Strength and Permeability Characteristics of Fibre Reinforced Liner Material

Debtanu Seth[1[0000-0001-7690-5306]], Suresh Prasad Singh[2[0000-0002-5818-3415]] and Shubham Singh[3]

[1]M.Tech, Civil Engineering Department, NIT Rourkela, Odisha -769 008,
E-mail: 217ce1033@nitrkl.ac.in
[2]Professor, Civil Engineering Department, NIT Rourkela, Odisha -769 008
E-mail: spsingh@nitrkl.ac.in
2M.Tech, Civil Engineering Department, NIT Rourkela, Rourkela-769008
E-mail: 218ce1027@nitrkl.ac.in

Abstract. Sand-bentonite mixture is a widely used liner material. After optimisation, it is observed that sand-bentonite mix with bentonite content 15% satisfies the criteria of compacted clay liner (CCL) material stipulated by the United States Environment Protection Agency (USEPA). One of the primary element of the mixture, Bentonite, is an expensive material. So, the focus of this study is to reduce the bentonite content with reinforcing the mix by random inclusion of polypropylene fibres. In this study sand-bentonite mixture with 10%, 15% and 20% bentonite content are used and 0, 0.2, 0.5 and 1% polypropylene fibre by weight of the mixture is added. Unconfined compressive strength (UCS) test is done to observe the strength characteristics of the mix. The UCS specimens are statically compacted to their respective maximum dry densities (MDD) at optimum moisture content (OMC). UCS values are determined at this moulded water content as well as in fully saturated conditions. It is observed that the failure strength and ductility of a sample with a given bentonite content increases with increasing fibre content. It is also noticeable that normalised strain energy is improved and reduction of post-peak strength is minimised with increasing fibre content. However, at a particular fibre content, the strength initially increases up to 15% bentonite content and after that it reduces. This trend is observed for all the samples. The UCS value of sand-bentonite specimens, containing 15% bentonite and compacted at OMC with compaction effort of 595 kJ/m3, increases from 60.92 kPa to 483.46 kPa when the fibre content increased from zero to 1% which is 694% increment of strength. Permeability test is done with distilled water under pressure head of 4 kg/cm2 to find out the effect of fibre content on hydraulic conductivity of the mixtures. It is noticed that inclusion of fibres increase the hydraulic conductivity of the compacted sand-bentonite mixes. Scanning Electronic Microscopy (SEM) is performed to observe the distribution of fibres in the sand-bentonite mixture.

Keywords: sand bentonite liner; fibre reinforcement; strength properties, permeability; microstructure

1. Introduction

Liner is an essential part of a sanitary landfill system. Among the two types of liners, (i) Compacted Clay Liner (CCL) and (ii) Geosynthetic Clay Liner (GCL), CCL is extensively used due to its low installation cost and availability of material. The primary criterion of CCL is to have very low permeability (in the range of 10^{-7} cm/sec) and adequate strength (more than 200 kPa). In most of the cases, the sand-bentonite mixture is used as a liner when the local soil is not fit for being compacted as liner. Due to high cost and less availability of bentonite, researchers showed interest in using less amount of bentonite in sand bentonite mixture to achieve the previously mentioned criteria of liner material. Fibres are inserted randomly in the sand-bentonite mix to reduce the bentonite content in the sand-bentonite mix and to enhance the mechanical properties. There are two types of fibres (i) natural fibre and (ii) synthetic fibre. In this study Polypropylene fibre (Recron–3S) is used, which is a synthetic fibre.

Previously, researchers focused on the effect of fibre reinforcing on geotechnical properties of cohesionless soil and the strength characteristics of cohesive soil. There is limited literature on the feasibility of using randomly inserted fibre in sand-bentonite liner material for enhancing its mechanical and hydraulic properties. Gray et al. (1983) investigated the effect of natural fibre, synthetic fibre and metal wires on the strength characteristics of sand and observed that fibre reinforcement increased the shear strength, decreased post-peak strength reduction and improved other strength behaviour. Maher and Gray (1990) investigated the effect of random glass, reed and palmyra fibre inclusion in sand. It was found that the fibre reinforcing increase the failure strength significantly under static load and the stiffness of the sand although low modulus fibres have less contribution to the strength increment of the sand. Abdi et al. (2008) studied the effect of short random fibre inclusion on the consolidation characteristics, compression behaviour, permeability and shrinkage property of a mixture of 75% kaolinite and 25% montmorillonite. Fibre of 1, 2, 4 and 8% were added as dry weight of soil with 5, 10 and15 mm lengths. It was found that consolidation settlement and swelling of the soil decreased with increasing fibre content. Shrinkage limit increases with increasing fibre content. Although the length of fibre doesn’t have any significant effect on the consolidation and compressibility characteristics of the soil, fibre content is constant. It was found that permeability increases slightly with increasing fibre content and length of fibre. However, this increase in permeability is not substantial enough to render the soil unsuitable to be liner or cover material. Miller and Rifai (2004) investigated the effect of fibre reinforcing on workability, compaction and permeability characteristics of low plastic clay. The soil was compacted at 2% of wet of optimum and fibres added are 0.2, 0.4, 0.6 and 0.8% of dry weight of soil. Fibre inclusion has little effect on the compaction characteristics of the soil. However, the crack reduction and tensile strength improved with increasing fibre content, although permeability rises slightly. The optimum fibre content is found to be 0.4 to 0.5%. Similarly, Moghal et al. (2018) discussed the effect of fibre reinforcment in chemically treated soil specimens and compared the results with untreated soil specimens.

In this study, polypropylene fibres are randomly mixed with optimised sand-bentonite mixture. Strength criteria of the soil is observed, and the change is investigated by unconfined compressive strength test, and permeability test is performed to monitor the hydraulic conductivity of the samples with different fibre content. X-ray diffraction test is performed to obtain the compounds present in the mixture. Scanning electronic microscopy is performed to observe the surface texture of the sand and bentonite.

2. Experimental Programme

2.1 Materials

Sand and commercially procured sodium-bentonite is used in this study. The sand is obtained from a river situated in Rourkela. The sand is then dried in an oven to remove the moisture attached to the sand particles and sieved through no. 10 ASTM sieve. The passing portion of the sand is collected. The values of the coefficient of uniformity and coefficient of curvature of sand are obtained as 2.76 and 1.19 respectively. According to the IS classification system and from the C_u and C_c value it can be concluded that the sand is poorly graded (SP). Bentonite is collected from Nilkantha MineChem , Jodhpur. X-ray diffraction confirms the presence of Montmorillonite, Quartz, Feldspar and Aluminum Silicate in sand-bentonite mixture. Physical properties of sand, bentonite and the mix are shown in table 1. Fig. 1 and 2 shows the SEM images of bentonite and sand. Three sand-bentonite mixtures are prepared with bentonite content 10, 15 and 20% by weight of the mix. The sand and bentonite are dried individually in oven before mixing. Before every test, a desired proportion of water is added to the sand-bentonite mixture and the mix is kept at least for 24 hours for homogeneous mixing of water. Different tests are performed following the IS codes.

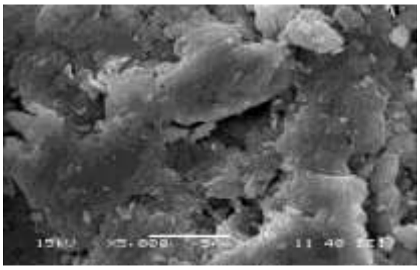


Fig. 1. Microscopic flaky structure of bentonite by SEM

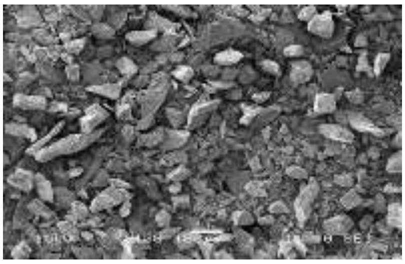


Fig. 2. Microscopic angular structure of sand by SEM

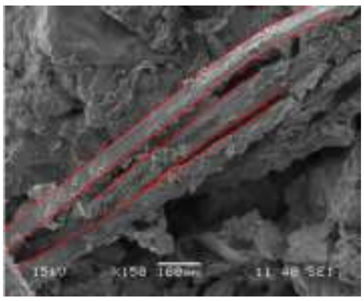
Recron-3S fibre is used in this study to randomly mix with the soil. Recron–3S is a polypropylene (PP) fibre with triangular cross-section, and it is developed by Reliance India Ltd, India to enhance strength criteria in different applications. Due to triangular cross-section, more surface area of the fibre comes in contact with the soil particles causing better pull out resistance in comparison to fibres with circular cross-sections. Fig. 3 shows the pullout resistance mechanism of fibre, and in Fig. 4 the fibres can be seen embedded in a soil matrix in a SEM image and outlined with red dotted lines. The properties of the fibres are given in Table 2.

Table 1. Geotechnical properties of bentonite and sand

Properties	Bentonite	Sand
Specific Gravity	2.72	2.56
Fine Contents (%)	97.07	3
Liquid Limit (%)	341	-
Plastic Limit (%)	32	-
Shrinkage Limit (%)	7	-
Plasticity Index (%)	291	-
Swelling Index (%)	625	-

Table 2. Physical properties of polypropylene fibre

Polypro-pylene Fibre	Spe-cific Gravity	Lengt h (mm)	Equiva-lent Diame-ter (mm)	Tensile Strength (MPa)	Strain at Failure (%)	Tensile Modulus (GPa)
	0.91	6	0.023	120	80	3



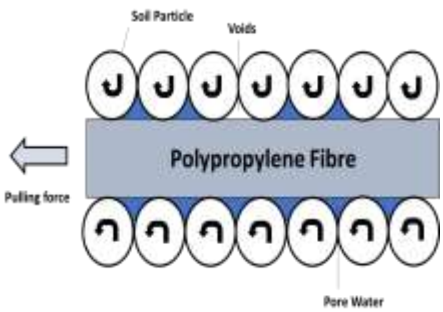


Fig. 3. Pull out mechanism of PP fibre

Fig. 4. PP fibre embedded in soil matrix

2.2 Methodology

Sample Preparation There is no stipulated method for mixing the fibre with the soil. While mixing the fibre and soil, the main difficulty is to attain homogeneity as the fibres are prone to be tangled, which causes an inhomogeneous mixture of fibre and soil. Three sand-bentonite mixtures are prepared with bentonite content 10, 15 and 20% by weight of the mix and by compacting them to their MDD at OMC and adding fibres as 0, 0.2, 0.3 and 0.6% of the dry weight of soil. The fibres are mixed thoroughly in random orientations with the soil to obtain a homogeneous mixture.

Unconfined Compression Test (UCS) The sample is prepared following the above process and for each percentage of mix two triplets are prepared, one triplet is tested in OMC, and another triplet is saturated before testing and later tested in saturated condition. Total 144 samples are tested for UCS among which, 72 are tested at their OMC and the rest 72 in saturation condition. Again, among those 72 samples, 36 are compacted to their MDD obtained from standard proctor test, and the rest 36 are compacted to their MDD obtained from modified proctor test. During UCS test, load was applied at a strain rate of 1.25 mm/min until the sample fails.

Hydraulic Conductivity Samples are prepared as described above. The samples are compacted in permeability moulds to their MDD at OMC obtained from light compaction test and heavy compaction test. Due to very low permeability of the mixture, a hydraulic gradient of 2 kg/cm^2 is applied, and the head is kept constant throughout the experimental procedure. The samples are permitted with water until the soil is saturated and later the reading is taken.

Scanning Electronic Microscopy Scanning electronic microscopy (JSM-6480LV, Magnification-100, 150 & 5000x, Accelerating Voltage - 15 kV) of the bentonite, sand and the sand-bentonite-fibre mixture is performed to observe the shape of the particles and the embedment of the fibres in them. Samples are collected and dried carefully without disturbing the surface texture. Later the samples are coated with platinum and mounted to the instrument. Later pictures are taken through a computer screen attached to the microscope at different magnification.

3. Result and Analysis

3.1 Effect of Fibre Addition on the UCS Value of Compacted Soil

From Fig 4 and Fig 5, it is evident that with increasing fibre insertion, the unconfined compressive strength of the soil rises for both heavy or light compacted soil. The rate of increase in UCS is non-linear unlike the linear trend observed by Das and

Singh 2019. The addition of fibre of 1% causes an increase in UCS value by 692% for standard compacted soil and 242% for heavy compacted samples in comparison to unreinforced samples for 15% bentonite content sample. It is evident that in case of standard compacted sand-bentonite mixture, percentage increase in UCS value is higher than percentage increase in case of heavy compacted sand-bentonite mixture, but the UCS value in case of heavily compacted soil is much higher than that of the lightly compacted soil. The variations of UCS value with fibre content are shown in figure 4 and figure 5, for sample compacted by standard compaction and heavy compaction methods respectively and tested in their OMC.

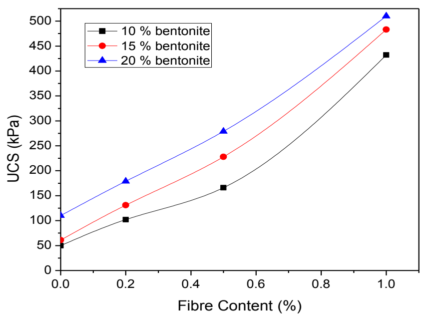


Fig. 4. Effect of addition of fibre for lightly compacted sample at their OMC

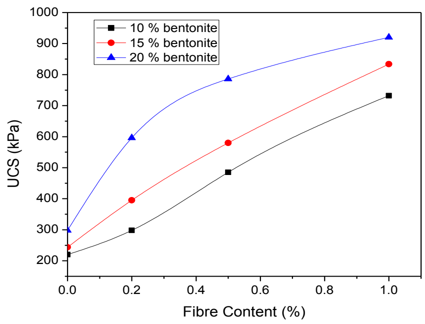


Fig. 5. Effect of addition of fibre for heavily compacted sample at their OMC

3.2 Effect of Fibre Addition on the UCS Value of Compacted Soil after Saturation

The compacted samples are saturated before testing for UCS. Similar to the previous case, the failure stress under static load increases with increasing fibre addition. The rate of increase in failure stress follows non-linear and gradually decreasing trends. In this case, the light compacted sample has 103% increase in strength after 1% fibre inclusion and 186% increase in strength in case of heavy compacted soil after 1% fibre inclusion in comparison to unreinforced sample. The rate of increase in failure strength and value of failure strength both are higher in case of heavy compacted soil in contrast to lightly compacted soil. The variation of UCS with fibre content for mixes with different bentonite contents and compacted by standard proctor method, are given in figure 6 and the same for the mixture compacted by heavy compaction method is given in figure 7. In both the cases, the samples were tested in saturated condition.

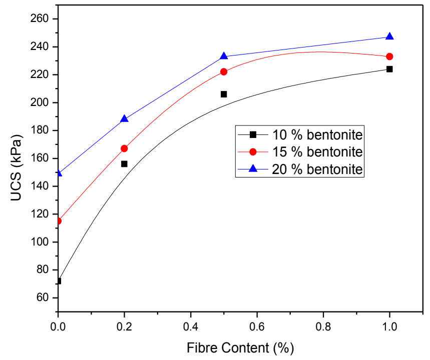


Fig. 6. Effect of addition of fibre on UCS valuefor lightly compacted sample at saturated condition

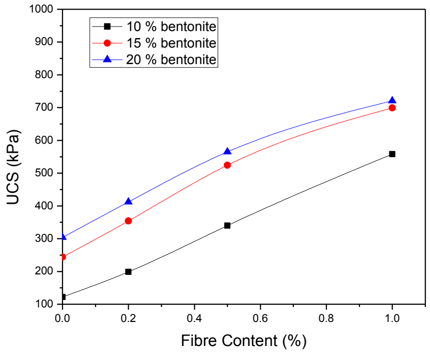


Fig. 7. Effect of addition of fibre on UCS value for heavily compacted sample at saturated condition

3.3 Effect of Moisture Content on the Stress-Strain Behavior of Soil

It is noticeable that at OMC, the stress curve is steeper than that at saturation condition, given all other parameters are constant, which indicates that with increasing water content, the soil become more ductile. It is also observed that with increasing moisture content, the UCS value decreases. The decrease in failure stress due to increased water content can be attributed to the loss of contacts between particles and lubrication effect of water with increasing water content. The effect of water content should be considered while studying the impact of fibre insertion in soil. In Fig. 8 SB_15B_0.5F_Mod_OMC indicates a soil sample with 15% bentonite compacted at OMC by modified Proctor and the other shows the same sample in saturated condition.

3.4 Effect of Fibre Inclusion on Strain Energy of Soil

It is evident from figure 9 that with addition of polypropylene fibre, the strain energy of the soil increases which indicates the capacity of soil to absorb energy increases with increasing fibre content. Thus, the ability of the liner to carry load without cracking increases, and also its resistance to sudden loads like earthquake loads enhances. This increase in strain energy of soil after the addition of fibre can be attributed to the anchorage action of the fibre in the soil matrix. Figure 8 and figure 9, which are given below, supports the above statement.

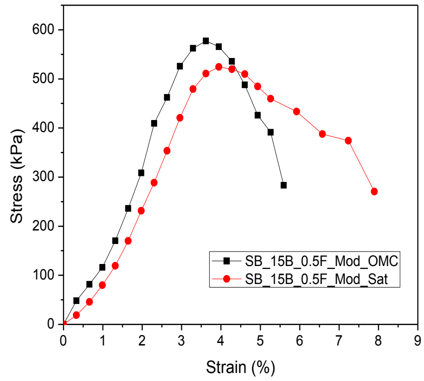


Fig. 8. Effect of water content on stress-strain curve

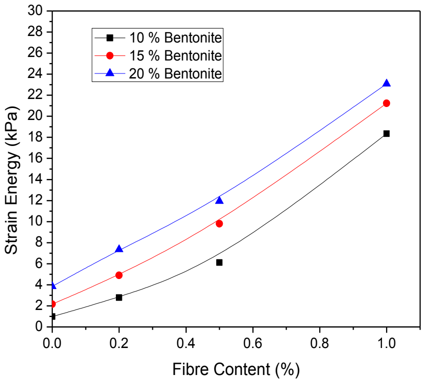


Fig. 9. Variation of strain energy with increasing fibre content for samples with different bentonite content

3.5 Effect of Fibre Inclusion on Hydraulic Conductivity of Soil

The hydraulic conductivity of the heavily compacted soil is measured after the soil attains saturation state. It is observed that with increasing fibre content, the hydraulic conductivity of the soil increases. The permeability for unreinforced sand bentonite mixture with 15% bentonite content and increases from 1.71 X 10^{-8} cm/sec to 3.20 X 10^{-8} cm/sec when reinforced with 1% polypropylene fibre, i.e. increase in permeability by 87.1% in comparison to that of unreinforced soil. Although there is an increase in hydraulic conductivity of soil, the increase not enough to render the soil unsuitable for being a liner material. The randomly inserted fibres are connected, and by drainage action, it increases the permeability of sand bentonite mixture (Maher et al.). Thus, with increasing fibre content, the permeability of the mixture increases.

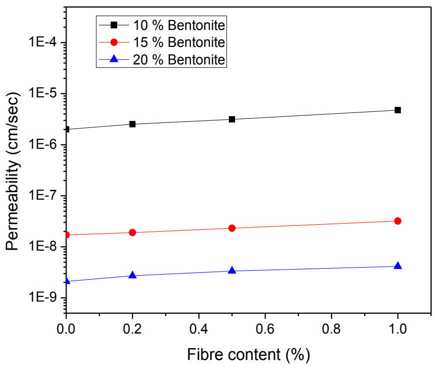


Fig. 10. Variation of hydraulic conductivity with fibre content

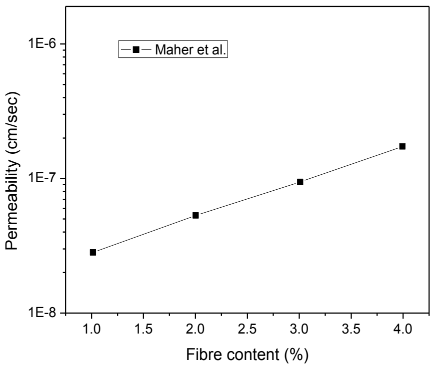


Fig. 11. Variation of hydraulic conductivity with fibre content as observed by Maher et al

4. Conclusion

Polypropylene fibre is randomly mixed with sand bentonite mixture and compacted. Various tests are performed to investigate the strength and hydraulic properties of the mix. The following conclusions can be drawn from the obtained test results.

The unconfined compressive strength of the mixture increases manifold with a slight increase in the percentage of fibre. The percentage increase in UCS value is more in lightly compacted soil in comparison to highly compacted soil, but the UCS value in case of heavily compacted sample is very much higher than samples compacted lightly. The saturated samples show an increasing trend in UCS value too. In this case, the percentage increase in both the lightly compacted samples and heavily compacted samples are almost same, although the UCS value for heavily compacted sample is much higher. It is also found that the strain energy increases and post-peak loss decreases with increasing fibre content. Addition of polypropylene fibre causes a slight increase in hydraulic conductivity.

From the above points and results, it can be concluded that sand bentonite mixture with 10% bentonite content can proficiently satisfy the strength criteria of liner material after addition of fibre, but it will fail to fulfil the permeability criteria whereas 15% bentonite content can appropriately meet both strength criteria (minimum 200 kPa UCS value) and permeability criteria (not exceeding 10^{-7} cm/sec). A bentonite content of 20% satisfy both strength and permeability criteria but for cost-effective design 15% bentonite content can be concluded as optimized bentonite content, and in the necessity of enhancing strength fibre can be added accordingly.

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