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Anti-hydrodynamic properties of fiber-reinforced soil and its application

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ABSTRACT: This paper demonstrates the excellent erosion or scour resistance of fiber-reinforced soil, referring to the results of scour resistance tests, and describes a case of fluvial embankment slope constructed by this technique. Besides, from the observation results of the slope and follow-up research on pull-out resistance of vegetable roots, it is shown that fiber-reinforced soil is suitable for vegetation bed in slopes liable to erosion by running water.

1. INTRODUCTION

Rainfall or running water erodes cutover slopes of mountains or hills and sandy soil slopes. Surface soil of eroded slopes tends to flow away, impeding thereby formation of stable slope covered with trees, well harmonized with the natural environment. Fiber materials have been widely utilized in civil engineering for anti-erosion and reinforcement of banking. The techniques using fiber materials do not, however, modify the characteristics of soil liable to flow away due to rainfall, since they just cover or restrain the ground surface with sheet, cloth or vegetation mats.

In contrast, the fiber-reinforced soil technique involves mixture of synthetic fibers such as polyester several centimeters long, of 1 to 100 De* with soil or stabilized soil (De is short for Denier: Denier is a unit of finesse for yarn equal to the finesse of a yarn weighing one gram for each 9000 meters). The mix proportion of fibers to soil is about 0.01 to 2 % on the basis of dry weight of soil. This technique offers greater unconfined compression strength, bending strength and greater toughness. Besides, it can modify sandy soil produced in construction, apt to flow away by rainfall or running water into banking material resistant to erosion, and it can allow construction of levees and banks covered with greenery, since reinforcing fibers prevent uprooting.

This paper demonstrates increase of scour resistance by mixture of fibers, that is to say, the critical flow velocity becomes higher at which the scouring starts, on the basis of the scour tests conducted on fiber-reinforced sandy soil, and tries to grasp the mechanics of such behavior.

Then, referring to a case of fiber-reinforced soil used for creating a surface bed of levee slope, this paper presents the apparatus and method for uniformly mixing on site fibers and sandy soil.

Besides, by observation results of the slope of fiber-reinforced soil and follow-up research of pull-out resistance of roots, we will see that, in the slope of fiber-reinforced soil, even 2 years after construction only very thin surface layer flowed away, without showing any significant erosion trace unlike in the plain soil slope, proving by this fact that the fiber reinforcement increases the surface erosion resistance and pull-out resistance of vegetable roots, and improves the vegetation conditions, verifying thereby that fiber-reinforced soil is suitable as bed for vegetation in slopes liable to erosion due to rainfall and running water.

2. INDOOR SCOUR TEST

Fibers for the technique discussed here must satisfy these conditions; 1) can be uniformly mixed with soil, 2) have a sufficient tensile strength, 3) be ensured to present a sufficient tensile strength for a long span of time, when a significant biological and/or chemical erosion resistance is required, 4) low cost convenient as an earthwork material, 5) easily available on the market and stable quality, etc. Polypropylene and polyester fibers are typical examples meeting these requirements, generally used in the fiber-reinforced soil technique.

Scour resistance tests using running water were conducted on polyester-fiber-reinforced soil.

2.1 Test practice

Fig. 1 shows the grain size distribution of silica sand used in the tests. The water content, density and compaction degree were kept constant in all the tests, whereas the diameter and length of the fibers were varied, that is, fibers of 46, 53 and 119 De in diameter, 64, 100 and 102 mm long were used. The mix proportion was varied in a range from 0.2 to 0.4% on the basis of dry weight of specimen soil. Table 1 summarizes the properties of fibers.

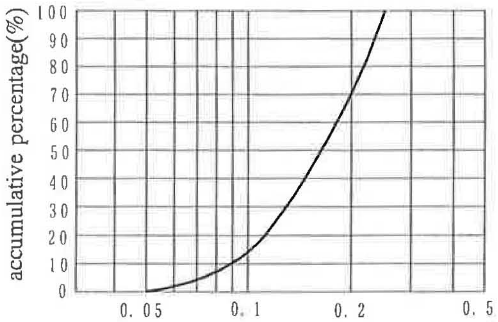

Fig. 1 Grain size distribution of the silica soil

Table 1 Properties of the fiber

case no.	1	2	3	4	5	6	7	8
Diameter D(μ m)	--	53	53	53	46	46	119	46, 119 mixed
Length L(mm)	--	64	64	64	100	100	102	100,102
MIX proportin n (%)	0	0.2	0.4	0.8	0.2	0.4	0.4	0.2+0.2

The specimens were prepared by agitating silica sand in a horizontal dual-axis mixer (capacity of 50 liters), gradually adding short fibers. Mixed soil was put in a mold with U-shaped groove 1.50 m long, 0.3 m wide, 0.15 m deep, and roller-compacted till the compaction degree became 90%.

Fig. 2 illustrates the scour resistance test equipment, having a square cross section is 0.30 m wide x 0.30 m high. It is a straight open water channel 9 m long in total, including a 5 m approach, 1.5 m zone for specimen and 2.5 m lower reaches. The specimen zone is provided with a box-shaped hollow on the bottom of the channel to accommodate the specimen. The specimen installed was gradually saturated, then left as it was for 24 hours.

The test was performed as follows. The valve on the water reservoir was opened to make water flow over the surface of fiber-reinforced soil specimen, increasing step by step the flow velocity with an

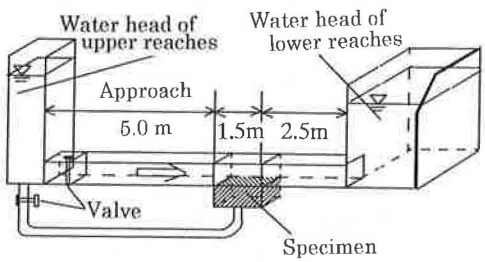

Fig.2 Sectional diagram of the scour resistance test equipment for fiber-reinforced soil

increment of 0.1 m/s. The duration for each flow velocity was 10 minutes. During this time interval, the variation of scoured depth, i.e., variation of irregularities of the specimen surface was observed visually and measured with a point gauge. Such water flow/measurement cycle at the same flow velocity was repeated three times, then the flow velocity was increased by 0.1 m/s to perform the next step.

The scour depth was measured at an interval of 5 cm in the longitudinal direction (85 points in total), to calculate the average depth. Before starting the test, the flow velocity was regulated to a specified value by controlling the flow rate. During the test practice also, the flow velocity was managed and controlled by measuring the vertical distribution of flow velocity above the specimen.

2.2 Scour resistance

The variation of flow velocity and scour depth along with time is shown in Fig. 3. The upper graph represents the flow velocities determined by the flow rate measurement weir. From the lower graphs of scour depth vs circulation time, it is clear that there are points where the gradient of the scour curve increases abruptly. Let us call the flow velocity at such a point "critical flow velocity" for scour. The figure shows that the critical flow velocity is 0.5 m/s for the specimen without fibers (plain soil), while that for fiber-reinforced specimens is 0.7 m/s or more.

This fact demonstrates that mixture of fibers increases the scour resistance. In the case of plain soil specimen, scour develops rapidly at a low flow velocity. On the contrary, in the case of fiber-reinforced specimens, scour develops slowly at the initial stage, then the scour depth increases abruptly when the flow velocity reaches a certain level. Let us compare the critical flow velocities for the specimens with the same fiber mixture proportion. When the mix proportion is 0.2 %, the critical speed is 0.7 m/s for the specimen with 64 mm long fibers and 0.8 m/s

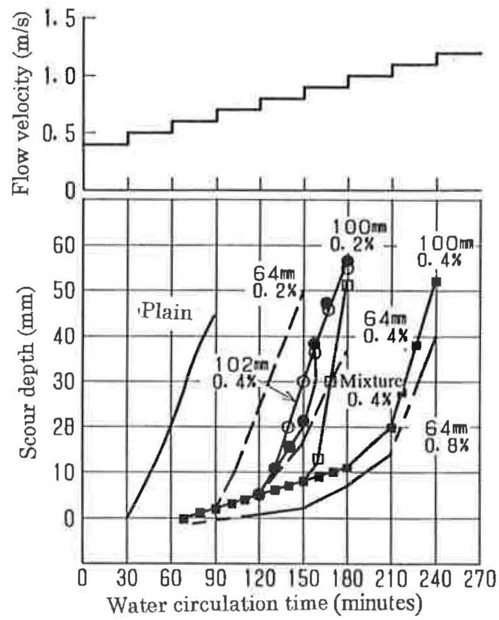

Fig. 3 Variation along with time of flow velocity and scour depth

for the specimen with 100 mm long fibers. When the mix proportion is 0.4%, the critical speed is 0.8 m/s for the specimen with 64 mm or 102 mm long fibers and 1.1 m/s for the specimen with 100 mm long fibers.

For studying the influence on the scour resistance, exerted by the ratio of fiber length to diameter and mix proportion of fibers, we rearranged the experimental results as follows. The ratio of fiber length to diameter is expressed as L/D. The values of L/D multiplied by the mix proportion (n%) are plotted along the abscissa axis, and the critical flow velocities along the ordinate axis. The plots are shown in Fig. 4. From this figure, it can be concluded that there is a proportional relationship between critical flow velocity and L/D x n, and that, use of longer fibers can reduce the mix proportion.

Considering these results, the scour resistance of fiber-reinforced soil can be evaluated by L/D x n which is a function of fiber geometry and mix proportion.

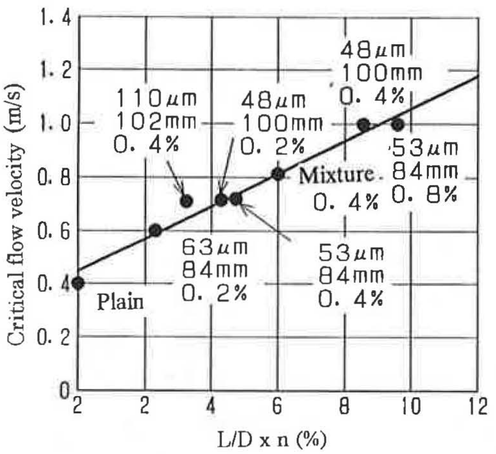

Fig. 4 Critical flow velocity vs L/D x n (%)

2.3 Discussion on the reinforcing mechanism

The author et al. have written many papers which describe the excellent mechanical characteristics of fiber-reinforced soil which is a tough material, manifesting a high resistance against failure.

Besides, the author et al. have demonstrated by experiments that, when soil, which is isotropic and homogeneous, is mixed with fibers, it is modified into an inhomogeneous material, preventing thereby remarkable failure due to stress concentration, that is to say, increasing the toughness by impeding generation of shear plane. It has been qualitatively known that the fiber-reinforced soil is a compound material which shows an excellent toughness because fibers in soil disperse the direction of microcracking to avoid stress concentration and fibers serve as bridges for preventing soil particles from moving under shear force.

However, quantitative design criteria have not yet been established, because it is difficult to predict the strength and toughness increasing effect of fiber-reinforced soil, which vary with soil particle composition, kind of fibers, material properties, stabilizing treatment.

We are going to discuss below the reinforcing mechanism against erosion by fluid, referring to the relationship between critical scour flow velocity determined by the tests and L/D x n which is a function of fiber geometry and fiber mix proportion. Let N be the number of fibers included per unit volume.

$$(D/2)^2 \pi L \rho_f N = \rho_d n \qquad (2.1)$$

where

ρ_f = mass of fibers

ρ_d = dry weight of soil material

Hence

$$n = \frac{(D/2)^2 \pi LN \rho_f}{\rho_d} \qquad (2.2)$$

The function L/D x n is expressed as follows.

$$L/D \times n = \frac{\rho_f \pi N}{4 \rho_d} DL^2 \qquad (2.3)$$

The lift F given by fluid acting on the soil particle surface is determined by the formula

$$F = \frac{1}{2} \rho C_L V^2 \qquad (2.4)$$

where

ρ = mass of water

V = flow velocity

C_L = Lifting coefficient

If it is assumed that scour starts when the magnitude of F exceeds the adhesion between particles, the adhesion is proportional to V^2.

If, from Fig. 4, the critical scour flow velocity is supposed to be in a proportional relationship with

L/D x n, the adhesion between particles is determined by, from the equations (2.3),(2.4), as a function of square of fiber length, fiber diameter and number.

The square of fiber length is expected to correspond to the size of soil particle block restrained by the fiber, the number of fibers to the number of soil particles. So it is predicted that the longer is the fiber and the larger is the number, the greater becomes the reinforcing effect. If the mixing proportion is kept constant and the fiber diameter is reduced to a half, the number of fibers is squared. So the reinforcement effect is expected to increase, even if the fiber diameter is decreased.

3. A CASE OF APPLICATION

As an example of application of the fiber-reinforcement technique, a trial work is reported here, which is a case of protection against erosion of the land-side slope of a provisional levee construction. This case was intended for preventing erosion of slope due to overtopping and protection before seed spraying. The simplified sectional diagram is shown in Fig. 5.

3.1 Characteristics of soil materials

The soil materials were sediment of sandy soil mixed

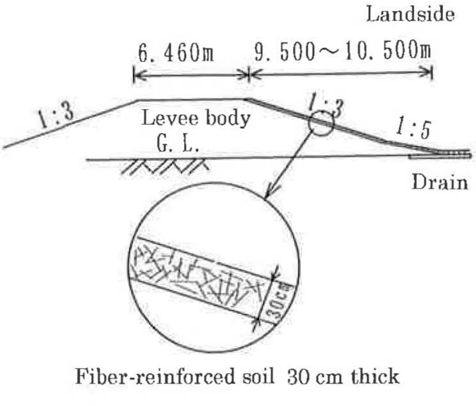

Fig. 5 Section of the levee

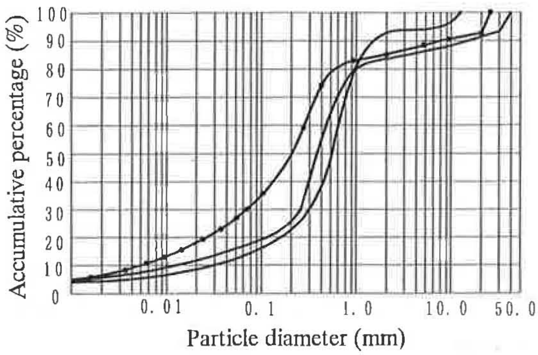

Fig. 6 Grain size distribution of the soil produced in the construction site

with gravel and vegetable roots. After removing these foreign substances with a sieve of 40 mm opening, the soil was kept in a hopper for use as raw material for fiber-reinforced soil. The grain size distribution is shown in Fig. 6. Though the grain size distribution varied with sampling location, it can be said that the average grain size was larger than the silica sand used in the scour tests, including silt and clayey particles.

3.2 Mixing method

Weighed soil was put in a batching-plant type mixing device to be blended with fibers. The mixing device was a backhoe with a compound ribbon-type mixer mounted in the attachment position. Fibers were compressed to a density of 0.1 g/cm^3. Compressed fiber packages were weighed and put into the mixer. The mixer capacity (one mixing batch) was 0.5 m^3 and one mixing cycle was 1 to 2 minutes. The mixing capacity per mixer at the time of the tests was about 5 m^3/hour. But, it has been increased up to 15 to 30 m^3/hour.

The mixing state of soil and fibers was checked by washing the mixture to take out fibers and weigh them. Table 2 summarizes the length, finesse and sectional geometry of the fibers, which were determined for each mix proportion. Three different sectional geometries of fibers were used. The data in this table demonstrate that fibers and soil were mixed uniformly. From visual observation too, it was known that fibers were randomly dispersed one by one in the matrix of soil particles, and no bundled fibers were found.

The fiber-reinforced soil was transported by a rubber-tired carrier and spread over the slope 200 m long in total, of 650 m2. Roller compaction was performed so that the covering thickness became 30 cm. After dressing the embankment, the density and soil hardness of the slope surface were measured to control the work quality.

Table 2 Mixing performance of fiber-reinforced soil

case No.	1	2	3	4	5
Planned mix proportion in %	0.2	0.4	0. 2	0. 2	0. 2
Fiber section	H-shaped	H-shaped	H-shaped	H-shaped	Continuous beads
Length in mm	32	32	51	64	32
Quantity in m^3	387	50	105	60	15
Actual mix proportion	0. 234	0. 430	0. 207	0. 247	0. 225

4. FOLLOW-UP RESEARCH

Follow-up research was implemented for two years after placement of the fiber-mixed soil, for inspecting erosion of the slope, vegetation, status of vegetable roots, their pull-out resistance.

4.1 Evaluation by visual check

From the observation results of the status of the slope a half year after the placement, which had experienced snowfall, snow melting, rainfall, it was verified that, in the slope with plain soil, the surface soil was eroded by rainfall, that is, rill erosion due to surface water flow and gully erosion producing gutters developed, whereas in the slope with fiber-reinforced soil, no rills, howsoever small, were created over the total length of 200 m. After this observation, seeds were sprayed over the slope.

At the time of the observations one year and two years after the placement, in the fiber-reinforced soil slope, plants 40 to 50 cm high such as mugwort grew densely. In contrast, over the plain-soil slope, plants were sparse. The slope surface of plain soil presented numerous groove-shaped erosion traces, while the fiber-reinforced soil slope showed almost flat surface with no erosion traces.

4.2 Evaluation by soil hardness

The variation of soil surface hardness after the placement was monitored with a Yamanaka-type soil hardness gauge. This gauge is 20 cm long, 3 cm in diameter, weighing 640 g, provided at the end with a cone 40 mm high, having a vertical angle of $12^{\circ}40'$, 18 mm in base diameter. The resistance generated when the cone is pushed into the ground is indicated by the elongation of the spring in the gauge or readout of the resistance per unit sectional area of penetration (kgf/cm^2).

Five measurements were performed per 5 cm square to calculate the average. The variation of soil hardness along with time is plotted in Fig. 7.

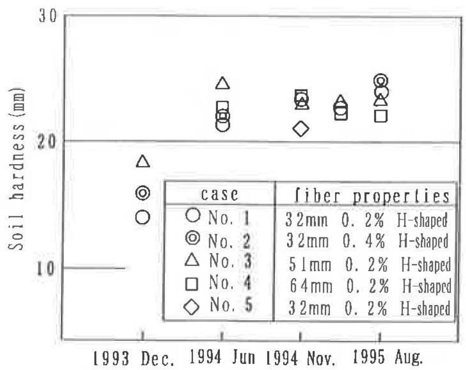

Fig. 7 Variation of soil hardness

As shown in the figure, the hardness is low immediately after the placement, but it remains almost constant around 20 to 25. Though the hardness slightly varies with kind of fiber and mix proportion, it is below 25 mm, which allows penetration of vegetable roots.

4.3 Evaluation by the pull-out resistance of roots

It is well known that ground covered with plants exhibits a higher erosion resistance. But the mechanism of improvement of erosion resistance by vegetable roots has not yet been thoroughly made clear. According to the current level of knowledge, increase of scour resistance is provided mainly by root hairs, and stems and leaves above the ground are secondary elements for it.

Thus, the pull-out resistance of roots was measured to investigate its relationship with diameter, density, depth of roots.

For determining the pull-out resistance, grass over a measurement area of 1 m x 1 m was cut down, then measurement was performed at 5 spots with a pull-out apparatus, and the 5 values obtained were averaged. Fig. 8 is a diagram of the pull-out rake of the test apparatus. The rake is put into the ground, gently for not disturbing the soil system, it is connected with a force gauge, then the rake is vertically pulled out by the operator. The maximum force for pull out is recorded. Pulled out roots were washed out with water to remove sticking soil for their evaluation.

Fig. 9 shows the results of pull-out resistance tests conducted one year after the placement. From this figure, it is known that the pull-out resistance for slope of fiber-reinforced soil is two to three times as large as that for plain soil slope. Such high resistance is equivalent to that of good grassland. This proves that an excellent greening bed was created a half year after seed spraying.

Let us now look at the relationship between pull-out resistance and global evaluation of roots (diameter, density and depth). The evaluation criteria are given in Table 3. The averages of evaluation results (5 grades) of the three items are plotted against the pull-out resistance in Fig. 10. The roots were graded by a point system, 5 is the best, 1 the worst. The straight line in the figure represents the results of the pull-out resistance tests of the plant community around the levee. The graphs demonstrate that, though the results for the slope of fiber-reinforced soil fluctuate, the roots show in general a greater pull-out resistance than those of the community in the surroundings. Besides, it is confirmed that, since there is almost no difference between the results one year and two years after the placement, the effect of fiber mixing is maintained.

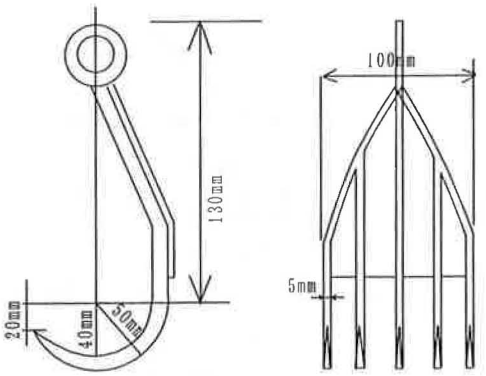

Fig. 8 Pull-out rake Plate

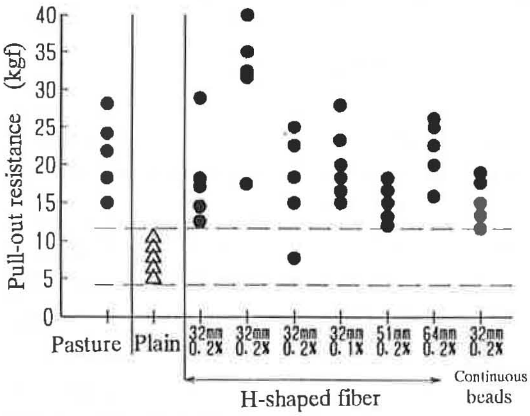

Fig. 9 Pull-out resistance of roots (one year after placement)

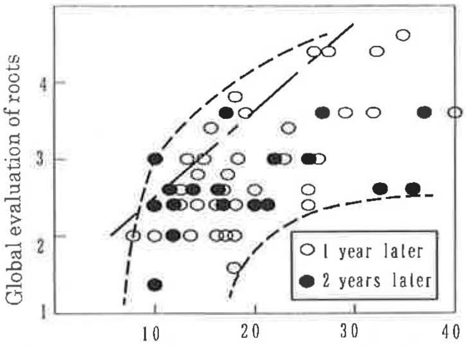

Fig. 10 Relationship between global evaluation of roots and pull-out resistance and

5. CONCLUSIONS

The resistance of fiber-reinforced soil against rainfall and running water has been verified in this paper by the indoor scour resistance test. The excellent properties of the fiber reinforcement technique for anti-erosion and greening beds have been verified by the actual construction case (slope). The conclusions reached are summarized as follows.

(1) As demonstrated by the scour tests, mixture with fiber increases the scour resistance.

(2) As inferred from the scour test results, the critical scour flow velocity is proportional to the function of fiber geometry and mix proportion, L/D x n. When the required critical scour flow velocity is the same, use of longer fibers can reduce the mix proportion.

(3) The follow-up investigation for two years of the case of levee slope showed that grooves due to rainfall were generated in the slope of plain soil, whereas in the slope with fiber-reinforced soil, no rills, howsoever small, were created over the total length of 200 m.

(4) A variety of plants densely grew over the fiber-reinforced soil. In contrast, on the plain-soil slope, plants were sparse.

(5) The soil hardness is below 25 mm, which allows penetration of vegetable roots.

(6) The roots in the fiber-reinforced slope presented pull-out resistances 2 to 3 times larger than those in the plain soil slope.

(7) The roots in the fiber-reinforced slope have a greater pull-out resistance than those of the community in the surroundings.

The fiber reinforcement technique can use either soil in situ or soil produced in construction sites. This technique will see wider application such as embankment, construction of revetments suitable as greening beds, provided with enhanced properties, that is, greater resistances against cracking, deformation, flow-out of soil, pull-out of plant roots, and against piping.

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