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Effect of Basis Weight on Paper Properties of Scots Pine and European Black Pine Kraft Pulp

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Research Article

Abstract − The physical, optical, and mechanical characteristics of handsheets made from kraft pulps of Scots pine (*Pinus sylvestris* L.) and European black pine (*Pinus nigra* Arn.) in basis weight ranging from 50 to 125 g/m^2 (15 g/m^2 intervals) were assessed in this study. The thickness, bulk, apparent density, opacity, burst strength, tear strength, tensile strength, stretch and tensile energy absorption (TEA) properties of papers obtained in different grammages were evaluated. The results showed that basis weight of handsheets had a significant effect of examined properties of handsheets. In both pulp samples, when the handsheet basis weight increased, the tensile strength, burst strength, tear strength, apparent density and opacity of the handsheets increased while bulk decreased. In all basis weight values, Scots pine handsheets had higher tensile and burst strengths, opacity, and apparent density than those of European black pine handsheets. Therefore, Scots pine pulps can be more suited for packaging purposes. This study shows that kraft pulps obtained from different wood species can be optimized and desired paper properties can be achieved by appropriate basis weight selections.

Keywords – *Scots pine, European black pine, basis weight, kraft pulp, paper properties*

Sarıçam ve Karaçam Kraft Kağıt Hamurunun Kağıt Özellikleri Üzerine Gramajın Etkisi

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Araştırma Makalesi

Öz − Bu çalışmada, sarıçam (*Pinus sylvestris* L.) ve karaçam (*Pinus nigra* Arn.) kraft hamurlarından 50 ile 125 g/m^2 (15 g/m^2 aralıklı) gramajda üretilen deneme kağıtlarının fiziksel, optik ve mekanik özellikleri değerlendirilmiştir. Farklı gramajlarda elde edilen kağıtların kalınlık, hacimlilik, yoğunluk, opaklık, patlama sağlamlığı, yırtılma sağlamlığı, kopma sağlamlığı, uzama ve kopma enerji absorpsiyonu özellikleri değerlendirilmiştir. Sonuçlar, deneme kağıtlarının gramajının incelenen kağıt özellikleri üzerinde önemli bir etkiye sahip olduğunu göstermiştir. Her iki kağıt hamuru örneğinde de, deneme kağıdı gramajı arttıkça, kağıtların kopma sağlamlığı, patlama sağlamlığı, yırtılma sağlamlığı, yoğunluk ve opaklığı artarken hacimliliği azalmıştır. Tüm gramaj değerlerinde, sarıçam deneme kağıtlarının kopma ve patlama sağlamlıkları, opaklığı ve yoğunluğu karaçam deneme kağıtlarına göre daha yüksektir. Bu yüzden, sarıçam kraft kağıtları paketleme amaçları için daha uygun olabilir. Bu çalışma, farklı ağaç türlerinden elde edilen kraft hamurlarının optimize edilebileceğini ve uygun gramaj seçimleri ile istenilen kağıt özelliklerine ulaşılabileceğini göstermektedir.

Anahtar Kelimeler – *Sarıçam, karaçam, gramaj, kraft kağıt hamuru, kağıt özellikleri*

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1. Introduction

Paper has long been one of the most significant mediums for communication and information exchange in human history. Paper is used in a wide range of applications, including packaging and printing. The mechanical and physical properties of paper are determined by several factors during the production process, one of which is the paper's basis weight (grammage). The basis weight of the paper (g/m²) refers to the mass per unit area. The basis weight of paper plays a critical role in determining the main properties of the paper such as mechanical strength, opacity, thickness and printing quality (Seth et al., 1989; Gülsoy et al., 2016).

Increasing the basis weight of the paper can alter its attributes such as thickness, stiffness, and durability, whereas lower basis weight papers are regarded as lighter, more flexible and generally more cost-effective alternatives. As a result, selecting the appropriate basis weight for paper manufacture and use is crucial to both economic efficiency and product performance (Gülsoy et al., 2016).

Several authors (Brandon, 1966; Skowronski, 1991; Nordstrom and Norman, 1996; Retulainen and Nieminen, 1996; Nordstrom, 2003) have documented how basis weight affects pulp properties. I'Anson et al. (2007) evaluated the effects of two important parameters in papermaking, formation and basis weight, on the sheet strength of the paper. They stated that in general, paper strength increases with increasing basis weight, but this relationship varies depending on the formation quality. Gülsoy et al. (2016) aimed to investigate the changes in paper properties of beaten (35°SR) and unbeaten (15°SR) kraft pulps obtained from European aspen (*Populus tremula* L.) and maritime pine (*Pinus pinaster* Ait.) species with decreasing basis weight (from 100 g/m² to 50 g/m², at 10 g/m² intervals). It has been determined that decreasing the basis weight, especially in unbeaten pulps, reduces the strength of paper more. However, it has been revealed that basis weight decreases of 10–20 g/m² have statistically insignificant effects on strength. Gülsoy and Şimşir (2017) investigated the mechanical strength properties of test liner papers produced from recycled fibers at different basis weights (85–115 g/m²). They stated that the basis weight of the test liner paper had significant effects on the mechanical properties of the paper, and TEA and air permeability showed the most consistent relationships with basis weight. They also found that the properties except the bursting index were affected by basis weight. Engin et al. (2023) investigated the effects of different fiber lengths and paper basis weights on the basic physical and mechanical properties of printed and unprinted laboratory-type handsheets. They found that fiber composition and paper basis weight have significant effects on printing quality and mechanical strength. Sonmez et al. (2024) investigated the effects of different paper basis weights and fiber blends (short and long fibers) on electrophotographic printing systems. Trend in electrophotographic digital printing among paper groups according to basis weight and fiber content was not significant.

This study examines the influence of basis weight (50, 65, 80, 95, 110, and 125 g/m²) on the physical, optical, and mechanical properties of papers produced from Kraft pulps of Scots pine (*Pinus sylvestris* L.) and European black pine (*Pinus nigra* Arn.). The analysis underscores the relevance of basis weight selection for specific end-use applications. To the best of our knowledge, this is the first comprehensive investigation that systematically compares these two economically and industrially significant softwood species in Türkiye over a broad grammage range, with particular emphasis on their fiber characteristics and resulting paper performance.

2. Materials and Methods

2.1. Preparation of wood samples

Scots pine (Gülsoy, 2023; Gülsoy, 2024a) and European black pine (Gulsoy and Eroglu, 2011; Gülsoy, 2024b) are important species for the pulp and paper industry. Wood samples used in this study were obtained from Bartın province of Türkiye. The debarked wood samples were cut into discs having 25 mm thickness. A chisel was used to manually obtain 25 × 15 × 5 mm chips from these discs for pulping. The wood chips were then air dried and stored in dry conditions.

2.2. Kraft pulping

Kraft pulping was carried out using a laboratory-type cylindrical rotary digester. The pulping conditions used in this study are shown in Table 1. After pulping, the pulp samples were washed for 10 min to remove the black liquor. The washed pulp was disintegrated with a laboratory pulp mixer. Then, pulp samples were screened using a Somerville type pulp screen (PTI type P40170) in accordance with the TAPPI T 275 sp-18 standard. The freeness level of the pulps obtained from Scots pine and European black pine wood were determined as 14 °SR and 12 °SR, respectively. In addition, fiber properties of pulps were determined with Valmet Fiber Image Analyzer (Valmet FS5). The slenderness ratio (fiber length/fiber width) of fibers was also calculated (Gülsoy, 2023). Kappa numbers of Scots pine and European black pine kraft pulps were 24.2 and 19.1, respectively.

Table 1
Kraft pulping conditions of Scots pine and European black pine wood.

Active alkali (%)	20
Sulfidity (%)	30
Liquor/wood chip ratio	4/1
Pulping temperature (°C)	165
Time to pulping temperature (min.)	90
Time at pulping temperature (min.)	90
H-Factor	1031

2.3. Preparation and characterization of handsheets

Handsheets of various basis weights (50, 65, 80, 95, 110 and 125 g/m^2) were obtained from the pulp of each wood species using a Rapid-Kothen Sheetformer (ISO 5269-2: 2004). The handsheets were aged overnight in a conditioning chamber before testing (TAPPI T 402 sp-13). Tensile strength, stretch and TEA, burst strength and tear strength of pulps were determined according to TAPPI T 494 om-22, TAPPI T 403 om-22 and TAPPI T 414 om-12, respectively. Thickness, apparent density, and opacity of handsheets were measured according to TAPPI T 411 om-21, TAPPI T 220 sp-21 and TAPPI T 519 om-22, respectively. Data were statistically analyzed using ANOVA and Duncan test at 95% confidence level (SPSS version 16.0). In all figures, different letters in the same row mean that there is a statistically significant ($P > 0.05$) difference in the mean values of the properties among the compared groups.

3. Results and Discussion

Fiber properties of Scots pine and European black pine kraft pulps are shown in Table 2. The fiber properties of Scots pine (Yaman, 2007; Köksal and Kılıç Pekgözlü, 2016; Gulsoy et al. 2013; Gülsoy, 2023; Kuştaş and Gülsoy, 2023) and European black pine (İstek et al., 2008, 2010; Gulsoy and Oztürk, 2015; Kılıç Pekgözlü et al. 2017) kraft pulps were similar to the literature. The effects of basis weight on the paper properties of Scots pine and European black pine kraft pulps are given in Table 3 and Table 4, respectively.

Table 2
Fiber properties of Scots pine and European black pine kraft pulps.

Fiber properties	Scots pine kraft pulp	European black pine kraft pulp
Fiber length (mm)	3.03	3.53
Fiber width (µm)	31.91	34.72
Slenderness ratio	94.95	101.67
Fiber coarseness (mg/m)	0.32	0.38
Kink (1/1000 fibers)	2617	2923
Curl (%)	7.06	9.33
Fine content (%)	3.10	2.70

Table 3
Effect of basis weight on paper properties of Scots pine kraft pulp.

Properties	50 (g/m^2)	65 (g/m^2)	80 (g/m^2)	95 (g/m^2)	110 (g/m^2)	125 (g/m^2)
Thickness (µm)	105.50±2.84	133.00±3.50	163.50±3.37	188.00±6.75	209.50±6.85	237.00±4.22
Bulk (cm^3/g)	2.11±0.06	2.05±0.05	2.04±0.04	1.98±0.07	1.90±0.06	1.90±0.03
Apparent density (g/cm^3)	0.48±0.01	0.49±0.01	0.49±0.01	0.51±0.02	0.53±0.02	0.53±0.01
Opacity (%)	95.07±0.17	98.28±0.05	99.38±0.05	99.60±0.10	99.81±0.03	99.95±0.03
Burst strength (kg/cm^2)	1.01±0.03	1.37±0.05	1.94±0.07	2.23±0.08	2.74±0.11	3.10±0.11
Tear strength (mN)	152.93±2.56	278.03±8.15	371.01±5.03	390.95±9.41	442.14±12.39	507.22±10.97
Tensile strength (kN/m)	2.36±0.08	3.07±0.07	4.03±0.12	4.79±0.14	5.34±0.08	6.21±0.22
Stretch (%)	1.30±0.04	1.40±0.05	1.57±0.06	1.59±0.06	1.67±0.04	1.64±0.03
TEA (J/m^2)	23.26±0.65	29.17±0.79	43.41±1.66	52.75±1.90	61.50±2.75	70.88±1.69

Table 4
Effect of basis weight on paper properties of European black pine kraft pulp.

Properties	50 (g/m^2)	65 (g/m^2)	80 (g/m^2)	95 (g/m^2)	110 (g/m^2)	125 (g/m^2)
Thickness (µm)	117.00±3.50	149.00±3.94	183.00±4.22	208.00±3.50	239.00±5.68	265.50±5.99
Bulk (cm^3/g)	2.34±0.07	2.29±0.06	2.29±0.05	2.19±0.04	2.17±0.05	2.12±0.05
Apparent density (g/cm^3)	0.43±0.01	0.44±0.01	0.44±0.01	0.46±0.01	0.46±0.01	0.48±0.01
Opacity (%)	91.66±0.12	96.72±0.20	98.54±0.05	99.36±0.11	99.63±0.02	99.83±0.05
Burst strength (kg/cm^2)	0.68±0.02	0.99±0.02	1.24±0.03	1.46±0.03	1.76±0.07	2.04±0.05
Tear strength (mN)	166.33±4.41	239.00±4.98	323.50±5.72	424.83±13.93	485.83±13.50	579.50±14.32
Tensile strength (kN/m)	1.90±0.04	2.40±0.04	3.01±0.06	3.54±0.04	4.46±0.05	4.76±0.03
Stretch (%)	1.03±0.04	1.02±0.04	1.01±0.03	1.05±0.04	1.01±0.04	1.05±0.04
TEA (J/m^2)	12.70±0.47	16.78±0.56	21.25±0.52	27.58±0.63	29.35±0.66	34.57±0.90

3.1. Thickness

In both species, as the basis weight increases, the amount of fiber per unit area increases, so the paper becomes thicker (Figure 1). When handsheets made from Scots pine and European black pine pulp of the same basis weight were compared, European black pine handsheets had thicker. On the other hand, this is a direct relationship, and is related to the accumulation of fibers in layers during the production process. However, this increase was linear for both species, but increases at a slightly decreasing rate for Scots pine. This may be due to the fact that the fibers are packed more tightly in higher basis weights and the voids between them decrease. Bloch et al. (2019) also found a linear correlation between thickness and basis weight of paper. The thickness of the paper significantly affects both its strength and its usage area. While thin papers are generally preferred for writing and printing, thicker papers are used in applications that require strength, such as packaging and cardboard. Thick papers can make printed materials more strength and also increase print quality. In addition, since the thickness of the paper is directly related to its opacity, it is a very important property for papers that will be printed on both sides. Consequently, thicker papers exhibit greater strength and solidity, making them appropriate for packaging purposes.

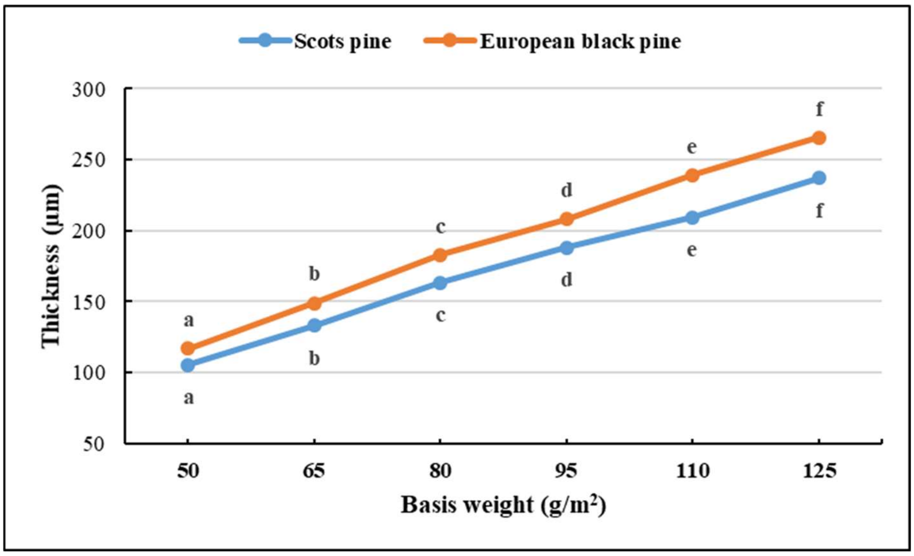

Figure 1. Effect of basis weight on thickness of handsheets.

3.2. Bulk and Apparent Density

As can be seen in Figure 2, it was found that the bulk of handsheets decreased linearly with increasing paper basis weight in both species. At the same basis weight, Scots pine samples were less bulky than black pine samples. Decreasing bulk indicates that the fibers are more tightly structured. As the spaces between the fibers decrease, the paper becomes more compact and its surface becomes smoother.

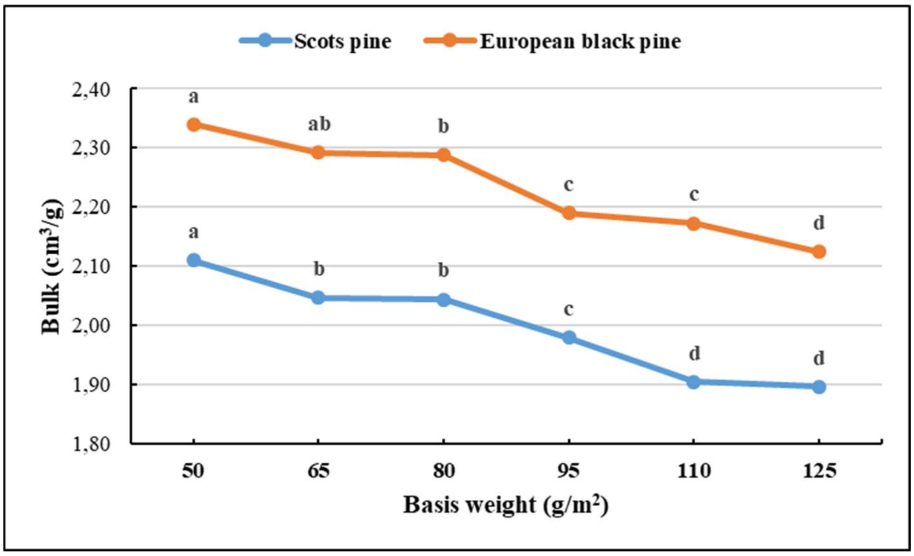

Figure 2. Effect of basis weight on bulk of handsheets.

The apparent density of handsheets increased with increasing basis weight in both species (Figure 3). This finding is consistent with earlier investigations (Seth et al., 1989; Honkasalo, 2004; Girlanda and Fellers, 2007; Gülsoy et al., 2016; Engin et al., 2023; Sonmez et al., 2024). Scots pine samples have a tighter and denser structure than European black pine samples. The apparent density of paper refers to the amount of mass per unit volume and affects properties such as strength and flexibility. Papers with higher apparent density are generally harder, smoother, less porous, and stronger, making them suitable for office papers, labels and high-quality printing. They also show better inter-fiber bonding in the paper (Brännvall and Annergren, 2009). Lower density papers are bulkier, more flexible and absorbent, making them preferred for book pages, tissue paper or packaging fillers. Apparent density is an important parameter in determining the feel, workability and end-use performance of paper. High apparent density provides advantages such as better print quality and water resistance. On the other hand, increasing density means that the paper becomes more compact. Thus, mechanical strength of paper increases. This is a positive development for load-bearing capacity, especially in the packaging industry.

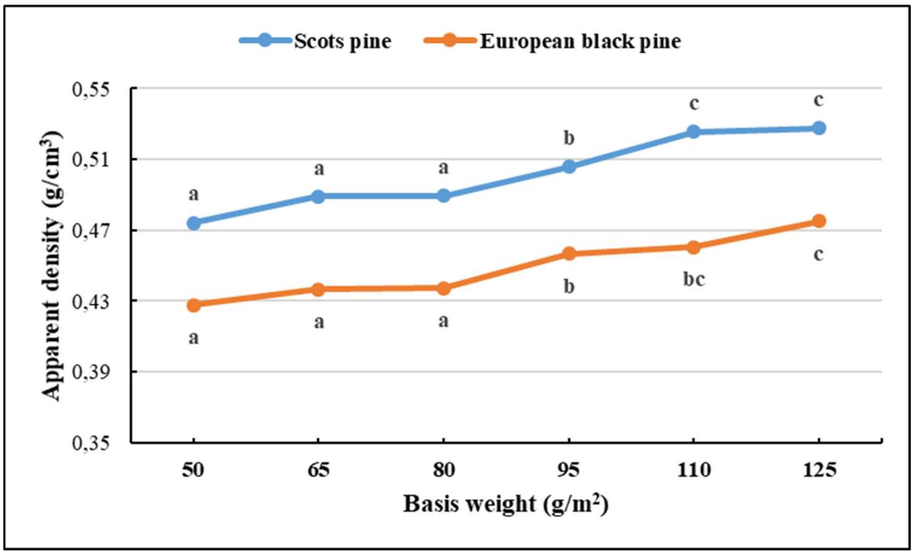

Figure 3. Effect of basis weight on apparent density of handsheets.

3.3. Opacity

In both species, a linear relationship was found between the opacity and basis weight of the handsheets (Figure 4). This can be ascribed to linear correlation between thickness and basis weight (I'Anson and Sampson, 2007; Mohlin, 1992). Gülsoy et al. (2016) and Seth et al. (1989) also observed a positive correlation between opacity and basis weight. Scots pine is more suitable for applications such as double-sided printing and book paper. Opacity is the degree to which light is prevented from passing through paper. As the basis weight increases, the fiber density also increases, making it more difficult for light to pass through. The result is a more opaque, or less transparent, paper. This property provides advantages in applications such as double-sided printing, packaging, and labeling. High opacity papers increase readability by preventing the text or images on the back surface from being visible on the front. For this reason, they are preferred in materials that are used on both sides, such as books, magazines and exam papers. Low opacity papers are generally used in single-sided printing or low-cost temporary applications.

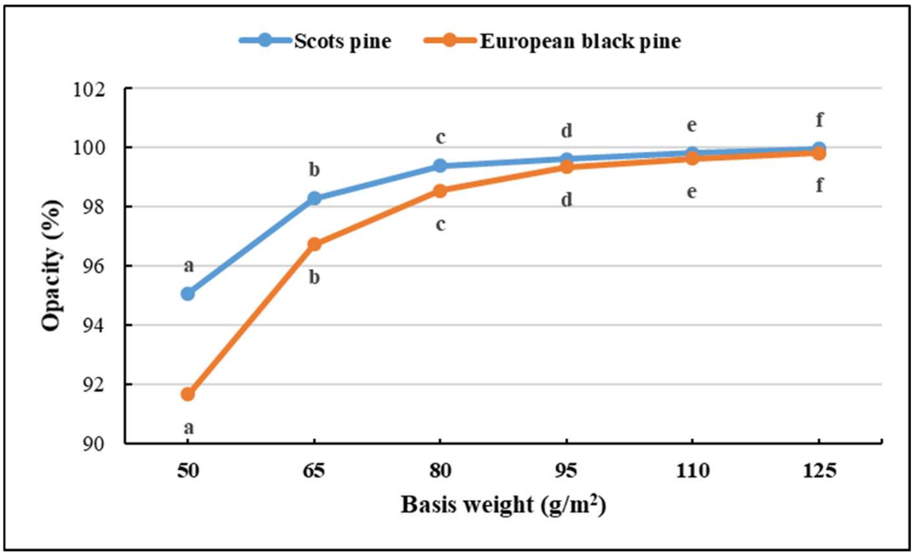

Figure 4. Effect of basis weight on opacity of handsheets.

3.4. Burst Strength

As can be seen in Figure 5, there was a linear correlation between burst strength and basis weight of handsheets. This result can be attributed to the fact that higher basis weight papers have more fibers per unit area and these fibers are bound more tightly to each other. This finding is in agreement with Gülsoy et al. (2016). Scots pine samples had higher burst strength values than those of European black pine samples in the all basis weight values. This result can be attributed to lower fiber coarseness and lower curl ratio of Scots pine pulp (Table 2). Gülsoy and Şimşir (2017) noted that the relationship between burst index and basis weight of test liner paper was statistically insignificantly. The burst strength of a paper indicates how long a paper can withstand pressure before it ruptures, and is a critical property in applications that require strength (Sakare et al., 2021). Papers with high burst strength are often used in areas that are subject to mechanical stress, such as packaging, bags, and durable document production. Papers with low burst strength are often used in short-life, low-strength, or single-use products. This property is directly related to the paper’s fiber structure, density, and additives used during production.

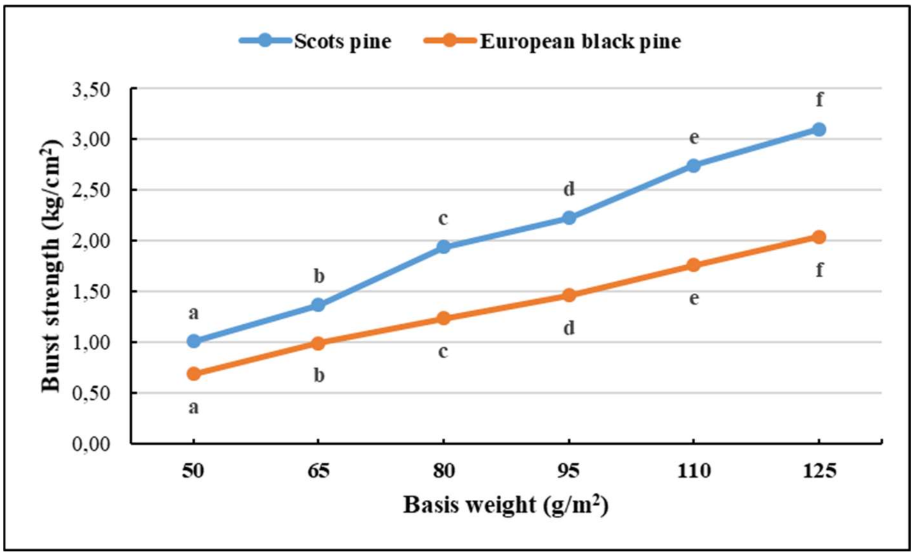

Figure 5. Effect of basis weight on burst strength of handsheets.

3.5. Tear Strength

In both species, tear strength of pulps increased significantly with basis weight, because basis weight refers to the mass of the paper per unit area, and higher basis weight papers contain more fibers. This strengthens the structural integrity of the paper and increases the number of bonds between the fibers, providing greater resistance to tearing. In addition, papers with thicker and denser fiber networks spread the tear force over a wider area along the fibers, increasing tear strength. In high basis weights (95, 110, and 125 g/m^2), European black pine was superior to Scots pine in tear strength (Figure 6). This result can be attributed to higher fiber coarseness and higher curl ratio of European black pine pulp (Table 2). Winters et al. (2002) and Gülsoy et al. (2016) also noted that tear index increased with increasing basis weight. The tear strength of paper is the resistance of the paper to tearing starting from one edge and is particularly important in applications such as transportation, wrapping and packaging. Papers with high tear strength are preferred for bag paper, packaging paper and industrial wrapping materials because they are more resistant to impact and stress. Papers with low tear strength can be used in applications where easy processing or controlled tearing is required, such as tissue paper or bill rolls. This property is closely related to the paper's fiber length, orientation and bond strength.

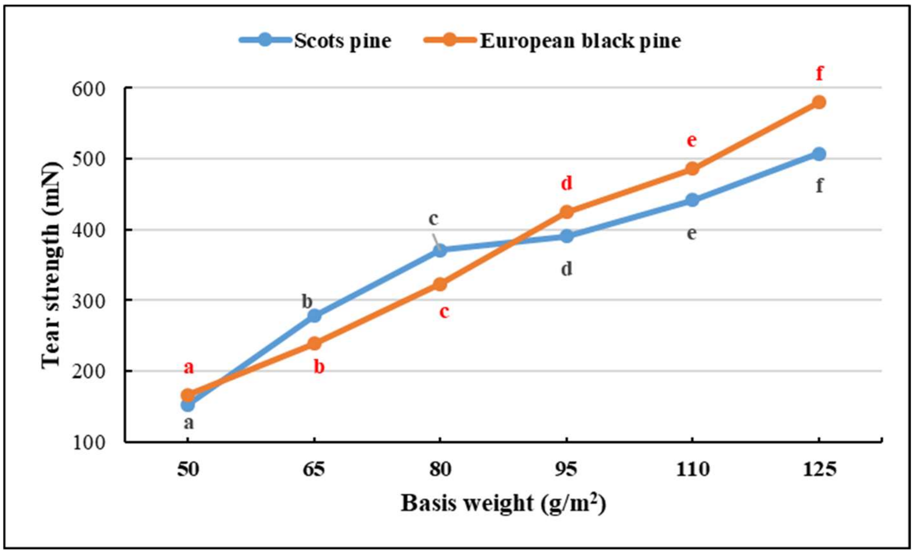

Figure 6. Effect of basis weight on tear strength of handsheets.

3.6. Tensile Strength, Stretch and TEA

In Scots pine and European black pine samples, tensile strength of pulps was increased with increasing basis weight (Figure 7). Previous investigations (Burgess, 1970; Seth et al., 1989; Mohlin, 1992; Winters et al., 2002; I'Anson and Sampson, 2007; I'Anson et al., 2007, 2008; Gülsoy et al., 2016; Engin et al., 2023) have indicated a positive relationship between handsheet basis weight and the tensile index. This positive relationship can be attributed to the increase in the amount of fiber per unit area with increasing basis weight. This increases the number of interfiber bonds and the total tensile strength. In the all basis weight values, Scots pine had higher tensile strength than those of European black pine. This can be ascribed to lower fiber coarseness and curl ratio of Scots pine pulp (Table 2) (Joutsimo et al. 2005). On the other hand, the residual lignin content in the pulps was estimated by multiplying their Kappa numbers by 0.15, resulting in coarse lignin values of 3.63% for Scots pine and 2.87% for European black pine. This minor difference is not substantial enough to markedly affect interfiber bonding or, consequently, the overall paper strength properties.

The tensile strength of paper indicates how much it can be stretched and how much force it can carry before tearing when a tensile force is applied. In usage areas requiring high strength such as packaging, bag paper, industrial wrapping, tensile strength is especially important. Papers with high tensile strength can withstand handling and processing without tearing or shredding. Papers with low tensile strength are generally preferred for single-use or delicate applications.

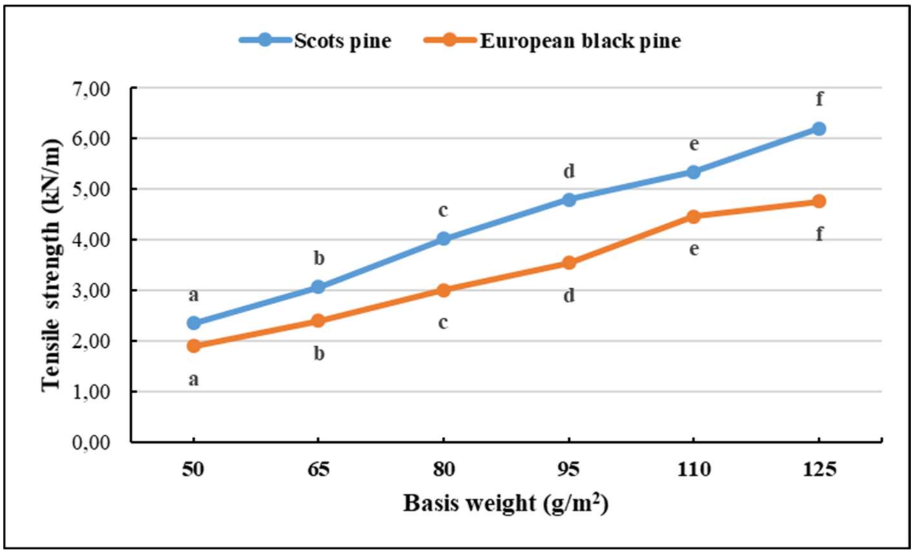

Figure 7. Effect of basis weight on tensile strength of handsheets.

In Scots pine, stretch of pulp was increased with increasing basis weight. Higher basis weight papers contain more fibers, which allow the fibers to work together to provide greater flexibility. However, there was not statistically significant relationship between stretch and basis weight of European black pine pulps (Figure 8). Gülsoy and Şimşir, (2017) noted that stretch of test liner papers was irregularly changed with increasing basis weight. The stretch of paper indicates how much it can stretch before breaking when tensile force is applied. This property determines the elasticity and impact resistance of the paper. Papers with high elongation capacity are preferred especially in packaging, bags, wrapping and industrial applications exposed to high tension. Papers with low elongation are suitable for more rigid and deformable applications.

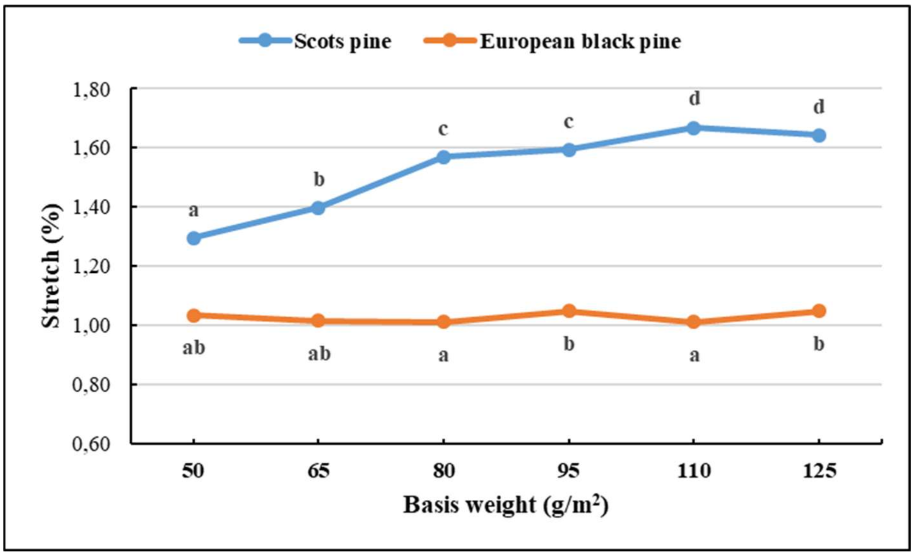

Figure 8. Effect of basis weight on stretch of handsheets.

In both species, there was a linear correlation between TEA and basis weight of paper (Figure 9). The positive relationship between TEA and basis weight was reported by previous studies (Seth et al., 1989; Gülsoy et al., 2016; Gülsoy and Şimşir, 2017). This result is due to the fact that the paper contains more fibers with increasing basis weight and that as the number of fibers and bond strength increases, more energy can be absorbed during the tensile force. Pulps of Scots pine had higher TEA than those of European black pine. This result can be attributed to more kink and higher curl ratio of European black pine pulp (Table 2). Kinks and curls in fibers act as stress concentrators and can reduce fiber strength and bonding efficiency, resulting in lower TEA values. The TEA of paper is an important property that indicates how much energy it can absorb before tearing or breaking when a force is applied. This property provides important information about the impact strength, elasticity and general mechanical strength of the paper. Papers with high TEA are preferred in applications under physical stress such as packaging, transportation, protective wrapping materials and industrial bags. Papers with low TEA are generally used in static applications, i.e., applications that are not subject to mechanical stress.

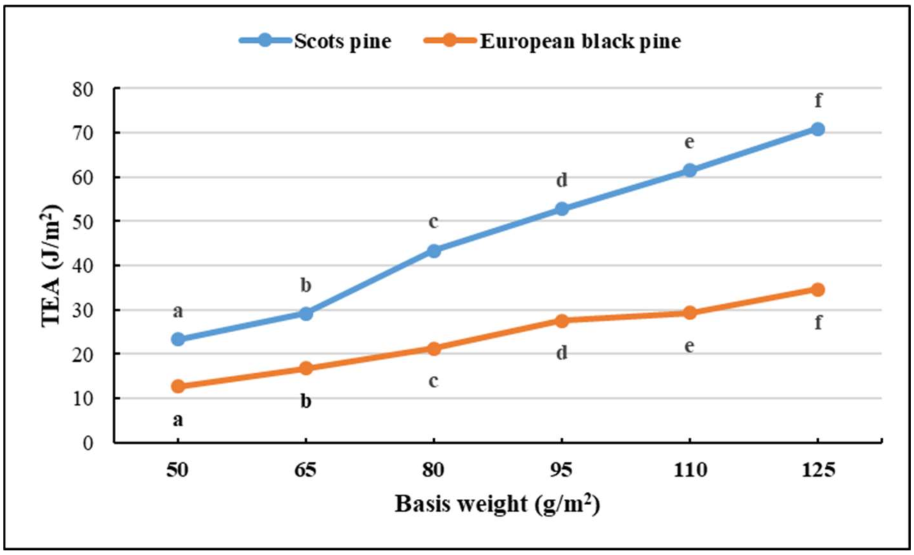

Figure 9. Effect of basis weight on TEA of handsheets.

4. Conclusions

In this study, the effects of handsheets of different basis weights obtained from Scots pine and European black pine kraft pulps on physical, optical and mechanical properties were investigated. According to the results, it was seen that the change in the basis weight of the pulps in both species caused significant changes in the examined properties of the pulps. In addition, it was observed that Scots pine pulps had higher strength than European black pine. In light of these results, it has been determined that Scots pine pulps are more suitable for usage areas requiring high strength, such as packaging, paper bags and transportation due to their high tensile and burst strength. On the other hand, European black pine pulps can be used in packaging and protection applications due to their absorbency and cushioning properties due to their high bulk. These data highlight the criticality of selecting the appropriate pulp and basis weight in paper production for different usage purposes. The findings provide fundamental information for optimizing wood species and basis weight combinations in areas such as packaging and industrial paper production.

Author Contributions

Sezgin Koray Gülsoy: Participated in all stages of the study.

Conflicts of Interest

The author declares no conflict of interest.

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