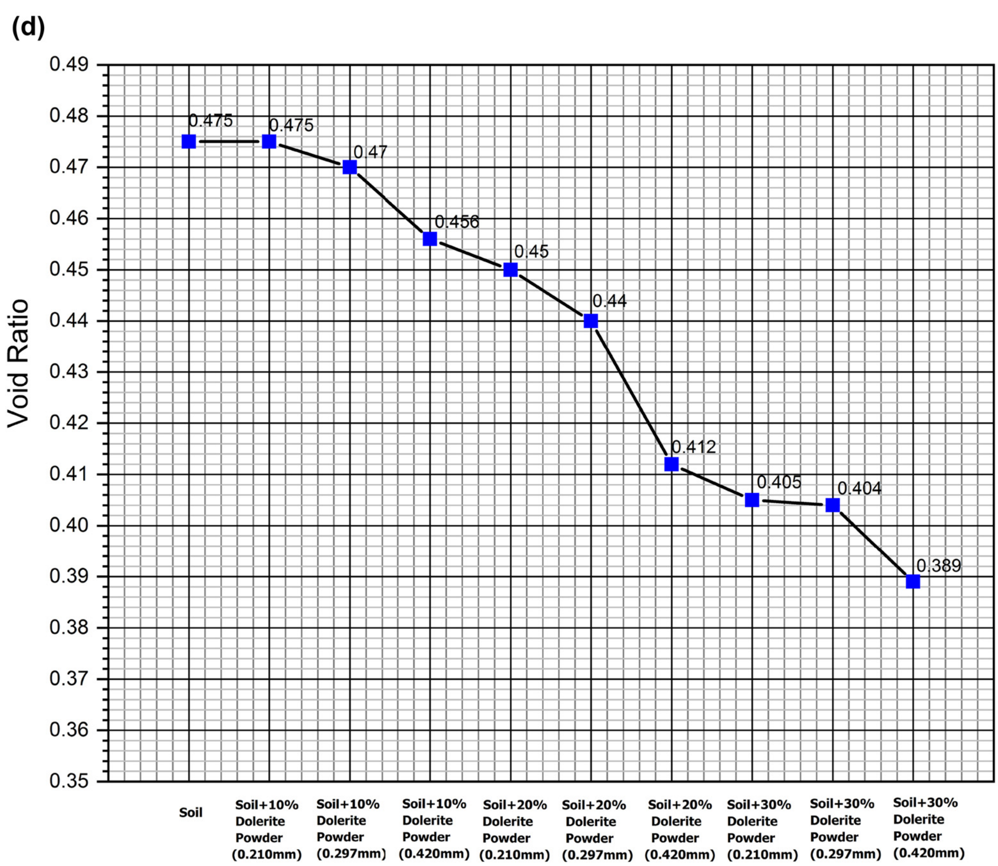
(a)

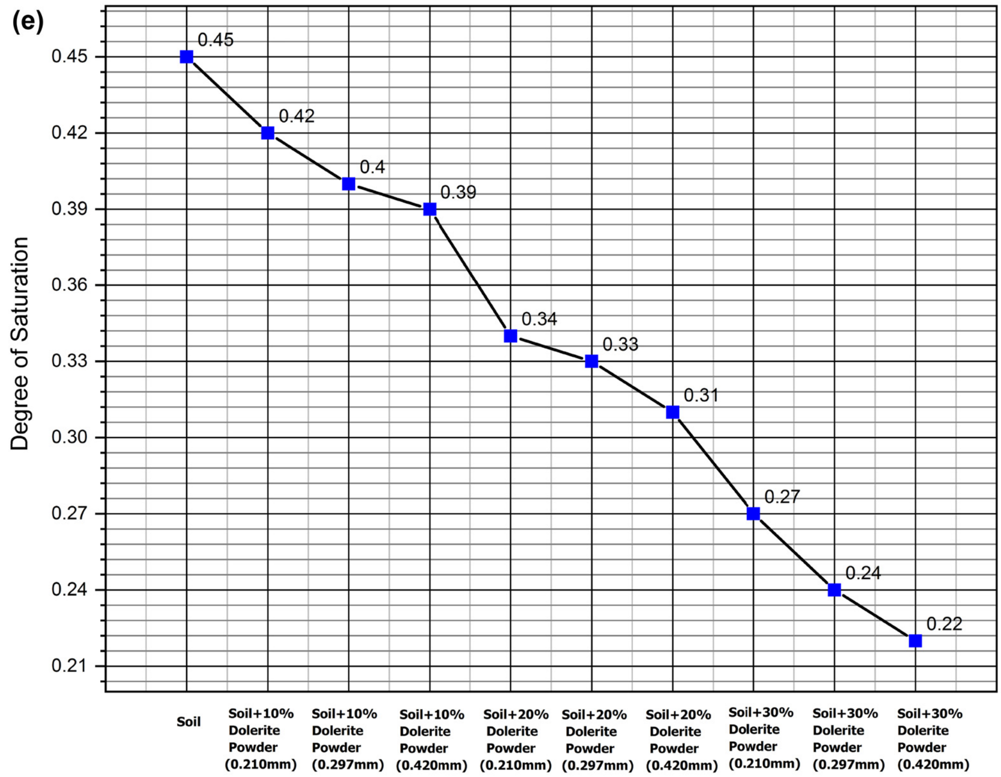

25
20
15
10
5
0
Maximum Dry Density (kN/m3)
Optimum Moisture Contents (%)
Soil
Soil+10% Dolerite Powder (0.210mm)
Soil+10% Dolerite Powder (0.297mm)
Soil+10% Dolerite Powder (0.420mm)
Soil+20% Dolerite Powder (0.210mm)
Soil+20% Dolerite Powder (0.297mm)
Soil+20% Dolerite Powder (0.420mm)
Soil+30% Dolerite Powder (0.210mm)
Soil+30% Dolerite Powder (0.297mm)
Soil+30% Dolerite Powder (0.420mm)

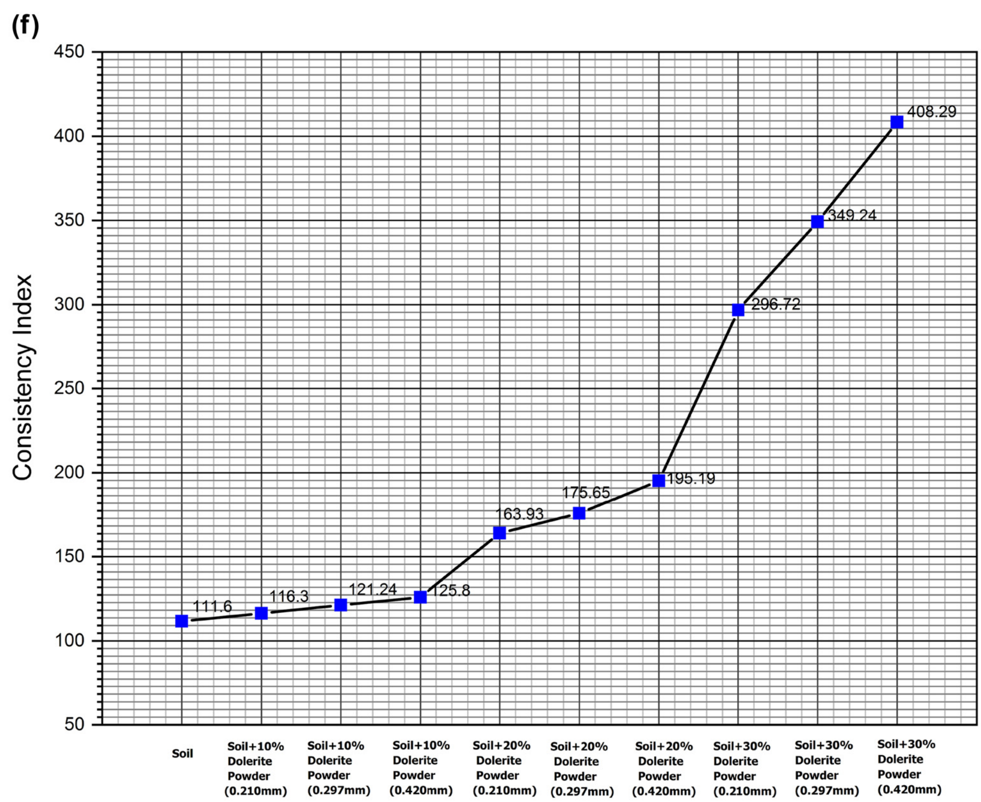
(b)


Specific gravity
2.85
2.82
2.79
2.76
2.73
2.70
2.67
2.64
2.61
2.58
2.55
2.55
2.6
2.61
2.63
2.66
2.68
2.7
2.74
2.77
2.81
Soil
Soil+10% Dolerite Powder (0.210mm)
Soil+10% Dolerite Powder (0.297mm)
Soil+10% Dolerite Powder (0.420mm)
Soil+20% Dolerite Powder (0.210mm)
Soil+20% Dolerite Powder (0.297mm)
Soil+20% Dolerite Powder (0.420mm)
Soil+30% Dolerite Powder (0.210mm)
Soil+30% Dolerite Powde (0.297mm)
Soil+30% Dolerite Powder (0.420mm)


(c)
Porosity
0.330
0.319
0.308
0.297
0.286
0.275
0.322
0.321
0.32
0.313
0.31
0.305
0.292
0.288
0.288
0.28
Soil
Soil+10% Dolerite Powder (0.210mm)
Soil+10% Dolerite Powder (0.297mm)
Soil+10% Dolerite Powder (0.420mm)
Soil+20% Dolerite Powder (0.210mm)
Soil+20% Dolerite Powder (0.297mm)
Soil+20% Dolerite Powder (0.420mm)
Soil+30% Dolerite Powder (0.210mm)
Soil+30% Dolerite Powder (0.297mm)
Soil+30% Dolerite Powder (0.420mm)


(d)
Void Ratio
0.49
0.48
0.47
0.46
0.45
0.44
0.43
0.42
0.41
0.40
0.39
0.38
0.37
0.36
0.35
0.475
0.475
0.47
0.456
0.45
0.44
0.412
0.405
0.404
0.389
Soil
Soil+10% Dolerite Powder (0.210mm)
Soil+10% Dolerite Powder (0.297mm)
Soil+10% Dolerite Powder (0.420mm)
Soil+20% Dolerite Powder (0.210mm)
Soil+20% Dolerite Powder (0.297mm)
Soil+20% Dolerite Powder (0.420mm)
Soil+30% Dolerite Powder (0.210mm)
Soil+30% Dolerite Powder (0.297mm)
Soil+30% Dolerite Powder (0.420mm)


(e)
Degree of Saturation
0.45
0.42
0.39
0.36
0.33
0.30
0.27
0.24
0.21
0.45
0.42
0.4
0.39
0.34
0.33
0.31
0.27
0.24
0.22
Soil
Soil+10% Dolerite Powder (0.210mm)
Soil+10% Dolerite Powder (0.297mm)
Soil+10% Dolerite Powder (0.420mm)
Soil+20% Dolerite Powder (0.210mm)
Soil+20% Dolerite Powder (0.297mm)
Soil+20% Dolerite Powder (0.420mm)
Soil+30% Dolerite Powder (0.210mm)
Soil+30% Dolerite Powder (0.297mm)
Soil+30% Dolerite Powder (0.420mm)


(f)
Consistency Index
450
400
350
300
250
200
150
100
50
111.6
116.3
121.24
125.8
163.93
175.65
195.19
296.72
349.24
408.29
Soil
Soil+10% Dolerite Powder (0.210mm)
Soil+10% Dolerite Powder (0.297mm)
Soil+10% Dolerite Powder (0.420mm)
Soil+20% Dolerite Powder (0.210mm)
Soil+20% Dolerite Powder (0.297mm)
Soil+20% Dolerite Powder (0.420mm)
Soil+30% Dolerite Powder (0.210mm)
Soil+30% Dolerite Powder (0.297mm)
Soil+30% Dolerite Powder (0.420mm)

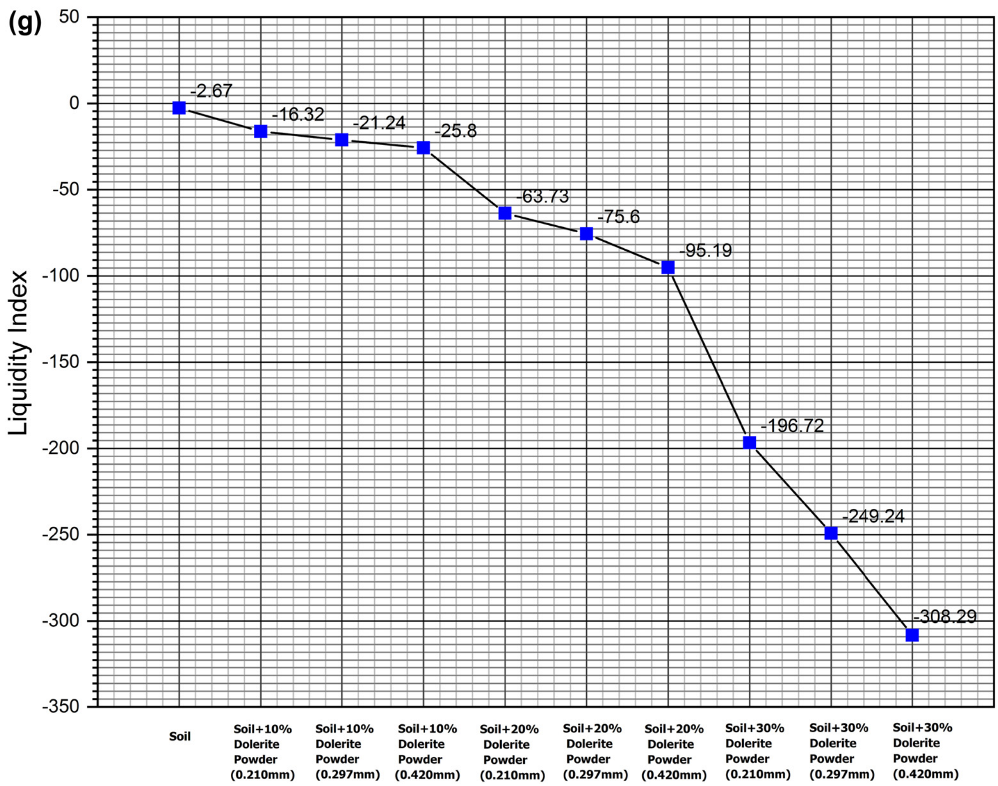


Figure 6: Impact of the amount and grain size of dolerite powder on the geochemical parameters of clay soil: (a) compaction parameters, (b) Gs, (c) porosity, (d) void ratio, (e) degree of saturation, (f) CI, and (g) LI.

Although the original (untreated) soil sample was classified as A7-6 type, the up to 30% addition of dolerite powder with different grain sizes as an admixture upgraded the soil to A4 type.

The values of compaction parameters (MDD and OMC) are displayed in Figure 6a. The addition of dolerite powder significantly improved the soil in terms of these two parameters, that is, enhancement in MDD and reduction in OMC. The observed positive impact on both the compaction properties is higher from coarser than the finer powders.

The impact of addition of dolerite powder on the soil Gs is illustrated in Figure 6b. As shown in the figure, an increase in the amount of the added dolerite powder enhances Gs. Addition of the dolerite powders reduced the values of porosity, void ratio, and degree of saturation, and hence improved the quality of soil especially its CBR and UCS (Figures 6c–e and 7a and b). The finer powders diminished these parameters to a lesser extent than the coarser powders. The data on CI and LI for the studied soil samples are shown in Figure 6f and g. The addition of dolerite led to an enhancement in CI and reduction in LI, that is, an improvement in the soil quality. The coarser dolerite powder caused greater improvement than the medium and finer ones.

4 Discussion

Knowledge of the Atterberg limits, compaction properties, and strength parameters is important for a better understanding of the behavior of clay soil, especially its bearing capacity and consolidation. The investigated clay soil is weak and of poor quality (Figure 5) as it exhibited high LL, OMC, and PI, and low CBR and UCS, most probably because of dickite and montmorillonite as its constituents. The addition of three different proportions of dolerite waste as powder with varying grain sizes has improved all these parameters. The values of LL, PI, and OMC were utilized also for determining the CI and LI values of the soil. Although being very important parameters for explaining the geotechnical behavior of soil, CI and LI had rarely been included in most of the previously published studies on soil stabilization. The LI is a measure of the extent of closeness of the soil moisture content to its LL. Where the soil is at its LL, the value of its LI is 100% and the soil acts as a liquid. In contrast, zero LI means that the soil is at its PL, while negative values of LI indicate that the water content of soil is lower than its PL and so the soil is hard [35]. In the present study, it was observed that the addition of dolerite powder

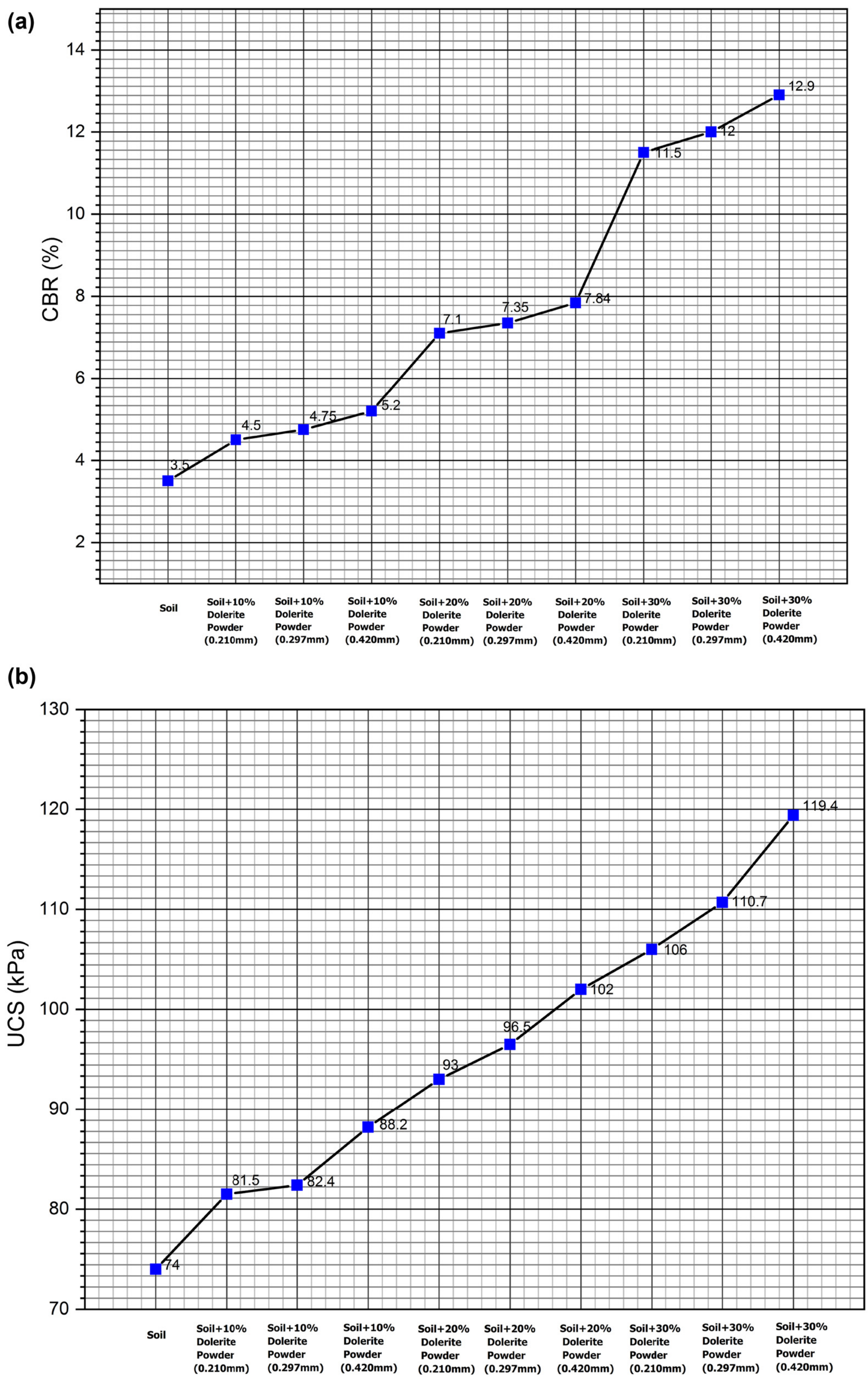


Figure 7: (a) Impact of the amount and grain size of dolerite powder on the CBR of clay soil. (b) Impact of the amount and grain size of dolerite powder on the UCS of clay soil.

reduced the values of LI, which means that the soil was getting harder, and led to an improvement in its bearing capacity.

A soil with zero CI means that it is in the liquid state and thus very soft and weak, whereas soil possessing high (e.g., 100) CI indicates that it is in the plastic state, that is, it is firmer/stronger. The soil becomes strong when its CI exceeds 100; increases in CI beyond 100 increases the strength of the soil significantly [34]. Dolerite addition enhances the soil CI and thus its suitability for construction. A possible reason for such a significant improvement in the Atterberg limits as well as of LI and CI could be that, unlike the untreated soil, the added dolerite waste powder can hold a very low amount of water (Table 3). The low water absorption capacity of dolerite is because it contains high amount of clinopyroxene and plagioclase minerals that are less hydrophilic (Figure 3). The addition of dolerite and thus less hydrophilic constituents reduces the concentration of water-friendly clay minerals in the treated soil. As a result, the water absorption capacity and hence the values of Atterberg limits and consistency parameters of the dolerite-treated soil samples are diminished. Similar improvements were also documented by various researchers [15–18,36,37] in their studies regarding clay stabilization through a variety of rock and industrial stone admixtures.

Characterization based on Atterberg limits groups the clay soil from the study area with soil of the A7-6 type (Figure 5). According to the relevant AASHTO standards, the strength of A7-6 soils is fair to poor. The addition of up to 30% dolerite waste powder upgrades the investigated soil to the A4-type, whose strength is considered to be excellent to good (AASHTO classification). The observed significant improvement in strength shows the suitability of dolerite waste for stabilization of clay soils.

The treatment with dolerite waste results in a reduction in the soil porosity, void ratio, and degree of saturation in addition to improving the compaction and strength parameters. The soil porosity, void ratio, and degree of saturation are directly related to soil bearing capacity as a reduction in their values enhances the soil's MDD, CBR, and UCS and hence lessens settlement issues. The observed increase in MDD, CBR, and UCS is obviously because the added dolerite waste powder is markedly denser than the pristine soil.

In addition to amount, grain size of the admixture is also found to be important in improving the geotechnical quality of soil as the addition of equal amount (e.g., 30%) of compositionally the same dolerite powder but with different grain sizes improves the soil properties to significantly different levels. Specifically, the impact of coarser admixture on soil stabilization is considerably higher than that caused by finer but otherwise similar substance. One of the possible explanations for this disparity could be that an increase in grain size leads to a decrease in specific surface area and thus a reduction in the moisture content, porosity, and enhancement in density, which in turn lowers the LL, PI, LI, porosity, degree of saturation, and void ratio, and enhances the values of PL, CI, MDD, UCS, and CBR.

5 Conclusion

Results from the current investigation lead to the following conclusions:

(1) The data on compaction parameters, Gs, and Atterberg limits can be used effectively in weight–volume relationships for the determination of void ratio, porosity, degree of saturation, LI, and CI of compacted clay.
(2) The addition of up to 30% dolerite powder significantly improves the geotechnical quality of compacted clay by (a) enhancing MDD, UCS, CBR, CI, and Gs and (b) significantly reducing porosity, void ratio, degree of saturation, OMC, LL, and PI. Hence, dolerite powder can be used as an admixture for clay stabilization.
(3) The positive impact on compacted clays is higher from coarser than finer dolerite powders.

Author contributions: This study is designed and completed by Syed Husnain Ali Shah (Lecturer, Department of Earth and Environmental Sciences, Hazara University, Mansehra, Pakistan) as the principal investigator under the guidance and technical support of Dr. Mohammad Arif (PhD, Leicester University, England). Dr. Arif also helped in manuscript writing and proofreading. Mr. Qasim ur Rehman (Assistant Professor, Department of Earth Sciences, University of Haripur, Haripur, Pakistan) and Mr. Fawaz Manzoor (PhD scholar, Department of Earth Sciences, University of Haripur, Haripur, Pakistan) performed the unconfined compressive strength test and also helped in the improvement of figures.

Conflict of interest: Authors state no conflict of interest.

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