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Effect of Polypropylene Macro Fiber on Geotechnical Characteristics of Black Cotton Soil: An Experimental Investigation and Correlation Analysis

Rao Asha Uday,[1] Dhanalakshmi Kiran,[1] Arun Kumar G S,[2] Prakash K G[1] and Balakrishna S Maddodi[1,*]

Abstract

Soil stabilization may be defined as modifying soil parameters using chemical or physical processes to improve the engineering quality of the soil. The soil stabilization method aids in achieving the essential soil qualities for building operations. Expansive soils, also known as swelling soils or shrink-expand soils, are soils that swell and shrink in response to changes in moisture content. As a result, major soil distress ensues, resulting in severe damage to the underlying structure. The impacts of polypropylene fiber on the geotechnical parameters of locally accessible Black Cotton (BC) soil near Haveri city, Karnataka, India, were investigated in this study. The soil sample was subjected to tests to determine its consistency limits, specific gravity, compaction, California bearing ratio, unconfined compressive strength, and shear strength. These experiments were carried out on both non-stabilized and stabilized soil by substituting 0%, 0.50%, 1%, 1.50%, 2%, 2.50%, and 3% of polypropylene fiber. The results show that polypropylene fiber improves several geotechnical parameters at various soil replacement percentages. The 2.5% of replacement is the best solution and an optimum replacement for different kinds of geotechnical-related works using this BC soil. The correlation between the different parameters is also determined from the analysis.

Keywords: Stabilization; Polypropylene fiber; Expansive soil; California Bearing Ratio; Black Cotton soil.
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1. Introduction

Infrastructure development, such as roads and other forms of connection, is expected to rise significantly in past decades in developing countries like India. Thus, it leads to a good construction site or soil requirement, which begins the enormous demand for land usage. Infrastructure growth, and its expansion over expensive soils are becoming inevitable nowadays. Because of the unavailability of good land for construction, many projects are currently being undertaken on expansive grounds previously considered unsuitable, In order to fill the need of over population. However, expansive soil was previously regarded as unsuitable land for construction, which is now being mainly used to meet demand. The construction with this type of soil for infrastructural development projects like highways, airport runways, berms, *etc*., over such weak soil is always a challenge for geotechnical engineers.[1] Construction on expansive soils is challenging, as engineers must overcome the obstacles of excess settlements and potential bearing failure.[2] The construction of roads and other infrastructure that works over such soils is cumbersome and complicated as expansive soil owing to poor shear strength and high swelling and shrinkage, low shear strength holds rich water content, and shows high compressibility. Such soil replacement is not easy and not economical, which puts a lot of pressure on engineers to improve expensive soils. Construction on such expensive soils always experiences large settlements, and, as a result, construction over such expensive soils is bound to undergo high settlements, and consequently, it induces catastrophic failure of structure built over on it.

The Black Cotton (BC) soil is one of India's most expansive soils. This BC soil is one of the major soil deposits of India, it is found in extensive regions of the Deccan trap and accounts for around 30% of India's geographical area. They are also referred to as bentonite, expansive, or BC soil. This expansive soil increases its volume or expands as it gets wet and decreases its volume or shrink as it dries out. The color of this soil is reddish-brown to black, and this is the most suitable

[1] *Department of Civil Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka 576104, India.*
[2] *School of Civil Engineering, KLE Technological University, Hubballi, Karnataka, 580031, India.*
**Email:* bs.maddodi@manipal.edu (B. S. Maddodi)

soil to grow cotton. BC soil is underlain as sticky soil. As said, BC soil tends to swell and contract in response to changes in moisture content.

Due to the high mineralogical concentration, BC soil needs to examine its volumetric changes. Thus, it is susceptible to significant expansion and contraction. This necessitates stabilization when it is used as barrow soil or exists as in-situ soil, and it is a standard method for preserving one or more engineering properties using chemicals, particularly in infrastructure development works. In general, the soil stabilization can be explained as the alteration of the soil properties by chemical or physical means in order to enhance the engineering quality of the soil.[3] It is a way of achieving the proposed goal and helps achieve the required properties in the soil needed, for the required construction work, at the same time, inexpensive and easy to apply practically on any soil. This soil stabilization will be an improvement. An extensive range of stabilization techniques is chosen based on economic factors. Traditional soil improvement techniques like densification, dynamic compaction, provision of the column, and chemical grouting have been used effectively to improve the engineering properties of expansive soils.

Nonetheless, these strategies have considerable downsides due to the potential for adverse environmental repercussions. Over the last decade, significant research has been conducted on applying natural and artificial materials as appropriate materials with more improvement strategies to improve the geotechnical qualities of expansive soils.[4-13] These stabilizing techniques are promising, environmentally friendly, and sustainable soil improvement in engineering properties.

In the present study, focus is given to study the effectiveness of providing polypropylene fiber for stabilizing BC soil to improve the geotechnical properties. BC soil used for the present research is collected near Haveri, in Karnataka state, India, at Longitude 15° 47' 36.7" and Latitude 76° 23' 00.5". This BC soil is a natural residual soil dug 60 cm below the natural ground surface to prevent capturing roots and vegetation, as well as any organic content. Tests for consistency limits, specific gravity, compaction, California bearing ratio, unconfined compressive strength, and shear strength were conducted on a soil sample. These tests have been carried out in both non-stabilized and stabilized stages, using 0%, 0.5%, 1%, 1.5 %, 2%, 2.5 %, and 3% polypropylene fiber included as a replacement for soil. The test results show the effect of polypropylene fiber in improving different geotechnical properties at different percentage addition in stabilizing the BC soil.

2. Materials used

2.1 Black cotton soil

The BC soil used in this investigation was sourced near Haveri city of Karnataka, India. It was a natural residual soil excavated 60 cm below the natural ground surface to avoid gathering roots, plants, and organic content, as illustrated in Fig. 1. It was made of a dark greyish thick clay. It was oven-dried before being processed by pulverizing it with a wooden mallet. The treated samples were put to various experimental examinations to determine their index and geotechnical properties.

Fig. 1 Black cotton soil sample used for the study.

Table 1. Index and engineering properties of BC soil.

Properties	Values
Specific gravity	2.01
Liquid limit (LL)%	41.50
Plastic limit (PL)%	20.93
Plasticity index (PI)%	20.57
Shrinkage limit (SL)%	50.0
Grain size distribution	
Gravel (>4.75 mm)	2
Sand (0.075-4.75 mm)	33
Silt and Clay (<0.075 mm)	65
Free swell index (FSI)%	50
Maximum dry density (MDD) (kN/m^3)	19.80
Optimum moisture content (OMC)%	20.65
California bearing ratio (CBR)	
Un-soaked	2
Unconfined compressive strength (kN/m^2)	582.51
Angle of internal friction ϕ (°)	23
Cohesion c (kN/m^2)	117.68

Table 1 lists the different index and engineering qualities of BC soil. According to IS: 2720 (Part 3) (1980), IS: 2720 (Part 4) (1985), IS: 2720 (Part 5) (1985), IS: 2720 (Part 5) (1985), IS: 2720 (Part 10) (1991), IS: 2720 (Part 7) (1980), IS: 2720 (Part 16) (1987), IS: 2720 (Part 13) (1991), IS: 2720 (Part 40) (1977),[14-20] these tests were conducted as prescribed by the Bureau of Indian Standards, New Delhi, India.

2.2 Polypropylene fibers

Polypropylene was the first stereoregular polymer to attain industrial significance. Polypropylene fiber was introduced to the textile industry in the 1970s and had become a vital component of the fast-developing family of synthetic fibers. Polypropylene ranked fourth behind the “big three” fiber classifications: polyester, nylon, and acrylic, however, in contrast to other commodity fibers. The sample of Polypropylene Fiber (PPF) is shown in Fig. 2.

Fig. 2 Polypropylene fiber sample used for the study.

Currently, PPF improves the soil's strength and enhances the soil's properties as stabilizing materials, minimizing shrinkage, and resisting chemical and biological deterioration. Properties and PPF specifications are shown in Table 2.

Table 2. Polypropylene fibers specifications.

Property	Specification
Colour	White
Specific gravity	0.9
Fibre length	12 mm
Fibre diameter	18 micron - nominal tensile
Strength	300-440 N/mm^2
Elastic modulus	6000-9000 (N/mm^2)

3. Experimental methodology.

3.1 Preparation of BC soil and polypropylene fibers (PPF).

The laboratory test was carried out on the composite sample of BC soil, and different percentages of PPF replacement are, as shown in Table 3, from the proportion by weight of the soil.

Table 3. Composition of soil and PPF with its respective sample number.

Sl. No.	Composition of soil and PPF	Sample Designation
01	99.5% soil + 0.5% PPF	0.5%
02	99.0% soil + 1.0% PPF	1%
03	98.5% soil + 1.5% PPF	1.5%
04	98.0% soil + 2.0% PPF	2%
05	97.5% soil + 2.5% PPF	2.5%
06	97.0% soil + 3.0% PPF	3%

4. Results and discussion

4.1 Geotechnical characterization

Geotechnical characterization was carried out for both BC soil, and PPF blended soil.

4.1.1 Specific gravity

The specific gravity test was carried out using oven-dried BC soil, passing through 4.75 mm IS sieve, and the test procedure was carried out for different percentages of polypropylene fiber as per IS: 2720 (Part 3) (1980).[14]

4.1.2 Atterberg's Limit.

The air-dried BC soil sample, passing through 425 µ IS sieve, was mixed with different percentages of polypropylene fiber and distilled water. Atterberg's limits (Liquid Limit (LL), Plastic Limit (PL)) tests were carried out as per IS: 2720 (Part 5) (1985).[16]

4.1.3 Compaction.

To establish the density-moisture relation of soil and PPF, a series of water-soil ratios, with different percentages of PPF, the standard proctor compaction tests were performed on BC soil, and PPF blended samples with different percentages, as per IS: 2720 (Part 7) (1980).[18]

4.1.4 California Bearing Ratio Test (CBR).

The CBR value for different percentage of PPF and soil was mixed with water up to the optimum moisture content, the unsoaked CBR tests were conducted as per IS: 2720 (Part 16) (1987).[19]

4.1.5 Unconfined Compressive Strength (UCS)

The undrained shear strength test for BC soil was carried out in accordance with IS: 2720 (Part 10) (1991).[17] Unconfined compressive strength (UCS) tests for PPF blended soil were performed in the laboratory to assess the increasing amount of shear strength behavior for different percentages of polypropylene fiber.

4.1.6 Direct shear test

To determine the shear parameters of BC soil and for PPF blended soil of different percentages of polypropylene fiber, direct shear tests were carried out as per IS: 2720 (Part 13) (1991).[20]

4.1.7 Swelling characteristics

Free swell index (FSI) tests were carried out for BC soil only to estimate the expansiveness and swelled potential of soil through the use of the method procedure of IS: 2720 (Part 40) (1977).[21]

4.1.8 Grain size analysis

A grain size analysis test was carried out for BC soil only to identify the percentage of gravel, sand, silt, and clay particles in the soil by adopting the procedure of IS: 2720 (Part 4) (1985).[15]

In the present study, PPF was mixed in different proportion to enhance strength characteristics. After replacing PPF from

0.5 to 3 %, the corresponding changes in specific gravity, Atterberg limits, compaction, shear strength parameters, and CBR are tabulated in Table 4.

From Table 4, it can be observed that specific gravity was decreased with the increase in PPF percentage replacement. Conversely, the Atterberg limits are increased with an increase in percentage replacement of PPF. The replacement of PPF at 2.5% improves most of the geotechnical parameters. The maximum value of MDD and the OMC also increases the moisture-density relation. In conjunction with this, the CBR value is increased by double the unreplaced BC soil. The compressive strength is increased by 66%, as noticed from the UCS test. Lastly, shear strength parameters are improved to the required extent at different replacement percentages.

Thus, 2.5% replacement is the best solution and an optimum replacement for different geotechnical-related works using this BC soil. Also, by referring to Table 4, one can find the required replacement percentage of PPF for the particular work, and the required geotechnical parameters can be achieved from the proper replacement of PPF to this BC soil.

4.2 Effect of PPF on geotechnical parameters

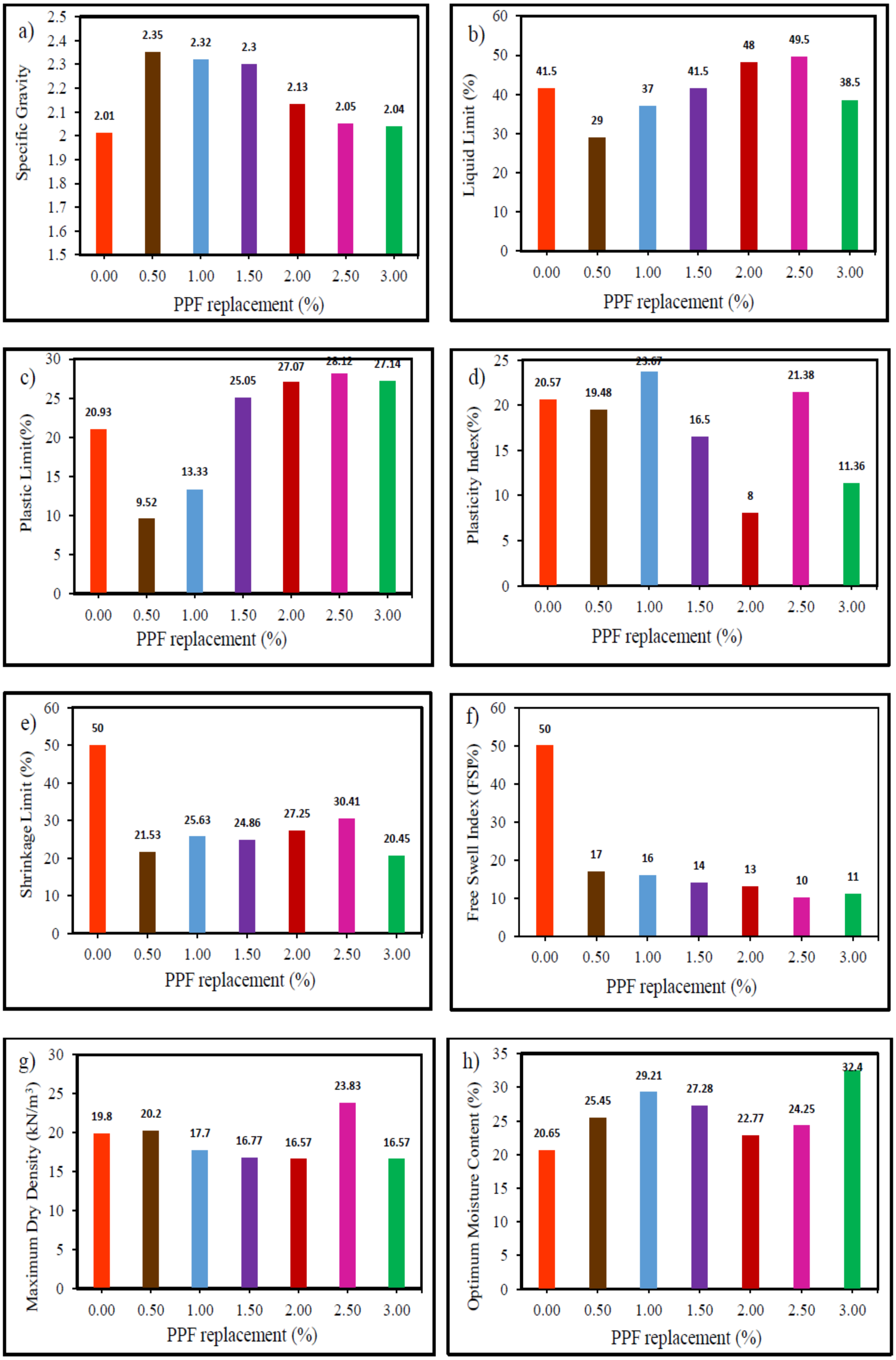
Figure 3 shows the effect of PPF on geotechnical parameters for various samples. From Fig. 3(a), it can be observed that the most effective replacement percentage in improving the specific gravity is 0.5%, followed by 1%, 1.5%, 2%, 3%, and finally, 4% is the least effective. The presence of PPF in the BC soil is decreased, with an increase in the percentage replacement of PPF in the specific gravity of the BC soil. Thus 0.5% replacement shows more specific gravity. In the present analysis for 0.5% replacement, specific gravity is found to be 2.35. Similarly, Tharini *et al.* 2020[22] found 2.47 for 0.5% replacement of PPF with BC soil, and Pallavi *et al*. 2016[23] found 2.48 for 10% replacement of fly ash.

From Fig. 3(b), it can be observed that the most effective replacement percentage in improving the liquid limit is 2.5%, followed by 2%, 1.5%, 3%, 1%, and finally, 0.5% is the least effective. Thus, 2.5% replacement has more water continent equal to the Liquid Limit. The presence of PPF in the BC soil increases the LL of the BC soil until 2.5% replacement, later onwards, LL is decreased. This indicates that the 2.5% replacement is the optimum replacement for the LL at 2.5% replacement and the BC soil present in it shows the highest binding in the BC soil to the obtained water content. Many researchers also carried out similar work, from different materials, with different replacement ratios.[22-33] Researchers like Thomas and Jhon 2016[28] found 62% LL for 0.5% replacement, 64% LL for 1% replacement, and 62% LL for 1.5% replacement of PPF with BC soil. Kamiya and Kumar 2020[29] found 79% LL for 0.5% replacement, 80% LL for 1% replacement, and 80% LL for 1.5% replacement of human hair fiber. Tharani *et al*. 2020[22] found 57.5% LL for 0.5% replacement of PPF with BC soil. Yohanna *et al*. 2022[33] found 50% LL for 0.5% replacement, 56% LL for 1% replacement, 50% LL for 1.5% replacement, and 49% LL for 2% replacement of sisal fibers with BC soil.

From Fig. 3(c), it can be observed that the most effective replacement percentage in improving the plastic limit is 2.5%, followed by 3%, 2%, 1.5%, 1%, and finally, 0.5% is the least effective. Thus, 3% PPF replacement has more water content equal to Plastic Limit. Since the soil shows good binding and with 2.5% soil replacement will just began to crumble when the soil was rolled over the glass plate from the palm. Again, it shows that the minimum water content is also 2.5% replacement and soil present in it shows the highest binding. Many researchers produce similar work using other materials with varying replacement ratios. Researchers like Thomas and Jhon 2016[28] found 45% for 0.5% replacement, 44% for 1% replacement, and 30% for 1.5% replacement of PPF with BC soil. Kamiya and Kumar 2020[29] found 49% for 0.5%

Table 4. Index and engineering properties of different BC soil samples.

Properties	0.5%	1%	1.5%	2%	2.5%	3%
Specific gravity	2.35	2.32	2.30	2.13	2.05	2.04
Liquid limit (LL)%	29.00	37.00	41.50	48.00	49.50	38.50
Plastic limit (PL)%	9.52	13.33	25.05	27.07	28.12	27.14
Plasticity Index (PI)%	19.48	23.67	16.50	20.93	21.38	11.36
Shrinkage Limit (SL)%	21.53	25.63	24.86	27.25	30.41	20.45
Free swell Index (FSI)%	17	16	14	13	10	11
Maximum dry density (MDD) (kN/m^3)	20.20	17.70	16.77	16.57	23.83	16.57
Optimum moisture content (OMC)%	25.45	29.21	27.28	22.77	24.25	32.40
California bearing ratio (CBR) (Un-soaked)	2	2	3	3	4	3
Unconfined compressive strength (UCS) (kN/m^2)	479.51	582.48	632.49	676.61	870.77	631.51
Cohesion c (kN/m^2)	39.61	78.45	98.45	102.96	107.87	44.12
Angle of internal friction ϕ (º)	27	39	10	11	14	40


a)
Specific Gravity
2.01
2.35
2.32
2.3
2.13
2.05
2.04
PPF replacement (%)
b)
Liquid Limit (%)
41.5
29
37
41.5
48
49.5
38.5
PPF replacement (%)
c)
Plastic Limit(%)
20.93
9.52
13.33
25.05
27.07
28.12
27.14
PPF replacement (%)
d)
Plasticity Index(%)
20.57
19.48
23.67
16.5
8
21.38
11.36
PPF replacement (%)
e)
Shrinkage Limit (%)
50
21.53
25.63
24.86
27.25
30.41
20.45
PPF replacement (%)
f)
Free Swell Index (FSI%)
50
17
16
14
13
10
11
PPF replacement (%)
g)
Maximum Dry Density (kN/m³)
19.8
20.2
17.7
16.77
16.57
23.83
16.57
PPF replacement (%)
h)
Optimum Moisture Content (%)
20.65
25.45
29.21
27.28
22.77
24.25
32.4
PPF replacement (%)
0.00 0.50 1.00 1.50 2.00 2.50 3.00

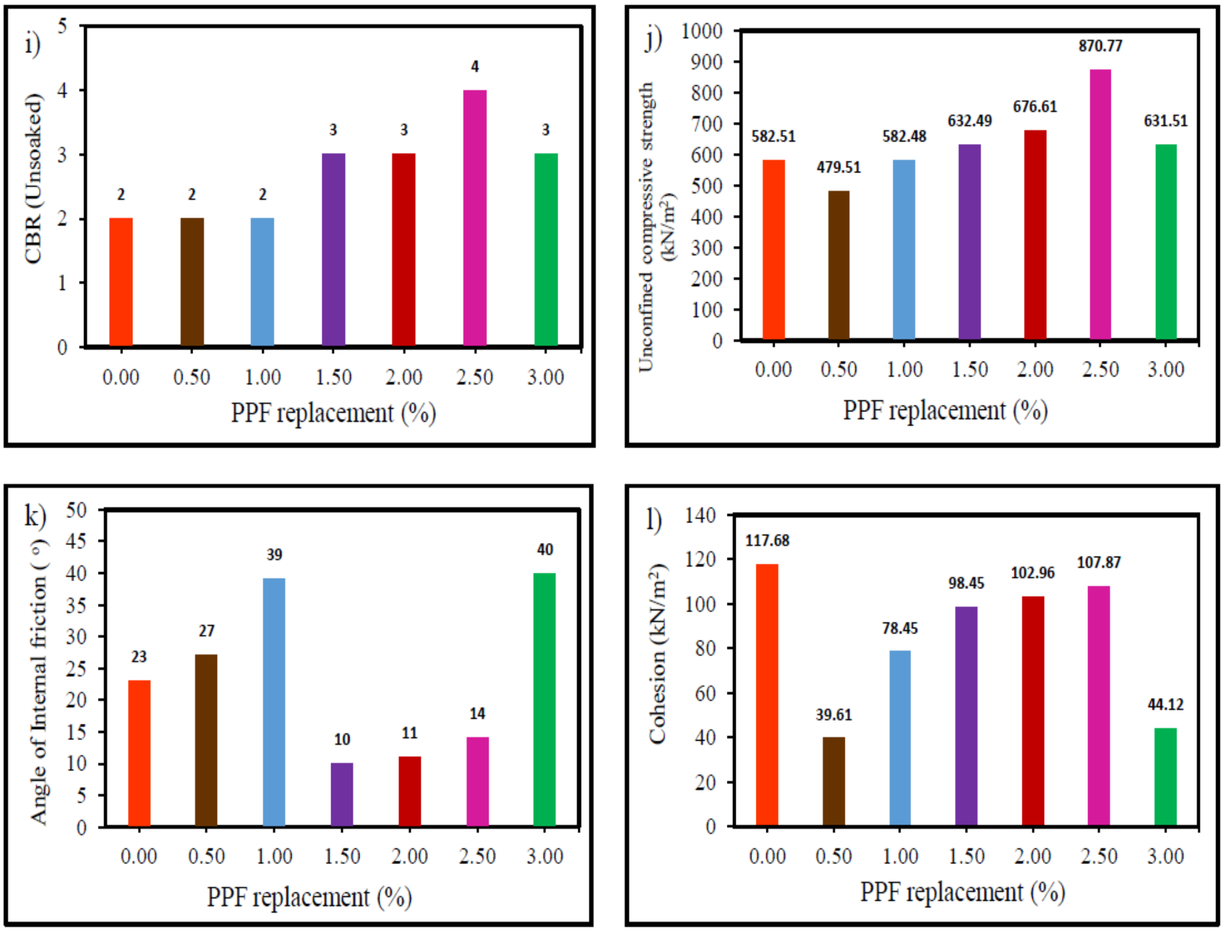


Fig. 3 Effect of PPF on geotechnical parameters for various samples a) Specific Gravity, b) Liquid Limit, c) Plastic Limit, d) Plasticity Index, e) Shrinkage Limit, f) Free Swell Index, g) Maximum Dry Density, h) Optimum Moisture Content, i) California Bearing Ratio (Unsoaked), j) CBR (Unsoaked), k) Angle of internal friction, l) Cohesion.

replacement, 50% for 1% replacement, and 50% for 1.5% replacement of human hair fiber. Tharani *et al*. 2020[22] found 38.46% for 0.5% replacement of PPF with BC soil. Yohanna *et al*. 2022[33] found 16% for 0.5% replacement, 21% for 1% replacement, 23% for 1.5% replacement, and 20% for 2% replacement of sisal fibers with BC soil.

From Fig. 3(d), it can be observed that the most effective replacement percentage in improving the plastic index is 1%, followed by 2.5%, 0.5%, 1.5%, 3%, and finally, 2% is the least effective. Thus 1% shows more plasticity index. With referring to Fig. 3(b) and Fig. 3(c), the advantage of 2.5% replacement is that there is not much difference in the water content for the 2.5% replacement except for 1% replacement. Thus, 2.5% replacement reduced the water content requirement, forming its good binding with the BC soil. Similarly, several researchers conducted work of a similar nature, from different materials, with different replacement ratios. Researchers like Thomas and Jhon 2016[28] found 18% for 0.5% replacement, 20% PI for 1% replacement and 30% PI for 1.5% replacement of PPF with BC soil. Kamiya and Kumar 2020[29] found 39% PI for 0.5% replacement, 40% PI for 1% replacement, and 40% PI for 1.5% replacement of human hair fiber with BC soil. Tharani *et al*. 2020[22] found 19.03% PI for 0.5% replacement of PPF with BC soil. Yohanna *et al*. 2022[33] found 40% PI for 0.5% replacement, 35% PI for 1% replacement, 30% PI for 1.5% replacement, 29% PI for 2% replacement of sisal fibers with BC soil.

From Fig. 3(e), it can be observed that, the most effective replacement percentage in improving the Shrinkage Limit is 2.5%, followed by 2%, 1%, 1.5%, 0.5%, and finally, 3% is the least effective. Thus, 2.5% shows more shrinkage Limit. Thus, 2.5% replacement reduces the shrinkage of the BC soil, again, it is because of its good binding effect with the BC soil. Thus, 2.5% replacement reduces the swelling characteristics of BC soil. This is one of the essential observations and much-needed parameters in modifying BC soil. It does not need any kind of gravel casing, such as the Cohesive Non-Swelling soils (CNS) layer; thus, it reduces the cost of additional burrow soil. Generally, as the shrinkage limit increases, the swelling nature of the soil decreases. Consequently, it is evident that as a converse FSI, from Fig. 3(f), it can be observed that the most effective replacement percentage in improving the Shrinkage Limit is 2.5%, followed by 3%, 2%, 1.5%, 1% and finally 1.5% is the least effective. Lesser the FSI value, the less expansion in BC soil. Thus, 2.5% replacement shows less FSI value. Hence it is a good replacement; evidently, 2.5% shows more Shrinkage Limit, as observed in Fig. 3(e). Similarly, Tharini *et al*. 2020[22] found 21.73% for 0.5% replacement of PPF with BC soil.

From Fig. 3(g), it can be observed that the most effective replacement percentage in improving the maximum dry density is 2.5%, followed by 0.5%, 1%, 1.5%, 2%, and finally, 3% is the least effective. Thus, 2.5% replacement provides the drier density. This is again because of its good binding with the BC soil. Thus, good compaction can be achieved with the 2.5% replacement of the BC soil, which can be used for the subgrade soil. Additionally, the 2.5% replacement percentage shows less shrinkage value, as referred to in Fig. 3(f). Corresponding to this, maximum dry density is achieved at the water content of 24.25%, as observed in Fig. 3(h). From Fig. 3(h), it can be observed that the most effective replacement percentage in improving the optimum moisture content is 3%, followed by 1%, 1.5%, 0.5%, 2.5% and finally 2%, the least effective. The water content corresponding to the 2.5% replacement should be used, even though 3% gives optimum water content, since it produces the highest maximum dry density. Similarly, several researchers produced similar work using various materials and with different replacement ratios. Researchers like Sachin *et al.* 2016[32] found 15.2 kN/m^3 and 22.53% for 0.5% replacement, 15.37 kN/m^3 and 24.37% for 1% replacement for MDD and OMC, respectively, for coconut coir fiber with BC soil. Kesavan and Rajalingam 2019[30] found 16.08 kN/m^3 and 23.4% for 0.5% for MDD and OMC, respectively, for replacing arecanut fibers with BC soil. Tharini *et al*. 2020[22] found 15.39 kN/m^3 and 34% for MDD and OMC, respectively, for 0.5% replacement of PPF with BC soil. Syed *et al.* 2020[27] 19.8 kN/m^3 and 17.2% for 0.4% replacement for MDD and OMC, respectively, for coir fiber with BC soil, 20.2 kN/m^3 and 17% for 0.4% replacement for MDD and OMC respectively for hemp fibers with BC soil, Kamiya, and Kumar 2020[29] found 15.49 kN/m^3 and 23% for 0.5% replacement, 15 kN/m^3 and 27% for 1% replacement, and 15.20 and 25% for 1.5% replacement for MDD and OMC, respectively, for human hair fiber with BC soil. Ganja 2020[31] found 14.6 kN/m^3 and 28% for 0.5% replacement, 14.04 kN/m^3 and 30% for 1% replacement, and 12.54 kN/m^3 and 32% for 1.5% replacement for MDD and OMC respectively for coir fiber with BC soil. Yohanna *et al*. 2022[33] found 15.69 kN/m^3 and 19% for 0.5% replacement, 15.20 kN/m^3 and 22% for 1% replacement, 14.70 kN/m^3 and 24% for 1.5% replacement and 15 kN/m^3 and 23% for 2% replacement for MDD and OMC respectively for coir fiber with BC soil.

From Fig. 3(i), it can be observed that the most effective replacement percentage in improving the optimum moisture content is 2.5%, followed by 1.5% and 2% also, 3%, finally, 0.5% and 1% are the least effective. Thus, 2.5% gives more CBR value. It is also evident from Fig. 3(g), once again this observation implies that thus with 2.5% replacement of the BC soil can be compacted to the required dry density and it can be used for the subgrade soil. Incorporating glass fiber, PPF and their mixed fibers into lightweight soil, PPF has a relatively higher flexural toughness efficiency[24,25] and can greatly improve lightweight soil's deformation capacity and bearing capacity.[25,26] Similar work is conducted from other researchers using other materials with different replacement ratios to find CBR. Researchers like Sachin *et al*. 2016[32] found 11.10 for 0.5% replacement, 7.42 for 1% replacement for CBR in coconut coir fiber with BC soil Kesavan and Rajalingam 2019[30] found 2.32 for 0.5% replacement of arecanut fibers with BC soil. Kamiya and Kumar 2020[29] found 3 for 0.5% replacement, 12 for 1% replacement, and 10 for 1.5% replacement of human hair fiber with BC soil.

From Fig. 3(j), it can be observed that the most effective replacement percentage in improving unconfined compressive strength is 2.5%, followed by 2%, 1.5%, 3%, 1%, and finally, 0.5% is the least effective. Thus 2.5% replacement percentage increases the compressive strength. Tharini *et al*. 2020[22] found 256 kN/m^2 for unconfined compressive strength for 0.5% replacement of PPF with BC soil. Again, it is because of its good binding with the BC soil. It increases the shear strength of the soil. Various researchers worked out a similar kind, but with different replacement ratios and materials. The unconfined compressive strength is also mentioned here. Thomas and Jhon 2016[28] found 8 kN/m^2 for 0.5% replacement, 16 kN/m^2 for 1% replacement and 3 kN/m^2 for 1.5% replacement of PPF with BC soil. Sachin *et al*. 2016[32] found 581.7 kN/m^2 for 0.5% replacement, 465.4 kN/m^2 for 1% replacement for CBR in coconut coir fiber with BC soil. Syed *et al*. 2020,[27] 569 kN/m^2 for 0.4% replacement for coir fiber with BC soil, 572 kN/m^2 for 0.4% replacement for hemp fibers with BC soil, Kamiya and Kumar 2020[29] found 147 kN/m^2 for 0.5% replacement, 274 kN/m^2 for 1% replacement, and 245 kN/m^2 for 1.5% replacement of human hair fiber with BC soil. Kesavan and Rajalingam 2019[30] found 118kN/m^2 for 0.5% replacement of arecanut fibers with BC soil. Yohanna *et al*. 2022[33] found 130 kN/m^2 for 0.5% replacement, 50 kN/m^2 for 1% replacement, 48 kN/m^2 for 1.5% replacement, 60 kN/m^2 for 2% replacement of sisal fibers with BC soil.

Also, from Fig. 3(k), it can be observed that the most effective replacing sample in improving the angle of internal friction is 3%, followed by 1%, 0.5%, 2.5%, 2%, and finally, 0.5% is the least effective. Thus, 3% increases the angle of internal friction of soil. From Fig. 3(l), it can be observed that the most effective replacement percentage in improving cohesion is 2.5%, followed by 1%, 1.5%, 1%, 3%, and finally, 0.5% is the least effective. Thus, 2.5% replacement increases soil cohesion. This is also evident from Fig. 3(g) that this 2.5% replacement has increased the maximum dry density. Similarly, several researchers conducted a similar kind of work by utilizing different materials and with different replacement ratios, such as, Sachin *et al*. 2016[32] found 51.83^o and 42.58 kN/m^2 for 0.5% replacement, 55.32^o and 32.4 kN/m^2 for 1% replacement for the angle of internal friction and cohesion, respectively, for coconut coir fiber with BC soil.

Table 5. Correlation between different geotechnical parameters for samples of PPF and black cotton soil.

	G	LL	PL	PI	SL	FSI	MDD	OMC	CBR	UCS	*c*	*ϕ*
G	1											
LL	-0.673	1										
PL	-0.821*	-0.055	1									
PI	0.467	-0.302	0.565	1								
SL	-0.321	-0.055	0.624*	-0.055	1							
FSI	-0.071	-0.168	-0.457	0.232	0.823*	1						
MDD	-0.179	0.771	0.846*	0.586	0.474	0.625	1					
OMC	-0.039	0.527*	0.613*	0.058	0.039	0.657	-0.425	1				
CBR	-0.793	0.845*	0.883*	-0.222	0.693	0.656	0.414	-0.266	1			
UCS	-0.739	0.771	0.900*	-0.010	0.529	0.425	0.510	-0.313	0.934**	1		
c	-0.209	0.550	0.861*	-0.005	0.319	0.345	0.171	-0.573	0.602	0.720	1	
ϕ	0.071	-0.068	-0.457	0.232	0.071	0.114	-0.206	0.795	-0.548	-0.464	-0.748	1

4.3 Correlation analysis

A correlation analysis was carried out for the test results for the values tabulated in Table 4 using SPSS software. The correlation between different parameters for samples of PPF and black cotton soil is tabulated in Table 5.

The interference of the correlation is shown in Table 5. From Table 5, it is observed that CBR shows a strong and positive correlation with UCS (*i.e.*, 0.934 at 1% significance level) and moderate correlation with *c*. This indicates that moderate increase of *c* (*i.e.*, 0.602) not only increases compressive strength of the soil, but also increases the bearing ratio significantly.

The PL shows an excellent correlation with UCS (*i.e.*, 0.900). It also shows similar correlation for CBR, *c*, MDD (>0.8) and a mild correlation with PI and OMC (>0.5 and >0.6). This indicates that the presence of moisture content equal to PL increases the bearing ratio, dry density to a maximum extent, and the compressive strength significantly (*i.e.*, 0.90 at a 5% significant level). This correlation also shows a good match with *c*. This also causes a good correlation with the above said other parameters conversely.

In the same way, the LL also shows a good correlation with the CBR, mildly with *c* and moderately with UCS. The presence of water at LL will be more comparable to PL. This reduces the correlation value of CBR, UCS, and *c*. it is not as good as a correlation of PL with the same parameters. The presence of moisture water content at exactly LL and PL directly causes a good correlation for the CBR (>0.8), and for LL shows a mild correlation for UCS (*i.e.*,0.77) and a moderate correlation for PL (*i.e.*,0.90). Similarly, the presence of more water content in LL reduced the moderately *c* (*i.e.*, 0.55) and increased compressive strength for PL (*i.e.*, 0.861).

The SL of the BC soil highly correlates with the FSI (*i.e.*, >0.80). This SL correlates with CBR and UCS, indicating that the proportion of PPF is successful in controlling the swelling (*i.e.*, 0.823). The FSI also shows a good correlation with MDD and OMC from the moisture-density relation (*i.e.*, >0.65).

4. Conclusion

The present study proposes to utilize the PPF as binders for the new generation of environmentally safe binders. This has the added benefit of removing conventional binders while lowering the cost of industrial by-products. In this current technique, the geotechnical properties of BC soil are modified by stabilizing with PPF in different percentages as a replacement to BC soil (0.5% to 3%) to stabilize the soil and contribute to enhancing the strength of BC soil. The following are the key results and conclusions:

1) The maximum dry density can be achieved for the BC soil at a replacement of 2.5% of PPF of soil by maintaining the corresponding optimum value moisture content.
2) The CBR value is 4% for the BC soil at a replacement of 2.5% of PPF of soil by maintaining the corresponding optimum value moisture content and maximum dry density.
3) The maximum compression strength is shown in 107.87 kN/m^2 for the BC soil at a replacement of 2.5% of PPF of soil.
4) The plasticity of the PPF-treated BC soil sample has decreased significantly. The sample with the most considerable decrease has a replacement rate of 2.5 %.
5) The test results of BC soil and its PPF as binders show that BC soil's stabilization with PPF improves the engineering properties. It mitigates the requirement of the Cohesive Non-Swelling soils (CNS) layer.
6) Using a readily accessible commercial product, this study offers an eco-friendly, sustainable binder that enhances the geotechnical qualities of a BC soil sample.
7) 2.5% replacement is the best solution and an optimum replacement for different geotechnical-related works using this BC soil.

8) The required replacement percentage of PPF for the particular work and required geotechnical parameters can be achieved with the proper replacement of PPF to this BC soil.
9) CBR shows a strong and positive correlation with UCS, this indicates that a moderate increase of *c* not only increases compressive strength of BC soil but also increases the bearing ratio significantly.
10) PL shows a good correlation with UCS, this mainly indicates that water content equal to PL increases the compressive strength of BC soil.

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Conflict of Interest
The authors declare no conflict of interest.

Supporting Information
Not applicable.

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Author Information

Dr. Rao Asha Uday *is a professor, in the Department of Civil Engineering at Manipal Institute of Technology, MAHE, Manipal, India. Her research interest is optimization, material characterization of concrete, slope stability, and sustainable concrete.*

Mrs. Dhanalakshmi Kiran *currently working as an Assistant Professor (Sr. Scale) in the Department of Civil Engineering at Manipal Institute of Technology, MAHE, Manipal, India. She has BE degree from Dr. Ambedkar Institute of Technology, Bangalore, India, and pursued her MTech degree in Structural Engineering specialization at Manipal Institute of Technology, Manipal, India, her research interest is material modelling, Behavior study of Masonry structure, Material characterization of concrete waste .*

Mr. Arun Kumar G S *Currently working as Assistant professor in school of civil Engineering, at KLE Technological University, Hubballi, Karnataka, India, He is having 6 years of research experience and 14 years of teaching experience at different engineering colleges in Karnataka, India. His research interest are structural Dynamics, Soil Structure interaction and energy dissipation systems.*

Mr. Prakash K G *currently pursuing his Ph.D. at Department of civil Engineering, Manipal Institute of Technology, India, He has BE civil engineering Degree from University B D T college of Engineering, Davangere, Karnataka, India. and pursued his M Tech. degree in Structural Engineering specialization at KLE Technological University (formerly Known as B V Bhoomaraddi college of Engineering and Technology) Hubballi, Karnataka, India. He is having 6 years of research experience and 15 years of teaching experience His research interest Includes Finite element Analysis, embankment constructed on soft consolidating soil and soil improvement.*

Dr. Balakrishna S Maddodi *is an Assistant professor (selection grade) in the Department of Civil Engineering at Manipal Institute of Technology, MAHE, Manipal, India. Engineering Geology, Environmental Studies, Solid waste Management, GIS and RS are the areas of his expertise.*

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