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Evaluation of TAPPI Brightness versus Other Brightness Indices

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Keywords: paper brightness, TAPPI brightness, spectrophotometers, variance, optical brightening agents (OBAs), paper manufacture

Abstract

The primary goal of the present research it to establish the variance that can be expected when measuring TAPPI brightness as a traceable metric with a laboratory-grade meter compared to brightness indices measured by production-grade spectrophotometers. It is also recognized that the variance between the analyzed metrics may differ based on the type of paper measured. Therefore, this research also aims to examine the brightness across several types of papers commonly used in the printing and packaging industry. In addition, an important property of many paper substrates known as optical brightness agents (OBAs) is analyzed with a goal of ascertaining its influence on brightness readings among the evaluated instruments and metrics. OBAs are commonly used chemical materials in paper pulp, which can enhance the "brightening" effect on the appearance of the material. After data collection and analysis, it is concluded that the brightness indices from the production-grade instruments used in this study result in higher readings than TAPPI brightness readings. The level of OBAs in the paper is also found to influence paper brightness readings.

Introduction

The Technical Association of Pulp and Paper Industry (TAPPI) defines peer-reviewed standards to ensure that paper and paperboard products meet industry best practices. These include a traceable metric known as TAPPI brightness (T452), designed to measure paper brightness and provide a means to compare and evaluate papers. A function of the reflectance characteristics of paper, TAPPI brightness is measured at CIE Standard 45°/0° geometry at 457-nanometer reflectance (IPSTESTING, 2017). Strict adherence to TAPPI brightness mandates a laboratory-grade measurement instrument that is dedicated mainly for the singular purpose of

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reading the metric. In contrast, production-grade spectrophotometers, which are commonly utilized by printers for quality assurance and process control, frequently provide a brightness index. Manufacturers of these measurement instruments contend that these brightness indices, while not officially meeting the requirements of TAPPI brightness, nonetheless provide a useful metric that, at a minimum, can be utilized in a relative manner by practitioners. The present research seeks to compare TAPPI brightness as measured by a laboratory-grade meter to the brightness indices of seven different production-grade spectrophotometers. The variance of the resultant measurements is analyzed across eleven different paper samples representative of a range of commonly-used printing substrates.

Research Questions

There are three research questions examined in the present study. Each question incudes a sub-question to evaluate the variance between paper samples with differing OBA levels:

1. How much variance can be expected when reading TAPPI Brightness using laboratory-grade Technidyne Tappi Brightness Meter?
    a. Is there a difference in TAPPI brightness variance when measuring paper with High OBA and Low OBA?
2. How much variance can be expected when reading "brightness indices" with production-grade instruments?
    a. Is there a difference in the variance of brightness indices when measured with production-grade instrumentation on papers with different OBA characteristics?
3. How close are the brightness indices as measured with production-grade instruments to TAPPI brightness as measured with a laboratory-grade instrument?
    a. Is there a difference in how close brightness indices as measured with production-grade instruments are to TAPPI brightness as measured with a laboratory-grade instrument when measuring papers with different OBA characteristics?

Methodology

An experiment was designed to evaluate the readings of TAPPI brightness and other brightness indices. After preparing samples and calibrating the instruments, data were collected and analyzed. Different levels of OBAs were also considered as a variable during the analysis to ascertain any possible effect between the different groups of paper samples.

Samples

The researcher chose eleven paper samples which can be categorized as six different paper types from various companies and mills. These samples varied in color, surface characteristics, and OBA level. Specifically, the papers were selected from the following categories that represent the most commonly used printing papers in the industry:

1. White paper, high OBA
2. White paper, low OBA
3. White paper, no OBA
4. Solid bleached sulfate (SBS)
5. Uncoated
6. Matte-coated

Instruments

Six different measurement instruments were utilized in the analysis. For the traceable TAPPI brightness index, the Technidyne Brightimeter S-4 at the Rochester Institute of Technology (RIT) Printing Applications Lab (PAL) was used, as this instrument measures TAPPI Brightness and conforms to TAPPI Official Test Method T452. Five different production-grade spectrophotometers were selected to be used for other brightness indices; as follows:

1. X-Rite eXact
2. X-Rite 530
3. X-Rite 939
4. X-Rite SpectroEye
5. Minolta FD-7

Data Collection

An experiment was designed to collect data regarding paper brightness. Ten sheets each of eleven types of paper were collected for the research. The paper samples were protected by acetate sheet protectors during the measurement procedure, with the samples exposed only to take the readings. Care was taken to keep the paper from becoming dirty or scuffed during measurement.

Before their paper brightness indices were collected, these paper samples were separated into two groups based on their OBA level. To determine the OBA level of paper samples, the OBA-Check function on Techkon SpectroDens was used to measure the influence of OBAs in the samples, and to categorize them accordingly. According to the table from Techkon SpectroDens Manual, there were seven out of eleven types of paper categorized as belonging to the low OBA group while the remaining four types of paper were considered as high OBA group, as illustrated in Table 1.

Types of Paper Sample	*OBA Categorization*	*OBA Amount*	*OBA Group*
Invercote T	no	no	low OBA
SBS	no	no	low OBA
60#sterling C1S	moderate	3.8	low OBA
4716 ecopoint	moderate	4.1	low OBA
5516 verso oxford	moderate	4.1	low OBA
Mosaic	moderate	4.5	low OBA
5516 Sappi luster cote	moderate	4.6	low OBA
5516 evergreen	high	6.5	high OBA
Invercote G	high	8.1	high OBA
80#cover sterling prem dull	high	8.7	high OBA
Neenah	high	11.2	high OBA

Table 1. *OBA-Check Results*

After measuring the OBA level of each type of paper samples, the researcher measured brightness indices of each paper on every instrument twice a day (once in the morning, and again in the late afternoon) for five days. Data were collected from each paper sample in both the grain and cross-grain directions. The average of these two readings was calculated and used for the subsequent analysis. To minimize potential variance for measurement repeatability and reproducibility, the researcher alone performed the readings, and the data from days three and four were utilized to assess consistency in the instruments and metrics.

Data Analysis

After collection, the data were analyzed. Boxplots and other graphics were used to graphically display possible variance. Because of the different operational characteristics of the instruments, some limitations of specific instruments were noted, were considered during the analysis. For example, the X-Rite 530 is only capable of showing whole numbers under 100, and if the paper brightness reading is over 100 the instrument will display only “XXX” on the screen. Because of this limitation, the brightness index from the highest OBA sample utilized (i.e.: Neenah) are not readable with X-Rite 530. As a result of that limitation, X-Rite 530 resulted in fewer readings than the other instruments. Raw data from the readings is provided in Appendix A.

Research Question 1

Before running the analysis for Research Question 1, data were visually analyzed for normality and outliers using a Q-Q test. Although results were not perfectly normal and some outliers were noted, it was determined that the outliers would remain in the analysis. To validate this decision, outliers were removed, and the tests were conducted again: in each case, the conclusions remained consistent.

After the normality test, a paired t test was performed and indicated that the difference in readings over two days did not elicit a statistically significant difference in TAPPI brightness, $t(109) = -1.79$, $p = 0.077$. The paired sample mean readings between Day 3 and Day 4 were highly correlated ($p < 0.001$). For Research Question 1, recorded variances were therefore minimal.

For the Research Question 1 sub question, distributions of the brightness values for the OBA groups were not similar, as assessed by visual inspection. Therefore, a parametric independent samples t test analysis was not utilized, rather the non-parametric Mann-Whitney U test was employed to determine if there were differences in TAPPI brightness between paper samples with high OBA and those with low- to-moderate OBA. Brightness values for high-OBA (mean rank = 85.29) were statistically significantly higher than for low- to moderate-OBA (mean rank = 38.48), U = 208.5, z = -7.404, $p < 0.001$, as illustrated in Table 2. It is suggested that there is more variance in readings of papers with high OBA level than low OBA level when reading TAPPI brightness.

OBA	N	Mean Rank	Sum of Ranks
Low OBA	70	38.48	2693.50
High OBA	40	85.293411.50	

Table 2. *TAPPI Brightness Mann-Whitney U Test Results Table*

Research Question 2

To determine how much variance can be expected when reading brightness indices, test-retest reliability was assessed through a paired samples t test; correlations were also reported. Day 3 and Day 4 brightness indices from each instrument were utilized for the analysis. The paired sample t test was performed and indicated that the difference in readings over two days did not elicit a statistically significant difference in brightness indices, except for the specific case of the X-Rite 939, $t(109) = -3.119$, $p = 0.002$, as illustrated in Table 3. The specific case of the X-Rite

Instrument	t	df	Sig.(2-tailed)
X-Rite 939	-3.119	109	0.002
X-Rite 530	-0.587	99	0.558
X-Rite eXact	1.890	109	0.061
X-Rite SpectroEye	1.820	109	0.072
Minolta FD-7	-0.799	109	0.426

Table 3. *Brightness Indices Paired t test Correlations Results*

939 is curious and resurfaces in the analysis of Research Question 3.
For the sub-question, it is noted that distributions of the brightness values for the OBA groups were not similar, as assessed by visual inspection. Therefore, a parametric independent samples t test analysis was not utilized, in favor of the non-parametric Mann-Whitney U Test. There was a statistically significantly difference in Brightness values between the OBA groups, as illustrated in Table 4.

Instrument	***U***	***z***	***p***	***High OBA Mean Rank***	***Low OBA Mean Rank***
X-Rite 939	300	-5.64	<0.001	75.50	39.79
X-Rite 530	243	-6.08	<0.001	77.40	38.97
X-Rite SpectroEye	167	-6.64	<0.001	79.93	37.89
Minolta FD-7	119	-7.00	<0.001	81.53	37.02
X-Rite eXact	679	-2.79	<0.001	62.87	45.02

Table 4. *Brightness Indices Mann-Whitney U Test Result Table*

Research Question 3

For research question 3, systematic bias and proportional bias are utilized for the analysis. Systematic bias is an assessment of agreement with a so-called "gold" standard, in this instance, the standard is the TAPPI brightness readings from the Technidyne laboratory-grade instrument. An independent samples t test is used to calculate the difference between TAPPI brightness and brightness indices to examine potential systematic bias.

Proportional bias is an analysis of agreement throughout the range of measurements. Tukey mean-difference plots, otherwise known as Bland-Altman plots, were utilized to examine possible proportional bias, and possible outliers were also identified.

Systematic bias

The presence of systematic bias is indicated if the mean value of the difference differs significantly from zero on the basis of the independent samples t-test. Results are indicated in Table 5; it is noted that the mean differences recorded were all statistically significant, and that they were all negative values.

Instrument	t	Df	Sig(2-tailed)	Mean Difference
X-Rite 939	-11.81	109	<0.001	-5.38
X-Rite 530*	-22.81	99	<0.001	-2.79
X-Rite SpectroEye	-19.97	109	<0.001	-2.42
Minolta FD-7	-16.05	109	<0.001	-1.87
X-Rite eXact	-54.13	109	<0.001	-6.29

* Brightness Index on the high-OBA Neenah Paper were not readable with X-Rite 530

Table 5. *Independent t test Results*

With the Tukey mean-difference plot, the mean difference represents the estimated bias, and the standard deviation is a measurement of fluctuations around the mean. Graphical results are illustrated in Figures 1 through 5.

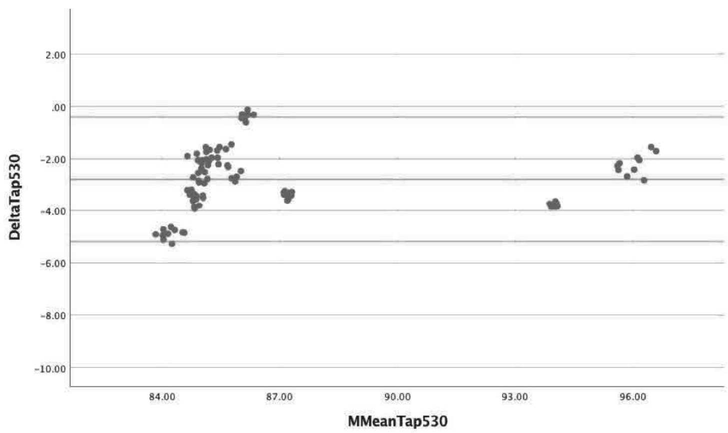

Figure 1. *X-Rite 530 Tukey Mean-Difference Plot*

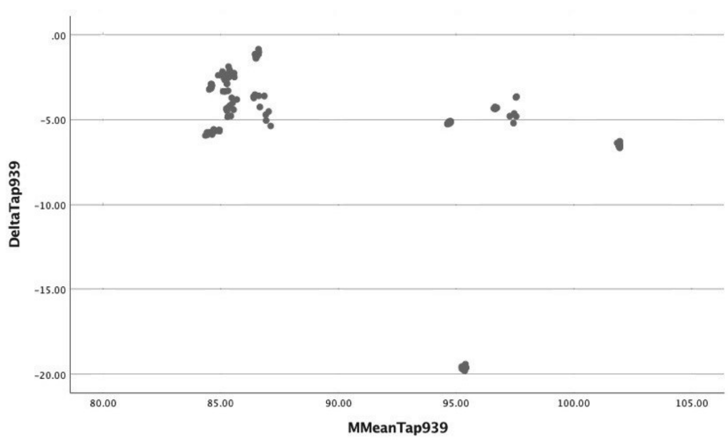

Figure 2. *X-Rite 939 Tukey Mean-Difference Plot*

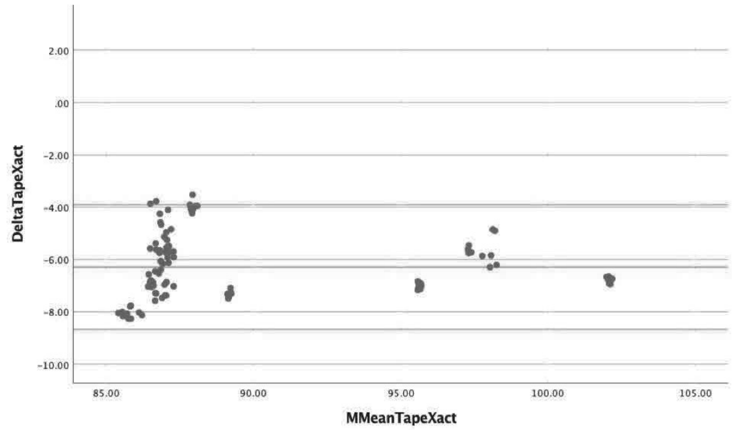

Figure 3. *X-Rite eXact Tukey Mean-Difference Plot*

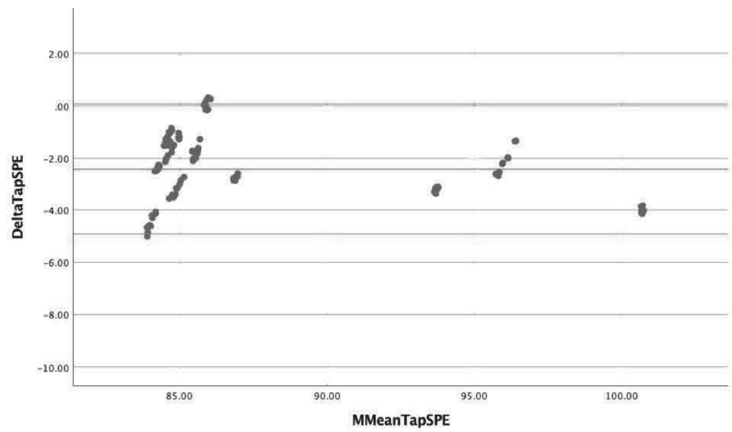

Figure 4. *X-Rite SpectroEye Tukey Mean-Difference Plot*

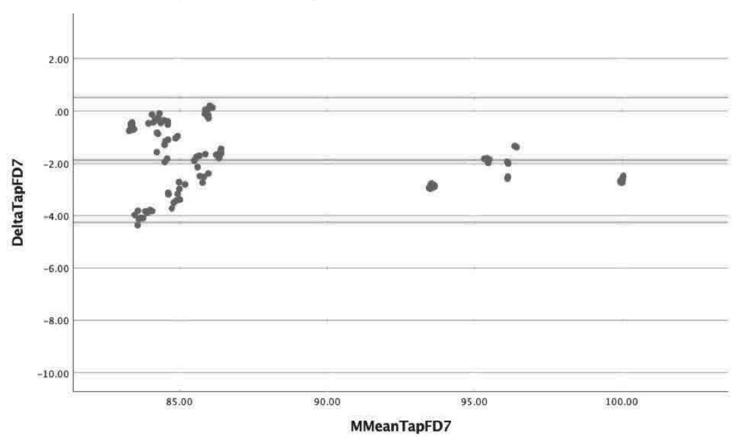

Figure 5. *Konica Minolta FD-7 Tukey Mean-Difference Plot*

A special case in noted again with the X-Rite 939. Here, one particular substrate, SBS, represented an outlier. As illustrated in Figure 3, there was a notable cluster of brightness readings showing a difference of nearly -20 from TAPPI brightness. While this was curious, it was recognized that this particular model is an older instrument model, especially when compared to the Konica Minolta FD-7 and the X-Rite eXact. The particular optical characteristics of the X-Rite 939 may have resulted in excessive variance due to the surface characteristics or other property of the SBS substrate; therefore, these particular readings were removed from the analysis. The resultant Tukey mean-difference plot is shown in Figure 6. Table 6 displays an updated t test for systematic bias with the problematic substrate removed from the X-Rite 939 readings: here, the results obtained by the X-Rite 939 were more consistent with the other instrumentation.

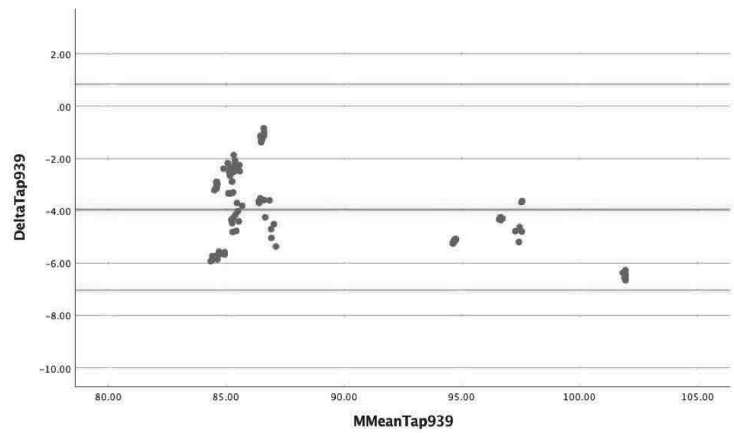

Figure 6. *X-Rite 939 Tukey Mean-Difference Plot with Outliers Removed*

Instrument	*t*	*Df*	*Sig(2-tailed)*	*Mean Difference*
X-Rite 939*	-24.88	99	<0.001	-3.95
X-Rite 530*	-22.81	99	<0.001	-2.79
X-Rite SpectroEye	-19.97	109	<0.001	-2.42
Minolta FD-7	-16.05	109	<0.001	-1.87
X-Rite eXact	-54.13	109	<0.001	-6.29

* Problematic SBS readings removed from X-Rite 939, Brightness Index on the high-OBA Neenah Paper is not readable with X-Rite 530

Table 6. *Independent t test Results, SBS removed from X-Rite 939 readings*

Discussion and Conclusions

The present study examined expected variance in reading TAPPI brightness and brightness indices across a range of commonly used printing papers and paperboards. Other than brightness, the presence of OBAs was the only other characteristic examined. These were operationalized though the OBA-Check feature of the Techkon SpectroDens. While this methodology does introduce limitations, practical and relevant conclusions can be observed from this work.

The first two research questions examined the variance that can be expected when using the selected instrumentation to measure brightness. In the case of the laboratory-grade Technidyne meter, the paired sample t test indicated that the difference in readings over a two day period did not elicit a statistically significant difference in TAPPI brightness, $t(109) = -1.79$, $p = 0.077$. The paired sample mean readings between Day 3 and Day 4 were highly correlated ($p < 0.001$). This suggests that variances were minimal when using the Technidyne meter across the range of papers analyzed. Similarly, for Research Question 2, a paired sample t test resulted in the observation that the difference in readings over two days did not elicit a statistically significant difference in brightness indices, except for the specific case of the X-Rite 939, $t(109) = -3.119$, $p = 0.002$. As previously discussed, the 939 was problematic with one of the substrates when compared with the other instruments.

To ascertain the effect of OBAs with the laboratory-grade Technidyne instrument, as examined in research question 1, and the production-grade instruments, as examined in research question 2, the non-parametric Mann-Whitney U test indicated that variances among the brightness indices for the instruments is noted. Users are cautioned about the observed increase in variance with higher OBA papers. These findings suggest that users of any of these instruments can confidently realize repeatable readings, particularly with low- and moderate-level OBA substrates. However, future researchers may want to conduct full Gage R&R studies, which could serve to further validate the results obtained here.

In addition to the aforementioned concerns with the X-Rite 939 in this context, it is also important to recognize the limitations of the X-Rite 530 versus the other instruments. As indicated, the model X-Rite 530 does not display brightness readings over 100, so it was impossible to record readings for the substrate selected that exhibited the highest level of OBAs. Further, the X-Rite 530 only displays whole numbers. First introduced in 1997, the model X-Rite 530 represents the oldest technology of all of the instruments analyzed, and when sold as new, was offered at the lowest cost. Users are cautioned of the limitations of older instruments in the present context.

It is relevant to note that both the X-Rite 530 and X-Rite 939, although popular in the field, were introduced before ISO 13655:2009. This ISO standard defines measurement conditions for color measurement instrument manufacturers with the goal of achieving better agreement between visual assessment and measurements (ISO, 2009). While it is also true that the X-Rite SpectroEye used in the present study was introduced prior to 2009, the X-Rite eXact and the Konica Minolta FD-7 utilized here comply with ISO 13655:2009. It is recognized that while some of the older instruments may be limited, from a practical standpoint moving ahead such legacy instrumentation will likely be utilized less and less, especially as factory service and certifications are retired.

Turning to the third, and primary research question, the data suggest that of all of the production-grade instruments evaluated, the Konica Minolta FD-7 was closest to the laboratory-grade TAPPI meter, and that the X-Rite eXact was the furthest. All of the instruments read higher brightness values than the TAPPI standard, and all were significantly different than the TAPPI readings obtained with the laboratory-grade Technidyne brightness meter.

In examining the difference between high- and low- OBA papers visually using the Tukey mean difference plots, the variances were generally similar across all production-grade instruments analyzed. As discussed, the X-Rite 939 represented an exception here. Some of the substrates seemed to increase the standard deviations: it is curious that these are the highest OBA values of the low-OBA group. This suggests that future researchers may choose a different methodology to separate high- and low-OBA papers. Furthermore, as OBA was the only paper characteristic analyzed by the present study, future researchers may choose to evaluate other factors, such as surface characteristics (e.g., smoothness, gloss) to better determine how these indices correlate to the standard.

Paper manufacturers are encouraged to indicate the specific brightness metric utilized and the brightness measurement technique (i.e.: grain direction, cross grain direction, average of the two) with paper label information. Meanwhile, consumers are cautioned to be advised of brightness differences depending on the metric utilized.

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