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Industrial trial of high-quality all green sizes composed of soy-derived protein and glycerol

Helan Xu [a], Maiping Yang [b], Xiuliang Hou [b], Wei Li [a], Xuzhong Su [b], Yiqi Yang [a, c, d, *]

[a] Department of Textiles, Merchandising and Fashion Design, 234, HECO Building, University of Nebraska-Lincoln, Lincoln, NE, 68583-0802, United States
[b] Key Laboratory of Science & Technology of Eco-Textiles, Ministry of Education, Jiangnan University, 1800 Lihu Road, Wuxi, Jiangsu, 214122, China
[c] Department of Biological Systems Engineering, 234, HECO Building, University of Nebraska-Lincoln, Lincoln, NE, 68583-0802, United States
[d] Nebraska Center for Materials and Nanoscience, 234, HECO Building, University of Nebraska-Lincoln, Lincoln, NE, 68583-0802, United States

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ABSTRACT

All-green textile sizes with satisfactory weaving performance and biodegradability were developed from soy protein and glycerol, two major byproducts from soy-based biodiesel production. Polyvinyl alcohol has long dominated textile sizing chemical market due to its excellent sizing performance, despite its non-biodegradability. Efforts have been devoted to replace polyvinyl alcohol for a more sustainable textile industry. Recently, substitute size developed from soy protein after using high amount of petro-based triethanolamine showed acceptable sizing properties. However, triethanolamine was not an eco-friendly additive, due to its petroleum origin and non-biodegradability. In this research, glycerol was used to plasticize soy protein to develop all-green soy size. Glycerol interrupted hydrogen bonds in the soy globulin, allowing them to extend in the films. Resultantly, the soy size films possessed high stretchability and work of rupture. Lab-scale experiments and industrial weaving proved that the all-green soy size had similar or better weaving performance and remarkably better degradability, comparing to polyvinyl alcohol and triethanolamine plasticized soy protein size. For the first time, a possible logarithmic relationship was found between work of rupture of the size film and relative weaving efficiency.

1. Introduction

To mitigate environmental problems caused by non-biodegradable synthetic polymers, using natural macromolecules as replacements is a feasible approach. In textile industry, sizing is an indispensable procedure to endow warp yarns with resistance to abrasion and tension during weaving. Polyvinyl alcohol (PVA) is the non-degradable synthetic polymer that dominates sizing chemical market with 2.5% global share, and leads to severe pollution (Freedoniagroup, 2008; Printing, 2012). PVA contributes to about 40% of COD (chemical oxygen demand) in effluents generated in textile processes (Shaw et al., 2002). Treating the textile effluent in anaerobic sludge for 300 days might still leave up to 85% of PVA intact (Chiellini et al., 2003). Release of the PVA-containing effluent could cause a series of ecological issues, such as, disturbing biological activities of aerobic microorganisms in water and soil (Hamad et al., 2014), and immobilizing heavy metals (Zheng and Wang, 2010). Hoque et al. suggested to use low BOD (biological oxygen demand) synthetic sizes to replace the current sizes (Hoque and Clarke, 2013), while Hasanbeigi and Price proposed using specialty surfactants to simultaneously remove sizes and scour the fabrics to avoid use of enzymes (Hasanbeigi and Price, 2015). Comparing to these methods, elimination of PVA for sizing might be the best approach to fundamentally solve the environmental problem.

Proteins could be suitable alternatives for PVA sizes with multiple advantages. Similar to PVA, proteins readily form films, and contain both hydrophobic and hydrophilic domains, and thus could have good adhesion to both hydrophilic natural fibers and hydrophobic synthetic fibers (Xu et al., 2011; Xu and Yang, 2014). Nevertheless, unlike PVA, proteins are readily biodegraded in nature (Dastidar and Netravali, 2013). Currently, soy protein, wheat gluten (Chen, et al., 2013a), feather keratin (Chen, et al., 2013b) and

* Corresponding author. Department of Biological Systems Engineering, 234, HECO Building, University of Nebraska-Lincoln, Lincoln, NE, 68583-0802, United States.
E-mail addresses: hxu14@unl.edu (H. Xu), yangmaiping@sina.com (M. Yang), houxiuliang@163.com (X. Hou), louisa.lee@vip.163.com (W. Li), suxuzhong@jiangnan.edu.cn (X. Su), yyang2@unl.edu (Y. Yang).

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corn protein showed good potential for textile sizing applications in lab-scale experiments (Reddy et al., 2013). These proteins are byproducts with abundance and low cost from production of edible oil, meat or starch, and thus, have good potential for large-scale textile utilization.

Among all the proteins, soy protein, which was widely investigated for packaging applications (Garrido et al., 2014; Guerrero et al., 2015), and could be readily composted (Leceta et al., 2014), showed the best sizing performance. After plasticized with high amount of triethanolamine (TEA), soy protein size could demonstrate similar or better protection to yarns, comparing to PVA size in industrial weaving trials (Zhao et al., 2015a, 2015b). However, TEA with BOD_5/COD (5-days biological oxygen demand/chemical oxygen demand) ratio, the standard determines biodegradability, of less than 0.01 is regarded as non-biodegradable (Mohr et al., 2010). Non-renewability and high cost of TEA could also hinder the industrial utilization of soy protein based sizes. Currently, TEA is derived from non-renewable petroleum, and sold at prices higher than $1300/ton (Zauba, 2015).

With remarkably lower cost, better renewability, better health, safety and degradation profiles, glycerol, the polyol that could be derived from soy, has the potential to replace TEA in developing all-green soy sizes (Shen et al., 2015; Xu et al., 2015). Glycerol with BOD_5/COD ratio of 0.87, which is higher than 0.5, is considered completely biodegradable (Hardesty, 2008). As the main byproduct accounts for up to 20% of biodiesel production, the current selling price for glycerol is around $50/ton (Quispe et al., 2013). Due to rapid expansion of biodiesel industry, the price of glycerol could be further decreased. Moreover, glycerol with HMIS (Hazardous Materials Identification System) health, flammability and reactivity ratings of 1, 0, 0 is safer and more convenient to handle and use, comparing to TEA with relevant ratings of 2, 1, 1 (Hardesty, 2008; Spectrum, 2015).

In this research, potential of using all-green soy size composed of soy protein and glycerol to replace PVA for textile sizing was evaluated via lab-scale characterizations and industrial-scale sizing and weaving experiments. Tensile properties of the size films and add-on were measured and correlated with the relevant weaving efficiencies. Desizing and degradation properties of the all-green soy sizes were evaluated and compared with TEA plasticized soy size and commercial PVA size.

2. Experimental

2.1. Materials

Polyester yarns (11s), soy protein isolate and commercial PVA size were used. Chemicals including glycerol, NaOH and triethanolamine (TEA) were purchased from Sinopharm Chemical Reagent Co. Ltd. (Shanghai, China). JFC was purchased from Demei Chemical, Wuxi, China. Defoamer was supplied by Shengshi Chemical, Wuhan, China. The commercial PVA size were composed of 80% of polyvinyl alcohol, 12% of starch and other additives.

2.2. Preparation of all-soy size solution and films

Soy protein was dispersed in NaOH solution at concentrations varying from 4 wt% to 10 wt%. The concentration of NaOH was in the range of 0.5 wt% and 1.5 wt%. Glycerol was added into the dispersion at different ratios (15 wt%–35 wt%) based on the weight of soy protein. The mixture was heated under 100 °C for 30 min with stir.

2.3. Viscosity of all-soy size solution

Penetration of sizing solution into the yarns also played an important role during sizing process, thereby viscosity of the sizing solution needed to be analyzed. The concentration of soy protein was controlled at 6 wt%. Apparent viscosity of the obtained all-soy size solution was measured on a NDJ-79 rotary viscometer (Changji Geological Equipment, Shanghai, China) at 90 °C with shear rate of 750 r/min.

2.4. Tensile properties of all-soy size films

Solutions of all-soy sizes (6 wt%) prepared under different conditions were poured in Teflon coated plates, and air dried to obtain films. Before testing, the films were balanced under standard condition (65% Relative Humidity, 21 °C) for at least 24 h. Tensile properties, including tensile strength, % elongation and work of rupture of size films were measured on a tensile testing machine (HD026NS, Hongda Textile Machinery, Nantong, China) according to ASTM standard D882. The dimension of the films was 1 cm × 10 cm and the crosshead speed was 50 mm/min. For each condition, more than 20 samples obtained from at least three different films were tested. Thickness of each piece of film was measured with a thickness gauge (Changzhou No.2 Textile Machinery, Changzhou, China) at three different spots.

2.5. Lab-scale sizing

The yarns were padded through the 90 °C sizing solution with one-dip-one-nip method on a lab-scale sizing machine (GA 392, Jiangyin Tongyuan Mechinery, Wuxi, China) and wound onto a spindle at 30 m/min. The padding pressure was adjusted to the highest level. The sized yarns were heated under 80 °C for 7 min. The sized yarns were balanced under standard condition (65% Relative Humidity, 21 °C) for at least 24 h. The add-on% was calculated based on weight of yarns before and after sizing as below in Equation (1).

$$\%\ \text{add-on of size} = \frac{\text{mass of sized yarn} - \text{mass of unsized yarn}}{\text{mass of unsized yarn}} \times 100\% \quad (1)$$

2.6. Observation of cross section of sized and unsized PET yarns

A Hitachi SU1510 Scanning Electron Microscope (SEM, Tokyo, Japan) was used to observe the distribution of cross sections of sized and unsized PET yarns. The samples were mounted on conductive adhesive tape, sputter coated with gold palladium and observed under a voltage of 5 kV. The magnification was 250×.

2.7. Abrasion resistance of sized yarns

Abrasion resistance of balanced sized and unsized yarns was measured on an abrasion testing machine (G552, Zweigle Instruments, Sonnenbergstrasse, Switzerland). The % add-on was controlled to ±0.5% for fair comparison. At least 20 yarns (each with length of 1 m) were tested for each sizing condition.

2.8. Industrial sizing and weaving trial

Selected conditions were used to prepare all-soy sizing solution with protein concentration of 10 wt%. The warped polyester yarns was sized in the solution at 90 °C with a double-dip-double-nip