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Properties and potential application of the selected natural fibers as limited life geotextiles

P. Methacanon[a,*], U. Weerawatsophon[a], N. Sumransin[a], C. Prahsarn[a], D.T. Bergado[b]

[a] National Metal and Materials Technology Center (MTEC), 114 Thailand Science Park, Paholyothin Rd., Klong 1, Klong Luang, Pathumthani 12120, Thailand
[b] Geotechnical Engineering Program, School of Civil Engineering, Asian Institute of Technology, Paholyothin Rd., Klong 1, Klong Luang, Pathumthani 12120, Thailand

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ABSTRACT

Environmental awareness and an increasing concern with sustainable development have stimulated many industries including ground engineering to replace the conventional synthetic fibers. In this work, four natural fibers, namely water hyacinth, reed, sisal, and roselle, were chosen for studies. Initially, the composition, morphology and properties of the four fibers were examined in order to select an appropriate fiber for manufacture of woven limited life geotextiles (LLGs). It was found that total cellulose content of sisal and roselle was higher than that of water hyacinth and reed, in contrast to hemicelluloses content. The highest lignin content was found in reed whereas water hyacinth possessed the highest ash content. Morphology and fiber length of the fibers were determined using optical microscope. The results showed that there was a positive correlation between tensile strength and fiber length; the longer fiber length, the higher tensile strength. Tensile strength of dry sisal, roselle was significantly higher than that of reed and water hyacinth, while elongation of all studied fibers with exception of water hyacinth was not significantly different. Moreover, it is interesting to note that when the fibers are wet, their tensile strength and elongation increase. Their moisture absorption and thermal property were also investigated. Finally, durability of the fibers was assessed in terms of mechanical properties after exposed under an accelerated weathering. From all obtained results, it can be concluded that sisal and roselle showed potential as raw materials for woven LLGs for soil reinforcement while the woven LLGs made of reed and water hyacinth would be suitable for soil erosion control.

1. Introduction

In the recent years, the intensity of torrential rainfall and its subsequent destructive influence on human community has become severe and unpredictable due to climate change including global warming. Landslide disaster is one of natural disasters resulting from the climate change. Ground improvement together with geosynthetic engineering has contributed greatly in undertaking scientific and systematic methodologies for declining the risk. Geotextiles derive their name from the two words "geo" and "textiles" and, therefore, mean the use of fabrics either woven or non-woven in association with the earth. Geotextiles, a core member of geosynthetic family, are widely used in civil engineering applications to improve soil structural performance. Geotextiles are not a single commodity. They are fabricated by both synthetic and natural fibers with different design, shape, size, and composition according to functional needs. Their main functions are aggregate separation, soil reinforcement, filtration, drainage, and liquid barriers (John, 1987).

In spite of availability and prominent advantages of natural fibers, including acceptable specific strength properties, low cost, low density, high toughness, good thermal properties, and the growing environmental concern all over the world, new geotextiles known as "Limited Life Geotextiles (LLGs)" have emerged. The LLGs are reinforcing fabrics that are only required to perform their duty for a limited time in many civil engineering applications, e.g. temporary roads over soft land, and basal embankment reinforcement (Sarsby, 2007). The natural geotextiles not only could be effective, affordable and compatible with sustainable land management but also help to suppress extreme fluctuations of soil temperature, increase soil moisture, provide seeds with a better chance to germinate and increase infiltration by reducing surface sealing (Sutherland & Ziegler, 2007). Although there are numerous of plant fibers available in the world, only few such as palm-leaf (Bhattacharyya, Fullen, Davies, & Booth, 2009), jute (Ranganathan, 1994), flax (Rawal & Anandjiwala, 2007), coir (Lekha & Kavitha, 2006; Subaida, Chandrakaran, & Sankar, 2008), sugarcane bagasse (Dinu & Saska, 2007), kenaf (English, 1995) and sisal (Anand, 2008),

* Corresponding author. Tel.: +66 2 564 6500; fax: +66 2 564 6445.
E-mail address: pawadeem@mtec.or.th (P. Methacanon).

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have been studied and used as a raw material in geotextile application. In addition, the market for geotextiles is growing, with worldwide sales of over 700 million square meters annually of which about 2% is biofibers (English, 1995). Therefore, it is clearly shown that there are many opportunities to expand the markets and develop new products made of natural fibers.

The main purpose of the work, being presented here just a part, is to assess the possibility of developing good performance woven LLGs made of the studied natural fibers: sisal, roselle, reed, or water hyacinth. Though, these natural fibers are one of the most natural fibers widely used in ropes, twines, rugs, mats, mattresses, and handcrafted articles, a large quantity of these economic and renewable resources is still under-utilized. In considering the aforementioned fibers for geotextiles, fiber chemistry and their properties were a major concern. Since the material composition determines their life in the field and properties determine their functions. However, as we know, information on chemical and physical properties of the natural fibers is scattered in the scientific literature. In addition, different analytical procedures have been used so it is difficult to compare one set of data with any other set. In this paper, the detailed chemical composition and interesting properties of the selected natural fibers including their degradation under an accelerated weathering condition, which rarely presented in the literatures were reported.

2. Experimental

2.1. Materials

Natural fibers used for this study were water hyacinth (*Eichhornia crassipes*), reed (*Phragmites vulgaris*), roselle or Thai kenaf (*Hibiscus sabdariffa*) and sisal (*Agave sisalana* Perr.). Each fiber was obtained from the handicraft communities in Nakhon Pathom, Buriram, Khon Kaen and Petchburi Provinces, respectively. All analyses were carried out on the as received fibers, except where otherwise noted.

2.2. Fiber composition

Total cellulose and hemicelluloses contents of the studied fibers were determined according to a method of Jenkins (1930). Lignin content in the fibers was determined as klason lignin in accordance with the standard method TAPPI T 222 om-88 (TAPPI Test Methods, 1996). Ash content in the fibers was investigated according to ASTM method E 1755-01 (ASTM, 2007). Moisture content was determined using oven at 105 °C for 24 h.

2.3. Morphology and single cell dimensions

Surface and cross-section morphology of the intact fibers were investigated using a optical microscope. For measurement of the cellulose single cell dimensions, the method of Kuznetsova et al. (2003) was modified. Briefly, the single cells of the fibers were obtained after the delignification process that was carried out at 80 °C for 6 h with the ratio hydrogen peroxide/acetic acid of 3/1, and repeated twice. After treatment, the samples were dialyzed using dialysis tubing (molecular weight cut off 3500) against distilled water until pH became neutral. Then, average length and diameter of the fiber single cells were measured under an optical microscope.

2.4. Moisture absorption

The intact fibers were twisted as yarns with a diameter of 2 mm, dried for 1 day at 50 °C and then placed at 23 ± 1 °C over saturated potassium sulfate, sodium chloride, and magnesium chloride salt solutions in a chamber having approximately 97, 75, and 33% relative humidity (RH), respectively. Weights of samples were measured as a function of time.

2.5. Thermogravimetric analysis (TGA)

Thermogravimetric analysis was carried out using TGA/SDTA 851^e (Mettler Toledo) in air with a heating rate of 10 °C/min. The temperature range scanned was from 25 to 800 °C.

2.6. Mechanical properties

To investigate their mechanical properties in relation to geotextile application, the studied fibers were twisted to yarns of 2 mm in diameter and 60 cm in length. Tensile strength and elongation at break of the dry and wet twisted yarns were determined using the Instron Universal testing machine (Instron 55R 4502) with a load cell of 10 kN, a crosshead speed of 50 mm/min, and a gauge length of 15 cm. In order to prevent grip slippage, hooked-type sample holders and extra length of yarns as mentioned above were prepared. In testing, each yarn sample was mounted between holders where a middle part of yarn was in the range of gauge length, and the rest of yarn was wrapped around the sample holder. Measurements were performed in 10 replicates. For the wet state, the twisted yarns were soaked in water for 16 h prior to testing.

2.7. Accelerated weathering test

Accelerated weathering test was carried out using an accelerated weathering tester (Model QUV/se with solar eye irradiance control) according to the ASTM G154-04 (ASTM, 2004). Samples were irradiated under a fluorescent bulb UVB with 0.63 W/m^2 irradiance (at 280–315 nm), with cycles of UV irradiation for 8 h (at 60 °C) followed by 4 h spray of water (at 50 °C) for total exposure time 5 weeks. The durability of each fiber was evaluated by comparing the mechanical properties of the samples after various exposure times. The mechanical testing condition was similar to that described above, but slightly different in gauge length (10 cm) and yarn length (30 cm).

2.8. Statistical analysis

Unless otherwise stated all measurements were performed in triplicate and mean values were reported. Analysis of variance (ANOVA) of the results was performed using STATISTICA 7 (StatSoft Co., Ltd). When significant differences were found, the Duncan' s multiple comparison test was applied to determine the difference among means ($p < 0.05$).

3. Results and discussion

3.1. Fiber composition

In general, chemical composition of lignocellulosic fibers is inherent, according to the particular needs of the plants. Cellulose, hemicelluloses and lignin are the three main constituents of any lignocellulosic sources, and the proportion of these components in a fiber depends on the age, source of the fiber and the extraction conditions used to obtain the fibers (Reddy & Yang, 2005). Cellulose is the main structural component that provides strength and stability to the plant cell walls. The amount of cellulose in fiber influences the properties and determines the utility of the fiber for various applications. As shown in Table 1, cellulose was found to be a main constituent of all studied fibers, ranging approximately from 48 to 73%. Sisal and roselle had a higher cellulose content compared with reed and water hyacinth. Hemicelluloses are plant cell wall polysaccharides closely associated to cellulose, which consist of

Table 1
Normalized chemical composition of the studied natural fibers.

Natural fiber	Composition (wt% on dry basis)				
	Cellulose	Hemicelluloses	Lignin	Ash	Moisture
Sisal	72.92	5.63	13.59	0.84	7.02
Roselle	70.20	7.21	14.91	0.72	6.97
Reed	47.46	18.75	19.81	4.65	9.32
Water hyacinth	52.20	16.78	9.42	12.14	9.46

comparatively low molecular weight polysaccharides built up from hexoses, pentoses, and uronic acid residues. They are also mainly responsible for moisture sorption and biodegradation (Rowell & Stout, 2007). In this study, hemicelluloses content in reed and water hyacinth is twice as much as those in sisal and roselle. Thus, it suggests that reed and water hyacinth could possess higher moisture sorption and biodegradation than sisal and roselle. Lignin is a highly crosslinked molecular complex with amorphous structure and acts as glue between individual cells. The lignin content of the fibers influences the structure, properties, morphology, flexibility and rate of hydrolysis (Sukumaran, Satyanarayana, & Pillai, 2001). From the result, it is worth noting that the reed possessed the highest content of lignin (ca. 20%), making its appearance coarse and less flexible. For other fibers, the lignin content was around 9–15%. Water hyacinth contained the highest amount of ash (ca. 12%), which might result from its metal adsorption ability. Consequently, there are numerous works, which reported that water hyacinth possesses the ability for the removal of toxic metals from wastewater (Hasan, Talat, & Rai, 2007; Milik, 2007). Moisture content present in the studied fibers was approximately between 7.0

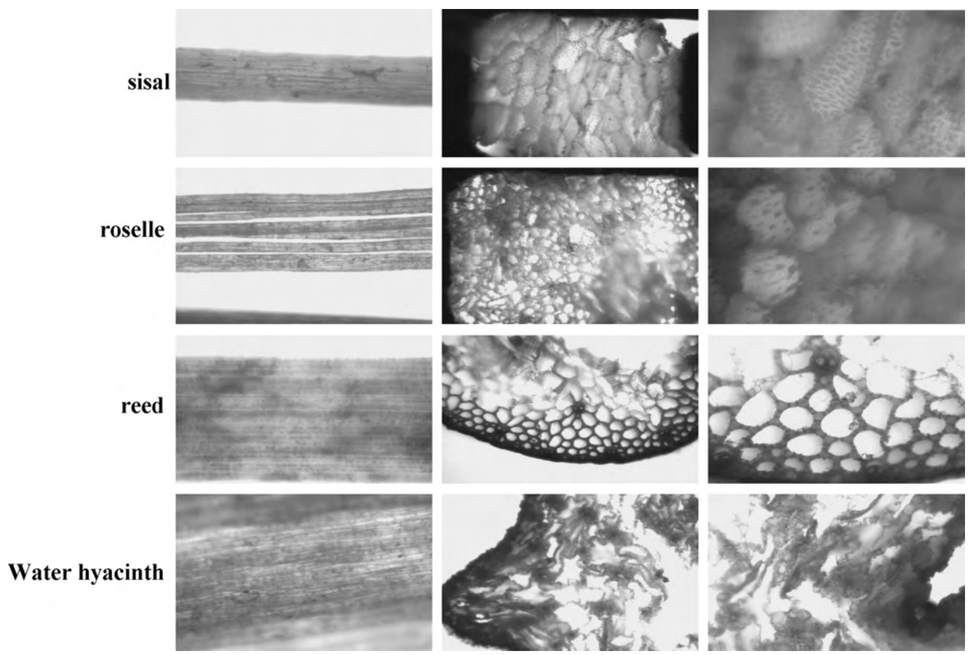

Fig. 1. Optical micrographs of surface (1st column) and cross-section (4×, 2nd column and 40×, 3rd column) morphology of the studied natural fibers.

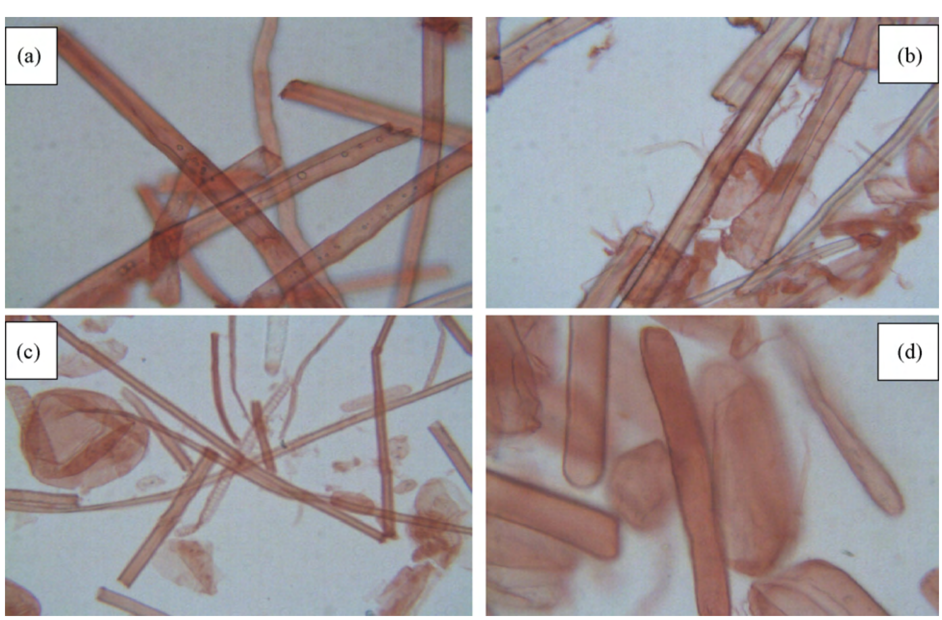

Fig. 2. Optical micrographs of single cells of: (a) sisal, (b) roselle, (c) reed, and (d) water hyacinth.

and 9.5%. The composition results are in accordance with the available previous studies (Gunnarsson & Petersen, 2007; Li, Mai, & Ye, 2000; Rowell, James, & Rowell, 2000) even though there are some variations existing. The variations probably come from age, source and the determination method.

3.2. Morphology

Since differences in physical properties could be due to differences in fiber morphology, the morphology of the fiber studied in this work was investigated. Fig. 1 illustrates surface and cross-section morphology of the intact four studied fibers. The surface of all fibers looked uniform meanwhile, within the leaf, a sandwich structure was present. The cross-sectional images of sisal and roselle are identical whereas that of reed is slightly different but still as numerous fiber cells. An obviously different morphology found in the water hyacinth is hollow cavities, which decrease the bulk density of the fiber making it lightweight. It is, therefore, interesting to note that the morphology of plants is highly dependent on their habitat. Sisal (leaf fiber plant) and roselle (bast fiber plant) are a land plant while water hyacinth is a water plant. For reed, it grows well on marshy ground or shallow water.

Since the fibers are composed of bundles of individual fiber cell as aforementioned. The dimension and arrangement of cells in a fiber determine the structure and also influence the properties of the fibers. In this wok, the single cell extraction was carried out prior to determination of single cellulose cell dimension under microscope (Fig. 2). As shown in Table 2, the width of single fiber cell was in range of 5–82 μm with the largest cells of water hyacinth and slimmest ones of reed. The width of individual cells in reed is smaller and can, therefore, form relatively finer fibers. The length ranges from approximately 108 to 201 μm with the longest one found in sisal. Individual cells in sisal and roselle are relatively longer and therefore these sources can produce long fibers. It was also reported that biofibers with longer unit cells have higher strength (Reddy & Yang, 2005). In some applications such as textiles and paper, an aspect ratio defined as length to diameter ratio of individual cells in a fiber affects the flexibility and resistance to rupture of the fibers and products made from them (Reddy & Yang, 2005). From the result, the aspect ratios of sisal and roselle

Table 2
Single cell dimension of the studied natural fibers.

Natural fiber	Length (L, μm)	Width (W, μm)	Aspect ratio (L/W)
Sisal	201.1 ± 51.3^a	13.2 ± 1.9^b	15.3
Roselle	164.6 ± 52.9^b	12.0 ± 3.3^b	13.7
Reed	108.8 ± 29.6^c	5.1 ± 1.3^c	21.5
Water hyacinth	129.9 ± 32.4^c	81.8 ± 7.9^a	1.6

Means with different superscripts (a–c) in the same column are significantly different ($p < 0.05$).

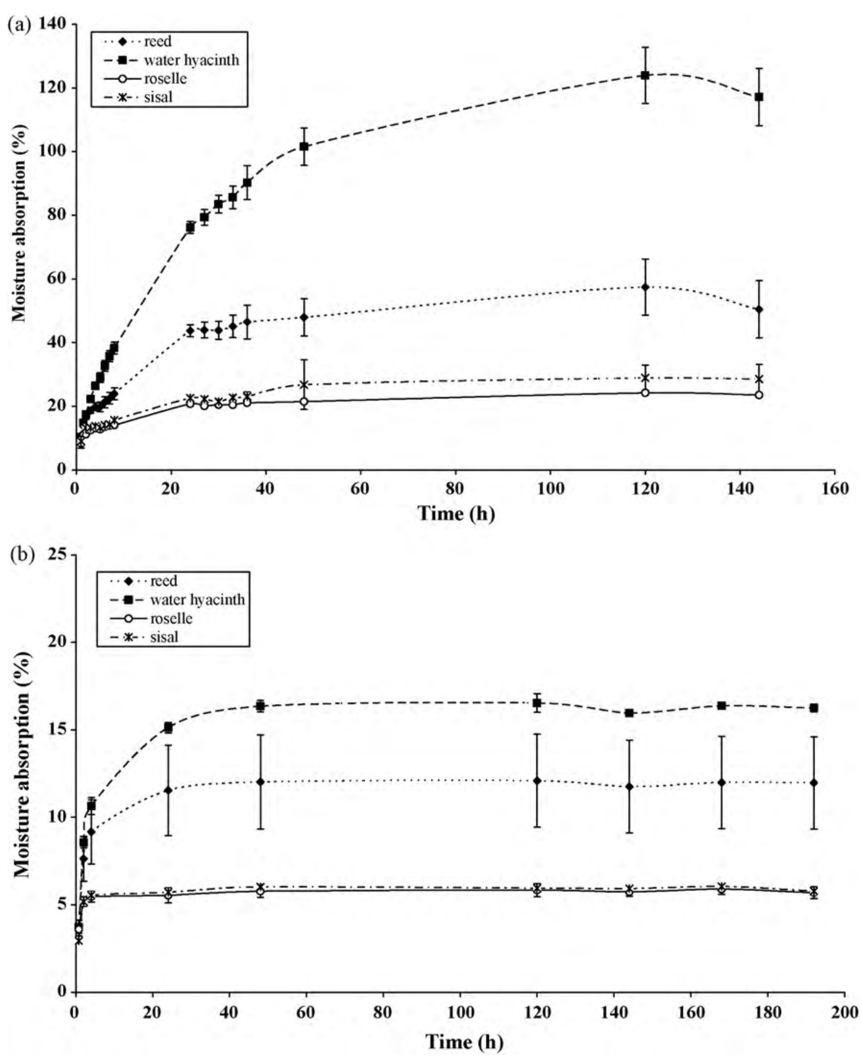

Fig. 3. Moisture absorption of the studied natural fibers at 23 °C; (a) 97% RH and (b) 75% RH.

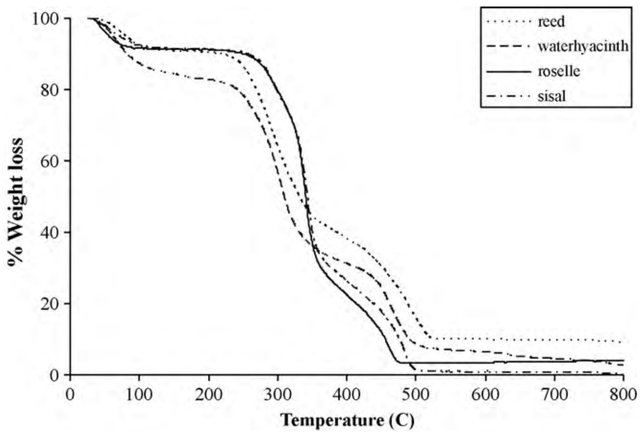

Fig. 4. TGA thermograms of the four studied natural fibers.

are in the same range (ca. 14–15) whereas those of reed and water hyacinth are highest (ca. 21) and lowest (ca. 2), respectively. Overall, the obtained results are relatively in agreement with previous studies (Li et al., 2000; Rowell et al., 2000) even there is a wide variation existing because the dimensions of individual cells in natural fibers are dependent on the species, maturity and location of the fibers in the plant and also on the fiber extraction conditions (Reddy & Yang, 2005).

3.3. Moisture absorption

With natural fibers being hydrophilic in nature, there is a need to address their moisture sorption characteristics for further suitable applications. In addition, the fiber properties such as moisture absorption, strength and elongation are measurable properties that

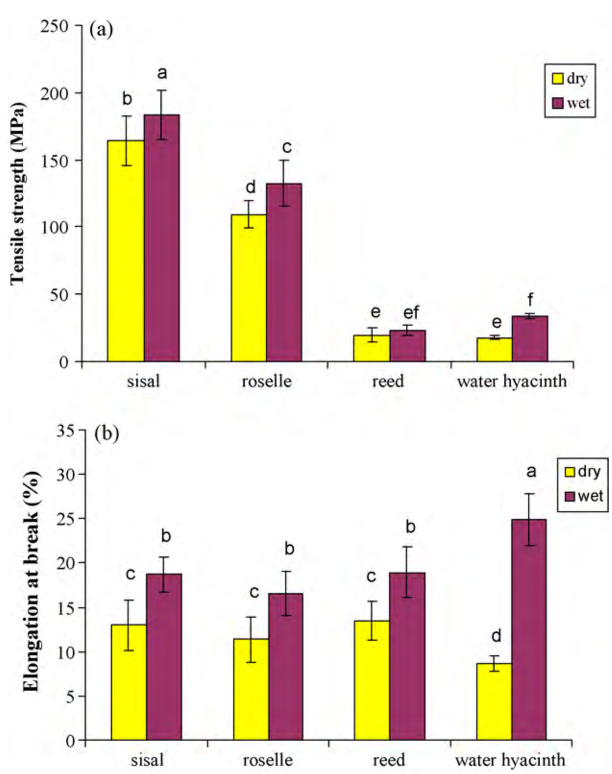

Fig. 5. Mechanical properties of the studied natural fibers: (a) tensile strength, and (b) elongation at break. Different letters are significantly different ($p < 0.05$).

are used to help comparing the fiber performance. Moisture absorption curves of the studied fibers stored at various relative humidity (RH) are shown in Fig. 3. As time increased, the moisture absorption was more rapid at the initial stage and lower amount of water was absorbed as time increased until it reached equilibrium indicating that they became equilibrated with surrounding RH. The moisture sorption of sisal and roselle was very close together and less than that of reed and water hyacinth. It was also found that the moisture absorption capacity of the fibers was associated with the surrounding RH; the higher the RH, the higher the moisture absorption capacity. At 97% RH, moisture absorption of water hyacinth dramatically increased almost 8 times higher than that at 75% RH while the moisture absorption of other fibers increased approximately 4 times. As would be expected, the moisture absorption results of the studied fibers corresponded well with the hemicelluloses content and fiber morphology as described earlier. In addition, the remarkable amounts of hollow cavity in water hyacinth fiber greatly contributed to its highest water absorption (ca. 120% at 97% RH). The results were also well supported by Sukumaran et al., which reported that the moisture absorption is related to the composition and internal structure of the fibers. Moisture content in the fibers also influences the degree of crystallinity, crystalline orientation, tensile strength, swelling behavior and porosity of the fibers (Sukumaran et al., 2001). However, it is worth noting that the high moisture absorption suggests ease of the microbial attack (biodegradation). In addition, it was found that almost no moisture absorption (less than 1%, data not shown) of all studied fibers was observed at 33% RH.

3.4. Thermogravimetric analysis (TGA)

TGA curves of the natural fibers were shown in Fig. 4. All samples showed similar thermal degradation behavior with T_d (decomposition temperature) appearing between 290 and 490 °C. Three main stages of weight loss were observed for all studied fibers, starting with evaporation of moisture in the fibers at temperature range of 50–100 °C, decomposition of hemicelluloses at temperature of about 200–350 °C, followed by weight loss due to lignin and cellulose degradation at about 400–500 °C. T_d of lignin has been found between 300 and 450 °C while hemicelluloses degraded at temperature range of 200–300 °C (Arno, 1989; Garćia et al., 2009; Sun, Tomkinson, & Jones, 2000). It can be seen that TGA curve and T_d of reed is similar to those of water hyacinth as well as sisal and roselle have the same TGA pattern and T_d. It is worth noting that reed and water hyacinth (T_d 290 °C) started to decompose earlier than roselle and sisal (T_d 340 °C), indicating less thermal stability.

3.5. Mechanical properties

Average values of tensile strength and elongation at break of yarns of the studied natural fibers in wet and dry states are shown in Fig. 5. It is notable that both maximum tensile strengths and elongations of all wet yarns were higher than those of dry ones. This probably resulted from moisture in the fiber that influenced the degree of crystallinity, and crystalline orientation of the fibers (Reddy & Yang, 2005). Tensile strength of reed yarn was similar to that of water hyacinth yarn (ca. 18–33 MPa) but much lower than those of roselle and sisal yarns (ca. 112–180 MPa, Fig. 5a). Although the measured strength of yarn cannot be exactly correlated to cellulose content, generally, the fibers with higher cellulose content, higher degree of polymerization of cellulose, longer cell length and lower microfibrillar angle could contribute better mechanical properties (Reddy & Yang, 2005). It was also reported that higher tensile strength of fibers was mostly due to higher amounts and better orientation of crystalline cellulose in the fibers (Reddy & Yang, 2007). As discussed in the previous sections (Sections 3.1 and 3.2), cellulose content and cell length of roselle and sisal fibers were found to be higher than those of reed and water hyacinth fibers. These could be attributed to the higher tensile strengths of roselle and sisal yarns observed. For elongation at break (Fig. 5b), at both states, there was no statistically significant difference found among all studied yarns, except water hyacinth. As well as the tensile strength, the elongation of yarns at wet state was higher than that at dry state. This finding can be described that, under wet state, the absorbed water molecules acted as a lubricant such that the fibers could slide over one another during stretching, resulting extra extension or elongation. Specifically, water hyacinth yarn showed remarkable increase in elongation at wet state due to numerous voids in its structure and consequent the highest water absorption capacity as previously described.

3.6. Accelerated weathering test

In geotechnical applications, geotextiles are used for many functions including soil erosion control. This usage differs from other applications in that these materials are laid on the ground surface and are not buried in the soil. They are used to stabilize slopes by reducing runoff, retaining soil particles and protecting bare ground from the sun, rain and wind for a restricted period. Hence, in this study, durability of the studied fiber yarns when exposed to sunlight and rain was of crucial importance. Natural weathering test is more reliable but time consuming, so the accelerated weathering test was selected for estimating durability of natural fibers in this study. Firstly, the effect of weathering on the appearance of samples exposed to the accelerated weathering environment was studied by visual inspection. The surfaces of samples were observed to change in form of color fading and partial shrinkage resulting in bending of samples. This was due to, during weathering, leaching of lignin and water soluble products from the samples (Beg & Pickering, 2008). However, the change in weight during weathering was not noticeable probably due to effect of moisture absorption of the samples during the water spray and condensation cycle. In addition, it has been reported an importance of the components in natural fibers for a range of different properties including UV, moisture as well as biological degradation. Lignin is considered to be most responsible for UV degradation, whereas, hemicelluloses are suggested as more important for moisture and biological degradation. Cellulose is greatly contributed to strength (Beg & Pickering, 2008). Fig. 6 shows the tensile strength and elongation at break of the weathered natural fibers versus exposure time. Tensile strength of the fiber yarns tends to decrease with increasing of exposure time. The dramatic reduction in tensile strength (ca. 50% of the original value) was found in sisal yarn after 1 week exposure, in contrast to the rest of fiber yarns. Elongation at break of all yarns, which is particularly sensitive to all the heterogeneities present in the materials and to any small defects in the samples, exhibited some statistical differences with exception of sisal. Although most samples tested in this study seem to be stable under the accelerated condition (50% of tensile strength reduction after 840 h exposure time), it is extremely difficult to transfer the artificial weathering to life expectancy under natural weathering conditions since rate of fiber degradation in nature depends on various external factors such as intensity of radiation, temperature, humidity, air pollution, etc. Nevertheless, it has been demonstrated that the tensile strength of polypropylene filaments which are one of the raw materials for geotextiles is reduced to approximately 55% after 1-year of outdoor weathering test whereas that in the accelerated weathering test is reduced to 50% (8-lamp tests, 70 h), 56% (4-lamp test, 140 h) and 55% (2-lamp test, 280 h) (Yang & Ding, 2006). From this result, it was presumed that the studied fibers except sisal would stay at least 1-year in the outdoor condition. In addition, it is worth noting that one of the most important weaknesses of the natural products is their quick biodegradability. Thereby, rate of degradation of all samples embedded in soil is being carried out.

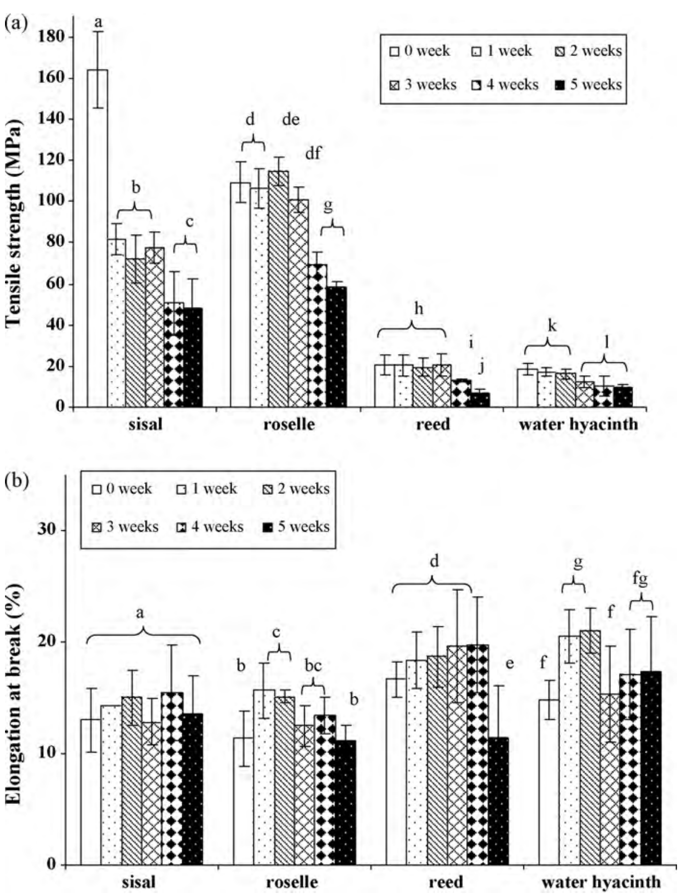

Fig. 6. Mechanical properties of natural fibers exposed to the accelerated condition for various times: (a) tensile strength, and (b) elongation at break. Different letters in each fiber are significantly different ($p < 0.05$).

4. Conclusions

From composition and properties of the four studied fibers, they could be classified into two groups; long fibers such as sisal and roselle, and short fibers such as reed and water hyacinth. In spite of location specific of geotextiles, their applications depend on several parameters such as climate condition, soil type and composition, land sloping, and so on. The unique properties such as low moisture absorption and high strength of roselle were similar to those of sisal, which would provide a good performance geotextile for soil reinforcement because strength and durability are the major characteristic properties needed for this application type of geotextiles. For reed and water hyacinth, it is worth to study due to their availability, lower cost and higher water absorption even though they have lower strength compared with sisal and roselle. They, therefore, would be appropriate for soil erosion control which must have the following properties; retain moisture to promote the growth of vegetation, reduce rain drop impact, reduce wind and run off velocities, improve soil fertility, compatible to land surface, and so on. Further ongoing studies of the woven geotextiles from roselle and water hyacinth such as geotechnical characteristics properties, life span, and field test are being carried out.

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