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Stabilization of Problematic Expansive Clays Using Polypropylene Fiber Reinforcement

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ABSTRACT

This experimental study examines the efficacy of the inclusion of randomly distributed polypropylene fiber *(PP)* reinforcement on the engineering properties of expansive clays. The effect of *PP* fiber inclusions (0%-0.8%) on compaction, unconfined compressive strength *(UCS)*, elastic modulus *(E_{50})*, California bearing ratio *(CBR)* and swell–consolidation parameters of test soil were explored. Experimental results showed significant improvement in the strength parameters of treated soils with an optimal fiber content at about 0.4% by weight of soil. The swell–consolidation parameters were also observed to be significantly ameliorated in fiber-reinforced samples. Test results indicate that the use of PP fiber as a reinforced stabilizer for expansive clays not only benefits the sustainable utilization of fiber wastes in soil stabilization, but also reduces the environmental footprint globally.

KEYWORDS: Polypropylene fibers, Expansive clays, UCS, CBR, Swelling, Consolidation, Soil stabilization.

INTRODUCTION

Expansive clays contain clay minerals, like montmorillonite and illite, showing significant volume changes upon slight variations in moisture content considering the environmental changes (Batool et al., 2021; Hamza et al., 2022a; Ijaz et al., 2022a; Ijaz et al., 2022b). These volumetric changes cause structural damage to pavements, foundations, airport runways and earthen dams by exerting swell pressure (Aziz et al., 2016; Ameer et al., 2022; Hamza et al., 2022b; Sharma & Sivapullaiah, 2016; Ijaz et al., 2022c). These soils are mainly found in the arid and semi-arid regions of Pakistan, South Africa, Australia, Canada, China, India, the United States, … etc. and cause billions of dollars of damage globally. In Pakistan, swelling soils exist in several regions, such as D.I Khan, D.G Khan, Sialkot, Narowal, Chakwal, Gujranwala,… etc. (Ijaz et al., 2020a; Rashid, 2015). Various soil stabilization methods have been developed to lessen the swelling behavior by using different types of techniques, such as pre-wetting, chemical additives, geotextile reinforcement, incorporation of various industrial waste by-products, … etc. (Ali et al., 2020; Aziz et al., 2015; Aziz, 2020; Guney et al., 2007; Hamza et al., 2022c; Ijaz et al., 2020b; Ahmad et al., 2021). However, with growing urbanization, it is always imperative to find new sustainable and low-cost solutions for engineering problems such as expansive clays (Salih et al., 2022; Melese, 2022; Ijaz et al., 2020c).

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Polypropylene (PP) fiber, the most commonly used geotextile material worldwide, has been chosen for this study due to its low cost, as well as hydrophobic and chemically inert nature (Ramasamy & Arumairaj, 2013). PP fiber is a geosynthetic material abundantly produced worldwide in about 4.1 million tons (Fiber Year, 2009). Geosynthetic fibers have been produced in large amounts globally. Polypropylene *(PP)* fibers improve the strength and deformation behavior of problematic expansive clays for pavement constructions. Expansive clays instigate failures, like rutting and fatigue cracks, in flexible pavements and sometimes make the pavements unserviceable.

Different researchers have examined different aspects of PP fibers on various types of soils. For instance, Sogancı (2015) reported the improvement of swelling soil by adding PP fibers and found 1% as optimal PP fiber considering the strength and swelling behavior of the soil. At optimal dosage, the soil UCS values were increased by 40%, whereas the swelling percentage was reduced by 56%. Similarly, Olgun (2013) reported that the inclusion of PP fiber improved the UCS and split tensile strength of clayey soil. It was found that 12 mm long fiber with an optimal value between 0.5% and 0.75% by dry weight of the soil could sufficiently ameliorate the engineering parameters. Moreover, Ramasamy and Arumairaj (2013) evaluated the stabilizing potential of using PP fibers in the improvement of compaction and strength characteristics of soil. Reinforced samples with an optimum value of 0.75% PP fiber showed remarkable improvement in UCS and CBR strength parameters, whereas the maximum dry density (MDD) of reinforced soil slightly decreased compared to unreinforced soil. A similar marginal decreasing trend in MDD with an increase in fiber percentage was also reported by Malekzadeh (2012), whereas UCS values were found to be increased by from 300 kPa to 420 kPa, while the swelling potential was considerably reduced by 57.4% at optimal PP fiber content of 1%. Overall, the literature highlights a promising potential in improving the geotechnical properties of clayey soils.

Although extensive studies have been conducted on soil stabilization by PP fiber reinforcement, minimal studies accounted for the reinforcement of problematic expansive clays with locally available PP fibers. Therefore, this research was conducted to add new information to the literature in this area. For this purpose, a comprehensive experimental investigation was performed to evaluate and examine the engineering properties (such as compaction characteristics, UCS, CBR and swell-consolidation behavior) of fiber-reinforced expansive clay.

MATERIALS AND METHODOLOGY

Test Soil

The soil used in this study was procured from Nandipur town of Gujranwala region, Punjab, Pakistan. It was collected at approximately 1-2.5 m below the ground surface. The soil sample was air-dried and pulverized. The soil sample comprised 38% clay-size, 60% silt-size and 2% sand-size particles and the soil is classified as fat clay (CH) according to the Unified Soil Classification System (USCS). The liquid limit and plastic limit of unreinforced soil were found to be 54.1% and 22.4%.

Polypropylene (PP) Fiber

The PP fibers used in this study are rod-shaped and generally have a uniform and homogeneous section of around 40 µm. PP fibers have very high tensile and flexural strengths and proved to be very effective in dealing with swelling issues of soil. PP fibers were commercially available and procured from Bloom Enterprises, Pakistan. The basic properties of PP fibers are shown in Table 1.

Table 1. Physical properties of polypropylene fibers

Property	Value/Description
Fiber type	Single fiber
Average length (mm)	12
Average diameter (mm)	0.04
Specific gravity, G_s	0.91
Unit weight (g/cc)	0.9-0.91
Breaking tensile strength (MPa)	358
Modulus of elasticity (MPa)	3400
Fusion point (°C)	176
Burning point (°C)	595
Acid and alkali resistance	Very good
Water absorption	Nil
Dispersibility	Excellent

Test Methodology

The test scheme comprised of carrying out different tests pertaining to compaction, strength, swelling and consolidation parameters. The soil samples were reinforced with PP fiber contents varying from 0-0.8%. Initially, the effect of various fiber contents on MDD and OMC was determined against each percentage as per ASTM D1557-12e1. Further, the soil samples were prepared at their respective MDDs and OMCs and subsequently subjected to testing. UCS, CBR (soaked and unsoaked) and swell-consolidation tests were conducted as per ASTM D2166/D2166M-16, ASTM D1883-16 and ASTM D2435/D2435M-11, respectively. In the case of the swelling-potential test, the soil samples were inundated and allowed to swell under a seating load of 7 kPa. It is pertinent to mention here that the outcome of the test results is the average of three test samples to take any potential error into account.

RESULTS AND DISCUSSION

Effect of PP Fiber on Compaction Characteristics

Figure 1(a) shows the effect of fiber inclusion on compaction characteristics of soil in terms of compaction curves under modified compaction effort. The effects of fiber inclusion on MDD and OMC of soil samples are shown in Figure 1(b).

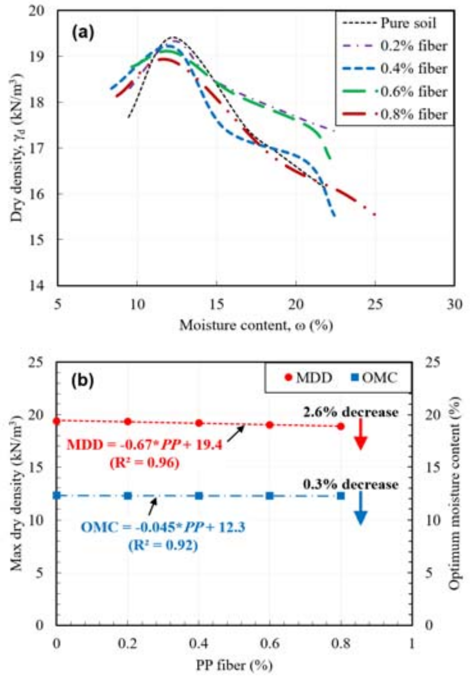


Figure (1): (a) Compaction curves of soil with different fiber contents and (b) Variation of MDD and OMC values of soil samples

Based on modified proctor test results, the MDD of unreinforced soil was marginally decreased by 2.6% (i.e., from 19.4 to 18.9 kN/m^3) with an increase in PP fiber content from 0–0.8%. The slight reduction in MDD with some variation in OMC could be attributed to the low specific gravity of PP fiber, coupled with PP fiber and soil particles' physical interaction which might lead to different micro-structural arrangements. On the other hand, the OMC value of fiber-reinforced soil samples does not show a significant change with fiber addition (falling in the range of 12.3-12.2%) due to the inert nature of PP fiber with no water absorption ability of fiber particles. Researchers (Ramasamy & Arumairaj, 2013; Soğancı, 2015; Viswanadham et al., 2009) observed similar trends in MDD and OMC values of soil samples reinforced with various percentages of PP fiber.

Effect of PP Fiber on UCS and E_{50} of Test Soil

Figure 2(a) presents the schematic sketch to determine the UCS and E_{50} values from the stress-strain curve. In this test, UCS and E_{50} values were calculated according to the presented illustration and the detailed results are shown in Figure 2(b). The test results show that the inclusion of reinforcement up to the optimum fiber content of 0.4% significantly enhanced the UCS of an unreinforced soil sample from 0.126 MPa to 0.211 MPa.

Meanwhile, with fiber content higher than the optimum value (i.e., 0.4%), the UCS value tends to reduce from 0.211 MPa to 0.188 MPa at 0.8% fiber addition. The reduction in soil strength beyond the optimum value could be attributed to excess PP fiber that adversely affects the interlocking force between fiber and soil particles. Likewise, E_{50} of reinforced soil was increased from 10.3 MPa to 17.6 MPa at 0.4% PP fiber content, while beyond 0.4% fiber content, a decreasing trend was observed; i.e., at 0.8%, the E_{50} value of 16.8 MPa was observed. Based on the specifications of Young's modulus proposed by Obrzud (2010), the unreinforced soil sample lies in the category of stiff to very stiff quality (17.6 ≥ 10 MPa). Still, the sample gradually changed to the category of hard quality (17 MPa) after strengthening with 0.4% fiber content.

To further understand the observed improvement at the micro-structural level, Figure 3(a) and Figure 3 (b) present the schematic illustration and scanning electron microscopic (SEM) image of soil–fiber interaction mechanism. The combined effect of interlocking force between soil particles and fiber, bond strength at the interface and frictional resistance between soil-fiber matrices which resist the soil particle movement are mainly responsible for enhancing the strength properties of weak pavement sub-grade.

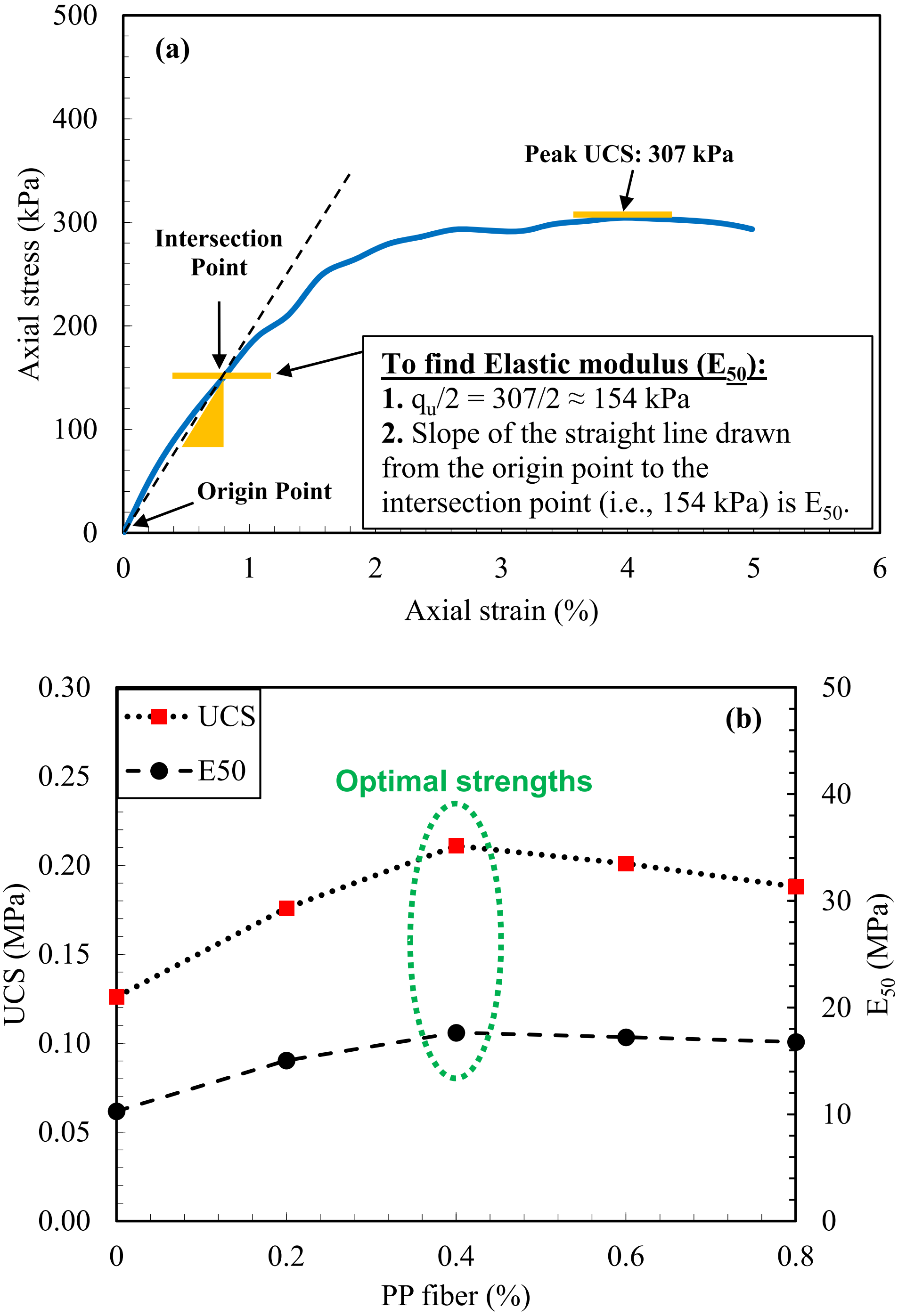


Figure (2): (a) Schematic sketch to determine UCS and E_{50} from the stress-strain curve and (b) Variation of UCS and E_{50} with PP fiber

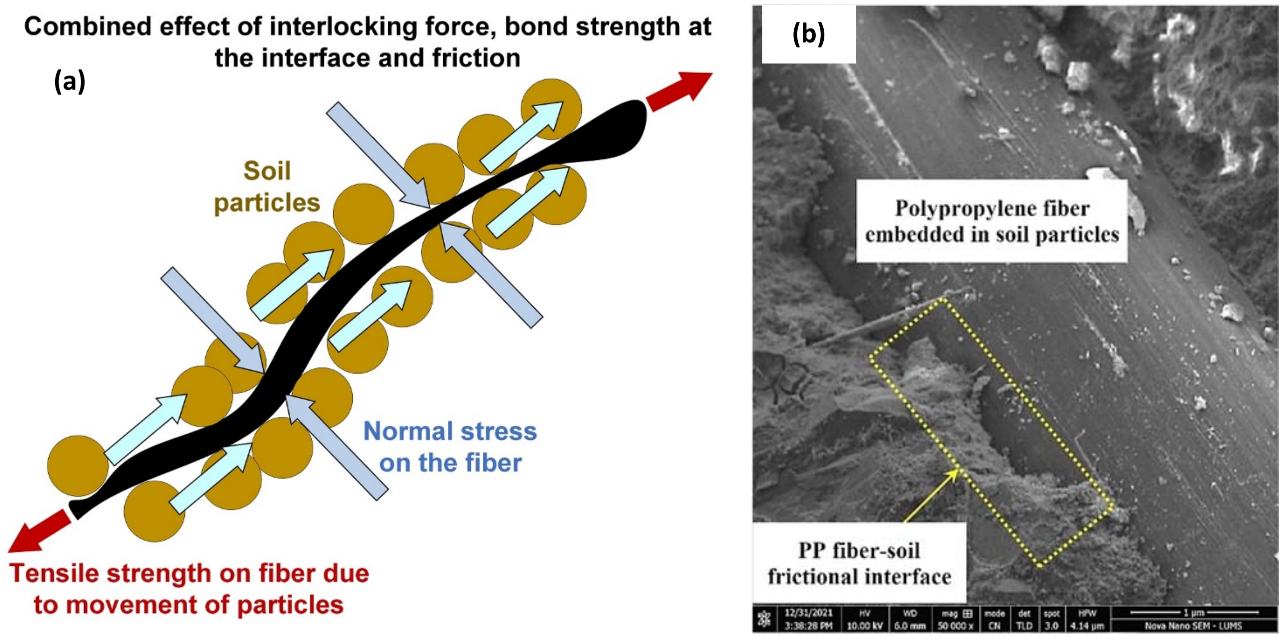


Figure (3): (a) Schematic illustration of soil-fiber interaction and (b) Scanning electron microscopic (SEM) image of soil-fiber interface

Effect of PP Fiber Inclusion on California Bearing Ratio (CBR) of Test Soil

The results of CBR test were presented in the form of load-penetration curves obtained under unsoaked and soaked conditions, as shown in Figure 4. The load-carrying capacity of the soil sample reinforced with fiber percentages (0–0.8%) was notably increased and the optimum dose of fiber was found to be 0.4%, which is consistent with the UCS results. The CBR values of test samples have been calculated for the loads corresponding to the penetration of 2.5 mm and 5.0 mm and the greater of these values has been adopted as CBR value. In the present research, the CBR values of fiber-reinforced soil at 5.0 mm penetration are greater than those at 2.5 mm penetration under both unsoaked and soaked conditions. This clearly shows that the PP fiber reinforcement is more effective in improving the soil strength at more significant deformations by increasing the resistance to penetration.

Figure 5 shows that with the increased percentage of fiber in soil samples up to 0.4% content, unsoaked CBR strength increased by 66% and soaked CBR strength increased by 57% compared to that of unreinforced soil. The increase in CBR value is attributed to the better load-bearing capacity of reinforced soil samples owing to the physical interaction of PP fiber which surrounds the particles and restricts their movement (Fig. 3).

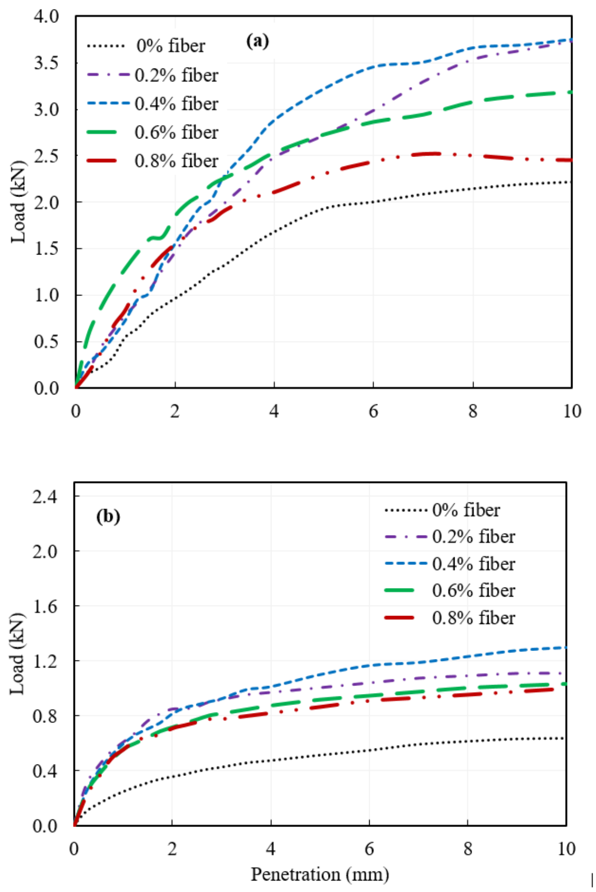
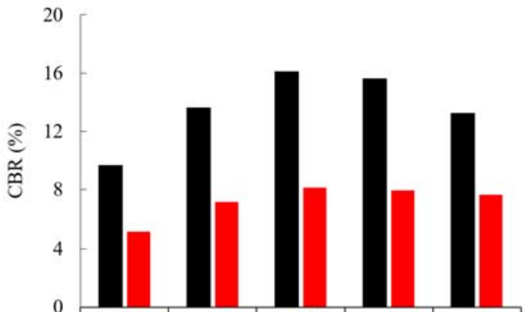


Figure (4): Variation of load-penetration curves (a) Unsoaked CBR and (b) Soaked CBR



	0.0	0.2	0.4	0.6	0.8
Unsoaked CBR	9.7	13.6	16.1	15.6	13.3
Soaked CBR	5.2	7.2	8.2	8.0	7.7

PP fiber (%)

Figure (5): Variation of unsoaked and soaked CBR values of soil samples with PP fiber

Effect of PP Fiber Inclusion on Swell–Consolidation Properties of Test Soil

Swell–consolidation tests conducted on unreinforced and fiber-reinforced soil samples are presented in the form of compression index (C_c), rebound index (C_s), swell percent (S_w) and swell pressure (S_p), as shown in Figure 6. C_c and C_s of unreinforced soil were considerably reduced with fiber addition, as shown in Figure 6(a). The maximum reduction of such soil parameters was observed to start at 0.4% fiber content, whereas no significant improvements were observed afterward. At 0.4% fiber content, the C_c and C_s values were reduced by 32% and 46%, respectively. The reason behind this significant reduction is attributed to the physical interaction of PP fiber and soil particles which restrict the particle movement and provide better resistance against the imposed loading. A similar trend was reported in pertinent literature (Ali et al., 2020; Moghal et al., 2018; Soğancı, 2015; Tang et al., 2016). Likewise, S_w and S_p were also considerably reduced with the inclusion of PP fibers, as shown in Figure 6(b). Based on the specifications proposed by USBR (1998), the soil sample treated with an optimal dosage of fiber (i.e., 0.4% in this study) was changed from medium-swelling class to low-swelling class, whereas the swell percentage of this sample was 0.55% which is less than the proposed permissible limit (i.e., ≤1.5%) for low-swelling class.

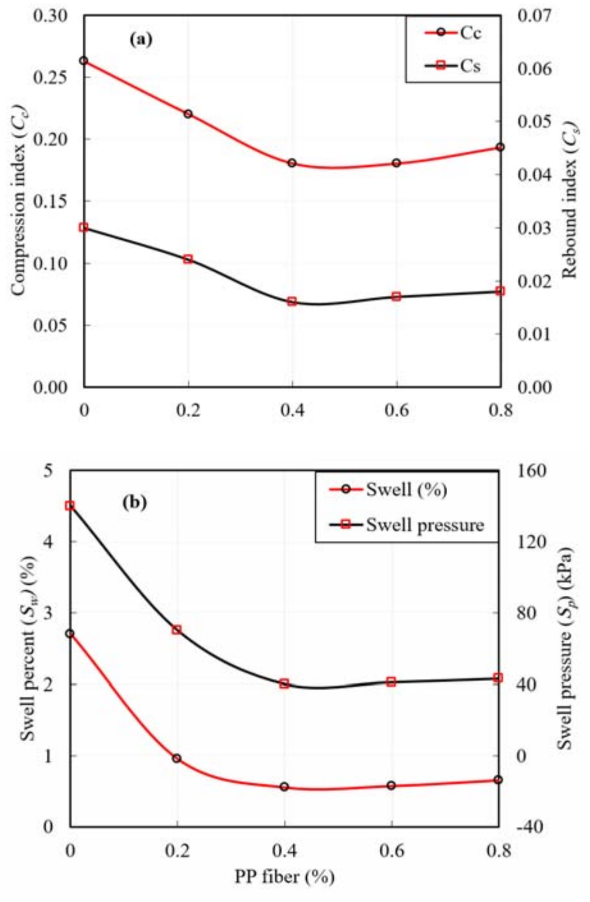


Figure (6): (a) Variation of C_c and C_s of soil samples with PP fiber and (b) Variation of swell percent and swell pressure of soil samples with fiber

CONCLUSIONS

The following conclusions are drawn from the findings of this study:

1. With PP fiber reinforcement, the MDD of the reinforced soil was marginally reduced with some variation in OMC, rendering the practicality of the PP fibers.
2. The inclusion of PP fibers has shown significant improvements in UCS, E_{50} and CBR of reinforced soil samples with an optimum value of 0.4%, thereby providing a better sub-grade for the construction of flexible pavements on such types of soil.
3. S_w and S_p of unreinforced soil are significantly reduced with the addition of 0.4% fiber content, transforming the soil from medium- to low-class swelling soil.
4. The consolidation parameters; i.e., C_c and C_s of unreinforced soil, were notably reduced at 0.4%

fiber inclusion, highlighting the efficacy of PP fibers.

The PP fiber provides a good alternative to reinforce the soil matrix by minimizing the adverse characteristics of problematic expansive clays. This study is mainly focused on the amelioration of the physical and mechanical properties of expansive clays. The authors recommend carrying out studies on other important aspects, such as performance under climatic variation (wetting-drying cycles), biodegradability and coupled performance with other potential additives, such as lime, cement, lignosulphonate and other industrial wastes that could be of significant interest in various civil-engineering projects.

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