Texsol: Material Properties and Engineering Performance

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Texsol is a composite material made of sand and continuous polyester fibers mixed together in situ to form a homogeneous construction material. The fiber content varies between 0.1 and 0.2 percent of the weight of sand. The fibers provide for the high cohesion of Texsol and its ability to sustain large strains without degradation of its mechanical properties. The sand is well-graded medium course material and provides for the internal friction resistance of Texsol and its self-draining characteristics. Substantial testing programs have been conducted by state agencies, universities, and research institutions in France and subsequently in Japan to assess the engineering performance of this composite material and develop relevant design methods for its various fields of application.

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Substantial testing programs have been conducted by state agencies, universities, and research institutions in France and subsequently Japan to assess the engineering performance of this composite material and develop relevant design methods for its various fields of application. The research and development programs, as well as field observations on more than 100 Texsol structures constructed since 1984, demonstrated that the engineering properties of Texsol include high shear resistance with anisotropic mechanically built-in internal cohesion and internal friction angle that are dependent on the fiber content (*1,2*), self-draining properties of the sand used, low creep potential under normal operating conditions, durability and sustainable resistance to chemical and biological attacks, high ductibility and large energy absorption capacity with high resistance to impact, explosions, and seismic effects (*3,4*); deformability and large tolerance to differential settlements; high resistance to runoff surface erosion (*5*), and high thermal resistance under fire-generated heat up to 600°F (*6*). In addition, Texsol provides a suitable support for plant roots to penetrate and seeds to germinate. Mixed in organic soil, fertilizer, and seeds, the Texsol green method enables the hydroseeding of steep natural slopes, excavated slopes, embankments, retaining walls, soundproof walls, and so forth, where conventional hydroseeding techniques are impractical.

Because of its remarkable features, Texsol has been increasingly used in a variety of engineering applications (Figure 1), including earth retaining walls, particularly on soft compressible soils, with facing slope angles of 65 to 75 degrees; stabilization of earth slopes in cuts and embankments; steepening of existing slopes for widening of motorways; surface protection of man-made and natural slopes against rock falls and surface erosion due to climate conditions (e.g., freezing temperature); and explosion-resistant facilities in civil and military installations for storage of explosives and liquefied gas, offering a remarkable market potential for civil engineering construction in earthquake zones.

This paper presents the main results of the research conducted to assess the material properties and engineering performance of Texsol's structural applications.

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MATERIAL PROPERTIES

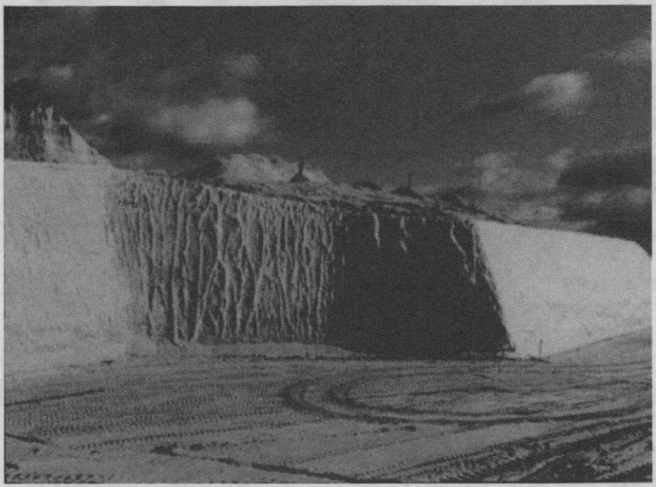
Sheer Strength Characteristics

The mechanical properties of Texsol depend on the characteristics of the granular material used, thread type, fiber content, production equipment, and compaction parameters (density and water content).

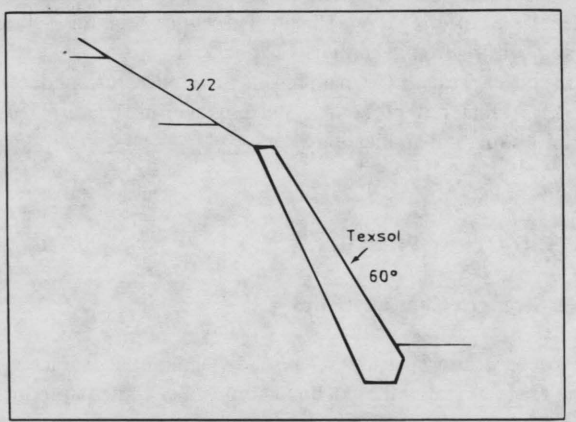
Figure 2 shows the results of triaxial compression tests performed on samples of Texsol and unreinforced sand under different confining pressures and the related characteristic failure curves of these materials. Test results illustrate that the shear modulus of Texsol and its hydraulic conductivity are similar to that of the natural sand. The main mechanical properties of Texsol are

- Unconfined compressive strength: 500 kPa/0.1 percent of fill content ratio by weight;
- Apparent cohesion of 100 kPa/0.1 percent of fill content ratio by weight;
- Internal friction angle that is equal or greater than that of the natural sand, with
  $\varnothing$ Texsol = $\varnothing$ soil + $\Delta\varnothing$,
  ($\Delta \varnothing$ varies from 0 to 10);
- Yield strain that is greater than that of the natural sand, indicating the ductile behavior of Texsol with
  $E^{\text{Texsol}} = E^{\text{soil}} + \Delta E^{r}$
  (ΔE varies from 0 to 10 percent);

Because of the production process of Texsol, the shear strength characteristics are anisotropic, that is, function of the inclination angle $\propto$ of the shear failure surface with respect to the depositional plane of the material. Figure 3 shows the results of direct shear tests of Texsol specimens prepared with a reference 0/5 mm sand, polyester fiber with a linear density of 167 define, and fiber content of 0.2 percent by weight, prepared at the normal proctor density. The results



Retaining wall in Asterix theme park Plailly (before seeding)



Widening of Highway A12 - Bois d'Arcy

FIGURE 1 Examples of Texsol engineering applications.

illustrate the effect of the inclination angle ∝ on the apparent cohesion C_t and the internal friction angle $\varnothing^c$ of the reference Texsol material. With the present state of knowledge, the anisotropy of ∅t is not taken into account and $\varnothing^t$ is assumed to be constant and equal to the friction angle of the natural granular material which results in a conservative design. The anisotropy of the apparent cohesion of Texsol follows the empirical equation derived from the analysis of the test results obtained for the reference Texsol material

$C_t = 0.03 \propto^2 + 1{,}27 \propto + 16.5$ (in kPa)

Creep Behavior and Durability Consideration

Creep behavior of construction materials must be considered in civil engineering the result of permanent load and long life duration of constructions. In the case of geotextile reinforcement, creep studies have been made in order to select the proper reinforcing material and to evaluate the long term deformations to be expected.

A first conclusion of that research is that creep effects depend on polymer type. Polymers are characterized by their glass transition temperature Tg. Tg of polyester is around 79°C and Tg of polyolefins is below 0°C. As soil-structure temperatures are usually in the 0° to 30°C range, the basic difference between these materials will affect their engineering behavior. Below the Tg temperature, the polymer is a solid and will creep only under high working loads; above that temperature, the polymer will creep even under low working loads. This fundamental difference between the polymers has been the prime reason for the selection of polyester thread for Texsol structures such as retaining walls that have to sustain permanent loading. Typical characteristics of the polyester fibers currently used in Texsol structures are indicated in Table 1.

Creep effects result in both a reduction of failure strength (resulting from long-term loading) and long-term strain. It has therefore been necessary to demonstrate that the polyester fiber–reinforced Texsol material is not affected by creep under the working loads generally used in civil engineering structures. To address these issues, two series of creep tests have been conducted.

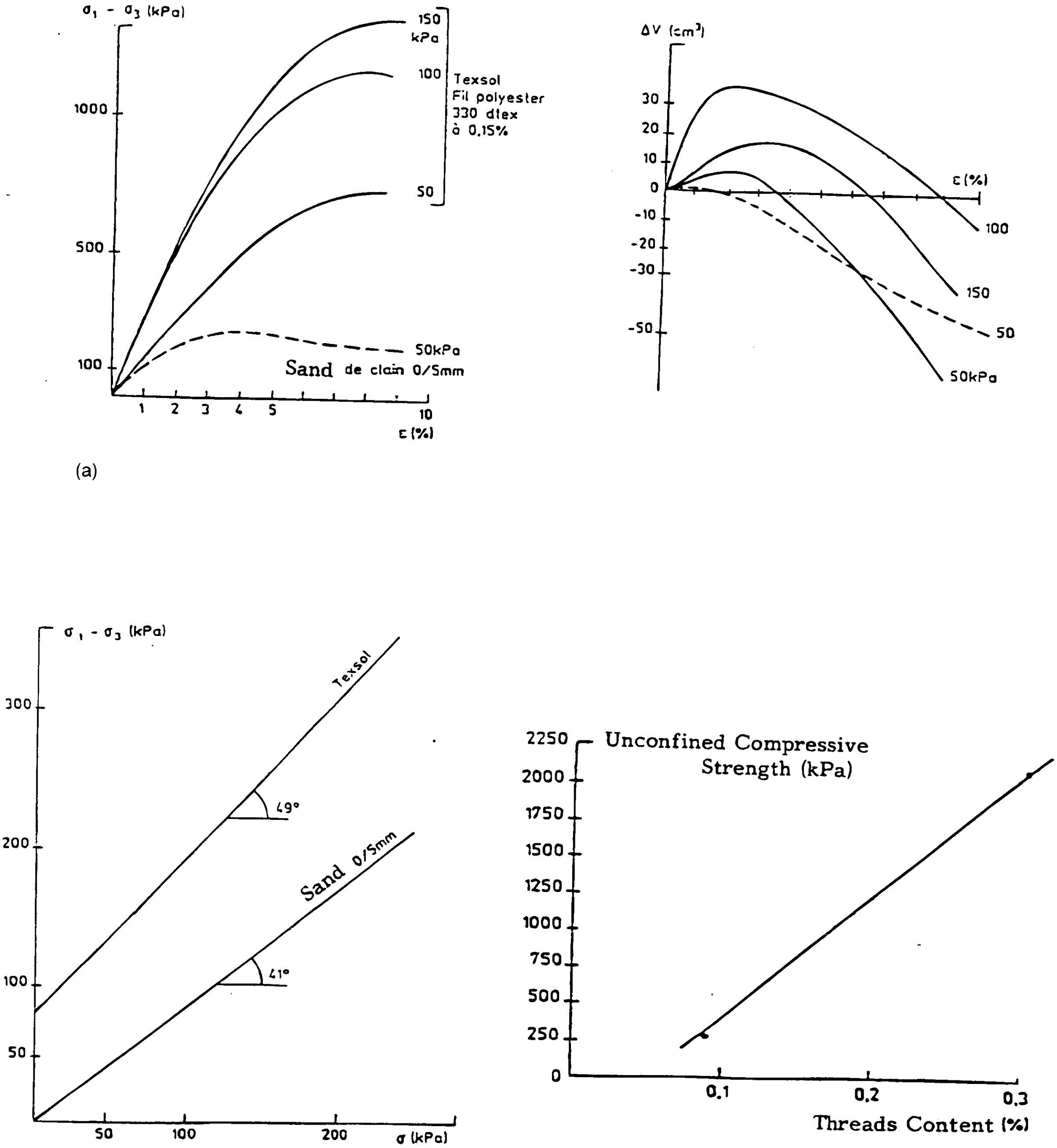
The first series of tests consisted of four long-term simple compression tests at room temperature. Two Texsol samples with a 0.12 percent proportion of polyester thread were submitted to 60 percent of their failure strength (as determined from another series of tests on reference samples) during 2.5 years, and two additional samples were loaded at 45 percent during 3 years. The rate of strain under the 60 percent load, after the initial settlement, has been linear with respect to log (t) with a slope smaller than 10-2 per cycle (i.e., less than 2 percent axial strain between 1 and 100 years). The samples loaded at 45 percent gave a strain rate of 5.10-3 per cycle of log (t). One sample loaded at 60 percent has been tested under compression after 850 days; the measured strength was equivalent to the short-term strength of the reference samples. These tests yield two important indications:

- Time-dependent deformations of the composite material made of polyester thread and granular material, for a given working load (as determined for the composite material itself), are significantly smaller than creep deformations measured on the thread alone for the same working load (as determined for the thread).
- Measured rate of strain, whether due to polymer creep, remains very low and does not generally need to be considered in geotechnical design of conventional retaining structures for fills and cuts.

The second group of creep loading tests has been done, at an elevated temperature (50°C or 60°C) to accelerate the creep under laboratory-controlled conditions. After triaxial loading at an elevated temperature, the samples were tested up to failure at ordinary temperature to measure their strength after preloading. This testing program included 50 samples. Preloading has been at two-thirds of the failure strength for most samples.

These tests have resulted in three main conclusions.

- The rate of strain under constant load has been found to be around 5.10-3 per cycle of log (t) at both 50°C and 60°C, which is close to the strain rate obtained under room temperature. Therefore, it is anticipated that this time-dependent deformation is not due to creep, because it is temperature independent. This deformation may be the result of the sand consolidation.
- As mentioned previously, the measured rate of time-dependent deformation can be ignored for most applications of the material (2 percent between 1 year and 100 years).
- Material strength is not decreased by the preloading: measured strength values after the loading period are equal or higher than the reference values determined on nonpreloaded samples. These



(a)

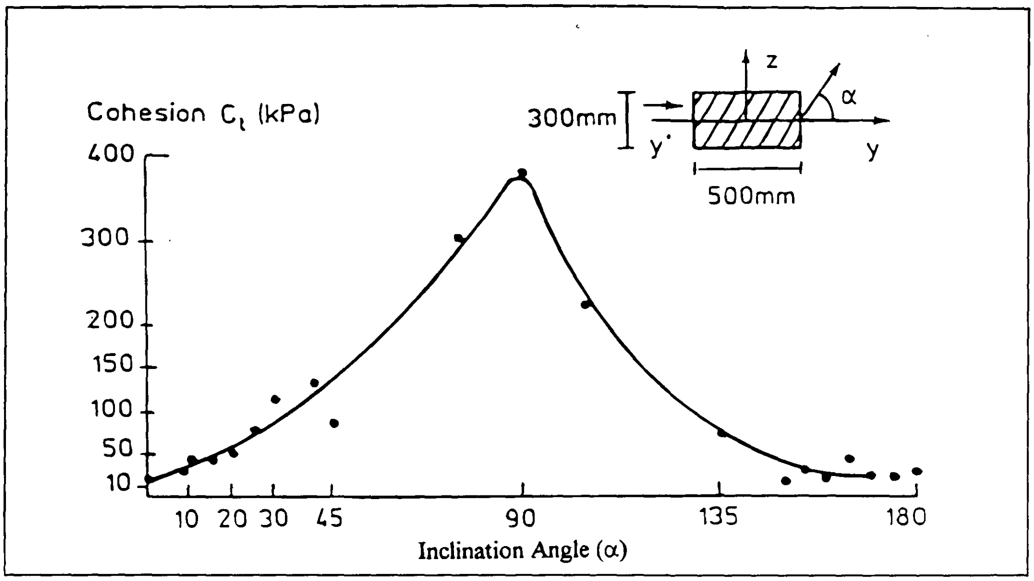
(b)

(c)

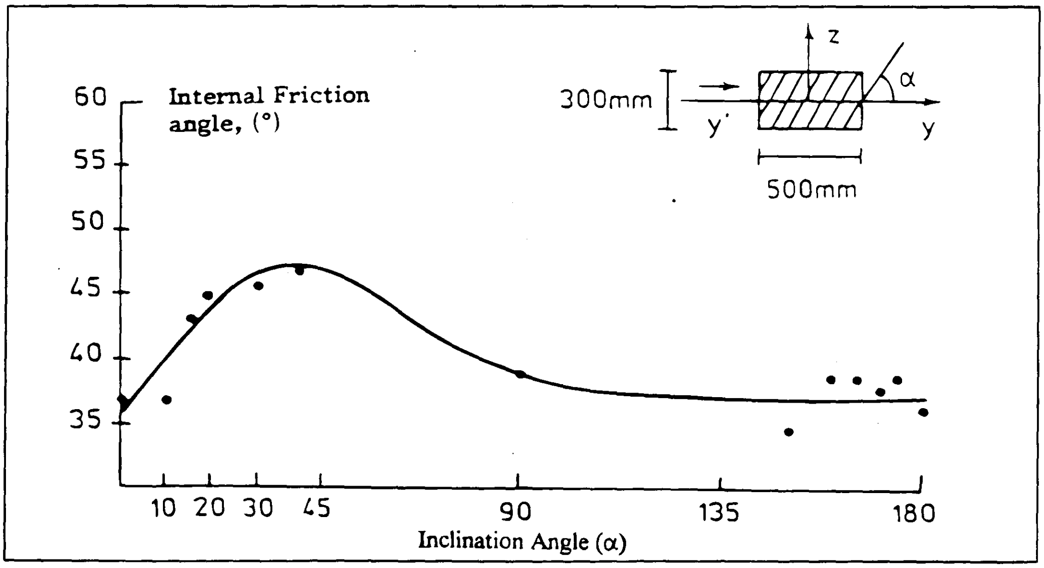
FIGURE 2 (a) Example of triaxial stress-deformation curves, (b) failure envelope for Texsol and natural sand, (c) Texsol T1: compressive strength versus threads proportion.

results further support the assumption of sand consolidation–induced deformation.

Degradations have been observed, which can be explained by mechanical stresses (compression, shear, abrasion), by ultraviolet light action, in case of long-term exposure, or by the influence of specific environments, such as cement during setting. However, the experience of more than 20 years with polyester geotextile structures illustrates that for fibers embedded into the soil mass, in most cases no chemical changes have been detected internally or on the surface of fibers. Furthermore, the statistical study of pH values of granular materials that can be used for Texsol shows that for the range of temperatures and pH values that are likely to be encountered in the natural environment, risk of hydrolysis degradation is not to be considered in design practice. However, the use of granular industrial wastes as a constituent of Texsol or applications in the presence of very specific industrial environments would require an appropriate investigation, which would also be routinely required if concrete, steel, or other materials are used. For extreme situations, different types of polymers could be used.



(a)



(b)

FIGURE 3 (a) Anisotropy of Texsol cohesion: experimental values from direct shear test, (b) internal friction angle of Texsol: experimental values from direct shear test (α—angle between layering plane and shearing plane).

TABLE 1 Typical Characteristics of Polyester Fiber used in Texol

Nature	Type of fill	Title (dtex)	Number of thread	Tenacity (cN/tex)	Extent. at failure (%)	Initial Modulus (cN/tex)
Polyester PES	Thread (integrated extrusion)	50	16	40	25	970
		167	30	36	26	770
		330	60	37	27	950
		280	60	58	19	790
		280	48	61	14	800

In situ observations and related laboratory analyses did not indicate any biological effect on the stability of polyester fibers. Furthermore, standard laboratory tests, using soils with a known bacteria content, indicated no reduction in the strength of polyester threads used for Texsol. It can therefore be concluded that Texsol has high durability and sustainable resistance to both chemical and biological attacks.

Dynamic Response Properties

Present knowledge on the seismic behavior of Texsol results from cyclic laboratory tests performed in France and both model studies and a full-scale experiment on a Texsol structure conducted in Japan.

The laboratory tests performed by Luong included

- Conventional triaxial tests with constant confinement, monotonic loading, repeated loading, long-duration cyclic loading, and large strain loading;
- Constant mean stress triaxial tests with monotonic loading and cyclic loading;
- Tests with monotonic or cyclic lateral loading;
- Liquefaction tests; and
- Longitudinal resonance tests and behavior under vibrations.

Impact behavior and wave propagation have also been considered.

The triaxial tests have shown the high ductility of Texsol and its high energy-absorption capacity, resulting from the high dilatancy occurring between the critical state (zero volumetric strain) and the peak strength. Energy absorption results from friction between particles of the material when deformation develops; the threads in the Texsol material allow large strains to exist in the granular material before failure; consequently, high energy absorption is possible while keeping a sufficient safety margin with respect to failure.

Cyclic compression and extension triaxial tests on reference Texsol material was performed (*7*) with a Fontainebleau sand, polyester 50/16 of 50 dtex with a fiber content of 0.2 percent by weight. For the high cyclic loading amplitude that exceeded the critical state (zero volumetric strain line), the test results illustrated in Figure 4 demonstrate a progressive densification of the Texsol material with the increasing number of cycles.

The liquefaction potential of Texsol has been investigated through cyclic triaxial deviatoric load testing, with cyclic loading amplitude exceeding the critical state line both in compression and extension. As illustrated in Figure 5, after a number of cycles, Texsol liquefaction tests show a stabilization of the stress-strain cycles indicating a high energy absorption resulting in high liquefaction resistance.

ENGINEERING PERFORMANCE OF TEXSOL WALLS

Static Loading

Several full-scale experiments have been conducted by the Regional Laboratory of Rouen in France to assess the engineering performance of Texsol walls. Figure 6a shows the cross section and site characteristics of the experimental wall, 3 m high with a facing inclination of 68 degrees, retaining an unreinforced Fontainebleau sand fill that was loaded up to failure. Figure 6b shows the facing displacements during the loading, illustrating a progressive rotational failure mechanism. The displacement records indicate that the surcharge loadings should exceed 75 percent of the failure loading to generate significant lateral displacements.

Seismic Loading

Tests performed in Japan (*4*) in cooperation with the National Research Institute of Agricultural Engineering (Ibaraki, Japan) and Kumagai Gumi Co., Ltd., included (a) a series of shaking table tests on models of earth dam with reinforced facing and (b) a 10-m-high test wall retaining an earth fill instrumented to evaluate its response to natural earthquakes.

Earth embankment models, 0.4 or 0.8 m high, were made of loose sand (with no impervious layer) with a downstream horizontal drain and tested with an upstream water level equal to three-fourths of the embankment height. Model facings were made of loose sand or reinforced with a compacted sand layer or a Texsol layer 10 to 15 cm thick. Models 0.4 m high were submitted to an input sine wave with a frequency of 10 Hz and with acceleration levels of 100, 200, 400, and 600 gal, applied during 10 sec. Models 0.8 m high were submitted to a 3-Hz vibration with acceleration levels of 150, 250, and 450 gal.

The parameters measured were acceleration, pore pressure, and settlement. Settlement of the crest and continuity of strains were considered indications of the effectiveness of the reinforcement method because they are critical to the risk of overflow. The models demonstrated that the use of Texsol significantly reduced settlements and created no cracks.

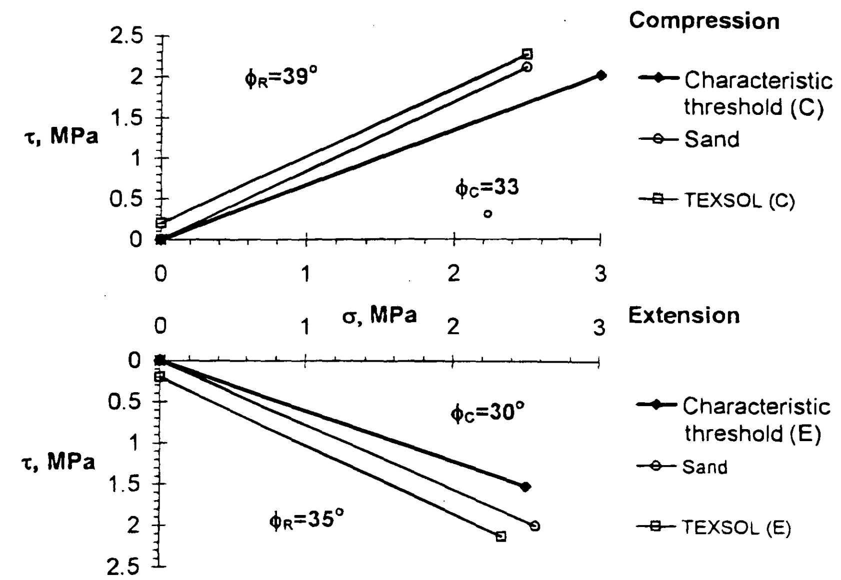
Figure 7 compares the settlements of the crest observed on the 0.4-m-high model under three conditions: unreinforced, reinforced with a dense sand layer, and reinforced with a Texsol layer. Four sec after loading, a settlement of approximately 25 mm occurred in the unreinforced model, but almost none occurred in the model reinforced with Texsol fibers. Seven sec after loading, the settlement of the model reinforced with continuous fibers (compared with the unreinforced one) was reduced to approximately one-third.

Figure 8 compares the settlement of the crest observed on the 0.8-m-high model at a 450-gal input. The crest settlement in the unreinforced embankment reached approximately 4 cm, and resulting cracks developed over the entire model embankment. In the model reinforced with the continuous fibers, almost no settlement occurred. The results of these large-scale shaking table tests demonstrated the effectiveness of the continuous fiber reinforcement.

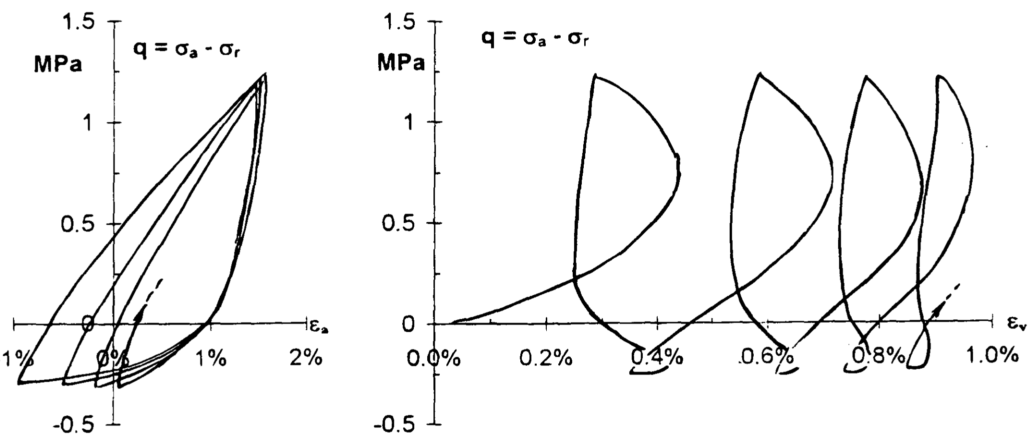
The 0.8-m-high model with Texsol had a maximum settlement of 6 mm, without cracks, whereas the unreinforced model showed a 41-mm settlement, with cracks propagated over the entire model, resulting in its collapse.

The 10-m-high wall illustrated in Figure 9 was monitored under natural conditions for a long-term performance evaluation. The retaining wall was completed in December 1988; since that date, it has undergone heavy rains, typhoons, and earthquakes up to a magnitude of 5.7 on the Richter scale (February 19, 1989). The wall showed no damage and stability was maintained.

The outer slope of the wall is 1:0.5 (63 degrees horizontally); the width at the base is 2.5 m and the width at the top is 1 m. The retained fill material has a density of 15.9 kN/m^3, a water content of 50 percent, a cohesion of 6 kPa, and an angle of internal friction of 18 degrees. During the February 19, 1989, earthquake, the measured acceleration at the ground surface perpendicular to the axis of the wall was 95 gal; the power spectrum showed accelerations from



(a)



(b)

FIGURE 4 (a) Texsol triaxial compression and extension tests; (b) densification behavior under high-amplitude repeated loading.

2 to 8 Hz. Vibration measurements on the wall allowed evaluation of its dynamic behavior (natural period around 0.4 sec).

Measurements of earth pressures on the wall between the fill and the Texsol material at different heights showed large variations of earth pressure during the earthquake because of the deformability and inertia of the wall. Figure 9 shows the cross section of the wall, its instrumentation, and the distribution of the maximum increase of the earth pressure during the earthquake. The observed distribution of the earth pressure increases from the static level to the maximum value as the earthquake is compared with the calculated values obtained based on the Mononobe-Okabe formula commonly used for earthquake-resistant design. This comparison indicates that the experimental distribution of the earth pressure generated by the seismic effect is not a triangular distribution, and it differs considerably from the distribution computed by the Mononobe-Okabe formula.

The major observation made during this natural earthquake was that, although the static safety of the wall was already at a critical state, no damage was found.

Resistance to Surface Erosion of Retaining Structures

Texsol constructions can be subjected to a large spectrum of erosion conditions according to type of structure, normal or exceptional operating conditions, local climate, and types of hydraulic attacks for which it is designed.

As an example, the use of Texsol in a bank protection system, possibly with other techniques or materials, does not require the study of the same mechanisms as does use in retaining structures. For walls, the surface erosion evaluation attempts to establish whether a progressive loss of granular material could occur at the surface of the Texsol material from rain and wind. Such a loss could result in a slow reduction of wall thickness.

Observations of existing walls before grassing or grassing by simple hydroseeding (without application of the Texsol green method) indicate that the effect of weathering on the surface of Texsol retaining structures does not result in continuous erosion of the wall beyond the construction phase and periods of rain occurring

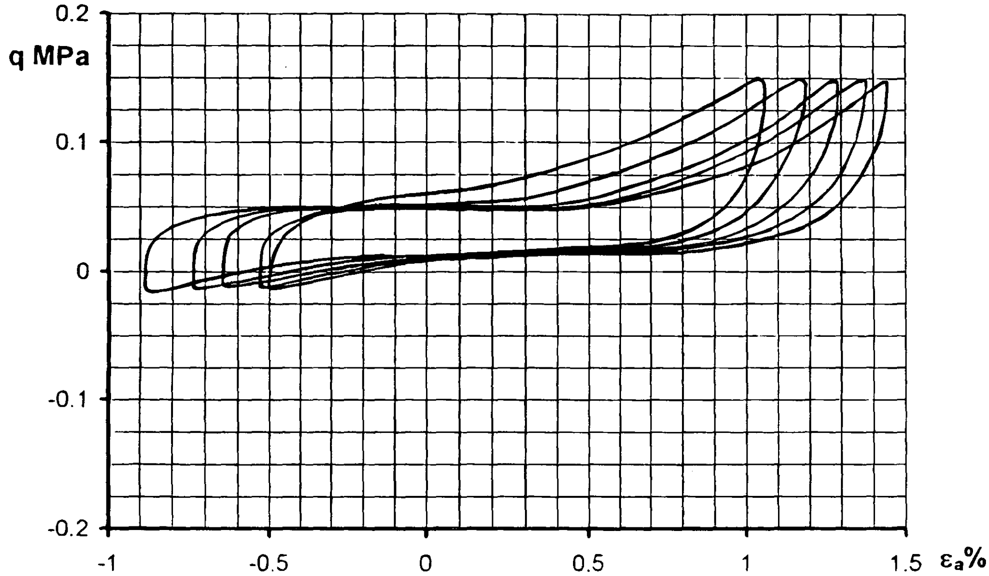


FIGURE 5 Liquefaction of saturated Texsol under controlled axial strain.

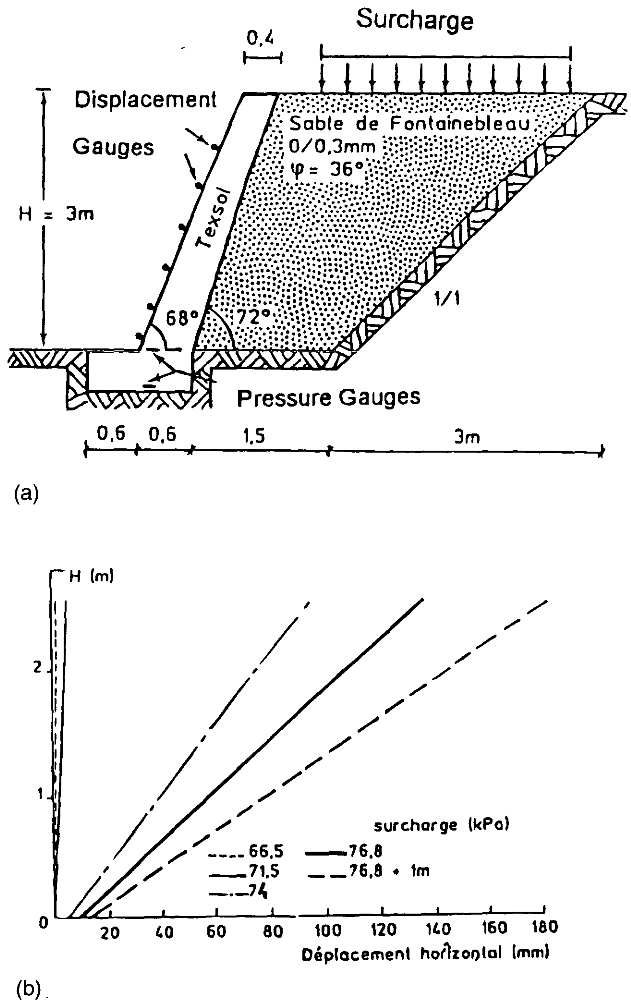


FIGURE 6 (a) Cross section of experimental wall, (b) successive deformation of wall No. 2 facing (*8*).

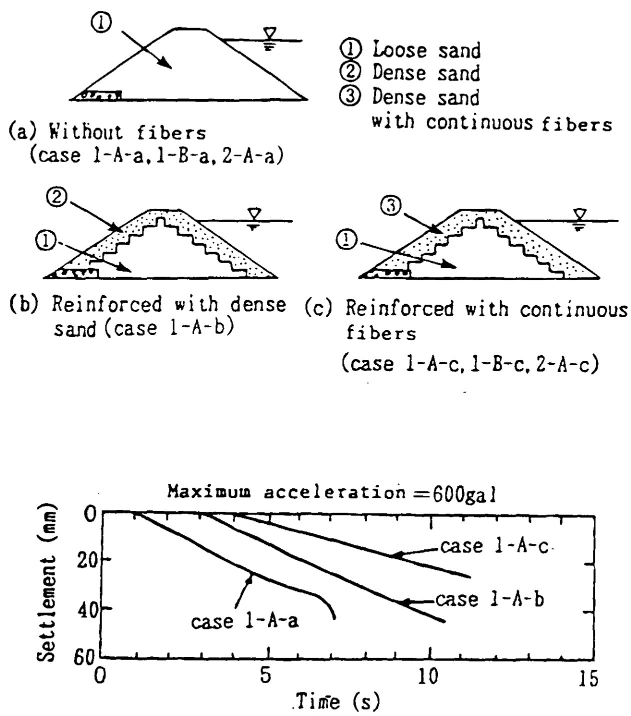


FIGURE 7 Small-scale shaking table test models: settlement of model crest (*4*).

shortly afterward. For example, such observations have been made on the many walls built along the A7 motorway in France. The longitudinal concrete surface collectors and drains placed in the cut areas where Texsol walls are built show no accumulation of sand material, which would have been carried from the toe of the walls toward the storm sewer.

In the course of a testing program on Texsol conducted by the Japanese Ministry of Construction, measurements have been made

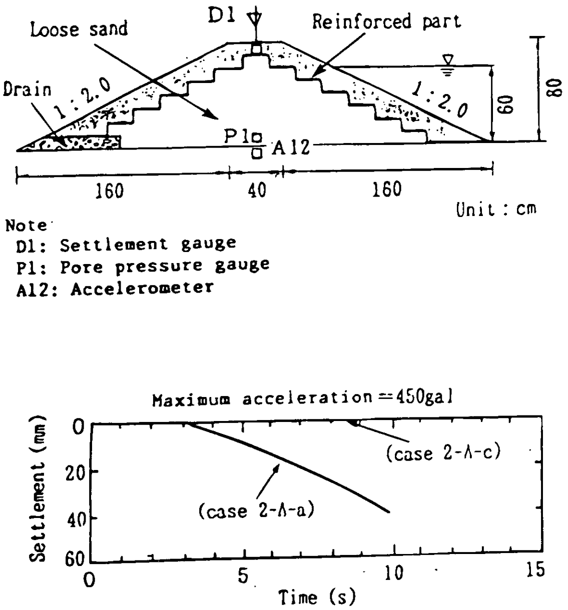


FIGURE 8 Large-scale shaking table test model (Model 2): settlement at D1 (Model 2, Sand A).

on a 5-m-high wall with a 63-degree slope, without vegetation. The wall was submitted to an intense artificial rain (30 mm/hr) and the amounts of eroded sand were measured. Translated into an average eroded thickness on the area of the face, the measured erosion showed the following values:

Total Rain (mm)	*Eroded Thickness (mm)*
100	5
200	9
300	12
400	14
500	15.2
600	16

It appears that the first rain periods have a washing effect on the surface, but that fairly quickly the erosion process slows down and, for all practical purposes, stops; extrapolating the experimental curve leads to a limiting value of 18 mm.

These measurements correspond well with observations made on actual projects, where the washed-out thickness occurring at an early age has been estimated, in temperate climate conditions, at an order of magnitude of 1 cm. However, incidental degradations have been observed as a result of a locally heavy running water flow: for example, the outflow at the top of a wall of a storm sewer resulted in local erosion important enough to require repair. Such surface water flows must be avoided. In particular, walls located below a large catchment area must be protected by an interceptor trench on top of the wall ensuring that an unknown quantity of water will not flow over the structure. Considering the relatively low rigidity of Texsol constructions, the trench is lined preferably with a material that will not crack, such as a geomembrane.

The absence of erosion under the action of rain is related to the intricate texture of the thread network contained in the Texsol material; in addition to this network knitted into the mass of the composite, the production process of Texsol often results in a superficial layer of threads oriented toward the slope and having weak connections with the material itself. All these threads are responsible for the erosion resistance that is observed, but the resulting appearance is often unsatisfactory when there is no vegetation or when simple grassing by seeding does not find sufficiently favorable growing conditions.

For this reason the Texsol green method has been developed (Figure 10) to reestablish appropriate conditions for a dense and durable vegetative cover, provided a proper water supply is available. The Texsol green method is used for the hydroseeding of Texsol walls or natural slopes where conventional hydroseeding techniques are impractical (e.g., excavated slopes, soundproof walls, steep embankments, etc.). It consists of Texsol mixed with fertilizer seeds and a coagulation agent, which is sprayed over the surface area of the structure. Artificial mesh is sometimes required to initially hold the Texsol green. Generally, the natural growth will take place gradually depending on the environment.

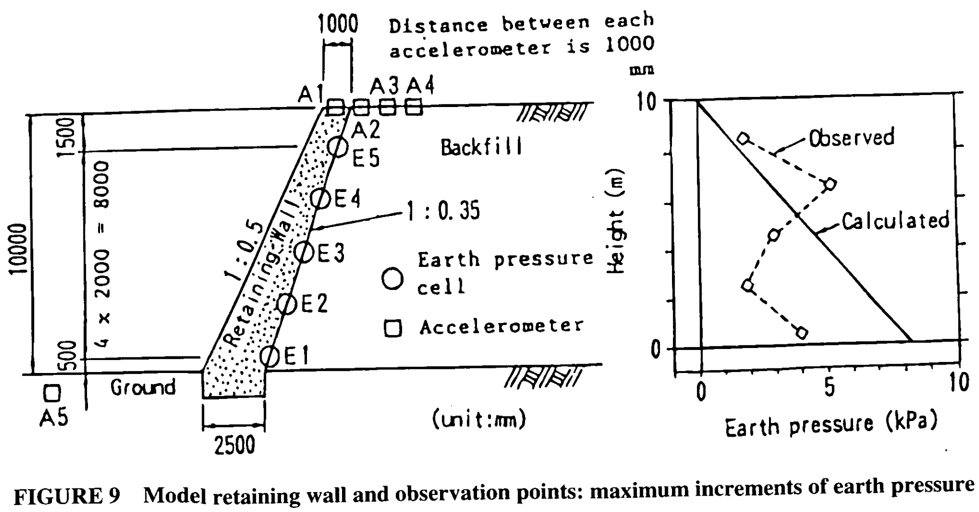
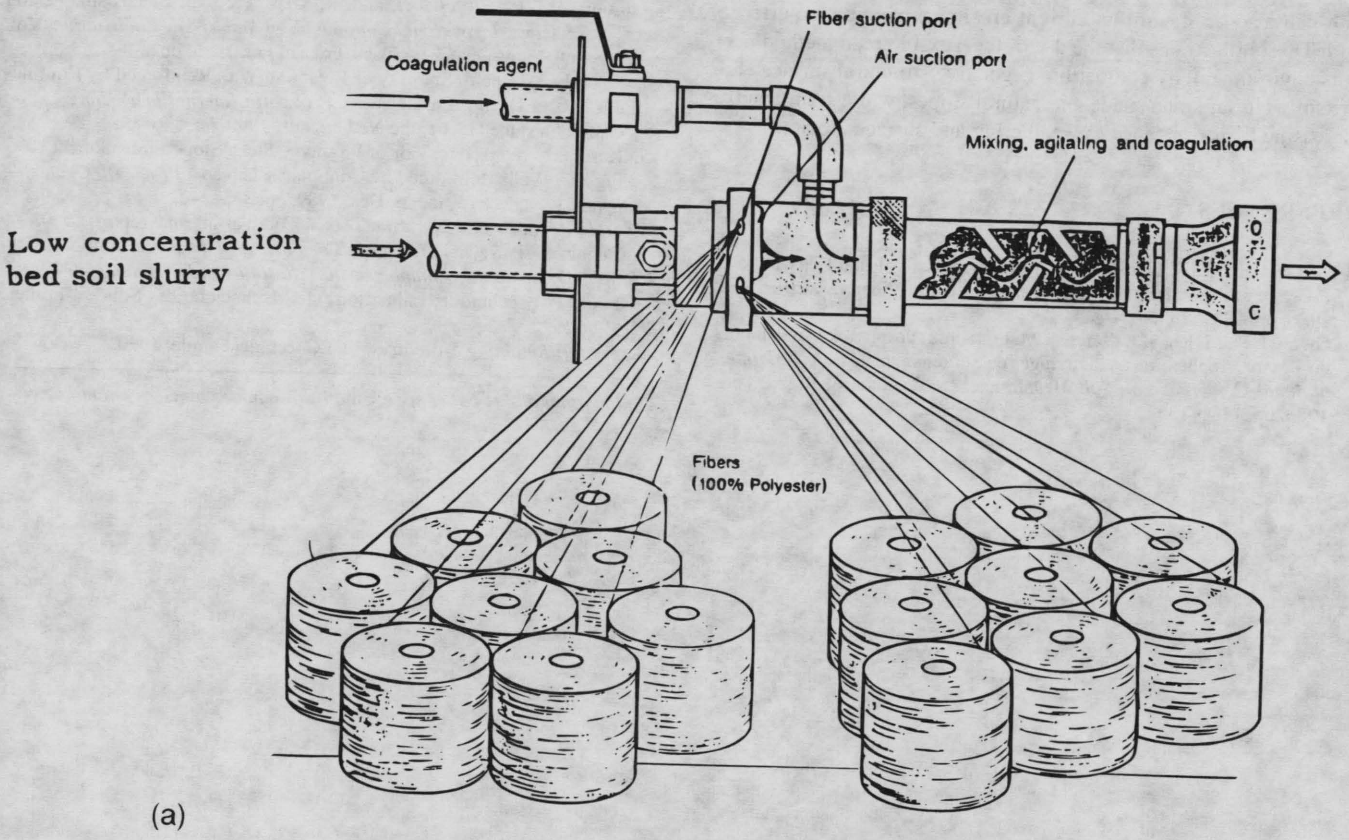


FIGURE 9 Model retaining wall and observation points: maximum increments of earth pressure due to earthquake.



(b)

FIGURE 10 (a) Schematic of green method of Texol production; (b) typical construction site using Texsol green method.

In addition to its landscaping purpose, application of the Texsol green method (through the additional layer it gives, its specific layer of thread, and the root network of the grass cover it generates) introduces an additional resistance to surface erosion. Using this technique is therefore advisable, not only on Texsol walls but also on natural slopes with soils or rocks prone to weathering and corrosion.

CONCLUSION

The testing programs conducted in France and Japan to assess the engineering performance of Texsol structures have demonstrated that the reinforcement of sand by continuous polyester fiber provides the composite material with apparent cohesion, ability to sustain large strains, and high energy-absorption capacity that make Texsol structures a cost-effective solution for highway retaining systems under difficult site conditions, such as compressible soft soils and earthquake zones.

As for durability, the experience gained from geotextiles made of polyester is applicable to the Texsol material. The creep studies on the Texsol material have demonstrated that

- Under normal operating conditions, the Texsol material using polyester thread does not creep; and
- There is no decrease of strength with loading time.

It can also be stated that current erosion protection experience with Texsol illustrates that the use of the Texsol green method permits environmentally compatible vegetative structural surfaces for Texsol walls and man-made and natural slopes, while significantly increasing their resistance to weathering and surface erosion.

REFERENCES

1. Leflaive, E., and P. Liausu. Le Renforcement des Sols par Fils Continus. *Proc., 3rd International Congress on Geotextiles*, Vienna, Austria, April 1986, pp. 523–528.
2. Gigan, J. P., M. Khay, J. Marchal, M. Ledelliou. Proprietes Mechaniques du Texsol: Application aux Ouvrages de Soutenement. *Proc., 12th International Conference on Soil Mechanics*, Rio de Janiero, Brazil, Aug. 1989, pp. 1251–1252.
3. Luong, M. P., E. Leflaive, and M. Khay. Proprietes Parasismiques du Texsol. *Proc., 1st National Colloquiam on Antiseismic Engineering*, Vol. 1, Saint-Remy-Les-Chevreuses, France. Jan. 1986, pp. 3-49–3-58.
4. Fukuoka, M., et al. Stability of Retaining Wall Reinforced by Continuous Fibers During Earthquakes. *Proc., 4th International Congress on Geotextiles*, the Hague, the Netherlands, 1990, pp. 546–558.
5. Kutura, K., et al. Behavior of Prototype Steep Slope Embankment Having Soil Walls Reinforced by Continuous Threads. *Proc., 4th Geotextile Symposium*, Tokyo, Japan, Dec. 1989, pp. 335–342.
6. *Stabilité au Feu du Materiau Texsol.* Totalgaz internal report, 1990.
7. Luong, M. P. *Recherches sur le Comportement du Texsol sous Sollicitations Dynamiques: Comportement Transitoire et Dynamique du Texsol.* Ecole Polytechnique, Laboratoire de Mechanique des Solides, France, 1986.
8. *Texsol: Retaining Structures.* LCPC technical guide, 1990.

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