Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Compression Molded Composites from Discarded Nylon 6/Nylon 6,6 Carpets for Sustainable Industries

Gangwei Pan^{1,2}, Yi Zhao², Helan Xu², Xiuliang Hou¹, Yiqi Yang^{1,2,3,4*}

¹Key Laboratory of Science and Technology of Eco-Textiles, Ministry of Education,
Jiangnan University, Wuxi 214122, China

²Department of Textiles, Merchandising & Fashion Design, University of
Nebraska-Lincoln, Lincoln, NE, 68583-0802, USA

³Department of Biological Systems Engineering, University of Nebraska-Lincoln,
Lincoln, NE, 68583-0802, USA

⁴Nebraska Center for Materials and Nanoscience, University of Nebraska-Lincoln,
Lincoln, NE, 68583-0802, USA

* Corresponding author: Yiqi Yang

Phone: 402-472-5197; Fax: 402-472-0640; Email: yyang2@unl.edu

Gangwei Pan Email: pangangwei@gmail.com

Yi Zhao Email: huahuati87@gmail.com

Helan Xu Email: hxu14@unl.edu

Xiuliang Hou Email: hoxiuliang@163.com

ABSTRACT

Discarded carpets with high amount of petroleum-based fibers are usually disposed in landfills, leading to waste of high value petro-polymers and environmental pollution.

A novel method to reuse nylon carpet targeting environmental protection and material saving was developed. Recent studies showed that melt blended nylon carpet

composites by screw extruder had low mechanical properties and disqualified carpet composites in transportation and construction industries. In this research, compression molded composites from discarded nylon 6/nylon 6,6 carpets had good sound absorption, mechanical properties and water stability. As compared with jute/PP composites, the compression molded composites from nylon 6/nylon 6,6 carpets had up to 40%, 59%, 124% and 32%, higher sound absorption, flexural strength, elastic modulus and impact resistance, respectively. Unshredded nylon 6,6 carpet yarns and styrene-butadiene-rubber/calcium-carbonate binders in carpets reinforced nylon 6 and polypropylene, and thus made the composites strong. Styrene-butadiene-rubber particles and multiple interfaces in the multi-component composites endowed compression molded nylon 6/nylon 6,6 carpet composites with good sound absorption.

Developing compression molded carpet composites with good mechanical properties and sound absorption provides a new method of reusing carpets.

Keywords: Nylon carpets reuse; Thermoplastic composites; Sound absorption; Compression molding

1. Introduction

Currently, petroleum-based materials are widely used in automotive and construction industries due to their good mechanical properties, low density and low cost. Non-degradable petro-materials, such as polyamide, polypropylene, and polyurethanes, are largely consumed in vehicle manufacturing and indoor finishing, including car doors (Carlson and Nelson, 1996), body panels (Alcock et al., 2008), car seats (Santos et al., 2007), and indoor partition boards (Liu et al., 2012). Polyamides share around 10.7% market of automobile materials and have an annual consumption of 1,000,000 tons in automotive industry (Lu et al., 2014). However, potential increase in prices of crude oil and more strict regulations towards environmental pollution (Koronis et al., 2013) forced material industries to actively seek environmentally friendly and economically feasible approaches to decrease usage of petroleum-based products (Correia et al., 2011), substitute (Zhao, et al., 2015a), recycle (Lopes et al., 2014) or reuse (Zhao et al., 2015b) petro-products.

Discarded carpet has been the solid waste with the largest amounts. There are 4-6 million tons carpets disposed in landfills worldwide annually (Mihut et al., 2001). Among waste carpets, 65% of carpets are nylon carpets containing thermoplastic polyamide yarns with selling price as high as \$5.5 per kg (Wang and Zhao, 2006) and poorly degradable styrene-butadiene-rubber (SBR) (Subramanian, 2000; Wang, 2010). Reusing waste nylon carpets could save new petro-based polymers, reduce environmental pollution, and therefore promote sustainability of material industries.

Being composed mainly of thermoplastics, nylon carpets could be reused via melt

1 blending. Compared to other reusing methods, such as depolymerization, polyamide
2
3 extraction, incineration and fiber separation, melt blending is preferred due to its low
4
5 cost, easy operation and high reuse rate. Melt blending of nylon carpets requires no
6
7 separation of fibers from carpets, because the shredded carpets were directly extruded
8
9 at about 250-350 °C (Mihut et al., 2001; David et al., 1997), at which, surface nylon
10
11 and backing polypropylene yarns melted, while SBR/CaCO₃ as carpet binders might
12
13 be damaged or decomposed (Radhakrishnan et al., 2007). In addition, the extruded
14
15 composites from shredded nylon carpets had low mechanical properties due to lack of
16
17 fiber reinforcement, and thus were not qualified for industrial applications. Nylon
18
19 carpet yarns, as fiber reinforcement, could effectively increase toughness, durability
20
21 and shrinkage of concrete (Wang et al., 2000), or increase mechanical properties of
22
23 polypropylene sheets (Abraham and George, 2009). Thermoplastic nylon was also
24
25 reinforced by high performance fibers and natural fibers, such as glass fibers
26
27 (Khondker et al., 2005), carbon fibers (Ishak and Berry, 1994), kevlar fibers, kenaf,
28
29 flax, hemp, sisal, and jute (Ozen et al., 2013) for manufacturing high-strength or
30
31 light-weight composites. However, there has been no report regarding developing
32
33 nylon 6 composites reinforced by nylon 6,6 yarns till now. Besides, function of SBR
34
35 and CaCO₃ in melt blended carpet composites have not been investigated.

36
37
38
39
40
41
42
43
44
45
46
47
48
49
50 In this research, we developed nylon 6,6 yarns and SBR/CaCO₃ particles reinforced
51
52 nylon 6/polypropylene composites via compression molding discarded nylon 6/nylon
53
54 6,6 carpets. Nylon 6,6 has higher melting temperature than nylon 6, and therefore
55
56 could preserve their fiber morphology for better reinforcement, when the pressing
57
58
59
60

temperature was between melting temperatures of nylon 6 and nylon 6,6. SBR particles (6-10 wt% of carpet weight) in the carpets could be prevented from damaging or decomposing when compression molded at the melting temperature (around 220 °C) of nylon 6 (Zhang et al., 2005). SBR with low density has high toughness and ability to absorb energy because of its high damping coefficient (Schopp, 2014; Gauthier et al., 2004). In addition, nylon 6 or nylon 6,6 yarns have characteristics of high abrasion resistance, thermal stability, and deformation resistance. Therefore, the composites from nylon 6/nylon 6,6 waste carpets should have good mechanical properties and sound absorption.

2. Experimental

This section is organized as follows: first, composition analysis of nylon carpets and fabrication of composites are described. The characterizations of the nylon 6/nylon 6,6 carpets composites are then provided in detail.

2.1 Materials

Both nylon 6 and nylon 6,6 loop pile carpets were purchased from Carpet Land Inc., Lincoln, NE. There are four basic materials in nylon 6 or nylon 6,6 carpets: nylon 6 or nylon 6,6, polypropylene (PP), styrene butadiene (SBR) and calcium carbonate (CaCO_3). Hydrochloric acid (HCl) (37%) was purchased from EMD Chemicals Inc., Gibbstown, NJ. Jute fibers were purchased from Bast Fibers LLC (Cresskill, NJ) and had an average fineness of 32 denier, tensile strength of 312 MPa, breaking elongation of 1.4% and Young's modulus of 24.3 GPa.

2.2 Composition analysis of nylon carpets

Chemical structures of surface yarns and backing yarns of the nylon carpets were characterized using Fourier Transform Infrared Spectrometry (FTIR). Measurements were taken on a Nicolet 380 (Thermo-Nicolet, Waltham, MA) spectrophotometer through the diffuse reflectance technique from 400 to 4000 cm^{-1} with a resolution of 4 cm^{-1} and 64 scans. The FTIR spectra obtained were analyzed using OMNIC software (Thermo Electron Corp., Waltham, MA). Surface nylon yarns and backing PP yarns were disconnected from the nylon 6 or nylon 6,6 carpets. Adhesives of SBR/ CaCO_3 particles were separated from nylon yarns on a Louet laboratory scale carding machine. To remove CaCO_3 , carpets were soaked in 1% HCl for 24 h and then rinsed in distilled water for 2 h. After dried at 50 °C for 12 h and balanced in a sealed desiccator for 2 h, calcium-free carpets were weighed. The weight ratio of nylon 6: CaCO_3 :SBR:PP in the carpets was 38:40:12:10; weight ratio of nylon 6,6: CaCO_3 :SBR:PP was 40:40:12:8.

2.3 Thermal analysis

Melting temperatures of nylon 6, nylon 6,6 and backing PP yarns were measured using a differential scanning calorimetry (DSC). About 15 mg of each type of yarns were placed in aluminum pans and the DSC Mettler Toledo D822e (Mettler Toledo Inc., Columbus, OH) was operated at a heating rate of 10 °C/min from 50 °C to 280 °C under nitrogen atmosphere. The obtained DSC thermogram was analyzed to determine the melting temperature of nylon 6, nylon 6,6 and PP filaments. SBR and calcium carbonate do not have melting temperature due to their non-thermoplasticity. Melting points of the nylon 6, nylon 6,6 and PP were around 220, 260, and 160 °C,

respectively.

2.4 Fabrication of compression molded composites

The nylon 6 and nylon 6,6 carpets were placed alternatively between two aluminum sheets and pressed in a laboratory-scale press (Carver, Inc., Wabash, IN) preheated to desired temperatures. Since melting temperatures of nylon 6 and nylon 6,6 were around 220 °C and 260 °C, respectively, temperatures of 220, 230, 240 and 250 °C were used to press the composites of nylon carpets, while the holding time periods were 3 and 5 min, respectively. The compression pressure was 10 MPa. Different numbers of nylon 6,6 carpet and nylon 6 carpet layers were prepared to obtain final composites with different ratios of nylon 6 and nylon 6,6. Thickness of the obtained composites was 4.5 ± 0.08 mm.

To investigate effect of CaCO_3 in the compression molded composites from nylon 6/nylon 6,6 carpets (nylon 6/nylon 6,6 composites), carpets were treated in 1% HCl for 24 h and rinsed in water to remove calcium carbonate. After dried at 50 °C for 12 h, carpets without CaCO_3 were obtained. To study SBR effect, polypropylene backing yarns were removed from calcium free carpets, while the separated nylon 6/nylon 6,6 carpet yarns were prepared for 0 wt.% SBR samples as controls.

Jute/PP composites containing 40 wt.% of jute fibers had good mechanical properties (Zou et al., 2010). Thus, jute/PP (40/60) composites were compression molded at 180 °C for 10 min as a control with the same density and thickness as carpet composites. Polypropylene carpets were also compression molded at 180 °C for 10 min as another control with the same density.

2.5 Tensile and flexural properties of compression molded composites

Tensile tests were performed on an MTS machine QTest10 (MTS Corporation, Eden Prairie, MN). Procedures in ASTM D638-03 were followed. Length of the samples was 165 mm, width of the sample was 19 mm, and gage length was 115 mm. Crosshead speed was 5 mm/min. Flexural tests were carried out on an MTS QTest10 tester following procedure of ASTM D790-03, sample size was 7.6 cm x 20.3 cm with 15.2 cm support length, load cell was 500 N, and the crosshead speed was 10 mm/min. Offset yield load was recorded at 2.0 mm.

2.6 Impact resistance of compression molded composites

Impact resistance test was performed on a Plastic Impact Tester by Tinius Olsen model 66 (Tinius Olsen, Horsham, PA) using procedure ASTM D256-03 (ASTM, 2003a). Sample size was 63.5 mm x 10.2 mm. The notch was cut perpendicular to the cross section.

2.7 Dynamic mechanical analysis

The viscoelastic properties of the composites were measured by a dynamic mechanical analyzer DMA Q800 (TA Instrument Inc., New Castle, DE) according to ASTM D4065 standard. The test was carried out by heating the samples from 40 to 145 °C at a rate of 5 °C/min. The samples were tested in a dual cantilever mode at an oscillating amplitude of 15 mm and frequency of 1 Hz.

2.8 Morphology

Cross-sections of the compression molded composites from nylon 6 carpets and nylon 6,6 carpets were observed using a variable pressure scanning electron

1 microscope (VPSEM) Hitachi S3000N (Hitachi, Tarrytown, NY). Samples were
2
3 sputter coated with gold palladium before observing under the SEM. Magnification of
4
5 SEM images was 150×.
6
7

8 9 *2.9 Water Stability*

10
11 The swelling and water absorption were conducted according to ASTM D 570
12
13 standard. Swelling was measured in the thickness direction of the composites. A piece
14
15 of carpet with dimension of about 3 cm x 3 cm was immersed in 20 °C and 50 °C
16
17 water for 1, 3, 5, 7 and 9 days. After removal from the water, the samples were dried
18
19 by patting with a towel before measuring thickness and weight. The data reported are
20
21 average values obtained from five separate samples.
22
23
24
25
26

27 28 *2.10 Sound absorption*

29
30 Sound absorption of the composites were determined according to ASTM standard
31
32 E1050-98 on a Bruel & Kjaer impedance tube (type 4206 A) (Bruel & Kjaer, Norcross,
33
34 GA) at 0 to 6.5 kHz. Three samples with diameter of 63 mm from different
35
36 composites were tested for the sound absorption and the average readings were used
37
38 to plot the absorption coefficient curves.
39
40
41
42
43

44 45 *2.11 Statistical analysis*

46
47 Data generated was analyzed using Tukey's multiple-pair wise comparison using
48
49 SAS program (SAS Institute, Raleigh, NC). A significance level of $\alpha=0.05$ was
50
51 considered as statistically significant. In each figure, data points without significant
52
53 differences were marked with same letters, numbers or symbols.
54
55
56
57

58 59 **3. Results and discussion**

To fabricate compression molded composites from waste nylon 6 and nylon 6,6 carpets, effects of concentration of nylon 6,6 carpets, solid SBR and CaCO₃, and hot pressing conditions on mechanical properties of carpet composites were studied. Dynamic mechanical properties, water stability and sound absorption of the carpet composites were also evaluated. Comparisons of the carpet composites and jute/PP composites in terms of mechanical properties, water stability and sound absorption were finally carried out.

3.1 Effect of concentration of nylon 6,6 carpets on the mechanical properties of the compression molded composites from nylon 6/nylon 6,6 carpets

Compression molded composites from nylon 6/nylon 6,6 carpets (nylon 6/nylon 6,6 composites) had substantially higher mechanical properties than those from either nylon 6 carpets or nylon 6,6 carpets. Compression molded composites from single nylon 6 carpets or nylon 6,6 carpets fabricated at their respective melting temperatures had no fiber reinforcement and therefore showed comparatively low mechanical properties as indicated in Fig. 1. Increasing concentration of nylon 6,6 carpets from 0 to 33% substantially increased impact resistance of molded composites, and slightly increased their tensile properties. Further increasing concentration of nylon 6,6 carpets to 66% increased flexural strength, elastic modulus, and impact resistance of the final compression molded composites by 57%, 262% and 72%, respectively, and slightly increased tensile strength and tensile modulus. Increasing concentration of nylon 6,6 carpets from 33% to 66% increased concentration of nylon 6,6 fibers from 13.2% to 26.4% in the compression molded composites. Therefore,

the unmelted nylon 6,6 fibers as reinforcement in the nylon 6/nylon 6,6 composites enhanced mechanical properties.

Fig. 1

3.2 Effect of hot pressing temperature and holding time on mechanical properties of the compression molded composites from nylon 6/nylon 6,6 carpets

As shown in Fig. 2, prolonging holding time from 3 min to 5 min at 220 °C and 230 °C increased tensile strength, tensile modulus, flexural strength, elastic modulus, and impact resistance of the nylon 6/nylon 6,6 composites. Increasing holding time from 3 min to 5 min at 240 °C and 250 °C decreased impact resistance of the compression molded composites from two types of nylon carpets. The nylon 6/nylon 6,6 composites had higher impact resistance at hot pressing temperature of 230 °C; while the nylon 6/nylon 6,6 composites had higher tensile and flexural strength at hot pressing temperature of 250 °C.

Fig. 2

Increasing compression molding temperature and holding time increased tensile and flexural strength of the nylon 6/nylon 6,6 composites, probably due to increased adhesion between fiber reinforcement and matrix. As shown in Fig. 3, either increasing compression temperature from 220 °C to 250 °C for the same holding time (3 or 5 min) or increasing holding time from 3 min to 5 min at the same compression temperature (230, 240, or 250 °C) improved combination of melted matrix (nylon 6) and unmelted fiber reinforcement (nylon 6,6). It is probably because increasing compression temperature increased softness of nylon 6,6 yarns. Since surface nylon

6,6 yarns had loop piles, unmelted nylon 6,6 yarns could be observed oriented randomly in the composites. SBR with good damping property was probably damaged under high temperature, resulting in decreased toughness and impact resistance of the final composites.

Fig. 3

3.3 Effect of SBR and CaCO₃ on mechanical properties of the nylon 6/nylon 6,6 carpet composites

As shown in Fig. 4, SBR increased impact resistance of the composites from nylon 6/nylon 6,6 carpet yarns, and did not decrease their tensile and flexural properties. CaCO₃ increased flexural strength and elastic modulus, slightly increased tensile modulus and slightly decreased tensile strength of the carpet composites. SBR has good toughness and could absorb more impact energy (Li and Nji, 2007). Therefore, the compression molded composites from nylon 6/nylon 6,6/SBR had better impact resistance than that from nylon 6/nylon 6,6. CaCO₃ particles have high stiffness and thus could increase tensile and flexural modulus of composites. However, CaCO₃ particles decreased interaction between reinforcement and matrix, thus decreased tensile strength of the composites (Qiu et al., 2000). Flexural strength is different from tensile strength, and is affected by surface stiffness of materials. Therefore, adding CaCO₃ could improve flexural strength.

Fig. 4

3.4 Comparisons of the mechanical properties of the compression molded composites from nylon 6/nylon 6,6 carpets, PP carpets, and jute/PP

Table 1 displays mechanical properties of the compression molded composites from nylon 6/nylon 6,6 carpets, PP carpets and jute/PP. Compared to the compression molded composites from PP carpets, the nylon 6/nylon 6,6 composites had 12%, 169%, 309%, and 48% higher tensile strength, flexural strength, elastic modulus, and impact resistance, but 22% lower tensile modulus, respectively. It is probably because the nylon 6/nylon 6,6 composites contain 13% more fiber reinforcement than the PP carpet composites. In addition, nylon 6/PP matrix had higher elasticity than PP matrix. However, reinforcing nylon 6,6 yarns with loop piles were not aligned straightly in the nylon 6/nylon 6,6 composites, and thus cannot substantially strengthen tensile strength of the compression molded composites. Compared to the jute/PP composites, the nylon 6/nylon 6,6 composites had 59%, 124%, and 32% higher flexural strength, elastic modulus, and impact resistance, but similar tensile modulus and lower tensile strength. It is probably because nylon 6,6 yarns had higher tensile strength than jute fibers. Also, nylon 6 and PP as matrix have better flexural properties than only PP. SBR had high damping property and thus endowed the nylon 6/nylon 6,6 carpet composites with good capability of absorbing impact energy. However, fiber reinforcement with loop piles in the nylon 6/nylon 6,6 composites did not effectively share tensile strength when stretching. Therefore, nylon 6/nylon 6,6 composites had higher flexural properties and impact resistance but lower tensile properties than jute/PP composites.

Table 1

3.5 Dynamic mechanical analysis

1 Nylon 6,6 yarns as reinforcement increased elastic modulus and damping properties
2
3 of the nylon 6/nylon 6,6 composites. Dependence of storage modulus (E') and loss
4
5 factor ($\tan \delta$) of the nylon 6/nylon 6,6 composites on temperature are depicted in Fig.
6
7
8
9 5. Increasing the amount of nylon 6,6 carpets increased storage modulus of the nylon
10
11 6/nylon 6,6 composites, indicating increased elasticity of the final composites. This
12
13 was in accordance with the changes in the previous tensile properties of the nylon
14
15 6/nylon 6,6 composites. Increasing temperature decreased storage modulus of the
16
17 compression molded composites with different ratios of nylon 6 and nylon 6,6 carpets
18
19 due to softening of nylon fibers and matrix. Compared to the compression molded
20
21 composites from nylon 6 carpets, substantial decrease in storage modulus of the
22
23 composites reinforced by nylon 6,6 carpets occurred at higher temperature due to the
24
25 high glass transition temperature of nylon 6,6, indicating better thermal stability of
26
27 compression molded composites with reinforcement of nylon 6,6.
28
29
30
31
32
33
34
35

36 Higher value of $\tan \delta$ indicates better damping property. Compression molded
37
38 composites from nylon 6 carpets had higher $\tan \delta$ than pure nylon 6 board due to
39
40 incorporation of solid SBR in carpets. SBR is capable of transforming sound energy
41
42 into heat via vibration and friction of molecular chains, and therefore could increase
43
44 sound absorption of materials. Compared to compression molded composites from
45
46 nylon 6 carpets or nylon 6,6 carpets, compression molded composites from nylon
47
48 6/nylon 6,6 (67/33) carpets and nylon 6/nylon 6,6 (33/67) carpets had higher $\tan \delta$,
49
50 due to high interfacial friction between nylon 6 matrix and nylon 6,6 reinforcement.
51
52
53
54
55
56
57
58 The hot-pressed composites reinforced by nylon 6,6 yarns showed high $\tan \delta$,
59
60
61
62
63
64
65

indicating their good damping properties and consequently good sound absorption.

Fig. 5

3.6 Water stability

As shown in Fig. 6, nylon 6/nylon 6,6 composites had good stability in water at 20 and 50 °C . With prolonged immersing days in 20 °C water from 1 day to 9 days, all the nylon 6/nylon 6,6 composites with different combination ratios had substantially lower increment of thickness and water absorption than jute/PP composites. Among the nylon 6/nylon 6,6 composites with different combination ratios, compression molded composites from nylon 6,6 carpets and nylon 6/nylon 6,6 (33/67) carpets showed comparative higher water stability. This was in accordance with results from Fuzek's research (Fuzek, 1985). On the 9th day, compression molded composites from nylon 6,6 carpets had $1.3 \pm 0.4\%$ increment in thickness and $5.8 \pm 0.3\%$ increment in water absorption, respectively, while jute/PP composites had $8.1 \pm 0.6\%$ increment in thickness and $14.3 \pm 4.4\%$ increment in water absorption, respectively.

In water at 50 °C, compression molded composites from nylon 6,6 carpets still showed much lower increment in thickness and water absorption compared to jute/PP composites during the 9 days. Jute fibers are hydrophilic and swell easily in wet condition (Nagarajan et al., 2013), leading to increased water absorption and thickness of jute reinforced PP composites. In the nylon carpets, nylon 6, nylon 6,6 fibers and SBR solids had substantially lower water absorption than jute fibers, while CaCO_3 as one type of desiccant could absorb moisture. However, in the carpet composites, CaCO_3 particles were discontinued and enclosed by the hydrophobic SBR, and thus

1 were not affected by water. Therefore, the nylon 6/nylon 6,6 composites had
2
3 satisfactory water stability at room temperature and high temperature.
4
5

6 **Fig. 6**

7 *3.7 Sound absorption*

8
9
10 Solid SBR endowed nylon 6/nylon 6,6 composites with good sound absorption. As
11
12 shown in Fig. 7, compression molded composites from nylon 6/nylon 6,6 carpet yarns
13
14 had substantially lower sound absorption compared to the compression molded
15
16 composites from nylon 6/nylon 6,6 yarns and SBR. The composites with SBR had
17
18 good sound absorption at frequency ranging from 3000 to 4500 Hz, but the
19
20 composites without SBR did not. Solid SBR with high damping coefficient could
21
22 absorb sound wave efficiently and thus endowed compression molded composites
23
24 with higher sound absorption (Najib et al., 2011).
25
26
27
28
29
30
31

32 Compared to jute/PP composite, compression molded composites from nylon
33
34 6/nylon 6,6 (33/67) carpets had similar and substantially higher sound absorption at
35
36 frequency lower than 2000 Hz and higher than 4500 Hz. Multiple interfaces in the
37
38 multi-component composites endowed compression molded nylon 6/nylon 6,6 carpet
39
40 composites with good sound absorption (Zhao et al., 2010). Sound absorption at
41
42 frequency lower than 2000 Hz and ranging from 3000 to 5000 Hz are desired for
43
44 some automotive and construction materials because these frequency zones
45
46 correspond with noise on high way (Zou et al., 2010; Ouis, 2001), in airport, grinding
47
48 or welding workshop (Siller et al., 2010). The nylon 6/nylon 6,6 composites could be
49
50 utilized as sound absorption panels for inside applications, such as automotive interior,
51
52 inside construction composites or road construction materials, and therefore could be
53
54
55
56
57
58
59
60
61
62
63
64
65

promising in transportation and construction industries.

Fig. 7

4. Conclusions

Compression molded composites from discarded nylon 6/nylon 6,6 carpets had good sound absorption, mechanical properties and water stability. SBR particles substantially improved sound absorption and impact resistance, and did not decrease tensile and flexural properties of the compression molded composites from nylon 6/nylon 6,6 carpet yarns. CaCO_3 particles could enhance elastic modulus, flexural strength and tensile modulus, but decrease tensile strength of the compression molded carpet composites. Multiple interfaces in the multi-component carpet composites endowed compression molded nylon 6/nylon 6,6 carpet composites with good sound absorption. Compared to jute/PP (40/60) composites, the nylon 6/nylon 6,6 composites showed 40%, 59%, 124%, 32%, and 9% higher sound absorption at medium/high frequency, flexural strength, elastic modulus, impact resistance and water stability, respectively, and 55% and 17% lower tensile strength and modulus, respectively. Therefore, compression molded composites from discarded nylon 6/nylon 6,6 carpets have good composite performances and show potential for transportation and construction industries. This work provides a novel method of reusing carpets and elucidated the advantage of this method.

Acknowledgements

This research was financially supported by Nebraska Environmental Trust (NET project 12-129), National Institute of Food and Agriculture of U.S. Department of

1 Agriculture (Multi-State Project S1054 (NEB 37-037) and USDA Hatch Act), and the
2
3 Agricultural Research Division at the University of Nebraska-Lincoln. Yi and
4
5 Gangwei are grateful to the China Scholarship Council for the financial support. The
6
7 authors appreciate support from Graduate Student Innovation Plan of Jiangsu
8
9 Province (CXZZ13_0751) and the Fundamental Research Funds for the Central
10
11 Universities (JUDCF13021) for Gangwei Pan and John and Louise Skala Fellowship
12
13 at the University of Nebraska-Lincoln for Yi Zhao.
14
15
16
17
18
19

20 **References**

- 21
22 Abraham, T.N., George, K.E., 2009. Studies on recyclable nylon-reinforced PP
23
24 composites: effect of fiber diameter. J. Thermoplast. Compos. Mater. 22(1). 5-20.
25
26
27 Alcock, B., Cabrera, N.O., Barkoula, N.M., Wang, Z., Peijs, T., 2008. The effect of
28
29 temperature and strain rate on the impact performance of recyclable
30
31 all-polypropylene composites. Compos. Part B-Eng. 39(3): 537-547.
32
33
34
35 Carlson, E., Nelson, K., 1996. Nylon under the hood: a history of innovation.
36
37 Automot. Eng. 104(12), 84-89.
38
39
40
41 Correia, J.R., Almeida, N.M., Figueira, J.R., 2011. Recycling of FRP composites:
42
43 reusing fine GFRP waste in concrete mixtures. J. Clean. Prod. 19(15), 1745-1753.
44
45
46 David, D.J., Dickerson, J.L., Sincok, T.F., 1997. Thermoplastic composition and
47
48 method for producing thermoplastic composition by melt blending carpet. U.S.
49
50 Paten. No. 5,591,802.
51
52
53
54
55 Fuzek, J.F., 1985. Absorption and desorption of water by some common fibers. Ind.
56
57 Eng. Chem. Prod. Res. Dev. 24(1), 140-144.
58
59
60
61
62
63
64
65

- Gauthier, C., Reynaud, E., Vassoille, R., 2004. Ladouce-Stelandre L. Analysis of the non-linear viscoelastic behavior of silica filled styrene butadiene rubber. *Polymer*. 45 (8), 2761-2771.
- Ishak, Z.A., Berry, J.P., 1994. Hygrothermal aging studies of short carbon fiber reinforced nylon 6.6. *J. Appl. Polym. Sci.* 51(13), 2145-2155.
- Khondker, O.A., Leong, K.H., Herszberg I., Hamada H., 2005. Impact and compression-after-impact performance of weft-knitted glass textile composites. *Compos. Part A-Appl. S* 36(5), 638-648.
- Koronis, G., Silva, A., Fontul, M., 2013. Green composites: a review of adequate materials for automotive applications. *Compos. Part B-Eng.* 44(1), 120-127.
- Li, G.Q., Nji, J., 2007. Development of rubberized syntactic foam. *Compos. Part A-Appl. S* 38(6), 1483-1492.
- Liu, W., Zhao, H.B., Inoue, Y.K.; Wang, X., Bradford, P.D., Kim, H., Qiu, Y.P., Zhu, Y.T., 2012. Poly (vinyl alcohol) reinforced with large-diameter carbon nanotubes via spray winding. *Compos. Part A-Appl. S* 43 (4), 587-592.
- Lopes, D., Ferreira, M.J., Russo, R., Dias, J.M., 2014. Natural and synthetic rubber/waste-EVA (Ethylene-Vinyl Acetate) composites for sustainable application in the footwear industry. *J. Clean. Prod.* 92, 230-236.
- Lu, Y., Broughton, J., Winfield, P., 2014. A review of innovations in disbonding techniques for repair and recycling of automotive vehicles. *Int. J. Adhes. Adhes.* 50, 119-127.
- Mihut, C., Captain, D.K., Gadala-Maria, F., Amiridis, M.D., 2001. Review: Recycling

- of nylon from carpet waste. *Polym. Eng. Sci.* 41(9), 1457-1470.
- Nagarajan, V., Mohanty, A., Misra, M., 2013. Sustainable green composites: value addition to agricultural residues and perennial grasses. *ACS Sustain. Chem. Eng.* 1(3): 325-333.
- Najib, N.N., Ariff, Z.M., Bakar, A.A., Sipaut,, C.S., 2011. Correlation between the acoustic and dynamic mechanical properties of natural rubber foam: Effect of foaming temperature. *Mater. Design.* 32(2), 505-511.
- Ouis, D., 2001. Annoyance from road traffic noise: a review. *J. Environ. Psychol.* 21(1), 101-120.
- Ozen, E., Kiziltas, A., Kiziltas, E.E., Gardner, D.J., 2013. Natural fiber blend—nylon 6 composites. *Polym. Compos.* 34(4), 544-553.
- Qiu, Y.P., Batchelor, S.D., Jack, P.R., McCord, M.G., 2000. Estimation of the axial tensile modulus of a particle-reinforced composite fiber with variable radius. *Compos. Sci. Technol.* 60(14), 2731-2737.
- Radhakrishnan, C.K., Sujith, A., Unnikrishnan, G., 2007. Thermal behaviour of styrene butadiene rubber/poly (ethylene-co-vinyl acetate) blends. *J. Therm. Anal. Calorim.* 90(1), 191-199.
- Santos, P.A., Spinacé, M.A., Fermoselli, K.K., Paoli, M.A., 2007. Polyamide 6/vegetal fiber composite prepared by extrusion and injection molding. *Compos. Part A-Appl. S* 38(12), 2404-2411.
- Schopp, S., 2014. Functionalized graphene and carbon materials as components of styrene - butadiene rubber nanocomposites prepared by aqueous dispersion

- blending. *Macromol. Mater. Eng.* 299 (3), 319-329.
- Siller, H., Drescher, M., Saueressig, G., Lange, R., 2010. Fly-over source localisation on a boeing 747-400. 3rd Berlin Beamforming Conference, BoBec-2010, February 2010.
- Subramanian, P.M., 2000. Plastics recycling and waste management in the US. *Resour. Conserv. Recycl.* 28(3), 253-263.
- Wang, Y.J., Wu, H.C., Li, V.C., 2000. Concrete reinforcement with recycled fibers. *J. Mater. Civil Eng.* 12(4), 314-319.
- Wang, Y., Zhao, D.M., 2006. Effect of fabric structures on the mechanical properties of 3-D textile composites. *J. Ind. Text.* 35(3), 239-256.
- Wang, Y.J., 2010. Fiber and textile waste utilization. *Waste Biomass Valor.* 1(1), 135-143.
- Zhang, H., Wang, Y., Wu, Y., Zhang, L., Yang, J., 2005. Study on flammability of montmorillonite/styrenebutadiene rubber (SBR) nanocomposites. *J. Appl. Polym. Sci.* 97(3), 844-849.
- Zhao, J., Wang, X.M., Chang, J.M., Yao, Y., Cui, Q., 2010. Sound insulation property of wood–waste tire rubber composite. *Compos. Sci. Technol.* 70(14), 2033-2038.
- Zhao, Y., Zhao, Y.Z., Xu, H.L., Yang, Y.Q., 2015a. A Sustainable Slashing Industry Using Biodegradable Sizes from Modified Soy Protein To Replace Petro-Based Poly (Vinyl Alcohol). *Environ. Sci. Technol.* 49 (4), 2391-2397.
- Zhao, Y.Z., Zhao, Y., Yang, Y.Q., 2015b. Modified soy protein to substitute non-degradable petrochemicals for slashing industry. *Ind. Crop. Prod.* 67 466-474.

Zou, Y., Shah, H., Yang, Y.Q., 2010. Lightweight composites from long wheat straw
and polypropylene web. Bioresour. Technol. 101(6), 2026-2033.

Figure Captions

Fig. 1. Effect of concentration of nylon 6,6 carpets on the mechanical properties of the compression molded composites from nylon 6/nylon 6,6 carpets. Compression molded composites from nylon 6 carpets, nylon 6,6 carpets, nylon 6/nylon 6,6 (67/33) carpets and nylon 6/nylon 6,6 (33/67) carpets were made at 220 °C, 260 °C and 240 °C for 5 min, respectively. Data points with different numbers, letters, or symbols indicate statistically significant difference.

Fig. 2. Effect of hot pressing temperature and holding time on mechanical properties of the compression molded composites from nylon 6/nylon 6,6 (33/67) carpets. Data points with different numbers, letters, or symbols indicate statistically significant difference.

Fig. 3. SEM images of the cross sections of the composites from nylon 6/nylon 6,6 (33/67) carpets compression molded at different temperatures for different times: a) 220 °C and 3 min, b) 220 °C and 5min, c) 230 °C and 3 min, d) 230 °C and 5min, e) 240 °C and 3min f) 240 °C and 5 min, g) 250 °C and 3 min h) 250 °C and 5 min. Magnification of SEM images (a-d) is 150×.

Fig. 4. Effect of SRB and CaCO₃ on the mechanical properties of the compression molded composites from nylon 6/nylon 6,6 carpets. Nylon 6/nylon 6,6 (33/67) carpet yarns with or without SBR, nylon 6/nylon 6,6 (33/67) carpets with or without CaCO₃ were compression molded at 230 °C for 5 min. Data points with different numbers, letters, or symbols indicate statistically significant difference.

Fig. 5. Temperature dependence of storage modulus (E') and loss factor (tan δ) of

1 compression molded composites from nylon 6 carpets, nylon 6,6 carpets and nylon
2
3 6/nylon 6,6 carpets.
4
5

6 **Fig. 6.** Water absorption and thickness increment of the compression molded
7
8 composites from nylon 6/nylon 6,6 carpets and jute/PP (40/60) immersed in 20 °C
9 water for 1 - 9 days a) increment of thickness, b) water absorption; In 50 °C water for
10
11 1 - 9 days c) increment of thickness, d) water absorption. Compression molded
12
13 composites from nylon 6 carpets, nylon 6,6 carpets, nylon 6/nylon 6,6 (67/33) carpets
14
15 and nylon 6/nylon 6,6 (33/67) carpets were made at 220 °C, 260 °C and 230 °C for 5
16
17 min, respectively. Jute/PP composites were compression molded at 180 °C for 10 min.
18
19 Data points with same numbers or letters indicate no statistically significant
20
21 difference.
22
23
24
25
26
27
28
29
30

31 **Fig. 7.** Sound absorption of the compression molded composites from nylon 6/nylon
32
33 6,6 carpets and jute/PP (40/60). Compression molded composites from nylon 6/nylon
34
35 6,6 (33/67) carpet yarns with or without SBR, and nylon 6/nylon 6,6 (33/67) carpets
36
37 were made at 220 °C, 260 °C and 230 °C for 5 min, respectively. Jute/PP composites
38
39 were compression molded at 180 °C for 10 min.
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Table 1 Comparisons of the mechanical properties of the compression molded composites from nylon 6/nylon 6,6 carpets, polypropylene carpets, and jute/polypropylene

Mechanical properties		Nylon 6/nylon 6,6 carpets ^a	Polypropylene carpets ^b	Jute/polypropylene (40/60) ^c
Tensile properties, MPa	Strength	11.1±0.6	9.9±0.5	24.6±1.8
	Modulus	1404.9±209.0	1803.2±151.0	1702.2±445.0
Flexural properties, MPa	Strength	31.7±0.7	11.8±1.3	20.0±1.3
	Modulus	5707.5±331.0	1397.1±796.0	2549.9±205
Impact resistance, J/m		260.9±12.9	176.0±10.5	197.6±17.9

a were nylon 6,6/ nylon 6 (66/34) carpets compression molded at 230 °C for 5 min.

b and c were compression molded at 180 °C for 10 min.

Density of a, b c was 1.3 g/cm³; thickness of a is 4.5 mm, thickness of b is 1.2 mm, thickness of c is 4.0 mm