JOURNAL OF MATERIALS SCIENCE **38** (2003) 3697 – 3707

Switchgrass (*Panicum virgatum* L.) as a reinforcing fibre in polypropylene composites

M. J. A. VAN DEN OEVER, H. W. ELBERSEN, E. R. P. KEIJSERS,
R. J. A. GOSSELINK, B. DE KLERK-ENGELS
Agrotechnological Research Institute (ATO bv), P.O. Box 17, 6700 AA, Wageningen,
The Netherlands
E-mail: martien.vandenoever@wur.nl

In this study the switchgrass (*Panicum virgatum* L.), a biomass crop being developed in North America and Europe, was tested as a stiffening and reinforcing agent in polypropylene (PP) composites with and without maleic anhydride grafted PP (MAPP) as a compatibiliser and to evaluate the effect of pulping and different sources of switchgrass on composite characteristics. The refiner pulping yield for two switchgrass varieties was estimated between 70–80%. The addition of 30% (by weight) switchgrass pulp resulted in an increase of the flexural modulus by a factor of about 2.5 compared to pure polypropylene. Which was only slightly lower than values found for jute and flax. The flexural strength of PP composites reinforced with pulped switchgrass and MAPP was almost doubled compared to pure PP and approached values found for jute and flax. The compatibilising effect of MAPP has been visualised by micrographs. The good mechanical properties are achieved despite the severe fibre length reduction as a result of thermoplastic compounding which is shown by fibre length analysis. The impact strength of switchgrass/PP composites was much lower than for pure PP. The use of different switchgrass varieties and harvesting time had a minor to no effect on the mechanical performance of the respective composites. The chemical composition of different varieties was fairly constant. The low price and the relatively good mechanical characteristics should make switchgrass an attractive fibre for filling and stiffening in thermoplastic composites. Further improvement of composite mechanical properties should be possible.

1. Introduction

Agrofibres are increasingly being used as a reinforcing material in composite materials [1–3]. For example in the automotive industry agrofibres are used as a reinforcing fibre because of their low weight compared to glass fibres which contributes to reduced costs [1].

Switchgrass (*Panicum virgatum* L.) is a perennial C_4 grass native to North America. The grass has a wide range of adaptation from Central America to deep into Canada but it is also grown in South America and Africa. It has high yields under poor, low input conditions and is used for forage production, soil conservation and as an ornamental crop. During the last 10 years it has been developed for energy and fibre applications in North America, Canada and more recently in Europe [4–7]. Production costs of switchgrass are much lower compared to annual fibre crops or compared to other biomass crops like short rotation willow and *Miscanthus*, this is mainly due to the low establishment costs and low input requirements [8, 9]. Switchgrass has been evaluated for use in paper pulp [10, 11], and in hardboard and medium-density fibreboard (MDF) [12]. Switchgrass pulp produced in the Kraft process was found to have short fibres with a high portion of fines, making it suitable for substitution of hardwoods in paper pulp [11]. Economic analysis of the use of switchgrass for pulp production has been performed for Ontario (Canada) indicating that switchgrass may be an attractive crop especially on marginal soils [13]. Switchgrass fibres may be an interesting reinforcing and filling agent for thermoplastic composites because they provide relatively good quality fibres that can be produced at low cost and in a sustainable way.

Polypropylene (PP) is a widely used polymer in which often filling and reinforcing material is used. Chalk and talk are used as filling materials in order to lower the costs and to increase the material stiffness. When a more pronounced mechanical performance is required, PP is reinforced by fibres. To obtain optimal composite characteristics, the fibres should be optimally adhered to the PP. For agrofibres, which are composites by themselves [14], this can be achieved by sufficient opening of the agrofibres. Opening of the agrofibres to fibres with a smaller diameter increases the interaction area between the fibre and the matrix and at the same time yields fibres with a higher strength than the starting fibres [14]. This opening of agrofibres is partially realised during extrusion compounding of agrofibres as shown for flax and jute in PP. Depending on the degree of shear forces introduced during compounding, the strong elementary fibres can be obtained. To ensure fibre opening, however, the agrofibres can be pulped before compounding.

An additional route to achieve optimal fibre adhesion is to optimise the fibre-matrix interaction. The interaction between the polar agrofibres and the a-polar PP can be enhanced using so called compatibilisers. Maleic anhydride grafted PP (MAPP) is a compatibilising agent commonly used to increase the bonding between PP and reinforcing fibres, like agrofibres [2, 3, 15], and glass fibres [16].

The objective of this study was to test the performance of switchgrass as a stiffening and reinforcing agent in PP composites with and without MAPP as a compatibiliser and to evaluate the effect of pulping and different sources of switchgrass on composite characteristics.

2. Materials and methods

2.1. Plant material

Experiments were conducted with air-dry switchgrass samples from southern England and from Quebec, Canada. Samples were harvested from a mature stand of variety Cave-in-Rock in Quebec, Canada after overwintering in the spring of 1998 (A) and shortly after maturing in the fall of 1998 (B). The other samples of the varieties Kanlow (C) and Cave-in-Rock (D) were harvested in winter 1998/1999 from 6 year old stands in southern England.

2.2. Pulping procedure

Switchgrass samples A and B (1.5 kg per sample) were soaked in 0.1 molar NaOH for 16 h with a water to dry matter ratio of 15:1. Both samples were washed in a single step by pressing out the water to 30% dry matter content using a screw press and adding clean water up to a 5% dry matter content slurry. This slurry was refined at 100°C and atmospheric pressure in a Sprout-Bauer 12-1 cp refiner. After this refiner stage water was pressed out of the pulp up to 30% dry matter content and a second refiner stage was performed. The overall refiner energy input was circa 500 kWh/ton. After pulping the pulp was stored frozen for two weeks and then air dried at 60°C overnight just before compounding.

2.3. Chemical composition

Kanlow and Cave-in-Rock switchgrass from 2nd year harvest was milled to pass a 0.5 mm sieve. Ash was determined by ignition at 575°C. Extractives were determined after successive extraction with ethanol/toluene (2:1 v/v), 95 vol% ethanol and hot water. The content of neutral sugars and lignin was determined after a two-step hydrolysis with 12 M sulfuric acid for 1 h at 30°C and at 1 M sulfuric acid for 3 h at 100°C according to modified TAPPI methods [17, 18]. Neutral sugars were determined in the neutralised hydrolysate with HPLC on an anion exchange column (Dionex, CarboPac PA1) and pulsed amperometric detection [19]. Uronic acids in the sulfuric acid hydrolysate were spectrophotometrically determined at a wavelength of 520 nm [20].

2.4. Compounding procedure

Pulped (A and B) and untreated switchgrass samples (A, B, C and D) were kneaded with PP pellets (ELTEX-P HV651, homopolymer, $MFI_{2.16,230} = 11$, provided by Solvay) in a 30:70 wt% ratio using a Haake Rheomix 300 equipped with roller rotors. The kneading was performed during 12 min at a temperature of circa 185°C and at a rotor speed of 100 RPM. Each fibre grade was kneaded as well with a 10:90 wt% blend of PP and maleic anhydride grafted polypropylene (MAPP) (GP12, provided by Solvay). As a reference PP and the blend of PP and MAPP was compounded as well. The kneaded composites were subsequently granulated using a KT Handling Ltd. peletiser before injection moulding.

2.5. Injection moulding of flexural and impact test bars

The granulated composite material was injection molded using a Demag ERGOtech 25–80 to flexural/impact test bars with dimensions $80 \times 10 \times 4$ mm^3. The test bars were conditioned at 50% relative humidity and 23°C for 7 days before mechanical testing.

2.6. Mechanical performance tests

The flexural properties were measured on a Zwick 1445 according to ISO 178 at a crosshead speed of 2 mm min^{-1} and a support length of 64 mm. The flexural strength and modulus was determined from 5 test bars per batch. The Charpy unnotched impact strength was determined using a Ceast pendulum impact tester according to ISO 179 using an impact hammer of 4J at a speed of 2.9 m/s. The Charpy impact strength was determined from 10 test bars per batch.

2.7. SEM photography

SEM micrographs were made from fracture surfaces of cryo-broken composite samples using a Jeol JSM-5600 LV scanning electron microscope. All observations were made on compounds of sample B, switchgrass variety Cave-in-Rock harvested in Quebec, Canada shortly after maturing in the fall of 1998.

2.8. Switchgrass fibre dimensions

Three grams of injection moulded compound B, containing Cave-in-Rock variety harvested in Quebec, Canada, shortly after maturing in the fall of 1998, was put into 125 ml of xylene and heated up to 140°C for three h. The resulting switchgrass fibre-xylene dispersion with dissolved PP was filtrated over a heated Büchner funnel. The remaining fibre material was heated again in 125 ml xylene at 140°C for three more hours and filtrated again. Part of the obtained fibres were put on an object glass and the visual length and diameter of circa 200 fibres was determined using optical microscopy. The same procedure was performed for three grams of pulped switchgrass/PP composite sample.

3. Results

3.1. Pulping and chemical compositions

The pulp yield of the switchgrass batches was estimated between 70–80%. The chemical composition of Kanlow and Cave-in Rock switchgrass varieties is presented in Table I. Differences in chemical composition between the two varieties were minor. The extractives and cellulose content was slightly higher for Kanlow, the lignin and hemicellulose content was slightly higher for Cave-in-Rock. Ash and pectin were similar for both varieties. The chemical composition of refiner pulped Cave-in-Rock switchgrass fibres is included in Table I. Pulping results in an increase of the cellulose and lignin content of the switchgrass.

3.2. Flexural modulus

As is shown in Table II, the addition of 30 wt% switchgrass enhanced the flexural modulus of PP by a factor of 2 to 2.5 depending on fibre pre-treatment. The increase in modulus was similar for all four switchgrass samples (A, B, C, D) tested. The flexural modulus was slightly higher for the PP composites reinforced with pulped switchgrass compared to the PP composites reinforced with untreated switchgrass. Addition of pulped switchgrass fibres resulted in a flexural modulus of up to 2900 MPa compared to 2718 MPa for untreated switchgrass. The use of MAPP as a fibre-matrix compatibiliser did not promote the flexural modulus of the (untreated) switchgrass compounds. When pulped switchgrass fibres were used, the addition of MAPP led to a very small increase in flexural modulus (from 2841 to 3003 MPa for sample A and from 2900 to 3147 MPa for sample B). As is shown in Table II, the modulus of pulped switchgrass compounds was somewhat lower than for flax and jute compounds (2850–3150 MPa vs. 3500–3900 MPa).

3.3. Flexural strength

The flexural strength of the switchgrass/PP composites is presented in Table II. Addition of switchgrass fibres, either pulped or untreated, did only slightly contribute

TABLE I Chemical composition of untreated and pulped spring harvested switchgrass samples from different sources

	Kanlow	Cave-in-rock	Pulped Cave-in-rock	Radiotis[a]	Madakadze[a]
Ash	1.9	1.8	2.6	1.5	4.8
Extractives	10.4	9.5	–[b]	1.6[c]	6.9[d]
Lignin	18.9	19.5	22.5	21.8	23.9
Cellulose	30.5	28.8	33.6	43.4[e]	43.4[e]
Hemi-cellulose	30.4	31.2	31.5	35.9	30.5
Pectin	1.4	1.3	1.7	–	–

[a] Literature references: [6] for Radiotis *et al.* and [11] for Madakadze.

[b] Pulp characterised without prior extraction.

[c] Alcohol/benzene extractives.

[d] Cold water, hot water and acetone extractives.

[e] Alpha-cellulose.

TABLE II Flexural and Charpy impact properties of switchgrass fibre reinforced PP and PP/MAPP composites

Fibre[a]	MAPP	Flexural modulus[b] (MPa)	Flexural strength (MPa)	Strain (%)	Charpy unnotched impact strength (KJ m^{-2})
–	No	1210 ± 74	42.6 ± 1.5	6.9 ± 0.2	51.8 ± 12.5
–	Yes	1384 ± 43	45.9 ± 0.6	6.7 ± 0.2	93.2 ± 8.2
30% A	No	2764 ± 105	47.0 ± 0.6	3.6 ± 0.1	7.0 ± 0.9
30% B	No	2718 ± 44	48.8 ± 0.8	3.7 ± 0.1	7.0 ± 1.8
30% pulped A	No	2841 ± 42	47.5 ± 0.6	3.1 ± 0.2	9.5 ± 1.4
30% pulped B	No	2900 ± 203	48.2 ± 0.5	3.0 ± 0.1	10.0 ± 0.7
30% A	Yes	2721 ± 159	56.6 ± 1.1	3.5 ± 0.1	8.3 ± 1.1
30% B	Yes	2672 ± 101	58.7 ± 0.6	3.7 ± 0.2	8.1 ± 1.2
30% C	Yes	2650 ± 126	54.1 ± 0.9	3.4 ± 0.2	7.6 ± 1.5
30% D	Yes	2795 ± 88	58.6 ± 1.2	3.4 ± 0.2	8.3 ± 1.4
30% pulped A	Yes	3003 ± 58	69.6 ± 0.5	4.1 ± 0.2	15.1 ± 1.3
30% pulped B	Yes	3147 ± 81	70.7 ± 0.5	4.1 ± 0.2	16.9 ± 1.3
30% jute[c]	Yes	3500–3900	64–77	4.5	25
30% flax[c]	Yes	3500	76	4.5	25

[a] A = Cave-in-Rock switchgrass, harvested in spring Canada; B = Cave-in-Rock switchgrass, harvested in fall in Canada; C = Kanlow switchgrass, harvested in winter at Rothamsted; D = Cave-in-Rock switchgrass, harvested in winter at Rothamsted.

[b] Values are ± standard deviation.

[c] Data obtained during separate research programs at ATO. These data are included for comparison reasons only.

to the strength. Additional use of MAPP, however, increased the strength by between 20 and 50%, depending on the fibre pre-treatment. Cave-in-Rock switchgrass (D) contributed slightly more to the composite strength than Kanlow (C). Harvesting in fall (B) yielded a slightly higher composite strength than harvesting in spring (A). The pulped switchgrass compounds approached the flexural strength of jute/PP and flax/PP compounds ranging between 64 and 77 MPa [21].

3.4. Strain at failure

The strain at failure of PP compounds was reduced by the addition of switchgrass to PP (Table II). The change in strain at failure was very similar for all four switchgrass samples tested. Addition of untreated switchgrass to PP with or without MAPP reduced the strain at maximum stress 3.6% compared to 7% for pure PP. Addition of pulped fibres yielded a strain at failure of 3.1%. When MAPP was used the strain at failure was 4.1%.

3.5. Charpy impact strength

The impact strength of untreated switchgrass/PP composites ranged between 7.0 and 8.3 kJ m^{-2}, irrespective of the use of MAPP as a fibre-matrix compatibiliser. This was much lower than the impact strength of pure PP which ranged between 52 and 97 kJ m^{-2}. The impact strength of pulped switchgrass/PP ranged from 9.5 kJ m^{-2} for pure PP to 16.9 kJ m^{-2} for PP with 10% MAPP as a compatibiliser. The Charpy impact strength of switchgrass composites appeared to be significantly lower than for flax and jute reinforced composites which have an impact strength of approximately 25 kJ m^{-2}. The Charpy impact strength was similar for all four switchgrass samples tested.

3.6. SEM photographs

Untreated switchgrass fibres in PP composites (Fig. 1A and C) were much coarser than pulped fibres (Fig. 1B and D). The pulped fibres were not 100% defibrated to elementary fibres, though. Small bundles of elementary fibres bonded together can be seen. The pulled-out fibres in both the untreated and pulped switchgrass/PP samples show fibre surfaces with no PP adhered. The addition of MAPP to the switchgrass/PP composite resulted in fibre splitting (Fig. 1C), the fibre halves being still stuck to the two composite parts. Addition of MAPP to the pulped switchgrass/PP sample reduced the fibre pull out length to nearly zero (Fig. 1D). Fig. 2 shows SEM micrographs of technical fibres in the switchgrass/PP composite. The fibres show pull-out of their own elementary fibres and a rather porous structure of the technical fibre (Fig. 2B). The switchgrass elementary fibres have different structures. Fig. 3 shows SEM micrographs of different switchgrass fibres at the fracture surface of the pulped switchgrass/PP composite. Most elementary fibres appear to be circular with a diameter of circa 10–15 μm, some of which have a concentric layer structure (Fig. 3A) and some of which have a structure with an outer and inner ring (Fig. 3B). Some elementary fibres have a flat layered structure and seem partly hollow (Fig. 3C).

TABLE III Dimensions of untreated and pulped Cave-in-Rock switchgrass fibres after compounding and injection moulding in PP

Fibre	Arithmetic			Length weighed	
	L (μm)	d (μm)	L/d	L (μm)	L/d
Untreated	1014 ± 761	303 ± 278	4.3 ± 2.5	1582	4.5
Pulped	243 ± 172	51 ± 39	6.7 ± 5.1	365	7.8

3.7. Switchgrass fibre dimensions

The Cave-in-Rock switchgrass fibres have a flat form after recovering from injection moulded switchgrass/PP composites, i.e., the cross section is not circular. This holds for both the untreated and pulped switchgrass fibres. The length of the switchgrass fibres, which were recovered from injection moulded switchgrass/PP specimens, range from 150 to 4100 μm for untreated fibres and from 40 to 1150 μm for pulped fibres. The fibre diameters range from 50 to 1500 μm for untreated fibres and from 10 to 250 μm for pulped fibres. The arithmetic and length weighed averages of fibre length and diameter are presented in Table III. The cumulative length over diameter (L/d) distributions of untreated and pulped switchgrass fibres, after recovering from injection moulded switchgrass/PP composites, are presented in Fig. 4. The averages are given in Table III. The average L/d ratio of the pulped fibres is about 1.5 times larger than of the untreated fibres.

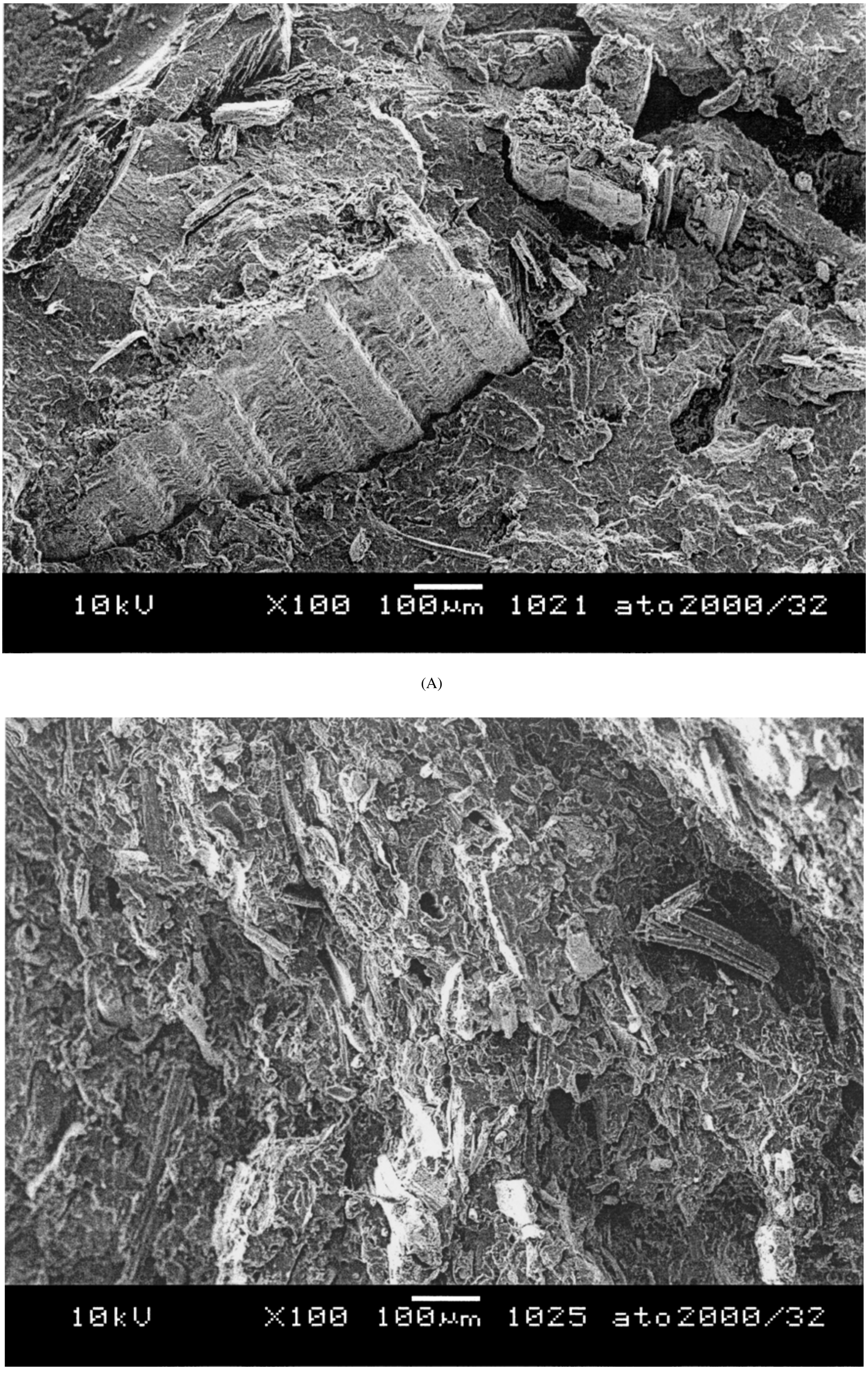
4. Discussion

The chemical composition of the mature Kanlow and Cave-in-Rock switchgrass is very similar (Table I). The data are comparable with switchgrass data presented by Radiotis *et al.* [6] and Madakadze [11]. The differences in chemical composition are mainly explained by the difference in analysis methods applied.

After pulping of Cave-in-Rock switchgrass, the cellulose and lignin content of pulped Cave-in-Rock is approximately 15% higher than in untreated material. During the pulping process extractives and hemicellulose are removed easier than cellulose and lignin, thus increasing the relative amount of these components. It is generally accepted that higher cellulose and lignin content have a positive effect on mechanical strength and stiffness of fibres.

In composites, the L/d aspect ratio of the fibres has a more direct relation to composite properties than the fibre length. Therefore, the fibre dimensions in the composite are presented as L/d aspect ratios in Fig. 4. As a result of the relatively low L/d values, the arithmetic and length weighed averages differ only slightly (Table III). The L/d values are similar to fibre aspect ratios which can be derived for compounded jute bast fibres in PP from experimental results presented by Karmaker and Youngquist [22].

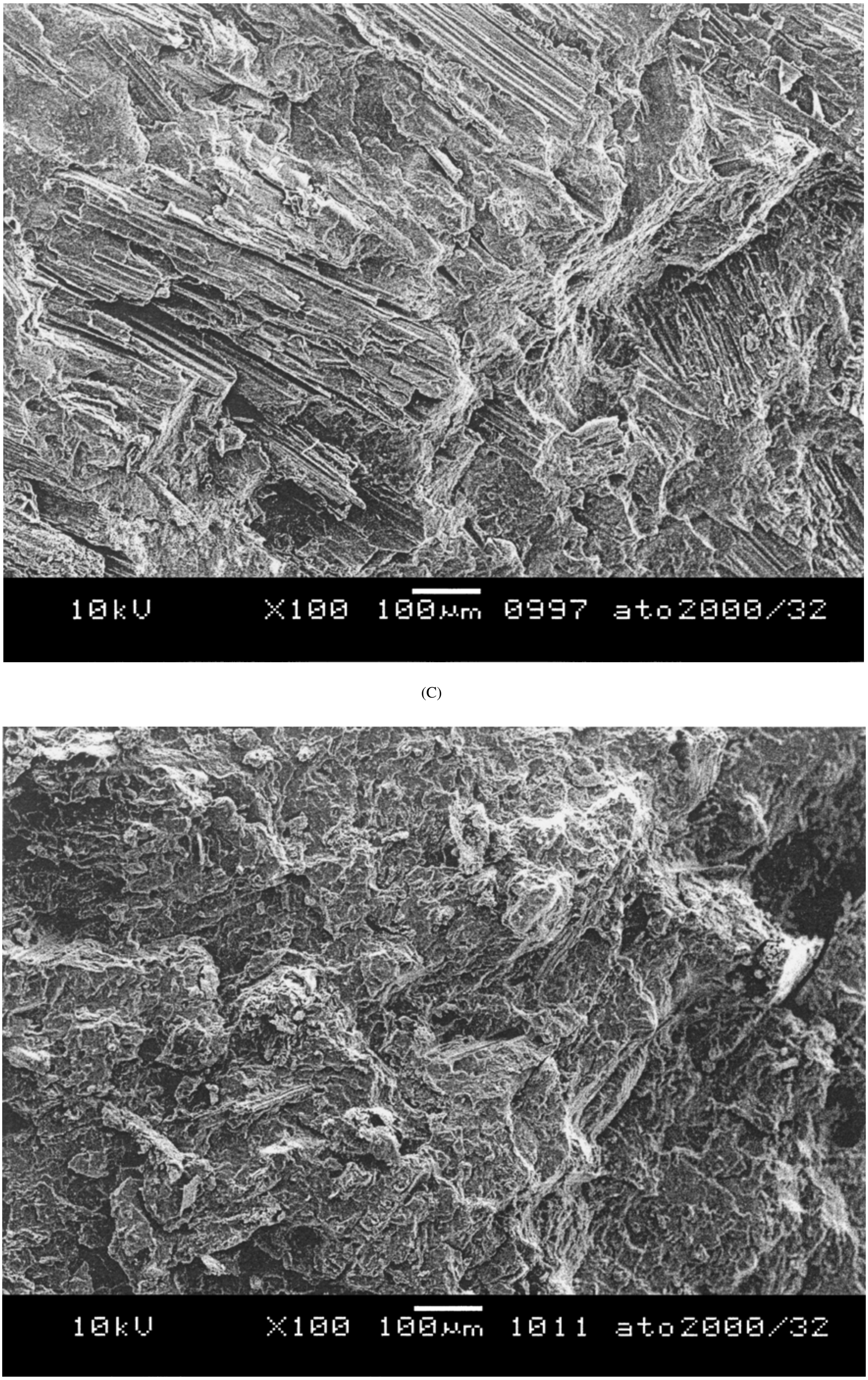
For switchgrass fibres, as far as the authors know, only fibre length and no L/d values are reported. Madakadze reports arithmetic and length weighed



(A)

(B)

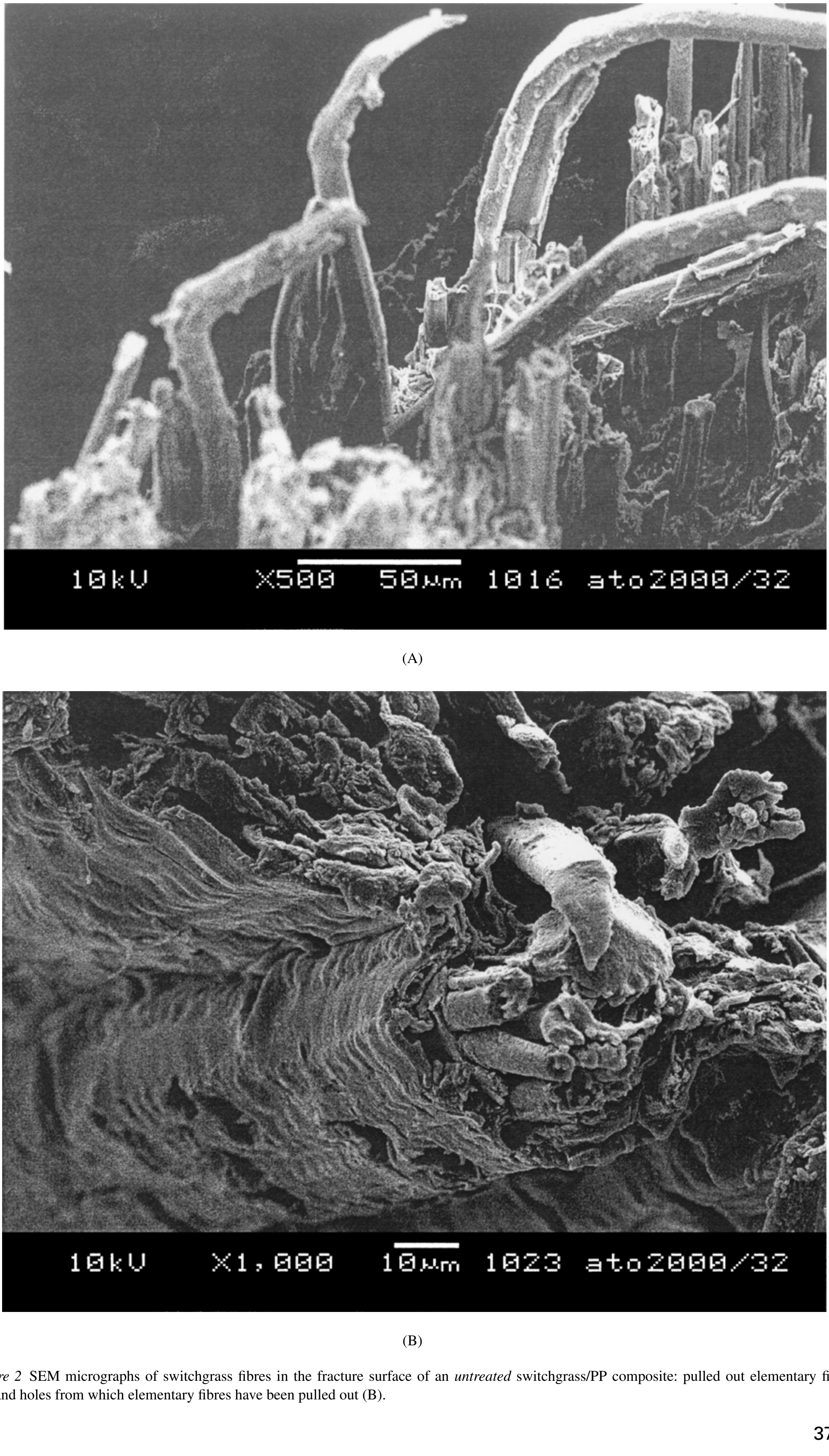
Figure 1 SEM micrographs of a fracture surface of switchgrass/PP composites: *untreated* switchgrass/PP (A), *pulped* switchgrass/PP (B), *untreated* switchgrass/PP/MAPP (C), *pulped* switchgrass/PP/MAPP (D). The magnification is indicated via the scale bar in the micrographs.



(C)

(D)

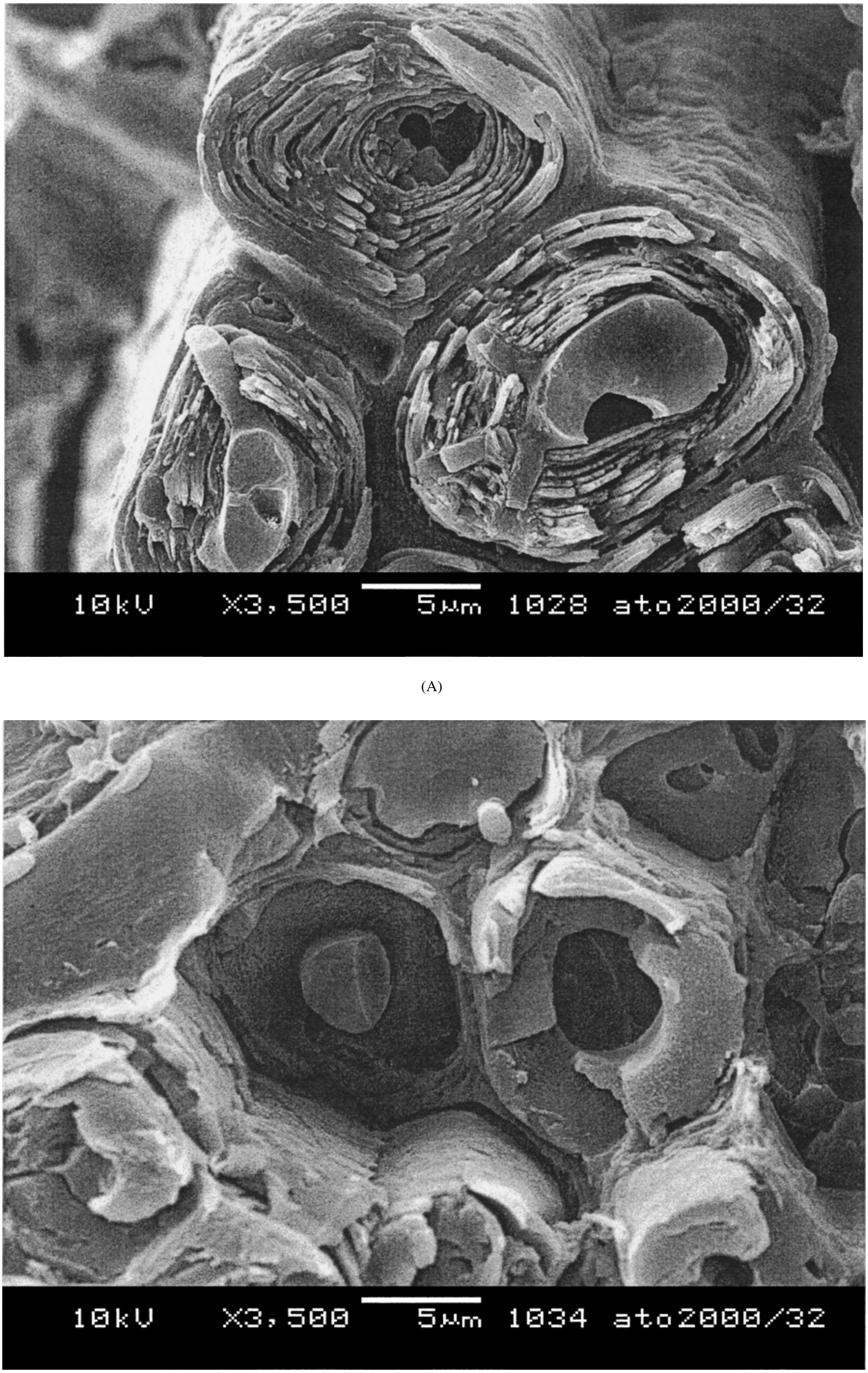
Figure 1 (*Continued*).



(A)

(B)

Figure 2 SEM micrographs of switchgrass fibres in the fracture surface of an *untreated* switchgrass/PP composite: pulled out elementary fibres (A) and holes from which elementary fibres have been pulled out (B).



(A)

(B)

Figure 3 SEM micrographs of a cross section of three different fractured *pulped* switchgrass fibres (A, B, C).

(C)

Figure 3 (*Continued*).

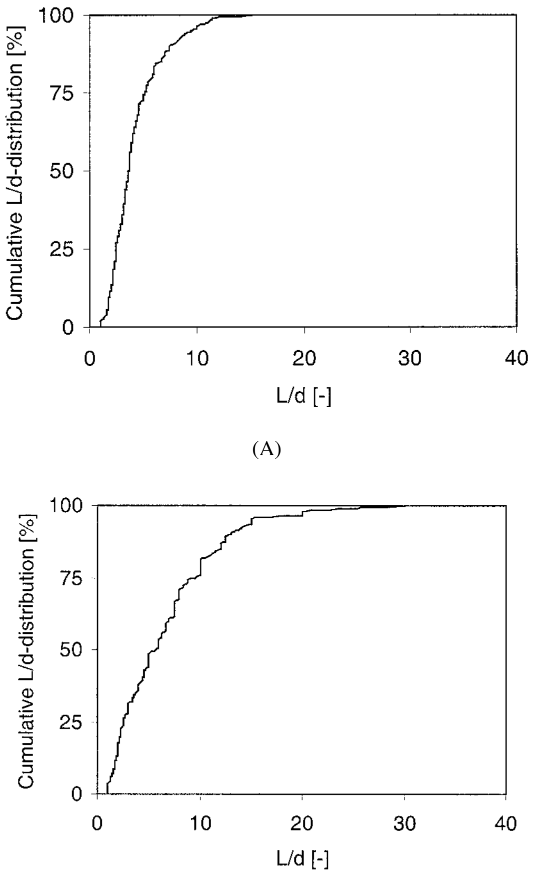
averages for pulped Cave-in-Rock switchgrass fibres of 0.32 and 0.76 mm, respectively [11]. These fibres are, however, not compounded in a thermoplastic polymer. The pulped, compounded and injection moulded switchgrass fibres from this study have arithmetic and length weighed average lengths of 0.24 and 0.37 mm respectively. These values are close to the arithmetic and length weighed average lengths of compounded kenaf bast fibres as determined by Snijder *et al.*, being 0.28 and 0.44 mm, respectively [23] Apparently, the thermoplastic compounding process has a pronounced fibre length reducing effect. This effect has been found previously for jute and kenaf bast fibres as well [22, 23]. Since fines, in contrast to paper properties, hardly affect composite properties, they are not specifically addressed in this paper.

The switchgrass fibres were pulped in order to obtain the elementary fibres, which are, similar to other agrofibres, expected to be stronger than the untreated fibres [14]. Pulping, followed by compounding and injection moulding, however, did not entirely split up the switchgrass to elementary fibres (Fig. 1B and D). The elementary fibres have a diameter of 10 to 30 μm (Fig. 3), whereas the visual diameter of pulped fibres, after recovery from injection moulded PP compounds by extraction with xylene, ranges from 10 to 250 μm. The limited splitting into elementary fibres during compounding and subsequent injection moulding is experienced before for flax core fibres, also called shives [24]. The pull-out of elementary switchgrass fibres from their technical fibre during composite fracture (Fig. 2), however, indicates that the bonding between the elementary fibres must be quite weak. Therefore, it is surprising that the combined effort of pulping, compounding and injection moulding is not sufficient to yield elementary switchgrass fibres.

For comparison, Goel *et al.* obtained mainly entirely separated elementary switchgrass fibres after pulping with diameters ranging between 10–15 μm [25]. Their switchgrass fibres, on the other hand, were very intensively pulped in 14% active alkali at 160°C during 1 h. The intensive pulping of Goel *et al.* also resulted in a low pulping yield of 45% whereas our pulping yield was estimated to be in the range 70–80%. Our pulping yield could not be measured precisely because of losses of the relatively small amount of switchgrass pulped in a pilot scale Sprout-Bauer refiner.

The flexural modulus of switchgrass composites is lower than of the flax and jute composites. Since the matrix material is similar for these composites and since the fraction of fibres in the composites could be very well selected as a result of the batch compounding procedure, the limited stiffness must be caused by the lower switchgrass fibre modulus.

The flexural stiffness of switchgrass composites seems to increase—though the increase is small—on pulping the switchgrass fibres and on adding MAPP. This trend can be explained by the larger amount of shear sensitive regions in untreated switchgrass fibres compared to pulped fibres. The presence of these shear



(A)

(B)

Figure 4 Cumulative length over diameter distribution of switchgrass fibres, recovered from injection moulded switchgrass/PP compounds: *untreated* fibres (A) and *pulped* fibres (B).

sensitive regions can be derived from Fig. 2 where the poor bonding between—part of—the individual elementary fibres is clearly visible. Pulping of the switchgrass apparently reduces the effect of these shear sensitive regions by partly removing them. Addition of MAPP also shows a small positive effect on the flexural modulus of the pulped switchgrass/PP composite. These data indicate that the fibre-matrix interface in the switchgrass/PP composites is a shear sensitive region as well. A similar, though more pronounced, trend has been found previously for the flexural modulus of flax fibre/ PP composites [26].

Bendzala and Kokta presented tensile results on switchgrass reinforced polyethylene (PE) and found an increase in stiffness by a factor of 3–4 by adding 45 wt% switchgrass fibre to PE [27]. Since they used a PE grade with a modulus of 400 MPa, a fourfold stiffness increase by adding 45 wt% switchgrass can be easily achieved. The increase in stiffness by the addition of 30 wt% switchgrass to PP is similar to that of 40 wt% chalk or 50 wt% waste newspaper flour in PP, viz. 3100 MPa and 3000 MPa, respectively [15, 28].

The addition of untreated and pulped switchgrass to PP only yielded a limited increase in strength. This is caused by the small *L*/*d* ratios of the switchgrass fibres in the composites (Table III and Fig. 4) and by a limited fibre-matrix adhesion as illustrated by the clean fibre surfaces in Fig. 1. The increase of the flexural strength by addition of MAPP, thus improving the fibre-matrix adhesion, supports this idea. Similar to the flexural modulus, the effect of MAPP on the strength of pulped fibre/PP composites is larger than for the untreated fibre based composites. The MAPP compatibiliser can enhance the fibre-matrix interaction, the weak regions inside the untreated fibre, however, are unaffected.

The pulped switchgrass composites have a relatively high strength compared to flax and jute compounds, 70 vs. 77 MPa. This might be called a remarkable result since elementary flax fibres, which are present in optimal flax compounds, have strength properties close to those of glass fibres; circa 1500 MPa [14]. It should be remarked here, however, that the full potential of the flax fibres is not utilised in the respective composites, which is mainly due to the relatively short fibre length which remains after extrusion compounding and injection moulding. Compared to commercial chalk filled PP, which yields a strength of up to 48 MPa [15], the optimal switchgrass/PP/MAPP compound from this research scores excellent with a strength of 70 MPa. In order to determine the full potential of switchgrass fibres, however, the tensile and compression properties of the elementary switchgrass fibres—which to our knowledge are not yet known—need to be determined.

The Charpy impact strength of agrofibre reinforced compound materials is usually limited compared to that of pure PP material [3]. This is mainly due to the decreased failure strain. Moreover, the brittle nature of agrofibres after processing at elevated temperatures causes a limited fibre pull-out. The low Charpy impact strength of switchgrass/PP composites (from 7 to 16.9 kJ m^{-2}) compared to flax/PP and jute/PP (approximately 25 kJ m^{-2}) is related to the lower stiffness, strength and failure strain of the switchgrass composites. The larger impact strength for pulped switchgrass fibre filled PP compared to the untreated switchgrass equivalent, both with and without MAPP as a fibre-matrix compatibiliser, is due to the larger *L*/*d* ratio of the pulped fibres and less weak regions inside these fibres.

The Charpy impact strength was also lower than for waste newspaper flour filled PP composites. Yuan *et al.* found values up to 23 kJ m^{-2} for 50 wt% newspaper flour filled PP with optimised fibre-matrix adhesion [28].

5. Conclusions

The presented results give a first indication of the performance of switchgrass/PP kneading compounds. In these compounds, the switchgrass is not entirely split up into elementary fibres, not even for the pulped fibres. The fibre length over diameter ratio appears to be small after kneading, around 4.5 and 6.5 for untreated and refiner pulped switchgrass fibres, respectively. The flexural stiffness of PP is nevertheless increased by a factor of circa 2.5 by addition of 30 wt% switchgrass. This stiffness approaches that of 30 wt% flax and jute/PP composites and equals or even surpasses the stiffness of 40 wt% chalk and 50 wt% waste newspaper flour filled PP composites. Addition of switchgrass fibre to PP does not enhance the flexural strength significantly. For a significant increase in strength of switchgrass/PP composites, the fibre-matrix adhesion has to be improved via e.g., MAPP. The improved adhesion has been visualised by micrographs and results in an increase in flexural strength of 30% compared to PP. Opening of the switchgrass fibres via refiner pulping yields an extra increase in flexural strength of PP up to 55% at a fibre fraction of 30 wt%. This performance approaches the strength of jute/PP and flax/PP composites. The refiner pulping yield was estimated between 70 and 80%. The impact strength of switchgrass/PP composites is much lower than for PP. Using pulped fibres and simultaneous use of MAPP as a compatibiliser increased the impact strength by 100%, however, these values are still some 50% lower than for flax, jute or newspaper flour filled PP. The difference in switchgrass varieties and harvesting time had no significant effect on the mechanical performance of the respective composites. The chemical composition of different switchgrass varieties is also fairly constant.

It is expected that composite mechanical properties can be improved when the performance of the elementary switchgrass fibres can be utilised. This should be possible with an optimised pulping via biorefinery.

Acknowledgements

The authors wish to acknowledge the financial support by the Commission of the European Communities, Agriculture and Fisheries (FAIR) program, CT97-3701 (www.switchgrass.nl). This publication does not necessarily reflect its views and in no way anticipates the Commission's future policy in this area. Financial support by the Dutch Ministry of Agriculture is kindly acknowledged.

The authors thank R. Samson and P. Girouard of REAP-Canada and D. Christian of Rothamsted (UK) for providing switchgrass material and much helpful information; D. Coppus for performing the composite manufacturing and testing; J. Donkers for assistance in making the SEM micrographs; H. Bos and M. Snijder for valuable suggestions in improving this paper.

References

1. A. BECKMANN and R. KLEINHOLZ, in Proceedings of 2nd International Wood and Natural Fibre Composites Symposium, Kassel, June 28–29 1999, edited by A. K. Bledzki *et al.* (Institut für Werkstofftechnik, Kassel, 1999) p. 30.
2. A. R. SANADI, R. A. YOUNG, C. CLEMONS and R. M. ROWELL, *J. Reinf. Plast. Comp.* **13** (1994) 54.
3. M. H. B. SNIJDER, E. WISSING and J. F MODDER, in Proceedings of The fourth International Conference on Woodfiber-Plastic Composites, Madison, May 12–14 1997, edited by R. Rowell and A. Sanadi (Forest Products Society, Madison, 1997) p. 181.
4. H. W. ELBERSEN, D. G. CHRISTIAN, N. EL BASSAM, W. BACHER, G. SAUERBECK, E. ALEXOPOULOU, N. SHARMA, I. PISCIONERI, P. DE VISSER and D. VAN DEN BERG, in Proceedings of Biomass and Energy Crops II, York, December 18–21 2001, edited by M. J. Bullard *et al.* (The Association of Applied Biologists) p. 21.
5. S. B. McLAUGHLIN, R. SAMSON, D. BRANSBY and A. WISELOGEL, in Proceedings of Bioenergy '96-the Seventh National Bioenergy Conference, Vol. 2, Nashville, September 15–20 1996, edited by The Southeastern Regional Biomass Energy Program, p. 1.
6. T. RADIOTIS, J. LI, K. GOEL and R. EISNER, *TAPPI J.* **82** (1999) 100.
7. M. A. SANDERSON, R. L. REED, S. B. MCLAUGHLIN, S. D. WULLSCHLEGER, B. V. CONGER, D. J. PARRISH, D. D. WOLF, C TALIAFERRO, A. A. HOPKINS, W. R. OCUMPAUGH, M. A. HUSSEY, J. C. READ and C. R. TISCHLER, *Bioresource Techn.* **56** (1996) 83.
8. D. G. CHRISTIAN and A. B. RICHE, in "Establishing Fuel Specifications of Non-Wood biomass Crops" (ETSU report B/U1/00612/REP, IACR, Rothamsted, 1999).
9. P. GIROUARD, J. C. HENNING and R. SAMSON, in Proceedings of the Canadian Energy Plantation Workshop, Gananoque, May 2–4 1996, edited by Natural Resources Canada (Canadian Forest Service, Ottawa, 1996) p. 11.
10. P. GIROUARD and R. SAMSON, in Proceedings of The Third Biomass Conference of the Americas, Vol. 1, Montreal, August 24–29 1997, edited by R. P. Overend and E. Chornet (Elsevier, Oxford, 1997) p. 197.
11. I. C. MADAKADZE, T. RADIOTIS, J. LI, K. GOEL and D. L. SMITH, *Bioresource Techn.* **69** (1999) 75.
12. M. KUO, D. ADAMS, D. MYTERS, D. CURRY, H. HEEMSTRA, J. L. SMITH and Y. BIAN, *Forest Prod. J.* **48** (1998) 71.
13. G. FOX, P. GIROUARD and Y. SYAUKAT, *Biom. Bioen.* **16** (1999) 1.
14. H. L. BOS, M. J. A. VAN DEN OEVER and O. C. J. J. PETERS, *J. Mater. Sci.* **37** (2002) 1683.
15. A. R. SANADI, D. F CAULFIELD, R. E. JACOBSON and R. M. ROWELL, *Ind. Eng. Chem. Res.* **34** (1995) 1889.
16. H. A. RIJSDIJK, M. CONTANT and A. A. J. M. PEIJS, *Comp. Sci. Techn.* **48** (1993) 161.
17. TAPPI Method T 222 om-83, in "Test Methods 1998–1999" (TAPPI Press, Atlanta, 1999).
18. TAPPI Useful Method UM250, in "Useful Methods" (TAPPI Press, Atlanta, 1991).
19. T. STOLLE-SMITS, J. G. BEEKHUIZEN, K. RECOURT, A. G. J. VORAGEN and C. VAN DIJK, *J. Agric. Food Chem.* **45** (1997) 4690.
20. N. BLUMENKRANTZ and G. ASBOE-HANSSEN, *Analytical Biochem.* **54** (1973) 484.
21. M. H. B. SNIJDER and H. L. BOS, *Comp. Interfaces* **7** (2000) 69.
22. A. C. KARMAKER and J. A. YOUNGQUIST, *J. Appl. Pol. Sci.* **62** (1996) 1147.
23. M. H. B. SNIJDER, M. J. J. M. VAN KEMENADE and H. L. BOS, WO Patent no. 9956936 (1999).
24. H. L. BOS, personal communications.
25. K. GOEL, T. RADIOTIS, R. EISNER, G. SHERSON and J. LI, *Pulp & Paper Canada* **101**(6) (2000) 41.
26. M. J. A. VAN DEN OEVER, H. L. BOS and M. J. J. M. VAN KEMENADE, *J. Appl. Comp. Mater.* **7** (2000) 387.
27. J. BENDZALA and B. V. KOKTA, in Proceedings of 2nd International Wood and Natural Fibre Composites Symposium, Kassel, June 28–29 1999, edited by A. K. Bledzki *et al.* (Institut für Werkstofftechnik, Kassel, 1999) p. 20.
28. X. YUAN, Y. ZHANG and X. ZHANG, *J. Appl. Pol. Sci.* **71** (1999) 333.

Received 13 March
and accepted 1 July 2003