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Effects of Recycled Fiber Fines on Hand Sheet Properties of Different Unbeaten and Beaten Pulps

Utjecaj finih recikliranih vlakana na svojstva ručno izrađenog papira od nemljevene i mljevene celuloze

Original scientific paper • Izvorni znanstveni rad
Received – prispjelo: 4. 2. 2019.
Accepted – prihvaćeno: 15. 7. 2020.
*UDK: 630*862.3; 630*862.42*
https://doi.org/10.5552/drvind.2020.1904

ABSTRACT • *In this study, 5, 10, and 15 % secondary fines of recycled pulp were added to unbeaten and beaten (28 ºSR) samples of recycled pulp, Turkish Calabrian pine (Pinus brutia Ten.) kraft pulp, and European aspen (Populus tremula L.) kraft pulp. The effects of the addition of fiber fines on hand sheets properties were evaluated. The addition of fiber fines to the unbeaten pulps improved the strength properties of hand sheets. The roughness of hand sheets was also decreased with the addition of fines. When fiber fines were added to the beaten pulps, the type of pulp strongly affected the paper strength properties. The strength properties of beaten pulps of Turkish Calabrian pine and European aspen were decreased with the addition of fiber fines, while the strength properties of beaten pulps of recycled pulp were increased. On the other hand, the air permeance of unbeaten and beaten samples was decreased with the addition of fiber fines. Consequently, the addition of fines to unbeaten and beaten pulps had a more pronounced effect on European aspen kraft pulp and recycled pulp than on Turkish Calabrian pine kraft pulp. Also, the strength of paper made of unbeaten recycled pulp with the addition of 15 % fines was higher than that of fines-free beaten recycled pulp.*

Keywords: *Populus tremula L.; Pinus brutia Ten.; recycled fiber; kraft; fines; pulp and paper properties*

SAŽETAK • *U radu je opisano istraživanje u kojemu je mljevenoj i nemljevenoj (28 °SR) recikliranoj celulozi, kraft celulozi od brucijskog bora (Pinus brutia Ten.) i kraf celulozi od jasike (Populus tremula L.) dodano 5, 10 i 15 % sekundarnih finih vlakana reciklirane celuloze. Utvrđeni su učinci dodavanja finih vlakana na svojstva ručno izrađenih papira. Dodatak vlakana nemljevenoj celulozi pridonio je povećanju čvrstoće i smanjenju hrapavosti ručno izrađenih papira. Pri dodavanju vlakana mljevenoj celulozi velik je utjecaj na čvrstoću papira imala vrsta celuloze. Čvrstoća mljevene celuloze od brucijskog bora i jasike dodatkom vlakana se smanjila, dok se čvrstoća mljevene reciklirane celuloze povećala. Usto, dodatkom vlakana smanjena je propusnost zraka mljevenih i nemljevenih uzoraka. Posljedično, učinak dodavanja vlakana mljevenoj i nemljevenoj celulozi bio je veći za kraft celulozu od jasike i recikliranu celulozu nego za kraft celulozu od brucijskog bora. Također, čvrstoća papira od mljevene reciklirane celuloze s dodatkom 15 % vlakana bila je veća od čvrstoće papira od mljevene celuloze bez dodatka vlakana.*

Ključne riječi: *Populus tremula L; Pinus brutia Ten; reciklirana vlakna; kraft; fina vlakna; svojstva celuloze i papira*

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1 INTRODUCTION
1. UVOD

The fines are defined as the cellulosic fiber fraction of a fiber suspension which can pass through a 200 mesh (200 wires per inch) screen with a 14.5 % open area and 76.2 μm diameter in Bauer McNett classifier (Meyers and Nanko, 2005). Therefore, the fines are sometimes named the P200 (Taipale, 2010). Also, the maximum and minimum fine length is detected as 0.2 mm and 0.072 mm, respectively (Meyers and Nanko, 2005). On the other hand, fines are extensively evaluated as all particles smaller than wood fibers present in the furnish (Krogerus *et al.,* 2002a). In accordance with this definition, fines may consist of various particles such as parts of wood cells, inorganic pigments and fillers, colloidal resins and latex, salt crystals, precipitates, deposits, etc. (Taipale, 2010).

Fines are generally categorized as primary and secondary fines. Primary fines are present in the pulp prior to refining, whereas secondary fines arise during refining. Primary fines consist mainly of ray cells, parenchyma cells and middle lamella lignin. (Bäckström *et al.,* 2008). Primary or secondary layers of cell wall are delaminated during refining, and they became detached from the fibers. So-formed secondary fines incline to be slender and flexible (Chen *et al.,* 2009).

Primary and secondary fines contribute differently to the mechanical properties of paper (Htun and de Ruvo, 1978). For a given fines content, the effect of secondary fines on strength properties of the pulp are more pronounced than those of primary fines (Hawes and Doshi, 1986; Bäckström *et al.,* 2008). Primary fines have a higher lignin content than kraft pulp fibers (Retulainen *et al.,* 2002). Secondary fines come mostly from the fiber surface during refining, and they have a higher lignin content compared to the fibers, but lower compared to the primary fines (Lindström and Nordmark, 1978). Secondary fines have about twice as much fibrils as primary fines (Krogerus *et al.,* 2002b). In chemical pulp, the cellulose and hemicellulose content of fines is higher than in the fiber fraction (Taipale, 2010). Also, the crystallinity of fines was lower compared to the long fiber fraction (Waterhouse and Omori, 1993).

The term *fines* is extensively used in the papermaking process, and fines have a significant influence on the behavior of the wet web and on all the properties of the final sheet (Bäckström *et al.,* 2008). Fines can help to fill in the voids between fibers in the paper structure. Fibrillar fines can bring fibers into closer contact with each other during the consolidation and drying of sheet (Johansson, 2008). In other words, fines increase inter-fiber bonding by acting as a bridge between fibers (Bäckström *et al.,* 2008; Retulainen *et al.,* 2002; Silveira *et al.,* 1996). If there are more bonds, the segments between bonds are shorter and there are fewer free loops (Retulainen *et al.,* 1993). Thus, a denser, stronger, and more uniform product is formed (Lin *et al.,* 2007). On the other hand, high levels of fines can make it more difficult to dewater the wet sheet (Liu *et al.,* 2001; Krogerus *et al.,* 2002b; Seth, 2003; Hubbe and Heitmann, 2007). The difficulty in dewatering produces a deceleration in the manufacturing process (Htun and de Ruvo, 1978; Taipale, 2010), causing an increase in the amount of energy required to dry the paper (Chen *et al.,* 2009).

The effect of fines on paper properties of mechanical pulps (Mohlin, 1977; Moss and Retulainen, 1997; Lu, 1999; Luukko and Paulapuro, 1999; Rundlöf, 2002; Vainio *et al.,* 2007; Asikainen *et al.,* 2010; Chen *et al.,* 2013; Moberg *et al.,* 2014) and chemical pulps (Kibblewhite,1972; Lobben, 1977; Htun and de Ruvo, 1978; Hartman, 1984; Przybysz and Czechowski, 1985; Retulainen *et al.,* 1993, 2002; Retulainen, 1997; Ferreira *et al.,* 2000; Krogerus *et al.,* 2002a; Taipale *et al.,* 2010) have been extensively studied. However, the influences of the addition of fines on the paper properties of the recycled pulps have seldom been reported. In general, fines (primary and secondary fines) of the recycled pulps are considered as undesirable for the strength properties, because the fines are produced from dried and hornified fibers. Mancebo and Krokoska (1985) noted that the fines of recycled pulp have a negative impact on paper strength as they act as filler material. The fines indicate the loss of bonding ability due to hornification, and it is claimed that the effect is irreversible even with refining. Also, Szwarcsztajn and Przybysz (1977) found that fines and fibers obtained from recycled paper hornified, causing the loss of the paper strength. Quite the contrary, Hawes and Doshi (1986) noted that fines of recycled paper are effective in increasing the strength of hand sheets made from recycled paper. The recycled fines act like virgin fines, so the removal of fines causes a reduction in the bonding index (Htun and de Ruvo, 1978; Klungness and Sanyer, 1981; Rushdan, 2005). Recently, the effect of fine content and quality on the recycled chemical pulps was studied by Lee *et al.,* (2011).

In this study, the effects of the addition of secondary fines to recycled pulp (5, 10, and 15 %) on hand sheet properties were evaluated. Three types of pulp were used, recycled pulp, Turkish Calabrian pine (*Pinus brutia* Ten.) kraft pulp, and European aspen (*Populus tremula* L.) kraft pulp, in order to determine the relationship between the addition of fines and the type of pulp. Also, two types of freeness level were used, unbeaten pulp and 28 ºSR pulp, in order to investigate the effect of fines on pulps at different freeness levels.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Unbleached recycled pulps used in this study were obtained from Oyka pulp mill in Turkey. Turkish Calabrian pine and European aspen wood samples were obtained from Bartin province of Turkey. The wood samples were debarked and chipped to 3 cm × 1.5 cm × 0.5 cm size for kraft pulping. The air dried wood chips were stored in dry conditions. The kraft cooking conditions of both species are given in Table 1.

Cooking was carried out in a 15-L electrically heated laboratory cylindrical-type rotary digester. After

Table 1 Kraft cooking conditions of both species
Tablica 1. Uvjeti kuhanja kraft celuloze od obje vrste drva

Tree species *Vrste drva*	**Active alkali** *Aktivna lužina* %	**Sulfidity** *Sulfidnost* %	**Cooking temp** *Temperatura kuhanja,* °C	**Cooking time to max. temp** *Vrijeme kuhanja do najviše temperature* min	**Cooking time at max. temp** *Vrijeme kuhanja na najvišoj temperaturi* min	**Liquor/ wood ratio** *Omjer otapalo/ drvo*
Turkish Calabrian pine *brucijski bor*	18	25	170	90	75	4/1
European aspen / *jasika*	16	20	170	90	60	4/1

digestion, pulps were washed to remove black liquor and were disintegrated in a laboratory-type pulp mixer. Disintegrated pulps were screened using a Somerville-type pulp screen with 0.15-mm slotted plate (TAPPI T 275). Pulps were then beaten to 28 ºSR in a Valley Beater according to TAPPI T 200. Kappa number (TAPPI T 236), screened yield (TAPPI T 210), viscosity (SCAN-CM 15-62), and freeness of pulps (ISO 5267-1) were determined according to relevant methods.

The secondary fines were acquired by refining the recycled pulps in a Valley beater for 7 h with loading according to TAPPI T 200. The refined pulp was fractionated in a Bauer–McNett classifier (TAPPI T 233) into five fractions: R30, R50, R100, R200, and R300 mesh. Fines passing through a 200 mesh screen and retained by a 300 mesh were used as paper additive. The fiber morphology of the different pulps and secondary fines was determined with light microscope. Some pulp properties and fiber morphology of different pulps and fines are given in Table 2.

Different mixtures of unbeaten and beaten pulps of different fibers (Turkish Calabrian pine, European aspen, and recycled fiber) and secondary fines were used to prepare hand sheets and to determine the effect of fines on paper strength properties. Four levels of fines were used: 0, 5, 10, and 15 % of the dry weight of the fibers (Table 3). More than 15 % fines were not used due to difficulty in dewatering and drainage during papermaking. Freeness of fines added pulps (ISO 5267-1) was also determined. The hand sheets (70 g/m^2) made by a Rapid-Kothen Sheet Former (ISO 5269-2) were conditioned (TAPPI T 402). Tensile index (ISO 1924-3), burst index (TAPPI T 403), tear index (TAPPI T 414), roughness (ISO 8791-2), apparent density (TAPPI T 220), and air permeance (ISO 5636-3) of the hand sheets were also determined.

The data of hand sheet properties were subjected to analysis of variance (ANOVAs) and Duncan test at a 0.05 probability level. The same lower case letter in all figures denotes that the difference in the average values

Table 2 Some pulp properties and fiber morphology of different pulps and fines
Tablica 2. Svojstva celuloze i morfologija vlakana od različitih vrsta celuloze i finih vlakana

Sample / *Uzorak*	**Viscosity** *Viskoznost* cm^3/g	**Kappa number** *Kappa broj*	**Fiber lengthmm** *Duljina vlakana* mm	**Fiber width** *Širina vlakana* µm	**Lumen width** *Širina lumena* µm	**Cell wall thickness** *Debljina stanične stijenke* µm
Turkish Calabrian pine kraft pulp *kraft celuloza od brucijskog bora*	888	31.4	2.90	54.50	28.50	13.00
European aspen kraft pulp *kraft celuloza od jasike*	1121	32.5	1.18	24.25	10.50	6.88
Recycled pulp / *reciklirana celuloza*	580	31.2	1.66	28.00	10.75	8.63
Fines / *fina vlakna*	-	-	0.21	23.50	11.00	6.25

Table 3 Fiber and fines mixing ratios used in this study
Tablica 3. Omjer vlakana i finih vlakana u smjesi rabljenoj u ovom istraživanju

Code *Oznaka*	**Mixing ratio** / *Omjer miješanja*
A0	100 % Turkish Calabrian pine kraft pulp / *100 % kraft celuloze od brucijskog bora*
A5	95 % Turkish Calabrian pine kraft pulp + 5 % fines / *95 % kraft celuloze od brucijskog bora + 5 % finih vlakana*
A10	90 % Turkish Calabrian pine kraft pulp + 10 % fines / *90 % kraft celuloze od brucijskog bora+ 10 % finih vlakana*
A15	85 % Turkish Calabrian pine kraft pulp + 15 % fines / *85 % kraft celuloze od brucijskog bora + 15 % finih vlakana*
B0	100 % European aspen kraft pulp / *100 % kraft celuloze od jasike*
B5	95 % European aspen kraft pulp + 5 % fines / *95 % kraft celuloze od jasike + 5 % finih vlakana*
B10	90 % European aspen kraft pulp + 10 % fines / *90 % kraft celuloze od jasike + 10 % finih vlakana*
B15	85 % European aspen kraft pulp + 15 % fines / *85 % kraft celuloze od jasike + 15 % finih vlakana*
C0	100 % recycled pulp / *100 % reciklirane celuloze*
C5	95 % recycled pulp + 5 % fines / *95 % reciklirane celuloze + 5 % finih vlakana*
C10	90 % recycled pulp + 10 % fines / *90 % reciklirane celuloze + 10 % finih vlakana*
C15	85 % recycled pulp + 15 % fines / *85 % reciklirane celuloze + 15 % finih vlakana*

of properties among the compared groups was statistically insignificant.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Pulp freeness
3.1. Sposobnost odvodnjavanja celuloze

Drainage, an important parameter in the paper manufacturing, restricts the production efficiency of a paper machine (Norell *et al.,* 1999). Important factors influencing wetness end drainage are pulp composition, average fiber length, fiber length distribution, fines content, charge level on the stock, and degree of stock hydration (Paradis *et al.,* 2002). Fines have a detrimental effect on dewatering of the pulp suspension due to their high water holding capacity (Htun and de Ruvo, 1978; Hartman, 1984; Waterhouse and Omiri 1993; Liu *et al.,* 2001; Hubbe and Heitmann 2007; Chen *et al.,* 2009; Taipale *et al.,* 2010; Lee *et al.,* 2011; Lindqvist *et al.,* 2011). Lu (1999) noted that the pulp containing 40 % of fines drains 10 times more slowly than fines-free pulp. Kibblewhite (1972) reported that the pulp freeness strongly affected the quality and quantity of fines. Seth (2003) noted that pulp freeness drastically decreases with the addition of fines. The effect of the addition of fines on pulp freeness of unbeaten and beaten pulps is given in Table 4. The pulp freeness was decreased with increasing fines ratio.

3.2 Tensile index
3.2. Vlačni indeks

Tensile index is one of the basic strength properties of paper. The effect of the addition of fines on tensile index of the unbeaten and beaten pulps was more pronounced in European aspen kraft pulp and recycled pulp than in Turkish Calabrian pine kraft pulp (Figure 1). On the other hand, the effect of the addition of fines on tensile index of unbeaten pulps was more prominent than of beaten pulps. The effect was more pronounced at a higher level of addition. Lobben (1977) reported that the fines of chemical pulps had a considerable effect on strength properties depending on fiber type and freeness level of pulp. The effect of the addition of fines was greater for a eucalypt kraft pulp than for a pine kraft pulp. Also, the effects were more pronounced in unbeaten pulps of long fiber fraction.

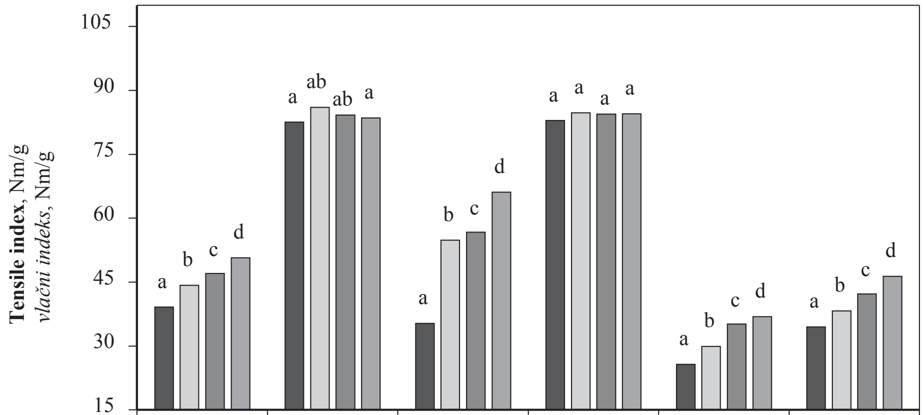
Table 4 The effect of fines addition on pulp freeness of unbeaten and beaten pulps
Tablica 4. Utjecaj dodatka finih vlakana na sposobnost odvodnjavanja mljevene i nemljevene celuloze

Code *Oznaka*	**Unbeaten pulp** *Nemljevena celuloza* ºSR	**Beaten pulp** *Mljevena celuloza* ºSR
A0	13	28
A5	15	41
A10	16	50
A15	27	59
B0	13	28
B5	17	38
B10	22	45
B15	28	51
C0	20	28
C5	25	35
C10	34	43
C15	37	55

As can be seen in Figure 1, the addition of 5, 10, and 15 % secondary fines to Turkish Calabrian pine unbeaten kraft pulps resulted in the increase in tensile index of 13.14 %, 20.22 %, and 29.68 %, respectively ($p<0.05$). The addition of 5, 10, and 15 % secondary fines to unbeaten European aspen kraft pulp resulted in the increase in tensile index of 55.22 %, 60.49 %, and 85.07 %, respectively. The addition of 5, 10, and 15 % secondary fines to recycled unbeaten pulps resulted in the increase in tensile index of 16.29 %, 36.80 %, and 43.49 %, respectively ($p<0.05$). Tensile index did not deteriorate with increasing addition of fines, and the more fines in hand sheet caused better bonding. These findings can be attributed to the increase in fiber-fiber bonding area due to the filling of inter-fiber gaps in the paper structure by fines. On the other hand, the addition of fines to fiber suspension results in the decreased average fiber length. However, tensile index of hand sheets did not decrease. This may be due to increasing fiber-fiber bonding thanks to the presence of fines, which overcompensated for the impaired tensile index caused by the decreasing average fiber length.

Previous studies revealed that the recycled fines act like virgin fines, causing an increase in the bonding index (Hawes and Doshi, 1986; Htun and de Ruvo, 1978; Klungness and Sanyer, 1981; Rushdan, 2005). In this study, the recycled fines did not act as a filler as found in other studies (Szwarcsztajn and Przybysz, 1977; Manchebo and Krokoska, 1985). Asikainen *et al.,* (2010) noted that tensile index increased with the addition of 10 % and 20 % primary fines to CTMP from 22.5 Nm/g to 26.8 Nm/g and 31.0 Nm/g, respectively. Retulainen (1997) reported that, by adding 3 % kraft fines to a kraft long fiber fraction, the tensile strength increases by 18 %. On the other hand, Lindqvist *et al.,* (2011) and Ferreira *et al.,* (2000) noted that the removal of fines resulted in decreased tensile index. The positive effect of the addition of fines on tensile index of hand sheets has been reported by several authors (Bäckström *et al.,* 2008; Retulainen, 1997; Mohlin, 1977; Hartman, 1984; Mancebo and Krokoska, 1985; Retulainen *et al.,* 1993; Waterhouse and Omiri, 1993; Waterhouse, 1994; Rundlöf, 2002; Vainio *et al.,* 2007; Taipale *et al.,* 2010; Zaytseva, 2010; Lee *et al.,* 2011).

In the beaten samples of Turkish Calabrian pine and European aspen kraft pulp, the addition of fines had not a statistically significant effect on tensile index of hand sheets ($p>0.05$) (Figure 1). The tensile index of recycled beaten pulps increased with the addition of 5, 10, and 15 % of secondary fines by 10.96 %, 22.47 %, and 34.47 %, respectively ($p<0.05$). These results can be attributed to better response to beating of virgin (flexible) fibers than recycled (stiff) fibers due to differences in their fiber morphology. Tensile index of



	Pine unbeaten *nemljevena celuloza od bora*	Pine beaten *mljevena celuloza od bora*	Aspen unbeaten *nemljevena celuloza od jasena*	Aspen beaten *mljevena celuloza od jasena*	Recycled unbeaten *nemljevena celuloza od recikliranog drva*	Recycled beaten *mljevena celuloza od recikliranog drva*
Control	39.12	82.53	35.33	82.92	25.71	34.49
5% fines	44.26	86.03	54.84	84.70	29.89	38.27
10% fines	47.03	84.21	56.70	84.44	35.17	42.24
15% fines	50.73	83.56	66.07	84.49	36.89	46.38

Figure 1 Effect of fines addition on tensile index of hand sheets of unbeaten and beaten pulps
Slika 1. Utjecaj dodatka finih vlakana na vlačni indeks papira od nemljevene i mljevene celuloze

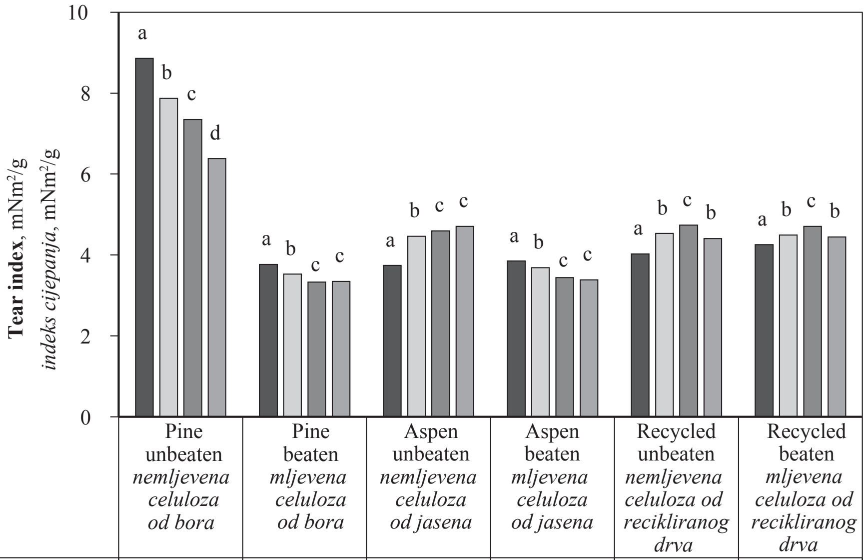
Turkish Calabrian pine and European aspen pulp samples was increased with beating to 28 ºSR by 110.97 % (from 39.12 Nm/g to 82.53 Nm/g) and 134.70 % (from 35.33 Nm/g to 82.92 Nm/g), respectively, while in recycled pulp samples this increase was only 34.15 % (from 25.71 Nm/g to 34.49 Nm/g). The lower tensile index increase in beaten recycled pulp was compensated with the addition of fines (Figure 1). On the other hand, tensile index of unbeaten recycled pulp (36.89 Nm/g), with the addition of 15 % fines, was higher than that of fines-free beaten recycled pulp (34.49 Nm/g).

3.3 Tear index
3.3. Indeks cijepanja

The effect of the addition of fines on tear index of hand sheet depends on the type of pulp and the amount of fines added. Tear index of Turkish Calabrian pine unbeaten kraft pulps decreased with the addition of 5, 10, and 15 % secondary fines by 11.17 %, 17.04 %, and 27.99 %, respectively ($p<0.05$). Quite the contrary, tear index of European black pine unbeaten kraft pulp and recycled unbeaten pulp increased with the addition of 5, 10, and 15 % secondary fines by 19.25 %, 22.99 %, 25.93 % and 12.40 %, 17.61 %, 9.42 %, respectively ($p<0.05$). These results showed that the addition of fines had a positive effect on tear index of hand sheets obtained from short fibers compared to long fibers (Figure 2). This result is consistent with previous work (Hawes and Doshi, 1986), which showed that tear index increased with the addition of 20 % secondary fines to recycled pulp from 8.7 mNm^2/g to 9.95 mNm^2/g. Ferreira *et al.,* (2000) noted that tear index increased from 9.5 mNm^2/g to 10.2 mNm^2/g when fines were removed from fiber suspension. The positive correlation between tear index and fines addition has also been reported by several authors (Mohlin, 1977; Hartman, 1984; Lee *et al.,* 2011). Quite the contrary, tear index decreased with the addition of fines (Waterhouse, 1994).

Tear index of Turkish Calabrian pine unbeaten kraft pulp decreased with the increasing addition of fines, while it increased for European aspen unbeaten kraft pulp and unbeaten recycled pulp (Figure 2). This result may be explained as follows. Tear index depends on several factors, including fiber length, wall thickness, inter-fiber bonding, fiber strength, etc. Fines contribute to tear index by increasing inter-fiber bonding due to their good flexibility and large surface area. Thus, tear index of short fiber European aspen and recycled pulp samples was increased with the addition of fines. As fines content increased, the average fiber length and wall thickness decreased. Also, the larger gaps between long fibers of Turkish Calabrian pine were not sufficiently filled by fines, resulting in lower inter-fiber bonding than samples without fines. Hence, tear index of Turkish Calabrian pine sample was decreased with the addition of fines.

In beaten pulps, tear index of Turkish Calabrian pine and European aspen kraft pulps decreased with the addition of 5, 10, and 15 % secondary fines by 6.37 %, 11.67 %, 11.14 % and 4.15 %, 10.65 %, 11.95 %, respectively ($p<0.05$) (Figure 2). Quite the contrary, the addition of 5, 10, and 15 % secondary fines to recycled unbeaten pulp resulted in the increase in tear index of 5.39 %, 10.56 %, and 4.46 %, respectively ($p<0.05$). These results showed that the effect of fines addition on tear index was more prominent than beating. For example, tear index of recycled unbeaten pulp was increased by beating up to 28 ºSR from 4.03 mNm^2/g to 4.26 mNm^2/g. However, with the addition of 15 % fines, tear



	Pine unbeaten	Pine beaten	Aspen unbeaten	Aspen beaten	Recycled unbeaten	Recycled beaten
Control	8.86	3.77	3.74	3.85	4.03	4.26
5% fines	7.87	3.53	4.46	3.69	4.53	4.49
10% fines	7.35	3.33	4.60	3.44	4.74	4.71
15% fines	6.38	3.35	4.71	3.39	4.41	4.45

Figure 2 Effect of fines addition on tear index of hand sheets of unbeaten and beaten pulps
Slika 2. Utjecaj dodatka finih vlakana na indeks cijepanja papira od nemljevene i mljevene celuloze

index of recycled unbeaten pulp was increased from 4.03 mNm²/g to 4.41 mNm²/g. On the other hand, when 15 % fines were added to unbeaten recycled pulp (4.41 mNm²/g), tear index was higher than that of fines-free beaten recycled pulp (4.26 mNm²/g).

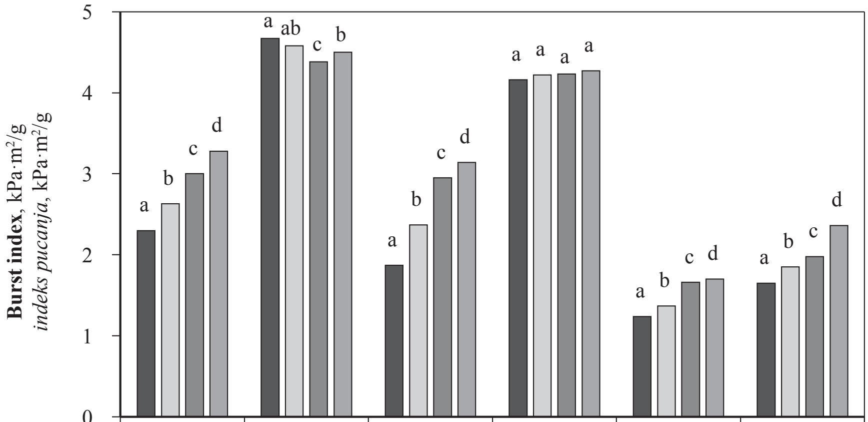
3.4 Burst index
3.4. Indeks pucanja

In unbeaten pulps of all types of pulp, the addition of fines caused an increase in burst index (Figure 3). The highest increase in burst index was determined in European aspen kraft pulp. The addition of 5, 10, and 15 % secondary fines to Turkish Calabrian pine kraft pulp resulted in the increase in burst index of 14.34 %, 30.43 %, and 42.60 %, respectively ($p<0.05$). The increase of burst index in European aspen kraft pulp and recycled pulp was found to be 26.73 %, 57.75 %, 67.91 % and 10.48 %, 33.87 %, 37.09 %, respectively ($p<0.05$). The burst index of hand sheets increased linearly with increasing proportion of fines (Figure 3). These findings can be ascribed to increasing inter-fiber bonding due to higher surface area of fines than fibers. The surface area of fines ranges from 10 to 50 m²/g, while the surface area of fibers is around 1 m²/g (Retulainen *et al.,* 1993).

Hawes and Doshi (1986) reported that burst index increased with the addition of 20 % secondary fines to recycled pulp from 1.39 kPam²/g to 3.86 kPam²/g. Ferreira *et al.*, (2000) noted that burst index decreased from 6.9 kPam²/g to 5.0 kPam²/g when fines were removed from fiber suspension. Other authors reported that burst index increases with the addition of fines (Mohlin, 1977; Htun and de Ruvo, 1978; Klungness and Sanyer, 1981; Hawes and Doshi, 1986; Waterhouse, 1994; Bäckström *et al.,* 2008).

In beaten pulps, the addition of 5, 10, and 15 % secondary fines to Turkish Calabrian pine kraft pulp resulted in burst index loss of 1.93 %, 6.21 %, and 3.64 %, respectively ($p<0.05$). Quite the contrary, the addition of secondary fines to European aspen kraft pulp resulted in a statistically insignificant increase of burst index, ($p>0.05$). On the other hand, an increase in burst index of 12.12 %, 20 %, and 43.03 %, respectively ($p<0.05$), was observed in recycled pulp with the addition of 5, 10, and 15 % secondary fines. In beaten pulps, the relationship between burst index and fines addition is drastically different depending on the type of pulp (Figure 3). These results can be explained by increased inter-fiber bonding that acts as a bridge of fines between hornified and stiff recycled fibers. Thus, the strength of paper made from recycled fibers with low bonding capacity increases with the addition of fines. Along with the beating, the decrease in fiber length and the improved fiber flexibility and plasticity increase the bonded area between fibers. Thus, the paper structure became more compact and burst index increased. Also, the mobility of fines may be lower in the wet sheet of collapsed, swollen, and externally fibrillated fibers compared to the more open structure in a wet sheet of unbeaten fibers (Hartman, 1984).

In the virgin pulp samples, freeness level of pulp had a more significant effect on burst index than the fines content. For example, burst index of Turkish Calabrian pine kraft pulp was increased with beating up to 28 ºSR from 2.30 kPam²/g to 4.67 kPam²/g. However, burst index of Turkish Calabrian pine unbeaten kraft pulp was increased from 2.30 kPam²/g to 3.28 kPam²/g with the addition of 15 % fines. In the recycled pulp sample, the effect of freeness level of pulp and fines addition on burst index was similar. Burst index of recy-



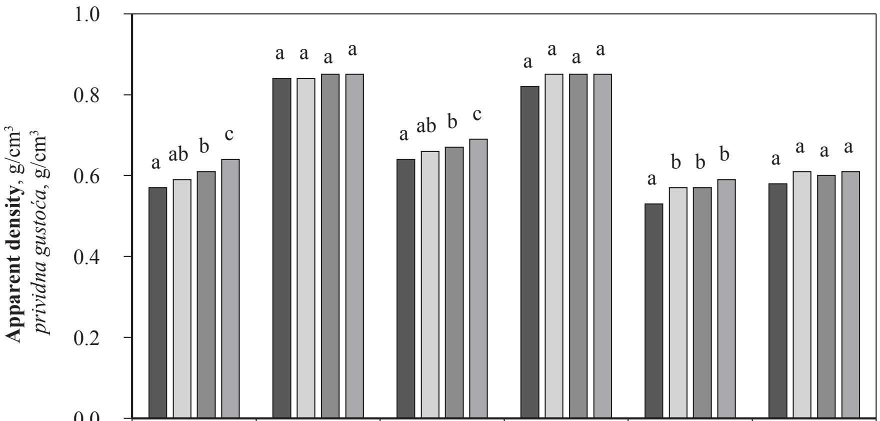
	Pine unbeaten *nemljevena celuloza od bora*	Pine beaten *mljevena celuloza od bora*	Aspen unbeaten *nemljevena celuloza od jasena*	Aspen beaten *mljevena celuloza od jasena*	Recycled unbeaten *nemljevena celuloza od recikliranog drva*	Recycled beaten *mljevena celuloza od recikliranog drva*
Control	2.30	4.67	1.87	4.16	1.24	1.65
5% fines	2.63	4.58	2.37	4.22	1.37	1.85
10% fines	3.00	4.38	2.95	4.23	1.66	1.98
15% fines	3.28	4.50	3.14	4.27	1.70	2.36

Figure 3 Effect of fines addition on burst index of hand sheets of unbeaten and beaten pulps
Slika 3. Utjecaj dodatka finih vlakana na indeks pucanja papira od nemljevene i mljevene celuloze

cled pulp was increased with beating up to 28 ºSR from 1.24 kPam²/g to 1.65 kPam²/g. However, burst index of recycled unbeaten pulp was increased from 1.24 kPam²/g to 1.70 kPam²/g with the addition of 15 % fines.

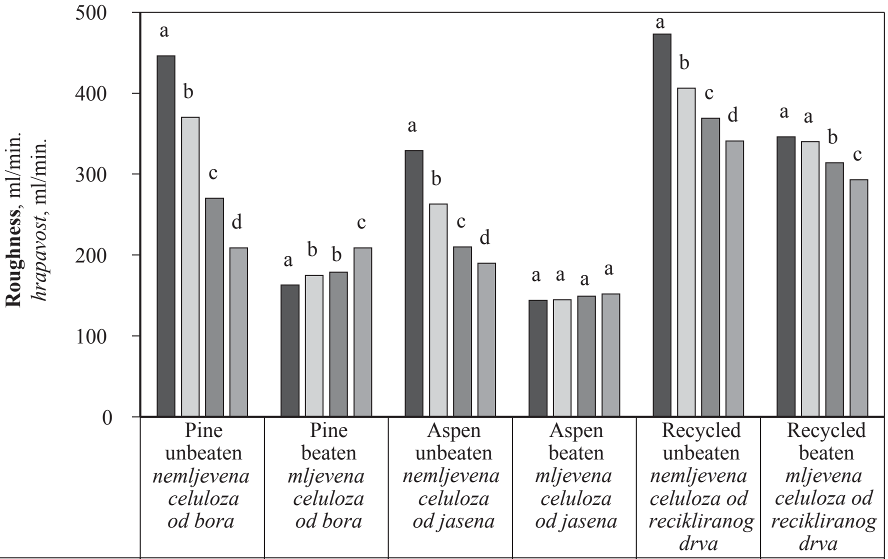
3.5 Apparent density
3.5. Prividna gustoća

As the addition of fines increased, the apparent density of the hand sheets increased linearly as shown in Figure 4. The highest increase in apparent density was determined in Turkish Calabrian pine kraft pulp. The addition of 5, 10, and 15 % secondary fines to Turkish Calabrian pine kraft pulp resulted in an increase in apparent density of 3.51 %, 7.02 %, and 12.28 %, respectively (p<0.05). An increase in apparent density of 3.13 %, 4.68 %, 7.81 % and 7.55 %, 7.55 %, 11.32 %, respectively (p<0.05), was determined in European aspen kraft pulp and recycled pulp. This is consistent



	Pine unbeaten *nemljevena celuloza od bora*	Pine beaten *mljevena celuloza od bora*	Aspen unbeaten *nemljevena celuloza od jasena*	Aspen beaten *mljevena celuloza od jasena*	Recycled unbeaten *nemljevena celuloza od recikliranog drva*	Recycled beaten *mljevena celuloza od recikliranog drva*
Control	0.57	0.84	0.64	0.82	0.53	0.58
5% fines	0.59	0.84	0.66	0.85	0.57	0.61
10% fines	0.61	0.85	0.67	0.85	0.57	0.60
15% fines	0.64	0.85	0.69	0.85	0.59	0.61

Figure 4 Effect of fines addition on apparent density of hand sheets of unbeaten and beaten pulps
Slika 4. Utjecaj dodatka finih vlakana na prividnu gustoću papira od nemljevene i mljevene celuloze



	Pine unbeaten	Pine beaten	Aspen unbeaten	Aspen beaten	Recycled unbeaten	Recycled beaten
Control	446	163	329	144	473	346
5% fines	370	175	263	145	406	340
10% fines	270	179	210	149	369	314
15% fines	209	209	190	152	341	293

Figure 5 Effect of fines addition on roughness of hand sheets of unbeaten and beaten pulps
Slika 5. Utjecaj dodatka finih vlakana na hrapavost papira od nemljevene i mljevene celuloze

with previous work (Lu 1999), which showed that the sheet density increased with the addition of 20, 30, and 40 % fines to mechanical pulp from 0.372 g/cm^3 to 0.511 g/cm^3, 0.555 g/cm^3 and, 0.563 g/cm^3, respectively.

Fines cause an increase in sheet density by filling the voids between the fibers. In addition, Hawes and Doshi (1986) noted that the sheet density increased with the addition of 20 % secondary fines to recycled pulp from 0.549 g/cm^3 to 0.629 g/cm^3. On the other hand, Ferreira *et al.,* (2000) reported that sheet density decreased when fines were removed from fiber suspension from 0.767 g/cm^3 to 0.708 g/cm^3. The positive correlation between fine addition and sheet density has also been reported by other authors (Mohlin, 1977; Hartman, 1984; Hawes and Doshi, 1986; Waterhouse and Omiri, 1993; Lu, 1999; Bäckström *et al.,* 2008; Lee *et al.,* 2011; Moberg *et al.,* 2014).

In beaten pulps of all types of pulp, the addition of fines had a statistically insignificant effect ($p>0.05$) on apparent density of hand sheets (Figure 4). These results indicated that the freeness level of pulp is more important for the apparent density than the content of fines. For example, apparent density of European aspen kraft pulp was increased with beating up to 28 ºSR from 0.64 g/cm^3 to 0.82 g/cm^3. Whereas, apparent density of European aspen kraft pulp with the addition of 15% fines was increased from 0.64 g/cm^3 to 0.69 g/cm^3.

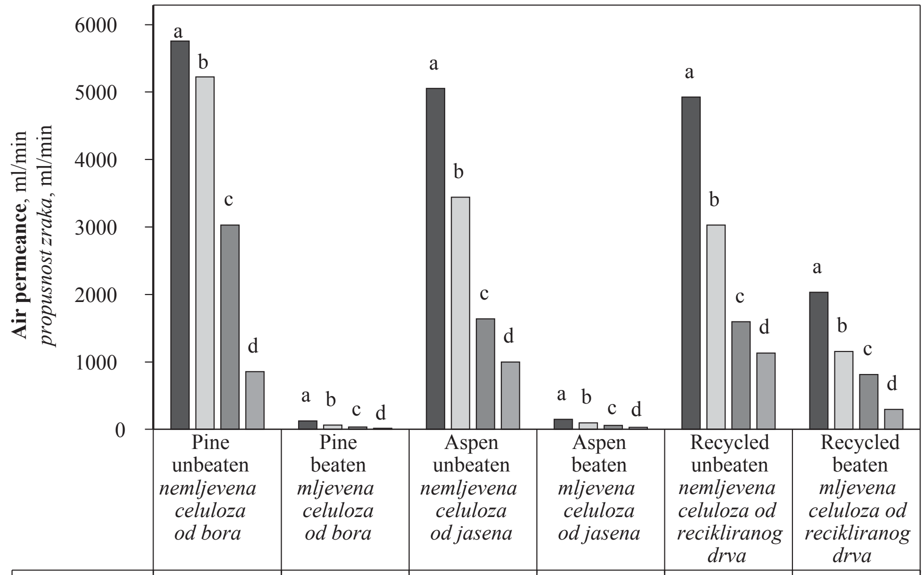
3.6 Roughness
3.6. Hrapavost

Hand sheet roughness was significantly affected by fines. In unbeaten pulps of all types of pulp, roughness of hand sheets decreased with the addition of fines (Figure 5). The effect of fines addition on roughness of Turkish Calabrian pine hand sheets was more pronounced than that of other pulps. In Turkish Calabrian pine unbeaten kraft pulp, the addition of 5, 10, and 15 % secondary fines resulted in a decrease in roughness of 17.04 %, 39.46 %, and 53.14 %, respectively ($p<0.05$). Roughness decrease in European aspen kraft pulp and recycled pulp was found to be 20.06 %, 36.17 %, 42.25 % and 14.16 %, 21.98 %, 27.90 %, respectively ($p<0.05$). These results can be explained by the fact that fines act as a filler material in the paper structure. Positive effect of fines on surface smoothness was also reported by Waterhouse and Omiri (1993) and Lu (1999).

In beaten pulps of Turkish Calabrian pine kraft pulp, hand sheet roughness increased with the addition of 5, 10, and 15 % secondary fines by 7.36 %, 9.82 %, and 28.22 %, respectively ($p<0.05$). Quite the contrary, the addition of 5, 10, and 15 % fines to recycled beaten pulp resulted in a roughness decrease of 1.73 %, 9.25 %, and 15.32 %, respectively ($p<0.05$). The effect of fines on hand sheet roughness of European aspen kraft pulp was statistically insignificant ($p>0.05$) (Figure 5).

3.7 Air permeance
3.7. Propusnost zraka

In unbeaten pulps of all types of pulp, air permeance of hand sheets decreased dramatically with increasing addition of fines (Figure 6). In Turkish Calabrian pines samples, the effect of fines on air permeance was more prominent than in other pulps. In Turkish Calabrian pine unbeaten kraft pulp, the addition of 5, 10, and 15 % fines caused an increase in air permeance of 9.24 %, 47.35 %, and 85.11 %, respectively ($p<0.05$). Air permeance of hand sheets of European aspen unbeaten kraft pulp and recycled unbeaten pulp decreased by 31.91 %, 67.54 %, 80.20 %, and



	Pine unbeaten *nemljevena celuloza od bora*	Pine beaten *mljevena celuloza od bora*	Aspen unbeaten *nemljevena celuloza od jasena*	Aspen beaten *mljevena celuloza od jasena*	Recycled unbeaten *nemljevena celuloza od recikliranog drva*	Recycled beaten *mljevena celuloza od recikliranog drva*
Control	5756	126	5052	151	4925	2032
5% fines	5224	62	3440	95	3028	1156
10% fines	3030	36	1640	60	1597	815
15% fines	857	17	999	32	1133	298

Figure 6 Effect of fines addition on air permeance of hand sheets of unbeaten and beaten pulps
Slika 6. Utjecaj dodatka finih vlakana na propusnost zraka papira od nemljevene i mljevene celuloze

38.52 %, 67.57 %, 76.99 %, respectively ($p<0.05$), with the addition of 5, 10, and 15 % fines. Increasing the amount of fines in furnish also leads to decreased air permeance. Fines cause the decrease in air permeance by filling the voids of the fiber network. In other words, air permeance (Figure 6) tends to decrease with the addition of fines due to better conformity, reduction of spaces between fibers and increase of resistance to air flow (Yasumura *et al.,* 2012). Decreasing air permeance with the addition of fines can also be attributed to increasing apparent density with the addition of fines. At higher apparent densities, the pores in the sheet begin to close up due to better bonding. This led to the decrease in air permeance. Reduced air permeance retards moisture escape and slows the drying rate. Both factors contribute to decreased paper machine productivity (Seth, 2003).

Lu (1999) reported that air permeance decreased with the addition of 20, 30, and 40 % fines to mechanical pulp from 2538 ml/min. to 922 ml/min., 124 ml/min., and 52 ml/min. respectively. Asikainen *et al.,* (2010) noted that air resistance (Gurley method) increased with the addition of 10 % and 20 % primary fines to CTMP from 2.8 sec. to 7.7 sec. and 22.2 sec., respectively. On the other hand, Ferreira *et al.,* (2000) noted that air permeance decreased when fines were removed from fiber suspension from 54.5 ml/min. to 26 ml/min. Htun and de Ruvo (1978) reported that the removal of fines resulted in increased air permeability. The effect of fines on hand sheet air permeance has also been reported previously (Hartman, 1984; Hawes and Doshi, 1986; Waterhouse and Omiri, 1993; Lu, 1999; Seth, 2003; Hubbe and Heitmann, 2007; Lee *et al.,* 2011).

Regarding unbeaten pulp samples, air permeance of beaten pulps decreased with the addition of fines (Figure 6). There was a linear correlation between fines addition ratio and air permeance of hand sheets. Air permeance of beaten kraft pulps of Turkish Calabrian pine and European aspen decreased by 50.79 %, 71.43 %, 86.51 %, and 37.08 %, 60.26 %, 78.80 %, respectively ($p<0.05$) with the addition of 5, 10, and 15 % fines. In the recycled beaten pulps, the addition of 5, 10, and 15 % fines caused an decrease in air permeance of 43.11 %, 59.89 %, and 85.33 %, respectively ($p<0,05$). For virgin pulps, the pulp freeness level had a more significant effect on air permeance than the content of fines, and vice versa for recycled pulp. For example, when the 15 % fines were added to Turkish Calabrian pine kraft pulp, hand sheet air permeance decreased from 5756 ml/min. to 857 ml/min. However, hand sheet air permeance was decreased with beating up to 28 ºSR from 5756 ml/min. to 126 ml/min. On the other hand, in the recycled pulp, hand sheet air permeance was decreased with beating up to 28 ºSR from 4925 ml/min. to 2032 ml/min, while hand sheet air permeance was decreased from 4925 ml/min. to 1133 ml/min with the addition of 15 % fines.

4 CONCLUSIONS
4. ZAKLJUČAK

Unless they are specifically removed, fines are present in any paper and influence its properties. In order to optimize the paper strength, it is important to control the fines content. In this study, the effect of fines on hand sheet properties was determined on different types of pulp (pine kraft pulp, aspen kraft pulp, and recycled pulp), as well as different pulp freeness levels (unbeaten pulp and 28 ºSR pulp). Based on the results, it can be concluded that secondary fines of recycled pulp have a significant impact on hand sheet properties. The effect of fines on hand sheet properties correlates strongly with the type of pulp, freeness level of pulp, and amount of fines addition. The effect of the addition of fines on hand sheet properties of unbeaten pulps was more prominent than of beaten pulps. On the other hand, effect of fines on hand sheet properties of the unbeaten and beaten pulps was dependent on the type of pulp. In the unbeaten and beaten pulp samples, the effect of fines addition was more pronounced in European aspen kraft pulp and recycled pulp than in Turkish Calabrian pine kraft pulp. The differences in hand sheet properties became more visible with the increasing fines content.

The highest paper strength increase rates were obtained from unbeaten pulps with 15 % fines. Paper strength of 15 % fines added unbeaten recycled pulp was higher than that of fines-free beaten recycled pulp. This demonstrates that it is possible to reduce the beating level by adding fines to recycled pulp. The results suggested that fines can be used as reinforcement for papermaking to improve the paper properties. In the papermaking process, fines can also be used as a potential control variable in order to obtain desirable paper properties. When the beating level and fines addition ratio are determined properly, refining energy requirements can be reduced, and paper strength can be improved.

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