Quantitative evaluation of quality of flexographic imprints by means of fuzzy logic

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Abstract

The article is devoted to the quantitative evaluation of quality of flexographic prints on polymer films. Based on the conducted analysis, we have set the key parameters of quality imprints, such as color difference, reproduction of a minimum raster dot, ink adhesion to the substrate, image positioning. In accordance with the known terms, the fuzzy knowledge base of parameters of imprints quality with the performance of the condition "if-then" has been formed. Based on this knowledge base, fuzzy logic equations of calculation of imprints quality options have been built and defuzzification by the method "center of gravity" has allowed to get the quantitative parameter of imprints quality that is the result of keeping to the relevant modes of flexographic printing process.

Keywords: Flexography, imprints quality, fuzzy logic, linguistic variable, knowledge base

1. Introduction

When the topic of modern printing trends is discussed, they always mention flexography in one way or another. This is one of those printing methods that have continued to develop dynamically in the new millennium. The possibility to print up various surfaces from paper to polymer and metal has made it one of the most universal ones. And the introduction of new technologies in the production of printing plates and revolutionary improvement of printing technologies and equipment ensures such quality of the original reproduction that flexography successfully competes with flatbed offset in the market of label products.

The dynamic development of flexography sets a number of problems before printers. And, of course, the key issue is quality, which, in its turn, is directly related to the issue of standardization. The problem of standard is not new in flexography, stating that this variable printing process is very difficult to bring to a certain standard, primarily because the range of materials that are printed up is very wide as well as a range of printing inks (from water and solvent to UV-curing). In addition, there is also a wide range of printing presses – from narrow web presses intended for label printing to presses with a central cylinder for printing on polymer films and large presses for printing on corrugated cardboard (*Dreher, 2004*). The attempts to embrace the flexographic workflow are concentrated in standards ISO 2846-5, ISO 12647-6 and guidelines (*Claypole; Flexographic Image Reproduction Specifications and Tolerances, 2002*).

One solution to the problem is the use of so-called "internal" standards for specific businesses that would take into account their specific features, equipment, properties of printing materials, etc. The design of such a standard is a laborious and time-consuming process. It begins, in its turn, with the design of a system of production quality control. Quality assurance must comply with three basic functions:

- quality planning;
- quality management;
- quality evaluation.

Quality planning should be understood as comprehension, optimization and setting pre-set values for all elements relating to the product quality. Quality management must carry out the task of control and regulation of all elements related to the quality of the order.

Reproduction quality is a value that has certain restrictions related to the subjectivity of visual perception and imperfection of printing equipment and technology. Some parameters of quality can be evaluated both subjectively and objectively, using devices. We have selected those quality parameters that are primary in the overall evaluation of the original reproduction and controlled in every enterprise: accuracy of image positioning, correctness of color reproduction (color difference), reproduction of a minimum dot and adhesion of ink layer to the substrate.

Image positioning (color register) is one of the most important parameters of prints quality. The easiest way to check the inks positioning is to examine a certain area of the image with a magnifying glass. If the magnifying glass is equipped with a measuring scale, the printer can evaluate the misalignment of inks and adjust it to the necessary extent. To simplify the process of control they print special register marks along the image. When printing multiple inks overlaying (e.g. CMYK) the marks are overlapped and form certain structures – register crosses or other elements, deviations from which are determined visually with a magnifying glass and subsequently taken into account when adjusting a printing press. Maximum non-positioning of directly overlapping inks, depending on the width of the printing (*ISO 12647-6*), shall not exceed 0,3 mm, and despite the fact that six ink printing is common in flexography.

In flexographic presses they move plating cylinders in the side direction to adjust ink positioning in that direction, taking the base position of one of them. They use as semi-automatic (with an electric motor) control of side color matching and automatic control system, one of which is the use of a sensor of the side edge position. Adjusting the longitudinal matching is done in semi-automatic mode by rotating the plating cylinders by the value of non-matching.

In practice, it is sometimes very difficult to achieve the ideal ink positioning because it is affected by too many factors. First of all it is necessary to take into account the quality of printing plate production, accuracy of installation and stability of printing equipment work. Image non-positioning may be the result of several factors, and it is difficult to determine exactly the cause of it in prints. Therefore, the knowledge of the causes of image register violations in the printing process and the physical nature of the phenomena that cause it are necessary to specialists at different levels (printers, engineers, mechanics). For example, non-positioning can be caused by such printing material properties as "creeping" – the ability to change its size over time under constant load (it is common for some polymer films, particularly polyethylene) that must be considered when printing (*Deutschspachinge Flexodruck-Fachgruppe and Meyer, 1999*).

The correctness of color reproduction (color difference) is also among the most important parameters of the printing process. The human eye can be considered as one of the most accurate measuring instruments. But it is not able to assign certain numeric values to the color and memorize the shades of color accurately. Quantitative characteristics of color and color differences are defined and evaluated by three numbers (necessary and sufficient color parameters) – color coordinates (e.g. color model CIE Lab), which are measured using a spectrophotometer. To compare colors they use the parameter ΔE_{00} – characteristics of color differences, which is a functional parameter of modern spectrophotometer. Mathematically, this parameter can be described as (*CIE, 2012):*

$$\Delta E_{00}=\sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2+\left(\frac{\Delta C'}{k_L S_L}\right)^2+\left(\frac{\Delta H'}{k_L S_L}\right)^2+R_T\left(\frac{\Delta C'}{k_c S_c}\right)\left(\frac{\Delta H'}{k_H S_H}\right)}, \quad (1)$$

where ΔL', ΔC', ΔH' – the color attributes (lightness, chroma and hue differences);

S_L, S_C , S_H – compensation for lightness, chroma and hue, according;

k_L=k_C=k_H=1 – parametric factors; R_T – rotation term.

The definition of the digital value ΔE allows you quickly and with relative high accuracy to determine the need for operational parameters adjusting of grade correction, color correction, dot gain, ink amount, etc.

Standard ISO 2846-5 approves the value ΔE of not more than 5 for yellow ink and not more than 6 for blue and purple. According to ISO

12647-6 the value ΔE for yellow ink should not be more than 6, and 5for the rest. If this value is exceeded, the eye will perceive color difference between the standard and the evaluated print. The excess of this value for mixed (Pantone) inks is especially critical (*Deutschspachinge Flexodruck-Fachgruppe, 1999*).

The minimum reproduction dot is determined by conducting tests on the printing press. In fact, the minimum dot size depends on several conditions: functional adjustments of the press, such as a printing plate type, printing material, ink properties. Regarding the printing material, it is the nature of the surface that determines the degree of reproduction of raster dots range. Thus, according to standard ISO 12647-6 the surface of uncoated paper can reproduce a minimum raster dot 3% and 2% of a polymer film. It should be noted that at present, the work is underway on reproducing 1% of a raster dot (*Siniak, Moyson, 2008*).

Another criterion of the prints quality is adhesion of the ink layer. Control of the level of adhesive resistance of the ink layer to the printed material is held immediately after printing, and when controlling the quality of finished products.

According to standard ASTM F 2252 and guidelines (*FINAT Technical Handbook, 2001*), a strip of an adhesive tape (e.g. Scotch 3M 610 or Tesa 7475) is put on a print, smoothed manually without pressing, but so that no air bubbles remain under the tape. Then the adhesive tape is pulled back with the angle 90° and removed quickly, but not abruptly. This test is performed after joining the adhesive tape with the print. The level of adhesive strength is measured at five-point system: five points if the ink layer is not removed and four to one points, depending on the amount of the ink layer left on the surface. For FINAT the adhesion estimated by inverse scale.

The reasons for the lack of adhesion may be several: not activated, reverse side of the roll has been printed up, the material is not appropriate for the ink type, the film requires additional treatment to improve adhesion (surface energy of the film has been reduced) (*Flexographic inks, 2000*).

In evaluating the quality of prints, all of the elements must be analyzed and evaluated in their entirety. The development of comprehensive evaluation of quality parameters of the original reproduction by the flexographic printing method is one of the key elements of designing the quality control system in a production environment. This article is devoted to the solution of this urgent problem by applying the principles of fuzzy logic.

2. Methodology

The design of intelligent systems that can adequately interact with the person requires mathematical tools that would translate ambiguous statements into the language of clear and formal mathematical formulas. It was implemented in the work of Lotfi Zadeh (*Bellman, Zadeh., 1970*), who laid the foundations of fuzzy logic and introduced the concept of some universal set for the entire problem area.

In general, the fuzzy logic is a logic that operates linguistic variables using rules that are understandable to a human and close in structure to the normal spoken language. The advantage of fuzzy logic systems is the ability to handle fuzzy input data, such as continuously variable time values.

The overall evaluation of prints quality by means of fuzzy logic includes:

- setting a universal term-set of values and corresponding linguistic terms of certain quality factors (linguistic variables);
- design of a matrix of pair wise comparisons for a set of linguistic terms of relevant range of values and obtaining a membership functions for each of matrices;
- development of fuzzy knowledge base using fuzzy logic statements of “if - then” type;
- design of fuzzy logic equations based on a matrix of knowledge and membership functions that define the relationship between the membership functions of input and output data;
- defuzzification of fuzzy sets, the essence of which is to calculate a numerical indicator of predicted quality, for example, by the method of gravity center of a plane figure (*Rothstein et al., 2008; Durnyak et al., 2014*).

3. Results and discussion

Qualitative parameters of prints are the result of some interaction of information, energy and material flows (*Velychko, 2005*). They depend on the characteristics of the used materials, equipment specifications and technological process modes (*Izdebska, 2015*) and must meet the quality parameters that are set by the previously obtained practical results and standards (Fig. 1).

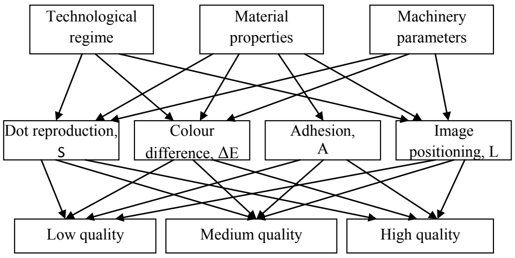

Figure 1. Effect of characteristics of materials, equipment and technological modes on quality parameters of imprints

Accordingly, the quality of flexographic prints is defined as:

$$Q = f(S, E, A, L) \quad (2)$$

where S – is a linguistic variable, which characterizes the reproduction of a minimum raster dot;

E – is a linguistic variable, which characterizes the parameter of color differences ΔE;

A – is a linguistic variable, which characterizes the parameter of adhesion of printing inks;

L – is a linguistic variable, which characterizes the positioning precision of printing inks.

The evaluation of linguistic variables is held through a system of quality concepts. Each of these concepts makes a relevant fuzzy set, i.e. some property that is considered as a linguistic term. Linguistic variables that provide print quality and evaluation terms, are shown in Table. 1

Table 1. Linguistic variables of the quality of flexographic prints

№	Variable name	Universal set	Fuzzy terms
1	Color differences, E	0-8 units	slight
			medium
			big
2	Image positioning, L	0-0,3 mm	high
			satisfactory
			low
3	Reproduction of minimum raster dot, S	1-5 %	high
			medium
			low
4	Adhesion to the substrate, A	1-5 point	poor
			good
			excellent

Based on the experts' statements in terms of the quality parameters of flexographic prints, we construct membership functions. According to the standards or recommendations, the parameter value "color differences" is defined in the universal set: u_1= 0 units; u_2= 2 units; u_3= 4 units; u_4= 6 units; u_5= 8 units.

For the linguistic evaluation of this parameter we use a set of fuzzy terms: T (E) = <slight, medium, big>. After the formation and solution of the matrix of pair wise comparisons of impact parameter on prints quality in accordance with these terms we get a membership function of the linguistic variable "color differences" (Fig. 2, a).

For the variable "reproduction of a minimum raster dot", the parameter is defined in the universal set: u_1= 1 %; u_2= 2 %; u_3= 3 %; u_4= 4 %; u_5=5 %.

For the linguistic evaluation of a variable we use a set of fuzzy terms: T (S) = <high, medium, low>. After forming the matrix of pair wise comparisons of the parameter "reproduction of a minimum raster dot" in relation to these terms, we obtain the membership function (Fig. 2, b).

We make the membership functions for the linguistic variable "image positioning" as one of the characteristics of prints quality (Fig. 2, c). Image positioning when printing is defined as the universal set: u_1 = 0 mm; u_2 = 0,05 mm; u_3= 0,08 mm; u_4 = 0,12 mm; u_5 = 0,3 mm.

For the linguistic evaluation of the parameter we use a set of fuzzy terms: T (L) = <high, satisfactory, low>. The effect of color matching on precision of prints quality in a membership function is shown in Fig 2, c.

Similarly to previous calculations we define the membership function of the linguistic variable "adhesion of ink layer" (Fig. 2, d). For the variable "adhesion of ink layer", the parameter is determined in the universal set: u_1 = 1 point; u_2 = 2 points; u_3 = 3 points; u_4 = 4 points; u_5 = 5 points. The set of relevant terms: T (L) = <poor, good, excellent>.

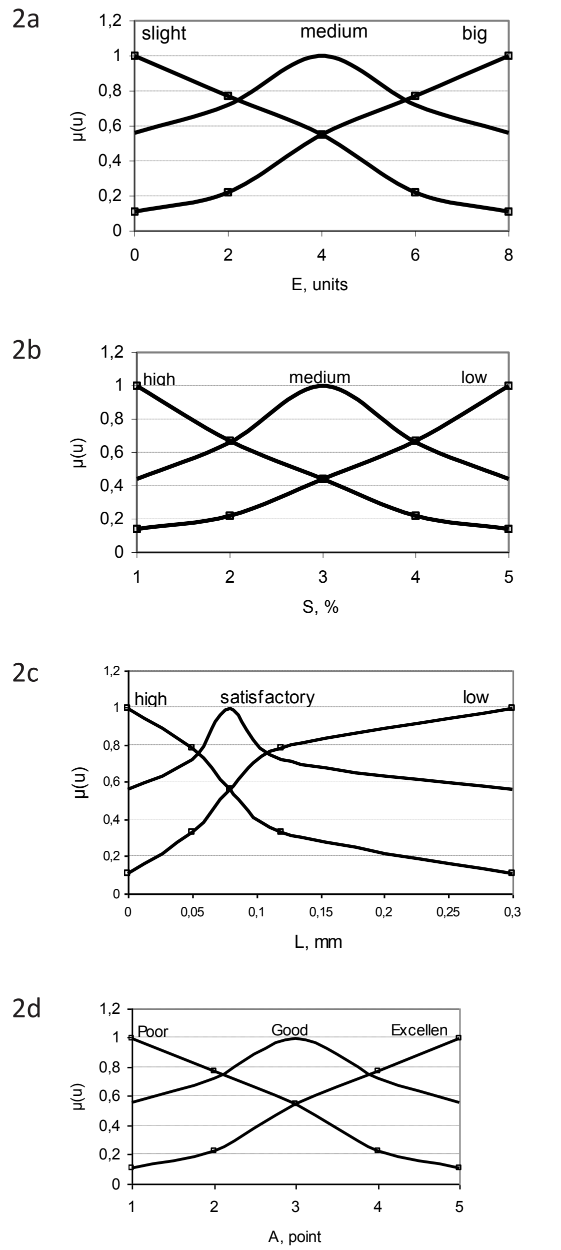

Figure 2. Membership function of linguistic variables: color differences for CMY-inks separately or the average value, E (a), reproduction of a minimum raster dot, S (b), image positioning, L (c), adhesion of ink layer, A (d).

We form the fuzzy knowledge base on the selected quality parameters of flexographic prints:

1. For the term of print quality "high":
   If (E is slight) and (L is high) and (S is high) and (is A excellent)
   or (E is slight) and (L is satisfactory) and (S is high) and (A is excellent)
   or (E is slight) and (L is high) and (S is medium) and (A is excellent)
   then (Q is high).
2. For the term of print quality «medium»:
   If (E is medium) and (L is satisfactory) and (S is high) and (A is excellent)
   or (E is medium) and (L is satisfactory) and (S is high) and (A is good)
   or (E is slight) and (L is low) and (S is medium) and (A is excellent)
   then (Q is medium).
3. For the term of print quality «low»:
   If (E is medium) and (L is satisfactory) and (S is high) and (A is poor)
   or (E is big) and (L is high) and (S is low) and (A is good)
   or (E is big) and (L is low) and (S is medium) and (A is excellent)
   then (Q is low).

Logic equations, providing the quality of flexographic imprints, are as follows:

$$\mu^{high} = \mu^{slight}(E) \wedge \mu^{high}(L) \wedge \mu^{high}(S) \wedge \mu^{\text{excel}}(A) \vee \mu^{slight}(E) \wedge \mu^{satisf}(L) \wedge \mu^{high}(S) \wedge \mu^{\text{excel}}(A) \vee \mu^{slight}(E) \wedge \mu^{high}(L) \wedge \mu^{medium}(S) \wedge \mu^{\text{excel}}(A) \quad (3)$$

$$\mu^{medium} = \mu^{medium}(E) \wedge \mu^{satisf}(L) \wedge \mu^{high}(S) \wedge \mu^{\text{excel}}(A) \vee \mu^{medium}(E) \wedge \mu^{satisf}(L) \wedge \mu^{high}(S) \wedge \mu^{good}(A) \vee \mu^{slight}(E) \wedge \mu^{low}(L) \wedge \mu^{medium}(S) \wedge \mu^{\text{excel}}(A) \quad (4)$$

$$\mu^{low} = \mu^{medium}(E) \wedge \mu^{satisf}(L) \wedge \mu^{high}(S) \wedge \mu^{poor}(A) \vee \mu^{big}(E) \wedge \mu^{high}(L) \wedge \mu^{high}(S) \wedge \mu^{good}(A) \vee \mu^{big}(E) \wedge \mu^{low}(L) \wedge \mu^{medium}(S) \wedge \mu^{\text{excel}}(A) \quad (5)$$

The operations determining minimum and maximum in logic equations are denoted as ˄ and ˅ respectively. Then for any values of two membership functions we obtain two resulting options:

$$\mu_1 \vee \mu_2 = \max(\mu_1, \mu_2) \qquad \mu_1 \wedge \mu_2 = \min(\mu_1, \mu_2) \quad (6)$$

Using the membership functions and substituting the degree of membership in the system of fuzzy logic equations (3-5), we can calculate one of the cases of the impact of selected parameters on the quality of flexographic imprints:

$$\mu^{high} = 0,72 \wedge 0,78 \wedge 0,67 \wedge 0,77 \vee$$
$$0,77 \wedge 0,72 \wedge 0,67 \wedge 0,77 \vee$$
$$0,77 \wedge 0,78 \wedge 0,66 \wedge 0,77 = 0,67$$
$$\mu^{medium} = 0,72 \wedge 0,72 \wedge 0,67 \wedge 0,77 \vee$$
$$0,72 \wedge 0,72 \wedge 0,67 \wedge 0,72 \vee$$
$$0,77 \wedge 0,72 \wedge 0,66 \wedge 0,77 = 0,67$$
$$\mu^{low} = 0,77 \wedge 0,72 \wedge 0,67 \wedge 0,22 \vee$$
$$0,22 \wedge 0,78 \wedge 0,67 \wedge 0,72 \vee$$
$$0,22 \wedge 0,33 \wedge 0,66 \wedge 0,77 = 0,22$$

We can set the upper and lower limit of the quality of flexographic prints Q: bottom – 1 unit, top – 10 units. After defuzzification of the obtained fuzzy values of prints quality (e.g. according to the principle of the center of gravity), we can get a quantitative evaluation of their quality (*Rothstein et al., 2008)*:

$$Q = \frac{\sum_{i=1}^{m} u_i \cdot \mu(u_i)}{\sum_{i=1}^{m} \mu(u_i)}, \quad (7)$$

where *ui* – the output value of linguistic variable on a corresponding interval; *μ(ui)* – membership function.

According, get a quantitative measure of quality:

$$Q = \frac{1 \cdot 0,22 + 5 \cdot 0,67 + 10 \cdot 0,67}{0,22 + 0,67 + 0,67} = 6,58 \ units$$

The formed knowledge base has been verified in simulation (Fig. 3) using Fuzzy Logic Toolbox system of the environment of technological calculations MATLAB on the basis of Mamdani (*Mamdani, Assilian, 1975*). As a defuzzification method we have used the method of "center of gravity".

3a

3b

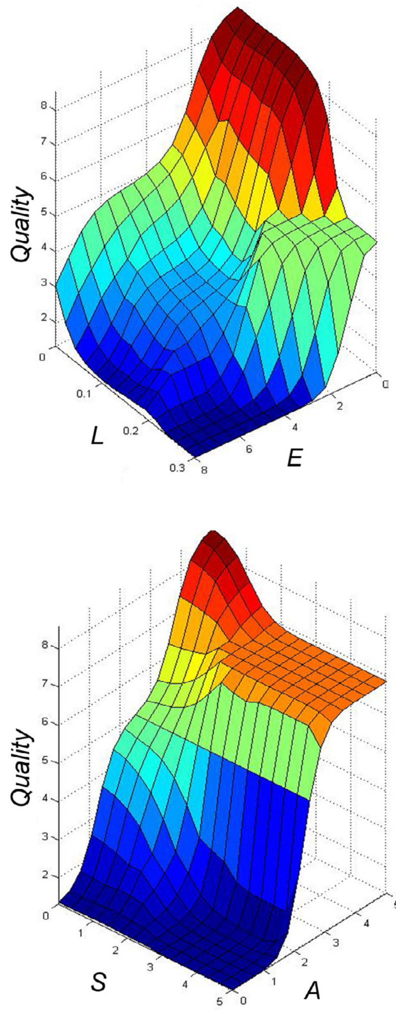

Figure 3. Effect of the print parameters on its quality: image positioning (L) and color difference (E) (a), reproduction of a raster dot (S) and adhesion of ink layer (A) (b).

The simulation results show the adequacy of the developed knowledge base and possibility of its use for the complex evaluation of prints quality for the purpose of statistical analysis of the printing technological process on the relevant production.

4.

Conclusions

Thus, the work has selected the parameters of prints that are independent of each other to some extent, and are taken into account for quality control in the printing production environment. The analysis of parameters of flexographic prints using the expert-linguistic information and "if-then" rule has allowed getting fuzzy logic equations of linguistic variables influence on the quality of flexographic prints and then, evaluating the quality of the printing process comprehensively and quantitatively. The suggested method of calculating imprints quality in a quantitative way enables the development of a simulation model of forecasting and statistical evaluation of the quality of the printing process.

References

1. ASTM F 2252:(2003): Standard Practice for Evaluating Ink or Coating Adhesion to Flexible Packaging Materials Using Tape.
2. Bellman, R., Zadeh, L., 1970. Decision-Making in Fuzzy Environment, Management Science, vol. 17, 4, pp. 141-160.
3. CIE DS 014-6/E:2012. Colorimetry – Part 6: CIEDE2000 colour-difference formula, CIE Central Bureau.
4. Claypole, T., 2003. Recommendation EFTA for colometric characterization of inks, Flexo Plus, 5, [Online] Avaliable from: http://www.kursiv.ru/kursivnew/flexoplus_magazine/archive/35/32.php [Accessed 23th January 2016].
5. Deutschspachinge Flexodruck-Fachgruppe e. V. and Meyer, K.-H., 1999. Technik des Flexodrucks, Verlag Coating Thomas & Co.
6. Dreher, M., 2004. About standardization of flexographic printing process. [Online] Avaliable from: http://www.kursiv.ru/kursivnew/flexoplus_magazine/archive/40/22.php [Accessed 23th January 2016].
7. Durnyak, B., Senkivskyi, V. and Pih, I., 2014. Information technologies prognostication and providing of quality publishing-polydiene processes (Methodology of decision of problem), Technological complexes, № 1 (9), pp. 21-24.
8. FINAT Technical Handbook, 2001. [Online] Avaliable from: http://www.etika.it/servizi/finat/thengels.pdf [Accessed 23th January 2016].
9. Flexographic inks: an integrated approach, 2000. Ukrainian Flexographic Technical Association, page 160.
10. Flexographic Image Reproduction Specifications and Tolerances, 2002. Ukrainian Flexographic Technical Association, page 172.
11. ISO 2846-5: (2005): Graphic technology – Colour and transparency of printing ink sets for four-colour printing. Part 5: Flexographic printing.
12. ISO 12647-6: (2006): Graphic technology – Process control for the production of half-tone colour separations, proofs and production prints. Part 6: Flexographic printing.
13. Izdebska, J. and Sabu T., 2015. Printing on Polymers: Fundamentals and Applications, William Andrew, pp. 15-16.
14. Mamdani, E. and Assilian, S., 1975. An experiment in linguistic synthesis with a fuzzy logic controller, International Journal of Man-Machine Studies, Vol. 7, 1, pp. 1-13.
15. Rothstein, O., Lariushkin, Ye. and Mityushkin, Yu., 2008. Soft Computing in biotechnology: multifactorial analysis and diagnostic, Universum-Vinnytsia, pp. 42-70.
16. Siniak, M., Moyson, P., 2008. Az egyszázalékos rácspont visszaadása a flexónyomtatásban, Magyar Grafika, 2, pp. 15-18.
17. Velychko, O., 2005. Processing of information flow by the interaction of the elements of the printed contact, Publishing center «Kyiv University», pp. 211- 234.

Evaluation of compressive test methods for paper using a mathematical model, based on compressive test for corrugated board

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Abstract

There are several methods for the measurement compressive strength of linerboard and fluting medium paper. The results of different method can vary up to 30% and more for same material sample and the biggest challenge is to determine compressive strength uninfected by other properties. It still isn't specified which method is technically more correct. The Short-Span Compressive Test (SCT) method is assumed to be more accurate. However, the Ring Crush Test (RCT) method is still widely use despite that it is established it is affected by buckling load of test specimen. In this study these two different methods were performed to measure the compressive strength of corrugated board's components. The results were implemented in Maltenfort equation for prediction of board compressive strength. The accuracy of methods was evaluated by comparing predicted compressive strength with measured board edgewise compressive strength (ECT). The result confirmed that SCT method is more successful for predicting compressive strength of corrugated board and therefor, more accurate.

Key words: compression testing, linerboard, fluting medium, corrugated board, Ring Crush Test, Short-Span Compressive Test, Edge Crush Test

1. Introduction

Mechanical resistance of packaging depends on the strength of the packaging material used; i.e. it depends on the paper components that the corrugated board is made of. Mechanical consistency of the packaging, as well as protection of the product inside, depends on compressive strength. Compressive strength is the largest compressive force that a test specimen tolerates without failing. It is one of the most important properties of paperboard (Niskanen, 2008).

Compressive strength of linerboard and/or fluting medium can be measured in various standardized ways: Ring Crush Test (RCT), Short span Compressive Test (SCT) and Corrugated Crush Test (CCT). Most common methods are RCT and SCT. Both measurements are supposed to measure the same property but results can vary up to 30% and more for same material sample (Markstrom, 1999). Principles of method are different; hence results differ because in most cases buckling cannot be prevented. SCT is considering the most reliable compressive strength measurement method however RCT specifications are still widely used as the primary strength characteristic for linerboard and fluting medium (Dimitrov and Heydenrych, 2010). SCT method uses a 0.7 mm length of a specimen which excludes any bending and buckling is prevented while RCT is a combination of compression and buckling failure (Fellers and Donner, 2002). It still isn't specified which method is technically more correct therefore the practice of using RCT method continues.

Compressive strength of linerboard and fluting medium directly depends on compressive strength of the corrugated board (van Eperen et al., 1983; Whitsitt, 1985; Markstrom 1999, Popil et al., 2004). Compressive strength of corrugated board is measured with Edgewise Crush Test (ECT) method. The ECT of corrugated board is used as a primary quality control parameter since it correlates to box stacking strength (McKee and Gander., 1962; Whitsitt, 1988). The ECT is mainly dependent on the compressive properties of the components as predicted by mathematical model known as Maltenfort equation (1) (Markstrom, 1999). It can be estimated using components' compression strength, measured either with RCT or SCT method:

$$ECT = k(\sigma_{c,L1} + \sigma_{c,L2} + \alpha\sigma_{c,F} \ldots) \quad (1)$$

where σ_c is the compressive strength in cross machine direction (CD) of boards' components, linerboard and fluting medium, α denotes take up factor of the specific fluting profile used (the ratio of the length of fluting medium to the length of liner), and the constant *k* should be always equal to unity, regardless of the paper compression strength test used (this is theoretically, if there would not be test errors).

The aim of this research is to estimate which method for compressive strength testing of linerboard and fluting medium gives better predictive accuracy based on Maltenfort equation; Ring Crush Test or Short span Compressive Test, compared to measured board compression strength values using Edgewise Crush Test. The paper confirm that proposed model which uses SCT strength provides significantly better predictor of the ECT then use of the RCT measured values.

2. Material and Methodology

Principle for compressive strength testing according to the RCT method implicated a sample of paper placed into a ring formation and subjected to an increasing edge compression force until it breaks (***, 2016). The main problem is how to prevent the buckling of a thin sample. There is discontinuity point; hence the ends of test specimen are not banded together as shown on Figure 1 (Niskanen, 2008). The RCT data is the average of 10 tests in CD. Measurements were made according to TAPPI – T 822 using L&W Crush Tester.

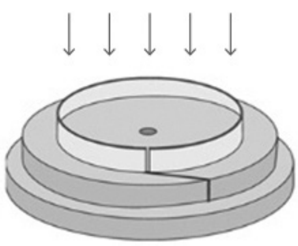

Figure 1. Test specimen in ring formation of RCT method

Compressive strength principle for testing according to the SCT method evaluates the short span compression properties of the paperboard. A test specimen is compressed in the length direction by two clamps 0.7mm apart, until rupture occurs as Figure 2 illustrates. Therefore the buckling is prevented and the compressive properties and strength of paper can be evaluated (Ek et al, 2009). The SCT data is the average of 20 tests in CD direction. Measurements were made according to ISO 9895:2008, for paper and board – compressive strength – Short span test using L&W Short span Compressive Test.

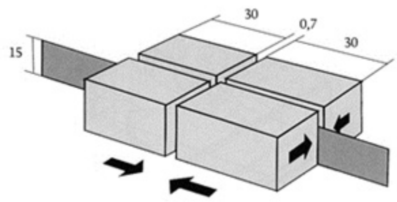

Figure 2. Principle of SCT method

A test specimen of prepared sample of corrugated board at ECT method is placed on its edge between parallel platens, one of which traverses towards the other and is connected to a load cell. Load direction is parallel to the flutes or the cross direction of the board (Figure 3). The ECT data is the averages of 10 tests according to ISO 3037:2013; for corrugated fibreboard - determination of edgewise crush resistance (unwaxed edge method). L&W Crush Tester was used.

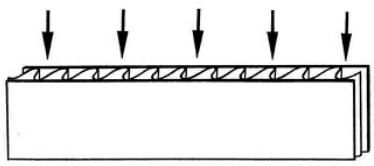

Figure 3. Test specimen consisted of cutting samples parallel to the flute direction (CD)

To determine correlation between compressive strength of corrugated board and its components, two single wall (double face) boards with B flute were analysed. Board known as quality 271 was analysed with its component's paper: two linerboards, 125 g/m² and 120 g/m²; and one medium 100 g/m² and board known as quality 276 with its component's paper: two linerboards, 180 g/m² and 170 g/m²; and one medium 150 g/m².

3. Results and Discussion

Results of compressive strength of linerboard and fluting medium measured with the RCT and SCT method are summarized in Table 1 and Table 2. As it was expected strength is increasing as basis weight of papers increase. Although these two methods are measuring the same property, outcomes are different. According to results it can be deduced that paper at RCT method had suffered certain failure, therefore measured values are lower up to 16%.

Table 3 obtained the ECT measured results of compressive strength of single wall corrugated boards known as quality 271 and quality 276, both with B flute.

Table 3. Test specimen results for ECT

	x̄ (kN/m)	σ	max (kN/m)	min (kN/m)	median (kN/m)
Board 271	2,50	0,06	2,63	2,40	2,51
Board 276	4,81	0,09	4,98	4,65	4,815

Comparisons are made with values of the predicted ECT calculated from equation (1) and actual ECT values obtained from Crush tester. The compression strength of linerboard and medium, measured by the short span compressive method uses constant k=0,6982; and for ring crush data uses k=1,028 (Seth, 1985; Dimitrov and Heydenrych, 2010). Take up factor for B flute amounts α=1,25.

Table 4. Predicted and calculated differs of ECT values

Method for ECT prediction	predicted ECT (kN/m)	empirical ECT (kN/m)	differ (%)
ECT from RCT (quality 271)	3,03	2,50	21,2
ECT from SCT (quality 271)	2,58	2,50	3,2
ECT from RCT (quality 276)	5,47	4,81	13,7
ECT from SCT (quality 276)	4,91	4,81	2,07

Predicted ECT values calculated from equation (1) differ from actual ECT values, depending on the selected testing method. According to results summarised in Table 4 disagreements of actual values from predicted values are larger for RCT data. Predicted ECT from RCT measured results differ by 21,2% for quality 271 and 13,7% for quality 276. An error in prediction for RCT occurs possibly in buckling failure. The expected ECT from SCT data is more precise. Predicted ECT from SCT measured results differ by 3,2% for quality 271 and 2,07% for quality 276. This statistically indicates that useful predictive model for ECT is better suited from SCT strength.

Table 1. Test specimen results for the RCT and the SCT of board 271 in CD

	RCT (CD)				SCT (CD)				
Paper	**x̄ (kN/m)**	**σ**	**max (kN/m)**	**min (kN/m)**	**x̄ (kN/m)**	**σ**	**max (kN/m)**	**min (kN/m)**	**differ (%)**
Medium 100 g/m²	0,97	0,12	1,17	0,81	1,08	0,12	1,17	0,81	-10,18
Linerboard 1 120 g/m²	1,27	0,05	1,34	1,19	1,48	0,14	1,68	1,42	-14,18
Linerboard 2 125 g/m²	1,37	0,07	1,42	1,24	1,59	0,14	1,70	1,47	-13,83

Table 2. Test specimen results for the RCT and the SCT of board 276 in CD

	RCT (CD)				SCT (CD)				
Paper	**x̄ (kN/m)**	**σ**	**max (kN/m)**	**min (kN/m)**	**x̄ (kN/m)**	**σ**	**max (kN/m)**	**min (kN/m)**	**differ (%)**
Medium 150 g/m²	1,63	0,33	2,59	1,45	1,92	0,13	2,1	1,69	-15,10
Linerboard 1 170 g/m²	1,78	0,28	2,18	1,33	2,09	0,18	2,54	1,9	-14,83
Linerboard 2 180 g/m²	1,85	0,18	2,11	1,53	2,22	0,33	3	1,9	-16,66

4. Conclusion

An analytical model that combines the compressive strength of the linerboards and fluting medium provides an important predictive accuracy for ECT data and reliable ECT information contribute to the paperboard packaging product with optimized mechanical properties at minimal cost without compromising the protection function of the packaging.

The ECT value of corrugated board was measured and analysed in this paper in three different methods for chosen approach of evaluating selected measurement techniques. Direct measured board edgewise compressive strength values were used to provide guidance for the interpretation and qualification of testing results of two most common methods for compressive strength testing of linerboard and fluting medium, the RCT and the SCT method. Measured results of each method were implemented in mathematical model of Maltenfort equation, calculated and gained results were compared to actual ECT values. Comparison showed that the SCT data used in mathematical model relates better to the ECT prediction since the gained result of Maltenfort equation with SCT data is nearly identical to direct measured ECT value. Additionally, it is expected that RCT data implicate buckling load which is seen as increased value of the ECT obtained from the RCT measured values. The analysis presented in this paper is a contribution to SCT method and implies substitution of RCT method which is still significantly used as relevant indicator of compressive strength of paper.

5. References

1. Dimitrov K, Heydenrych M. 2010. Relationship between the edgewise compression strength of corrugated board and the compression strength of liner and fluting medium papers, Southern Forests: a Journal of Forest Science, 2009, 71(3): 227–233, ISSN 2070–2620
2. Ek M., Gellerstedt G., Henriksson G., 2009, Pulp and Paper Chemistry and Technology, Paper Products Physics and Technology, Berlin: De Gruyter
3. Fellers C, Donner BC. 2002. Edgewise compression strength of paper. In: Mark RE, Habeger CC Jr, Borch J, Lyne MB (eds), Handbook of physical testing of paper, vol. 1 (2nd edn). New York: Marcel Dekker. pp 481–525.
4. Markstrom H. 1999. Testing methods and instruments for corrugated boards (5th edn). Ostervala: Lorentzen and Wettre.
5. McKee RC, Gander JW. 1962. A study of the dominant factors of box compression strength. Part 2, verification of the simplified formula for top-load compression strength of commercial boxes.
6. Niskanen K., 2008. Papermaking Science and Technology, Paper Physics, Finland: Finnish Paper Engineers' Association/Paperi ja Puu Oy
7. Popil RE, Coffin DC, Kaewmanee P. 2004. The role of liner buckling on the edgewise compressive strength of corrugated board. Abstract for paper presented at the 2004 Progress in Paper Physics Seminar, Trondheim, Norway, 21–24 June.
8. Seth, R.S. 1985 ."Relationship between edgewise compressive strength of corrugated board and its components," Tappi Journal 68(3), 98-101
9. van Eperen RH, Sprague CH. 1983. ECT/component relationships. Project 3511, report two: a progress report to the Fourdrinier Kraft Board Group of the American Paper Institute and Fiber Box Association. Appleton: Institute of Paper Chemistry, Georgia Institute of Technology.
10. Whitsitt WJ. 1985. Compressive strength relationships and factors. IPC Technical Paper Series No. 163. Appleton: Institute of Paper Chemistry, Georgia Institute of Technology.
11. Whitsitt WJ. 1988. Papermaking factors affecting box properties. PC Technical Paper Series No. 288. Appleton: Institute of Paper Chemistry, Georgia Institute of Technology.
12. ***(2016) http://www.tappi.org/content/sarg/t822.pdf, (accessed 4th February 2016)