Journal of Industrial and Engineering Chemistry xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Industrial and Engineering Chemistry

journal homepage: www.elsevier.com/locate/jiec

Cardboard boxes as raw material for high-performance papers through the implementation of alternative technologies: More than closing the loop

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A R T I C L E I N F O

Article history:
Received 30 January 2017
Received in revised form 20 March 2017
Accepted 14 May 2017
Available online xxx

Keywords:
Enzymatic refining
Enzymatic hydrolysis
Cellulose nanofibers
Recycled fibers
Mechanical properties

A B S T R A C T

The aim of this work is to develop high-performance papers from recovered cardboard boxes. To tackle this objective, cardboard boxes were enzymatically refined and subsequently reinforced with CNF. Results revealed that although cardboard boxes are usually used for test-liner paper production, they could be used for high-performance applications. In this sense, stronger papers than common test-liner were produced through the use of harmless techniques for fibers. In terms of circular economy, the proposed combined approach goes further than closing the loop: new markets can be achieved or lighter papers could be used, leading to significant resources savings.

Introduction

Paper recycling is becoming one of the main activities of paper mills [1–3]. In this sense, 54% of the worldwide fibers used for paper production come from recovered papers [1,3,4], and in some paper grades, such as containerboard and newsprints, the rate of recycled fibers can be even higher [5]. Moreover, several strategies to enhance mechanical properties, decrease the paper basis weight, or replace fibers for fillers, are currently under investigation. The environmental awareness of society, together with petroleum depletion, has resulted in an intensive use of paper as substitute of oil-based materials in several sectors during last years. Although cellulose is a renewable and abundant raw material, society is not consuming it sustainably [3], and this is why recycling is gaining interest and prominence. However, some processes involved in paper recycling cause fiber deterioration due to hornification phenomena, reducing thus life span of paper products. Traditionally, this loss is compensated submitting the fibers to a mechanical refining stage, promoting again swelling and, thus, recovering bonding capacity. However, this process causes irreversible structural damages that, in the long term, also reduces paper products' life span [6]. The deterioration of fibers and the increase of fines fraction involve in turn a reduction on pulp suspension dewatering. Therefore, the search of new fiber treatments to reduce or replace mechanical refining has been one of the main challenges during the last years. This search is aimed by giving to recycled slurries the capacity to produce papers with the technical requirements by different approaches such is the case of using virgin fibers from agroforestry waste [7,8], enzymatic refining, adding nanocelluloses, or new chemical-based bonding strategies [3].

One of the most relevant methodologies has been the incorporation of cellulose nanofibers (CNF) into the pulp suspensions [9–11]. Several investigations proved the incorporation of cellulose nanofibers as an effective treatment to improve mechanical properties of paper [10,12–15]. Moreover, cellulose nanofibers do not cause morphological damages on fibers, fact that leads to an increase on the number of the recycling cycles [16,5]. Many of the studies have used TEMPO-mediated CNF [17] but, however, recent works have shown the effectivity of enzymatic hydrolysis or mechanical fibrillation as an alternative to produce CNF in terms of paper reinforcing potential [15,18–21].

Another approach is the addition of endo-β-1,4-glucanases in paper slurries to increase the swelling of fibers and, thus, their bonding capacity. Enzymes were already known in paper industry for pulping or deinking purposes. Several previous studies [1,22] showed that enzymatic refining significantly increased the mechanical properties of paper with no negative effects on pulp drainability.

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http://dx.doi.org/10.1016/j.jiec.2017.05.016

For all the above, the aim is to develop high-performance papers from recovered cardboard boxes by means of producing recycled pulp, enzymatically refine it and, finally, to incorporate cellulose nanofibers in bulk. The effects on ultimate paper properties and pulp drainability will be studied. In addition, the obtained results will be extrapolated to a real papermaking process using existing data from a specific paper mill.

Materials and methods

Materials

Saica Natur Noroeste S.A. (Zaragoza, Spain) kindly provided different papers and pulps from their manufacturing process (Fig. 1), including: pulp from the head box (3), paper from before the size press (2) and end product (liner-grade paper at pope, 1). These materials were used to determine the process parameters and the minimum requirements of the produced papers.

Used cardboard boxes were kindly supplied by Gros Mercat S. A. (Spain). Enzymatic refining was carried out with a commercial endo-β-1,4-glucanase enzyme cocktail (Serzym 50), supplied by SERTEC–20 S.L. (Spain), with an activity of 84,000 CMU/g at 60 °C and at pH 4.8 over a carboxymethylcellulose (CMC) substrate. Cellulose nanofibers were prepared from bleached kraft hardwood pulp (BKHP), kindly supplied by Torraspapel S.A. (Spain), and its enzymatic hydrolysis was performed with another enzyme cocktail (Novozyme 476) provided by Novozymes A/S (Denmark), containing 2% of endo-β-1,4-glucanases with an activity factor of 4500 CNF-CA/g of cellulose (tested over a CMC substrate). All the reagents required for the experimentation of this work were acquired at Sigma Aldrich (Spain) and were used as received.

Cellulose nanofibers production

Enzymatic hydrolysis was carried out according to the methodology reported by Tarrés et al. [15]. BKHP was dispersed at 1.5 wt% in water in a laboratory pulper for 30 min at 3000 rpm. Then, the fibers were filtered until 10 wt% consistency and refined in a PFI mill for 4000 revolutions. This process was carried out to swell the fibers and thus to promote the activity of enzymes. Briefly, refined fibers were suspended in water again (until reaching a pulp consistency of 5 wt%), and 0,1 N HCl was dropped until achieving a pH of 5. Then, the suspension was heated until 50 °C under constant stirring to avoid temperature gradients. At this step, the enzyme cocktail was dropped into the suspension and stirred for 4 h. The enzymatic process was stopped by heating the suspension to 80 °C for 15 min, where the enzyme used suffers its denaturation. Enzyme dosage was set at 320 g/Tn. The enzymatically hydrolyzed pulp then was washed with distilled water and kept at 4 °C.

The treated suspension (1 wt% consistency) was gradually homogenized in a PANDA Plus laboratory homogenizer (Gea Niro Soavi, Italy) following the sequence of three passes at 300 bar, three passes at 600 bar and three passes at 900 bar. The main reason of increasing gradually the pressure was to avoid clogging in the pressure chambers.

Cardboard boxes pulping

Used cardboard boxes were first torn in small pieces to be disintegrated in a pilot scale pulper equipped with a helicoidal rotor, with a maximum capacity of 50 L of suspension. In our experiment, 2 kg (dry weight) were disintegrated at 10 wt% consistency at 60 °C during 20 min in presence of 1% of sodium hydroxide to further promote fiber individualization. The rotational speed of the rotor was set at 1100 rpm. Finally, excess water was removed by centrifugation until achieving a consistency of 25 wt% and the pulp was stored in hermetic plastic bags at 4 °C.

Mechanical refining

Cardboard boxes pulp at 10 wt% was refined in a PFI mill (NPFI 02 Metrotec S.A.) at 500, 1000 and 1500 revolutions.

Enzymatic refining

Enzymatic refining was performed according to Delgado-Aguilar et al. [5], taking advantage of the process optimization reported in that work. In this sense, the enzyme dosage was set at 350 g/Tn of dry pulp at 5 wt% consistency at pH 4.8 and stirred for 30 min, maintaining the temperature at 60 ± 3 °C.

Cellulose nanofibers addition

Enzymatically refined pulp was dispersed in water in a pulp disintegrator for 90 min at 3000 rpm. CNF were added to the slurry during this disintegration process. The amount of CNF was calculated to obtain 1.5, 3 and 4.5% CNF-reinforced paper sheets. After disintegration, pulps were stirred for 30 min at 500 rpm in presence of 0.5% and 0.8% of cationic starch and colloidal silica, respectively. These two last additives were added as retention agents. The neat paper, without CNF, did not contain neither cationic starch nor colloidal silica.

Pulps characterization

All cardboard boxes pulps, including neat, mechanically refined, enzymatically refined and containing CNF were characterized in terms of morphology and drainability.

The morphological analysis was carried out using a MorFi Compact analyzer (TechPap, France) equipped with a CCD video camera. About 30,000 fibers were analyzed by the software MorFi v9.2. Among other parameters, this software was able to calculate mean fiber length, mean diameter and fines percentage (fibers shorter than 76 µm). All characterizations were performed in triplicate.

Drainability was measured by means of Schopper — Riegler degree (°SR), which was determined in a Schopper — Riegler Tester (mod. 95587 PTI) following ISO standard 5267-1 [23].

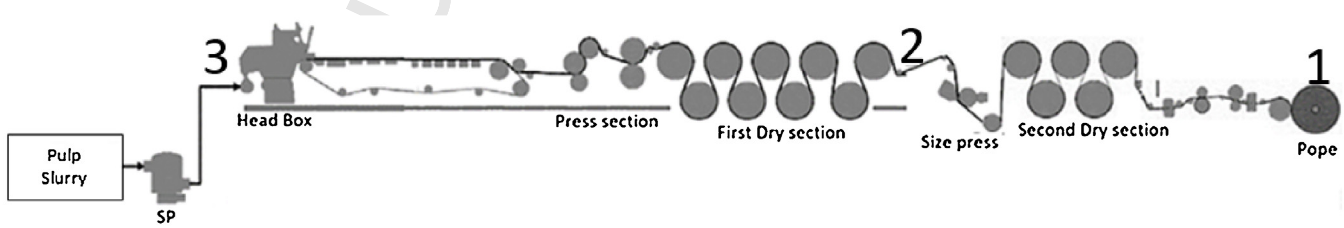

Fig. 1. Liner paper manufacturing process.

Please cite this article in press as: Q. Tarrés, et al., Cardboard boxes as raw material for high-performance papers through the implementation of alternative technologies: More than closing the loop, J. Ind. Eng. Chem. (2017), http://dx.doi.org/10.1016/j.jiec.2017.05.016