

STRENGTH OF SOIL REINFORCED WITH FIBER MATERIALS (PAPYRUS)

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Construction of building and other civil engineering structures on weak or soft soil is highly risky because such soil is susceptible to differential settlements, poor shear strength, and high compressibility. Various soil improvement techniques have been used to enhance the engineering properties of soil. Soil reinforcement by fiber material is considered an effective ground improvement method because of its cost effectiveness, easy adaptability, and reproducibility. Hence, in the present investigation, papyrus fiber has been chosen as the reinforcement material, and it was randomly included into the soil at four different percentages of fiber content, i.e., 5, 10, 15, 25% by volume of raw soil. The main objective of this research is to focus on the strength behavior of soil reinforced with randomly included papyrus fiber. Direct shear, consolidation, and displacement tests were performed on papyrus-reinforced specimens with various fiber contents. The results of these tests have clearly shown a significant improvement in the failure deviator stress and shear strength parameters (c and ϕ) of the studied soil with a percent addition of 10% (the preferred percent). Moreover, this addition ratio reduced the displacement of the soil under loading. It can be concluded that papyrus fiber can be considered an appropriate soil reinforcement material.

1. Introduction.

The concept of soil reinforcement is an ancient technique and is demonstrated abundantly in nature by animals, birds, and the action of tree roots. Constructions using these techniques are known to have existed in the fifth and fourth millennia B.C. (Jones, 1985). This concept is used for the improvement of certain desired properties of soil such as bearing capacity, shear strength (c and ϕ), permeability, etc. This concept and principle was first developed by Vidal (1969), in which he demonstrated that the introduction of reinforcing elements in a soil mass increases the shear resistance of the medium. At present, the soil reinforcement technique is well established and is used in various applications such as improving bearing capacity, filter, and drainage control. Conventional reinforcement methods comprise continuous inclusions of strips, fabrics, and grids into the soil mass. Also the random inclusion of various types of fibers is considered to be a modification of the same technique. These fibers act to interlock particles and aggregates in a unitary coherent matrix.

This work investigates the use of papyrus fiber for similar purposes. Mostly, the discrete fibers are simply added and mixed with the soil much the same as cement, lime, or any other additives. One of the main advantages of randomly distributed fibers is the maintenance of strength isotropy and absence of potential failure planes, which can develop parallel to the oriented reinforcement (Chakraborty and Dasgupta, 1996).

Reinforcing elements in the form of rods, sheets, strips, and membranes are typical traditional soil improvement techniques. Use of natural materials, such as jute, coir, sisal, and bamboo as reinforcing materials in soil is widespread in many countries such as India, Ceylon, Philippines, etc., but very limited information has been reported on the use of randomly distributed discrete papyrus fibers for soil reinforcement.

The main advantage of these materials is that they are locally available and are very cheap. They are biodegradable and hence do not create disposal problems in the environment. Processing of these materials into a usable form generates employment activity in rural areas in these countries. If these materials are used effectively, the rural economy can get uplifted. In addition, the cost of construction can be reduced if the material use leads to beneficial effects in engineering construction. Papyrus is useful in different applications for erosion control, improving the performance of embankments, and improving the bearing capacity of the soil. Embankment soils, when mixed with fibers, show improvement in strength and stiffness properties. Such improvement is very useful in short-term stability and deformation requirements. Studies have also shown that durability can be improved using coatings of fibers with phenol and bitumen, which are easily available in these areas. Lekha (2004) and Vishnudas et al. (2006) present a few case studies of construction and performance monitoring of fiber geotextile reinforced bunds and show that the use of such materials is a cost-effective ecohydrological measure compared to stone pitching and other stabilization measures used in the protection of slopes and bunds in rural areas. However, comprehensive studies on the strength behavior of soil mixed with papyrus fibers are not available, and thus the results presented in this paper are of importance in this regard.

This paper presents the experimental results on the influence of papyrus (reed) fibers on the strength and stiffness response of a typical soil. Tests were conducted using different fiber contents, and expressions for obtaining strength parameters, namely cohesion, friction angle, and stiffness are proposed.

The main aim of this research is to study the effect of fiber papyrus reinforcement on the strength and stiffness of soil. A series of direct shear tests and consolidation tests was carried out to evaluate the influence of papyrus on soil structures as natural reinforcement material.

2. Literature review

Gray and Ohashi (1983) conducted a series of direct shear tests on dry sand reinforced with different synthetic, natural, and metallic fibers to evaluate the effect of different aspects such as fiber orientation, fiber content, fiber area ratios, and fiber stiffness on the shear strength. Based on the test results, Gray and Ohashi concluded that an increase in shear strength is directly proportional to the fiber area ratio. The shear strength envelopes for fiber-reinforced sand clearly showed the existence of a threshold confining stress below which the fibers try to slip or pull out. Maher and Gray (1990) conducted triaxial compression tests on sand reinforced with discrete, randomly distributed fibers and observed the influence of various fiber properties, soil properties, and other test variables on soil behavior. Maher and Ho (1994) evaluated the mechanical properties of a kaolinite-fiber soil composite by conducting a series of unconfined compression, splitting tension, and three point bending tests. Wahab et al. (1997) conducted detailed studies to evaluate the effect of individual polypropylene fibers on the total and effective strength parameters of the soil. Rao and Balan (2000) carried out triaxial compression tests with coir fibers using different fiber contents.

3. Materials properties and experimental study

3.1. Soil sample

The Soil used in this study can be classified as sandy clayey silt. The physical properties are given in Table 1.

3.2. Papyrus fibers

Papyrus has a wide range distribution in swamps, streams, lakes, and wet lands. The mineral composition of papyrus differs in different parts of the plant. This variation in mineral composition is

TABLE 1

Soil properties	Values
LL	28.2%
PL	20.8%
PI	7.4%
Water content	21%
Specific gravity [t/m ³]	2.64
Sand	9 %
Silt	79%
Clay	12%
Porosity (n)	39%
Dry unit weight [kN/m ³]	16.1

TABLE 2

Elements	Concentration, %
<i>N</i>	29.62
<i>P</i>	1.37
<i>K</i>	55.46
<i>Na</i>	7.23
<i>Ca</i>	4.82
<i>Mg</i>	0.62
<i>Fe</i>	0.13
<i>Mn</i>	0.72

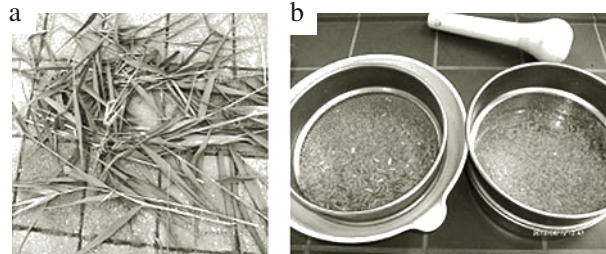


Fig.1. Papyrus before drying and crushing (a), and papyrus after treatment and sieving (b).

probably related to differences in the age of various portions and differences in nutrient percentage (Gaudet, 1975). In this research the tests were carried out by using papyrus leaf fibers collected from swamps in the Netherlands. Table 2 shows the mineral composition of the papyrus used.

3.3. Shear test

The papyrus (fibers) used in this test were dried and crushed to finer grain size in order to obtain randomly reinforced soil sample. The size of the fibers was chosen after passing through sieves for suitable size mixture ranging between 0.5 to 1.5 mm (Fig. 1). The fibers were mixed with the soil until distributed effectively. Different percentages of papyrus (5, 10, 15, and 25%) were added in order to investigate the influence of each percentage on the soil stiffness compared with unreferenced sample.

The experimental study involved performing a series of direct shear tests. The tests were conducted in a shear box of size 70 mm by 20 mm (diameter and depth). The tests were performed as consolidated and drained tests at normal stresses of $\sigma_n = 100, 200, \text{ and } 400$ kPa in order to completely define the shear strength parameters (i.e., the effective angle of shear strength (ϕ') and cohesion (c')) for both unreinforced and reinforced soil specimens. The loading rate was 0.002 mm/s in the tests. Shear stresses were recorded as a function of horizontal displacement up to a total displacement of 10 mm. A shear rate of 0.05 mm/min was applied according to the German standards DIN-18137 with duplicated specimens to observe the post-failure behavior as well.

3.4. Consolidation and settlement

Odometer tests were performed according to the German Standard 18134. Apparatuses with a diameter of 7 cm and height 1.4 cm were put in the consolidation cells. The soil was mixed with different fibers content of 5, 10, 15 and 25%. The soil samples were enclosed in a metal ring and placed into the consolidometer. The sample was sandwiched between two filter plates, allowing two-way drainage of the sample. Water was added into the cell around the sample, so that the sample remained saturated during the test. Seven vertical static load increments were applied. The changes in the displacement of the sample against time were recorded during each loading increment.

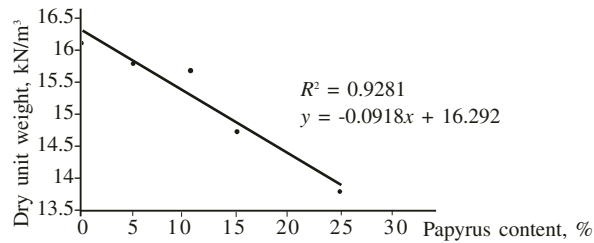


Fig. 2. Relation between dry unit weight and papyrus content of the soil samples.

TABLE 3

Papyrus content, %	c , kN/m ²	ϕ°	Dry Unit Weight, kN/m ³
0	0.95	31.8	16.1
5	8.5	32.41	15.81
10	17.5	35.78	15.8
15	11.8	35.2	14.8
25	11.76	35.7	13.9

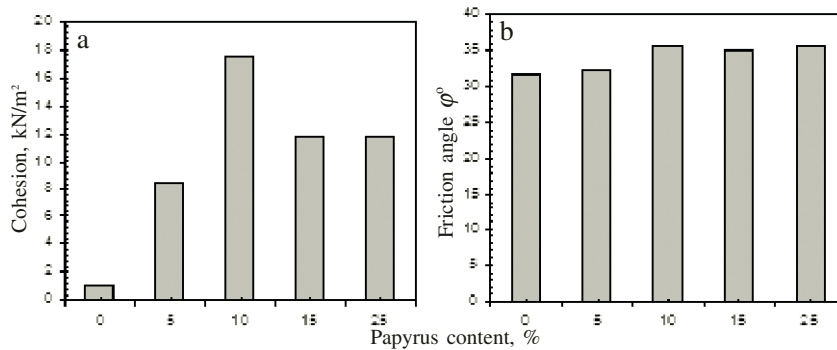


Fig.3. Variation of cohesion and friction angle for unreinforced and reinforced soil.

4. Results and discussions

4.1. Effect of fiber content on dry density

The effect of fiber content on dry density is presented in Fig. 2. For any particular fiber content, an increase in fiber content causes a reduction in dry density. As already explained, this is due to the reduction of average unit weight of the solids in the soil fiber mixture. It is observed from Fig. 2 that the plot of variation of dry density with respect to fiber content is an inverse linear relationship. This result matches that of Parbakar and Sridhar (2002).

4.2. Shear strength

The variation of cohesion c and friction angle ϕ is given in Table 3 and Fig. 3. The variation of cohesion and friction angle with fiber content shows a nonlinear relationship. The result shows that the cohesion of the soil reinforced with 10% of papyrus is highest among the different percent additions, and lowest in the reference soil (zero% papyrus). Following the same trend, the internal friction of the reinforced soil increased with increasing percentage of the papyrus added to the soil, but a 10% addition showed the highest value, which is compatible with the cohesion of the soil. Based on the direct shear test results, the study indicated that fiber reinforcement increased the peak shear strength and limited post-peak reductions in shear resistance, with significant increase in stiffness of the fiber-soil composite.

Since the horizontal displacements at failure were high ($s = 10$ mm) for both kinds of materials (i.e., unreinforced and reinforced), the strain developed in the fiber reinforcements was likely to be high

Table 4

Soil samples	e_o	Cc	Cr	Ps	CR	RR	E , MN/m ²
0%(reference)	0.64	0.116	0.12	980	0.0707	0.0731	463
5%	0.67	0.085	0.09	981	0.0508	0.0538	466
10%	0.68	0.126	0.09	1,005	0.0750	0.0535	685
15%	0.79	0.094	0.11	980	0.0560	0.0614	480
25%	0.9	0.085	0.09	970	0.0447	0.0473	420

as well. However, due to the lack of a peak, fiber contribution to peak strength and strain at failure were insignificant in the tests (Yetimoglu and Salbas 2003). It is observed, however, that the quasi-brittle behavior of the soil without reinforcement is somehow changed into a more ductile one if the fiber content reaches 10%. For the tests with 10% papyrus and for the lowest vertical stress (i.e., $\sigma_v = 100$ kN/m²), the material showed first a contraction (up to 3 mm) and then a dilatation. This behavior was observed twice in the same materials prepared individually. Fig. 3, a shows that cohesion increases and reaches maximum values with 10% papyrus, and thereafter it decreases as fiber content increases. It can also be seen that as the fiber content increases, the angle of friction marginally increases and the peak was at 10%. It should be noted that the shear resistance of the reed-reinforced soil consists of two components, friction and cohesion and hence there is an improvement in shear strength of plain soil due to the random reed inclusions at 10%. A possible explanation for the increased cohesion with 10% fiber content may be the increased density of the soil fiber mass resulting in a decreasing void ratio. The values agree also with previous works (Babu and Vasudevan, 2008).

Bauer and Oancea (1996), based on shear tests, stated that the secant modulus as an indication of stiffness within the initial vertical strain of 2% decreases with increasing polypropylene fiber content up to 50%. Consoli et al. (1998) conducted triaxial compression tests and showed that fiber reinforcement increased the peak and residual strengths but decreased stiffness. Kumar et al. (1999) reported that the optimum fiber content for silty sand was approximately of 0.3-0.4%. The disagreement among the results might be attributed to differences in the material properties, percentage of additions, and testing conditions.

4.3. Consolidation

The effect of papyrus fiber addition in soil on consolidation shows that a 10% papyrus addition increases the stiffness of the soil by about 9%. The odometer test is shown in Table 4. However, the relation between compression and compression index is not a direct relation, and the compression index (Cc) does not represent the compressibility of the soil. Wesly (1988) mentioned that it is more realistic to use the compression ratio (CR) to determine the compressibility value:

$$CR = Cc/1 + e_o.$$

In contrast, the rebound (swelling) ratio (RR) is more accurate than the swelling index (Cr):

$$RR = Cr/1 + e_o.$$

Moreover, Al-Adili (1998) concluded that the compressibility and rebound ratios may increase while the compressibility and rebound indices decrease. The results showed that the compression ratios of the fiber-reinforced soil were reduced for 5, 15 and 25% additions, while they increased with a 10% addition, even though the initial voids were increased by increasing papyrus additions (Table 4). The results of the tests carried out on different fiber contents varying from 5 to 25% by volume of soil are presented in Fig. 4. From this figure, it is clear that the strength of reinforced soil with 10% papyrus addition leads to increasing elasticity moduli, and this 10% represents the preferred per-

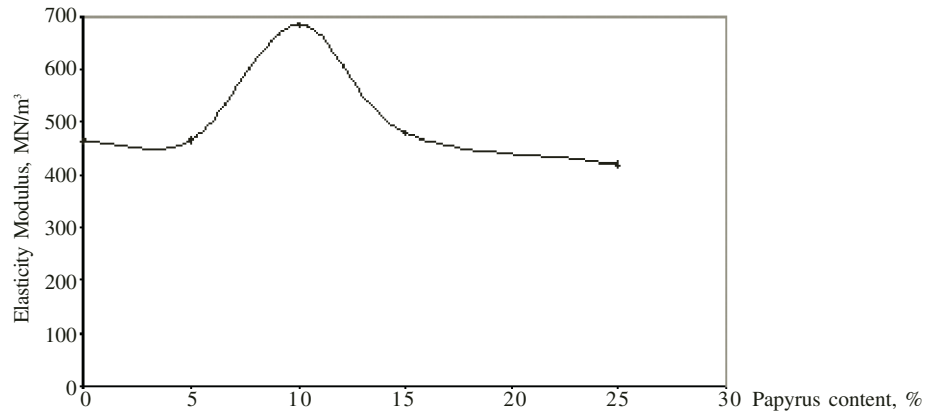


Fig. 4. Modulus of elasticity of the fiber-reinforced soil samples.

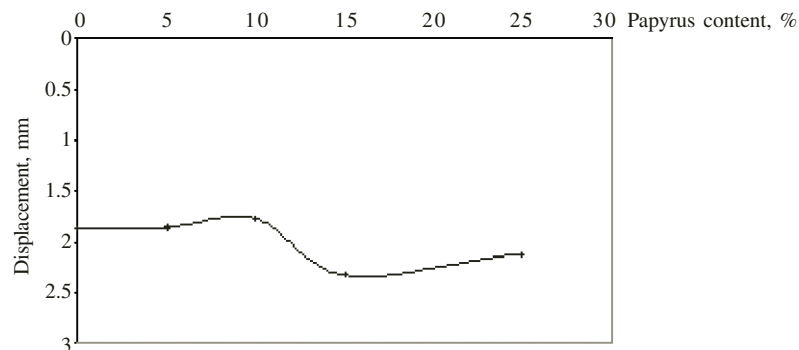


Fig. 5. The displacement of the soil under loading.

centage of fiber reinforcement for improving the soil strata. The increase in the cohesion of the soil-fiber matrix may be due to the increase in the confining pressure as a result of the effect of fiber content on fiber tension, and the moisture in the fiber helps to form an absorbed water layer on the soil particles, which enables the reinforced soil to act as a single coherent matrix of soil fiber mass (Prabakar and Sridhar, 2002).

4.4. The Displacement

The fiber content percentage plays an important role in the displacement of the fiber-reinforced soil. Settlement tests of the soil showed that a 10% addition of papyrus improved the soil structure, while other fibers contents increase the displacement (Fig. 5). This result agrees with the results of other test on this type of reinforcement, such as shear and consolidation.

Nevertheless, the initial void ratio and porosity increased with increasing papyrus ratios in the soil, but a 10% addition appears to be the preferred percentage because it acts like a bond between the soil particles and the elongated shape of the fibers, and the pore pressure somehow forced the displacement.

5. Conclusion

The study presents comprehensive experimental results on the strength and stiffness response of papyrus fiber-reinforced soil. Based on the test results and discussions, the following conclusions can be made:

1. Based on experiments conducted to study the influence of papyrus fiber (random inclusion) as reinforcement material on the strength behavior of soil, it is seen that papyrus fiber reduces the dry density of the soil due to its low specific gravity and unit weight.

2. The shear stress of fiber-reinforced soil was improved by the addition of 10% papyrus fibers. The cohesion improved the soil structure, and the 10% addition represents the preferred fiber reinforcement.
3. Also, this research concludes that 10% addition of papyrus improves the strength of the soil by increasing the elasticity and reducing the displacement. This is due to the bonding action of the fibers, thus reducing the tensile stress.
4. The stiffness of the soil increases considerably due to the fiber inclusion, hence immediate settlement of the soil can be reduced by incorporating fibers in the soil.
5. One disadvantage of this reinforcement method is the degradation of the papyrus during long-term use in the tropical environment. Hence, it is recommended to impregnate the papyrus when used in such an environment.

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