Multicomponent Composite Emulsion Treated Geotextile on Landfill with Improved Long-Term Stability and Security

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ABSTRACT
Polypropylene geotextiles were treated with multicomponent composite emulsion consist of polytetrafluoroethylene (PTFE), nona-silica and fluorous acrylate. After process of treatment, the treated geotextiles showed greater long-term stability and security than untreated geotextiles on the landfill slope. Firstly, the surface of fibers was investigated by scanning electron microscopy (SEM). Composite thin film was found on them, indicating the successful attachment of ternary composite agents on fibers through pad-drying method. Subsequently, the effect of weathering stability and metallic ions (cupric ions usually) resistance on mechanical properties of samples were studied by using tensile machine. The friction angle values of various interfaces and tension in geotextile versus slope angle were also studied via tilt table test. Our mechanics performance tests indicated that the weathering ability and cupric ions resistance of geotextile were greatly improved via treatment with the composite emulsion. The roughness of geotextile surface, the friction angles of all interfaces and tension in geotextile on landfill slope were decreased.

Keywords: Landfill; Geotextile; Polytetrafluoroethylene; Nona-silica

INTRODUCTION
Currently, urban development and significant growth of population have resulted in a rapid increase in the quantity of municipal solid waste (MSW). According to Statistics [1], the per-capita generation of MSW in the developed countries has increased to approximately 1.5 kg each day. Therefore, a large number of municipal solid-waste landfills were built because of the gross pollution of huge amount of MSW.

Nowdays, modern landfills are mainly consisting of gas collection and control systems, top cover system, liner system, leachate collection and removal systems [2,3] to reduce the potential influence on the ambient environment as shown in *Figure 1a*.

In municipal solid-waste landfills, liner system is anchored at bench levels with the purpose of isolation MSW from the groundwater and surrounding environment to avoid potential contamination [4,5]. Unlike the early landfills, which only had a single clay liner, a typical liner system of modern landfill consists of geotextile, geomembrane and geosynthetic clay liner (GCL) as shown in *Figure 1b*.

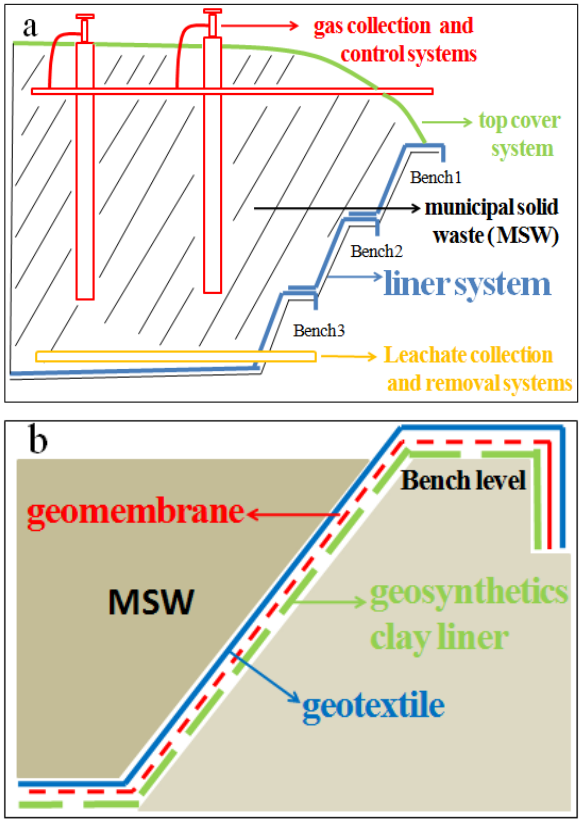


FIGURE 1. (a) The typical cross section of modern landfill, (b) The typical cross section of liner system.

Geomembrane, consisting of high density of polyethylene (HDPE) [6], is easy to cut and puncture by poignant objects in MSW because of its small thickness of commonly only 1mm and low strength. Hence, goetextile are commonly used to place on the upper layer to protect the geomenbrane from mechanical damages, which may lead to leakage of leachate and pollution of surrounding environment [7].

Except leakage prevention, the long-term stability and security of liner system is other concern for designers in modern landfill because of its 50 years life time requirement. Geotextile [8] is usually consists of chemical fibers, such as polypropylene and polyester fibers. However, the microscopic structure of fiber destroyed and mechanical properties of geotextile declined quickly by acidic/alkaline leachate and metallic ions (cupric ions usually) in MSW and long-term ultraviolet radiation. In the study of Al-Shabanat 2011 [9], the degradation behavior of polypropylene (PP) under natural weathering in Saudi Arabia was investigated by the mechanical properties and morphology. The results showed that the mechanical properties of PP were decreased after exposure over a period of 6 months due to the effect of polymer degradation where could be attributed to the natural photo-oxidation of the PP. In the other study of Carneiro *et al*. 2014 [10], the existence of synergisms between degradation agents (cupric ions and temperature) of geotextile was investigated. The results showed that the combined effect of the previous associations of cupric ions and temperature is greater than the effect of each agent alone.

On the other hand, importantly, for the liner system placed on side slope of a landfill, both of its stability and security are influenced by shear strength caused by waste settlement [11-13] because it can cause huge tension in geotextile placed on landfill side slopes. After the closure of a landfill, normal forces on the geotextile from slope, net and horizontal forces on geotextiles from MSW form a balance situation. In this condition, there are few tension acting on geotextile.

However, the effect of enhanced biodegradation of waste [14] lead to down-drag caused by settling waste induces huge tension in geotextile and forces on it are unbalanced due to different friction angles of MSW-geotextile and goetextile-geomenbrane interfaces. According to the early study [15,16], the friction angles of MSW-geotextile, geotextile-geomembrane and goemembrane-GCL interfaces is 25~44 °, 7~15 °, 10~18 ° respectively. There is a big difference of shear strength between lower and upper interface of geotextile, which lead to its broken and easily loss of protecting function for geomembrane.

In summary, previous researchers investigated the effect of cupric ion and weathering on the long-term stability of geotextile, most of them prepared geotextile via using anti-aging materials to improve its weatherability and cupric ion resistance. However, the effect of this method was not satisfactory, lacking of the research of afterfinish technology of geotextile to improve its long-term stability. Besides, importantly, the effect of surface friction coefficient on security of geotextile on landfill slope has been discussed when the enormous shear strength was produced due to the upper MSW settlement. However, there is no practical solution came up until now.

The current paper presents the study on effect of treatment of anti-aging PP geotextile with multicomponent composite emulsion consist of nano-silica, polytetrafluoroethylene (PTFE) and fluorous acrylate [17-19] through pad-dry method (a process comprising of mixing, immersing , calendaring and drying) [20] to protect geotextile from acidic/alkaline leachate, ultraviolet radiation and metallic ions damages [21-22] as shown in *Figure 2*.

The goals we investigate are following:
(1) Forming a homogeneous thin film (protect layer) on the surface of fibers and geotextile.
(2) Decrease the surface friction coefficient of geotextile due to the PTFE exist in the thin film as the solid lubricant.
(3) The surface of geotextile become more smooth by calendaring process.

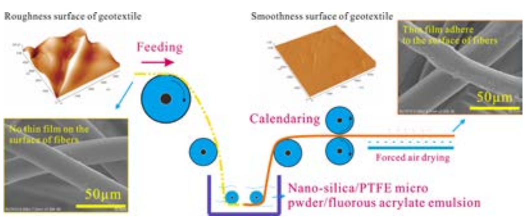


FIGURE 2. Rationale of the study presented.

THEORY

Geotextile may experience enormous tension caused by friction forces on it, especially, when horizontal stress is not enough to purpose waste rest on the landfill slope. *Figure 3* shows the static forces on the geotextile.

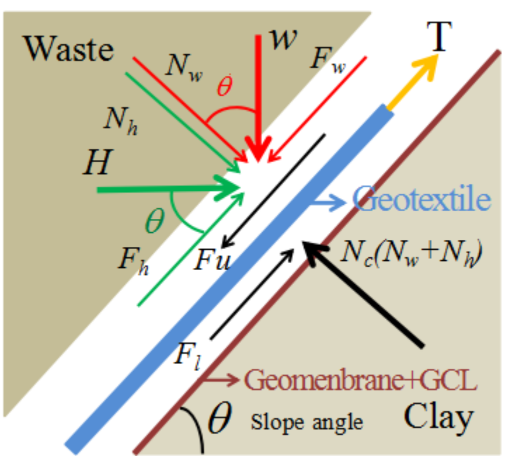


FIGURE 3. Forces acting on geotextile on a landfill side slope.

W is vertical force exerted by weight of cover waste on the upper part of geotextile and *H* is horizontal force. The equation can be expressed by Eq. (1)

$$H = k_x W \tag{1}$$

Where k_x represents the ratio of horizontal to vertical force developed during the placement of MSW.

N_w and N_h is normal component force of *W* and *H* changed with slope angle respectively. F_w and F_h is component force of *W* and *H* parallel with geotextile respectively. N_c is normal force on the geotextile from clay, F_u and F_l is upper and lower friction respectively. There are four regions when tension is experienced by the geotextile (weight of the geotextile was ignored).

Region (1): F_w is equal to F_h, the frictional forces are balanced and geotextile experience no tension. The equation can be expressed by Eq. (2)

$$F_l = F_w - F_h = T = 0 \tag{2}$$

Region (2): F_w is greater than F_h, the difference between F_w and F_h enhances with slope angle until it is equal to maximum static friction of lower interface. At the same time, the frictional forces are balanced and geotextile experience no tension as before. The equations can be expressed by Eq. (3) and Eq. (4)

$$F_u = F_w - F_h = F_l \tag{3}$$

$$T = F_u - F_l = 0 \tag{4}$$

Region (3): The difference between F_u and F_l is the tension in geotextile. F_l from static becomes dynamical friction when F_u remain the static friction and continue heightens. The equation can be expressed by Eq. (5):

$$T = F_u - F_l \tag{5}$$

Region (4): In this region, friction is not sufficient to keep waste remain the slope, it starts settling on upper interface of geotextile, F_u from static becomes dynamical friction like F_l. The equation of tension in geotextile can be expressed by Eq. (5).

For example, assuming upper and lower interface friction angle is 25° and 7° respectively, k_x is 0.3. The tension in geotextile vs. slope angle as shown in *Figure 3*.

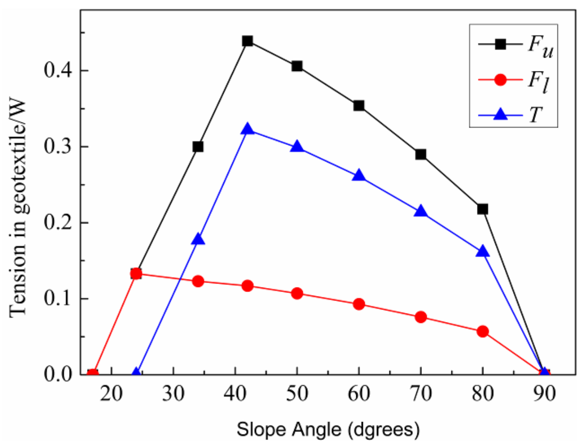


FIGURE 4. Tension in geotextile vs. slope angle.

Figure 4 shows that F_u is equal to F_l when slope angle from 17° to 24°. In this region, geotextile experience no tension. When slope angle is greater than 24°, lower interface friction increases and upper interface friction continue enhances, tension in geotextile experience enhances until slope angle reach 42°. When slope angle is greater than 42°, both upper and lower interface friction and tension in geotextile decreases until slope angle is equal to 90°.

EXPERIMENTAL SECTION

Materials

Polytetrafluoroethylene (PTFE, D90 200nm) emulsion, fluorous acrylate emulsion was purchased from Zhejiang Chuanhua Co., Ltd China. Anti-aging polypropylene nonwoven geotextile (400g/m^2) was purchased from ShenZhou geotextile Co., Ltd China. Nano-silica (D90, 12nm) was purchased from SuZhou NaFang engineering material Co., Ltd China. Triethanolamine and Sodium dodecyl benzene sulfonate (SDBS) was purchased from JiNing HuaKai Resin Co., Ltd China.

Preparation of Composite Emulsion

Nano-SiO_2 were emulsified with triethanolamine and sodium dodecyl benzene sulfonate (SDBS). Aerosil 200 (1 g) was firstly dispersed into 10 ml deionized water with the aid of ultrasound bath for 30 min. Then a small quantity of triethanolamine and sodium dodecyl benzene sulfonate (SDBS) was added into the dispersion and was vigorously stirred for 30 min at 40°C with a magnetic stirrer [23].

Afterwards, 140g of 50% wt. polytetrafluoroethylene emulsion, 60 g of 50% wt. fluorous acrylate emulsion and 250 ml deionized water were added into solution and agitation was continued for 1 h.

Preparation of Treated Geotextile

The sample was firstly immersed in sodium hydroxide solution to remove the impurities adhered to the surface of fibers. Then the sample was washed three times with 1/1 ethanol/water (V/V) solution to remove the excess amount of sodium hydroxide solution. Afterwards, it was immersed, in polytetrafluoroethylene / nona-silica / fluorous acrylate composite emulsion for 10min at room temperature. After the immersing process, sample was fed into a calendaring at a temperature of 100°C and at pressure of 1KPa. Finally, the treated sample was cured in a constant temperature oven at a temperature of 100°C for 30 min.

Measurements and Characterization

To test the weather stability of geotextile in natural weathering condition, untreated and treated geotextiles were exposed on the landfill of MaCheng City in China and lasted for 90 days, as shown in *Figure 5*.

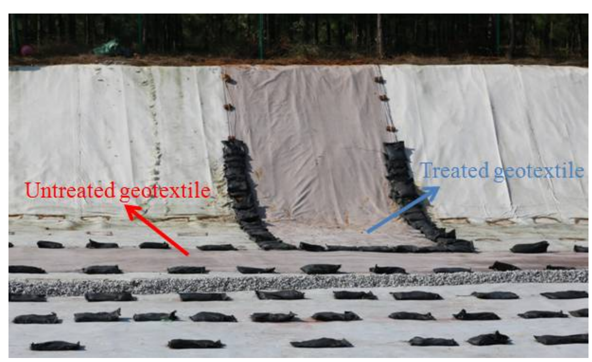


FIGURE 5. Untreated and tread geotextiles in weathering test.

The properties of cupric ions resistance of samples were test through immersing and heating. The samples were immersed, at 25°C, in copper (II) nitrate (Cu(NO3)2.3H2O) [10]. This process was performed in a thermostatic bath and lasted for 72 h. Then they were heated at 120°C for 18 days in a constant temperature oven.

The changes in the tensile behavior of the samples (in the various test) were studied in a tensile machine (DaRong, China) equipped with a load cell of 5 KN. Each test was carried out with 3 specimens (length between grips of 200 mm).

Scanning electron microscope (SEM, Hitachi SU1510; Hitachi Ltd., Beijing, China) was used to analyze the surface morphology of the untreated and treated sample at an accelerating voltage of 20 kV and before SEM imaging, geotextile samples were coated with 5 nm Au (PECS-682). The samples were sputter coated with a thin layer of Au nanoparticles to reduce the charging effects.

Atomic Force Microscope (SAFM, NANOVEA, USA) was used to analyze the surface roughness of samples. The scanning range of both x and y axis is 70 µm (resolution ratio is 1.0 nm) and the scanning range of z axis is 14 µm (resolution ratio is 2.0 nm).

The change in surface friction angle values of various interfaces of the samples were performed via a tilt table device which developed by author in the laboratory, as shown in *Figure 6*.

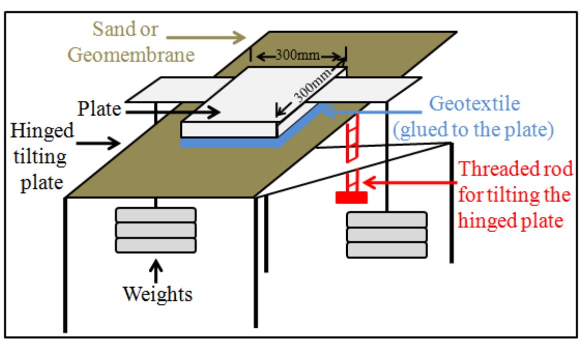


FIGURE 6. Sketch of the tilt table device.

RESULTS AND DISCUSION

Surface Morphology of Fibers Through SEM Analysis

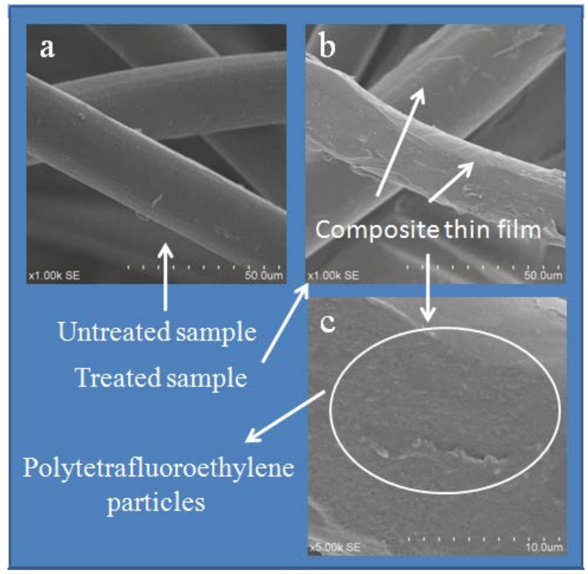


FIGURE 7. Surface morphology of treated fibers.

Figure 7 shows the surface features of polypropylene fibers treated with multicomponent composite emulsion. As we can see in the *Figure 7b*, the composite thin film which consists of PTFE nanoparticles, fluorous acrylate and nano-silica exist on the surface of polypropylene fibers. PTFE nanoparticles have no caking and film-forming properties, with adding the coalescing agents (fluorous acrylate), the whole and successive composite thin film is formed. By carefully observing *Figure 7c*, it can be seen that there are numerous particles (PTFE) are exposed at the surface of the composite thin film result in protecting the fibers from some damages and reduced friction angle of geotextile surface.

FTIR Analysis

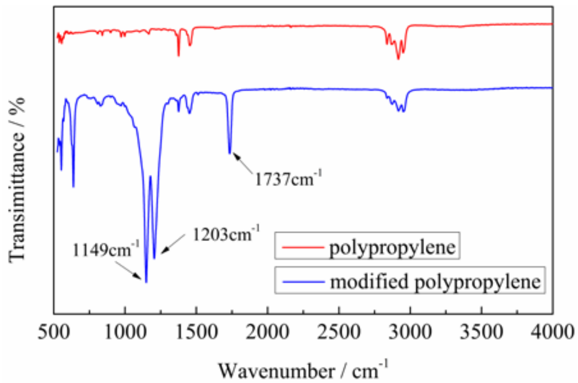


FIGURE 8. FT-IR spectrograms obtained from the untreated sample and the treated sample in the range of 4000-500 cm^{-1}.

The infrared spectra of the untreated and treated samples are obtained by FTIR to observe the chemical structures of geotextile via treated with multicomponent composite emulsion. The FTIR spectrum shows absorption band in the regions of 1149 cm^{-1} and 1203 cm^{-1} are assigned to the presence of $-CF_2-$ asymmetric stretching vibrations and $-CF_2-$ symmetrical stretching vibrations, which is in good agreement with the characteristic bands of PTFE reported in the literature [24]. In the regions of 1149 cm^{-1} and 1203 cm^{-1}, groups (C-O-C) and (Si-O) maybe exist but overlapped with the groups ($-CF_2-$) [25,26]. The absorption band at 1737 cm-1 for treated sample are attributed to the presence of C=O stretching vibrations reported in the literature [27]. From the infra-red spectrogram of treated sample, it can be inferred that the characteristic peaks of the PTFE particles, nano-silica and fluorous acrylate are superimposed over the curve of the PP itself. This result indicates that there are no interactions between the PTFE particles, nano-silica, fluorous acrylate and PP. Moreover, the phase structure of the pp is not destroyed by mixing and heating.

The Effect of Treatment on Weather Ability of Geotextile

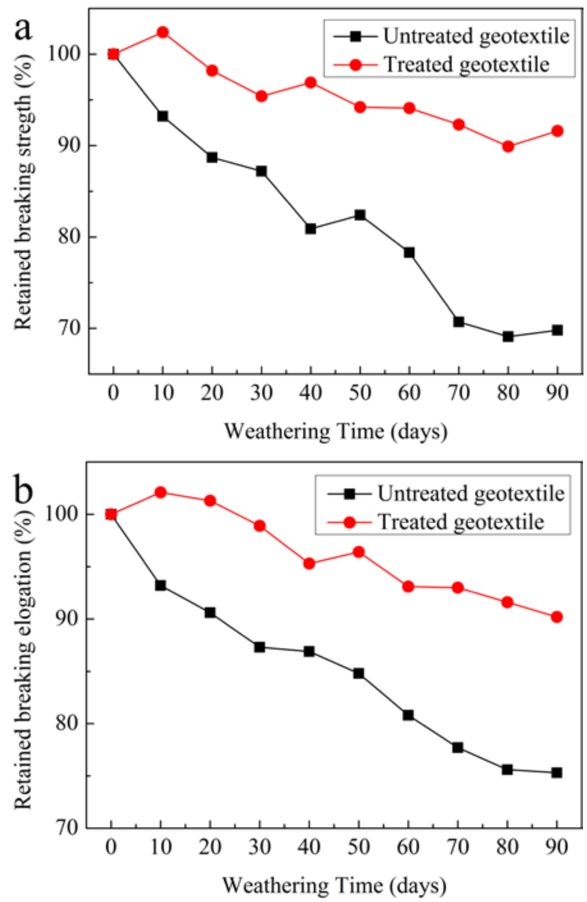


FIGURE 9. (a) Retained breaking strength as a function of weathering time (days), (b) Retained breaking elongation as a function of weathering time (days).

The change of breaking strength and elongation as a function of weathering time (days) is shown in *Figure 9.*

After exposure, mechanical properties of untreated sample declines rapidly to a point below that of treated sample over a period of 90 days (3 months) due to effects of weathering like heat, humidity, rain and sunshine which can be responsible for severe damages. Particularly, ultraviolet light (UV-light) is most serious than other factors which can cause polypropylene photo-oxidation and extensive chain scission [28]. The retained breaking strength and elongation of untreated sample is 69.8% and 75.3% respectively.

On the other hand, the mechanical properties of treated sample declines slowly over exposure time for 90 days (3 months) and have outstanding retention of mechanical properties. The retained breaking strength and elongation of it is 91.6% and 90.2% respectively during weathering test. This can be explained, it is possible that anti-ultraviolet property of geotextile can be enhanced via treating with composite emulsion, which contain a small quality of nano-silica. It is a kind of common nano-materials with the good UV-light resistance due to similar diameter with the wavelength of UV, leading to the UV-light absorbed and reflected.

The nano-silica used in this article could reside inside the thin film, which coat on the surface of the fibers, resulting in the transmittance of light reducing in the UV range [29] and the ratio of photo-oxidation of PP fibers decreasing. It reveals that the composite thin film isolates UV-light from the treated sample and prevent the photo-oxidation reaction of polypropylene effectively.

The Effect of Treatment on Cupric Ions Resistance of Geotextile

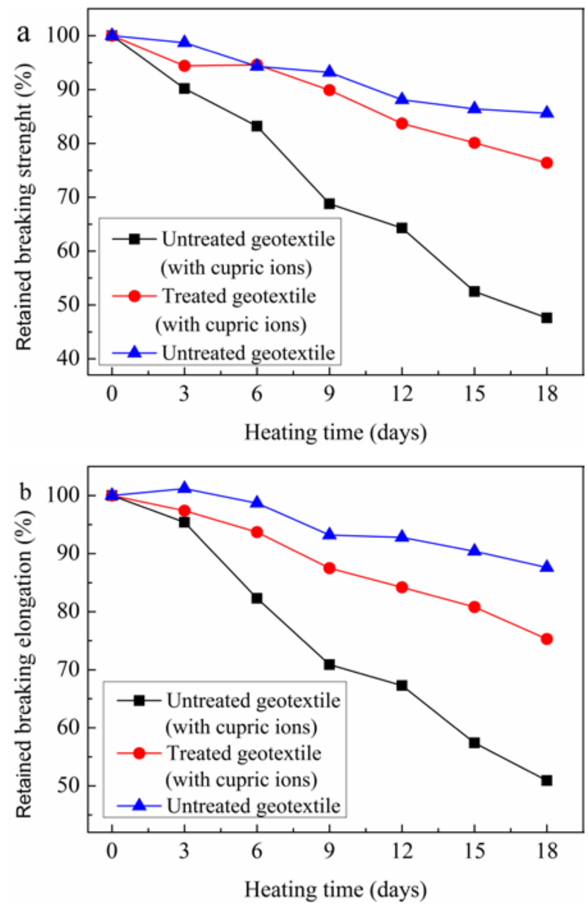


FIGURE 10. (a) Retained breaking strength as a function of heating time (days), (b) Retained breaking elongation as a function of heating time (days).

The thermal oxidation reaction mechanism of polypropylene can be explained that aging process of polypropylene include chain initiation, chain growth, chain branching and chain termination. In the stage of chain branching, the products of various equations (single molecule, bimolecular and pesudounimolecular reaction) are hydroperoxide. Decompose of hydroperoxide needs high temperature, however, metallic ions (cupric ions generally) could accelerate this reaction as the catalyst. The catalytic action can be expressed by Eq. (6).

$$2POOH\bullet \xrightarrow{Cu2^{+}} PO_2\bullet + PO\bullet + H_2O \qquad (6)$$

As shown in *Figure 10*, the heating test after immersion in cupric ions solution have a greater impact in the tensile properties of the reference sample (untreated geotextile) and treated sample. Indeed, this test causes higher decrease in breaking strength and elongation. During the heating test, at 120°C, for 18 days, the retained breaking strength and elongation of sample untreated via cupric ions solution is 85.6% and 87.6% respectively. However, the retained breaking strength and elongation of untreated sample (after immersing in cupric ions solution) is 47.6% and 50.9% respectively because of the catalytic effect of cupric ions.

Contrarily to reference sample, the heating test causes less change in breaking strength and elongation of treated sample (after immersing in cupric ions solution). Fluorous acrylate [30] is fabricated through modifying the acrylate, in this process the fluorine could be grafting into acrylate. Fluorous acrylate used has excellent acid-base leachate and cupric ion resistance and lower friction coefficient. under a concern condition (100°C for 30 min), it form a thin film coating on the surface of fiber, which acts as protecting layer to prevent the cupric ions from contacting with the fibers, avoiding the catalytic action of cupric ions on thermal-oxidation of fibers to a large extent.

Hence, the retained mechanical properties of treated sample (after immersing in cupric ions solution) is greater than those of untreated sample (after immersing in cupric ions solution), the retained breaking strength and elongation of it is 76.4% and 75.3% respectively.

Surface Roughness of Geotextile Through AFM Analysis

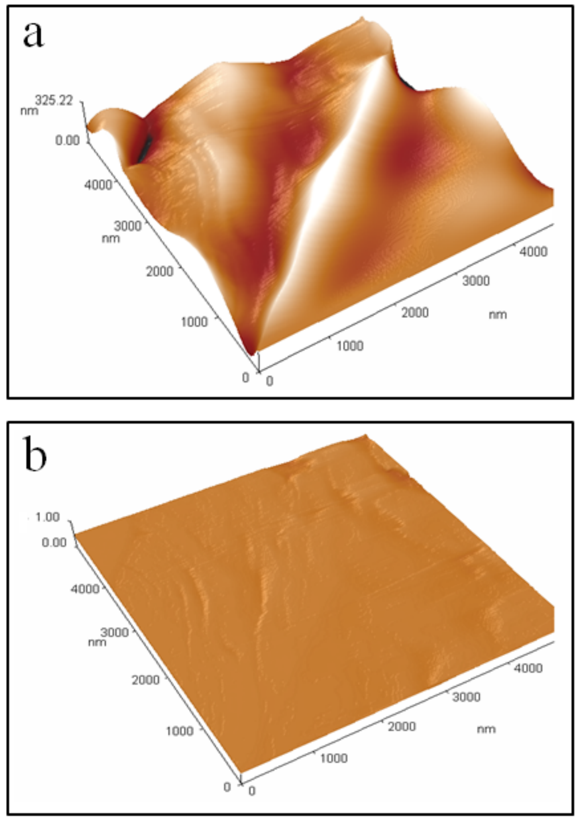


FIGURE 11. (a) AFM image of untreated sample, (b) AFM image of treated sample.

AFM investigation reveals that the smoothness of geotextile surface generally increases through a calendaring at a temperature of 100°C and at pressure of 1KPa. A rough surface with clear structure (untreated sample) is observed as illustrated in *Figure 11a*. *Figure 11b* shows the smoothness of the treated geotextile surface which is more than that of untreated geotextile.

The Effect of Treatment on Interface Friction Angle Values

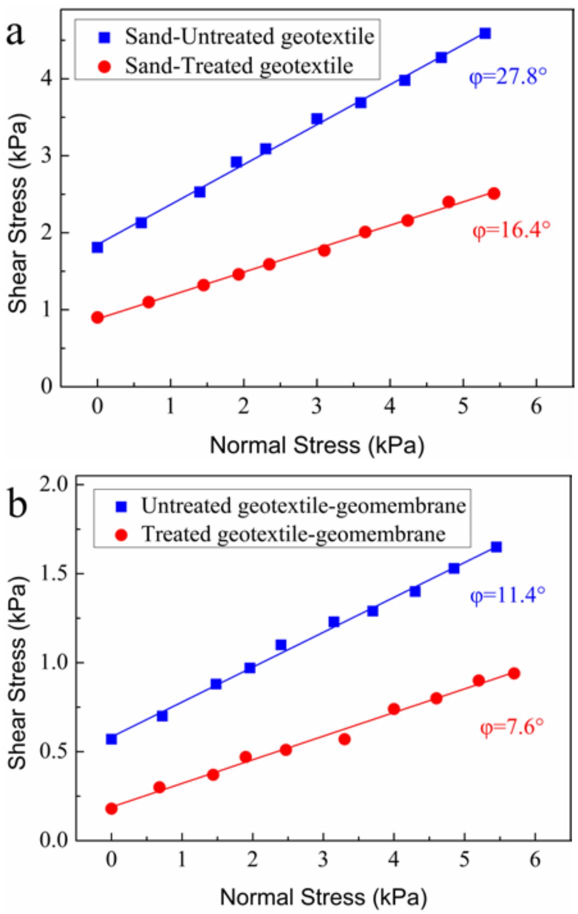


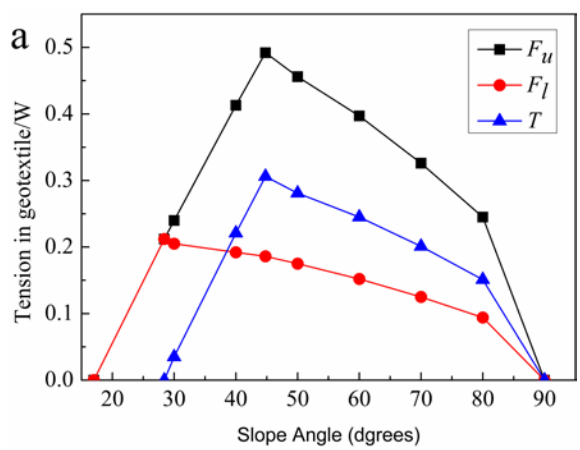
FIGURE 12. (a) Tilt table test results of sand-geotextile interface, (b) Tilt table test results of geotextile-geomembrane interface.

Figure 12a shows the tilt table test interface envelopes have relatively small adhesion values (c=1.81 and 0.9 kPa) for sand-untreated geotextile and sand-treated geotextile interface respectively. Sand-untreated geotextile interface yields 11.4° and higher angles of interface friction as well as higher adhesion values than those of sand-treated geotextile interface.

In *Figure 12b*, it is found that the tilt table test interface envelopes have relatively small adhesion values (c=0.57 and 0.18 kPa) for untreated geotextile-geomembrane and treated geotextile-geomenbrane interface respectively. Untreated geotextile-geomembarne interface yields 3.8° and higher angles of interface friction as well as higher adhesions than those of treated geotextile-geomembrane interface.

This can be explained that the PTFE micro powder [19] experiences excellent self-lubricating property and low frictional coefficient due to its unique chemical structure. It is the smoothest solid in known organic compounds, which usually used as the filler and blending with resin to prepare self-lubricating layer adhere to the surface of other materials. Thus, in this case, a mass of the PTFE micro powders exists on the surface of fibers and geotextile, leading to the friction angles of sand-geotextile and geotextile-geomembarne interfaces decrease simultaneously, but the decreased value of friction angles of sand-geotextile interface is less than that of geotextile-geomembarne interface.

The Effect of Treatment on Tension in Geotextile vs. Slope Angle



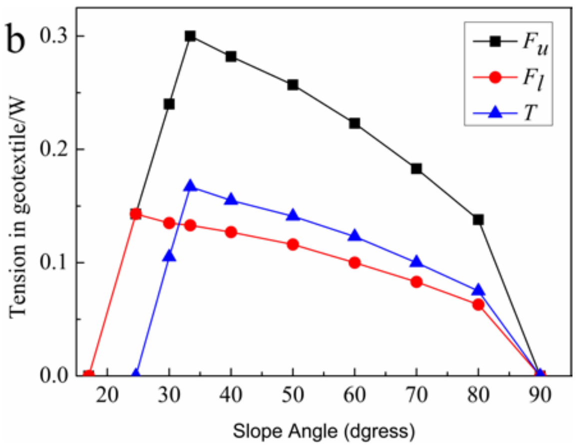


FIGURE 13. (a) Tension in untreated geotextile vs. slope angle, (b) Tension in treated geotextile vs. slope angle.

In *Figure 13a*, it is found that the frictional forces are balanced when slope angle increases from 17° to 28.4°, it is less than all interface friction angles. In this stage, the geotextile is in a state of pure shear and experience no tension. When the slope angle is greater than 28.4°, the static friction becomes dynamical friction of lower interface (untreated geotextile-geomenbrane interface) and F_l decreases vs. slope angle. On the contrary, F_u continue increases rapidly until the slope angle is equal to 44.8°. When the slope angle is larger than 44.8°, the static friction is insufficient to support MSW rests on surface of the untreated geotextile, it start to slippage result in the tension in geotextile declines vs. slope angle.

In *Figure 13b*, it is found that the frictional forces are balanced when slope angle increases from 17° to 24.6°, it is less than all interface friction angles. In this stage, the geotextile is in a state of pure shear and experience on tension. When the slope angle is greater than 24.6°, the static friction becomes dynamical friction of lower interface (treated geotextile-geomenbrane interface) and F_l decreases vs. slope angle. On the contrary, F_u continue increases rapidly until the slope angle is equal to 33.4°. When the slope angle is equal to 33.4°, the static friction is insufficient to support MSW rest on surface of the treated geotextiles, it start to slippage result in tension in the geotextile declines vs. slope angle.

It is evident from *Figure 13a* and *Figure 13b* that the tension in treated and untreated sample, for a given load *W* acting on them, the maximal tension in treated geotextile is lower than it of untreated geotextile, obviously, it is approximately 0.16 *W* and 0.31 *W* respectively. The security of treated geotextile is greater than it of untreated geotetile. Actually, in order to save ground and construction cost, the slope side angle of the modern urban landfills are usually higher than 35° determined by the designers.

CONCLUSION

Effect of treatment with composite emulsion on geotextile was investigated in field and laboratory; the following conclusions can be drawn:

(1) After treatment with polytetrafluoroethylene / nano-silica / silicone-acrylate composite emulsion, the composite thin film exists on the surface of fibers as a protective layer and the long-term stability and security of geotextile had been improved.

(2) The weathering ability and property of cupric ions resistance were enhanced. After a period of weathering and heating test (after immersing in the cupric ions solution), both retained tensile strength and elongation in all treated samples is higher than those of untreated samples obviously.

(3) Roughness of geotextile surface decreases via immersing and calendaring. The friction angle value of sand-treated sample interface and treated sample-geomembrane interface is 16.4° and 7.6° respectively. The maximal tension in treated geotextile is lower than it of untreated geotextile, obviously, it is approximately 0.16 *W* and 0.31 *W* respectively.

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