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Research Paper

Experimental Investigation on the Effect of Teff Straw Fiber and Lime on Strength and Compressibility of Black Cotton Soil

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Abstract

Black cotton soils often do not meet the geotechnical requirement as they exhibit high swelling-shrinkage behavior and compressibility. Therefore, stabilization of such soils with different additives is a common practice in geotechnical engineering. On the other hand, replacing traditional stabilizers with industrial and agricultural by-products has both economic and environmental significance. In this work, the effect of teff straw fiber, which is one of the common agricultural by-products in Ethiopia, on strength and compressibility characteristics of black cotton soil, was investigated. The combined effect of fiber reinforcement and lime treatment was also investigated. The black cotton soil sample was collected from Sendafa town. Samples of soil reinforced with various contents (0%, 0.5%, 0.75%, and 1% by weight) and lengths (20mm, 40mm, and 60mm) of teff straw fibers and mixed with various percentages of lime (2%, 4%, and 6%) were prepared to conduct compaction test, unconfined compressive strength (UCS) test, and consolidation test. The result showed that maximum dry density (MDD) decreased and optimum moisture content (OMC) increased with increasing both fiber and lime percent, while USC increased until 0.75% for teff straw fiber with each length and 4% (optimum %) of lime. The strength increased by more than double when the soil is reinforced with optimum percentage (0.75%) of fiber content and treated with lime (4%) as compared to when the soil is stabilized by lime (4%) only. Similarly, fiber reinforcement and lime stabilization significantly reduced the compressibility and swelling potential of soil. The finding of the work suggests that a combination of fiber reinforcement and lime stabilization is more effective for ground improvement than lime stabilization or fiber reinforcement alone.

1. Introduction

All engineering structures are built on or in the ground. However, the undesirable behavior of black cotton soil such as high swelling-shrinkage, excessive and uneven settlement make constructions on expansive black cotton soils challenging (Nelson and Miller, 1992; Prusinski and Bhattacharja, 1999; Atahu et al., 2019). Avoiding construction on such soils is one alternative considered in engineering practice. However, currently because of the limitation of land due to rapid population growth and increase in urban development, there is a tendency towards enhancing the properties of the soil and reuse it rather than avoiding the site. Various soil improvement techniques such as mechanical method, soil reinforcement, or adding some admixtures within the soil are commonly employed to enhance the engineering properties of soil (Diamond and Kinter,

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1965; Verhasselt, 1990; Bell, 1996; Maubec et al., 2017; Guidobaldi et al., 2017; Vitale et al., 2017). The suitability of particular methods depends upon the site condition and economy.

Chemical stabilization techniques involve the addition of chemical binders such as lime, cement, fly ash, etc., and a combination of them. In the presence of these additives, swelling potential and plasticity of clayey soil decrease in the short-term, and mechanical strength increases in the long-term (Bell, 1996; Al-Mukhtar et al., 2010; Pomakhina et al., 2012; Eisazadeh et al., 2012; Guidobaldi et al., 2017; Vitale et al., 2017; Das et al., 2021). The long-term stabilization is related to precipitation of cementitious hydrated gel, while the short term modification is related to exchange of surface cations by calcium. Even though chemical stabilization improves mainly the soil property under compression, its effect on the tensile behavior of soil is minimal (Wang et al., 2019).

Soil reinforcement is also an important practice in geotechnical engineering to enhance stability, increase bearing capacity and tensile strength, and reduces settlements and lateral deformation of soil (Wang et al., 2019; Murthi, 2020; Taha et al., 2021). Several researchers investigated the application of various inclusion of synthetic and natural fiber reinforcement in weak soils such as polypropylene, carbon, nylon, steel mesh, sisal, coir, bamboo, Enset ventricosum, wheat straw, oil palm, palm kernel and coconut palm fiber (Yusoff, 2010; Hejazi, 2012; Deb and Narnaware, 2015; Mehta, 2017; Maja, 2018; Salim et al., 2018; Jeludin et al., 2019; Wang et al., 2019; Murthi, 2020; Bao et al., 2021; Taha et al., 2021; etc.). Adding both synthetic and natural fiber in clay soil improves the tensile behavior and cohesion among the soil particles and reduces compression index and volume compressibility up to certain fiber content. Moreover, combining fiber reinforcement with chemical treatment such as lime and cement has been reported to be more effective in altering undesirable soil behavior (Khandaker, 2011; Shen et al., 2021). However, the reported optimum fiber content in previous works was different for different fibers and soil type. Therefore, it is important to know the optimum fiber content considering the fiber and soil type for use in the engineering practices.

The use of locally available natural fibers as a reinforcement material can potentially be cost effective and environmentally friendly. Hence, recently, there is a tendency to replace traditional chemical stabilizers and synthetic fibers with industrial and agricultural by-products. Teff straw fiber is agricultural by-products of teff which is the famous small-grained cereal in Ethiopia. Even though teff grain yield is low compared to other cereals, its processing generates significant amounts of agricultural by-product. The proper utilization of this material has both economic and environmental benefits. There are only a few studies that describe the beneficial use of teff straw fiber in soil improvement. It is found that random inclusion of teff straw in soil is effective in increasing compressive strength and unsoaked CBR values of expansive soil (Tirfu Maja, 2018; Abebe Arega, 2020). However, to date, there is no studies that focused specifically on the use of the teff straw fiber to improve compressibility performance of soil. The present work, therefore, aimed to investigate the influence of teff straw fiber on consolidation characteristics of black cotton soil. In addition, the combined effect of teff straw fiber reinforcement and lime treatment was also investigated.

2. Materials and Methods

2.1. Expansive Soil

The black cotton soil sample used in this study was collected from Sendafa town where the area is predominantly covered by expansive soil. In this town and surrounding areas, the high swelling and shrinkage potential of the soil and its effect is commonly manifested by cracks on floors, walls and pavement. The soil sample was collected from a depth of 1.5 m by excavating test pit. The basic properties of the soil are summarized in Table 1. It is classified as CH and A-7-6 as per the unified soil classification and American Association of State Highway and Transportation Officials (AASHTO) classification system, respectively.

2.2. Teff Straw Fiber and Lime

Teff straw fibers were also collected around Sendafa town from farming communities. It is the predominant cereal crop produced in the area and its processing produces large volume of straw fiber. A proper usage of this agricultural by-product material can obviously reduce storage areas and environmental concern arising from the disposal. The physical characteristics of fiber were determined in the laboratory and the outcomes are tabulated in Table 2. Hydrated lime ($Ca(OH)_2$) with purity > 90% was used in this study.

2.3. Experimental Work

Four types of samples were prepared: pure soil, teff straw fiber reinforced soil, lime treated soil and lime treated-teff straw fiber reinforced sample (Table 3). Compaction, UCS on 7 days cured conditions, and consolidation test were conducted on the prepared samples. All tests were conducted as per ASTM standards. Soil samples reinforced with different percentages (0.5, 0.75 and 1% by weight of dry soil) and lengths (20, 40 and 60mm) of teff straw fiber were prepared by mixing manually the fiber with soil. For each mix, the MDD and OMC were determined from proctor compaction test. For UCS test, cylindrical soil sample were prepared by compacting the soil mixed with fiber at respective OMC to attain the MDD. The test was conducted on samples at a deformation rate of 1%/min until shear failure. The correlations between compressive stress and strain were recorded to plot stress-strain curve and to identify the peak load. Then, the optimum length and percentage of teff straw fiber were determined from the test result. For the preparation of lime treated-fiber reinforced soil, the soil sample were first thoroughly mixed with different percentages of lime (2%, 4%, and 6% by weight) and mixed with optimum length and percentage of teff straw. After that, the optimum lime content was added to soil and reinforced with optimum percentages of fiber for the consolidation test. The samples were subjected to compression and recompression. The loading and unloading were conducted by doubling and halving the load, respectively. The time duration for all load increments and decrements was 24 h.

Table 1: Properties of soil

Properties	Results
Specific gravity	2.78
Liquid Limit (%)	81.8
Plastic Limit (%)	32.18
Plasticity Index (%)	49.62
Free swell (%)	70
Sand (%)	6.80
Silt (%)	48.20
Clay (%)	45.00
Maximum dry density (MDD) (Kg/m^3)	1452
Optimum moisture content (OMC) (%)	24.06
Natural Moisture Content (%)	40.31

Table 2: Physical characteristics of teff straw fiber

Properties	Result
Water absorption (%)	60.7
Average length (cm)	5
Average diameter (mm)	0.4
Angle of bending before break	260^o-280^o
Color	Brown-reddish and white

Table 3: Mix proportions of black cotton soil, lime, and teff straw fiber

Material used and Mix Proportion (%)				Test conducted		
Black cotton soil	Teff straw fiber		Lime	Standard Compaction test	UCS test	One-dimensional Consolidation test
	Percentage	Length				
100	-	-	-	✓	✓	✓
99.5	0.5	20 and 40mm	-	✓	✓	-
99.25	0.75		-	✓	✓	-
99	1		-	✓	✓	-
99.5	0.5	60mm	-	✓	✓	-
99.25	0.75		-	✓	✓	✓
99	1		-	✓	✓	-
97.25	0.75	60mm	2	✓	✓	-
95.25	0.75		4	✓	✓	✓
93.25	0.75		6	✓	✓	-
96	0	60mm	4	✓	✓	-
95.5	0.5		4	✓	-	✓
95	1		4	✓	-	-

3. Result and Discussion

3.1. Compaction Characteristics

Figure 1 demonstrates the influence of teff straw fiber content and length on MDD and OMC. It can be seen from the figure that MDD decreased and OMC increased as the percentage of fiber increased. The effect is related to the lower density and high water absorption properties of fiber compared to the soil. On the other hand, as the length of fiber increased, both OMC and MDD decreased. The decrease of OMC with increasing fiber length in contrary to fiber content may be related to a strong reinforcement between soil particles by longer fibers that results lower porosity and water absorption.

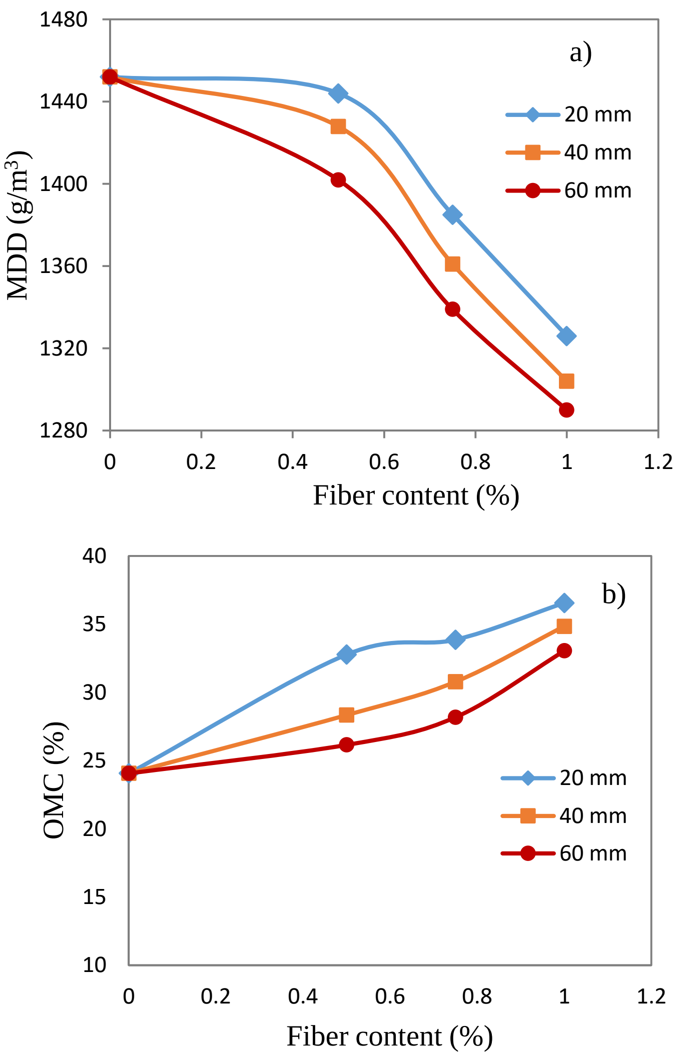

Figure 1: Variation of MDD (a)) and OMC (b) of soil fiber percentages and lengths

3.2. Strength of fiber reinforced Soil

Figure 2 shows the influence of teff straw fiber content and length on strength of the soil. As the percentage and length of teff straw fiber increased, the UCS and cohesion of the soil tended to increase, but it decreased when the fiber content increased more than 0.75%. Hence, 0.75% of fiber content is found to be the optimum percentage of fiber for different length. The strength of the soil increased due to a strong reinforcement between soil particles which restrict movement of soil particles during deformation by external load. This binding ability increased with increasing the length of the fiber (from 20 to 60 mm), however the effect is more pronounced when the fiber length increased from 40 to 60 compared to length change 20 to 40 mm. When the fiber content increased more than the optimum fiber content (0.75%), effect on soil particles reinforcement and strength is negative as the fibers occupies the space of the original soil particles and compactness of soil decreases (Zhao et al., 2020).

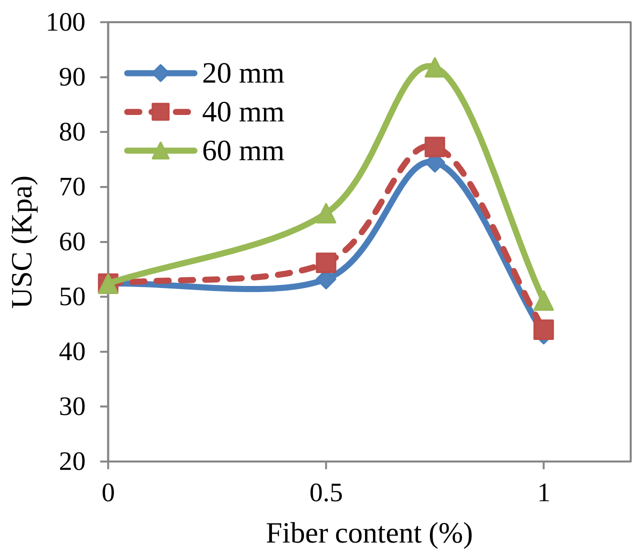

Figure 2: Variation of UCS with content of teff straw fiber

3.3. Effect of Lime on Strength of Fiber Reinforced Soil

Figure 3 shows the influence of lime treatment on strain-stress relationship of soil reinforced by optimum content of teff straw fiber (0.75%). The stiffness and strength of the fiber reinforced soil improved with increasing lime content up to 4% and decreased for a further increase to 6% (Figure 4). Therefore, lime content

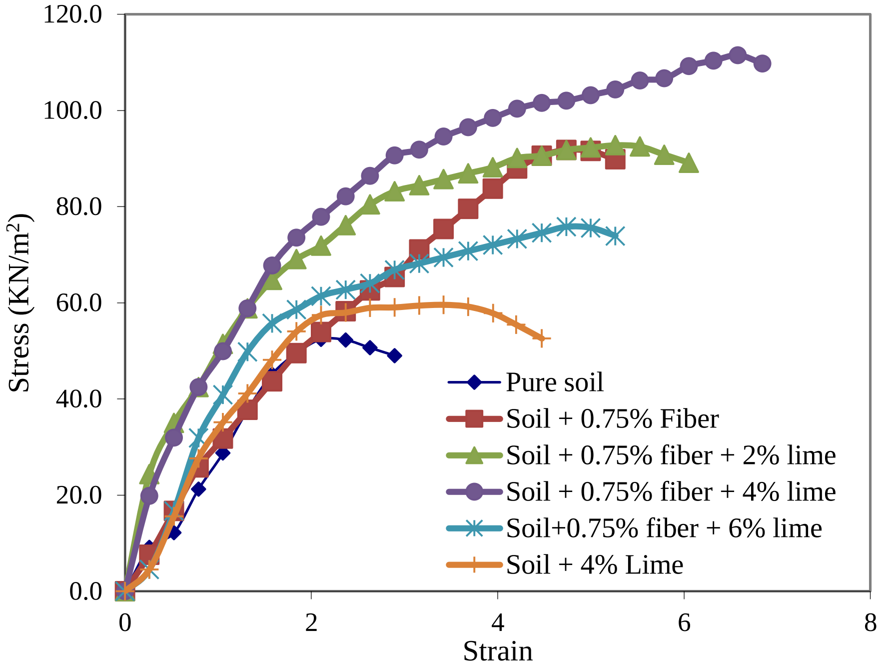

Figure 3: Stress-Strain relationship of fiber reinforced soil for different lime content (7 days cured).

of 4% is considered as the optimum lime percentage for further study. The improvement in strength of the soil with lime treatment can be attributed to the short-term cation exchange reaction and long-term pozzolanic reaction that leads to flocculation of soil particle and precipitation of cementitious material, respectively (Diamond and Kinter, 1965; Verhasselt, 1990; Bell, 1996; Deneele et al., 2016; Maubec et al., 2017; Guidobaldi et al., 2017; Vitale et al., 2017). It is also worth to notice that the increase in strength brought by combination of lime stabilization and fiber reinforcement is almost 8 times that derived from lime treatment alone (4% lime treated) for 7 days curing time. It indicates that a combination of teff straw fiber reinforcement and lime treatment is more effective for ground improvement than lime stabilization alone. In addition, the fiber reinforcement imparted strain-hardening behavior to the mechanical behavior of the soil, while lime treated and raw soil exhibit strain-softening behavior.

3.4. Effect of Lime on Compressibility of Fiber Reinforced Soil

3.4.1. Compression and Re-compression Index

The results of consolidation test are depicted in Figure 4 as a relationship between the void ratio and the logarithm of effective stress curve for the untreated soil, fiber reinforced soil and fiber reinforced-lime treated soil. It can be seen that at a given pressure level, the void ratio of fiber reinforced soil and fiber reinforced-lime stabilized soil (Figure 4) is lower than the natural soil. It can be attributed to the filling/closure of the void with teff straw fiber and cementitious hydrated gel. In addition, the compression index decreased when soil is reinforced with teff straw fiber, stabilized by lime and lime stabilization and fiber reinforcement coupled (Figure 5). However, the combination of lime treatment and fiber reinforcement is more effective in decreasing the compressibility of the soil than lime treatment or fiber reinforcement alone. This is also noticed in the comparisons of the recompression index between the combined treatment and the individual treatments (Figure 6). The effect is appeared to be coupling rather than a simple summation of their respective effects as the decrease in compression and recompression brought by 0.75% fiber reinforcement of 4% lime treated soil is higher than the sum of change brought by individual treatment. The reduction of recompression and compression index is probably due to the fiber reinforced soil mass and the soil particles cemented together by cementitious hydrated gel, which prevents soil particles movement during deformation and swelling during water absorption.

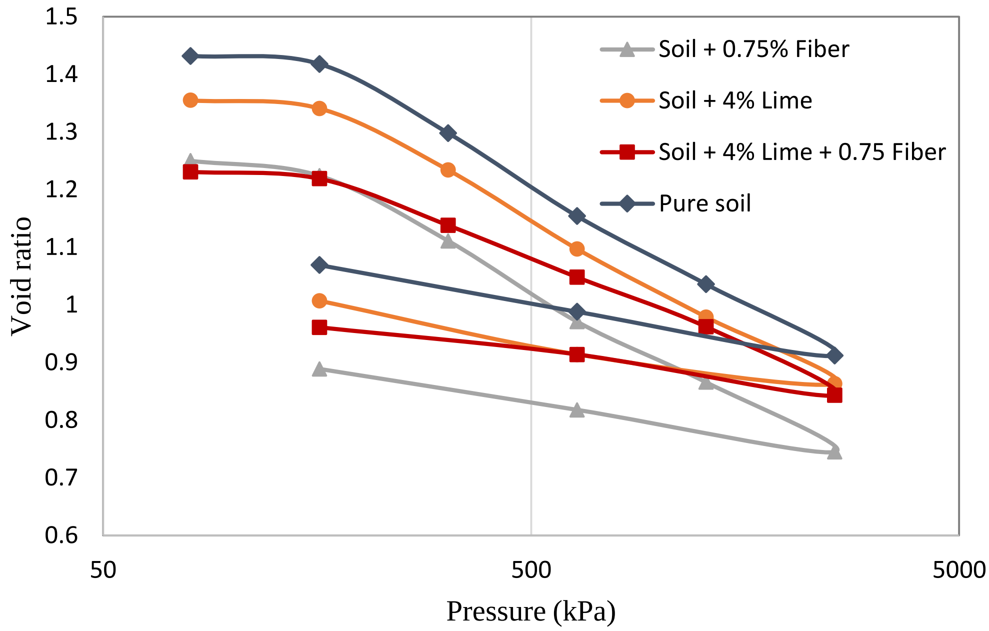

Figure 4: Void ratio-pressure curves (logarithm) for untreated and treated soils

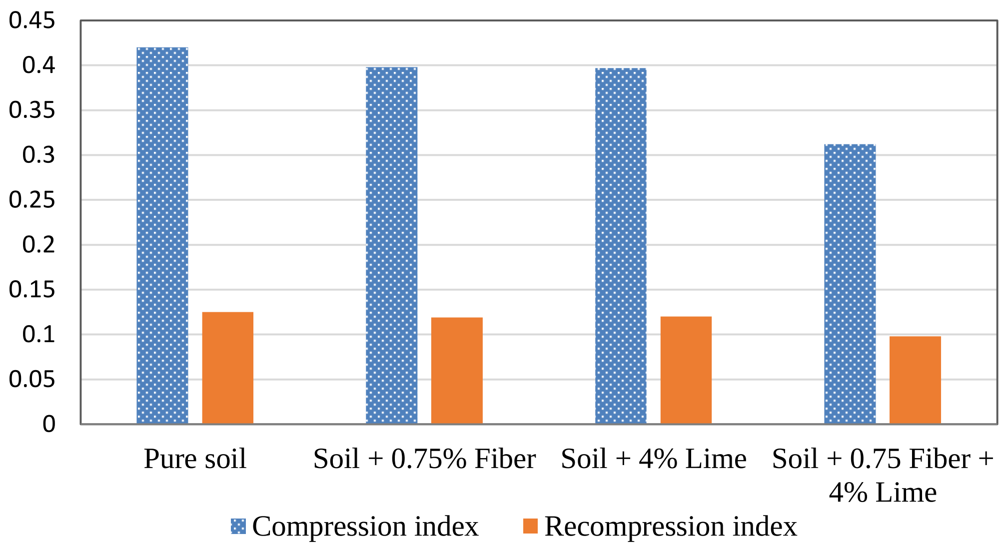

Figure 5: Void ratio-pressure curves (logarithm) for untreated and treated soils

3.4.2. Consolidation Characteristics

The coefficient of consolidation, which is determined by using Taylor's square root of time fitting method for different loading pressure, increased both when the soil is reinforced with teff straw fiber and stabilized with lime. However, the change (increase) in coefficient of consolidation is more pronounced for a combination of fiber reinforcement and lime stabilization (Figure 6). The increase in coefficient of consolidation implies that the duration of consolidation (i.e. the time for dissipation of excess pore water pressure) reduced after the soil treated with lime and reinforced by fiber. Similar improvement of the coefficient of consolidation was observed for coir fiber (Jeludin et al., 2019) and synthetic fiber (Deb and Narnawar, 2015) reinforced soil. This is probably related to increase in pore size or interconnected pore space due to flocculation of soil particles (by lime) and interlocking between the soil particles and fibers. This in turn increases the permeability of the soil. Generally, the combination of lime treatment and fiber reinforcement in clay soil not only increases the stuffiness of the soil, but also increases the rate of consolidation

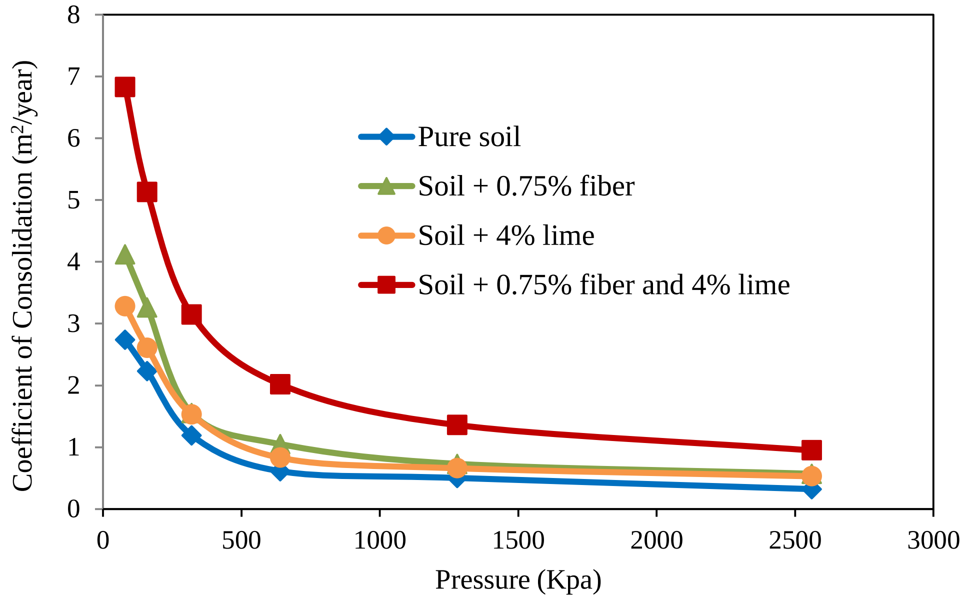

Figure 6: Coefficient of consolidation versus pressure for different conditions.

4. Conclusion

In this study, the effect of teff straw fiber reinforcement, lime treatment and the combination of them on the strength and compressibility behavior of black cotton soil was investigated and the following conclusions were drawn:

- Unconfined compressive strength of the soil increases when fiber content increases from 0% to 0.75% and decreases when fiber content increases > 0.75%. The specimens reinforced with 0.75% content of 60 mm length showed the highest strength. Hence, the optimum teff straw fiber required for stabilizing the soil was found to be 0.75% by dry weight.
- The strength of soil also increased with increasing lime content from 0% to 4% and decreased for further increase to 6%. Therefore, for the investigated soil, the optimum lime content was found to be 4%.
- The combination of fiber reinforcement and lime treatment produced high increase in strength of the soil as compared to lime treatment or fiber reinforcement alone.
- The combination of lime treatment and fiber reinforcement not only reduced the compressibility of the soil, but also increases the rate of consolidation which can reduce the duration of consolidation and leads to an improvement in the stability and bearing capacity of the soil.

Generally, a combination of teff straw fiber reinforcement and lime stabilization is more effective for ground improvement. In addition, the potential use of this fiber as a stabilization admixture has dual advantage in terms of cost and environmental concerns related to using chemical stabilizers.

However, further research is recommended to explore and understand stabilization/or reinforcement mechanism. The durability of the stabilized soil shall also be checked as it is important requirement for use in engineering practice.

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